14th International Conference on the Physics of Highly Charged Ions

HCI2008

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The University of Electro-Communications

Chofu, Tokyo, JAPAN

Book of Abstracts

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HCI2008, Tokyo, JAPAN

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Scientific Program

SCIENTIFIC PROGRAM

Monday, 1st September

08:30 -		Registration & paper submission
09:00 - 09:20		Opening session

Chair: Yasunori Yamazaki

09:20 - 10:05	RL1	**Bernd A. Huber (France)** *Slow ion collisions involving molecules of biological interest*
10:05 - 10:25	ST1	**Li Chen (France)** *Fragmentation of Small biomolecules induced by highly charged ion impact*
10:25 - 11:00		Coffee break

Chair: Amine Cassimi

11:00 - 11:30	PR1	**Walter Meissl (Austria)** *Response of insulator surfaces to a very slowly approaching highly charged ion*
11:30 - 11:50	ST2	**Rene Heller (Germany)** *Formation of nano pits on the KBr (001) surface induced by single impact of slow highly charged ions*
11:50 - 12:10	ST3	**Christopher A. Hunniford (United Kingdom)** *Low energy carbon ion irradiation of water ices*
12:10 - 12:30	ST4	**Takato Hirayama (Japan)** *Potential sputtering of ionic species from rare gas solids by multiply charged ion impact*
12:30 - 14:30		Lunch break

Chair: Yaming Zou

14:30 - 15:15	RL2	**Leonti Labzowsky (Russia)** *Tests of fundamental theories with heavy ions: Current status and future prospects*
15:15 - 15:35	ST5	**Matthias Hobein (Sweden)** *Re-trapping and Cooling Highly-Charged Ions*
15:35 - 16:05	LR1	**Shunsuke Ohtani (Japan)** *Construction and operation of the Tokyo EBIT*

16:30 - Tokyo-EBIT Laboratory tour

Tuesday, 2nd September

Chair: Eva Lindroth

09:00 - 09:45 RL3 **Stefan Schippers (Germany)**
Electron-ion collision experiments at storage rings: Fundamental processes and astrophysical implications

09:45 - 10:05 ST6 **Xiaolong Zhu (China)**
The first test experiment performed at the electron cooler of storage rings in Lanzhou

10:05 - 10:25 ST7 **Christian Beilmann (Germany)**
Observation of higher order resonant electron recombination processes by highly charged krypton ions

10:25 - 11:00 Coffee break

Chair: to be announced

11:00 - 11:30 PR2 **Theo J.M. Zouros (Greece)**
Non-statistical population of 1s2s2p ^{4}P quartet states by electron transfer into multiply charged ions

11:30 - 11:50 ST8 **Miriam Frankel (USA)**
X-ray signatures of charge exchange in L-shell ions

11:50 - 12:10 ST9 **Yoh Itoh (Japan)**
State-selected differential cross section measurements for the one-electron capture processes in the F^{4+} - He, Ne, Ar systems at E_{lab} = 45 eV

12:10 - 12:30 ST10 **Zoran D. Pešić (Germany)**
Strong forward-backward asymmetry of H_2O ionic fragments by slow highly charged ions impact

12:30 - 14:30 Lunch break + Posters set up

Chair: Joachim Burgdörfer

14:30 - 15:00 PR3 **Kenji Motohashi (Japan)**
Fragmentation and desorption in low-energy highly charged ion collisions with molecules and surfaces

15:00 - 15:30 PR4 **Henning Lebius (France)**
Regular nanostructures by swift heavy ions

15:30 - 15:50 ST11 **Nenad Bundaleski (France)**
Collisions of ions with insulating surfaces: Charging and discharging dynamics

16:00 - 18:00 **Poster session A**

Wednesday, 3rd September

Chair: Ronnie Hoekstra

09:00 - 09:45 RL4 **Tetsuya Watanabe (Japan)**
Spectroscopy of highly charged ions in solar and astrophysical plasmas

09:45 - 10:05 ST12 **Peter Beiersdorfer (USA)**
Evolution of X-ray calorimeter spectrometers at the Lawrence Livermore electron beam ion trap

10:05 - 10:30 Coffee break

Chair: Fred J. Currell

10:30 - 11:00 PR5 **Roger Hutton (China)**
Progress of the spectroscopy research platform at the Shanghai EBIT

11:00 - 11:30 PR6 **Katharina Kubiček (Germany)**
High accuracy test of QED at the Heidelberg EBIT

11:30 - 11:50 ST13 **Oleg Yu. Andreev (Russia)**
QED calculation of interelectron interaction corrections for transition probabilities in two-electron ions

11:50 - 13:00 Lunch break

13:00 - 22:00 **Excursion + Conference dinner (Hotel Mt. Fuji)**

Thursday, 4th September

Chair: to be announced

09:30 - 10:15 RL5 **Gerry O'Sullivan (Ireland)**
Emission and absorption in laser produced plasmas: Processes and applications

10:15 - 10:35 ST14 **Anatoly Ya. Faenov (Russia)**
Observation and modeling of hollow multicharged ions X-ray spectra radiated by laser produced plasma

10:35 - 11:00 Coffee break

Chair: Jose R. Crespo López-Urrutia

11:00 - 11:30 PR7 **Andrey Surzhykov (Germany)**
Relativistic and many–body effects in radiative recombination of heavy ions

11:30 - 11:50 ST16 **Ke Yao (China)**
Precise experimental and theoretical studies on resonant energies of the KLL dielectronic recombination processes for He- up to O-like xenon

11:50 - 12:10 ST17 **Martin Andersson (China)**
Hyperfine dependent lifetimes in neon like ions

12:10 - 14:00 Lunch break + Posters set up

Chair: Dominique Vernhet

14:00 - 14:30 LR2 **Tetsuya Ishikawa (Japan)**
Compact X-ray free electron laser in Japan

14:30 - 14:50 ST18 **Yuji Nakano (Japan)**
Selective formation of multiply excited states by resonant coherent excitation

14:50 - 15:10 ST19 **Vsevolod Balashov (Russia)**
Density matrix description of resonant coherent excitation of swift highly charged ions in oriented crystals

15:30 - 17:30 **Poster session B**

Friday, 5th September

Chair: Fernando Martín

09:00 - 09:45 RL6 **Robert Moshammer (Germany)**
Strong field electron dynamics in intense laser fields

09:45 - 10:05 ST20 **Kengo Moribayashi (Japan)**
Atomic processes of damage on bio-molecules irradiated by XFEL

10:05 - 10:25 ST21 **Yew Kam Ho (Taiwan)**
Effects of Debye plasmas on the resonance states of highly stripped two-electron ions using the stabilization method

10:25 - 11:00 Coffee break

Chair: Henrik Cederquist

11:00 - 11:30 PR8 **Shuhei Yoshida (Austria)**
Momentum distribution of highly charged ions formed by strong laser fields

11:30 - 11:50 ST22 **Christophe Prigent (France)**
Optimal pulse duration in laser-cluster interactions

11:50 - 12:10 ST23 **Lokesh C. Tribedi (India)**
Evidence of giant dipole plasmon resonance in electron spectrum of C_{60} and beam induced polarization

12:10 - 12:30 ST24 **Henning Zettergren (Spain)**
Stability of highly charged fullerene cations and anions

12:30 Adjourn

14:30 (SPARC session)

Invited Talks

Slow ion collisions involving molecules of biological interest

Bernd A. Huber

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In recent years the interest in studying collision induced processes with biomolecular species has increased considerably, not only motivated by the aim to better understand the fundamental fragmentation processes at the molecular level, but also due the relevance of these processes in radiation damage schemes and their possible importance for cancer therapy applications. Whereas collision studies with fast ions, x-rays and electrons have started out much earlier, the interest in slow ion collisions is more recent as it was recognised that they may play an important role as primary particles when high-energy ions are slowed down due to the interaction with matter to the so-called Bragg Peak energy, where most of the energy is deposited, or as slow recoil particles produced along the ion track formed by the primary irradiation.

For detailed studies many experiments have been performed in the gas phase with isolated biomolecules applying mass spectrometric techniques. The practical relevance of these studies might be questioned due to the absence of a natural environment. Small biomolecular systems are mostly produced by evaporation techniques, whereas larger ones require the use of Electro Spray or ablation techniques. The latter ones allow also for preparing solvated systems and fore studying the influence of the environment on the fragmentation and dissociation patterns. Thus, experiments with isolated systems and those embedded in water clusters or in a 'chemical' environment, like biomolecular clusters, become feasible and the results can be compared.

In the present contribution we will focus on different collision processes and the corresponding induced molecular damage. We will discuss different cases where in the collision either only energy is transferred to the biomolecular system leading to collision induced dissociation processes (CID), or where electron(s) are taken away by multi-electron capture forming unstable multiply charged biomolecules or where electron(s) are added to an ionic system provoking its dissociation (ECID). The results will be discussed for isolated as well as for 'nano-solvated' species.

TESTS OF FUNDAMENTAL THEORIES WITH HEAVY IONS: CURRENT STATUS AND FUTURE PROSPECTS

Leonti Labzowsky

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During the last few decades a considerable progress was made both in experimental and theoretical studies of the few-electron Highly Charged Ions (HCI). These studies can be considered as the tests of the Quantum Electrodynamics (QED) in strong fields. The Coulomb field of the nucleus in the HCI exceeds by its magnitude all the electric fields available at the moment in the laboratories. The most accurate comparisons of the experimental and theoretical results were performed for the energy levels including the second-order (two-loop) radiative corrections, for the hyperfine splittings and for the bound-electron g-factors. The measurement of g-factors combined with the precise theoretical calculations allowed for the new and most precise determination of the electron mass.

Up to now the tests of QED are the unique tests of the fundamental theories with HCI where the experimental results are available. However, in principle, the HCI provide the possibilities for testing the very broad field of the modern fundamental theories. First, it concerns the tests of the Standard Model (SM) in the low-energy limit via observing the space Parity Nonconservation (PNC) effects in HCI. Up to now the PNC effects were observed only in the heavy neutral atoms where the theoretical calculations required for the extraction of the SM parameters from the experimental data, are very involved. At the moment the agreement with the high-energy results for SM does exist. Still the PNC experiments with the few-electron HCI where the theory is much more clearer would be of essential importance. The most feasible PNC experiments with HCI require the employment of the polarized HCI beams . Suggestions for the ion beam polarization also are discussed in this talk.

The PNC experiments with the polarized HCI beams would allow a direct observation of the anapole moments of the nuclei which originate from the PNC effects inside the nuclei and represent the new nuclear property. Up to now only the indirect observation of the nuclear anapole moment contribution to the PNC effect was registered in the experiments with neutral atoms.

There are suggestions to observe the effects of the space- and time-parity nonconservation (P,T-nonconservation) in HCI. These effects, discovered more than 50 years ago in the meson physics, should allow also for the existence of the Electric Dipole Moment (EDM) of the particles: electrons, protons, neutrons, nuclei, atoms, molecules etc. In spite of the very intensive experimental search for the EDMs of all these particles , initiated by numerous theoretical suggestions, no firm evidence for the existence of EDM is yet found..The HCI physics provides some prominent possibilities for the observation of the EDMs for the nuclei. These possibilities are discussed in the present talk.

The latest developments in the modern fundamental theories include the search for the time variation of the fundamental constants. The first observation of such time dependence for the fine structure constant which follows from the astrophysical data was reported recently. This observation is not yet confirmed neither by the other astrophysical observations nor by the laboratory experiments. The HCI provide a good opportunities for testing the time dependence of the fine structure constant and the electron to proton mass ratio. These opportunities are also discussed in the talk.

Electron-Ion Collision Experiments at Storage Rings: Fundamental Processes and Astrophysical Implications

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Heavy-ion storage rings equipped with electron coolers are an excellent experimental environment for electron-ion collision studies. Some recent studies of dielectronic recombination (DR) focussed on high-resolution spectroscopy of highly-charged ions. Highlights of this research are the measurement of the hyperfine induced decay rate of the $1s^2\,2s\,2p\;{}^3P_0$ state in berylliumlike Ti^{18+} [1] utilizing DR at the storage ring TSR of the Heidelberg Max-Planck-Institute for Nuclear Physics, the observation of the isotope shift in DR of three-electron Nd^{57+} [2] using different isotopes of this ion at GSI's storage ring ESR and the observation of the hyperfine splitting of Sc^{18+} low-energy DR resonances at the TSR high-resolution electron target [3]. The latter experiment resulted in the determination of the $Sc^{18+}(2s_{1/2} - 2p_{3/2})$ energy splitting with an uncertainty of only 4.6 ppm which is less than 1% of the few-body effects on radiative corrections [4].

Another line of research is the determination of absolute photorecombination rate coefficients for astrophysical and other plasma physical applications [5-8]. Storage ring experiments provide particularly valuable information on DR in low-temperature plasmas such as photoionized plasmas that occur e. g. in active galactic nuclei in the vicinity of super-massive black holes. In such plasmas highly charged ions exist at relatively low temperatures. For many ions, the DR rate coefficients, that determine the charge balance in these plasmas, depend sensitively on the low-energy DR resonance structure at relative electron-ion energies below $\lesssim 3$ eV [9]. Even state-of-the-art theoretical methods are not always capable of calculating the low-energy DR resonance structure with sufficient accuracy to satisfy the astrophysical data needs [10]. For the time being, storage ring experiments are the only reliable source for low-temperature DR data and therefore provide valuable benchmarks for the further development of the theoretical tools.

References

[1] S. Schippers *et al.*, Phys. Rev. Lett. **98**, 033001 (2007).

[2] C. Brandau *et al.*, Phys. Rev. Lett. **100**, 073201 (2008).

[3] A. Wolf *et al.*, Hyperfine Interact. **172**, 111 (2006).

[4] M. Lestinsky *et al.*, Phys. Rev. Lett. **100**, 033001 (2008).

[5] A. Müller and S. Schippers, ASP Conference Proceedings, **247**, 53 (2001).

[6] I. Orban *et al.*, Astron. Astrophys. **459**, 291 (2006).

[7] D. W. Savin *et al.*, Astrophys. J. **642**, 1275 (2006).

[8] E. W. Schmidt *et al.*, Astrophys. J. Lett. **641**, L157 (2006).

[9] S. Schippers *et al.*, Astron. Astrophys. **421**, 1185 (2004).

[10] G. Ferland, Annu. Rev. Astron. Astrophys. **41**, 517 (2003).

Spectroscopy of Highly Charged Ions in Solar and Astrophysical Plasmas

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Matter in the Universe is not distributed uniformly; some is very hot, highly ionized, may not be in thermal equilibrium, or even not thermalized. Spectroscopy of lines originating from highly charged ions is surely of crucial importance to understand the characteristics of these hot plasmas in the Universe. One of the fastest ways to understand the characteristics of astrophysical plasmas is to understand those of solar plasma, because it is believed that most of the phenomena happening somewhere in the Universe really take place on the Sun. In addition, the Sun serves as "a laboratory in space," which shows interesting experiments of plasma physics on a gigantic scale. Spectroscopic observation of EUV emission lines in the transition-region and corona provide unique information on physical conditions in these outer atmospheres of the Sun.

The EUV Imaging Spectrometer (EIS) on board Solar-B [1] is capable of observing, for the first time in Solar EUV observations, spectra and monochromatic images of possibly non-ionization-equilibrium plasmas in the solar transition-region and corona at two-wavelength bands of 170 - 210Å and 250 - 290Å, with typical time-resolutions of 1 - 10 seconds. Dynamic plasma accelerations and heating are found to take place in the solar atmospheres, and they are confined in tiny structures.

Time-dependent collisonal-radiative model for the element of iron is developed to diagnose temperatures and densities of those plasmas in the outer atmospheres of the Sun; no systematic models yet exist for iron ions at the ionization stages of L- and M-shells, which are very important for coronal plasma diagnostics. Adopting the best available theoretical calculations of atomic parameters of these iron ions, as well as generating the experimental data, it is one of the aims of our research that the mechanism of coronal heating is addressed via accurate diagnostics information obtained by the EIS instrument.

References

[1] J. L. Culhane, L. K. Harra, A. M. James, K. Al-Janabi, L. J. Bradley, R. A. Chaudry, K. Rees, J. A. Tandy, P. Thomas, M. C. R. Whillock, B. Winter, G. A. Doschek, C. M. Korendyke, C. M. Brown, S. Myers, J. Mariska, J. Seely, J. Lang, B. J. Kent, B. M. Shaughnessy, P. R. Young, G. M. Simnet, C. M. Castelli, S. Mahmoud, H. Mapson-Menard, B. J. Probyn, R. J. Thomas, J. Davila, K. Dere, D. Windt, R. Hagood, R. Moye, H. Hara, T. Watanabe, K. Matsuzaki, T. Kosugi, V. Hansteen and Ø. Wikstol; Solar Phys., **243**, 19 - 61 (2007).

EMISSION AND ABSORPTION IN LASER PRODUCED PLASMAS; PROCESSES AND APPLICATIONS

Gerry O'Sullivan,

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Laser produced plasmas have been used for many years as intense sources of extreme ultraviolet (EUV) and soft x-ray radiation. Depending on the choice and composition of target the EUV spectra can be dominated by line, unresolved transition array or continuum emission. Nowadays, volume microchip manufacturing is performed using 193 nm excimer laser radiation with which feature sizes of 45 nm can be attained. However Moore's Law requires a doubling of processor speed every eighteen months and is predicated on a 40% reduction in feature size. To begin manufacturing at feature sizes of 32 nm and below requires the introduction of a new technological step, namely EUV Lithography, which is based on the availability of mirrors with high reflectivity in a 2% bandwidth at 13.5 nm wavelength. Much effort is being expended on the development of suitable sources because of the power requirement of ~500 W of in-band radiation with no ions or debris for high volume manufacturing. The UTA emission from laser produced plasmas using tin provide a potential solution [1].

The results of recent experimental measurements of absolute in-band and out of band intensity, ion distribution and debris will be presented. It has been shown that, because of opacity effects, the conversion efficiency is sensitive to ion density and laser wavelength [2, 3]. Various schemes to improve the conversion efficiency will be discussed. The results of recent plasma modelling calculations will also be presented and compared with experiment.

In addition, laser produced plasmas of some high Z elements emit intense line free continua over extensive energy ranges [4]. Some recent results on inner shell photoabsorption spectra of ions obtained using these continua will be discussed. .

References:

[1] *"EUV Sources for Lithography"* editor Vivek Bakshi, Publ. SPIE 2006

[2] P. Hayden, A. Cummings, N. Murphy, G. O'Sullivan, P. Sheridan, J. White, and P. Dunne, *J. Appl. Phys 99* 093302 2006

[3] K. Nishihara *et al. Proceedings of 6th International Sematech EUVL Symposium*, Sapporo, Japan 2007

[4] J. T. Costello, E. T. Kennedy, J.-P. Mosnier, P. K. Carroll, and G. O'Sullivan, *Phys. Scr.*, T **34**, 77 (1991).

Strong field electron dynamics in intense laser fields

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So-called 'Reaction Microscopes' enable kinematically complete experiments of atomic and molecular break-up reactions with ultimate completeness. We used these 'bubble chambers' of atomic physics to investigate the many-electron quantum-dynamics under the influence of external time-dependent fields in various situations: The response of atoms and molecules on femtosecond (10^{-15} s) time-scales has been probed by exposing them to intense (up to 10^{16} W/cm^2) ultra-short laser pulses. In pump-probe experiments the rotational and vibrational motion of small molecules was followed in real-time and it is hoped that in near future even the formation of new bonds can be traced as function of time. In first experiments with VUV laser pulses from the free-electron laser FLASH in Hamburg the simultaneous absorption of two or three photons has been studied, a regime that is completely unexplored up to now. In very recent experiments at FLASH it was found that the conformational and electronic structure of molecules can be explored in utmost detail with intense VUV laser pulses. Presently, work is in progress to visualize, for the very first time, the breaking of chemical bonds as a function of time and, thus, to realize the dream of producing a "molecular movie".

RESPONSE OF INSULATOR SURFACES TO A VERY SLOWLY APPROACHING HIGHLY CHARGED ION

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Contrary to the interaction of slow highly charged ions with conducting targets, the physical scenario of their impact on insulators is not very well understood by now. A deeper understanding of this interaction is desirable as it would aid their employment as a gentle tool for surface nanostructuring, where they have been recently shown to induce similar defect as swift (≈ GeV) heavy ions, but at a much lower cost and without damaging the deeper layers of the target.

Upon impact on a solid surface the potential energy stored in slow highly charged ions (HCI) is primarily deposited into the electronic system of the target. With respect to electron emission, the charge mobility on these targets is limited; therefore the electron holes created during the impact of a HCI might interfere with the incoming projectile and therefore alter the interaction process ("trampoline-effect"?). Electron emission experiments were performed on insulating KBr, LiF and CaF_2 single crystal surfaces bombarded by slow highly charged xenon ions. We have recently shown [1] that for somewhat faster ions (≈ keV/amu) impinging on insulators, the "hollow-atom" decay process is by far not complete at the time of impact, as a strong sub-surface contribution to the electron emission yield was found. More recent experiments with very slow (down to 30 eV/amu) Xe HCI show a velocity dependence of the electron yield on the impact velocity that clearly deviates from the case of metallic surfaces.

CaF_2(111) surfaces that have been irradiated by slow highly charged ions have been analyzed by atomic force microscopy (AFM). We have observed hillock-like topographic nanostructures which are stable in air and non erasable by AFM scanning [2]. The number density of surface structures is identical to the applied fluence, thus every individual ion creates one nano-hillock. A sharp and well-defined threshold of potential energy is required for the onset of hillock formation but neither the threshold nor the size of the structures strongly depend on the kinetic energy of the projectiles [2,3]. We show that similar to the swift heavy ion case, the emission of energetic electrons into the solid and the conversion of these electrons into lattice vibrations give rise to a local melting of the impact region. Simulations of the dissipation of potential energy into the target material on the basis of an extended classical over-the-barrier model have been performed to facilitate the interpretation of the experimental findings [4].

This work has been supported by Austrian Science Foundation FWF (P17449-N02) and by the European Project RII3\#026015. Transnational access to the Rossendorf ion beam facilities was provided through AIM (EU contract no. 025646).

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References

[1] W. Meissl, *et al.*, e-J. Surf. Sci. Nanotech. **6** (2008) 54
[2] A. S. El-Said, *et al.*, Phys. Rev. Lett. 100 (2008) 237601
[3] F. Aumayr, A. S. El-Said, W. Meissl, Nucl. Instum. Meth. Phys. Res. B **266** (2008), 2729
[4] C. Lemell, et al., Solid State Electron., **51** (2007) 1398

NON-STATISTICAL POPULATION OF 1s2s2p ^{4}P QUARTET STATES BY ELECTRON TRANSFER INTO MULTIPLY CHARGED IONS

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A mechanism for the *selective* population of 1s2s2p ^4P_J states by electron capture in energetic collisions of F^{7+}(1s2s ^{3}S) ions with H_2 and He has recently been elucidated [1]. Detailed single electron capture calculations within the Continuous Distorted Wave (CDW) [2] and Classical Trajectory Monte Carlo (CTMC) [3] frameworks both indicate (1s2s ^{3}S) nl ^{2}L doublet and ^{4}L quartet levels to be approximately evenly populated for n=2-5. Following electron capture into the (1s2s ^{3}S) metastable fraction of the ion beam, the populated (1s2s ^{3}S) nl ^{2}L doublet states are found to Auger decay strongly to the $1s^2$ ground state, and thus only negligible feeding to other lower lying doublets by radiative transitions is possible. The (1s2s ^{3}S) nl ^{4}L quartet states, however, find both Auger or radiative decay to the $1s^2$ ground state blocked by spin conservation. Instead they can only radiatively cascade through lower lying *quartets*, eventually strongly populating the lowest-lying 1s2s2p ^4P_J levels [4]. These theoretical results based on Hartree-Fock calculations using the Cowan code and a time dependence cascade analysis are in agreement with existing experimental zero-degree Auger projectile measurements by Lee *et al.* [5] for collision energies above 0.7 MeV/u and also with the recent results of Tanis *et al.* [6]. However, for collision energies below 0.7 MeV/u the present theory seems to underestimate the populations of both 1s2s2p ^{2}P doublets and 1s2s2p ^4P_J quartets for reasons not yet understood. The present status of our results will be presented together with a discussion of alternative scenarios such as the recently proposed Pauli exchange interaction [6, 7].

References

[1] T. J. M. Zouros, B. Sulik, L. Gulyás and K. Tőkési, Phys. Rev. A**77**, 050701R (2008).
[2] L. Gulyás, P. D. Fainstein, and T. Shirai, Phys. Rev. A **65**, 052720 (2002).
[3] K. Tőkési and A. Kövér, J. Phys. B**33**, 3067 (2000).
[4] T. J. M. Zouros, B. Sulik, L. Gulyás, and A. Orbán, J. Phys. B **39**, L45 (2006).
[5] D. H. Lee, P Richard, J. M. Sanders, T. J. M. Zouros, J. L. Shinpaugh and S L Varghese, Phys. Rev. A**44**, 1636 (1991); *ibid.* Nucl. Instrum. Meth. Phys. Res. B**56/57**, 99 (1991).
[6] J. A. Tanis, A. L. Landers, D. J. Pole, A. S. Alnaser, S. Hossain and T. Kirchner, Phys. Rev. Lett. **92**, 133201 (2004); *ibid*. **96**, 019901(E) (2006).
[7] D. Strohschein, D. Röhrbein, T. Kirchner, S. Fritzsche, J. Baran, J. A. Tanis, Phys. Rev. A**77**, 022706 (2008).

FRAGMENTATION AND DESORPTION IN LOW-ENERGY HIGHLY CHARGED ION COLLISIONS WITH MOLECULES AND SURFACES

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Electron capture, which is one of the most fundamental and characteristic phenomenon in low-energy highly charged ion (HCI) collisions, often induces fragmentation of molecules and desorption from or sputtering of surfaces. The reactions have significant selectivity, since the excitation processes have quasi-resonant features and very large cross sections. Roughly speaking, electron-capture cross section increases linearly with an increase in the charge state of incoming HCIs. [1] Some electronic transitions can only participate in the reaction when nuclear motion does not affect the collision. Therefore, HCI excitation makes it possible to induce state-selective reactions more effectively than excitation with any other charged particles such as electrons, singly charged ions, and cluster ions. Electron-capture collisions with small scattering angles or large impact parameters, in other words, offer the possibility of filtering a specific reaction channel, because nuclear motion does not affect the reaction much. [2, 3]

Coincidence detection of multiple emitted particles is a powerful tool in the spectroscopic studies of reactions. Momentum imaging offers a new method of analysis when combined with translational energy spectroscopy or energy-gain spectroscopy of scattered HCIs. [2-4]

This technique was successful in specifying the reaction pathways of the electronic transitions of molecules and following the dissociation processes in CF_4 and N_2. [2, 3] Recently, we had success in secondary ion mass spectroscopy (SIMS) of the topmost layer of both GaN (0001) and $(000\bar{1})$ surfaces. [5] The SIMS technique allows us to develop an *in situ* quantitative lattice-polarity analysis of compound crystals. We are developing SIMS with atomic-depth resolution, [6] and have already obtained preliminary results of proton desorption with atomic-depth resolution. [7] This HCI-SIMS technique makes it possible to measure depth profiles of hydrogen adsorbed in interstitial sites very sensitively. [8] The technique will be useful for the surface analysis of various hydrogen storage capacitors, as well as those of typical semiconductors and alloys.

References

[1] M. Kimura, N. Nakamura, H. Watanabe, I. Yamada, A. Danjo, K. Hosaka, A. Matsumoto, S. Ohtani, H.A. Sakaue, M. Sakurai, H. Tawara and M. Yoshino, J. Phys. B: At. Mol. Opt. Phys. **28**, L643 (1995)
[2] K. Motohashi and S. Tsurubuchi, J. Phys. B: At. Mol. Opt. Phys. **36**, 1811 (2003)
[3] S. Tsurubuchi and K. Motohashi, J. Phys. B: At. Mol. Opt. Phys. **36**, 3847 (2003)
[4] S. Yaltkaya, E.Y. Kamber and S.M. Furguson, Phys. Rev. A **48**, 382 (1993)
[5] K. Motohashi, K. Hosoya, M. Imano, S. Tsurubuchi and A. Koukitu, Surf. Sci. **601**, 5304 (2007)
[6] K. Motohashi, The handbook and abstracts of the 10th Asia Pacific Physics Conference (APPC-10) pp. 155 (2007)
[7] K. Motohashi, Extended Abstracts of the 55th Spring Meeting of the Japan Society of Applied Physics and Related Societies **2**, pp. 740 (2008)
[8] K. Motohashi and S. Tsurubuchi, Nucl. Instrum. Phys. B **264**, 15 (2007)

Regular Nanostructures by Swift Heavy Ions

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In the last few years numerous experiments on surface modifications studied by irradiation under grazing angles of insulators such as $SrTiO_2$, TiO_2 and Al_2O_3 have been performed. As shown in [1], irradiation under grazing angles leads under certain conditions to almost periodic hillock chains at the surface.

The focus of our present studies is on the surface modifications of typical ionic materials such as CaF_2, LiF as well as KBr and SrF. Although some of these materials have been studied intensively in the past (see e.g. [2]) , the irradiation under grazing angles provides new insights into these systems.

Scanning probe microscopy (SPM) measurements of CaF_2 and LiF surfaces after ion bombardment with swift heavy ions have clearly shown chains of nanodots with different features. While the main part of these chains is nearly regularly arranged, the initial region exhibits randomly distributed nanodots. Depending on the angle of incidence the overall length of the chains varies between 200 nm and over 1000 nm. Moreover, each of these ion-induced tracks is completely enclosed by a flat region (see Fig. 1) with a height of 1 nm.

Freshly cleaved LiF and polished CaF_2 samples with (111) surface orientation have been irradiated without prior surface treatment at the ion beam facility IRRSUD of the GANIL, France. The irradiation was performed using of Pb and Xe ions with kinetic energies of 130 MeV and 93 MeV, respectively. This energy corresponds to a stopping power of 20 keV/nm and 15 keV/nm respectively as calculated with SRIM [4]. The fluences were typically chosen to yield between 10 and 15 tracks on a surface area of $1\mu m^2$. After irradiation all samples were analyzed by means of SPM.

Although neither the chains of nanodots nor the plateaus are completely understood, one can assume that the spatial electron density plays a key role in the track production as has recently been demonstrated for $SrTiO_3$ [1,4,5].

References

[1] E. Akcöltekin, T. Peters, R. Meyer, A. Duvenbeck, M. Klusmann, I. Monnet, H. Lebius and M. Schleberger, Nature Nanotechnol., Vol. **2**, 290 (2007).

[2] R. Neumann, Nuclear Instruments and Methods in Physics Research B 151 (1999) 42-55

[3] J. F. Ziegler and J.P. Biersack, http://www.srim.org

[4] E. Akcöltekin, S. Akcöltekin, O. Osmani, A. Duvenbeck, H. Lebius and M. Schleberger, New J. Phys.,10(2008) 053007 J. M. Smith, *Molecular Dynamics* (Academic, New York, 1980).

[5] O. Osmani, E. Akcöltekin, A. Duvenbeck, H. Lebius and M. Schleberger, Journal of Physics: Cond. Matter, submitted (arXiV 0801.3381v1).

PROGRESS OF THE SPECTROSCOPY RESEARCH PLATFORM AT THE SHANGHAI EBIT.

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The Shanghai Electron Beam Ion Trap (EBIT) has been in operation for a short time now and is slowly approaching the initial design parameters, see [1]. At this stage in its development the Shanghai EBIT is dedicated to studies using photon spectrometers and detectors. In the near future an ion-extraction line will be constructed along with a recoil-ion momentum microscopy. However in this report we will focus on spectrometer development, spectroscopic studies and a few other recent developments at the Shanghai EBIT laboratory. Currently the Shanghai EBIT has three spectrometers covering totally the wavelength region of 1 to 10000 Å. Two of these instruments are home made. A flat crystal spectrometer covers the wavelength range of around 1 – 20 Å while a flat field instrument covers the range of around 20 – 400 Å. The 3rd instrument is a commercial McPherson 225 normal incidence spectrometer. All spectrometers employ CCD cameras for photon detection. The Shanghai EBIT is also equipped with high purity Germanium detectors for amongst other things dielectronic recombination studies [2] and time evolution studies of ion distributions[3]. To back up these experimental studies computer codes have been developed for calculation of charge state balances etc. Parallel to the experimental program we have also developed experience at running a number of atomic structure codes (MCHF, MCDF, FAC) for various systems, e.g. the M3 decay of the $3d^9 4s\ ^3D_3$ for Ni-like ions [4].

References

[1] M. He *et al.*, J. Phys Conf. Ser. **58,** 419 (2007).
[2[W.D. Chen *et al.*, Physics of Plasmas **14**, 103302 (2007).
[3] W. Hu, *et al.*,Can. J. Phys. **86**, 321 (2008).
[4] K. Yao *et al.*, Phys. Rev. Lett. **97**, 183001 (2006).

HIGH ACCURACY TEST OF QED AT THE HEIDELBERG EBIT

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An experimental cornerstone of atomic theory and quantum electrodynamics (QED) is the precise determination ($\delta\lambda/\lambda = 2 \times 10^{-14}$) of the $1S$-$2S$ transition wavelength in hydrogen by the group of Hänsch [1]. Here, the experimental precision exceeds the theoretical by far due to the large uncertainty in the proton radius. This makes experimental results suitable for predicting other transitions in hydrogen and getting relative theoretical uncertainties smaller than that of the Rydberg constant.
For highly charged ions (HCI) the ($Z\alpha$)-perturbation expansion (α being the fine structure constant and Z the nuclear charge) used for the description of low Z systems is no longer applicable, and HCIs are therefore well suited for testing QED in its non-pertubative limit. Theoretical precision in this regime, such as in all-order non-pertubative calculations, still exceeds experimental precision by a factor 10 in case of U^{91+}.
On the other hand theory of few-electron ions has difficulties including interelectronic correlation into calculations. For He-like ions the unified method (UM) [2], all-order method (AO)[3] and recent calculation by Artemyev *et al.* [4] are different theoretical approaches of taking electron-electron interaction into account. Even the most accurate experiment ($\Delta\lambda/\lambda$ =12 ppm) [5] is by a factor of 5 not precise enough to distinguish among the various calculations.
We report about our recent absolute and relative high-precision wavelength measurements of HCI at the Heidelberg Electron Beam Ion Trap (EBIT) performed in order to overcome this situation. The results were obtained with a novel flat crystal (Si-111) x-ray spectrometer [6] using two light fiducial beams to determine the incoming direction of the x-rays, and thus the Bragg angle. Absolute wavelength measurements were carried out using the Bond method [7]. Experiments on the Lyman-α_1 transition in S^{15+}, measured absolutely for the first time, resulted in a transition energy of $2622.692(27)$ eV with an experimental uncertainty of only ($\delta\lambda/\lambda = 10$ ppm). This points at the possibility of establishing absolute x-ray wavelength standards using Lyman-α_1 transitions in the future. For the $1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ resonance line in He-like Ar^{16+} an uncertainty of $\delta\lambda/\lambda = 2 \times 10^{-6}$ was achieved [8]. This is the most precise wavelength reported for highly charged ions up to now and allows to test recent predictions on QED two-electron and two-photon radiative corrections for He-like ions.

References

[1] M. Nierig, R. Holzwarth, J. Reichert, Phys. Rev. Lett. **84**, 5496 (2000)

[2] G.W.F. Drake, Can. J. Phys. **66**, 586 (1988)

[3] D.R. Plante, W.R. Johnson, J. Saphirstein, Phys. Rev. A **49**, 3519 (1994)

[4] A.N. Artemyev, V.M. Shabaev, V.A. Yerokhin, Phys. Rev. A **71**, 062104 (2005)

[5] R.D. Deslattes, H.F. Beyer, F. Folkmann, Phys. Rev. B **17**, L689 (1984)

[6] J. Braun, H. Bruhns, J. R. Crespo López-Urrutia, Rev. Sci. Instrum. **76**, 073105 (2005)

[7] W.L. Bond, Acta Cryst. **13**, 814 (1960)

[8] H. Bruhns, J. Braun, K. Kubicek, Phys. Rev. Lett. **99**, 113001 (2007)

RELATIVISTIC AND MANY–BODY EFFECTS IN RADIATIVE RECOMBINATION OF HEAVY IONS

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Studies on the capture of electrons by heavy, highly-charged ions have a long tradition [1]. In the *radiative recombination*, for example, a free (or quasi-free) electron is transferred from the target to the ion under simultaneous emission of a photon. During the last decade this capture process has been found to provide a unique tool for improving our understanding of the electron-electron and electron-photon interactions in the presence of strong electromagnetic fields [2]. Therefore, a large number of experiments have been performed in order to investigate the properties of the *recombination* radiation. Owing to the recent progress in the detector design, these experiments have dealt not only with spectra and angular distributions of emitted x-ray photons but also with their polarization properties [3].

In this contribution, we present the recent theoretical advances in describing the electron capture into highly-charged hydrogen- and lithium-like ions. Emphasis will be placed on the angular and polarization properties of the recombination photons [4] as well as the (subsequent) characteristic Kα radiation [5,6]. It is shown in particular, that the angle- and polarization resolved x-ray spectroscopy provides an efficient way for studying the many-body and relativistic effects on the structure and dynamics of high-Z, relativistic ions. To illustrate these effects, detailed calculations will be presented for the recombination of both, decelerated and ultrarelativistic heavy projectiles, and the results will be compared with available experimental data.

References

[1] J. Eichler, Th. Stöhlker, Phys. Rep. **439**, 1 (2007)

[2] S. Fritzsche, P. Indelicato, Th. Stöhlker, J. Phys. B **38**, S707 (2005)

[3] S. Tashenov *et al*, Phys. Rev. Lett. **97**, 223202 (2006)

[4] A. Surzhykov, S. Fritzsche, S. Taschenov, Th. Stöhlker, Phys. Rev. Lett. **94**, 203202 (2005)

[5] A. Surzhykov, U. D. Jentschura, Th. Stöhlker, S. Fritzsche, Phys. Rev. A **73**, 032716 (2006)

[6] A. Surzhykov, U. D. Jentschura, Th. Stöhlker, S. Fritzsche, Phys. Rev. A **74**, 052710 (2006)

Momentum distribution of highly charged ions formed by strong laser fields

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Technological advances in laser and in atomic collision physics have opened new pathways for measurements beyond the ion yield production. Foremost, the momentum distribution of ionized atoms produced by linearly polarized lasers with moderate intensity has been intensively analyzed employing COLTRIMS. The measured distributions of the doubly charged ion momentum parallel to the polarization of the laser show for Ne and Ar two symmetrical peaks with a dip at zero momentum. This is known as an indication of the electron-electron interaction in the system, i.e. non-sequential ionization of two electrons [1]. In the strong field regime, on the other hand, ions with higher charges can be produced and the momentum distributions of each individual ion show Gaussian-like distributions centered at zero momentum [2]. This suggests that the interaction between electrons is relatively weak and each electron is ionized sequentially. For ionization of multiply charged ions by intense multi-cycle (~ 200 fs) laser field with a maximum intensity of $\sim$ (50-70) PW/cm^2, ions with different charge states are produced during a single laser shot due to a spatial variation of the laser intensity within the beam focus. The measurements show approximately a simple linear relation between the width of the momentum distributions and the ionization potential of the ions. Such a power law scaling appears to be universal, *i.e.*, largely independent of the target atoms used. The underlying ionization dynamics is analyzed using a quasi-classical tunneling theory for a single active electron model assuming that the interaction between electrons is negligible in such a strong-field limit. Due to the laser envelope, ionization saturates even before the peak intensity of the envelope is reached. This saturation intensity, rather than the peak intensity, determines the width of the final momentum distribution [3].

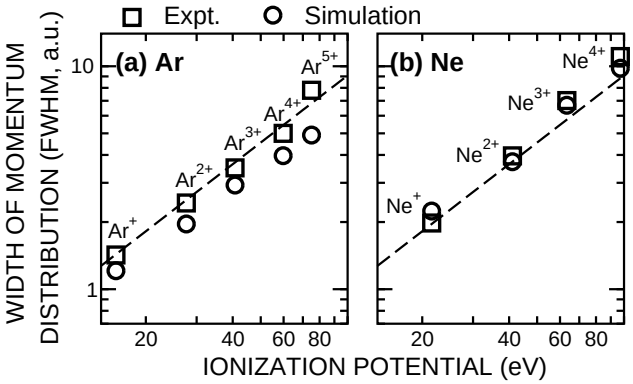

Figure 1: Width (FWHM) of the ion momentum distribution as a function of ionization potential. The atoms (Ar or Ne) are subject to a 200 fs laser pulse with a wave length of 775 nm and a peak intensity of 50 - 70 PW/cm^2. The measured results (squares) are compared with the calculated widths (circles) using the classical trajectory Monte Carlo method including tunneling.

References

[1] T. Weber *et al*, Nature **405**, 658 (2000); A. Rudenko *et al*, J. Phys. B **41**, 081006 (2008).

[2] H. Shimada *et al*, Nucl. Inst. Meth. Phys. Res. B **235**, 221 (2005).

[3] K. I. Dimitriou *et al*, Phys. Rev. A **75**, 013418 (2007).

CONSTRUCTION AND OPERATION OF THE TOKYO EBIT

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1. History

In late 1970s, the collaborative research group was organized in the Institute of Plasma Physics, Nagoya, by Professors Y. Kaneko and T. Iwai to study atomic processes of slow highly charged ions (HCIs) , in which N. Kobayashi, K. Okuno, H. Tawara, S. Ohtani and others participated as young collaborators. This activity was called "NICE project", where a few EBISes were constructed with different characteristics, and by using them, the systematic study of state-resolved electron capture processes of slow HCIs was developed. Thereafter, in early1990s, the inter-University research program, named "Atomic Physics of HCIs" began to be operated as a small national project. In this activity, Kobayashi and Ohtani planned that various HCI-sources would be designed and installed at several research facilities to perform the collaborative study. The Tokyo EBIT was considered to be constructed as one of major HCI-sources in the Institute for Laser Science (ILS), Tokyo.

2. Tokyo EBIT

In 1990, the high energy Super EBIT was constructed at the Lawrence Livermore National Laboratory, California, which has produced a lot of pioneering works by observing high q/Z ions trapped ions in the drift tube. However, the structure seems to be somewhat complicated, that is, the Super EBIT basically consists of an original EBIT and the additionally connected floating electron gun and collector. Therefore, we considered that the Tokyo EBIT should have a more simple shape, from which trapped ions can be easily extracted. Although the conceptual design and the whole rough structure were considered by Ohtani in 1992,the most important parts such as the optimum structures of the electrodes and the magnets were determined by graduate students (N. Nakamura, H. Watanabe et al.) through the elaborated computer simulation of electron beam trajectories under the various shapes of electro-magnetic fields, where the maximum design parameters were Ee=300 keV, Ie=300mA, B=4.5T. F. Currell, M. Sakurai and other young collaborators also participated in the detailed design of the apparatus. Since the contribution by above young colleagues was essentially important for design and construction, the Tokyo EBIT team is named "YEBISU (Young Electron Beam Ion Source Unit)" After the preliminary experiments with Ee=10-80keV, we have made the collaborative study from 1997 for five years on the HCI-spectroscopy with Oxford University where the 20keV EBIT has been operated. During this activity, we have prepared two extraction beam lines from the trap. In 2000s, the resonance interaction of trapped HCIs with the beam electrons has been intensively investigated by observing the charge state variation of extracted HCIs as a function of Ee. In addition, by using the extracted ions, the HCI-surface interaction has been also studied eagerly in relation to the HCI-based nano-science.

3. The near future plan

Since the Tokyo EBIT has been operated continuously for ten years and accumulated several wrong parts, we would like to dismantle, overhaul and improve the apparatus in the near future. It is also expected that the Tokyo EBIT will be provided to the international collaborations.

COMPACT X-RAY FREE ELECTRON LASER IN JAPAN

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Japan started construction of an x-ray free electron laser (XFEL) as one of the five Key Technologies of National Importance. The XFEL is a self-amplified spontaneous emission (SASE) based light source using an 8 GeV electron linear accelerator and a long undulator. Assembly of innovative technologies developed in Japan enabled us to make the facility size to be 1/3-1/4 of the corresponding US and European ones. All the newly developed technologies have been verified by constructing and operating a smaller-size prototype free electron laser operating at 50-60 nm ultraviolet regions with 0.25 GeV electrons. The 8 GeV XFEL will be completed in 2010 and emit up to 20 keV laser pulse with 60 Hz repetition. As an intense and coherent x-ray source, the XFEL will be applied to advanced material researches and life science researches. The present status of the construction project as well as the envisaged scientific cases will be discussed.

Selected Contributions

Fragmentation of Small biomolecules induced by highly charged ion impact

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The fragmentation is a characteristic behaviour of complex systems such as large molecules and clusters upon excitation. A large number of experimental investigations have been performed on C_{60} and small molecules of DNA bases during the last years using photon excitation (laser and synchrotron source) and electron or ion beam impact excitation. Collision induced fragmentation using highly charged ions from ECR source has been demonstrated to be a powerful method providing complementary information comparing to other experimental methods. The specificity of experiments with an ECR source is related to the large choice of the charge and the atom of beams, the easy scan and high selectivity of the kinetic energy and the possibility to perform multi-coincidence measurements in event by event mode.

In this poster, we present experimental results on the fragmentation of DNA bases induced by impact of highly charged ions, Kr^{17+} (13 kV) and Xe^{23+} (10 kV). Multicharged ion beams delivered by the ARIBE facility allowed us to prepare charged molecules at low internal energy via electron capture process at large impact distances. By coincidence detection of the scattered projectile, the charged fragments and the ejected electron number, we were able to study the fragmentation dynamics and delayed dissociation processes. These results will be compared with the fragmentation patterns of DNA bases induced by singly charged ion beams using a novel experimental method, the so-called CIDEC (collision induced dissociation under energy control) [1-3].

References

[1] L. Chen, S. Martin, J. Bernard et R. Brédy, Phys. Rev. Lett. **98**, 193401 (2007)
[2] S. Martin, L. Chen, A. Salmoun, B. Li, J. Bernard, and R. Brédy, Phys. Rev. A **77**, 043201 (2008)
[3] S. Martin et al. Phys. Rev. A (2008)

Formation of Nano Pits on the KBr (001) Surface Induced by Single Impact of Slow Highly Charged Ions

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In recent years investigations of the potential energy dissipation of slow highly charged ions (HCI) on solid surfaces have brought out many new interesting phenomena, e.g. hollow atom formation, enhanced sputter yields, and potential electron emission [1].
The rapid release of the potential energy of a HCI produces a highly excited electronic system in the surface comparable to the excitation by high power ultra-short laser pulses or swift heavy ions [2]. This far from equilibrium state is known to induce various changes in the topography of insulating surfaces on a nanometer scale. Hence, HCIs are considered to be a promising tool for nano structuring and analysis [3]. However, the underlying detailed microscopic mechanisms, especially on atomically flat surfaces, are less investigated so far.
Therefore, we have studied the interaction of slow (300 eV/amu) highly charged Xe ions with the KBr (001) surface. The individual impact of such projectiles induces nanometer size pit-like structures on the surface. Thereby, the pit formation ability and the pit volume are found to depend strongly on the projectiles initial charge state and their kinetic energy. From complementary high fluence irradiations evidence is found that the pit formation is associated with the agglomeration of electronic defects induced by the potential energy dissipation into complex centers (X-centers).

References

[1] F. Aumayr, P. Varga, and H. P. Winter, Int. J. Mass Spec. 192, 415 (1999)
[2] E. Akcoltekin et al., Nature Nanotechnology 2, 290 (2007)
[3] F. Aumayr, and H. P. Winter, e-J. Surf. Sci. Nanotech. 1, 171 (2003)

LOW ENERGY CARBON ION IRRADIATION OF WATER ICES

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Ion processing plays an important role in the chemical and physical modification of ice surfaces in astrophysical environments. Magnetospheric ions surrounding the Gas Giants in the outer Solar System impinge upon and modify the icy satellite surfaces creating new chemical species, incorporating elements not originally present in the local ice composition.

$^{13}C^{+}$ and $^{13}C^{2+}$ ions were produced by an Electron Cyclotron Resonance ion source, accelerated by a low energy accelerator and were incident upon pure water ice samples. Modifications to the ice were measured using an FTIR spectrometer. The most significant modifications observed within the IR spectra were the growth of features corresponding to $^{13}CO_2$ and H_2O_2 and the decrease of features corresponding to H_2O. Additionally, a feature corresponding to 'dangling OH' bonds was seen to decrease, indicating a change in the porosity of the ice being irradiated. It was also interesting to note that no signature for ^{13}CO was observed at any stage during the experiments.

Figure 1 shows the formation of $^{13}CO_2$ as a function of ion fluence at kinetic energies of 2 (left) and 4 keV (right). It is clear that, at both energies, significantly different yields of $^{13}CO_2$ were observed with the two different ion charge states. This difference is believed to be a result of the additional potential energy depostited by the doubly charged ion during an electron capture event.

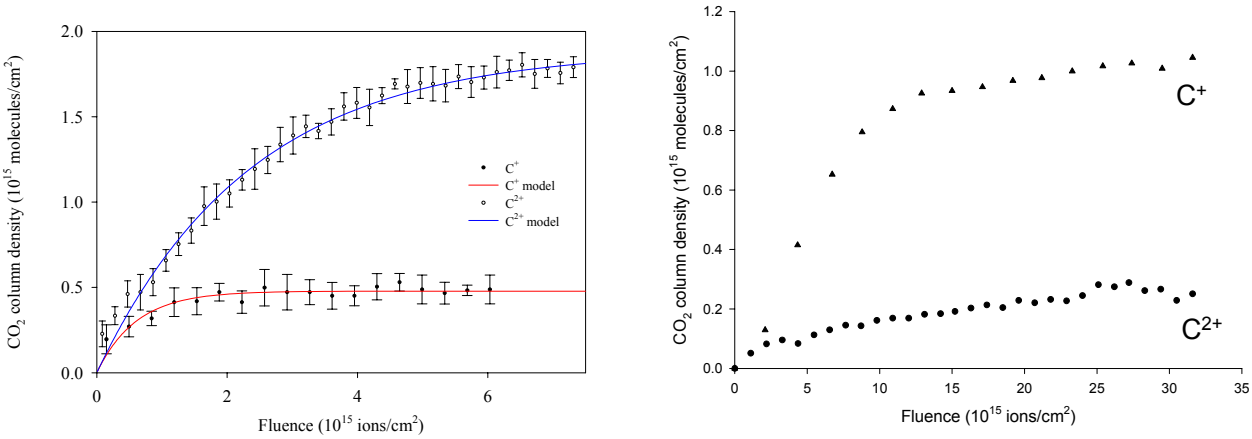

***Figure 1**: CO_2 growth at 2 (left) and 4 (right) keV. In both cases, the yield of CO_2 is significantly different for the two charge states.*

[1] Anita Dawes, Adam Hunniford, Philip D Holtom, Robin J Mukerji, Robert W McCullough and Nigel J Mason *Phys. Chem. Chem. Phys.* **9** 2886-2893 DOI: 10.1039/b618026d (2007)

POTENTIAL SPUTTERING OF IONIC SPECIES FROM RARE GAS SOLIDS BY MULTIPLY CHARGED ION IMPACT

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Interaction of rare gas solids (RGS) with low energy photons and electrons were well studied in these two decades [1]. In these studies, creation of excitons and ions is found to play an important role in the desorption processes. Sputtering of ions from RGS by singly charged ion impact has been investigated by some groups [2, 3], however little report can be found by multiply charged ion impact. Here we report the results for the potential sputtering yields of ions from RGS by multiply charged ion impact.

Figure 1 shows mass spectra of ions sputtered by the impact of 1 keV Ar^+ and Ar^{7+} from solid Ne. Very large cluster ions up to cluster size n ~100 are observed (not shown in the figure). One can find that the intensity and size distribution for small clusters ($n \leqslant 3$) strongly depend on the charge state q of the incident ion, while almost no dependence on q has been observed for the large clusters ($n \geqslant 7$), suggesting that the kinetic sputtering is dominant for the desorption of large cluster ions.

Considering that the potential energy of Ar^+ (15.76 eV) is less than the creation energy of an exciton (17.1 eV) and an ion (21.6 eV) in solid Ne, we assume that only the kinetic sputtering occurs by Ar^+ impact, and estimate the potential sputtering yield Y_{PS}. The results (Fig. 2) show that Y_{PS} is proportional to the potential energy of the projectile ion, which suggests that all of the potential energy is consumed to create excitons and ions in the solid. Detailed discussion will be given at the conference.

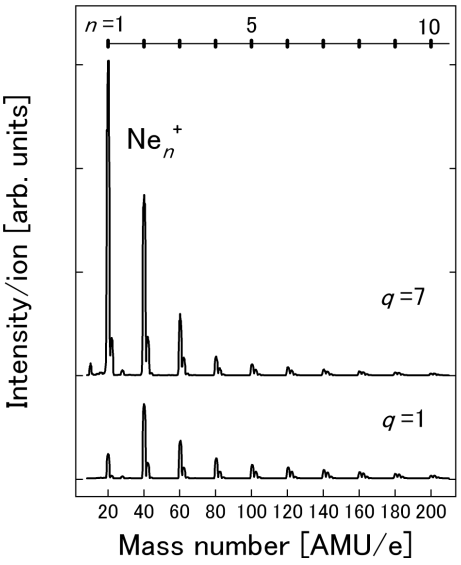

Fig. 1. Mass spectra of sputtered ions from the surface of the solid Ne by 1keV Ar^{q+} (q = 1, 7) impact. Thickness of the solid Ne is about 600ML.

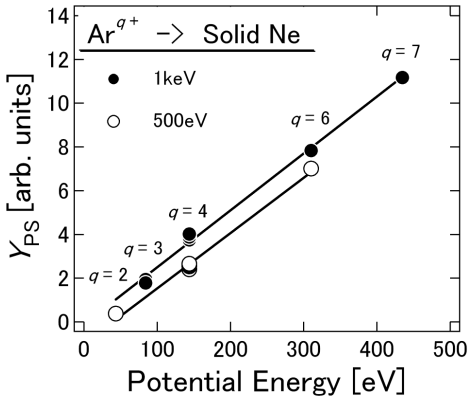

Fig. 2. Potential sputtering yields of ions sputtered by Ar^{q+} (q = 2, 3, 4, 6, 7) from the surface of solid Ne. Full and open circles correspond to 1 keV and 500 eV impact energy of incident ions, respectively.

References

[1] for example, T. Hirayama and I. Arakawa, J. Phys.: Cond. Matt. **18**, S1563 (2006) , and references therein.

[2] R.G. Orth, H.T. Jonkman, D.H. Powell and J. Michl, J. Am. Chem. Soc. **103**, 6026 (1981).

[3] K. Hiraoka, M. Watanabe, D. Eguchi, S. Okazaki and T. Sato, Rapid Commun. Mass Spectrom. **16**, 1016 (2002).

Re-trapping and Cooling Highly-Charged Ions

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Presently, a trapping system for cooling highly-charged ions that were extracted from the new Stockholm electron-beam ion trap (S-EBIT) is being set up at AlbaNova (Fig.1). The experiment aims at production of low temperature (emittance) highly-charged ions at very low energy for injection into the precision trap of SMILETRAP II. As a first step the Penning-type cooling trap with deceleration and acceleration system, which facilitates the injection and extraction, was brought into position and successfully tested. Ions can be created either externally, i.e., in the ion sources S-EBIT or SMILIS, or internally by transmitting a 4 kV electron beam through the trap to ionize rest gas. The segmented centre electrode allows for rf-excitation for cleaning the cooling trap from unwanted ions. Currently, a pepper-pot emittance meter is being installed to monitor the emittance of trapped ions in real-time.

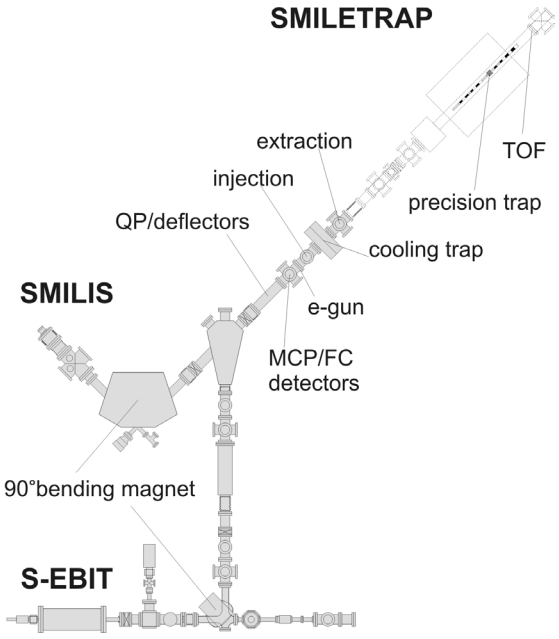

Fig.1 Layout of the HCI facility at AlbaNova.

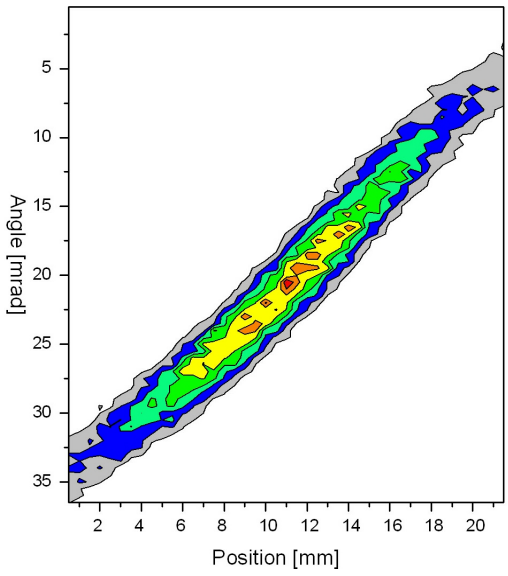

Fig.2 Emittance of Ar^{16+} ions trapped for 100 us.

From S-EBIT and SMILIS two ion species, highly-charged and low charged ions (e.g. S^{14+} or Ar^{16+} and He^{+}) could be injected sequentially and stored simultaneously in the cooling trap. The emittance of the trapped ions was measured (Fig.2), which will be used for optimizing the evaporation of the light ions to cool the highly-charged ions in the cooler trap. For the primary ions, emittances in the order of a few mm·mrad and energy spreads of few qeV were measured. It is expected that these values will be reduced and highly charged ions of 0.1 qeV energy spread can be extracted as pure ion beam.

THE FIRST TEST EXPERIMENT PERFORMED AT THE ELECTRON COOLER OF STORAGE RINGS IN LANZHOU

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The cooler storage ring CSR project was launched in 2000 at the Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou. The project consists of two rings, the main cooler storage ring CSRm and the experimental cooler storage ring CSRe. Both CSR rings are equipped with electron cooling devices [1]. In 2007, the installation was completed and the commissioning of CSRs gained great success, a new highly precise generation of collision experiments will become accessible even for the heaviest ion species. The CSR provides unique and unprecedented conditions for experiments based on the use of highly charged ions and in particular for research in the realm of atomic and nuclear physics. The interaction of the brilliant beams of cooled high-Z ions with low-dense gaseous matter as well as with electrons can be now studied under almost completely background free experimental conditions and with highest luminosity [2,3].

Recombination between electrons and ions is one of the most fundamental atomic collision processes for all kinds of plasmas in the universe. For such investigations, the electron cooler of the storage rings can be used as an electron target for ion-electron interaction studies. In the electron cooler environment, two processes compete: dielectronic recombination (DR) and radiative recombination (RR). The rate coefficient, most important parameters in plasma modelling, can be obtained for various electronic configurations and detailed information on the atomic structure can be deduced in addition. Theoretical investigations of the DR process show that DR might be a powerful tool for the investigation of influence of nuclear effects on the atomic structure and may even be used to obtained model independent information on the nuclear structure, e.g. the nuclear charge radius. This has just been confirmed experimentally [4]. Because the experimental storage ring CSRe can accumulate and store radioactive ions produced by nuclear fragmentation, DR experiments open a novel way for studying the ground-state properties of nuclei far from stability.

A commissioning RR experiment was performed at the electron cooler for Ar^{18+} ions, the results were presently under evaluation. A further RR experiment is being under preparation for krypton ions. A program is planned to be completed before the end of this year for fine detuning the electron beam energy in order to perform high precision DR experiments.

[1] J. W. Xia, W.L. Zhan, B.W. Wei, et. al., Nucl. Instr. Meth. A 488 (2002) 11

[2] R Schuch and S Böhm, J. Phys.: Conf. Ser. 88 (2007) 012002

[3] X. Ma, X. L. Zhu, H. P. Liu, et. al., J. Phy. Conf. Series 72 (2007) 012015

[4] C. Brandau, C. Kozhuharov, Z. Harman, et. al., Phys. Rev. Lett. 100 (2008) 073201

OBSERVATION OF HIGHER ORDER RESONANT ELECTRON RECOMBINATION PROCESSES BY HIGHLY CHARGED KRYPTON IONS

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By measuring resonant electron capture processes by highly charged ions, where the kinetic energy of the captured electron is transferred to bound electrons, atomic structure calculations can be tested stringently. These data are also relevant for plasma diagnostics applications. Many measurements of dielectronic recombination (DR) have been reported in recent years, see e. g. [1,2]. More detailed benchmarking of theory would results from the measurement of higher order resonant electron capture processes In the so called "trielectronic recombination" (TR) or "quadruelectronic recombination" (QR) resonances, two respectively three bound electrons are excited by the captured electron. Among the few reported related experiments, there exists an upper limit determination of the cross section for the TR-process in krypton [3] and also an observation of TR resonances in outer shells of Be-like chlorine at the Test Storage Ring [4]. We present the first observation of TR resonances including the K shell (*KL-LLL* TR) in highly charged krypton ions. Signatures of QR resonances

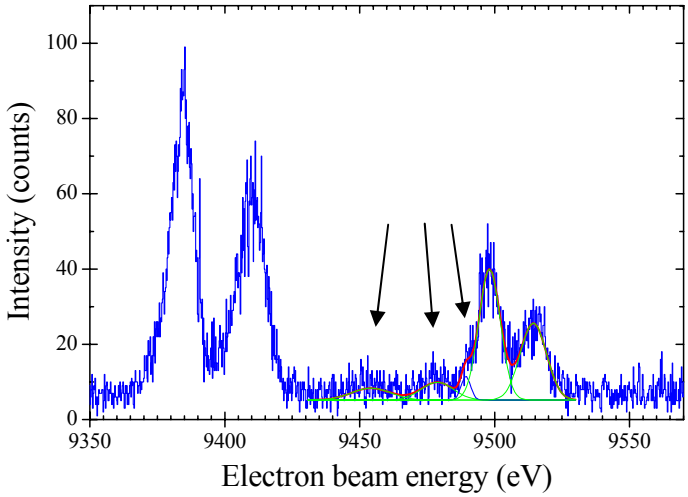

Fig. 1. Recombination of Kr HCI as a function of the electron beam energy. Mean peaks are due to C-like and N-like Kr. The weak features indicated by the two leftmost arrows were reproduced in several measurements and can be identified as the predicted TR of C-like krypton. The rightmost arrow appears at the position predicte for Be-like QR. The energy scale is preliminary.

have also been found for the first time (*KLL-LLL* QR). The excellent resolution achieved, has yielded more accurate data also for the DR resonances. These results have brought a further reduction of the uncertainty in the determination of the absolute resonance energies, and show good agreement with newest predictions of their values.

References

[1] A.J. González-Martínez *et al.*, Phys. Rev. Lett. **94** (2006) 203201
[2] Y. Zou, J. R. Crespo López-Urrutia and J. Ullrich, Phys. Rev. A **67** (2003), 043703
[3] M. Chevallier *et al.*, Phys. Rev. A **61** (2000), 022724
[4] M. Schnell *et al.,* Phys. Rev. Lett. **91** (2003) 043001

X-RAY SIGNATURES OF CHARGE EXCHANGE IN L-SHELL IONS

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The X-ray signature of L-shell charge exchange in Sulfur was studied in the laboratory. Charge states from S^{11+} to S^{14+} were created in the LLNL Electron Beam Ion Trap and were left to interact via charge exchange with neutral SF_6 gas. The measurements were monitored with the EBIT Calorimeter Spectrometer. Comparison of these charge exchange (CX) spectra with those obtained under electron-impact excitation showed marked differences. In the CX spectra, an enhancement was observed in the high-n transitions; $n = 4,5,6 \rightarrow n = 2$, in comparison to the $n = 3 \rightarrow n = 2$ transitions that dominate the direct excitation spectra. An even greater enhancement was recorded in transitions from the levels of electron capture to the ground states; $n_c = 7,8,9 \rightarrow n = 2$. The spectra mainly consist of S^{13+} lines, but lower charge states such as S^{12+}, S^{11+} and S^{10+} are also present. These are the first high-resolution results of L-shell charge exchange. The spectra have been compared to low-resolution data on charge exchange in L-shell Iron, and showed a similar spectral structure. However, the high-resolution spectra from Sulfur exhibit a significant enhancement in transitions from the electron capture-levels n_c=7,8,9, whereas the low-resolution spectra of Iron showed the greatest enhancement in the transitions from n=4,5 levels.

Part of this work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and NASA grants to LLNL, SAO, and GSFC.

STATE-SELECTED DIFFERENTIAL CROSS SECTION MEASUREMENTS FOR THE ONE-ELECTON CAPTURE PROCESSES IN THE F^{4+} - He, Ne, Ar SYSTEMS AT E_{lab} = 45 eV

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Using a crossed-beam apparatus[1], we are measuring systematically the relative state-selected differential cross sections for the charge-transfer processes at very low energy region. A small electron-beam ion-source is employed to produce multiply charged ions. The mass- and energy-selected primary ion-beam was crossed at a right angle with a supersonic nozzle-beam. The scattered ions were energy-analyzed by a one-dimensional position-sensitive detector. The energy spectra of the scattered ions at different angles were recorded by rotating the analyzer.

Typical energy spectrum of the scattered ions observed in F^{4+} - He collisions at E_{lab} = 44 eV is shown in figure 1. The peak (a) corresponds to the elastically scattered ions, and (b) is due to the one-electron capture process. This peak is assigned to the following reactions:

$F^{4+}(2s^2 2p\ ^2P) + He$ ---> $F^{3+}(2s^2 2p3s\ ^1P) + He^+ + 10.0$ eV,
---> $F^{3+}(2s^2 2p3s\ ^3P) + He^+ + 10.9$ eV.

The relative differential cross section, $d\sigma/d\Omega$, for the reaction is shown in figure 2.

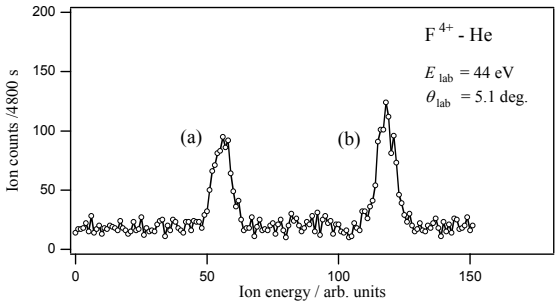

Figure 1: Energy spectrum of the scattered ions.

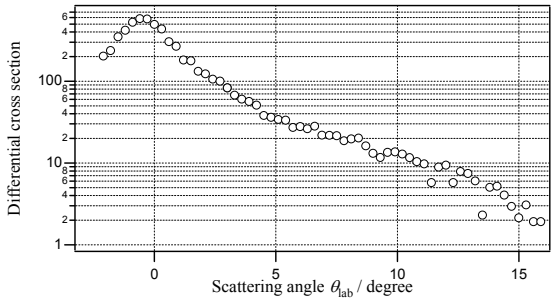

Figure 2: Relative differential cross sections.

The cross section shows a peak around 0° and decreases monotonically with the increase of the scattering angle, while the differential cross sections obtained in F^{4+} - Ne and Ar collisions at the same collision energy show clear angular thresholds. The reaction channels observed in these systems are

$F^{4+}(2s^2 2p\ ^2P) + Ne$ ---> $F^{3+}(2s^2 2p3p\ ^3D) + Ne^+ + 9.6$ eV,
---> $F^{3+}(2s^2 2p3s\ ^1P) + Ne^+ + 13.1$ eV,

and

$F^{4+}(2s^2 2p\ ^2P) + Ar$ ---> $F^{3+}(2s^2 2p3d\ ) + Ar^+ + \sim 9$ eV.

As the differential cross sections are very sensitive to the shape of the interaction potentials, it can be considered that the interaction potentials for the F^{4+} - He system is much different from those for the F^{4+} - Ne and Ar systems.

References

[1] Y. Itoh, J. Phys. B : At. Mol. Opt. Phys **35**, 3217 (2002)

STRONG FORWARD-BACKWARD ASYMMETRY OF H_2O IONIC FRAGMENTS BY SLOW HIGHLY CHARGED IONS IMPACT

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Fragmentation of molecules subsequent to the interaction with ions has been studied intensively in the last decade [1]. If the projectile is fast that the interaction time is orders of magnitude smaller than the dissociation time, the collision can be considered as a two-step process [2]. On the other hand, for slow ($v < 1$ a. u.), highly charged projectiles the energy and angular distribution of fragments is determined by the energy and momentum transferred from the projectile, in addition to the energy gained by the repulsive dissociation of the molecule [3].

We present the results of the fragment ion spectroscopy studies of water molecules subsequent to impact of highly charged 1-220 keV Xe^{q+} ions (q=10, 15 and 22). We observed a strong forward-backward asymmetry in the emission of the ionic fragments. For example, the ion yield in the forward direction is almost completely suppressed for the impact of below 10 keV Xe^{22+} ions. These results are compared with our previous studies of water fragmentation induced by $He^{1,2+}$ and $Ne^{(3-9)+}$ ions [1, 4, 5]. For projectiles with low charge state, the final kinetic energy is apparently determined by the related Franck-Condon transition. In order to guide the interpretation of the experimental data, we performed a classical trajectory simulation within the framework of a Coulomb Explosion model wherein a satisfactory agreement is achieved. Finally, the integrated cross sections over all fragmentation channels are compared with results of the semiempirical scaling law deduced from a multi-electron capture model [6].

References

[1] N. Stolterfoht *et al.*, Advanc. in Quantum Chem. **52**, 149 (2007) and references therein
[2] B. Siegmann *et al.*, J. Phys. B: At. Mol. Opt. Phys. **34**, L587 (2001)
[3] C.R. Feeler *et al.*, Phys. Rev. A **60**. 2112 (1999)
[4] P Sobocinski *et al.*, J. Phys. B: At. Mol. Opt. Phys. **39**, 927 (2006)
[5] Z. D. Pešić *et al.*, J. Phys. B: At. Mol. Opt. Phys. **37**, 1405 (2004)
[6] N Selberg *et al.*, Phys. Rev. A **54**. 4127 (1996)

COLLISIONS OF IONS WITH INSULATING SURFACES: CHARGING AND DISCHARGING DYNAMICS.

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Guiding and focussing of keV to MeV ions by insulator micro-capillaries offers exciting perspectives for the production of low divergence micro-sized beams and a fine spatial control over the irradiated zone. Such high quality beams may find applications in surface nano- structuring. A spectacular demonstration of the effective use of a tapered capillary is the direct injection of ions inside a living cell [1]. The guiding effect results from the local charging of the capillary inner wall, so this effect depends only on the charging dynamics of the insulating material.
Finding the best material for these applications requires that the charge induced processes are well understood. For that purpose, we have studied the dynamical behaviour of charge deposition and beam deflection on well defined planar geometry where the exact number of charges left on the surface as well as the time dependant beam deflection can be monitored. Depending on surface composition, temperature and structure, discharging time constant vary by orders of magnitude giving rise to different characteristic behaviour.
We have also performed numerical simulations that, besides giving access to the field distribution above the surface plane, point to the importance of the intensity distribution within the incident beam.

[1] Y. Iwai, T. Ikeda, TM. Kojima, et al., App. Phys. Lett. **92** , 023509 (2008)

Evolution of X-ray Calorimeter Spectrometers at the Lawrence Livermore Electron Beam Ion Trap

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High-resolution broadband, non-dispersive x-ray spectrometers have been under development for spaceflight since 1984. As an offshoot of the significant NASA investment in this technology, we have developed a series of calorimeter instruments for laboratory use and installed them at the Electron Beam Ion Trap (EBIT) facility at the Lawrence Livermore National Laboratory. Coupled with dispersive instruments at the facility, the calorimeter instruments have made significant contributions to our laboratory astrophysics program. Our laboratory astrophysics program involves benchmarking the spectral synthesis codes and the underlying atomic physics calculations that are used to model high-resolution x-ray spectra obtained with current and future x-ray observatories. The calorimeter instruments at EBIT have significantly enhanced our capabilities to study the physics of highly charge ions including broad band measurements of emission from charge exchange recombination and absolute cross sections for collisional excitation.

The first GSFC calorimeter instrument was installed at the EBIT facility in July of 2000 and has seen two major and a number of minor revisions since then. The performance of the instrument has significantly improved with time from the initial instrument that had a resolving power of ~500 at 6 keV, and essentially no quantum efficiency at energies above 20 keV, to the current instrument that has a resolving power of 1350 and 95% quantum efficiency at 6 keV, and a resolving power of 1800 and 32% quantum efficiency at 60 keV. The advances in resolution are especially apparent at lower energy, where, for example, O VII Kβ at 665 eV evolved from a distinguishable “shoulder” on the high-energy side of O VIII Lyα, to a well resolved line. These improvements have significantly increased the scientific yield of the calorimeter instrument at both high and low energies. We discuss the improvements in the instrument performance and the significant impact on the science yield at EBIT.

Part of this work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and is also supported by NASA grants to NASA/GSFC and LLNL.

QED CALCULATION OF INTERELECTRON INTERACTION CORRECTIONS FOR TRANSITION PROBABILITIES IN TWO-ELECTRON IONS

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We present *ab initio* QED calculation of the transition probabilities for two-electron ions with nuclear charge numbers $Z = 10 - 92$. Employing the line profile approach [1], higher orders of interelectron interaction corrections are taken into account. The radiative corrections were not considered. In particular, calculations are performed for nondegenerate levels $(1s2s)\,^3S_1$, $(1s2p_{3/2})\,^3P_2$ ($M1$ and $M2$ transitions, respectively) and for quasidegenerate levels $(1s2p)\,^1P_1$, $(1s2p)\,^3P_1$ ($E1$ transitions), decaying to the ground state $(1s1s)\,^1S_0$. Both the "velocity" and "length" gauges for describing the emitted photons are considered.

This is the first exact QED calculation of the transition probabilities for the quasidegenerate levels. In the case of quasidegenerate levels the standard QED perturbation theory has a slow convergence for ions with the nuclear charge $Z < 50$. There is a necessity to take into account the higher-order interelectron interaction corrections. Within the framework of the line profile approach we developed a special technique to evaluate the higher-order interelectron interaction corrections to the transition probabilities. One- and two-photon exchange Feynman graphs are considered. The QED perturbation theory applied here is eligible for further improvement of the accuracy of calculation order by order. Calculating the contribution of the interelectron interaction, the QED radiative corrections to the transition probabilities for the quasidegenerate levels become also relevant.

References

[1] O. Yu. Andreev, L. N. Labzowsky, G. Plunien, D.A. Solovyev, Physics Reports **455**, 135 (2008)

OBSERVATION AND MODELING OF HOLLOW MULTICHARGED IONS X-RAY SPECTRA RADIATED BY LASER PRODUCED PLASMA.

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Plasma of multicharged ions (Z =10 – 20) with the electron temperature 10 – 100 eV and the electr on density 10^{22} – 10^{23} cm^{-3} is produced usually by interaction of a high-contrast femtosecond laser pulses with solids or clusters. The same plasma parameters are also realized when nanosecond shor t-wavelength laser pulses (KrF or XeCl or 3d, 4th harmonics of Nd glass lasers) interact with the sol ids. Highly charged ions plasma with such parameters is already weakly- coupled and it is very inte resting to investigate radiation property of it. It has been shown in [1-5] that the X-Ray emission sp ectra of such plasma contain some exotic spectral lines caused by radiative transitions in the so call ed "hollow ions", that are the highly charged ions with an empty inner K-shell.

In the present work the role of hollow highly charged ions to the X-Ray emission spectra is investigated for 2 cases: 1) plasma obtained under irradiation of Ar clusters by ultrashort laser pulses and 2) Mg-plasma heated by a short-wavelength long-pulse (nanosecond) laser.

For the first case, cluster-gas targets were irradiated by short laser pulses with various intensities, durations and contrasts. Calculations in support of these measurements have been performed using a detailed atomic kinetics model with the ion distributions found from solution of the time-dependent rate equations. The calculations are in reasonably good agreement with the measurements and the role of hollow highly charged ions in the resulting complicated spectra is analyzed. It is demonstrated that, although the presence of hollow atoms is estimated to add only around 2% to the total line emission, signatures of hollow atom spectra can be identified in the calculations, which are qualitatively supported by the experimental measurements.

In the case of long-lived plasma, produced by XeCl laser irradiation of solid Mg target, clear signatures of transitions from hollow ions are observed in the experimental spectrum. Spectra were identified from large-scale atomic kinetics calculations using the recently developed mixed-UTA (MUTA) model [6]. The relative strength of hollow ion spectral lines is explored and the temperature and density regions in which they are produced are analyzed. Large density and temperature gradients are required to simulate the observations, and additional influence to the hollow atom spectra were simulated with using a hot electron component in the electron distribution function

The kinetic simulations were made with collisional rates calculated in the isolated-atom approximation. The relatively good agreement between theoretical and experimental spectra means that use of such an approximation for the description of the collisional processes is justified for weakly-coupled plasma with the electron-ion coupling factor $\Gamma_{ei} < 1$.

This work was partly performed under the auspices of the US Department of Energy through the Los Alamos National Laboratory and with the support of the RFBR (Projects No. 06-02-16174 and 06-02-72005-MNTIa) and by the RAS Presidium Program of basic researches No. 9.

References

[1] A. McPherson, B.D. Thompson, A.B. Borisov et al., Nature. **370**,631 (1994)

[2] J.-C. Gauthier, J.-P. Geindre, P. Audebert et al., Phys. Rev. E. **52**, 2963 (1995)

[3] A.M. Urnov, J. Dubau, A.Ya. Faenov et al., JETP Letters. **67**, 489 (1998)

[4] A.Ya. Faenov, A.I. Magunov, T.A. Pikuz et al., Physica Scripta **T80,** 536 (1999)

[5] J. Abdallah, Jr., I.Yu. Skobelev, A.Ya. Faenov et al., Quantum Electronics. **30**, 694 (2000)

[6] S. Mazevet, J. Abdallah, Jr. J. Phys. B. **39**, 3419 (2006)

THEORETICAL INVESTIGATION ON QUANTUM INTERFERENCE EFFECTS BETWEEN DIELECTRONIC RECOMBINATION AND RADIATIVE RECOMBINATION FOR HIGHLY CHARGED IONS

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The photorecombination (PR) process of a multiply charged ion with a free electron is traditionally described in terms of two distinct recombination mechanisms. The first is nonresonant or direct radiative recombination (RR), which is the inverse of the ordinary photoionization process, and the second corresponds to the two-step, resonant dielectronic recombination (DR) process. These two recombination mechanisms are usually treated as independent processes. It has been recognized, however, that the traditional description of RR and DR, as two independent, noninterfering processes, is not strictly permissible within the framework of a rigorous quantum-mechanical theory [1].

Indeed, more than 40 years ago, Fano [2] predicted the interference between transition amplitudes leading directly into the ionization continuum and those indirectly proceeding via a discrete intermediate resonant state. Several theoretical investigations have been carried out in pursuit of prominent manifestations of the quantum-mechanical interference between RR and DR. Asymmetrical PR cross-section profiles, which are characteristic spectral signatures of a prominent quantum-interference effect, have been observed firstly by Knapp *et al.* [3] for the PR of very highly charged uranium ions, and also have been detected for highly charged mercury ions by González Martínez *et al.* [4] recently.

Using a projection-operator and resolvent-operator approach [1], total cross section of electron-ion photorecombination processes are calculated for highly charged Hg^{75+} ion. This approach provides a unfied quantum-mechanical description of the combined electron-ion PR process, including radiative and dielectronic recombination as coherent, interfering components. The related energy levels, wavefunctions and transition data for B-like Hg ion have been obtained using GRASP92 package [5], component program REOSS99 [6] and AUGER [7], which is based on multiconfiguration Dirac-Fock method. The RR cross section calculated using our recent developed program RERR06 [8]. The present theoretical results show evident asymmetrical profile in the $KL_{12}L_3$ DR resonant region.

References

[1] M. Zimmermann, N. Grün, W. Scheid, J. Phys. B **30**, 5259 (1997)

[2] U. Fano, Phys. Rev. **124**, 1866 (1961)

[3] D. A. Knapp, P. Beiersdorfer, M. H. Chen *et al.*, Phys. Rev. Lett. **74**, 54 (1995)

[4] A. J. González Martínez, J. R. Crespo López-Urrutia, J. Braun *et al.*, Phys. Rev. Lett. **94**, 203201 (2005)

[5] F. A. Parpia, C. Froese Fischer, I. P. Grant, Comput. Phys. Commun. **94**, 249 (1996)

[6] S. Fritzsche, C. Froese Fischer, C. Z. Dong, Compt. Phys. Commun. **124**, 340 (2000)

[7] S. Fritzsche, H. Aksela, C. Z. Dong *et al.*, Nucl. Instrum. Methods B **205**, 93 (2003)

[8] J. J. Wan, C. Z. Dong, C. C. Sang *et al.*, J. Phys: Confer. Ser. **58**, 367 (2007)

PRECISE EXPERIMENTAL AND THEORETICAL STUDIES ON RESONANT ENERGIES OF THE KLL DIELECTRONIC RECOMBINATION PROCESES FOR HE- UP TO O-LIKE XENON

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Dielectronic recombination (DR) is a resonant process, in which a free electron is captured by an ion, and at the same time a bound electron of the ion is excited, followed by radiative stablization. Studies of DR processes are very important, not only for researches relevant to hot plasmas, but also for atomic structure and collision theory, as DR processes carry information on quantum electrodynamics, relativistic effects, many body interactions and so on.

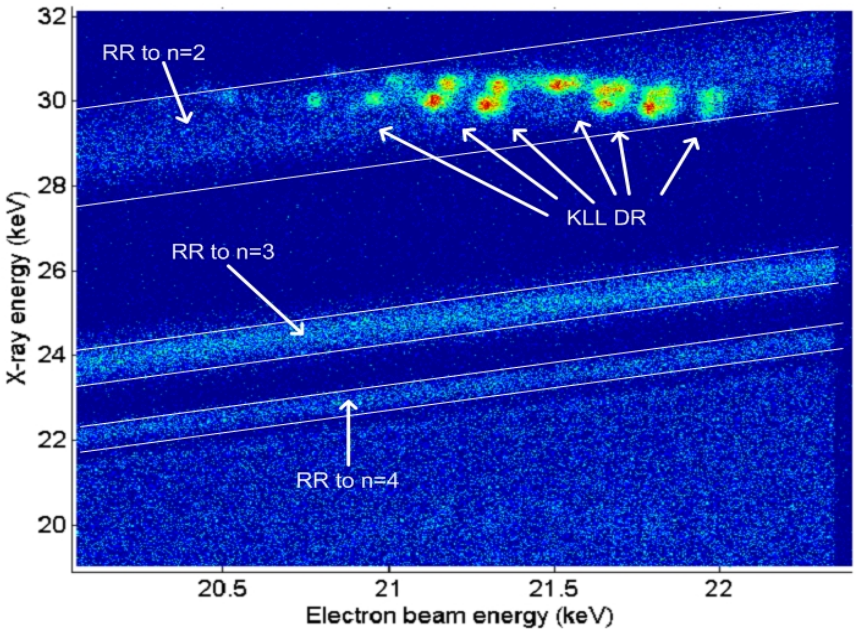

Fig. 1: Scatter plot of X-ray counts over electron beam energy and photon energy, taken at electron beam current of 62 mA. The KLL DR resonant events and radiative recombination to n=2, 3, 4 are shown.

Precise experimental studies of the resonant energies of KLL DR processes of He-, Li-, Be-, B-, C-, N-, and O-like xenon ions were performed at the Shanghai Electron Beam Ion Trap, by monitoring the electron beam energies over the KLL DR resonance region, see Fig. 1, employing home developed high precision, high stability high voltage dividers. Effects of the space charge of the electron beam and the ion neutralization, retardation by the capacitor of experimental setup, contact potential as well as fringing field effects were taken into account. Fifteen experimental resonant energies were obtained at an average uncertainty level of 0.03%.

At the same time, calculations using relativistic configuration interaction (RCI) theory, relativistic many-body perturbation (RMBPT) theory were also performed for the above-mentioned KLL DR resonant energies. Comparisons of experimental and theoretical results were made. 13 out of the 15 predictions by RMBPT are in good agreement with our experimental results, while only 5 out of the 15 predictions by RCI calculation agree with our experiments. Three literature available DR resonant energies by multi-configuration Dirac-Fock calculation agree very well with our experiments.

Hyperfine dependent lifetimes in Neon like ions

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As part of our ongoing investigations of hyperfine dependent lifetimes of metastable levels [1-4] we report on a theoretical investigation of hyperfine quenching in Neon-like ions. The studies were done along the iso-electronic sequence ranging from neutral Ne (Z=10) to Au^{69+} (Z=79). $2p^5 3s\ ^3P_2$ is the first excited level in Ne-like systems and it can only decay to the ground state, $2p^6\ ^1S_0$, through a magnetic quadrupole (M2) transition. For the ions up to $Z \approx 51$, were there is an energy level crossing between the $2p^5 3s\ ^3P_0$ and the $2p^5 3d\ ^3P_0$ level [5], the former is the third excited level and it can only decay to $2p^5 3s\ ^3P_1$ through a magnetic dipole (M1) transition and to $2p^5 3s\ ^3P_0$ through an electric quadrupole (E2) transition. Also it has no possibility to decay to the ground state except through a two-photon decay. In the presence of a nuclear spin though, the hyperfine interaction introduce a small mixing of $2p^5 3s\ ^3P_1$ and $^1P_1$ into $2p^5 3s\ ^3P_2$ and $^3P_0$ respectively, opening up hyperfine induced electric dipole (hpf-E1) transition channels to the ground state for both of the metastable levels.

Extensive multiconfiguration Dirac-Hartree-Fock calculations were performed to calculate the transition probabilities for the various transitions from the two metastable levels as well as the transition matrix elements of the $2p^6\ ^1S_0 - 2p^5 3s^3P_1$ and the $2p^6\ ^1S_0 - 2p^5 3s^1P_1$ E1 transitions. Also the off-diagonal hyperfine interaction constants between the metastable levels and the $2p^5 3s\ ^3P_1$ and the $^1P_1$ levels were calculated. First order perturbation calculation were used to calculate the $2p^6\ ^1S_0 - 2p^5 3s\ ^3P_2$ and the $2p^6\ ^1S_0 - 2p^5 3s\ ^3P_0$ hpf-E1 transition rates and the hyperfine dependent lifetimes of the hyperfine levels of the metastable levels. It is shown that the $2p^5 3s\ ^3P_2$ level is sensitive to hyperfine interaction all along the iso-electronic sequence ranging from Z=10 to Z=79. It is also shown that the $2p^5 3s\ ^3P_0$ level is very sensitive to the hyperfine interaction in the beginning of the iso-electronic sequence where the hpf-E1 transition, in many cases, are orders of magnitude larger than the M1 and E2 transition rates. This sensitivity decreases with Z since both the M1 and the E2 transition channels have a higher order of Z dependence compared to the hpf-E1 transition channel. However even for highly charged ions, if the nuclear magnetic dipole moment is large, the hyperfine quenching can have a substantial influence on the lifetime of the $^3P_0$ level. An example is the hyperfine quenching of $^3P_0$ in In^{39+} which is lowering the lifetime by about 25%.

References

[1] K. Yao, M. Andersson, T. Brage, R. Hutton, P. Jönsson and Y. Zou, Phys. Rev. Lett. **97** 183001 (2006)

[2] K. Yao, M. Andersson, T. Brage, R. Hutton, P. Jönsson and Y. Zou, Phys. Rev. Lett. **98** 269903 (2007)

[3] M. Anderssin, K. Yao, R. Hutton, Y. Zou, C.Y. Chen and T. Brage, Phys. Rev. A **77** 042509 (2008)

[4] M. Andersson, Y. Liu, C.Y. Chen, R. Hutton, Y. Zou and T. Brage, Phys. Rev. A (submitted)

[5] C.Z Dong, L.U. Xie, J.J Wan and J. Jiang, Chin. Phys. Soc. **14**, 1108 (2005)

SELECTIVE FORMATION OF MULTIPLY EXCITED STATES BY RESONANT COHERENT EXCITATION

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Multiply excited states attract great interests for the test of theories involving the strong electron correlations. Especially, investigation of triply excited Li or Li-like ions has progressed significantly in recent years. However, the triply excited Li-like system of heavier ions can be formed only by the atomic collisional processes such as electron capture to the outer shell since the synchrotron radiation is not applicable. Here we demonstrate a novel method for the formation of selective multiply-excited states of heavy ions.

We utilized three-dimensional resonant coherent excitation (3D-RCE) [1] of energetic heavy ions in a crystal, in which the traveling ions are resonantly excited through the interaction with the periodic crystal fields. With the use of ions at relativistic velocity, the available transition energy of RCE rises up to the x-ray region which enables us to excite the inner shell electron of highly-charged heavy ions. Since the oscillating field consists of numerous frequency components, the double resonance of RCE can be realized by adopting two of them simultaneously to the resonance.

We excited the two $1s$-electrons of He-like Ar^{16+} and Li-like Ar^{15+} into the $n = 2$ orbitals by successive 3D-RCEs of different harmonics. The energy diagrams are shown in Fig. 1(a) and (b). The double resonance conditions are satisfied by independently adjusting two rotating angles of the thin Si crystal keeping the ion velocity constant, which is a significant advantage over the previous 2D-RCE method [2]. The experiment was performed at the heavy ion medical accelerator in Chiba (HIMAC) with the $\sim$ 400MeV/u ions. We observed the charge state distribution of the ions emerging from the crystal together with the emitted x-ray yields and their polarization. In both cases, our result provided clear evidence that the multiply excited states are formed in the crystal.

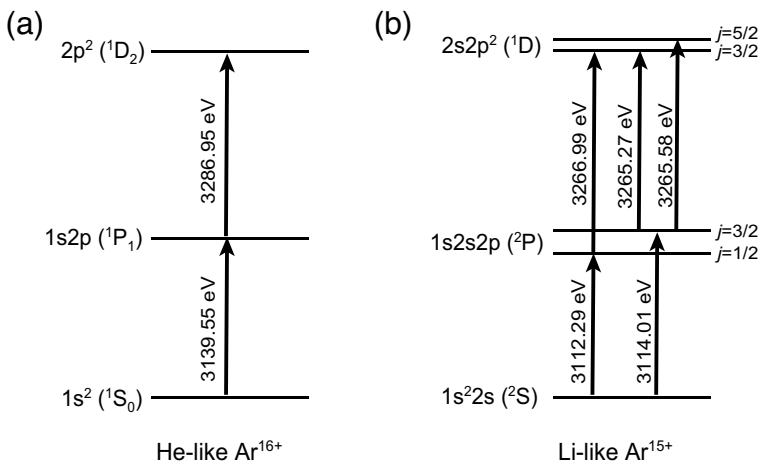

Figure 1: The level diagram of double electron excitation of (a) He-like Ar^{16+} and (b) Li-like Ar^{15+}.

References

[1] C. Kondo *et al.* Phys. Rev. Lett. **97**, 135503 (2006)

[2] Y. Nakano *et al.* J. Phys. Conf. Ser. **58**, 359 (2007)

Density matrix description of resonant coherent excitation of swift highly charged ions in oriented crystals

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Experimental and theoretical studies on resonant coherent excitation (RCE) of channeled ions in crystals started about 40 years ago from pioneering works of V.Okorokov [1]. Unambiguous observation of *the Okorokov effect* by S.Datz group at Oak-Ridge and wide variety of RCE measurements performed recently by Tokyo collaboration have made main contribution to the present-day image of the RCE process [2].

Density matrix description [3,4] considers RCE ion as an open quantum system involved into coherent and incoherent interactions with the crystal medium. Systematic numerical calculations based on the generalized Master equation for density matrix show it as a good instrument for unified approach to charge state distribution of the RCE ions and the yield and angular distirbution of their characteristic X-ray radiation. Other RCE observables including metastable ion production in a usual RCE process [5] and Auger electron production in a doubly resonant process (dRCE) [6] were considered in the same theoretical approach and suggested for experimental observation. Following our long-time interest in the problem of alignment of excited ions in the RCE process we extend previous density matrix calculations [3,7,8] on this point by theoretical predictions for Stokes parameters of linear and circular polarization of the X-ray radiation from relativistic resonant coherently excited channeled ions.

Our current theoretical studies in the field [9] being closely correlated with main trends in the latest RCE experiments by the Tokyo group [10-13] concern also such novel aspects of the RCE process as its trajectory resolved characteristics and resonant coherent excitation of highly charged ions in non-channeling conditions. Corresponding calculation results and our seeing of general perspectives of further development of the density matrix approach in the RCE studies will be presented at the conference.

The work is supported by the Russian Foundation for Basic Research (grant 06-02-16367).

[1] V.V.Okorokov, JETP Lett. **2** (1965) 111; Yad. Phys. **2** (1965) 1009 [Sov. J. Nucl. Phys. **2** (1965) 719].
[2] D.Dauvergne, J.Phys.Conf .Ser. 58 (2007)25.
[3] V.V.Balashov, I.V.Bodrenko, Moscow University Physics Bulletin, **56** (2001) 33, N1.
[4] V.V.Balashov, I.V.Bodrenko, Phys.Lett. A **352** (2006) 129.
[5] V.V.Balashov, I.V.Bodrenko, NIM B **245** (2006) 52.
[6] V V Balashov, A A Sokolik , A V Stysin, JETP (in press).
[7] V.V. Balashov, I.V. Bodrenko, ICPEAC XIV, Rosario, Argentina, 2005; Book of Abstracts, Tu 133.
[8] V V Balashov, A A Sokolik, Optics and Spectroscopy **103** (2007) 761.
[9] V.V.Balashov, *Density matrix description of the RCE process* (lecture course), Tokyo Metropolitan University, Tokyo, April 3-24, 2008 (unpublished).
[10] C.Kondo, S.Masugi, Y.Nakano, et al., Phys.Rev.Lett. **97** (2006) 135503.
[11] Y.Nakano, S.Masugi, T.Muranaka, et al., J.Phys.Conf. Ser. **58** (2007) 395.
[12] C.Kondo, S.Masugi, T.Muranaka, et al., NIM B **256** (2007) 157.
[13] T.Azuma, Y.Takabayashi, C.Kondo, et al., Phys.Rev.Lett. **97** (2006) 145502.

ATOMIC PROCESSES OF DAMDE ON BIO-MOLECULES IRRADIATED BY XFEL

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The analysis of three-dimensional structure of single bio-molecules has lately attracted considerable attention for the application of x-ray free electron lasers (XFEL) [1, 2]. This analysis comes from diffraction patterns, which are produced from the irradiation of XFEL onto the bio-molecules. However, the x-ray flux required for this analysis is so large that the bio-molecules are damaged, that is, the atoms in the bio-molecules are more often ionized. This damage appears as noise for the analysis of the three dimensional structure. Therefore, it is indispensable to estimate the damage.

We treat C, N, O atoms which are the main elements of bio-molecules and some atomic processes such as photo-ionization, Compton scattering, Auger, electron impact ionization, and radiative transitions. The atomic data of Auger and radiarive transitions are shown in Ref. [3]. By the application of the atomic data of these processes to rate equations, we have calculated the change of electronic states or charge numbers as a function of times for various parameters such as x-ray flux, x-ray pulses, and wavelength of XFEL the size of bio-molecules .

Figures 1 (a) and (b) show the change of charge number of C as a function of time for the wavelength of 0.1 nm and 0.1 nm of XFEL, respectively. The x-ray flux, pulse of XFEL and the size of bio-molecules are 10^{22}/pulse/mm^2, 10 fs, and 20 nm, respectively. We have found that shorter wavelength produce smaller damage. In our presentation, we will show the results for various parameters and suitable parameters for the experiment of diffraction pattern of bio-molecules.

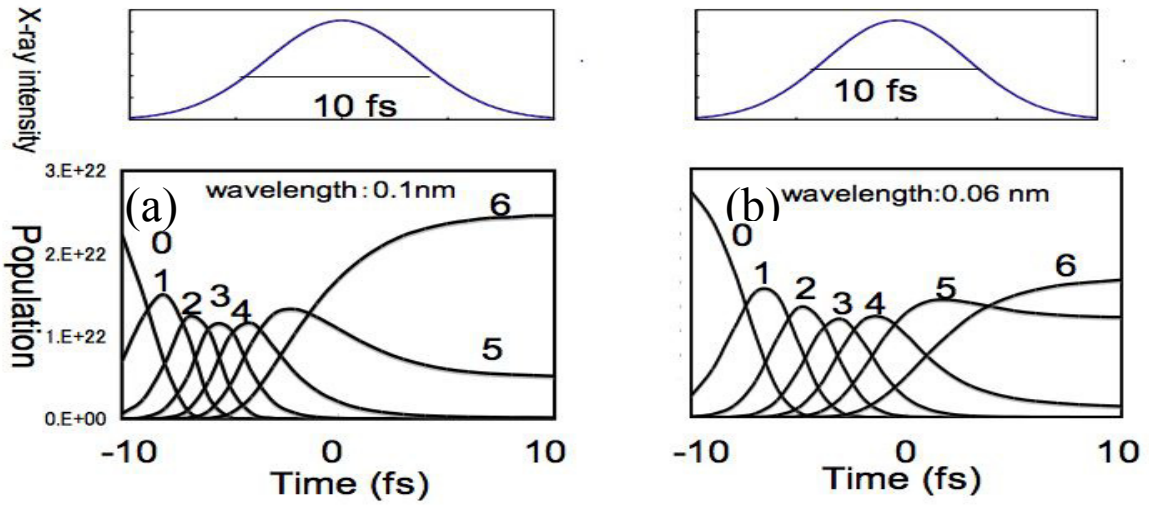

Figure 1 Population of charge number of C vs. time for the wavelengths of (a) 0.1 nm and (b) 0.06 nm, respectively.Upper figure shows the x-ray intensity. The pulse, flux of x-rays, and the size of bio-molecules are 10 fs, 10^{22} /pulse/mm^2, and 20 nm, respectively. The figures shown here are charge numbers.

References

[1] Neutze R, Wouts R, Spoel D, Weckert E, and Hajdu J, Nature, **406**, 752 (2000).
[2] Hau-Riege S P, London R ., Szoke A, Phys.Rev.E, **69**, 051906 (2004).
[3] K. Moribayashi, J. Phys.B, **41**, 085602 (2008).

EFFECTS OF DEBYE PLASMAS ON THE RESONANCE STATES OF HIGHLY STRIPPED TWO-ELECTRON IONS USING THE STABILIZATION METHOD*

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The effects of screened Coulomb potentials in atomic or molecular processes have become an active and relevant search topic in the recent years ([1-4], references therein). Recently, we have initiated resonance state calculations ([3-4], references therein) on different atomic and molecular systems under the influence of screened Coulomb potentials. In the present work, we investigate the resonance states of two-electron atoms, Mg^{10+} and Si^{12+} interacting with screened Coulomb potentials of the form : exp(-μr)/r, where μ is called the Debye screening parameter (μ=1/ λ_d, λ_d the Debye length). We employ highly correlated exponential basis functions, supported by a widely used quasirandom process [1,3] of the form $\varphi_i = r_1^L P_L(\cos\vartheta)\exp[-(\alpha_i r_1 + \beta_i r_2 + \gamma_i r_{12})] \pm$ exchange, for S-, P- states calculations, whereas for D-wave resonance calculations, we employ CI-type basis functions with certain approximations [4]. The stabilization method [5], a simple and powerful technique that needs only L^2 type basis functions, is used to extract resonance energies (E_r) and widths (Γ). We have obtained several doubly-excited *S*-, *P*- and *D*- waves resonance states of the proposed systems for each μ, below the *n*=2 thresholds of the respective two-body subsystems. In Fig.1, we present lowest S- and D-wave resonance widths of Mg^{10+} and Si^{12+} as functions of μ.

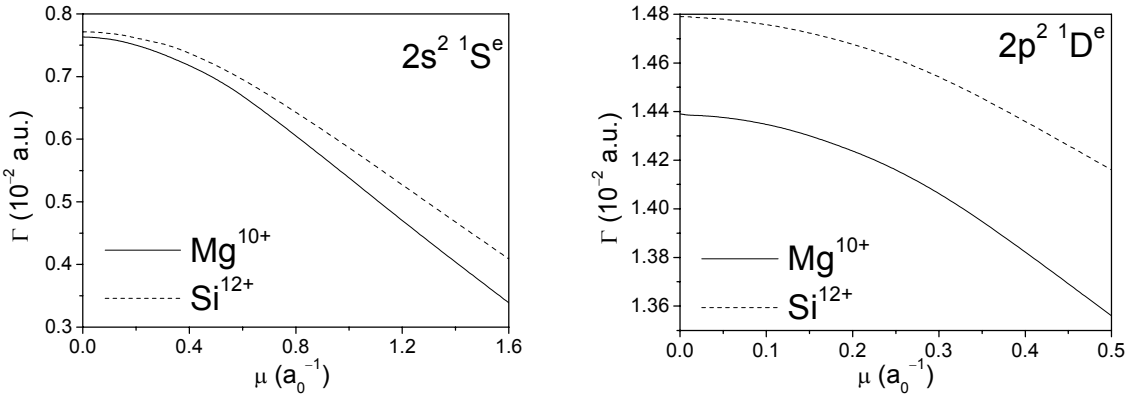

Fig. 1. Lowest S- and D- waves resonance widths of Mg^{10+} and Si^{12+} in terms of μ.

References

[1] S. Kar, Y. K. Ho, *Chem. Phys. Lett*. **424**, 403 (2006); **449**, 246 (2007); *Phys. Rev. A***77**, 022713 (2008); *Phys. Plasmas* **15**, 013301 (2008); *Phys. Lett. A* **372**, 4253 (2008); *JQSRT* **109**, 445 (2008).

[2] L Zhang, P. Winkler, *Chem. Phys*. **329**, 338 (2006); A.N. Sil, *et al. JQSRT* **109**, 873 (2008).

[3] S. Kar, Y. K. Ho, *Phys. Rev. E* **70**, 066411(2004); *Chem. Phys. Lett.* **402**, 544 (2005); *J. Phys. B* **39**, 2445 (2006); Phys. Rev. A **75**, 062509 (2007); **73**, 032502 (2006); **72**, 010703 (R) (2005).

[4] S. Kar, Y. K. Ho, *Phys. Scr.* **75**, 13 (2007); *Int. J. Quantum Chem.* **108**, 1492 (2008).

[5] V. A. Mandelshtam et al. *Phys. Rev. Lett.* **70**, 1932 (1993); S. S. Tan, Y. K. Ho, *Chin. J. Phys.* **35**, 701 (10997); S. Kar, Y. K. Ho, *J. Phys. B* **37**, 3177 (2004); *Euro. Phys. J. D* **35**, 453 (2005).

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OPTIMAL PULSE DURATION IN LASER-CLUSTER INTERACTIONS

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The study of the interaction of intense short laser pulses with clusters has received much attention during the last decade [1]. The ions and quasi-free electrons in the cluster form a "nano-plasma" of solid density, where the electrons are efficiently heated by the combined fields of the laser and the surrounding particles [2,3]. Electron-impact ionization produces highly charged ions as well as inner-shell vacancies, which are at the origin of X-ray radiation. As a fraction of the electrons leaves the cluster, a net positive charge is left behind and the cluster begins to expand before disintegrating completely in a Coulomb explosion.

The size of the system and the multitude of mechanisms at play provide a challenge for the theoretical description of the interaction. Due to the large number of atoms ($N > 10000$) in a cluster, a full ab-initio simulation still seems impractical. We therefore opt for an open effective mean-field approach, in which many-particle effects are included via stochastic processes. The roles played by different effects such as cluster polarization, surface disintegration, and microscopic atomic dynamics (elastic electron-ion scattering, electron-impact ionization etc.) can thus be studied.

The measurement of the 3.1 keV characteristic K-shell X-ray radiation emitted from argon clusters [4] provides an excellent experimental tool to gain insight into the dynamics of the interaction on the short time-scale of the irradiating laser pulse ($\tau > 60\,\mathrm{fs}$). High resolution X-ray spectroscopy gives access to the charge state distribution of the highly charged cluster ions Ar^{q+} with $q > 12$.We achieve good quantitative agreement between the simulated and experimental absolute X-ray yields, and the ionic charge-state distributions are also well reproduced at high laser intensities.

By varying the pulse duration, additional information on the interplay between ionic and electronic dynamics during the cluster explosion process can be gained. One highlight is the existence of an optimum pulse duration that maximizes the X-ray yield at constant laser pulse energy. We give an interpretation of this effect different from the previously invoked nanoplasma resonance [5].

This work is supported by FWF SFB-16 (Austria).

References

[1] U. Saalmann, Ch. Siedschlag, and J.M. Rost, J. Phys. B **39** R39 (2006).

[2] C. Deiss et al., Phys. Rev. Lett. **96**, 013203 (2006).

[3] C. Deiss and J. Burgdörfer, Jour. of Phys. Conf. Ser. **88** 012036 (2007).

[4] E. Lamour et al., Nucl. Instr. and Meth. B **235** 408 (2005).

[5] T. Ditmire et al., Phys. Rev. A **53** 3379-3402 (1996).

EVIDENCE OF GIANT DIPOLE PLASMON RESONANCE IN ELECTRON SPECTRUM OF C_{60} AND BEAM INDUCED POLARIZATION

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Mechanisms of electron emission in collisions with clusters involving C_{60}-fullerene are governed by more complicated processes than in ion-atom collisions. The fullerenes are "small" particles with diameter ~10Å over which a large electron density similar to that of a solid is sampled. Fullerenes are known to exhibit collective excitation: *giant dipole plasmon resonance* (GDPR). Effect of GDPR on x-ray emission from fullerene and multiple ionization under heavy ion impact has been reported earlier [1-5]. However, a direct evidence of this process in fast ion-collisions was awaited. The plasmon excitation de-excite through emission of electrons of particular energy, which is characteristic of the plasmon frequency. This presents a unique possibility of observing the GDPR peak in the low energy electron spectrum of C_{60}. The electron energy due to the decay of GDPR-excited state is expected at ~10 eV (i.e. 20 eV- I_P, I_P=ionization potential). We measured the low energy (1-300 eV) e^- - DDCS spectrum from C_{60} in collisions with 4 MeV/u bare F ions at various angles. We observe a broad hump like structure near the expected GDPR peak position in all the electron spectra. The C_{60} DDCS spectra are different from the DDCS spectra of other atomic gaseous targets like Ne [Fig.1]. The low energy spectrum was collected with lot of precaution and spectrometer performance was verified by measuring expected spectral shapes from atomic targets.

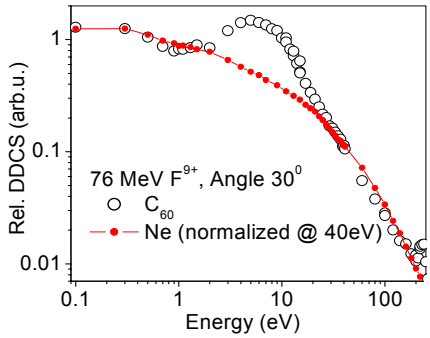

Fig.1 : Typical electron DDCS spectrum from C_{60} (o) and Ne.

We have also measured the angular distributions of the electrons. The electron emission (at ~10 eV i.e. at GDPR peak) is maximum in forward and backward direction w.r.t. to the projectile beam and a dip is observed at 90^0**.** This distribution is just opposite to the expected behaviour for atomic targets. The angular distribution suggests that the dipole oscillations are induced preferably along the projectile beam direction. This is for the first time that such an angular distribution of e-emission in plasmon decay in C_{60} or any type of clusters has been measured.

References

[1] T. LeBrun et al. Phys. Rev. Lett., 72, 3965 (1994)
[2] H Tsuchida, A Itoh, Y Nakai, K Miyabe and N. Imanishi, J. Phys. B 31, 5383 (1998).
[3]U. Kadhane et al. Phys. Rev. Lett. **90**, 093401 (2003)
[4] U. Kadhane et al. Phys. Rev. A (Rapd comm.) **75**, 041201 (R) (2007)
[5] A. H. Kelkar et al. J. Phys. B **40**, 2481 (2007) and Nucl. Instrm. Meth. B 256 114 (1007)

STABILITY OF HIGHLY CHARGED FULLERENE CATIONS AND ANIONS

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The most abundant fullerenes, C_{60} and C_{70}, and all the pure-carbon fullerenes larger than C_{70} synthesized so far follow, with no exception, the isolated-pentagon rule (IPR)[1-2]. Fullerenes containing adjacent pentagons (APs) are less stable due to the additional strain. Surprisingly, recent experiments have shown that a few endohedral fullerenes[3], for which IPR structures are possible, hence expected to be the most stable ones, are stabilized in non-IPR cages. These cages are either positively or negatively charged, depending on the character of electron acceptor or electron donor of the encapsulated species. It has been argued that this unexpected stability of charged non-IPR fullerenes is associated with electronic properties of the carbon cage, such as unusually large HOMO-LUMO gaps or bond resonance energies[4,5]. These properties might be related to a reduction of strain induced by the encapsulated species, but the ultimate reasons remain unclear.

By performing density functional theory calculations[6-8] on a large number of C_{60} and C_{70} derivatives with both IPR and non-IPR cages, we show that, apart from strain, the physical property that governs the relative stability of highly charged fullerenes is the charge distribution in the cage[9]. This charge distribution is controlled by the number and location of two different structural motifs, one electrofilic (the pentalene motif, i.e., the pairs of APs,) and the other one electrophobic (the pyrene motifs). APs are the preferential sites to host additional electrons, either by adding explicitly those electrons or by making the AP bonds to react (or both). On the contrary, when one electron is removed from the fullerene cage, the resulting positive charge locates in the pyrene motifs, not in the pyrene bonds but in the more aromatic bonds surrounding the latter. Thus by playing with the number and position of pyrene bonds it is possible to generate non-IPR fullerenes with strongly non uniform positive charge distributions. We show that, when AP and pyrene motifs are uniformly distributed in the cage and well separated from each other, stabilization of non-IPR endohedral and exohedral fullerenes, as well as pure-carbon fullerene anions and cations, is more the rule than the exception. This suggests that non-IPR charged fullerenes might be even more common than IPR ones, which can be relevant to interpret recent experiments in which highly charged fullerenes are produced in collisions with ions or in storage rings.

References

[1] H. W. Kroto, Nature 1987, 329, 529-531.
[2] K. M. Kadish, R. S. Ruoff and Eds, Fullerene: Chemistry, Physics and Technology, Wiley, New York, 2002.
[3] S. F. Yang, A. A. Popov and L. Dunsch, Angewandte Chemie-International Edition 2007, 46, 1256-1259.
[4] J. Aihara, Theor. Chem. Acc. 1999, 102, 134-138.
[5] J. Aihara, Chem. Phys. Lett. 2001, 343, 465-469.
[6] S. Díaz-Tendero, M. Alcamí and F. Martín J. Chem. Phys. 2003, 119, 5545-5557.
[7] G. Sánchez, S. Díaz-Tendero, M. Alcamí and F. Martín Chem. Phys Lett. 2005, 416, 14-17.
[8] S. Díaz-Tendero, M. Alcamí and F. Martín Phys. Rev. Lett. 2005, 95, 013401.
[9] H. Zettergren, M. Alcamí and F. Martín ChemPhysChem. 2008, 861-866.

Posters A
(2 September)

Posters A (Tuesday, 2 September)

a) Fundamental aspects, Structure and Spectroscopy

A-a01 EUV spectroscopy of heavy elements near Z=74 at the NIST EBIT
Ilija N Draganic, John D Gillaspy, Joseph N Tan, Joshua M Pomeroy, Yuri Ralcehnko, Joseph Reader

A-a02 Experimental studies of 3.1-3.5 keV X-ray spectra of highly charged Au ions at Shanghai EBIT
Jun Xiao, Zhixian Geng, Yang Yang, Ke Yao, Yunqing Fu, Baoren Wei, Di Lu, Xuemei Zhang, Roger Hutton, Yaming Zou

A-a03 Experimental study of X-ray transition in Li-like ions with EBIT
Xue Mei Zhang, Chong Yang Chen, Martin Andersson, Yong Liu, Roger Hutton, Ya Ming Zou, Nobuyuki Nakamura, Shunsuke Ohtani

A-a04 Soft X-ray laser spectroscopy of HCIs with free electron lasers
S. W. Epp, M. C. Simon, T. Baumann, G. Brenner, V. Maeckel, N. Guerassimova, E. A. Schneidmiller, R. Treusch, J. R. Crespo Lopez-Urrutia, J. Ullrich

A-a05 Precision lifetime determinations of the green and red iron coronal lines in an electron beam ion trap
Guenter Brenner, Jose R. Crespo Lopez-Urrutia, Joachim Ullrich

A-a06 Microcalorimeter observations of the L-shell spectra of Ne- through Fe-like Au ions in an EBIT
Elmar Traebert, Stephanie B. Hansen, Gregory V. Brown, Peter Beiersdorfer, Klaus Widmann, Hyun-kyung Chung

A-a07 Hyperfine interaction induced decays in highly charged ions: Successful radiative decay rate measurements and some puzzling problems
Elmar Traebert

A-a08 Comparison of the effective electron density for ions in different charge states in an electron beam ion trap
Guiyun Y. Liang, Jose R. Crespo Lopez-Urrutia, Thomas M. Baumann, Sascha W. Epp, Anastasia Gonchar, Alain Lapierre, Paul H. Mokler, Martin C. Simon, Hiroyuki Tawara, K. Yao, G. Zhao, Yaming Zou, Joachim Ullrich

A-a09 Radiative decay of few-electron ions
Lakshmi Natarajan, Anuradha Natarajan

A-a10 Quasirelativistic *ab initio* study of gallium-like molybdenum and tungsten
Pavel Bogdanovich, Olga Rancova, Rasa Karpuškienė

A-a11 The hyperfine quenching of polarized two-electron ions in an external magnetic field
Anastasiya Bondarevskaya, Anton Prozorov, Leonti Labzowsky, Gunter Plunien, Dieter Liesen, Fritz Bosch

A-a12 Hyperfine dependent lifetimes in neon like ions
Martin Andersson, Roger Hutton, Yaming Zou

A-a13 QED calculation of interelectron interaction corrections for transition probabilities in two-electron ions
Oleg Yu. Andreev, Leonti N. Labzowsky, Guenter Plunien

A-a14 The resonant states of Li II between the n=2 and 3 thresholds
Ming- Keh Chen

A-a15 Observation and modeling of hollow multicharged ions X-ray spectra radiated by laser produced plasma
Anatoly Faenov, Tatiana Pikuz, Igor Skobelev, Yuji Fukuda, James Colgan, Joe Abdallah, Jr

A-a16 A tale of two lines in promethium-like ion spectra
Elmar Traebert, Marius J. Vilkas, Yasuyuki Ishikawa

A-a17 Line emission from M-shell titanium ions
Joel Clementson, Peter Beiersdorfer, Reginald D. Wood

A-a18 EUV spectra from highly charged tin ions observed in low density plasmas in LHD
Chihiro Suzuki, Takako Kato, Kuninori Sato, Naoki Tamura, Daiji Kato, Shigeru Sudo, Norimasa Yamamoto, Hajime Tanuma, Hayato Ohashi, Shintaro Suda, Gerry O'Sullivan, Akira Sasaki

b) Collisions with Electrons, Ions, Atoms and Molecules

A-b01 Precise experimental and theoretical studies on resonant energies of the KLL dielectronic recombination proceses for He- up to O-like xenon
Weidong Chen, Ke Yao, Jun Xiao, Yang Shen, Yunqing Fu, Baoren Wei, Fanchang Meng, Chongyang Chen, Di Lu, Xuemei Zhang, Roger Hutton, Yaming Zou

A-b02 Angle-resolved studies of hypersatellite radiation following dielectronic recombination of heavy ions
Andrey Surzhykov, Nikolai M. Kabachnik, Stephan Fritzsche

A-b03 Photorecombination of sodiumlike silicon ions: Astrophysically motivated storage ring experiments and MCDF calculations
Eike Schmidt, Stephan Fritzsche, Dietrich Bernhardt, Jens Hoffmann, Claude Krantz, Michael Lestinsky, Dragan Lukic, Alfred Mueller, Dimitry Orlov, Daniel Wolf Savin, Stefan Schippers, Andreas Wolf

A-b04 Experimental rate coefficient for dielectronic recombination of neonlike iron forming sodiumlike iron
Eike Schmidt, Dietrich Bernhardt, Jens Hoffmann, Michael Lestinsky, Dragan Lukic, Alfred Mueller, Dimitry Orlov, Daniel Wolf Savin, Stefan Schippers, Andreas Wolf, Dejang Yu

A-b05 Evaluation of direct ionization cross sections for C_{60} by electron interaction
Neeraj Kumar, Satyendra Pal

A-b06 Determination of angular cross sections for electron dissociative ionization of CCl_4 molecule
Satyendra Pal, Anshu Neeraj Kumar

A-b07 The first test experiment performed at the electron cooler of storage rings in Lanzhou
Xinwen Ma, Lingjie Meng, Huiping Liu, Jiawen Xia, Hushan Xu, Zhenguo Hu, Xiaodong Yang, Meng Wang, Ruishi Mao, Dacheng Zhang, Lijun Mao, Guohong Li, Shengli Yang, Youjin Yuan, Jianhua Zheng, Guoqing Xiao, Wenlong Zhan

A-b08 Angular momentum transfer and polarization degree of ions with one-valence electron by electron-impact
Kenichi Akita, Takeshi Kai, Shinobu Nakazaki, Akinori Igarashi

A-b09 Effective collision strengths for Mg-like iron peak ions
Patrick H Norrington, Claire E Hudson

A-b10 Dielectronic and radiative recombination of Si to N-like tungsten ions
Christoph Biedermann, Rainer Radtke, Robert Seidel, Ehud Behar

A-b11 Electron impact excitation of Ni II
C M Cassidy, C A Ramsbottom, M P Scott, P G Burke

A-b12 Effect of electron-impact ionization in damage of bio-molecules irradiated by XFEL
Takeshi Kai, Kengo Moribayashi

A-b13 High-energy electron-impact excitation cross-sections of hydrogen-like iron and nickel ions
Daniel B. Thorn, Peter Beiersdorfer, Gregory V. Brown, Richard L. Kelley, C. A. Kilbourne, F. Scott Porter

A-b14 Angular momentum transfer and polarization degree of ions with two-valence electron by electron-impact
Kenichi Akita, Takeshi Kai, Shinobu Nakazaki, Akinori Igarashi

A-b15 Electron impact ionization of multiply charged xenon and tin ions
Alexander Borovik, Mohammad Gharaibeh, Stefan Schippers, Alfred Mueller

A-b16 Excitation rates for transitions in Kr XXXII
Kanti M Aggarwal, F P Keenan, K D Lawson

A-b17 Neutron radiation effects on metal oxide semiconductor (MOS) devices
Haider F Al-Shemeri, Abdullah Chik

A-b18 Structure deformation dynamics of acetylene molecules following electron loss and capture collisions of 6 MeV O^{4+} ions
Tomoya Mizuno, Takahiro Yamada, Yoichi Nakai, Hidetsugu Tsuchida, Akio Itoh

A-b19 Systematic multiconfiguration dirac-fock method study of the K X-ray spectra of silicon
Katarzyna Slabkowska, Marek Polasik

A-b20 Electron angular distributions for He single ionization in collisions with "fixed-in-space" H_2^+ ions at 0.5 MeV and 1 MeV
Shaofeng Zhang, J Suske, D Fischer, K U Kuehnel, S Hagmann, A Voitkiv, B Najjaril, A Krauss, R Moshammer, J Ullrich, Xinwen Ma

A-b21 Electron-molecular and atom-molecule scattering in few-body approach
Serguey Alekseevich Pozdneev

A-b22 State-selected differential cross section measurements for the one-electon capture processes in the F^{4+} - He, Ne, Ar systems at E_{lab} = 45 eV
Yoh Itoh, Kazumasa Ohtsuki

A-b23 Branching ratio of N_2 in collisions with Ar^{q+} ($q \geq 6$) at energies below 1 keV/u
Yoko Inoue, Kunikazu Ishii, Hidemi Ogawa

A-b24 Interference effects in electron emission spectra for 3 MeV $H^+ + O_2$ collisions
Melike Winkworth, Pablo D. Fainstein, Mariel E. Galassi, Jamie L. Baran, Susanta Das, Buddhika S. Dassanayake, Tamer Elkafrawy, David Cassidy, Asghar Kayani John A. Tanis

A-b25 Electron capture processes from excited hydrogen atoms by highly charged ions of beryllium and carbon
Noriyuki Shimakura, Naoki Kobayashi, Mayumi Honma, Tomohide Nakano, Hirotaka Kubo

A-b26 Isotope effect in dissociation of methanol dications produced by collision of Ar^{8+}
Kenichi Hayakawa, Jun Matsumoto, Haruo Shiromaru, Yohji Achiba

A-b27 Analysis of charge asymmetric Coulomb explosion of N_2 molecules with slow Kr^{8+} ions
Tomoko Ohyama-Yamaguchi, Atsushi Ichimura

A-b28 Coster-kronig electrons from N^{q+} (q=1-3) Rydberg states produced in high energy collisions with He
Kiyoshi Kawatsura, Katsumi Takahiro, Masao Sataka, Makoto Imai, Hiroyuki Sugai, Kouichi Ozaki, Kazuhiro Kawaguchi, Hiromi Shibata, Ken-ichiro Komaki

A-b29 Coster-Kronig electrons from O^{q+} (q=1-4) Rydberg states produced in high energy collisions with He
Kiyoshi Kawatsura, Katsumi Takahiro, Masao Sataka, Makoto Imai, Hiroyuki Sugai, Kouichi Ozaki, Kazuhiro Kawaguchi, Hiromi Shibata, Ken-ichiro Komaki

A-b30 Single charge transfer in collisions of diatomic molecules with slow highly charged ions
Mykhaylo Khoma, Olexandr Karbovanets, Myroslav Karbovanets, Robert Buenker

A-b31 Theoretical predictions of the structure of m-X-ray lines of heavy atoms
Piotr Matuszak, Karol Koziol, Marek Polasik, Katarzyna Slabkowska

A-b32 Influence of changes in the valence electronic configuration on the structure of L-X-ray spectra
Marek Polasik, Karol Koziol, Katarzyna Slabkowska, Marcin Czarnota, Marek Pajek

A-b33 Cahrge transfer cross sections of W^{2+} ions in collisions with rare gas targets
Manabu Saito, Makoto Imai, Syunsuke Hosokawa, Yoichi Haruyama, Akio Itoh

A-b34 X-ray signatures of charge exchange in L-shell ions
Miriam Frankel, Peter Beiersdorfer, Gregory V. Brown, Joel Clementson, Ming F. Gu, Richard L. Kelley, C. A. Kilbourne, F. Scott Porter, Bradford Wargelin

A-b35 Studies of X-ray production following charge exchange recombination between highly charged ions and neutral atoms and molecules
Gregory V. Brown, Peter Beiersdorfer, Hui Chen, Joel Clementson, Miriam Frankel, Ming F. Gu, Richard L. Kelley, C. A. Kilbourne, F. Scott Porter, Daniel B. Thorn, Bradford Wargelin

A-b36 Vacuum ultraviolet spectra in charge transfer collisions of multiply charged Sn ions
Shintaro Suda, Hayato Ohashi, Hajime Tanuma, Shinsuke Fujioka, Hiroaki Nishimura, Katsunobu Nishihara

A-b37 Dissociative and non-dissociative charge-changing processes in 1.0-2.0 MeV/u O^{5+} + O_2 collisions
D P Cassidy, E Y Kamber, A Kayani, J A Tanis

A-b38 Charge transfer processes in collisions of slow highly charged ions with polar molecules CO and C_3H_8
Makoto Imai, Mykhaylo V Khoma, O M Karbovanets, Y Kikuchi, Manabu Saito, Yoichi Haruyama, M I Karbovanets, I Yu Kretinin, Akio Itoh, Robert J Buenker

A-b39 Single electron capture in collisions of N^{2+} with He at low energies
Keisuke Toida, Kouichi Soejima, Atsunori Danjo

A-b40 Gross and partial ionization cross sections in 6-MeV/amu bare-ion collisions with methane
Yumiko Ohno, Takashi Matsuo, Toshiyuki Kohno, Tomoharu Nakazato, Shin-ichi Watanabe, Takeshi Murakami

A-b41 QED approach to calculating electron collision strengths for multicharged ions in a plasma: within the debae approximation
Alexander V. Glushkov, Olga Yu. Khetselius, Andrew V. Loboda, Elena V. Mischenko, Ludmila Lovett

c) Interactions with Clusters, Surfaces and Solids

A-c01 Fragmentation of small biomolecules induced by highly charged ion impact
Bin Li, Li Chen, Richard Brédy, Jérome Bernard, Guillaume Montagne, Xinwen Ma, Serge Martin

A-c02 Evidence of giant dipole plasmon resonance in electron spectrum of C_{60} and beam induced polarization
Aditya Kelkar, S Kasthurirangan, S Chatterjee, Lokesh C Tribedi

A-c03 Angular anisotropy in KLL Auger electron emission from C_{60} and CH_4 in collision with 4 MeV/u F^{9+}
Aditya Kelkar, Lokesh C Tribedi

A-c04 Low energy carbon ion irradiation of water ices
Christopher Adam Hunniford, Daniele Fulvio, Anita Dawes, Bhala Sivaraman, Tony L Merrigan, Robert W McCullough, Nigel J Mason, Maria Elisabetter Palumbo

A-c05 Optical emission spectroscopy of excited atoms sputtered on a Ti surface under irradiation with multicharge Ar ions
Kenji Motohashi, Yuichi Saitoh, Sin-iti Kitazawa

A-c06 Potential energy threshold for nano-hillock formation on CaF_2 by impact of very slow, highly charged ions
Ayman S. El-Said, Walter Meissl, Rene Heller, Robert Ritter, Stefan Facsko, Christoph Lemell, Beate Solleder, Ille C. Gebeshuber, Gerhard Betz, Wolfhard Moeller, Joachim Burgdoerfer, Friedrich Aumayr

A-c07 Electron emission from insulators bombarded with very slow highly charged ions
Walter Meissl, Daniel Winklehner, Rene Heller, Stefan Facsko, Wolfhard Moeller, Friedrich Aumayr

A-c08 Secondary-ion emission from GaN(0001) and dodecanethiol/Au(111) surfaces irradiated with Ar^{q+} (q = 3-6) at glancing angle
Kenji Motohashi, Marcos Flores, Yasuyuki Kanai, Yasunori Yamazaki

A-c09 Simulation of ion guiding through nanocapillaries: Energy dependence
Klaus Michael Schiessl, Karoly Tőkési, Christoph Lemell, Joachim Burgdörfer

A-c10 Potential energy threshold of surface nanostructures formation by the interaction of slow xeon ions on a HOPG surface
Yu Yu Wang, Guo Qing Xiao, Yong Tao Zhao, De Hui Li, Di Zhao, Zhong Feng Xu, Fu Li Li

A-c11 Absolute sputtering yields from solid rare gases by singly- and multiply-charged ion impact
Shinya Fujita, Takayuki Tachibana, Tetsuo Koizumi, Takato Hirayama

A-c12 Potential sputtering of ionic species from rare gas solids by multiply charged ion impact
Kentaro Fukai, Shinya Fujita, Takayuki Tachibana, Tetsuo Koizumi, Takato Hirayama

A-c13 Secondary ion emission from a KCl(001) surface by grazing-angle incidence of swift ions
Kaoru Nakajima, Motofumi Suzuki, Kenji Kimura

A-c14 Guiding of very highly charged ions with a glass capillary
Akira Yamazaki, Ryo Nakayama, Masahide Tona, Nobuyuki Nakamura, Hirofumi Watanabe, Nobuo Yoshiyasu, Chikashi Yamada, Shunsuke Ohtani, Makoto Sakurai

A-c15 STM observations of highly charged ion irradiated alkanethiol monolayers
Brian E O'Rourke, Marcos Flores, Vladimir Esaulov, Yasunori Yamazaki

A-c16 Theory of crystal-assisted free-bound pair production by relativistic ions
Hideo Nitta

A-c17 Electron transfer proceess in ion neutralisation on nanoscale metal systems
Hicham Hamoudi, Lin Chen, Thirunavukkarasu Kandasamy, Celine Dablemont, Vladimir A Esaulov

A-c18 Density matrix description of resonant coherent excitation of swift highly charged ions in oriented crystals
Vsevolod Balashov, Igor Bodrenko, Alexey Sokolik, Alexey Stysin

A-c19 Unexpected differences between kinetic energy release distributions for C_2^+-emission from multiply charged C_{60} and C_{70} fullerenes
Henrik Cederquist, Nicole Haag, Zoltán Berenyi, Peter Reinhed, Daniel Fischer, Magnus Gudmundsson, Henrik A.B. Johansson, Henning T. Schmidt, Henning Zettergren

A-c20 Hydrogen atoms sputtered by highly charged ions from a Si(111)-H surface
H.Watanabe, J. Sun, M. Tona, N. Nakamura, M. Sakurai, C. Yamada and S. Ohtani

A-c21 Imaging dynamics of charge-self-organisation in glass capillaries: Latest results and prospectives
A.Cassimi, L.Maunoury, P.Rousseau, B.Manil, T.Muranaka, B.Huber, K.Rani Dey, H.Lebius, D.Lelievre, J.M.Ramillon, T.Been, T.Ikeda, Y.Kanai, T.M.Kojima, Y.Iwai, Y.Yamazaki, H.Khemliche, N.Bundaleski, P.Roncin

d) Interactions with Photons, Plasmas and Strong Field Processes

A-d01 A systematic study of the 4d-giant resonance in Xe^{n+} (n=0,1-7)
Andrew Domondon, Xiao Min Tong, Tsutomu Watanabe

A-d02 Photoionization of highly charged ions in an electron beam ion trap by synchrotron radiation
Martin C. Simon, Sascha W. Epp, Jose R. Crespo Lopez-Urrutia, Joachim Ullrich

A-d03 Lowly ionized Ar and Xe plasma diagnostics and modeling
Konstantinos Katsonis, Chloe Berenguer, Marguerite Cornille

A-d04 Effects of Debye plasmas on the resonance states of highly stripped two-electron ions using the stabilization method
Yew Kam Ho, Sabyasachi Kar

A-d05 Probing electrons and ions in stagnation layers at the collision front between colliding laser produced plasmas
Padraig Hough, Conor McLoughlin, Thomas Kelly, Sivanandan Harilal, Jean Paul Mosnier, John Costello

A-d06 Two-photon transitions in the He+ ion embedded in strongly coupled plasmas
H. F. Lai, Y. C. Lin, Y. K. Ho

A-d07 Atomic processes of damage on bio-molecules irradiated by XFEL
Kengo Moribayashi, Takeshi Kai

A-d08 Progress of opacity experiment on “Shengguang II” laser facility
Jiamin Yang, Jiyan Zhang, Yan Xu, Jianmin Yuan, Jun Yan, Yaonan Ding, Yang Zhao, Fengtao Jin, Zhimin Hu, Guohong Yang, Baohan Zhang

e) Production, Experimental developments and Applications

A-e01 Theoretical and experimental research of ion charge state evolution in electron beam ion trap
Zhixian Geng, Ke Yao, Yaming Zou

A-e02 Simulation of electron beam in Shanghai EBIT
Xincheng Wang, Yang Yang, Baoren Wei, Yong Liu, Yaming Zou

A-e03 A tandem linear Paul trap as an ion source
Kenji Izawa, Hiroyuki Higaki, Hiroshi Yamate, Kiyokazu Ito, Haruki Hitomi, Masao Kuriki, Hiromi Okamoto

A-e04 The SPARC EBIT at GSI; Comissioning and future plans at the HITRAP beamline
Brian E O'Rourke, Sabrina Geyer, Alexey Solokov, Gleb Vorobjev, Oliver Kester, Thomas Stohlker

A-e05 Development of high current electron beam ion traps for charge breeding of radioactive ion beams
Jose R. Crespo Lopez-Urrutia, Stefan Schwarz, Georg Bollen, Jens Dilling, Joachim Ullrich

A-e06 Electron beam density distribution studies using an portable slit imaging slit imaging system at the Shanghai electron beam ion trap
Yang Yang, Ke Yao, Weidong Chen, Yong Liu, Jun Xiao, Zhixian Geng, Baoren Wei, Di Lu, Xuemei Zhang, Roger Hutton, Yaming Zou

A-e07 The multi-parameter data acquisition system at Shanghai EBIT
Xincheng Wang, Baoren Wei, Xuemei Zhang, Jun Xiao, Yang Shen, Yaming Zou

A-e08 A progress report of 320 kV multi-discipline research platform for highly charged ions
Xinwen Ma, Huiping Liu, Lingting Sun, Mingtao Song, Xiaolongzhu Zhu, Shan Sha, Wentian Feng, Dacheng Zhang, Jinyu Li, Daqing Gao, Zhiguang Wang, Xiaohong Cai, Wenjian Li, Pingzhi Wang, Lizhen Ma, Kaidi Man, Shaofeng Zhang, Bin Li, Guoqing Xiao, Hongwei Zhao, Wenlong Zhan

A-e09 Evolution of X-ray calorimeter spectrometers at the Lawrence Livermore electron beam ion trap
F. Scott Porter, Peter Beiersdorfer, Gregory V. Brown, Ming F. Gu, Richard L. Kelley, C. A. Kilbourne, Daniel B. Thorn

A-e10 The MEVVA source ion injection at the Shanghai EBIT
Yunqing Fu, Yaming Zou, Baoren Wei

A-e11 A power saving and compact electron beam ion source using a periodic permanent magnet system
Toshio Kusakabe

A-e12 Diagnostics of the highly charged ion beam extracted from the tokyo-EBIT
Takahiro Shimazaki, Masahide Tona, Hirofumi Watanabe, Nobuyuki Nakamura, Chikashi Yamada, Shunsuke Ohtani

A-e13 Enhancement of soft X-ray emission from fs laser plasma by using mixture of molecule and atomic gases as cluster jet targets and its application for nanostructure imaging
Tatiana Pikuz, Anatoly Faenov, Igor Skobelev, Sergei Gasilov, Alexei Boldarev, Vladimir Gasilov, Yuji Fukuda, Masaki Kando, Hideyuki Kotaki, Izuru Daito, Takayuki Homma, Keigo Kawase, Takashi Kameshima, Tetsuya Kawachi, Paul Bolton, Hiro Daido, Toyoaki Kimura, Toshiki Tajima, Yoshiaki Kato, Sergei Bulanov

A-e14 Narrowband X-ray source for applications in medicine
Ilija N. Draganic, John D. Gillaspy, Yuri Ralchenko, Jacek Capala

A-e15 The atomic model of the Sn plasmas for the EUV sources
Akira Sasaki, Atsushi Sunahara, Katsunobu Nishihara, Takeshi Nishikawa, Fumihiro Koike, Hajime Tanuma

EUV SPECTROSCOPY OF HEAVY ELEMENTS NEAR Z=74 AT THE NIST EBIT

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We report recent measurements and identifications of extreme ultraviolet (EUV) spectra for highly-charged ions of heavy elements obtained with the NIST Electron Beam Ion Trap (EBIT) [1-4]. Particular emphasis is given to ions of tungsten relevant to magnetic fusion research.

Electron beam energies varied from 2 to 20 keV, allowing us to produce ions in the range of 35+ to 68+. Detailed identification of spectral lines from M- and N-shell ions was based on large scale collisional-radiative modeling of the EBIT plasma.

We present more than 100 newly identified allowed and forbidden lines that can be used for the diagnostics of hot plasmas.

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References

[1] Yu. Ralchenko, J. N. Tan, J. D. Gillaspy, J. M. Pomeroy, and E. Silver, Phys. Rev. A **74**, 042514 (2006).

[2] Yu. Ralchenko, J. Reader, J. M. Pomeroy, J. N. Tan and J. D. Gillaspy, J. Phys. B: At. Mol. Opt. Phys. **40**, 3861-3875 (2007).

[3] Yu. Ralchenko, I. N. Draganic, J. N. Tan, J. D. Gillaspy, J. M. Pomeroy, J. Reader, U. Feldman and G. E. Holland, J. Phys. B: At. Mol. Opt. Phys. **41**, 021003 (2008).

[4] http://physics.nist.gov/MajResFac/EBIT/ebit.html

EXPERIMENTAL STUDIES OF 3.1-3.5 KEV X-RAY SPECTRA OF HIGHLY CHARGED AU IONS AT SHANGHAI EBIT

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Spectroscopic study of highly charged Au are very important, both for atomic structure study and for hot plasma diagnostics, especially for laser induced fusion plasma studies [1-2].
In this paper, studies of M-shell X-ray spectra of highly charged Au ions were reported. The experiments were done at the newly developed electron beam ion trap at Fudan University in Shanghai, Shanghai EBIT [3]. This EBIT was designed for high electron energy operation, with electron beam energy of 2-200 keV. At present, the beam energy can cover a range of 0.9-130 keV, but with obviously much lower current at low energy, i.e. 5 mA at 0.9 keV. In the experiments reported in this paper, spectra were taken at several electron beam energies in the range of 5-20 keV, with electron beam currents of 20 to 80 mA. Low charge gold ions were produced by a home made metal vapour vacuum arc, MEVVA ion source and injected into the Shanghai EBIT during the experiments. The X-rays of highly charged Au ions in the range of 3.1-3.5 keV were dispersed by a home made flat crystal spectrometer, and recorded by a charge coupled device (CCD) detector. The crystals used in the experiments are LiF(200) (2d=0.4027nm) and SiO_2(1010) (2d=0.8512nm), with spectral resolution, $\lambda/\Delta\lambda$ around 3000.
The experimental results will be displayed and discussed in the paper.

References

[1]M. E. Foord, S. H. Glenzer, R. S. Thoe, K. L. Wong, K. B. Fournier, B. G. Wilson, and P. T. Springer, Phys. Rev. Lett. **85**, 992 (2000).
[2]M. J. May, K. B. Fournier, P. Beiersdorfer, H. Chen, and K. L. Wong, Phys. Rev. E **68**, 036402 (2003).
[3] Xiaofeng Zhu, Yong Liu, Xincheng Wang, Yafeng Liu, Panlin Guo, Di Lu, Xuemei Zhang, Wei Hu, Mianhong He, Leif Liljeby, and Yaming Zou, Nucl. Instr. and Meth. B **235** (2005) 509-513.

EXPERIMENTAL STUDY OF X-RAY TRANSITION IN LI-LIKE IONS WITH EBIT

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As mentioned in many papers[1, 2, 3, 4, 5, 6], measurements of Li-like systems can provide data to be more sensitive to higher-order QED terms than those of H-like systems, though the calculation of QED terms for Li-like ions is more complex than for H-like ions due to the presence of two additional electrons. And the treatment of QED in many-particle environment is still a field in development.

The X-ray transition in Li-like Cu^{27+} and Pb^{79+} were investigated by using flat crystal spectrometer.

The lines from Cu^{27+} were observed at Shanghai EBIT [7]. The Tokyo-EBIT [8] was used to produce and trap Li-like Pb^{79+}.

As a result, the wavelength of the $1s^22p_{3/2} - 1s^22s_{1/2}$ transition in $^{208}Pb^{79+}$ has been determined to be 2642.18±0.06 eV. In order to get the QED contribution, the Non-QED part 2667.22eV was subtracted from the measured energy. Therefore, -25.04±0.06 eV was obtained for QED contribution.

References

[1] P. Beiersdorfer, K. Knapp, R. E. Marrs, S. R. Elliott, and M. H. Chen. Phys. Rev. Lett. 71, 3939 (1993).
[2] P. Beiersdorfer, A. Osterheld, S. R. Elliott, M. H. Chen, D. Knapp, and K. Reed. Phys. Rev. A 52, 2693 (1995).
[3] P. Beiersdorfer, A. L. Osterheld, J. H. Scofield, J. R. Crespo López-Urrutia, and K. Widmann. Phys. Rev. Lett. 80, 3022 (1998).
[4] P. Beiersdorfer, H. Chen, D. B. Thorn, and E. Träbert. Phys. Rev. Lett. 95, 233003 (2005).
[5] C. Brandau, C. Kozhuharov, A. Müller, W. Shi, S. Schippers, T. Bartsch, S. Böhm, C. Böhme, A. Hoffknecht, H. Knopp, N. Grün, W. Scheid, T. Steih, F. Bosch, B. Franzke, P.H. Mokler, F. Nolden, M. Steck, T. Stöhlker, and Z. Stachura. Phys. Rev. Lett. 91, 073202 (2003).
[6] P. H. Mokler, Radiation physics and chemistry, 75,1730 (2006.).
[7] X. Zhu, Y. Liu, X. Wang, Y. Liu, P. Guo, D. Lu, X. Zhang, W. Hu, M. He, L. Liljeby and Y. Zou. Nucl. Instrum. Methods Phys. Res. B, **235**: 509(2005).
[8] N. Nakamura, J.Asada, F. J. Currell, T. Fukami, T. Hirayama, K. Motohashi, T. Nagata, E. Nojikawa, S. Ohtani, K. Okazaki, M. Sakurai, H. Shiraishi, S. Tsurubuchi and H. Watanabe, Phys. Scr. T73, 362 (1997)

Soft X-ray Laser Spectroscopy of HCIs with Free Electron Lasers

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Resonant laser spectroscopy of soft x-ray transitions in highly charged ions (HCIs) by means of Free Electron Lasers (FELs) has been proven [1] to be a promising technique with the potential to achieve unprecedented precision on energetic transitions unreachable by traditional laser spectroscopy. The technique relies on combining two advanced technologies, a state-of-the-art EBIT [2] with the Free electron LASer at Hamburg (FLASH [3]), measuring the resonant fluorescence yield by the trapped HCIs as a function of the wavelength of the FLASH-light.

Here we report on our latest results applying improved alignment techniques to quickly find and guarantee optimum overlap of the ion cloud and the FLASH beam. Three fundamental transitions at energies E_0 were investigated, namely $1s^2 2s\ ^2S_{1/2}$–$1s^2 2p\ ^2P_{1/2}$ in Li-like Fe^{23+} at 48.6 eV, Li-like Cu^{27+} at 55.2 eV, and $1s^2 2s\ ^2S_{1/2}$–$1s^2 2p\ ^2P_{3/2}$ in Fe^{23+} at 65.3 eV. The later demonstrates resonant laser spectroscopy of multiply or highly charged ions at more than one order of magnitude higher transition energies as reported elsewhere [4]. The resolutions achieved were around $E_0/\mathrm{FWHM} = 3000$ for the individual spectral lines, resulting in relative precisions (preliminary) of 2 parts-per-million (ppm) for determining the center-of-mass wavelength.

By means of known absorption lines present in neutral neon we were able to achieve an absolute accuracy (preliminary) in the Fe^{23+} case of roughly 20 ppm, which is close to the accuracy of the most accurate reported measurements [5]. Pushing the absolute accuracy further down (e.g. to the achieved relative precision) can hardly be done by comparison to absorption lines of rare gases, but instead requires lines of H-like and He-like low-Z ions (C,N,O,F) for calibration, which then would establish independent wavelength standards in this spectral region with ppm accuracy.

Thus, we expect significant impact of our technique on precision spectroscopy of transitions important for atomic structure theory, e.g. strong-field QED [6], or of astrophysical relevance.

References

[1] S. W. Epp *et al., Phys. Rev. Lett* **98**, 183001 (2007).

[2] M. A. Levine *et al., Nucl. Instrum. Meth. B* **43**, 431 (1989).

[3] V. Ayvazyan *et al., Eur. Phys. J. D* **37**, 297 (2006).

[4] I. Klaft *et al., Phys. Rev. Lett* **73**, 2425 (1994).

[5] J. Reader, J. Sugar, N. Acquista, R. Bahr, *J. Opt. Soc. Am. B* **11**, 1930 (1994).

[6] P. J. Mohr, G. Plunien, G. Soff, *Phys. Rep.* **293**, 227 (1998).

PRECISION LIFETIME DETERMINATIONS OF THE GREEN AND RED IRON CORONAL LINES IN AN ELECTRON BEAM ION TRAP

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The lifetimes of the forbidden lines of Fe XIV and Fe X (the green and red coronal lines) have been measured at the Heidelberg electron beam ion trap by monitoring its optical decay to the ground state by magnetic dipole (M1) transitions at λ= 530.29 nm and 637.64 nm, respectively. A new trapping scheme was applied to enhance sensitivity. Possible systematic effects were investigated by studying in detail the dependence of the decay curves on various trapping conditions with high statistical significance. The highly accurate result of the FeXIV [1] measurements shows an unexplained discrepancy in comparison with the average value of existing theoretical predictions. The inclusion of the electron anomalous magnetic moment within the theoretical calculations increases this disagreement, thus pointing at other possible origins of this discrepancy. The FeX measurement provides an experimental value for this important line in agreement with an existing extrapolation.

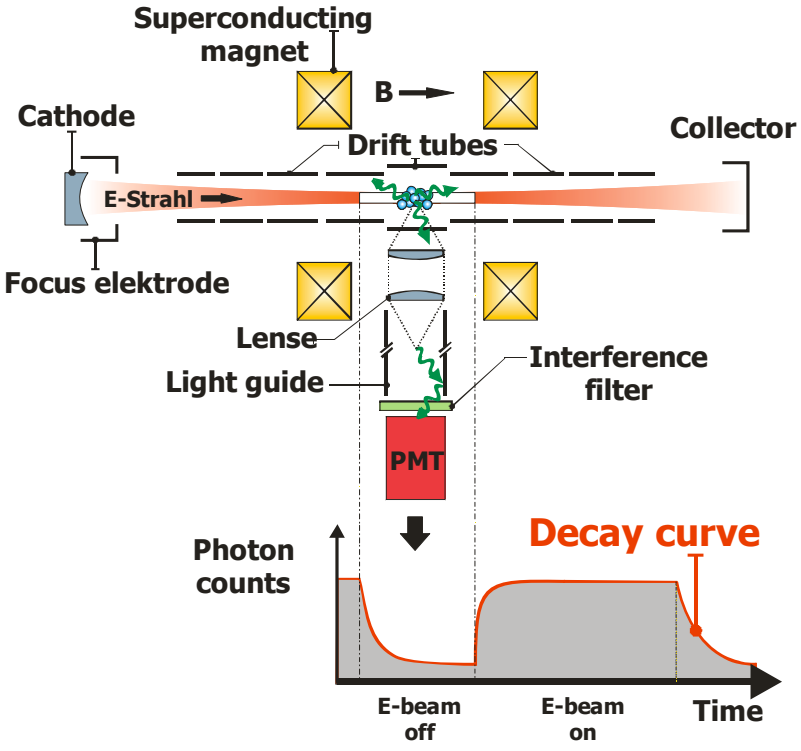

Fig. 1. Sketch of the method used for lifetime measurements in an electron beam ion trap

References

[1] G. Brenner, J. R. Crespo López-Urrutia, Z. Harman, P. H. Mokler, and J. Ullrich, Phys. Rev. A. **75**, 032504 (2007)

MICROCALORIMETER OBSERVATIONS OF L-SHELL SPECTRA OF NE- THROUGH FE-LIKE AU IONS IN AN EBIT

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Reduced-size hohlraums are of interest for generating high-temperature radiation environments. Small hohlraums fill with hot (multi-keV) expanding plasma on the 1-ns timescale of a laser pulse, then partly blocking the hohlraum entrance against further irradiation. Spectral diagnostics based on the L-shell emission of Au are being developed to determine the parameters (temperature, charge balance) of the effluent plasma. For this purpose we have simulated the L-shell emission from highly charged gold ions in the SuperEBIT electron beam ion trap under bombardment by electrons at energies from 10 to 18 keV [1]. The emission was recorded with an x-ray microcalorimeter, featuring an instrumental line width of 10 eV in the region of primary interest. Lines from ironlike Au^{53+} through neonlike Au^{69+} ions were identified. We find that the strong $3d_{5/2} => 2p_{3/2}$ emission features are well separated for at least the highest 13 charge states and can be used to diagnose the charge state distribution. Collisional-radiative calculations relate the observed charge state distribution and the inferred average ion charge $< Z >$ to the electron temperature. Moreover, our calculations indicate a number of density effects that come into play at higher density ; indeed, corresponding line shifts due to the presence of satellite lines can now be recognized in earlier beam-foil spectroscopic observations [2].

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References

[1] G. V. Brown, S. B. Hansen, E. Träbert, P. Beiersdorfer, K. Widmann, H. Chen, H. K. Chung, J. H. T. Clementson, M. F. Gu, D. B. Thorn, Phys. Rev. E **77**, (2008) (submitted)
[2] G. A. Chandler, M. H. Chen, D. D. Dietrich, P. O. Egan, K. P. Ziock, P. H. Mokler, S. Reusch, D. H. Hoffmann, Phys. Rev. A 39, **565** (1989).

HYPERFINE INTERACTION INDUCED DECAYS IN HIGHLY CHARGED IONS: SUCCESSFUL RADIATIVE DECAY RATE MEASUREMENTS AND SOME PUZZLING PROBLEMS

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In Ni-like ions, the lowest excited configuration is $3d^9$ 4s, and the lowest excitation level, $^3D_3$, can decay to the $3d^{10}$ ground state only by emission of magnetic octupole (M3) radiation. Such high multipole order radiation is of low transition probability at low Z, but it increases steeply with Z. For the ion Xe^{26+}, the predicted level lifetime is about 15 ms. A measurement at an electron beam ion trap at Livermore has determined this value with an uncertainty of only about 1.5 % [1]. In isotopes with a nonvanishing nuclear spin, hyperfine interaction mixes HFS sublevels of the $^3D_3$ level with those of $^3D_2$; the ensuing M3/E2 mixing reduces the lifetime of such sublevels of $^3D_3$. Again, Livermore EBIT measurements on the isotope ^{129}Xe have corroborated specific calculations [2].

Compared to Ni-like ions, Be- and Mg-like ions appear to be much simpler. However, some older calculations of the hyperfine-induced decay rate of the nsnp $^3P\ ^o_0$ [3,4] levels need to be updated, as newer, unpublished, calculations indicate lifetimes that are lower by some 20 %. Two experiments at the heavy-ion storage ring TSR (Heidelberg), one on Be-like Ti^{18+} ions [5], the other on Mg-like ions $^{63,65}Cu^{17+}$ [6], find results that differ by much more (about 40 %) from those vintage expectations. The reason for the discrepancy is not yet understood. At the same time, TSR measurements [6] of the 3s3p $^3P^o_2$ level lifetime in Mg-like Ni and Cu find excellent agreement with recent calculations (our own and [7]), when taking into account M1, E2, M2, and HFS-induced decay channels.

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References

[1] E. Träbert, P. Beiersdorfer, G. V. Brown, Phys. Rev. Lett. **98**, 263001 (2007)
[2] K. Yao, M. Andersson, T. Brage, R. Hutton, P. Jönsson, and Y. Zou, Phys. Rev. Lett. **97**, 183001 (2006), Erratum: Phys. Rev. Lett. **98**, 269903 (2007).
[3] J. P. Marques, F. Parente, P. Indelicato, Phys. Rev. A **47**, 929 (1993).
[4] J. P. Marques, F. Parente, P. Indelicato, At. Data Nucl. Data Tab **55**, 157 (1993).
[5] S. Schippers, E. W. Schmidt, D. Bernhardt, D. Yu, A. Müller, M. Lestinsky, D. A. Orlov, M. Grieser, R. Repnow A. Wolf, Phys. Rev. Lett. **98**, 033001 (2007).
[6] E. Träbert, J. Hoffmann, C. Krantz, S. Reinhardt, A. Wolf, P. Indelicato (work in progress)
[7] K. Aggarwal, V. Tayal, G. P. Gupta, F. P. Keenan, At. Data Nucl. Data Tab. **93**, 615 (2007).

COMPARISON OF THE EFFECTIVE ELECTRON DENSITY FOR IONS IN DIFFERENT CHARGE STATES IN AN ELECTRON BEAM ION TRAP

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In model calculations simulating the plasma conditions in an EBIT it was assumed [1] and also confirmed experimentally [2] that the electron density, as estimated from the design parameters, is on the order of 10^{13} cm^{-3}. The *effective* electron density was determined from the excitation of several EUV lines of different simultaneously trapped highly charged Fe ions. *Effective* means here that ion-electron collision rate is reduced by the fact that the ions do not dwell all the time within the electron beam diameter. We used a collisional-radiative model to take the mono-energetic electron

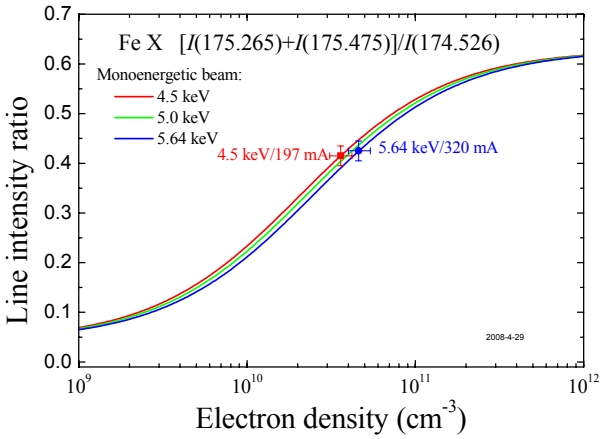

Fig. 1. Intensity ratio I(175.265 Å)/I(175.475 Å) of Fe X vs. effective electron density.

conditions in the EBIT into account. Figure 1 shows the line intensity ratio as a function of the electron density for three Fe X lines. The *effective* electron density under operating conditions of 4.50 keV/197 mA and 5.64 keV/320 mA was 4×10^{10} cm^{-3}, two orders of magnitude smaller than the electron density calculated for that current value and the diameter of the electron beam. We found a value for lines of Fe XXI of 3×10^{11} cm^{-3} under identical conditions. We interpret these differences as a result of the varying overlap between the electron beam and the more extended trapped ion distribution. Indeed, direct observations of the ion distribution in EBITs show that the ion orbits are larger than the size of the electron beam, with ions in high charge states overlapping more strongly with the electron beam than those in lower charge states [2,3]. The present results on *effective* electron densities help to analyze ion production rates within a given set of operating conditions.

References

[1] F.R. Currell, in *Trapping Highly Charge Ions* (Nova Science Publ., 1999)
[2] H. Kuramoto *et al.*, Phys. Scripta **T92**, 351 (2001)
[3] J.V. Porto *et al.*, Rev. Sci. Instr. **71,** 3050 (2000)
[4] H. Chen *et al.*, Astrophys. J. **611,** 598 (2004)

Radiative decay of few- electron ions in the range Z=14 to 54

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Relativistic energies and transition probabilities of the spectral lines arising from states of 2s3p configuration of some selected He-like ions in the range Z= 14- 54 are computed using Multi-configuration Dirac-Fock wave functions in the active space approximation [1,2].Higher order corrections like Breit interaction, self energy and vacuum polarization are also included in the evaluation of transition parameters. To improve the theoretical accuracy of the calculated energies, the quantum electrodynamic (QED) corrections for the 1s2s configuration have been taken from the most recent compilation of Artemyev *et al* [3]. The convergence of the eigenvalues and the effect of configuration mixing of the various virtual shells on the rates have been studied as the active space is being gradually increased [4]. Our calculations show that strong configuration mixing reduces substantially the single configuration allowed E1 rates from He-like ions whereas the trend is irregular for the spin flip dipole rates. To the best of our knowledge, such transitions from ions with empty K shell have not been reported and hence a comparison could not be made.

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References:

1] C.Froese Fischer, T.Brage and P.Jonnson, *Computational Atomic Structure (Bristol: Institute of Physics Publication,* 1997*)*.
2) F. A. Parpia, C. F. Fischer, C. and I. P. Grant, Comput. Phys. Comm. **94**, 249, 1996.
3] A.N.Artemyev, V.M.Shabaev *et al*. Phys.Rev.A **71 ,** 062104.,2005
4] Anuradha Natarajan and L.Natarajan. Phy.Rev A **75** , 062502,2007

QUASIRELATIVISTIC *AB INITIO* STUDY OF GALLIUM-LIKE MOLYBDENUM AND TUNGSTEN

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The quasirelativistic approach, when the relativistic effects accurate up to α^2 are taken into account while solving the equations similar to the Hartree-Fock ones (QRHF), has been created as far back as the seventies. This approach is described in details in the monograph [1] and references therein. The computer code created on the basis of these methods is widely spread. However the detailed analysis of this approach revealed that it was possible to obtain somewhat more precise equations, which allowed one to avoid some oversimplification while solving the equations. Due to this fact the work has been started to create different quasirelativistic approach adjusted for *ab initio* calculations. First it has been proposed to take into account a finite size of the atomic nucleus while solving QRHF equations. For this purpose the model of the charge density distribution inside the nucleus has been created in [2]. This model is appropriate for the applied approach and it allows one to obtain the convenient expansion of the radial orbitals (RO) in the nucleus area. QRHF equations obtained from the Dirac-Fock equations do not require the using of the statistical or model potentials while solving them [3]. The analysis of the solutions obtained for hydrogen-like ions [4] revealed, that it was necessary to take into account the contact interaction with the nucleus while calculating RO not only of s-electrons, but of p-electrons as well [5]. The method of accounting for the virtual excitations when applying the configuration interaction (CI) and the features of the calculations of radial integrals are described in [6]. The implementation of the above mentioned approach allowed us to perform the real calculations of the spectral characteristics of highly charged ions of heavy atoms.

The calculations of the spectral characteristics of Ga-like ions of molybdenum and tungsten have been performed as one of the first examples of the application of the developed quasirelativistic approach. The calculations were performed within CI method. The transformed RO's with variable parameters were used to describe the virtual excitations. The energy spectra, the characteristics of E1-transitions and the radiative lifetimes of $4s^24p$, $4s4p^2$, $4p^3$, $4s4p4d$, $4s^24d$, $4s^24f$, $4s4p4f$, $4p^24d$ and $4s4d^2$ configurations of Mo^{+11} and W^{+43} have been calculated. The obtained results are in good agreement with the available data.

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References

[1] R. D. Cowan, *The theory of atomic structure and spectra,* (University of California Press, 1981).
[2] P. Bogdanovich and O. Rancova, Lithuanian. J. Phys. **42**, 257 (2002).
[3] P. Bogdanovich and O. Rancova, Phys. Rev. A **74,** 052501 (2006).
[4] P. Bogdanovich, V. Jonauskas and O. Rancova, Nucl. Instr. Meth. B **235**, 145 (2005).
[5] P. Bogdanovich and O. Rancova, Phys. Rev. A **76,** 012507 (2007).
[6] P. Bogdanovich and O. Rancova, Phys. Rev., (submitted).

THE HYPERFINE QUENCHING OF POLARIZED TWO-ELECTRON IONS IN AN EXTERNAL MAGNETIC FIELD

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The hyperfine quenching (HFQ) in the isoelectronic sequence of He-like highly charged ions (HCI) was successfully used for the determination of the transition probabilities and the fine structure intervals in [1 - 5]. In [6] it was proposed to use the HFQ for observing the parity nonconservation (PNC) effect in He-like Eu. The choice of Eu (Z=63) is determined by the near-crossing of the metastable 2^3P_0 level with the opposite parity 2^1S_0 level and by the inequality $\Gamma(2^3P_0) > \Gamma(2^1S_0)$ where Γ denotes the total width. The latter inequality allows to avoid a huge background effect in the proposed PNC experiment, which assumes the employment of a polarized ion beam. The possible beam polarization method was described in [7]. In the present paper we discuss a method of measuring the beam polarization via the same HFQ mechanism in an external magnetic field. We will show that the HFQ probability in an external magnetic field depends on the beam polarization and this dependence can be measured by standard experimental HFQ techniques [1 - 5]. In the case of the 2^1S_0, 2^3P_0 states with zero total electron angular momentum the ion polarization exists as nuclear polarization. The maximum value of the degree of the nuclear polarization is 93% according to [7]. We should add that polarized ion beams can be used not only for PNC experiments but also for many other purposes, e.g. for testing the time-reversibility [8].

References

[1] R. Marrus, A. Simionovici, P. Indelicato, D.D. Dietrich, P. Charles, J.-P. Briand, K. Finlayson, F. Bosch, D. Liesen, F. Parente, Phys. Rev. Lett. **63**, 502 (1989)

[2] R.W. Dunford, C.J. Liu, J. Last, N. Berrah-Memsur, R. Vondrasek, D.A. Churah, L.J. Curtis, Phys. Rev. A **44**, 764 (1991)

[3] P. Indelicato, B.B. Birkett, J.-P. Briand, P. Charles, D.D. Dietrich, R. Marrus, A. Simionovici, Phys. Rev. Lett. **68**, 1307 (1992)

[4] B.B. Birkett, J.-P. Briand, P. Charles, D.D. Dietrich, K. Finlayson, P. Idelicato, D. Liesen, R. Marrus, A. Simionovici, Phys. Rev. A **47**, R2454 (1993)

[5] A. Simionovici, B.B. Brikett, J.-P. Briand, P. Charles, D.D. Dietrich, K. Finlayson, P. Indelicato, D. Liesen, R. Marrusi, Phys. Rev. A **48**, 1695 (1993)

[6] L. N. Labzowsky, A.V. Nefiodov, G. Plunien, G. Soff, R. Marrus, D. Liesen, Phys. Rev. A **63**, 054105 (2001)

[7] A. Prozorov, L. Labzowsky, D. Liesen, F. Bosch, Phys. Lett. B **574**, 180 (2003)

[8] I.B. Khriplovich, Phys. Lett. B **444**, 98 (1998)

Hyperfine dependent lifetimes in Neon like ions

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As part of our ongoing investigations of hyperfine dependent lifetimes of metastable levels [1-4] we report on a theoretical investigation of hyperfine quenching in Neon-like ions. The studies were done along the iso-electronic sequence ranging from neutral Ne (Z=10) to Au^{69+} (Z=79). $2p^5 3s\ ^3P_2$ is the first excited level in Ne-like systems and it can only decay to the ground state, $2p^6\ ^1S_0$, through a magnetic quadrupole (M2) transition. For the ions up to $Z \approx 51$, were there is an energy level crossing between the $2p^5 3s\ ^3P_0$ and the $2p^5 3d\ ^3P_0$ level [5], the former is the third excited level and it can only decay to $2p^5 3s\ ^3P_1$ through a magnetic dipole (M1) transition and to $2p^5 3s\ ^3P_0$ through an electric quadrupole (E2) transition. Also it has no possibility to decay to the ground state except through a two-photon decay. In the presence of a nuclear spin though, the hyperfine interaction introduce a small mixing of $2p^5 3s\ ^3P_1$ and $^1P_1$ into $2p^5 3s\ ^3P_2$ and $^3P_0$ respectively, opening up hyperfine induced electric dipole (hpf-E1) transition channels to the ground state for both of the metastable levels.

Extensive multiconfiguration Dirac-Hartree-Fock calculations were performed to calculate the transition probabilities for the various transitions from the two metastable levels as well as the transition matrix elements of the $2p^6\ ^1S_0 - 2p^5 3s^3P_1$ and the $2p^6\ ^1S_0 - 2p^5 3s^1P_1$ E1 transitions. Also the off-diagonal hyperfine interaction constants between the metastable levels and the $2p^5 3s\ ^3P_1$ and the $^1P_1$ levels were calculated. First order perturbation calculation were used to calculate the $2p^6\ ^1S_0 - 2p^5 3s\ ^3P_2$ and the $2p^6\ ^1S_0 - 2p^5 3s\ ^3P_0$ hpf-E1 transition rates and the hyperfine dependent lifetimes of the hyperfine levels of the metastable levels. It is shown that the $2p^5 3s\ ^3P_2$ level is sensitive to hyperfine interaction all along the iso-electronic sequence ranging from Z=10 to Z=79. It is also shown that the $2p^5 3s\ ^3P_0$ level is very sensitive to the hyperfine interaction in the beginning of the iso-electronic sequence where the hpf-E1 transition, in many cases, are orders of magnitude larger than the M1 and E2 transition rates. This sensitivity decreases with Z since both the M1 and the E2 transition channels have a higher order of Z dependence compared to the hpf-E1 transition channel. However even for highly charged ions, if the nuclear magnetic dipole moment is large, the hyperfine quenching can have a substantial influence on the lifetime of the $^3P_0$ level. An example is the hyperfine quenching of $^3P_0$ in In^{39+} which is lowering the lifetime by about 25%.

References

[1] K. Yao, M. Andersson, T. Brage, R. Hutton, P. Jönsson and Y. Zou, Phys. Rev. Lett. **97** 183001 (2006)

[2] K. Yao, M. Andersson, T. Brage, R. Hutton, P. Jönsson and Y. Zou, Phys. Rev. Lett. **98** 269903 (2007)

[3] M. Anderssin, K. Yao, R. Hutton, Y. Zou, C.Y. Chen and T. Brage, Phys. Rev. A **77** 042509 (2008)

[4] M. Andersson, Y. Liu, C.Y. Chen, R. Hutton, Y. Zou and T. Brage, Phys. Rev. A (submitted)

[5] C.Z Dong, L.U. Xie, J.J Wan and J. Jiang, Chin. Phys. Soc. **14**, 1108 (2005)

QED CALCULATION OF INTERELECTRON INTERACTION CORRECTIONS FOR TRANSITION PROBABILITIES IN TWO-ELECTRON IONS

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We present *ab initio* QED calculation of the transition probabilities for two-electron ions with nuclear charge numbers $Z = 10 - 92$. Employing the line profile approach [1], higher orders of interelectron interaction corrections are taken into account. The radiative corrections were not considered. In particular, calculations are performed for nondegenerate levels $(1s2s)\,^3S_1$, $(1s2p_{3/2})\,^3P_2$ ($M1$ and $M2$ transitions, respectively) and for quasidegenerate levels $(1s2p)\,^1P_1$, $(1s2p)\,^3P_1$ ($E1$ transitions), decaying to the ground state $(1s1s)\,^1S_0$. Both the "velocity" and "length" gauges for describing the emitted photons are considered.

This is the first exact QED calculation of the transition probabilities for the quasidegenerate levels. In the case of quasidegenerate levels the standard QED perturbation theory has a slow convergence for ions with the nuclear charge $Z < 50$. There is a necessity to take into account the higher-order interelectron interaction corrections. Within the framework of the line profile approach we developed a special technique to evaluate the higher-order interelectron interaction corrections to the transition probabilities. One- and two-photon exchange Feynman graphs are considered. The QED perturbation theory applied here is eligible for further improvement of the accuracy of calculation order by order. Calculating the contribution of the interelectron interaction, the QED radiative corrections to the transition probabilities for the quasidegenerate levels become also relevant.

References

[1] O. Yu. Andreev, L. N. Labzowsky, G. Plunien, D.A. Solovyev, Physics Reports **455**, 135 (2008)

The RESONANT STATES of LIII BETWEEN THE N=2 AND 3 THRESHOLDS

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Doubly excited states of two-electron atom and ions have attracted physicists to study experimentally and theoretically. The doubly excited $^1P^o$ resonant states of Li^+ have been observed firstly by Dual Laser Plasma technique[1]. After high-resolution monochromators at synchrotron-radiation facilities have been developed, high-resolution measurements on Li^+ ion were performed at the Advanced Light Source[2] and Super-ACO[3]. Recently, absolute cross-section measurements for the double photoexcitation of Li^+ ion have been performed by using the photo-ion merged-beam endstation. Accurate measurements on several members of the $(_2(0,1)^+_n$, $_3(1,1)^+_n)$ $^1P^o$ Li^+ ion have been made[4,5]. On the theoretical side, some resonances have been studied by the R-matrix method[4,5] and saddle-point complex rotation method[6].

In the present work, we studied lowest five doubly excited $^1P^o$ resonant states of Li^+ between the N=2 and 3 thresholds by saddle-point complex rotation method with B-spine functions. In a Configuration Interaction scheme, we constructed the wave functions in terms of B splines of order k and total number N, defined between two end points, r_{min}=0 and r_{max}= R, and built vacancies into the wave functions. By saddle-point variation method, we obtained the saddle-point energies and wave functions. After the saddle-point variation is carried out, we calculate the resonance energies and widths by a complex-rotation method. In the present, the values of R for end points are chosen to be 400 a.u. so that the saddle-point energies are converged to within uncertainty of 10^{-8} a.u. We included 10 partial waves at least in calculating the resonant sates of Li^+ to ensure the saddle-point energies converged within uncertainty of 10^{-8} a.u. For each partial wave, our results converged to within 10^{-8}. a.u. with increasing order k and total number N of the B spline. We also calculated the expectation value of the angle between the two electrons, θ_{12} ,the average value of r for the inner electron and outer electron, $r_<$, $r_>$, and the average values of r and r^2. The doubly excited states are grouped in Rydberg series labeled by the quantum numbers K, T, A. For lowest five $^1P^o$ resonant states, there are two members in the $_3(1,1)^+_n$ series, one member in the $_3(2,0)^-_n$, $_3(-1,1)^+_n$ and $_3(-1,0)^-_n$ series.

References

[1] P. K. Carroll and E. T. Kennedy, Phys. Rev. Lett. 38, 1008(1997)
[2] S. Diehl *et. al.*, J. Phys. B30. L595(1997)
[3] S. Diehl *et. al.*, J. Phys. B32. 4193(1999)
[4] S. W. J. Scully *et. al.*, J. Phys. B38. 1967(2005)
[5] S. W. J. Scully *et. al.*, J. Phys. Conf. Ser. **58**, 387(2007)
[6] M.-K. Chen., J. Phys. Conf. Ser. **58**, 125(2007)

OBSERVATION AND MODELING OF HOLLOW MULTICHARGED IONS X-RAY SPECTRA RADIATED BY LASER PRODUCED PLASMA.

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Plasma of multicharged ions (Z =10 – 20) with the electron temperature 10 – 100 eV and the electr on density 10^{22} – 10^{23} cm^{-3} is produced usually by interaction of a high-contrast femtosecond laser pulses with solids or clusters. The same plasma parameters are also realized when nanosecond shor t-wavelength laser pulses (KrF or XeCl or 3d, 4^{th} harmonics of Nd glass lasers) interact with the sol ids. Highly charged ions plasma with such parameters is already weakly- coupled and it is very inte resting to investigate radiation property of it. It has been shown in [1-5] that the X-Ray emission sp ectra of such plasma contain some exotic spectral lines caused by radiative transitions in the so call ed “hollow ions”, that are the highly charged ions with an empty inner K-shell.

In the present work the role of hollow highly charged ions to the X-Ray emission spectra is investigated for 2 cases: 1) plasma obtained under irradiation of Ar clusters by ultrashort laser pulses and 2) Mg-plasma heated by a short-wavelength long-pulse (nanosecond) laser.

For the first case, cluster-gas targets were irradiated by short laser pulses with various intensities, durations and contrasts. Calculations in support of these measurements have been performed using a detailed atomic kinetics model with the ion distributions found from solution of the time-dependent rate equations. The calculations are in reasonably good agreement with the measurements and the role of hollow highly charged ions in the resulting complicated spectra is analyzed. It is demonstrated that, although the presence of hollow atoms is estimated to add only around 2% to the total line emission, signatures of hollow atom spectra can be identified in the calculations, which are qualitatively supported by the experimental measurements.

In the case of long-lived plasma, produced by XeCl laser irradiation of solid Mg target, clear signatures of transitions from hollow ions are observed in the experimental spectrum. Spectra were identified from large-scale atomic kinetics calculations using the recently developed mixed-UTA (MUTA) model [6]. The relative strength of hollow ion spectral lines is explored and the temperature and density regions in which they are produced are analyzed. Large density and temperature gradients are required to simulate the observations, and additional influence to the hollow atom spectra were simulated with using a hot electron component in the electron distribution function

The kinetic simulations were made with collisional rates calculated in the isolated-atom approximation. The relatively good agreement between theoretical and experimental spectra means that use of such an approximation for the description of the collisional processes is justified for weakly-coupled plasma with the electron-ion coupling factor $\Gamma_{ei} < 1$.

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References

[1] A. McPherson, B.D. Thompson, A.B. Borisov et al., Nature. **370**,631 (1994)

[2] J.-C. Gauthier, J.-P. Geindre, P. Audebert et al., Phys. Rev. E. **52**, 2963 (1995)

[3] A.M. Urnov, J. Dubau, A.Ya. Faenov et al., JETP Letters. **67**, 489 (1998)

[4] A.Ya. Faenov, A.I. Magunov, T.A. Pikuz et al., Physica Scripta **T80,** 536 (1999)

[5] J. Abdallah, Jr., I.Yu. Skobelev, A.Ya. Faenov et al., Quantum Electronics. **30**, 694 (2000)

[6] S. Mazevet, J. Abdallah, Jr. J. Phys. B. **39**, 3419 (2006)

A TALE OF TWO LINES IN PROMETHIUM-LIKE ION SPECTRA

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Highly charged ions in the promethium sequence (61 electrons) have been suggested to show spectral features resembling the alkali sequence ions [1,2]. Guided by calculations, the possibly prominent 5s - 5p resonance lines have been sought in a variety of experiments, ranging from laser-produced plasmas, beam-foil spectroscopy [3,4], ion-atom collisions to electron beam ion traps [4] and tokamaks [5], and from W (Z=74) to U (Z=92). Most of the experiments, however, did not find any prominent lines as would be typical for alkali-like systems, and several earlier claims of identification are not substantial enough to be accepted. With the most extensive calculations of Pm-like ions available now [6], applying relativistic multi-reference Møller-Plesset second-order perturbation theory, the experimental evidence is reviewed, and options for a sensitive search are explored. The 5s and 5p levels are the lowest of their respective symmetries only for very heavy ions, and therefore it is only in those ions that any alkali-like signature may be found in the spectra. However, the ionization potentials of the ions of interest are so low that any existing EBIT could be used.

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References

[1] L. J. Curtis and D. G. Ellis, Phys. Rev. Lett. **45**, 2099 (1980).
[2] C. E. Theodosiou and V. Raftopoulos, Phys. Rev. A **28**, 1186 (1983).
[3] V. Kaufman, E. Träbert, P. H. Heckmann, G. Möller, V. Lodwig, and J. H. Blanke, Phys. Scr**. 42**, 705 (1990).
[4] R. Hutton, Y. Zou, J. Reyna Almandos, C. Biedermann, R. Radtke, A. Greier, and R. Neu, Nucl. Instrum. Meth. Phys. Res. B **205**, 114 (2003).
[5] K. B. Fournier, M. Finkenthal, S. Lippmann, C. P .Holmes, H. W. Moos, W. H. Goldstein, and A. L. Osterheld, Phys. Rev. A **50**, 3727 (1994).
[6] M. J. Vilkas, Y. Ishikawa, and E. Träbert, Phys. Rev. A **77**, 042510 (2008).

LINE EMISSION FROM M-SHELL TITANIUM IONS

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We have investigated the M-shell emission from highly charged titanium ions. The spectral lines of interest from Ti^{4+} through Ti^{7+} fall between 240 and 280 Å. The emission was measured with a grazing-incidence flat-field spectrometer described in ref. [1] using a 1200 lines/mm variable line spacing spherical Hitachi grating and a 100 μm slit. The R = 5.6 m EUV instrument has a wavelength resolution of about 0.3 Å FWHM and can cover the 25 - 450 Å range. A cryogenically cooled back-illuminated Photometrics CCD camera was used as the detector.

The emission lines were observed in the SSPX spheromak [2] at the Lawrence Livermore National Laboratory. The SSPX hydrogen plasmas had densities of a few times 10^{14} cm^{-3} and achieved temperatures from 10 eV up to over 500 eV, corresponding to titanium charge states up to neon-like Ti^{12+}. Titanium was confirmed as an intrinsic ion impurity in the spheromak by injecting atomic titanium into the machine and thus enhancing specific spectral features.

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References

[1] J. Clementson, P. Beiersdorfer, E. W. Magee, Rev. Sci. Instrum., submitted (2008)

[2] E. B. Hooper, L. D. Pearlstein, R. H. Bulmer, Nucl. Fusion **39**, 7 (1999) 863

EUV SPECTRA FROM HIGHLY CHARGED TIN IONS OBSERVED IN LOW DENSITY PLASMAS IN LHD

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Recently the needs for experimental databases of extreme ultraviolet (EUV) spectral lines from highly charged tin (Sn) ions have grown in connection with high density tin plasmas as a promising candidate for the light source around 13.5 nm for the semiconductor lithography process. On the other hand, low density plasmas generated in magnetically confined devices for fusion research are more suitable to meet the needs for the databases because they are optically thin and have relatively mild temperature and density gradients which are easily controlled.

In this study, we have measured EUV spectra (11–15 nm) from highly charged tin ions in the low density plasmas produced in the Large Helical Device (LHD) at the National Institute for Fusion Science. A small amount of tin was introduced into a background high temperature ($\simeq$1000 eV) and low density ($\simeq 10^{19}$ m^{-3}) hydrogen plasma by injecting a tracer encapsulated solid pellet (TESPEL). The EUV spectra were monitored by a grazing incidence spectrometer SOXMOS [1] whose absolute wavelength was calibrated with the accuracy of 0.02 nm by using allowed transition lines of iron ions.

Spectral feature of the unresolved transition array (UTA) around 13.5 nm according to 4d–4f transition of tin ions has been clearly observed after the plasma is sufficiently cooled due to the pellet injection. The comparisons with the other experimental data [2,3] indicates that the dominant ionization stages for this feature are from Sn^{11+} to Sn^{13+}, which would correspond to the electron temperature around 50 eV assuming the coronal ionization equilibrium. However, the actual electron temperature measured by a Thomson scattering diagnostic is much higher (300–400 eV) at the point of the pellet ablation, which implies that the plasma lies far from the ionization equilibrium.

Besides the lines from Sn^{11+} to Sn^{13+} ions, we have observed several sharp lines in 13.8–14.6 nm which are similar to the charge exchange collision spectra [3] from much highly charged tin ions. The validity of this speculation will also be discussed based on the dependence of these line intensities on the electron temperature and the comparisons with theoretical calculations.

References

[1] J. L. Schwob, A. W. Wouters, S. Suckewer, Rev. Sci. Instrum. **58**, 1601 (1987).

[2] S. S. Churilov, A. N. Ryabtsev, Phys. Scr. **73**, 614 (2006).

[3] H. Ohashi, H. Tanuma, S. Fujioka, H. Nishimura, A. Sasaki, K. Nishihara, J. Phys. Conf. Ser. **58**, 235 (2007).

PRECISE EXPERIMENTAL AND THEORETICAL STUDIES ON RESONANT ENERGIES OF THE KLL DIELECTRONIC RECOMBINATION PROCESES FOR HE- UP TO O-LIKE XENON

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Dielectronic recombination (DR) is a resonant process, in which a free electron is captured by an ion, and at the same time a bound electron of the ion is excited, followed by radiative stablization. Studies of DR processes are very important, not only for researches relevant to hot plasmas, but also for atomic structure and collision theory, as DR processes carry information on quantum electrodynamics, relativistic effects, many body interactions and so on.

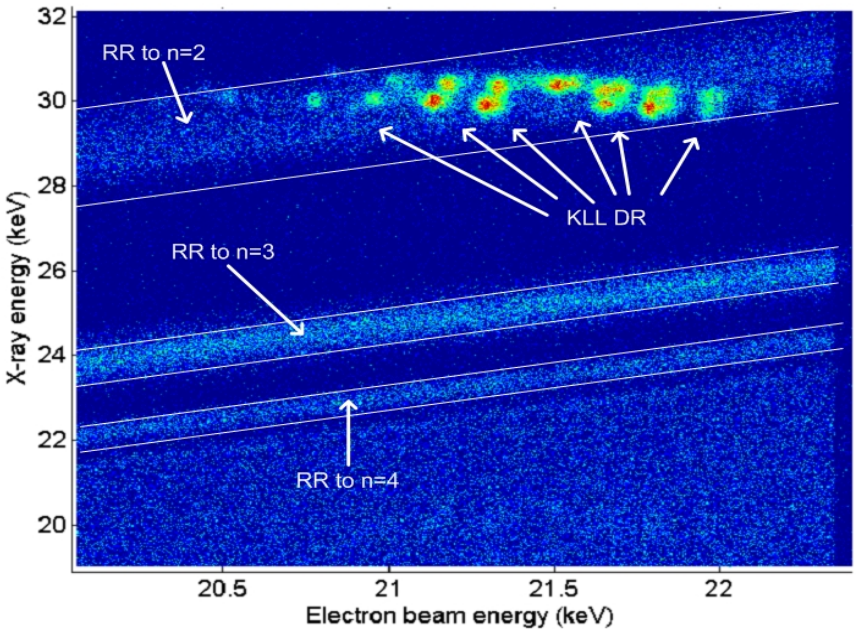

Fig. 1: Scatter plot of X-ray counts over electron beam energy and photon energy, taken at electron beam current of 62 mA. The KLL DR resonant events and radiative recombination to n=2, 3, 4 are shown.

Precise experimental studies of the resonant energies of KLL DR processes of He-, Li-, Be-, B-, C-, N-, and O-like xenon ions were performed at the Shanghai Electron Beam Ion Trap, by monitoring the electron beam energies over the KLL DR resonance region, see Fig. 1, employing home developed high precision, high stability high voltage dividers. Effects of the space charge of the electron beam and the ion neutralization, retardation by the capacitor of experimental setup, contact potential as well as fringing field effects were taken into account. Fifteen experimental resonant energies were obtained at an average uncertainty level of 0.03%.

At the same time, calculations using relativistic configuration interaction (RCI) theory, relativistic many-body perturbation (RMBPT) theory were also performed for the above-mentioned KLL DR resonant energies. Comparisons of experimental and theoretical results were made. 13 out of the 15 predictions by RMBPT are in good agreement with our experimental results, while only 5 out of the 15 predictions by RCI calculation agree with our experiments. Three literature available DR resonant energies by multi-configuration Dirac-Fock calculation agree very well with our experiments.

ANGLE–RESOLVED STUDIES OF HYPERSATELLITE RADIATION FOLLOWING DIELECTRONIC RECOMBINATION OF HEAVY IONS

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In the process of dielectronic recombination a free (or quasi–free) electron is resonantly captured by an ion under the simultaneous excitation of an ionic electron. For many years, such an electron capture has been of great interest both, for experiment and theory since it occurs frequently in high temperature plasmas. Apart from the plasma studies, dielectronic recombination (DR) is also playing an important role for understanding the interelectronic interaction effects. In order to explore these effects in heavy atomic systems, a number of DR experiments have been carried out recently for relativistic collisions of highly–charged projectile ions and target electrons at ion storage rings. At the GSI storage ring in Darmstadt, for example, $K-LL$ dielectronic recombination of (finally) helium–like uranium U^{90+} ions and their subsequent radiative decay have been studied in detail [1]. While measured data were generally well understood within the Dirac's relativistic theory [2], a considerable discrepancy was found for the angular distribution of the Kα_1 hypersatellite radiation following the $K-L_{1/2}L_{3/2}$ resonant electron capture [1,2].

In the present work, we apply the density matrix theory together with the multiconfiguration Dirac–Fock method in order to re–investigate the dielectronic recombination of (initially) hydrogen–like ions and their subsequent radiative decay. Special emphasis is placed on the characteristic x–ray emission whose angular distribution may be modified by higher (non–dipole) terms in the expansion of the electron–photon interaction. In particular, we show that the emission pattern of the hypersatellite K$\alpha_{1,2}$ lines is notably influenced by the interference between the leading electric dipole $E1$ and — the much weaker — magnetic quadrupole $M2$ decay channels [3]. Detailed calculations for such a multipole–mixing phenomena are performed for the decay of the doubly–excited LL resonances of U^{90+} ions and are compared with the previous experimental [1] and theoretical [2] data.

References

[1] X. Ma *et al*, Phys. Rev. A **68**, 042712 (2003)

[2] S. Zakowicz, Z. Harman, N. Grün, W. Scheid, Phys. Rev. A **68**, 042711 (2003)

[3] S. Fritzsche, N. M. Kabachnik, A. Surzhykov, Phys. Rev. A *in preparation* (2008)

PHOTORECOMBINATION OF SODIUMLIKE SILICON IONS: ASTROPHYSICALLY MOTIVATED STORAGE RING EXPERIMENTS AND MCDF CALCULATIONS

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The origin of large-scale structure in the universe, the history of star and galaxy formation, the metagalactic radiation field, and the chemical evolution of the intergalactic medium (IGM) can be studied by the use of spectroscopic observations of absorption lines in the IGM (see [1] and references therein). Coupled with calculations of the ionization balance, these observations provide important constraints for IGM studies.

However the accuracy with which one can infer the properties of the IGM is limited by uncertainties in the underlying atomic data. Of particular importance are reliable electron-ion recombination data for the process known as dielectronic recombination (DR). This is the dominant recombination process for most ions under IGM conditions. Recent investigations [2] have shown that uncertainties in the DR data for C IV, N V, O VI, and Si IV limit the ability to constrain the metagalactic radiation field and the initial mass function for the earliest generations of stars.

This situation has motivated us to measure the Si IV to Si III recombination rate coefficient employing the electron-ion merged-beams method at the Heidelberg heavy-ion storage ring TSR. The measured electron-ion collision energy range of 0–186 eV comprises DR resonances associated with $3s \rightarrow 3p$, $3s \rightarrow 3d$, $2p \rightarrow 3l$ and $2p \rightarrow 4s$ excitations. The present experimental Si IV merged-beams recombination rate coefficient allows us to benchmark theory for a light, low charged sodium-like ion over a wide range of energies.

The present study is complemented by calculations of DR cross sections and rate coefficients based on the multiconfiguration Dirac-Fock (MCDF) method, in particular at low electron-ion collision energies. At these energies the calculation of accurate resonance positions and strengths is most critical for the derivation of accurate plasma rate coefficients [3]. Our experimental results are compared with other experimental and theoretical results [4].

References

[1] A. Aguirre et al., Astrophys. J. **602**, 38 (2004)

[2] D. W. Savin, Astrophys. J. **533**, 106 (2000)

[3] S. Schippers et al., Astron. Astrophys. **421**, 1185 (2004)

[4] E. W. Schmidt et al., Phys. Rev. A **76**, 032717, (2007)

EXPERIMENTAL RATE COEFFICIENT FOR DIELECTRONIC RECOMBINATION OF NEONLIKE IRON FORMING SODIUMLIKE IRON

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Emission lines from highly charged iron ions are prominent in the high resolution x-ray spectra from many astrophysical objects as has been observed, for example, with the x-ray telescopes CHANDRA and XMM-NEWTON [1]. The Fe^{16+} $2p^6 - 2p^5\,3s$, $2p^6 - 2p^5\,3d$, and $2p^6 - 2p^5\,4d$ lines in the 12–17 Å wavelength range are strong emission features of many coronal sources. Interpreting the emission from these lines depends partly on accurately knowing the underlying ionization balance of the emitting gas.

One of the important processes for determining ionization structure is dielectronic recombination (DR) which is the dominant electron-ion recombination mechanism for most ions in cosmic plasmas. Over the last few years a number of groups have systematically calculated DR cross section and plasma rate coefficients for ions with an open K- and L-shell (see [2] for an overview). But these results for Ne-like ions can differ up to 140% depending on the ion species and the plasma electron temperature [2].

In our ongoing effort of providing reliable DR rate coefficients for astrophysical applications (see e. g. [3, 4]) we have measured the DR rate coefficient of Ne-like Fe^{16+} forming Na-like Fe^{15+} employing the merged electron-ion beams technique at the heavy-ion storage ring TSR of the Max-Planck-Institut für Kernphysik in Heidelberg, Germany.

The present experiment is the first merged-beams measurement for an ion of the Ne-like isoelectronic series and, therefore, represents an important benchmark for theoretical calculations. We find good agreement between our experimentally derived rate coefficient in a plasma and recent theoretical results [5, 6].

References

[1] F. B. S. Paerels and S. M. Kahn, Annu. Rev. Astron. Astrophys. **41**, 291 (2003)

[2] P. Bryans et al., Astrophys. J. Suppl. Ser. **167**, 343 (2006)

[3] S. Schippers et al., Astron. Astrophys. **421**, 1185 (2004)

[4] E. W. Schmidt et al., Astrophys. J. **641**, L157 (2006)

[5] O. Zatsarinny et al., Astron. Astrophys. **426**, 699 (2004)

[6] M. F. Gu, Astrophys. J. **590**, 1131 (2003)

Evaluation of direct ionization cross sections for C_{60} by electron interaction

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Electron interaction with fullerenes like C_{60} has a growing interest in the present time due to its manifold applications. Despite many experimental and theoretical studies about the collisional interaction between electrons and fullerenes, so far there exist only a few absolute electron impact ionization cross sections measurements of C_{60}. This is generally due to the great difficulty in calibrating measured relative cross section functions, which requires, among other pre requisites, as a quantitative knowledge of target and ionizing electron beam. In the present study, we have extended a previously developed semi empirical method [1-2] for the calculation of ionization cross sections corresponding to the formation of singly charged ions C_{60}^{+}, doubly charged ions C_{60}^{++} and triply charged ions C_{60}^{+++} in electron-C_{60} collision. The calculations are made in the energy range varying from ionization onsets to 1 KeV. The major input, required oscillator strengths are used from the recent established experimental measurements of Jaensch and Kamke [3], Reinköster et.al. [4] and Berkowitz [5]. The calculated cross sections shown in the figure compare well with the experimental data of Märk et al. [6].

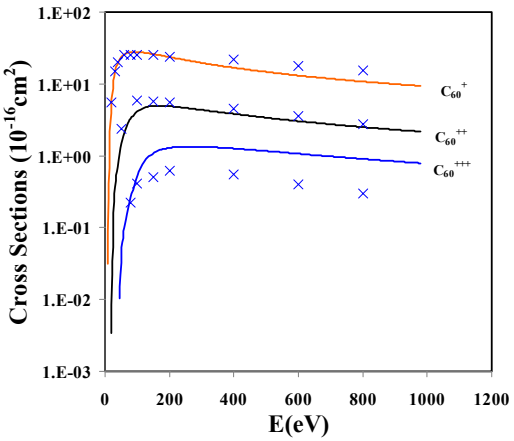

Figure: Electron impact ionization cross sections (designated by solid lines) in comparison with the experimental data designated by × [6]

References:

1. S. Pal, *Phys. Scr.,* **77** (2008) 055304.
2. S. Pal, P. Bhatt, *Chem. Phys.,* **326** (2006) 428.
3. R. Jaensch, W. Kamke, *Mol. Mater.*, **13** (2000) 163.
4. A. Reinköster, S. Korica, G. Prümper, J. Viefhaus, K. Godehusen, O. Schwarzkopf, M. Mast, U. Becker, *J. Phys. B: At. Mol. Opt. Phys.,* **37** (2004) 2135.
5. Berkowitz, J., *J. Chem. Phys.*, **111** (1999), 1446.
6. S. Matt, B. Dünser, M. Lezius, H. Deutsch, K. Becker, A. Stamatovic, P. Schier, T. D. Märk, *J. Chem. Phys.,* **105(5)** (1996) 1880.
7. V. Foltin, M. Foltin, S. Matt, P. Scheier, K. Becker, H. Deutsch, T. D. Märk, *Chem. Phys. Lett.*, **289** (1998) 181.
8. P. Scheier, H. Deutsch, K. Becker, T. D. Märk, *Int. J. Mass Spectrom.*, **233** (2004) 293.

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DETERMINATION OF ANGULAR CROSS SECTIONS FOR ELECTRON DISSOCIATIVE IONIZATION OF CCl_4 MOLECULE

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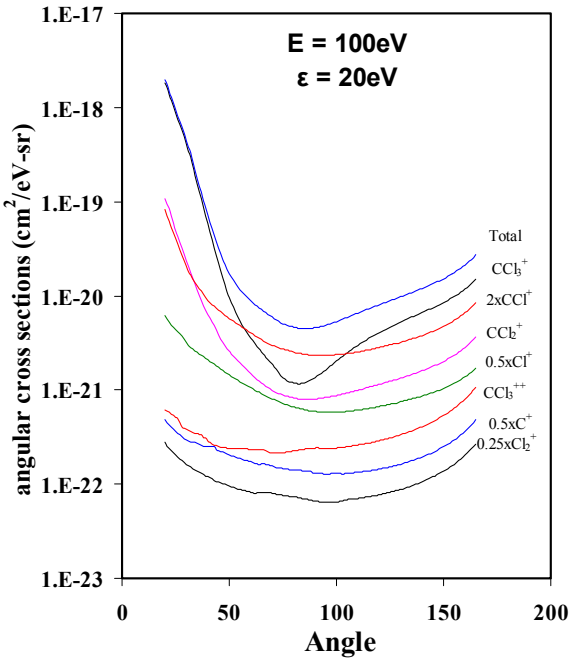
The CCl_4 molecule has attained a widespread interest in plasma technology and the atmospheric studies. It is used as a reactive etching gas for silicon wafers in semiconductor industry in consequence for plasma modelling study to obliterate the parent molecule. Angle dependent differential cross sections for the product ions CCl_n^+ (n=0-3), Cl^+, Cl_2^+ and CCl_3^{++} resulting from dissociative ionization of CCl_4 by electron collision have been calculated at fixed incident electron energy of 100eV and fixed secondary electron energy of 20 eV. The semiempirical formulation which requires the oscillator strength data as a major input has been employed [1-2]. The results are presented in the figure given below.



References:

[1] S.Pal, J.Kumar, T.D.Märk, J. Chem. Phys. 120 (2004) 4658.
[2] S. Pal, Phys. Scr. 77 (2008) 055304.

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THE FIRST TEST EXPERIMENT PERFORMED AT THE ELECTRON COOLER OF STORAGE RINGS IN LANZHOU

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The cooler storage ring CSR project was launched in 2000 at the Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou. The project consists of two rings, the main cooler storage ring CSRm and the experimental cooler storage ring CSRe. Both CSR rings are equipped with electron cooling devices [1]. In 2007, the installation was completed and the commissioning of CSRs gained great success, a new highly precise generation of collision experiments will become accessible even for the heaviest ion species. The CSR provides unique and unprecedented conditions for experiments based on the use of highly charged ions and in particular for research in the realm of atomic and nuclear physics. The interaction of the brilliant beams of cooled high-Z ions with low-dense gaseous matter as well as with electrons can be now studied under almost completely background free experimental conditions and with highest luminosity [2,3].

Recombination between electrons and ions is one of the most fundamental atomic collision processes for all kinds of plasmas in the universe. For such investigations, the electron cooler of the storage rings can be used as an electron target for ion-electron interaction studies. In the electron cooler environment, two processes compete: dielectronic recombination (DR) and radiative recombination (RR). The rate coefficient, most important parameters in plasma modelling, can be obtained for various electronic configurations and detailed information on the atomic structure can be deduced in addition. Theoretical investigations of the DR process show that DR might be a powerful tool for the investigation of influence of nuclear effects on the atomic structure and may even be used to obtained model independent information on the nuclear structure, e.g. the nuclear charge radius. This has just been confirmed experimentally [4]. Because the experimental storage ring CSRe can accumulate and store radioactive ions produced by nuclear fragmentation, DR experiments open a novel way for studying the ground-state properties of nuclei far from stability.

A commissioning RR experiment was performed at the electron cooler for Ar^{18+} ions, the results were presently under evaluation. A further RR experiment is being under preparation for krypton ions. A program is planned to be completed before the end of this year for fine detuning the electron beam energy in order to perform high precision DR experiments.

[1] J. W. Xia, W.L. Zhan, B.W. Wei, et. al., Nucl. Instr. Meth. A 488 (2002) 11

[2] R Schuch and S Böhm, J. Phys.: Conf. Ser. 88 (2007) 012002

[3] X. Ma, X. L. Zhu, H. P. Liu, et. al., J. Phy. Conf. Series 72 (2007) 012015

[4] C. Brandau, C. Kozhuharov, Z. Harman, et. al., Phys. Rev. Lett. 100 (2008) 073201

ANGULAR MOMENTUM TRANSFER AND POLARIZATION DEGREE OF IONS WITH ONE-VALENCE ELECTRON BY ELECTRON-IMPACT

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When velocity distribution of electrons in plasma is anisotropy, ions in excited states have unequal distribution for magnetic sublevels owing to collisions with such electrons. The radiation emitted from ions with unbalanced sublevel population is polarized and its detection is available as a plasma diagnostic tool [1].

The Stokes parameters (P_1, P_2 and P_3), which are deduced from measurements of the emitted radiation after electron-impact excitation processes, give detailed information about scattering amplitudes for magnetic sublevels [2]. Expectation value of angular momentum component perpendicular to the scattering plane is called *angular momentum transfer* $L_\perp(=-P_3)$. In electron-atom impact at low energies, the value of $L_\perp$ is positive for S $\rightarrow$ P transition at small scattering angles [3]. Srivastava *et al.* [4] reported that $L_\perp$ for electron collisions with H-like ions (Z=2, 6, ∞) and He-like ions (Z= 3, 8, ∞) is also positive at small scattering angles.

Kai *et al.* [5] have found a case where $L_\perp$ is negative in low-energy electron scattering with Mg-like Si^{2+} ion using the R-matrix method. We calculate $L_\perp$ and polarization degree in electron scattering by Li^{2+}, B^{2+} and Al^{2+} to investigate their behavior for doubly charged ions with one-valence electron systematically. The R-matrix calculation is adopted to obtain transition-matrix for the excitation. Our results show that $L_\perp$ in Li^{2+}, B^{2+} and Al^{2+} at small scattering angles is positive, negative and negative, respectively, at low-energies. We will report details of our calculations and results at the HCI conference.

References

[1] T. Kawamura, T. Kai, F. Koike, S. Nakazaki, Y. Inubushi, H. Nishimura, Phys. Rev. Lett. **99** 115003 (2007).

[2] N. Andersen, K. Bartschat, J. T. Broad, I. V. Hertel, Phys. Rep. **279**, 251 (1997)

[3] N. C. Steph, D. E. Golden, Phys. Rev. A **21**, 1848 (1980)

[4] R. Srivastava, Y. Itikawa, K. Sakimoto, Phys. Rev. A **43**, 4736 (1991)

[5] T. Kai, R. Srivastava, S. Nakazaki, J. Phys. B: At. Mol. Phys. **37**, 2045 (2004)

EFFECTIVE COLLISION STRENGTHS FOR MG-LIKE IRON PEAK IONS

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Berrington et al [1] have calculated effective collision strengths for Fe XV using both the Breit-Pauli and Dirac R-matrix methods. The calculation was undertaken in the spirit of a case study to lay to rest assertions that the Dirac method is superior for such ions. They found good agreement between the two methods. Current development of the DARC program [2] is aimed at improving the quality of the target states. As a first step we have included the Breit interaction directly in the bound-bound continuum hamiltonians. DARC is based on the Dirac-Coulomb hamiltonian and in order to treat heavier systems correctly it is necessary to include the Breit interaction. We have also used Fe XV as a case study for this code development and in addition examined Cr XIII and Ni XVII. The effects on the effective collision strengths for the iron peak ions are as expected small. The work illustrates the extent to which the DARC program can be automated for isoelectronic series.

References

[1] K.A. Berrington, C.P. Ballance, D.C. Griffin, N.R. Badnell, J. Phys. B: At. Mol. Opt. Phys. **38**, 1667-1678 (2005)

[2] S. Ait-Tahar, I.P. Grant, P.H. Norrington, Phys. Rev. Let. **79**, 2955-2958 (1997)

Dielectronic and Radiative Recombination of Si to N-like Tungsten Ions

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Dielectronic recombination (DR) is an important recombination process in high temperature plasmas. DR is the resonant electron capture of a free electron, where simultaneously a bound electron of the ions is excited. The resulting doubly excited intermediate state stabilizes by photon emission. Present and future fusion devices are armoured with the heavy element tungsten as wall material which may be sputtered and ionized by the high temperature plasma. The radiative transitions from DR processes contribute to radiation energy loss in fusion plasma, change the charge state balance and satellite lines can alter line shapes, width and intensities of the parent transitions. On the other hand, understanding the radiation pattern of the highly-charged heavy element ions can provide detailed diagnostics of the high-temperature plasma and test atomic structure calculations.

We have performed x-ray spectroscopic measurements of the dielectronic recombination resonance strength for the LMn (n=3, ..., 6) series of Si-like W^{60+} to N-like W^{67+} tungsten ions. Highly charged tungsten ions were produced, stored and excited with the Berlin electron beam ion trap and the emitted radiation was analyzed with a solid state detector. Information on the charge state abundance in the trap was extracted from a fit of the theoretical radiative recombination intensity to measured values. Good agreement was obtained when the fine structure, angular momentum of the recombination channels is taken into account. Our measurement of x-rays from n=2-3, 2-4 and higher DR resonance transitions was compared to relativistic calculations of the DR cross sections and rate coefficients calculated with the Hebrew University Lawrence Livermore Atomic Code (HULLAC). The theoretical predictions for Ne-like tungsten (W^{64+}) [1] were extended with calculations for ions in adjacent charge states and compare well with the observed DR resonance structure.

References

[1] E. Behar, P. Mandelbaum, and J.L. Schwob, Phys. Rev. **A59**, 2787 (1999).

Electron Impact Excitation of Ni II

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Considerable demand exists for electron excitation data for the ions of Fe, Co and Ni, since lines from these elements in low ionization stages are observed in many types of astrophysical spectra. Electron scattering from these ions is complicated by the 'open' $3d$-shell in the target, which gives rise to hundreds of fine structure levels and thousands of coupled channels. In this study we represent the complex Ni II target by a sophisticated configuration interaction (CI) expansion, based on the following five target configurations - the $3d^9$ ground state configuration and the $3d^84s$, $3d^74s^2$, $3d^84p$ and $3d^74s4p$ excited configurations. These configurations give rise to 295 target states and over 1900 scattering channels if we consider transitions between fine structure levels. We are using the new parallel R-matrix suite of codes (RMATRXII and PFARM) on HPCx to calculate Maxwellian averaged effective collision strengths for low-lying forbidden transitions in Ni II, over a range of astrophysically significant temperatures. To our knowledge this is the most extensive Ni II R-matrix calculation undertaken to date. Latest results will be presented at the conference.
This work is currently supported by a STFC rolling grant.

EFFECT OF ELECTRON-IMPACT IONIZATION IN DAMAGE OF BIO-MOLECULES IRRADIATED BY XFEL

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In x-ray free electron laser (XFEL) application, the analysis of three-dimensional structure of single bio-molecules which almost consist of H, C, N and O atoms is one of the critical issues [1,2]. In this case, target samples are damaged by high-intense x-ray as well as ionization processes by electron impact. The processes are very significant to investigate the damage for electron distribution in the bio-molecule since secondary electrons produced by the high-intense x-ray make the targets ionized again.

There are many reports of ionization-cross section for ground states by electron impact [3]. However, available ionization-cross sections for inner-shell excited states produced by high-intense x-ray have never been reported. In this presentation, we address ionization processes by electron impact for the ground states as well as those for the inner-shell excited states to investigate the damage of the target samples. The cross sections are calculated by using Flexible Atomic Code [4] based on relativistic distorted wave approximation in H, C, N and O atoms and ions.

Figure 1 shows the results of the ionization-cross sections for the ground state in C^{1+} ion. For comparing present result with the recommended experimental result [3], we present the sum of the cross sections for 2s- and 2p-orbital. Our result is good agreement with the recommended data [3]. We compare the results of *L*-shell ionization-cross section for the ground state with those for the inner-shell excited states in figure 2. It is seen that the ionization-cross section for the inner-shell excited states are larger than those for the ground state. We will discuss the effect of electron-impact ionization for the damage to solve rate equation using the present results.

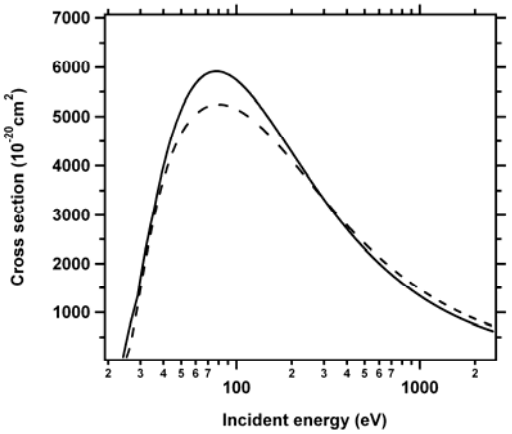

Figure 1 Ionization cross section of C^{1+}. Solid line; present, dashed line; recommended data [3]

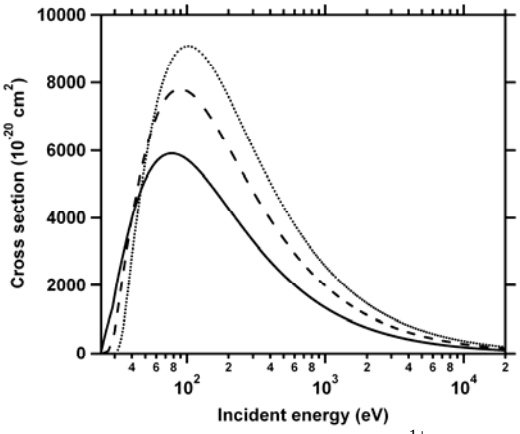

Figure 2 Ionization cross section of C^{1+}. Solid line; $1s^22s^22p$ state, dashed line; $1s2s^22p^2$ state, dotted line; $2s^22p^3$ state.

References
[1] Neutze R, Wouts R, Spoel D, Weckert E, and Hajdu J, Nature, **406**, 752 (2000).
[2] Hau-Riege S P, London R, Szoke A, Phys. Rev. E, **69**, 051906 (2004).
[3] Suno H and Kato T, Atomic Data and Nuclear Data Tables, **92** 407 (2006).
[4] Gu M F, Astrophys. J, **582,** 1241 (2003).

HIGH-ENERGY ELECTRON-IMPACT EXCITATION CROSS-SECTIONS OF HYDROGEN-LIKE IRON AND NICKEL IONS

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Electron-impact excitation cross-sections of K-shell ions are used in interpreting the spectra from astrophysical and laboratory produced high-temperature plasmas. Of special importance are K-shell cross-sections of iron and nickel as they have relatively high elemental abundances in celestial sources as well as being present in many laboratory produced high-temperature sources. Yet, for energies well above excitation threshold, where the high-energy tails of the electron temperature-distribution can contribute considerably to the excitation, very little experimental data exist, or none at all.

Here we present a measurement of the cross-sections for the electron-impact excitation of the Lyman-α_1 line of hydrogen-like iron (Z=26) and nickel (Z=28) over a broad range of energies using the Lawrence Livermore National Laboratory SuperEBIT electron beam ion trap facility. These measurements were performed with electron beam energies between 35 keV and 85 keV. The hydrogen-like spectrum of iron and nickel was observed, and fully resolved, with the NASA/GSFC microcalorimeter which allowed for an absolute cross-section to be measured by normalizing to the radiative recombination x-ray emission. These results are compared to theory.

Part of this work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-C52-07NA27344 and is also supported by NASA grants to LLNL, and the NASA/GSFC.

ANGULAR MOMENTUM TRANSFER AND POLARIZATION DEGREE OF IONS WITH TWO-VALENCE ELECTRON BY ELECTRON-IMPACT

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The radiation emitted from ions with unbalanced magnetic sublevel population by electron impact is polarized and its detection is available as a plasma diagnostic tool [1]. Kai *et al.* [2] have calculated the polarization degree for He-like ions by electron-impact of the $1s^2\ ^1S_0 \rightarrow 1s2p\ ^1P_1$ transition using the non-relativistic and the semi-relativistic R-matrix method.

The Stokes parameters (P_1, P_2 and P_3) give detailed information about scattering amplitudes for magnetic sublevels [3]. Expectation value of angular momentum component perpendicular to the scattering plane is called *angular momentum transfer* $L_\perp$, and $L_\perp$ is equivalent to $-P_3$. In electron-atom impact at low energies, the value of $L_\perp$ is positive for S $\rightarrow$ P transition at small scattering angles [4]. Srivastava *et al.* [5] reported that $L_\perp$ for electron collisions with H-like ions (Z=2, 6, ∞) and He-like ions (Z= 3, 8, ∞) is also positive at small scattering angles.

Kai *et al.* [6] have found a case where $L_\perp$ is negative in low-energy electron scattering with Mg-like Si^{2+} ion using the R-matrix method. We calculate $L_\perp$ in Be^{2+} and C^{2+} from the ground state to the $2\ ^1P^o$ state by electron-impact to investigate their behavior for doubly charged ions with two-valence electron systematically using the R-matrix method. We also calculate the polarization degree for electron-impact excitation of the $3s3p\ ^1P^o$ of Si^{2+} using the same method. Our results show that $L_\perp$ in Be^{2+} and C^{2+} at small scattering angles is positive and positive, respectively, at low-energies. We will report details of our calculations and results at the HCI conference.

References

[1] T. Kawamura, T. Kai, F. Koike, S. Nakazaki, Y. Inubushi, H. Nishimura, Phys. Rev. Lett. **99** 115003 (2007).

[2] T. Kai, S. Nakazaki, K. A. Berrington, Nucl. Instrum. Methods Phys. Res. B, **235**, 249 (2005)

[3] N. Andersen, K. Bartschat, J. T. Broad, I. V. Hertel, Phys. Rep. **279**, 251 (1997)

[4] N. C. Steph, D. E. Golden, Phys. Rev. A **21**, 1848 (1980)

[5] R. Srivastava, Y. Itikawa, K. Sakimoto, Phys. Rev. A **43**, 4736 (1991)

[6] T. Kai, R. Srivastava, S. Nakazaki, J. Phys. B: At. Mol. Phys. **37**, 2045 (2004)

ELECTRON IMPACT IONIZATION OF MULTIPLY CHARGED XENON AND TIN IONS

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New interest in electron impact ionization of Xe and Sn ions has been invoked by applications in fusion research and in connection with EUV light sources. Xenon is envisaged as a coolant gas to be injected into the edge plasma of future tokamaks. Further, xenon admixtures in fusion plasmas serve to diagnose a variety of plasma properties including electron temperature and density, as well as ion temperature and impurity transport. In order to predict the effect of xenon injection on the performance of fusion plasmas accurate cross section data are needed. Furthermore, recent interest in applying the EUV radiation of xenon or tin ions to lithography has led to the construction of light sources based on laser-produced plasmas or gas discharges. In the effort to optimize radiation output detailed understanding of the production of the radiating ions is necessary.

We perform absolute measurements of electron-impact single and multiple ionization cross sections for highly charged ions of xenon and tin using an electron-ion crossed-beams technique [1]. Energies range from thresholds to 1 keV. With their many subshells at comparatively low binding energies the xenon ions offer rich oportunities to see processes such as excitation followed by autoionization and resonant electron capture with subsequent multiple electron emission. Because of this reason beside the measurement of absolute cross sections an energy-scanning method is applied to uncover detailed structures in the ionization cross sections which correspond to the population and decay of intermediate excited states. An example for the measurements is shown in Fig. 1.

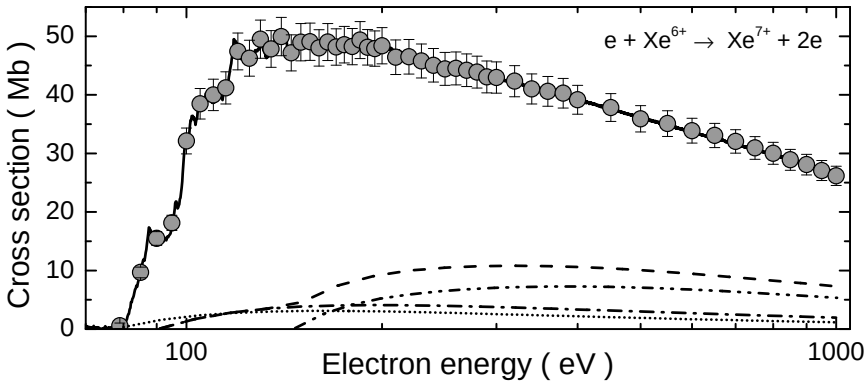

Figure 1: Electron impact ionization cross sections of Xe^{6+} ions: absolute experimental data [shaded circles with error bars]; normalized energy scan [solid curve]; theoretical cross section data for direct ionization of $5s$ [dash-dot] and $4d$ [dash-dot-dot] electrons together with their sum [long-dash curve] calculated by using the LANL atomic physics code package. The dotted curve represents the theoretical cross section of the metastable Xe^{6+} ($5s5p\ ^3P$) configuration assuming a 100% fraction in the incident ion beam.

References

[1] J. Jacobi et al. Phys. Rev. A**70**, 042717 (2004).

EXCITATION RATES FOR TRANSITIONS IN Kr XXXII

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Krypton is an important impurity element in tokamak fusion plasmas where high temperatures ($> 10^6$ K) give rise to many of its ionisation stages. Therefore, atomic data (namely energy levels, oscillator strengths or radiative decay rates, collision strengths, etc.) are required for many ions in order to estimate the power loss from the impurities. In a recent paper [1] we reported energy levels, lifetimes, and radiative rates for four types of transitions, namely electric dipole (E1), electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2) for five Kr ions (Kr XXXII - Kr XXVIII). Here we report our results for excitation rates for transitions in boron-like Kr XXXII. These results along with those already reported [1] will be helpful in the modelling of plasmas.

Earlier calculations for Kr XXXII ([2], [3]) included only 20 levels among the $2s^22p$, $2s2p^2$, $2p^3$ and $2s^23\ell$ configurations, reported values of collision strengths (Ω) at a few energies above thresholds, and did not include resonances which can significantly contribute to the determination of excitation rates, even at the high temperatures found in fusion plasmas, at least for some of the transitions. Therefore, in the present work we include 125 levels belonging to the $2s^22p$, $2s2p^2$, $2p^3$, $2s^23\ell$, $2s2p3\ell$ and $2p^23\ell$ configurations of Kr XXXII.

Our calculations are fully relativistic in the jj coupling scheme for which we have adopted the GRASP and DARC codes. The R-matrix radius is adopted to be 1.48 au, and 15 continuum orbitals are included for each channel angular momentum for the expansion of the wavefunction. This allows us to compute values of Ω up to an energy of 500 Ryd, more than sufficient to determine the values of excitation rates up to a temperature of $10^{7.3}$ K. Furthermore, in order to obtain convergence of Ω for all transitions and at all energies, we have included all partial waves with angular momentum $J \leq 40$. To account for the inclusion of higher neglected partial waves, we have also included a top-up, based on Coulomb-Bethe approximation for allowed transitions and geometric series for others. Resonances in the thresholds region have been resolved in a narrow energy mesh, and results for effective collision strengths (Υ) have been obtained after averaging the values of Ω over a Maxwellian distribution of electron velocities. Detailed results for all 7750 transitions over a wide temperature range below $10^{7.3}$ K will be available during the conference.

This work has been partly funded by the EPSRC, UK, and partly by the European Communities under the contract of Associations between EURATOM and UKAEA. FPK is grateful to AWE Aldermaston for the award of a William Penney Fellowship.

References

[1] K. M. Aggarwal, F. P. Keenan, K. D. Lawson, At. Data Nucl. Data Tables **94**, 323 (2008)

[2] A. K. Bhatia, U. Feldman, J. F. Seely, At. Data Nucl. Data Tables **35**, 319 (1986)

[3] H. L. Zhang, D. H. Sampson, At. Data Nucl. Data Tables **56**, 41 (1994)

NEUTRON RADIATION EFFECTS ON METAL OXIDE SEMICONDUCTOR (MOS) DEVICES

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The main purpose of this study is to provide the knowledge and data on Deuterium-Tritium (D-T) fusion neutron induced damage in MOS devices. Silicon Metal Oxide Semiconductor (MOS) devices are currently the cornerstone of the modern microelectronics industry. However, when a MOS device is exposed to a flux of energetic radiation or particles, the resulting effects from this radiation can cause several degradation of the device performance and of its operating life. The part of MOS structure (Metal Oxide Semiconductor) most sensitive to neutron radiation is the oxide insulating layer (SiO_2). When ionizing radiation passes through the oxide, the energy deposited creates electron-hole pairs. These electron-hole pairs have been seriously hazardous to the performance of these electronic components. The degradation of the current gain of the dual *n*-channel depletion mode MOS caused by neutron displacement defects, was measured using *in-situ* method during neutron irradiation. The average degradation of the gain of the current is about 35 mA, and the change in channel current gain increased proportionally with neutron fluence. The total fusion neutron displacement damage was found to be 4.8×10^{-21} dpa per n/cm^2, while the average fraction of damage in the crystal of silicon was found to be 1.24×10^{-12}. All the MOS devices tested were found to be controllable after neutron irradiation and no permanent damage was caused by neutron fluence irradiation below 10^{10} n/cm^2. The calculation results shows that (n,α) reaction induced soft-error cross-section about 8.7×10^{-14} cm^2, and for recoil atoms about 2.9×10^{-15} cm^2, respectively.

References

[1] Audet, S. A. and Wouters, S. E., 1990, "Monolithic Integration of a Nuclear Radiation Sensor and Transistors on High-Purity Silicon", *IEEE Transaction on Nuclear Science,* 37, 15-19.

[2] Ausman, G. A., and McLean, F B., 1975, "Electron-Hole Pair Creation Energy in SiO_2", *J. Appl. Phys*. 45, 4506.

[3]Bakhtiar, H., Picard, C., Brisst, C., Hoffmann, A., Mialhe, P., and Charles, J. P., 1999, "Characterization of Ionizing Radiation Effects in MOS Structures by Bipolar Operation Study", *IEEE, Fifth Con. on Radiation and Its Effects on Components and System,* 548.

[4] Belove, C., 1986, "Hand Book of Modern Electronics and Electrical Engineering", John Wiley and Sons, Inc., New York.

[5] Beutler, D. E., Beezhold, W., Browning, J. S., Fleetwood, D. M., Counts, N. E., Knott, D. P., Freshman, C. L., and Conners, M.P., 1990, "Comparison of Photocurrent Enhancement and Upset Enhancement in CMOS Devices in a Medium Energy X-ray Environment", *IEEE Transaction on Nuclear Science,* NS-37, 4, 1541.

[6] Binder, D., Smith, E.C., and Holman, A. B., 1975," Satellite Anomalies from Galactic Cosmic Rays", *IEEE Transaction on Nuclear Science.* NS-22, 2675.

STRUCTURE DEFORMATION DYNAMICS OF ACETYLENE MOLECULES FOLLOWING ELECTRON LOSS AND CAPTURE COLLISIONS OF 6 MeV O^{4+} IONS

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Ion-induced molecular fragmentation has been intensively investigated by using 3D momentum imaging techniques [1-5]. When applied to fragmentation of polyatomic molecules such as CO_2 and C_2H_2, one can obtain important information about structural deformation of a molecule prior to its dissociation because the momentum vectors of product ions are sensitive to the structure prior to dissociation. To date, however the mechanism of structural deformation induced by ion impacts has not been understood yet.

In this work, we investigate the momentum correlation among fragment ions produced by coulomb explosion of acetylene in charge-changing collisions of 6 MeV O^{4+} ions. Figure 1 shows an angular correlation between fragment ions of H^+ and C^+ produced in $(C_2H_2)^{4+**} \rightarrow (H^+ + C^+ + C^{2+} + H)$ measured for single electron capture collisions. The abscissa θ is the angle between the momenta of two ions $P(C^+)$ and $P(H^+)$. One can see that the spectrum shows two peaks at about 20 and 160 degrees, respectively. This result indicates clearly the two dissociation schemes associated with an intact ion of $(C_2H_2)^{4+}$**. Namely, they are $(HC^{2+}\text{-}C^+H^+)$ and $(H^+C^{2+}\text{-}C^+H)$ prior to dissociation. In the former case, therefore, both C^+ and H^+ move in the same direction after dissociation and separate afterwards as depicted in the figure, giving rise to the correlation angle of 20 degrees. In the latter case, C^+ and H^+ start to move in the opposite direction, giving rise to the peak of 160 degrees.

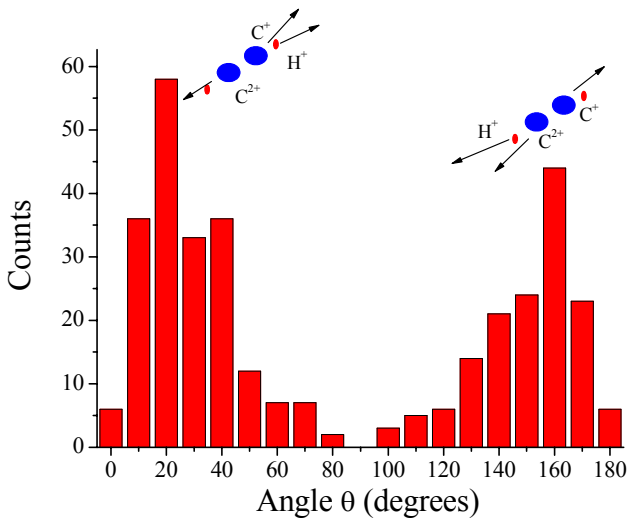

Fig.1 Angular correlation between two momenta of C^+ and H^+ produced in $(C_2H_2)^{4+**} \rightarrow (H^+ + C^+ + C^{2+} + H)$ measured for electron capture collisions of 6 MeV O^{4+}.

In conclusion, the first stage of molecular dissociation may be understood precisely by the present 3D imaging techniques.

References

[1] G. Veshapidze et al. J. Phys. B **37**, 2969 (2004)
[2] L. Adoui et al. Nucl. Instrum. Methods B **245**, 94 (2006)
[3] B. Siegmann et al. J. Phys. B **34**, L587 (2001)
[4] S. De et al. J. Phys. Chem. **127**, 051101 (2007)
[5] T. Mizuno et al. J. Phys. Conf. Ser. **58**, 173 (2007)

SYSTEMATIC MULTICONFIGURATION DIRAC-FOCK METHOD STUDY OF THE *K* X-RAY SPECTRA OF SILICON

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Extensive multiconfiguration Dirac-Fock calculations with the inclusion of the transverse Breit interaction and QED corrections [1] have been performed for silicon to explain the influence of removing electrons from L and M shells on the shapes and parameters (the average $K\alpha$ and $K\beta$ transition energies and the values of $K\beta/K\alpha$ intensity ratio) of its K x-ray spectra. For $K\alpha$ and $K\beta$ diagram lines and each types of L- and M-satellite lines the theoretical stick spectra (line positions with their relative intensities) have been presented. Moreover for each type of lines the theoretical spectra being a sum of the Lorentzian natural line shapes [1] have been synthesized.

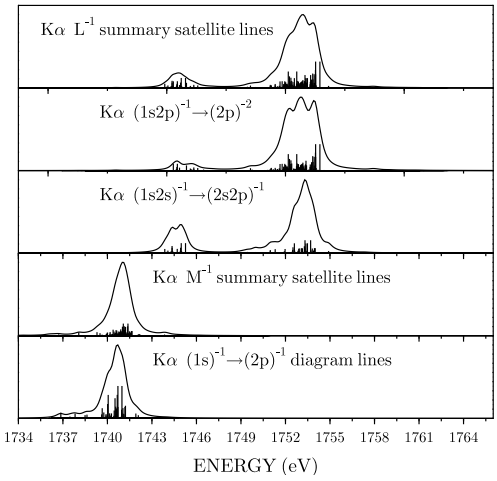

Figure: Theoretical $K\alpha_{1,2}$ x-ray spectra for diagram, L- and M-satellite transitions in silicon.

It has been found that the very large shifts of $K\beta$ and $K\alpha$ transition energies are only in the case of the ionization of the $2p$ and $2s$ subshells. The calculated $K\beta/K\alpha$ intensity ratio is influenced, first of all, by the ratio of the number of electrons in $3p$ and $2p$ subshells, and, secondly, by ionization degree of $2s$ and $3s$ subshells. It is very important to note that the effects of removal of electrons from the subshells on the $K\beta$ and $K\alpha$ transition energies are strong nonadditive, i.e. the $K\beta$ and $K\alpha$ transition energies increase much faster than linearly with the number of holes in a given subshell. Moreover, the effects of removal of electrons from different (L and M) shells on the K x-ray spectra parameters are also strongly nonadditive. The preliminary theoretical results of presented study have been already applied to perform the interpretation of the $K\alpha$ x-ray emission spectra of the low-density SiO_2 aerogel target bombarded by ^{48}Ca ions with initial energy of 11.4 MeV/u measured with a high spectral and spatial resolution along the ion beam stopping path [2]. They can also be helpful in interpreting various silicon target K x-ray spectra induced by photons or different projectiles.

References

[1] M. Polasik, Phys. Rev. A **39**, 5092-5097 (1989)

[2] J. Rzadkiewicz, O. Rosmej, A. Blazevic, V.P. Efremov, A. Gójska, D.H.H. Hoffmann, S. Korostiy, M. Polasik, K. Słabkowska, and A. E. Volkov, High Energy Density Physics **3**, 233-236 (2007)

ELECTRON ANGULAR DISTRIBUTIONS FOR HE SINGLE IONIZATION IN COLLISIONS WITH "FIXED-IN-SPACE" H_2^+ IONS AT 0.5MeV and 1MeV

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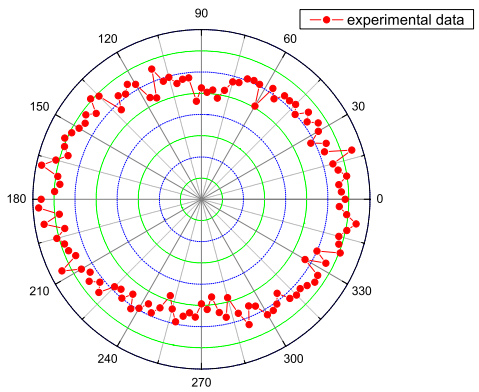
Two center effects in collisions of fast ions with H_2 molecules have been intensively studied, both theoretically [1] and experimentally [2]. We investigated in a kinematical complete experiment the ionization He in collisions with H_2^+-molecular ions at 0.5 and 1MeV at the Max Planck Institute for Nuclear Physics at Heidelberg within a cooperation of Chinese Academy of Sciences and the Max Planck Society. The momenta of the recoiling He ions and the electrons produced in the collisions were measured using a "Reaction Microscope" [3]. The fragments of the H_2^+ were separated by a dipole magnet after the interaction region and detected by two position sensitive MCP detectors. From this information the orientation and internuclear distance of the molecular ion at the instance of the collision could be determined. Pronounced structures are found both in experimental data and theoretical calculations, indicating that the emitted He electron shows a slight preferential emission parallel to the molecular axis. Electron angular distributions in the plane perpendicular to the beam propagation with respect to the molecular axis are shown in Fig.1 and Fig.2 in which case the molecular ion is in the same plane too.



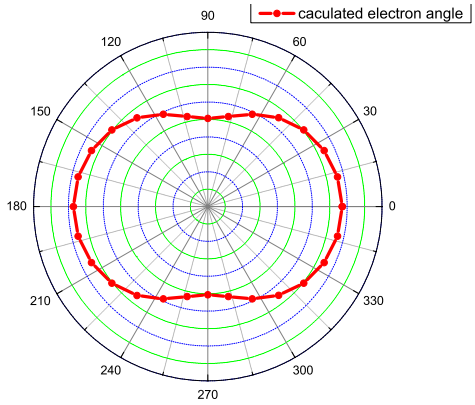


Fig.1 experimental results **Fig.2** theoretical calculation

Fig.1: Electron emission angle with respect to molecular axis (the molecular axis is along 0 and 180 degree: horizontal line). Fig.2: Theoretical results. Further detailed analysis is under progress.

References

[1] S.E. Corchs et al., Nucl. Instrum. Methods Phys. Res., Sect. B **149**, 247 (1999).

[2] N. Stolterfoht et al., Phys. Rev. Lett. **87**, 023201 (2001).

[3] J. Ullrich et al., Rep. Prog. Phys. **66**, 1463 (2003)

ELECTRON-MOLECULAR AND ATOM-MOLECULE SCATTERING IN FEW-BODY APPROACH

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A quantum theory of few-body scattering based on the Faddeev-Yakubovsky equations (FYE)[1] is applied to calculation of the cross-sections of different simplest chemical reactions [2]:

$$S(^3P) + O_2(^3\Sigma_g^-) \to SO(X^1\Sigma^-) + O(^3P),$$

$$S(^3P) + O_2(^3\Sigma_g^-) \to SO(X^1\Sigma^-) + O(^3P),$$

$$H + H + H \to H_2(X^1\Sigma_g^+, v) + H,$$

$$H + H_2(v_1, j_1) \to \begin{cases} H_2(v_n, j_n) + H \\ H + H + H \end{cases}$$

$$D + D_2(v_1, j_1) \to \begin{cases} D_2(v_n, j_n) + D \\ D + D + D \end{cases}$$

$$H + T_2(v_1, j_1) \to \begin{cases} TH(v_n, j_n) + T \\ H + T + T \end{cases}$$

$$T + H_2(v_1, j_1) \to \begin{cases} T + H_2(v_n, j_n) \\ HT(v_n, j_n) + H \\ T + H + H \end{cases}$$

$$T + D_2(v_1, j_1) \to \begin{cases} TD(v_n, j_n) + D \\ T + D + D \end{cases}$$

$$T + HD(v_1, j_1) \to \begin{cases} HT(v_n, j_n) + D \\ DT(v_n, j_n) + H \\ T + H + D \end{cases}$$

$$O(^3P) + N_2(X^1\Sigma_g^+) \to NO(X^2\Pi) + N(^4S),$$

$$O(^3P) + O_2(X^1\Sigma_g^+) \to O_2(X^2\Sigma_g^+) + O(^3P),$$

$$O(3^P) + CS_2(X^1\Sigma^+) \to \begin{cases} CO(X^1\Sigma^+, v) + S_2(^2\Sigma_g^-) \\ CS(X^1\Sigma^+, v) + SO(X^3\Sigma^-) \end{cases}$$

$$O(^3P) + OCS(X^1\Sigma^+) \to CO(X^1\Sigma, v) + SO(X^3\Sigma^-),$$

$$HCl(v) + HCl(v = 0) \to HCl(v = n-1) + HCl(v = 1),$$

$$O + CF_3I \to IO + CF_3.$$

The results of this calculations are compared with available experimental data and of other approximation. Thus, it is important to understand the physical meaning of numerous approximations applied to the few-body problem and their limitations. The following questions concider in this way. 1. What formalism should be used in investigation of the dynamics of a few-body system? It could be classical or quantum-mechanical equations of the motion, empirical or semi-empirical models, and so on. 2. What is the aim of the simulation? It can be a study of dynamic or static characteristics of a few-body system, calculations of the binding energy, cross sections, rate constants, thermodynamic features, etc. 3. Are the considered models adequate to real physical systems? Answers to many of these questions can be found within the framework of the rigorous mathematical theory suggested by L.D.Faddeev, O.Ya.Yakubovsky and S.P.Merkuriev [1] which describes the dynamics of a few-body system using the correct mathematical basis.

Results of the calculations of the phase shifts, cross sections and Efimov states [1] scattering atom with diatomic molecules based on the three body approximation also are present [2-3].

References

[1] L.D. Faddeev, S.P Merkuriev, Quantum scattering theory for several particles systems, Kluwer, London, (1993).

[2] S. Pozdneev, Application of quantum theory scattering to the calculations of different processes in nuclear, atomic and molecular physics, Moscow, Janus-K, (2001); JETP, 99, 913, (2004); J.Russsian Laser Research, 26, 1, (2005).

[3] G.J.Schultz, Rev.Mod.Phys., 45,423, (1973); D.A.Micha, Adv.Chem.Phys., 30, 7, (1975).

[4] V.Efimov, Nucl.Phys., A362, 45,(1981); A378, 581, (1982); Phys.Rev., C47, 1876, (1993);

STATE-SELECTED DIFFERENTIAL CROSS SECTION MEASUREMENTS FOR THE ONE-ELECTON CAPTURE PROCESSES IN THE F^{4+} - He, Ne, Ar SYSTEMS AT E_{lab} = 45 eV

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Using a crossed-beam apparatus[1], we are measuring systematically the relative state-selected differential cross sections for the charge-transfer processes at very low energy region. A small electron-beam ion-source is employed to produce multiply charged ions. The mass- and energy-selected primary ion-beam was crossed at a right angle with a supersonic nozzle-beam. The scattered ions were energy-analyzed by a one-dimensional position-sensitive detector. The energy spectra of the scattered ions at different angles were recorded by rotating the analyzer.

Typical energy spectrum of the scattered ions observed in F^{4+} - He collisions at E_{lab} = 44 eV is shown in figure 1. The peak (a) corresponds to the elastically scattered ions, and (b) is due to the one-electron capture process. This peak is assigned to the following reactions:

$F^{4+}(2s^2 2p\ ^2P) + He$ ---> $F^{3+}(2s^2 2p3s\ ^1P) + He^+ + 10.0$ eV,
---> $F^{3+}(2s^2 2p3s\ ^3P) + He^+ + 10.9$ eV.

The relative differential cross section, $d\sigma/d\Omega$, for the reaction is shown in figure 2.

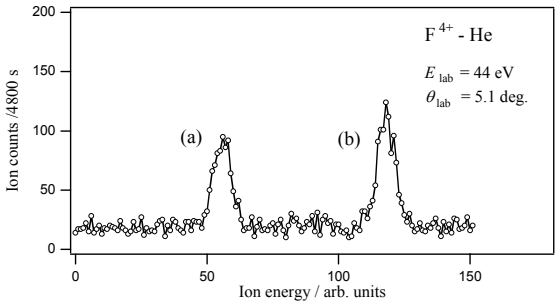

Figure 1: Energy spectrum of the scattered ions.

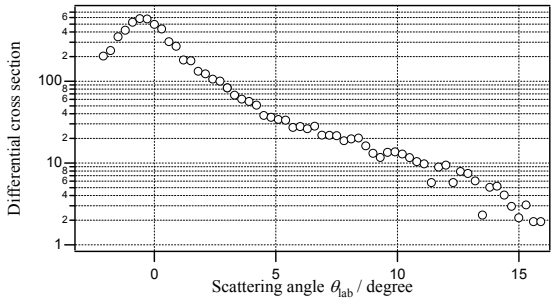

Figure 2: Relative differential cross sections.

The cross section shows a peak around 0° and decreases monotonically with the increase of the scattering angle, while the differential cross sections obtained in F^{4+} - Ne and Ar collisions at the same collision energy show clear angular thresholds. The reaction channels observed in these systems are

$F^{4+}(2s^2 2p\ ^2P) + Ne$ ---> $F^{3+}(2s^2 2p3p\ ^3D) + Ne^+ + 9.6$ eV,
---> $F^{3+}(2s^2 2p3s\ ^1P) + Ne^+ + 13.1$ eV,

and

$F^{4+}(2s^2 2p\ ^2P) + Ar$ ---> $F^{3+}(2s^2 2p3d\ ) + Ar^+ + \sim 9$ eV.

As the differential cross sections are very sensitive to the shape of the interaction potentials, it can be considered that the interaction potentials for the F^{4+} - He system is much different from those for the F^{4+} - Ne and Ar systems.

References

[1] Y. Itoh, J. Phys. B : At. Mol. Opt. Phys **35**, 3217 (2002)

BRANCHING RATIO OF N_2 IN COLLISIONS WITH Ar^{q+} ($q \geq$6) AT ENERGIES BELOW 1 keV/u

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Charge transfer processes involving ionization, electron capture and molecular-fragmentation of multiply charged ions (MCIs) in collisions with atoms and molecules play an important role not only in atomic physics but also in astrophysics and plasma physics. Recently, fragmentation processes of diatomic molecules in electron capture collisions of MCI at energies below 1 keV/u were studied both experimentally[1] and theoretically[2]. In collisions of MCI with diatomic molecules at energies below 1 keV/u, they have experimentally measured two fragment ions in a direction perpendicular to the projectile beam axis in coincidence with the projectile after double and triple electron capture. As a result, an interesting observation of the charge-asymmetry effect between the far and near fragment ions from incident MCI beam axis was reported, i.e., it is dominant process that the far site fragment ion is more highly than near site fragment ion.

In this work, in order to clarify the charge-asymmetry effect, we have measured molecular- fragmentation of N_2 molecule in electron capture collisions of Ar^{q+} ($q \geq 6$) ions in the collision energy from 30 to 150 eV/u and have determined branching ratios for each reaction channel. We used the MCI beam extracted from mini-EBIS (Electron Beam Ion Source). The MCI beam were collided with an effusive target gas of N_2 in a collision region. Outgoing projectile ions from a collision region were analyzed by a parallel plate electrostatic analyzer with a 2D-PSD which resolves energy and scattering angle of the particles. Two fragment ions were detected separately by two time-of-flight analyzers installed respectively at 90^o and -90^o with respect to the projectile beam axis. All signals were directly recorded by PC though digitizers as a single event.

For the single, double and triple electron capture processes in collisions of Ar^{q+} ($q \geq 6$) ions with N_2 at the collision energies from 30 to 150 eV/u, we have measured the branching ratio of the molecular fragmentation including charge-asymmetry effect. Experimental results involving detailed discussions will be presented at the conference.

References

[1] T. Kaneyasu, T. Azuma and K. Okuno, J. Phys. B: At. Mol. Opt. Phys. **38**, 1341 (2005).

[2] T. Ohyama-Yamaguchi and A. Ichimura, J. Phys. Conf. Ser. **58**, 247 (2007).

INTERFERENCE EFFECTS IN ELECTRON EMISSION SPECTRA FOR 3 MeV $H^+ + O_2$ COLLISIONS

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In recent studies electron interference effects have been studied for $H^+ + H_2$ [1] and $H^+ + N_2$ [2] collisions. Both primary interference structures analogous to Young's two slit experiment as well as secondary interferences attributed to intramolecular scattering have been observed [1]. The primary interferences observed in 1-5-MeV/u $H^+ + H_2$ collisions [1] showed a strong dependence on the electron observation angle and a smaller dependence on the projectile velocity, while the second-order interferences superimposed on the main oscillatory structures were independent of angle and velocity. More recent results for $H^+ + N_2$ at similar projectile energies revealed apparently only secondary oscillations [2]. In the present work, the experimental investigations are extended to 3-MeV $H^+ + O_2$. As a result of the larger "slit" separation for O_2 of 2.28 a.u., compared with 2.1 a.u. for N_2 and 1.4 a.u. for H_2, the primary interference structures would be expected to have higher frequencies. Experimental measurements were conducted at Western Michigan University using the tandem Van de Graaff accelerator. A collimated proton beam interacted with an O_2 target supplied by a gas jet. Emitted electrons were detected with a parallel-plate analyzer equipped with a channel electron multiplier for observation angles of 30º, 60˚, 90º and 150˚ with respect to the incident beam direction and for ejected electron energies of 5-400 eV. The measured molecular O_2 cross sections were normalized to corresponding theoretical O_2 cross sections calculated using one-center wave functions. Ratios of the measured experimental to theoretical cross-sections for each angle were fit with a sinusoidal function $f(k) = A[\sin(kcd–w)]+B$ as shown in Fig. 1, where c is a frequency fitting parameter and w allows for a phase shift. Notably, the frequencies of the oscillatory structures are independent of the observation angle while the phase shifts seem to vary systematically with angle, qualitatively in agreement with results for $H^+ + N_2$ [2]. The analysis gives an oscillation interval for O_2 of $\Delta k \sim 4$ a.u., while for N_2 a value of $\Delta k \sim 2$ a.u. was found. The independence of the oscillation frequency on the observation angle suggests the structures are due to secondary interferences with no obvious evidence for primary interferences. However, this conclusion needs further theoretical and experimental investigation.

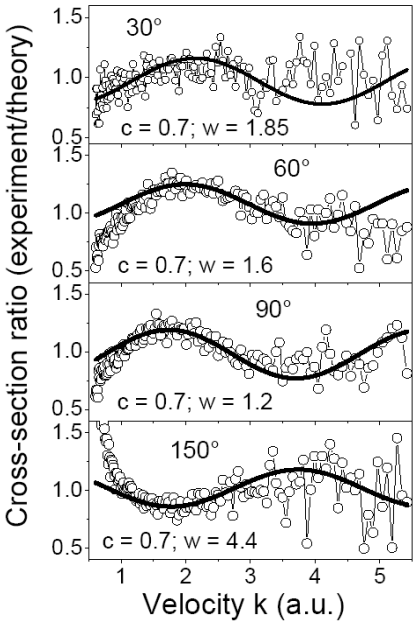

Fig. 1 Experimental to theoretical electron emission cross section ratios for 3 MeV/u $H^+ + O_2$ plotted as a function of ejected electron velocity.

[1] S. Hossain *et al*., Phys. Rev. A **72** (2005) 010701(R)
[2] J.L. Baran *et al*., J. Phys.: Conf. Ser. **58** (2007) 215

ELECTRON CAPTURE PROCESSES FROM EXCITED HYDROGEN ATOMS BY HIGHLY CHARGED IONS OF BERYLLIUM AND CARBON

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Until now there have been numerous experimental and theoretical studies for electron capture processes in collisions of highly charged ions with hydrogen atoms being in electronically ground state. However, reports of electron-capture cross sections are scarce for the case of electronically excited hydrogen atoms, in spite of recognitions that such processes are very important for understanding of impurity behavior in tokamak divertors. To our knowledge, only two theoretical estimations have been performed in C^{4+} + H(n=2) collisions, one is classical trajectory Monte Carlo calculation by Zaniol *et al* [1] at a collision energy of 1 eV/amu and the other is molecular state close coupling calculations by Shimakura *et al*. [2].

In this paper, electron-capture cross sections in collisions of bare and Helium-like ions of Be and C with excited H atoms (n=2) are calculated in the collision energy range between 60 eV/amu and 6 keV/amu using a molecular state close coupling method.

As an example, the total and partial cross sections for the electron capture into $C^{5+}(nl)$ states in C^{6+} + H(2s) collisions are shown in Fig.1. This figure shows that electrons tend to be captured into specific state. Furthermore, the cross sections are huge values as anticipated by Macek-Ovchinnikov model [3]. That is to say, the total cross sections in the case of excited hydrogen atoms H(2s) are about twenty times larger compared with that for ground state hydrogen atoms, which is about 40×10^{-16} cm^2 at E = 1keV/amu.

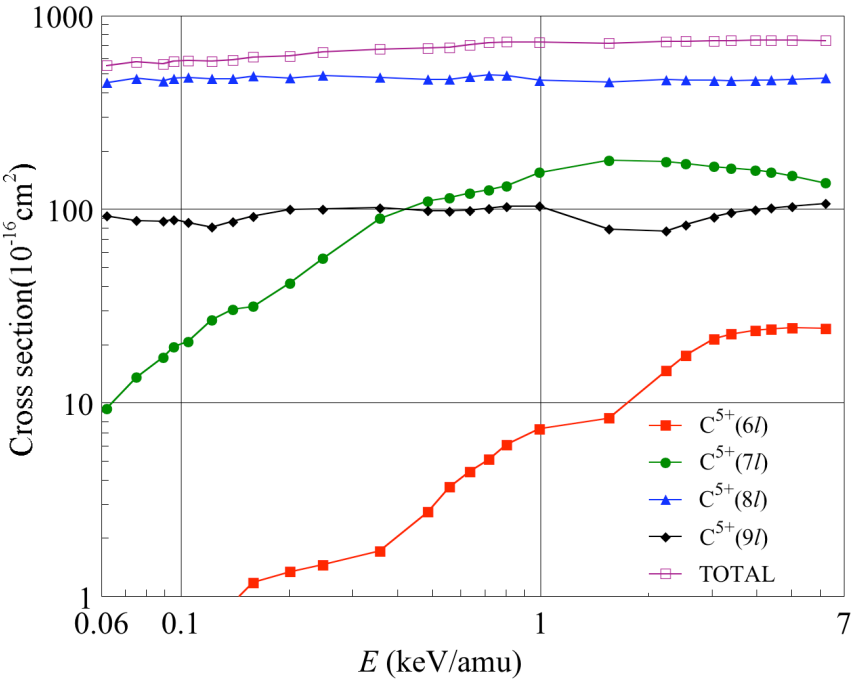

Fig.1 Total and partial cross sections for the electron capture into $C^{5+}(nl)$ states in C^{6+} + H(2s) collisions

References

[1] B. Zaniol, R. C. Isler, N. H. Brooks, W. P. West, and R. E. Olson, Phys. Plasmas **8**, 4386 (2001)
[2] N. Shimakura, M. Honma, and H. Kubo, J. Plasma Fusion Res. Ser. **7**, 199 (2006)
[3] J. Macek and S. Y. Ovchinnikov, Phys. Rev. Lett. **69**, 2357 (1992)

ISOTOPE EFFECT IN DISSOCIATION OF METHANOL DICATIONS PRODUCED BY COLLISION OF Ar^{8+}

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The H/D isotope effects in the dissociation of multiply charged molecular ions stimulate widespread interest since these provide information on the reaction dynamics, for example, intramolecular H migration. So far, strong isotope effects are found for ion-pair dissociation of water dication (HDO^{2+}), that is, the (H^+, OD^+) channel is much more preferable than the (D^+, OH^+) channel, and these channels also considerably differ in the kinetic energy release (KER) distributions [1, 2]. In the case of HDO molecule, the D-substitution breaks the C_{2v} symmetry of water, which may be a key factor for strong isotope effects. On the other hand, the isotopomers of methanol may present the isotope effects with keeping the same C_s symmetry. So far, the coincidence study on the dissociation of collisionally prepared methanol dication has been reported [3], whereas the details of the isotope effects in this molecule are still an open question. In the present study, branching ratios and the KER for various ion-pair dissociation channels of methanol dications were measured focusing on the effects of H/D substitution.

The target molecules, methanol and deuterated methanol (CD_3OH and CD_3OD) were doubly ionized by collisions of 120 keV Ar^{8+}, and the fragment ion pairs were detected with using the position-sensitive time-of-flight (TOF) technique. The ion-ion dissociation channels forming H^+ ~ D_3^+ together with heavier fragment ions as counterparts, two-body dissociation channels and those associated with evaporation of neutral species, were identified in the TOF coincidence map of the fragment ions. The obtained branching ratios do not show notable variation by the H/D substitution.

The KER for each dissociation event was determined from TOFs and positional data. The KER distributions of the two-body dissociation channels yielding trihydrogen cations are shown in Fig. 1, for the three isotopomers. As can be seen in the figure, the KER distributions for the (H_3^+, CHO^+) and the (D_3^+, CDO^+) channels are very similar, peaked at about 4.5 eV, whereas that for the (D_3^+,CHO^+) shifts to the low energy, peaked at about 4.1 eV. It should be noted that the KER distribution of (HD_2^+, CDO^+) is essentially the same with that of (D_3^+, CHO^+), that is, the peak position of the sum of these two is also shifted from the other isotopomers. According to double ionization experiments by 30.4 nm photon impact, the peak positions of KER distributions for two-body dissociation channels forming H^+ or D^+ are essentially the same [4]. However in the present study, small differences in the KER distribution for these channels are also observed among isotopomers.

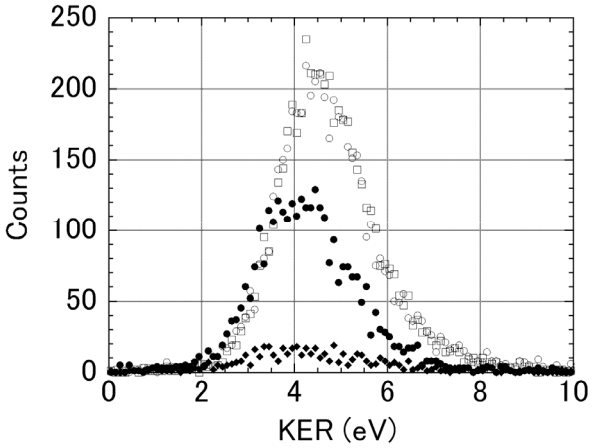

Fig. 1. KER distribution of trihydrogen-forming two-body dissociation channels; ○ (H_3^+, CHO^+), □ (D_3^+, CDO^+), ● (D_3^+, CHO^+), ◆ (HD_2^+, CDO^+). Since the plots are not normalized by Ar^{8+} beam intensity nor accumulation time, the intensity ratio is meaningful only between the plots ● and ◆.

[1] S. Legendre et al., J. Phys. B: At. Mol. Opt. Phys. **38** (2005) L233.
[2] A. M. Sayler et al., J. Phys. B: At. Mol. Opt. Phys. **39** (2006) 1701.
[3] S. De et al., Phys. Rev. Lett. **97** (2006) 213201.
[4] J. H. D. Eland et al. Int. J. Mass. Spectrom. Ion Processes. **113** (1992) 167.

ANALYSIS OF CHARGE-ASYMMETRIC COULOMB EXPLOSION OF N_2 MOLECULES WITH SLOW Kr^{8+} IONS

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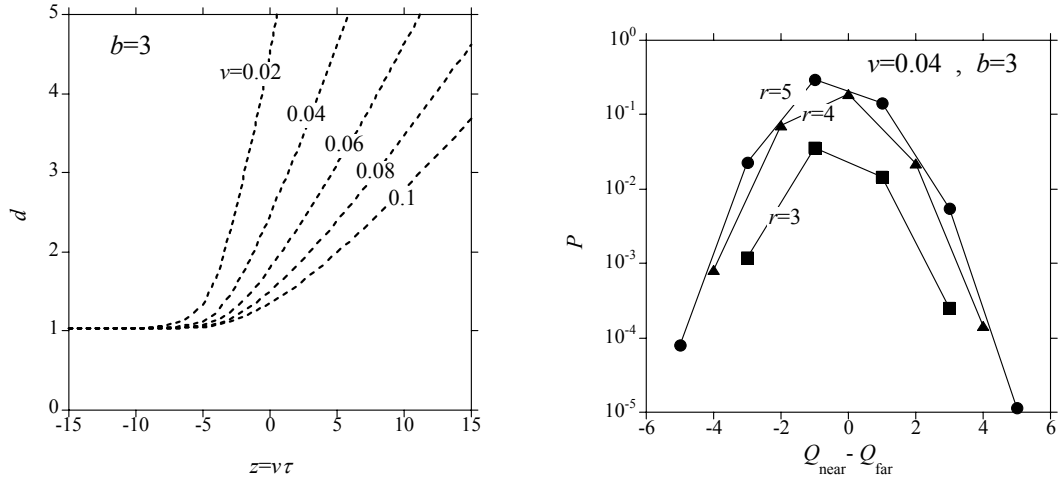
Much attention has been called to the Coulomb explosion of molecules in a variety of collision processes on the basis of the momentum imaging technique. In particular, Kaneyasu and coworkers [1] have made a triple coincidence measurement in a coplanar geometry for N_2 molecules colliding with slow (10 - 100 eV/amu) Kr^{8+} ions. They employ an experimental setup where the fragment ion pair $N^{Q+}N^{Q'+}$ is detected 'back-to-back' transverse to the beam axis and in coincidence with the scattered ion. The most remarkable aspect in their measurement is unequal strengths of charge-asymmetric ($Q \neq Q'$) fragmentation between the near and far sites relative to the point of closest approach on a projectile trajectory [1]. For a given charge pair (Q, Q'), the asymmetry parameter $A = (P_> - P_<)/(P_> + P_<)$ is obtained through the coincidence populations $P_> = P[Q_{far} > Q_{near}]$ and $P_< = P[Q_{far} < Q_{near}]$. The experiment indicates a positive asymmetry $A>0$; the far site is populated more by the higher charge than by the lower charge.

In this contribution, we analyze the experimental result [1] by taking the three-center Coulombic over-the-barrier model developed by the present authors [2]. We investigate the collisions of $Kr^{8+}+N_2$ at velocities of v = 0.02~ 0.1 atomic unit *(i.e.*, 10 ~ 250 eV/amu) and consider 10 covalent electrons in the N_2 molecule. We assume a linear trajectory of incidence with the impact parameter of b = 3, together with a dissociation trajectory retaining the initial orientation. Time evolution $d(\tau)$ of half the bond length is calculated and shown in the left figure, where the horizontal scale is taken $v\tau$, representing the projectile position along the linear trajectory. The probabilities $P(Q_{near}, Q_{far}; r)$ are shown in the right figure, where r denotes the number of removal electrons from the molecule. The charge-asymmetry obtained is found consistent with the experimental result [1]. Further calculations for the asymmetry parameter and its velocity dependence are in progress.



References
[1] T. Kaneyasu, T. Azuma and K. Okuno, J. Phys. B**38**, 1341 (2005).
[2] T. Ohyama-Yamaguchi and A. Ichimura, J.Phys. Conf. Ser. **58**, 247 (2007).

COSTER-KRONIG ELECTRONS FROM N^{q+} (q=1-3) RYDBERG STATES PRODUCED IN HIGH ENERGY COLLISIONS WITH He

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In the present, we have measured Coster-Kronig (C-K) electrons from high-Rydberg states produced in 21 MeV(1.5 MeV/u) N^{3+} + He collisions with high resolution to compare with double electron capture (DEC) and dielectronic recombination (DR) processes. We have extended our measurements from N^{3+} to N^{2+} projectile ions. The measured spectra have been compared to our results obtained from 32 MeV(2.0 MeV/u) O^{q+} (q = 3, 4) + He [1,2].

For Be-like N^{3+} projectiles, a series of $1s^22pnl$ - $1s^22s\varepsilon l'$ (n = 5-9) C-K transitions is assigned. The high resolution spectrum in the low-energy region, where the $1s^22p5l$ state contributes, shows that the line intensity due to the low angular momentum l = 1 is the most intense peak, which obeys dipole selection rules. This result for the l distributions is very similar to that for high-energy O^{4+} projectiles, but different from those of the DEC spectrum and also of the DR spectrum where the radiative stabilization is necessary [3].

For B-like N^{2+} projectiles, a series of $1s^22s2p(^3P)nl$ - $1s^22s^2\varepsilon l'$ (n = 4-8) C-K transitions is assigned. In this case, C-K transitions from $1s^22s2p(^3P)4l$ states are energetically forbidden for l = 0 and 1, but those from the states of l = 2 and 3 are clearly observed. For the higher n, the angular momenta of l = 0-3 states are populated. The measured spectra have been compared with dielectronic recombination (DR) processes [4].

We have also measured Coster-Kronig electrons from high-Rydberg states produced in 14 MeV(1.0 MeV/u) N^+ + He collisions. For C-like N^+ projectiles, the C-K electron spectra are more complicated than those from Be-like N^{3+} and B-like N^{2+} projectiles. A series of $1s^22s2p^2(^4P)nl$ - $1s^22s^22p\varepsilon l'$ (n = 3-8) C-K transitions is clearly assigned. A detailed analysis will be presented at the conference.

Autoionization has been systematically observed form high Rydberg states in N^{q+} (q = 1-3) ions for the first time, which are created by th electron excitation in N^{q+} projectile ions in collisions with He.

This work is supported by the Common Use Program of JAEA.

References

[1] K. Kawatsura *et al*., Nucl. Instr. and Meth. **B205**, 528 (2003).
[2] K. Kawatsura *et al*., Nucl. Instr. and Meth. **B245**, 44 (2006).
[3] P. Glans *et al.*, Phys. Rev. **A64**, 043609 (2001).
[4] M. Fogle *et al*., A&A **442**, 757 (2005).

COSTER-KRONIG ELECTRONS FROM O^{q+} (q=1-4) RYDBERG STATES PRODUCED IN HIGH ENERGY COLLISIONS WITH He

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Recently we have reported on Coster-Kronig (C-K) electron spectra in high energy collisions of 32 MeV O^{4+} and O^{3+} ions with a He gas target [1,2]. For Be-like O^{4+} projectile ions, the C-K spectra are compared with double electron capture (DEC) [3-5]. For B-like O^{3+} ions, we compared with previous results [6] and confirmed the autoionization transition from the $1s^22s2p(^3P)5s$ state. In the present, we have measured systematically C-K electrons from high-Rydberg states produced in high energy collisions of 30 MeV O^{2+} and 15 MeV O^{+} ions with a He gas target and also of 32 MeV $O^{3+,4+}$ ions with higher resolution. .

For Be-like O^{4+} projectiles, a series of $1s^22p(^2P)\,nl$ - $1s^22s\varepsilon l'$ (n = 6-11) C-K transitions is assigned. The high resolution spectrum for the $1s^22p6l$ state shows that the line intensity due to the low angular momentum l = 1 is the most intense peak, which obeys dipole selection rules. This result for the l distributions is found to be different from those of the DEC [3-5]. For B-like O^{3+} projectiles, a series of $1s^22s2p(^3P)nl$ - $1s^22s^2\varepsilon l'$ (n = 5-11) C-K transitions is assigned. It is found that the angular momenta of l = 0-3 states are populated and the maximum intensity is attributed to the states with higher angular momenta l > 1. the C-K spectra are also compared with dielectronic recombination (DR) processes [7].

For C-like O^{2+} projectiles, a series of $1s^22s2p^2(^4P)nl$ - $1s^22s^22p\varepsilon l'$ (n = 4-9) C-K transitions is clearly assigned. This means that these transitions are mainly due to 2s-nl electron transition of the ground state O^{2+} $1s^22s^22p^2(^3P)$ to the $1s^22s2p^2(^4P)nl$ excited state. For N-like O^{+} projectile ions, the C-K electron spectra are much more complicated than those from the other charge states of ions, i.e., Be-, B- and C-like $O^{4+,3+,2+}$ ions. A detailed analysis of ejected electron spectra for these collision systems is still underway and will be presented at the conference.

This work is supported by the Common Use Program of JAEA.

References

[1] K. Kawatsura *et al*., Nucl. Instr. and Meth. **B205**, 528 (2003).
[2] K. Kawatsura *et al*., Nucl. Instr. and Meth. **B245**, 44 (2006).
[3] N. Stolterfoht *et al*., Phys. Rev. Lett., **57**, 74 (1986).
[4] F.W. Meyer *et al*., Phys. Rev. Lett., **60**, 1821 (1988).
[5] N. Stolterfoht *et al*., Nucl. Instr. and Meth. **B40/41**, 28 (1989).
[6] T.M.J. Zouros *et al*., Nucl. Instr. and Meth. **B99**, 27 (1995).
[7] M. Fogle *et al*., A&A **442**, 757 (2005).

SINGLE CHARGE TRANSFER IN COLLISIONS OF DIATOMIC MOLECULES WITH SLOW HIGHLY CHARGED IONS

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An analytic study is presented of asymptotic properties of the three–center quasimolecular system $\mathrm{A}_2^{(Z_a-1)+} + \mathrm{B}^{Z_b+}$ consisting of a homonuclear diatomic molecule $\mathrm{A}_2^{(Z_a-1)+}$ and a highly charged atomic ion B^{Z_b+}. The potential of the one–electron exchange interaction of this system is calculated asymptotically correctly (for large distances R between interacting particles) in the framework of the non–perturbative semiclassical and the Landau–Herring approaches. The total cross sections of the electron capture in $\mathrm{H}_2 + \mathrm{Ar}^{q+}$ ($q = 6, 8, 14, 16$) collisions in the energy region from 5.0 to 2×10^3 eV/amu were calculated and compared with available experimental and theoretical data (see Fig. 1). It is shown that with increasing of projectile (atomic ion Ar^{q+}) charge, use of the semiclassical expression describing such electron exchange interaction provides noticeably better (than with use of the Landau–Herring one) agreement between the calculated cross sections and experimental data.

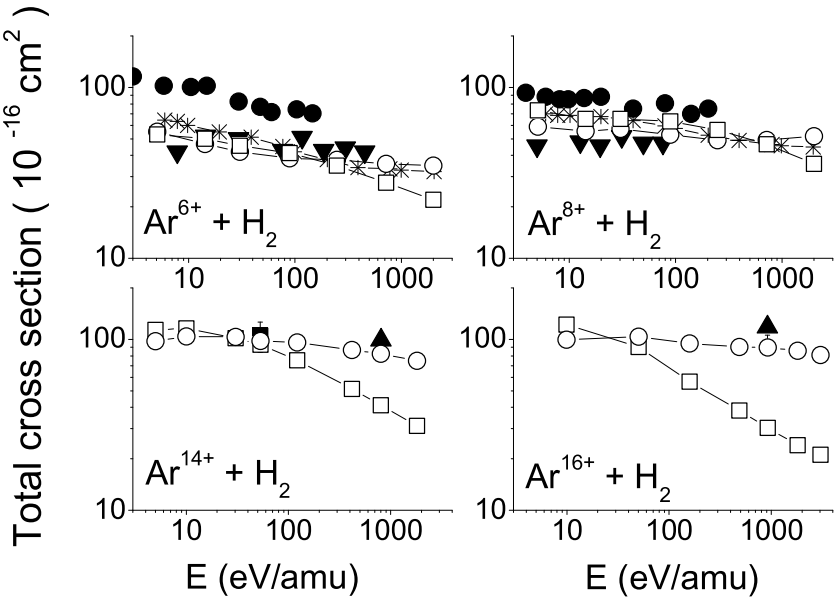

Figure 1: The total cross sections for single electron capture in $\mathrm{H}_2 + \mathrm{Ar}^{q+}$ ($q = 6, 8, 14, 16$) collision. Theory, —∗— : MO-calculation from Ref. [1a]. Present calculations, —○—: semiclassical approach; —□—: Landau–Herring approach. Experimental data, ●: Ref. [1a]; ▼: Ref. [1b]; ▲: Ref. [2a], ■: Ref. [2b].

References

[1] (a) S. Kravis *et al*, Phys. Rev. A. **58**, 1206 (1995); (b) C. Can *et al*, Phys. Rev. A. **31**, 72 (1985)

[2] (a) R. Mann, Z. Phys. D. **3**, 85 (1986); (b) J. Vancura *et al*, Phys. Rev. A. **47**, 3758 (1993)

THEORETICAL PREDICTIONS OF THE STRUCTURE OF M-X-RAY LINES OF HEAVY ATOMS

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A very complex origin of the X-ray spectra of target atoms, resulting from multiple ionization, makes it absolutely essential to carry out theoretical study on the effect of the ionization of various shells on the positions and shapes of different K-, L- and M-X-ray lines [1-3]. In the present work very extensive multiconfiguration Dirac-Fock calculations with the inclusion of the transverse (Breit) interaction and QED corrections have been carried out on gold, thorium and uranium to elucidate the structure of various satellite (additional vacancies in N and/or O shells) and hypersatellite (additional vacancies in M or M and N shells) $M\alpha_{1,2}$ ($M_5N_{6,7}$) and $M\beta_1$ (M_4N_6) lines in its X-ray spectra. For every calculated type of $M\alpha_{1,2}$ and $M\beta_1$ lines the theoretical stick spectra (line positions with their relative intensities) have been presented. Moreover for each type of lines two theoretical spectra have been predicted: one being a sum of the Lorentzian natural line shapes and the other one being a convolution of the sum of the Lorentzian natural line shapes with the Gaussian instrumental response. The obtained theoretical results will be very helpful in reliable and quantitative interpretation of a very complex origin structure of $M\alpha_{1,2}$ and $M\beta_1$ lines in various high-resolution X-ray spectra of heavy atoms induced by different light and heavy projectiles.

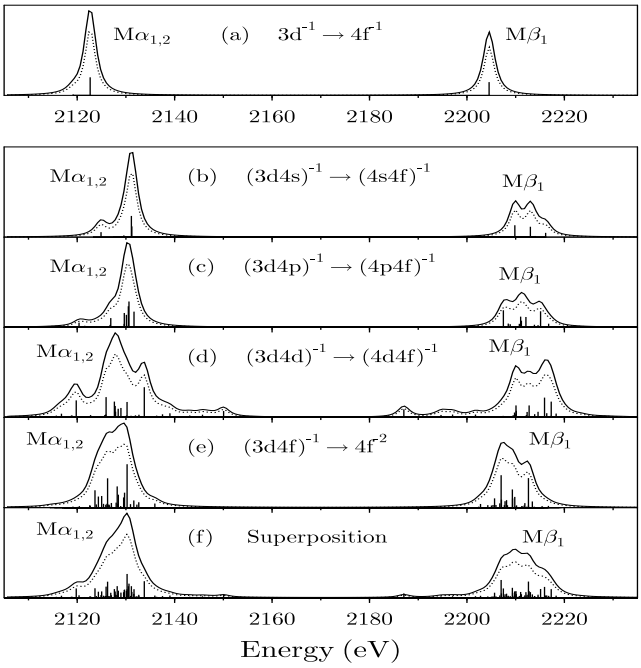

Figure 1: Calculated stick and predicted spectra for the $M\alpha_{1,2}$ and $M\beta_1$ diagram [spectrum (a)] and N-shell satellite transitions [(b)-(f)] in gold. Spectrum (f) is the summary spectrum [(b)+ (c)+(d)+(e)].

References

[1] M. Polasik, Phys. Rev. A **39**, 5092-5097 (1989); Phys. Rev. A **52**, 227-235 (1995).

[2] K. Słabkowska, M. Polasik, Radiat. Phys. Chem. **75**, 1471-1476 (2006); J. Phys.: Conf. Ser. **58**, 263-266 (2007).

[3] M. Polasik, K. Słabkowska, Radiat. Phys. Chem. **75**, 1497-1502 (2006).

INFLUENCE OF CHANGES IN THE VALENCE ELECTRONIC CONFIGURATION ON THE STRUCTURE OF L-X-RAY SPECTRA OF MOLYBDENUM

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The $L\alpha_{1,2}$ ($L_3M_{4,5}$) and $L\beta_1$ (L_2M_4) lines in the X-ray spectra of molybdenum induced by X-ray photons, 279-MeV oxygen ion and 178-MeV neon ion beams [1] have been measured by means of a high-resolution von Hamos crystal spectrometer having the energy resolution of about 1 eV. In the present work extensive multiconfiguration Dirac-Fock calculations with the inclusion of the transverse (Breit) interaction and QED corrections [2] have been carried out on molybdenum to explain the dependence of the structure of $L\alpha_{1,2}$ and $L\beta_1$ lines on the changes in configurations of the valence electrons [belonging to a different of the three $4d^{m-r}5s^r$ (r=2,1,0) types]. The most complicated case occurs for the $4d^55s^1$ configuration (see Figure 1), in which occupation of $4d$ shell and $5s$ shell is half-and-half. For this case we have 417 initial states of the type $2p^{-1}$, 647 final states of the type $3d^{-1}$, and 119 383 X-ray transitions. The obtained results are very helpful in reliable and quantitative interpretation of a very complex origin structure of $L\alpha_{1,2}$ and $L\beta_1$ lines in various high-resolution X-ray spectra of $4d$ transition-metals induced by X-ray photons and different light and heavy projectiles.

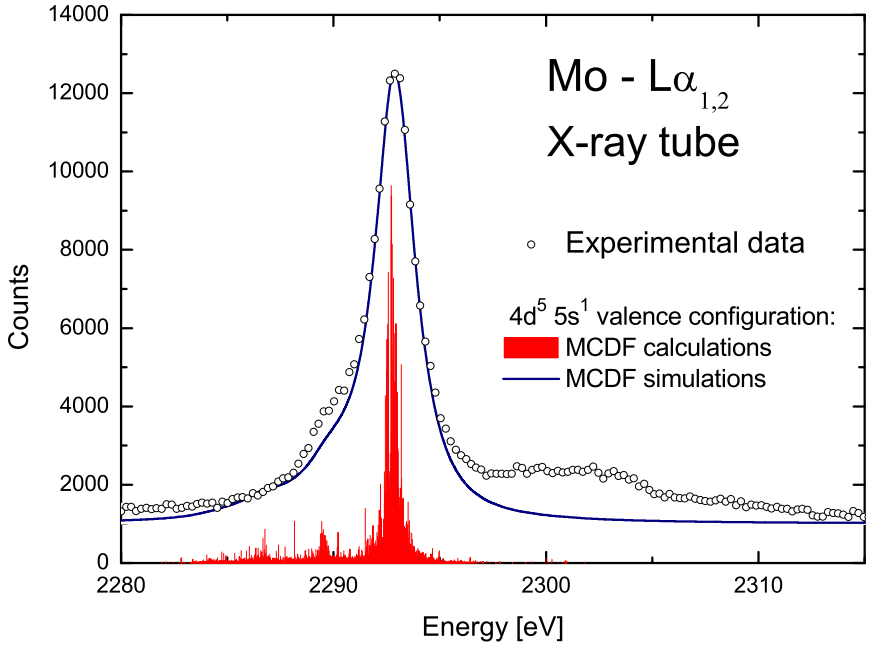

Figure 1: Comparison of the measured structure of the X-ray spectrum of molybdenum induced by X-ray photons with the MCDF predictions for diagram $L\alpha_{1,2}$ lines in the case of $4d^55s^1$ configuration.

References

[1] M.Czarnota, M. Pajek, D. Bana, D. Chmielewska, J. Rzadkiewicz, Z. Sujkowski, J.-Cl. Dousse, M. Berset, O. Mauron, Y.-P. Maillard, P.A. Raboud, J. Hoszowska, M. Polasik, K. Słabkowska, Nucl. Instr. and Meth. in Phys. Res. B **205**, 133-138 (2003)

[2] M. Polasik, Phys. Rev. A **39**, 5092-5097 (1989); Phys. Rev. A **52**, 227-235 (1995).

CAHRGE TRANSFER CROSS SECTIONS OF W^{2+} IONS IN COLLISIONS WITH RARE GAS TARGETS

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Charge transfer is one of the important collision processes not only for atomic physics but also for controlled thermonuclear fusion. The understanding of charge transfer processes is essential for studying the influence of impurity ions in fusion plasma. From this point of view, Itoh *et al*. and Imai *et al*. have measured charge transfer cross sections of Be, B, C, Cr, Fe, and Ni ions in collisions with He, Ne, Ar, Kr, H_2, CO, CO_2, CH_4, C_2H_6, C_3H_8, CO, CO_2 and N_2 targets at energies less than a few keV/u [1,2]. Recently, higher-Z elements including tungsten have been proposed as the divertor plate material of the ITER (formerly, International Thermonuclear Experimental Reactor). As experimental and theoretical investigations of charge transfer for tungsten ions are still scarce now, we have started experimental study of charge-transfer cross sections for highly charged tungsten ions colliding with atomic and molecular gas targets.

Figure schematically shows the present experimental setup. The experiment has been done using the Van de Graaff Accelerator Facility of the Quantum Science and Engineering Center, Kyoto University. Doubly charged tungsten ions are obtained by Ion-Impact-Ion-Source. A beam of 0.8-MeV CO_2^+ ions from the accelerator were focused on a pure tungsten wire set in a sputter-type ion source. Sputtered ions were extracted perpendicularly to the CO_2^+-beam direction, and were accelerated to the desired kinetic energy. The extracted ions were then focused by an einzel lens, and were momentum-analyzed by a Wien-filter. Neutrals produced in collisions with residual gases through beam passage were rejected electrostatically by a neutral particle rejector. The analyzed W^{2+} ion beam was impinged upon gas target in a collision cell. Outgoing ions were electrostatically deflected according to their charge states, and were detected by a position-sensitive MCP detector with a resistive anode.

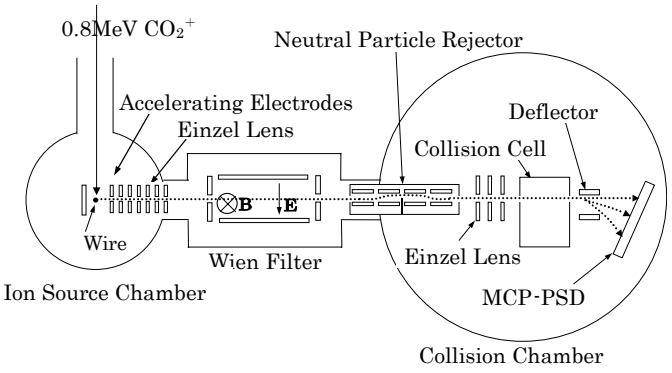

Figure Experimental setup.

Measurements for W^{2+} + Ne, Ar, Kr collisions at 15 keV have been in progress. The obtained data will be compared with the previous data for other high-Z ions [2], and discussed at the conference.

References

[1] A. Itoh, N. Imanishi, F. Fukuzawa, N. Hamamoto, S. Hanawa, T. Tanaka, T. Ohdaira, M. Saito, Y. Haruyama, T. Shirai, J. Phys. Soc. Jpn. **64**, 3255 (1995)

[2] M. Imai, T. Shirai, M. Saito, Y. Haruyama, A. Itoh, N. Imanishi, F. Fukuzawa, H. Kubo, J. Plasma Fusion. Res. SERIES **7**, 323 (2006)

X-RAY SIGNATURES OF CHARGE EXCHANGE IN L-SHELL IONS

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The X-ray signature of L-shell charge exchange in Sulfur was studied in the laboratory. Charge states from S^{11+} to S^{14+} were created in the LLNL Electron Beam Ion Trap and were left to interact via charge exchange with neutral SF_6 gas. The measurements were monitored with the EBIT Calorimeter Spectrometer. Comparison of these charge exchange (CX) spectra with those obtained under electron-impact excitation showed marked differences. In the CX spectra, an enhancement was observed in the high-n transitions; $n = 4,5,6 \rightarrow n = 2$, in comparison to the $n = 3 \rightarrow n = 2$ transitions that dominate the direct excitation spectra. An even greater enhancement was recorded in transitions from the levels of electron capture to the ground states; $n_c = 7,8,9 \rightarrow n = 2$. The spectra mainly consist of S^{13+} lines, but lower charge states such as S^{12+}, S^{11+} and S^{10+} are also present. These are the first high-resolution results of L-shell charge exchange. The spectra have been compared to low-resolution data on charge exchange in L-shell Iron, and showed a similar spectral structure. However, the high-resolution spectra from Sulfur exhibit a significant enhancement in transitions from the electron capture-levels n_c=7,8,9, whereas the low-resolution spectra of Iron showed the greatest enhancement in the transitions from n=4,5 levels.

Part of this work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and NASA grants to LLNL, SAO, and GSFC.

STUDIES OF X-RAY PRODUCTION FOLLOWING CHARGE EXCHANGE RECOMBINATION BETWEEN HIGHLY CHARGED IONS AND NEUTRAL ATOMS AND MOLECULES

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We have used microcalorimeters built by the NASA/Goddard Space Flight Center and the LLNL EBIT facility to measure x-ray emission produced by charge exchange reactions between highly charged ions colliding with neutral helium, hydrogen, and nitrogen gas. Our results show the measured spectral signatures produced by helium, hydrogen, and nitrogen donors. The measurements are compared to theory where available. These results can be used to interpret x-ray spectra produced by a variety of laboratory and celestial sources including cometary and planetary atmospheres, the Earth's magnetosheath, the heliosphere, tokamaks, and electron beam ion traps.

Part of this work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and is also supported by NASA grants to LLNL, SAO, and the NASA/GSFC.

VACUUM ULTRAVIOLET SPECTRA IN CHAEGE TRANSFER COLLISIONS OF MULTIPLY CHRAGED Sn IONS

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The Mo/Si multilayer mirrors having peak reflectivity around 13.5 nm, which is in the extreme ultraviolet (EUV) region, will be used in the next-generation semiconductor lithography. The laser-produced Sn plasma, which has strong emission around 13.5 nm, is a promising light source for the EUV lithography. However, there is not enough spectroscopic information about multiply charged Sn ions composing Sn plasmas. In order to provide the spectroscopic data of multiply charged Sn ions, we have measured the EUV emission spectra following charge transfer collisions of the charge-selected Sn ions with neutral gas targets. The experimental results on the wavelengths of the unresolved transition array (UTA) have been employed in the hydrodynamical simulation of the Sn plasma [1].

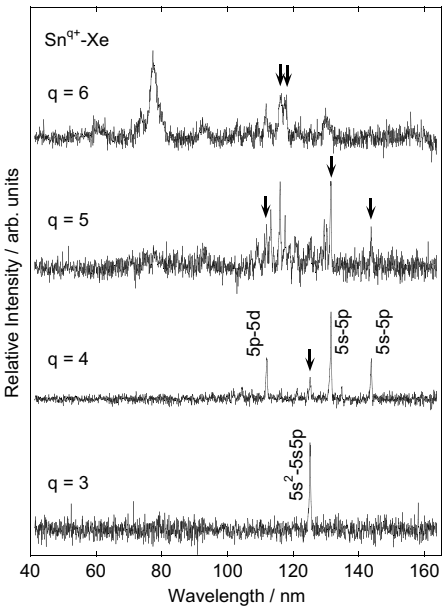

Figure 1: The emission spectra in collisions of Sn^{q+} ($q = 3 - 6$) with Xe. The lines indicated by arrows are considered to be emissions from ions which are produced by the double-electron capture.

Not only the "in-band" light around 13.5 nm, but also the "out-of-band" light with wavelengths longer than 130 nm can be reflected by the Mo/Si mirror in the EUV exposure system with high reflectivity. In this work, we measured the VUV (vacuum ultraviolet) emission spectra by means of charge exchange spectroscopy. Figure 1 shows the emission spectra in collisions of Sn^{q+} ($q = 3 - 6$) with Xe measured with a compact Seya-Namioka spectrometer. As can been seen in this figure, several lines have been observed in collisions of different charge ions. This finding means that the multiple-electron capture processes are significant in these collisions. Generally, the single-electron capture is dominant in collisions of highly charged ions, and the scaling law can be applied for the capture cross sections. However, the double-electron capture can be significant in collision of moderately charged ions [2].

Some of the emission lines observed in collisions of $q \leq 5$ ions are assigned by literature, and others could be done by using the established energy levels. However, several lines in collisions of $q = 6$ can not be identified because of no information. We have performed the similar measurements using the other rare gas targets. The emission spectra strongly depend on the target gases.

References

[1] H. Ohashi, H. Tanuma, S. Fujioka, H. Nishimura, A. Sasaki, and K. Nishihara, J. Phys. Conf. **58**, 235 (2007).

[2] K. Ishii, K. Okuno, and A. Itoh, Phys. Rev. A **70**, 042716 (2004).

DISSOCIATIVE AND NON-DISSOCIATIVE CHARGE-CHANGING PROCESSES IN 1.0-2.0 MeV/u O^{5+} + O_2 COLLISIONS

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Fundamental interactions of molecular oxygen in collisions with charged particles are relevant to many fields of study including astrophysics, atmospheric physics, and the life sciences. In an effort to gain additional understanding of such interactions, dissociative and non-dissociative products of O_2 associated with single electron capture, single electron loss, and direct ionization have been measured for 1.0, 1.5, and 2.0 MeV/u O^{5+} + O_2 collisions. These measurements were conducted at Western Michigan University using the tandem Van de Graaff accelerator. Time-of-flight techniques were used to detect coincidences between target ion fragments and individual outgoing projectile charge state components. A collimated O^{5+} beam interacted with O_2 contained within a differentially pumped target gas cell, in which the pressure was kept below 2.0 mTorr. Recoiling target ions were extracted by an electric field transverse to the beam direction and detected with a set of coupled microchannel plates. Following interaction with the target gas, the projectile beam was magnetically analyzed and the individual charge-changed components were counted using silicon surface-barrier detectors. To ensure the validity of the data, spectra for He [1] and Ne [2] were collected and the ratios for multiple ionization were compared with previously measured values as well as the measured yields for total single electron capture and loss [1]. These latter yields also provided the calibration factor to determine absolute cross sections for the O_2 data. In all cases, spectra were measured for several target pressures to check for single-collision conditions. Fig. 1 shows the target ion products associated with projectile electron capture in 1.0 – 2.0 MeV/u O^{5+} + O_2 collisions compared with the corresponding spectrum for 2 MeV/u O^{5+} + Ne. Both non-dissociative molecular and dissociative atomic products are formed with charge states up to 4+. In Fig. 1 the total integrated beam current is the same for each spectrum, indicating a strong decrease in the relative cross sections as a function of projectile energy. The spectra for projectile electron loss and direct ionization gave similar results. Absolute cross sections will be calculated, as well as the relative yields for dissociative and non-dissociative ionization of O_2 to determine detailed information on the mechanisms for the molecular fragmentation of O_2. Additional measurements for incident oxygen charge states 6, 7, and 8+ will be carried out to determine the charge-state dependence of the various processes.

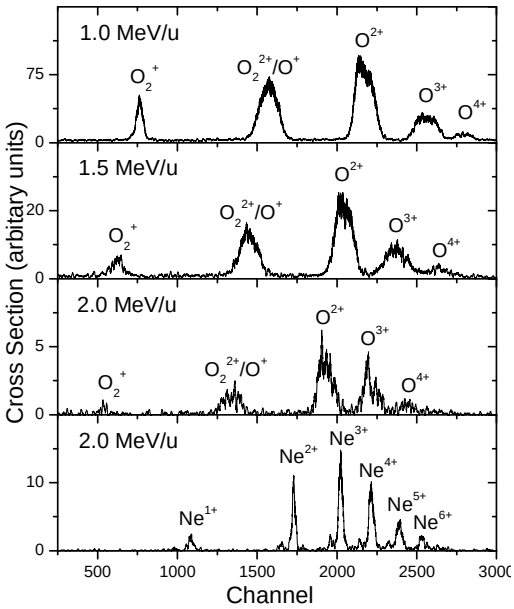

Fig. 1 Target ion fragments associated with projectile electron capture for 1.0, 1.5, and 2.0 MeV/u O^{5+} + O_2 collisions compared with the corresponding spectrum for 2.0 MeV/u 0^{5+} + Ne.

References

[1] R. Price, M.A. thesis, Western Michigan University, 1988, unpublished.
[2] R. J. Maurer, C. Can, R. L. Watson, Nucl. Instrum. Meth. A **262**, 99 (1987).

CHARGE TRANSFER PROCESSES IN COLLISIONS OF SLOW HIGHLY CHARGED IONS WITH POLAR MOLECULES CO AND C_3H_8

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Charge transfer processes resulting from low energy collisions of polar molecules CO and C_3H_8 with highly charged Be^{2+} and B^{2+} ions have been investigated experimentally and theoretically. The experiment was performed using the Van de Graaff Accelerator Facility of the Quantum Science and Engineering Center, Kyoto University. A schematic view of the experimental apparatus is given in Fig. 1a. Theoretical study based on a semiclassical analysis of the wave function of tunneling electron (see Ref. [1]) was also carried out. The potential for the one–electron exchange interaction between a non–central target (polar molecule) and projectile (atomic ion) were obtained in closed analytical form. Our theoretical calculations for absolute cross sections of the electron transfer have been found to be in fairly good agreement with the measured data (see Fig. 1b).

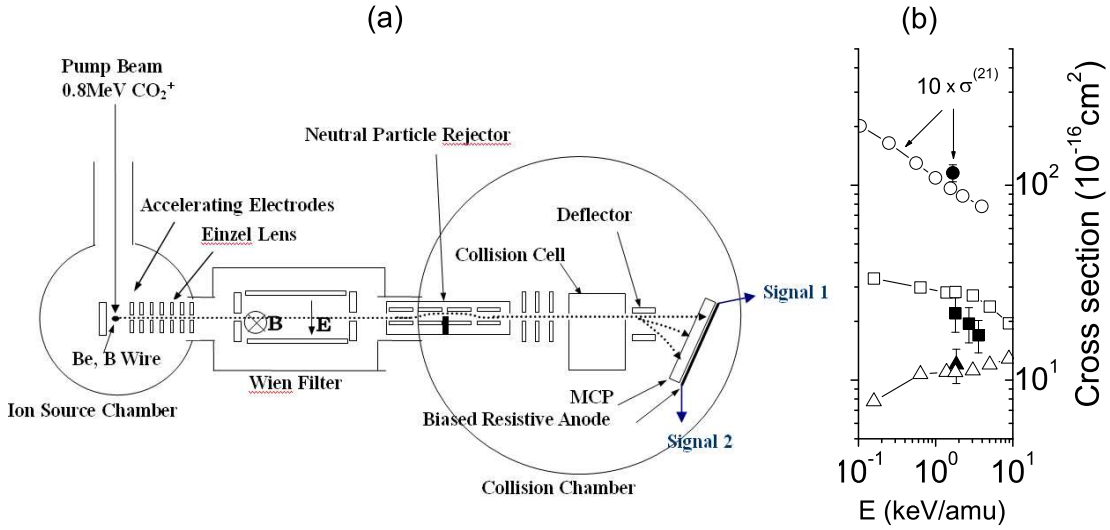

Figure 1: (a). The experimental setup. (b). Measured cross sections for single electron capture $\sigma^{(21)}$, ■: C_3H_8 + Be^{2+}; ●: $CO + Be^{2+}$; ▲: $CO + B^{2+}$. Solid lines with open symbols: present calculations. [In this figure cross sections for the collision $CO + Be^{2+}$ multiplied by a factor of 10].

References

[1] M.I. Chibisov, R.K. Janev, Phys. Rep. **166**, 1 (1988).

SINGLE ELECTRON CAPTURE IN COLLISIONS OF N^{2+} WITH He AT LOW ENERGIES

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The absolute total cross sections for single electron capture of N^{2+} on He have been measured in the energy range between 0.1 and 300 eV/u. In the collision system, the differential cross sections for single electron capture have an enlargement at 0 degree, which may be responsible for the glory scattering [1]. In slow neutral-neutral collisions, it is well known that an oscillatory structure due to glory effect may appear on the total cross sections [2]. In ion-atom collisions, there is no report about the oscillatory structure. We confirmed whether the oscillation can be observed or not even for ion-atom collisions to measure the fine energy dependence of the cross sections.

The apparatus and the experimental procedure used in this study have already been described elsewhere [3]. Only the brief features are summarized here. The apparatus consists of a tandem mass spectrometer and an EBIS type ion source. The collision cell in the spectrometer possess ion beam guide system named Octa Pole Ion beam Guide (OPIG) which prevent slow ion beam from diverging with RF field. Using the OPIG, we can decrease the collision energy down to 0.1 eV/u. The absolute gas pressure was measured with MKS Baratron type 690A. The energy width of the primary ions is estimated about ΔE=0.2 eV/u.

The cross sections measured are shown in figure 1. The energy dependence of the cross sections has interesting structures. In the collision energy below 1eV/u, the cross sections have a little scattering tendency. And around the collision energy of 70 eV/u, a clear dip can be observed on the cross sections.

In low energy region, the two paths as follows are contributed to the reaction mainly:

$N^{2+}(2p\ ^2P)+He \rightarrow$ (1) $N^+(2p^2\ ^1D)+ He^+ +3.0eV$

(2) $N^+(2p^2\ ^3P)+He^+ +5.0eV$.

The grand state of quasi-molecular potential corresponding to the reaction path of (2) has a potential well with 2 eV [4]. The attractive potential surface is considered the cause of the glory scattering. Though the clear evidence of the oscillation could not be observed on the cross sections, the scattering tendency in low energy region may be responsible for the glory effect. The reason of appearance of the dip is considered that the main path is changed from (2) to (1) with increasing the collision energy.

In the present measurements, it is known that the precise measurement of energy dependence of total cross sections can be access the information of reaction potential energy surface.

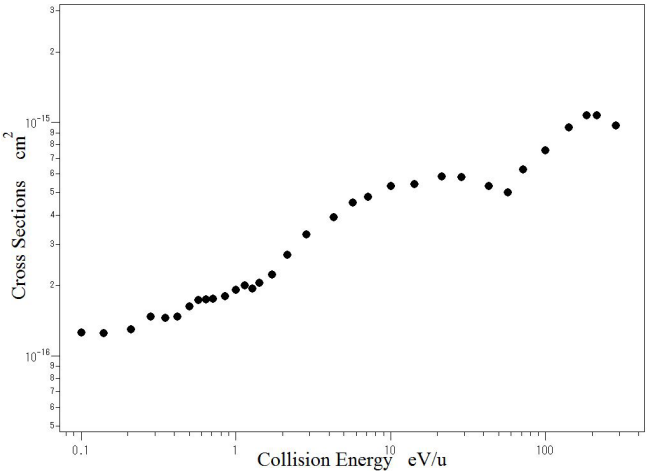

Figure 1. Present single electron capture cross sections in collisions of N^{2+} with He.

References

[1] Y. Ito, private communication
[2] W. Neumann and H. Pauly, PRL, **20**, 357 (1968).
[3] K. Okuno et al., NIM B, **53**, 387 (1991).
[4] G. P. Lafyatis et al., PRA, **48**, 321 (1993).

GROSS AND PARTIAL IONIZATION CROSS SECTIONS IN 6-MEV/AMU BARE-ION COLLISIONS WITH METHANE

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For understanding the ionization mechanisms in molecules, gross ionization cross sections have been measured with a condenser-plate method in bare ion impact on CH_4 molecules. Moreover, a mass-spectroscopic technique has been applied to separate recoiled ions to get partial ionization cross sections. Secondary ions produced in collisions were extracted with an electrostatic lens, mass/charge-analyzed by a double focusing sector magnet and finally detected by a Channeltron detector. The projectile ions such as 6-MeV/amu-H^+, -He^{2+}, -C^{6+} -$Ne^{10+}$and -Ar^{18+} were provided by the Heavy Ion Medical Accelerator in Chiba (HIMAC) of the National Institute of Radiological Sciences.

In Fig. 1, mass/charge spectra for CH_4 in H^+ and Ne^{10+} impact are shown for comparison. They are characterized by several peaks corresponding to fragmented ions as well as the most prominent peak for parent CH_4^+ ions. It can be noted that relative intensities of the fragmented ions increase as the projectile charge increases.

Partial ionization cross sections can be calculated from the relative intensities of the peaks in mass spectra and gross ionization cross sections measured in a separate experiment. Figure 2 shows the obtained partial cross sections as a function of projectile charge q. The cross sections for CH_4^+ and CH_3^+ ions are prominent, and they increase with a slope of around 2 in a log-log plot. This indicates that they are mainly produced at distant collisions, where the first Born approximation would be applicable. On the other hand, fragmented ions, such as CH_2^+, CH^+ and C^+, show charge dependence quite different from the Born approximation, indicating that other mechanisms might contribute to their production. Doubly and triply charged carbon ions have been detected with remarkable intensities in highly charged Ne^{10+} and Ar^{18+} ion impact.

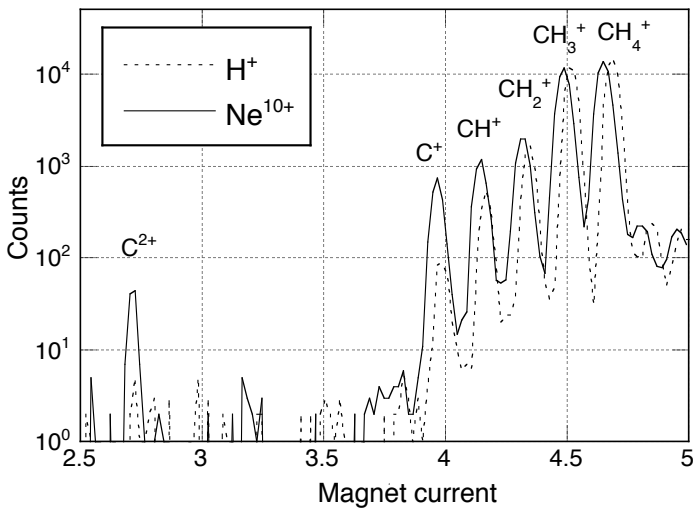

Fig. 1

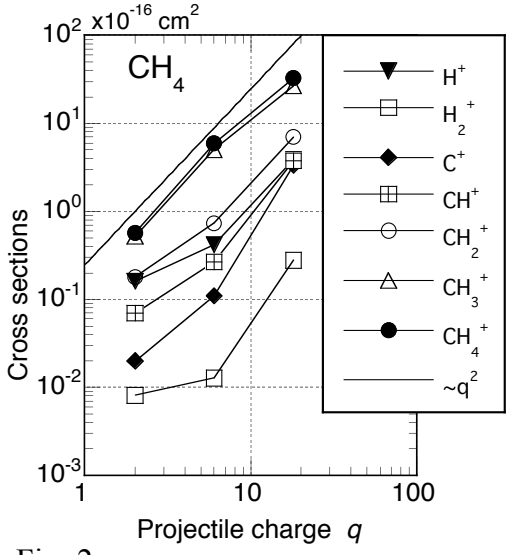

Fig. 2

QED APPROACH TO CALCULATING ELECTRON COLLISION STRENGTHS FOR MULTICHARGED IONS IN A PLASMA: WITHIN THE DEBAE APPROXIMATION

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We present the uniform energy approach, formally based on the QED perturbation theory (PT) [1,2] for the calculation of electron collision strengths and rate coefficients in a multicharged ions (in a collisionally pumped plasma). An account for the plasma medium influence us carried out within a Debae shielding approach. The aim is to study, in a uniform manner, elementary processes responsible for emission-line formation in a plasma. The electron collision excitation cross-sections and rate coefficients for some plasma Ne-like multicharged ions are calculated within QED energy approach [1,2]. The energy shift due to the collision is arisen at first in the second PT order in the form of integral on the scattered electron energy ε_{sc} :

$$\mathrm{Im}\Delta E = \pi G(\varepsilon_{iv}, \varepsilon_{ie}, \varepsilon_{in}, \varepsilon_{sc})$$

where G is the squared combination of the two-particle matrix elements:

$$V(1,2;4,3) = \sqrt{(2j_1+1)(2j_2+1)(2j_3+1)(2j_4+1)}(-1)^{j_1+j_2+j_3+j_4+m_1+m_2} \times$$
$$\times \sum_{\lambda,\mu}(-1)^{\mu}\begin{bmatrix} j_1.....j_3...\lambda \\ m_1.-m_3...\mu \end{bmatrix}\begin{bmatrix} j_2.....j_4...\lambda \\ m_2.-m_4..\mu \end{bmatrix}(Q_\lambda^{Qul}+Q_\lambda^{Br})$$

The values $Q_\lambda^{\mathrm{Qul}}, Q_\lambda^{\mathrm{Br}}$ are corresponding to the the Coulomb part $exp(i|\omega|r_{12})/r_{12}$ i and Breiht part $exp(i|\omega|r_{12})\ \alpha_1\alpha_2/r_{12}$. of the inter particle interaction. The cross-section is σ=-2 ImΔE. We have carried out a detailed studying the collision cross-sections and collision strengths (the incident electron energies 0.425,0.5,0.75,1.045 кeV) for Ne-like ions ClVIII, ArIX , CaXI, TiXIII, CrXV from the ion ground state to a set of excited states ($2s_{1/2}2p_{1/2,3/2}$, $2p_{3/2,1/2}3s_{1/2}$, $2p_{3/2,1/2}3p_{3/2,1/2}$, $2p_{3/2,1/2}3d_{5/2,3/2}$, $2s_{1/2}3s_{1/2}$, $2s_{1/2}3p_{1/2,3/2}$, $2s_{1/2}3d_{3/2,5/2}$ [J=0,1,2,3,4]) and Ar-like ion of Ba (the incident electron energy 5.8, 9.5 кeV), for majority of which there are absent exact data. To test the results of calculations we compare the obtained data for Ne-like ions of Fe, Ar with other authors' calculations and available experimental data. The inclusion of Na-like states, accounting for diffusion-like processes, can increase the population inversion for the "lasing candidates" by at least a factor of two for a wide range of plasma conditions.

References

[1] A.V.Glushkov, L.N.Ivanov, Phys.Lett.A. **170**, 36 (1992); E.P. Ivanova, L.N.Ivanov, L. Knight, Phys. Rev. A. **48**, 4365 (1993); A.V.Glushkov, E.P. Ivanova, J.Quant. Spectr. Rad. Tr. (US) **36**,127 (1986); E.Ivanova, L.N.Ivanov, A.V.Glushkov, A.S.Kramida, Phys.Scr. **32,** 512 (1985); Preprint ISAN N1 Moscow 1992; A.V.Glushkov et al, J.Phys.CS.**11**, 188 (2005); Int. Journ. Quant.Chem. **104**, 512 (2005);
[2] A.V.Glushkov, E.P.Gurnitskaya, A.V.Loboda, In: Low Energy Antiproton Phys., AIP Serie. **796**, 217 (2005); A.V.Glushkov et al, Nucl. Phys.A. **734**, 21 (2004); Int. Journ. Quant.Chem. **99**, 879 (2004); **99**, 936 (2004); J.Phys.CS.**35**, 420 (2006).

Fragmentation of Small biomolecules induced by highly charged ion impact

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The fragmentation is a characteristic behaviour of complex systems such as large molecules and clusters upon excitation. A large number of experimental investigations have been performed on C_{60} and small molecules of DNA bases during the last years using photon excitation (laser and synchrotron source) and electron or ion beam impact excitation. Collision induced fragmentation using highly charged ions from ECR source has been demonstrated to be a powerful method providing complementary information comparing to other experimental methods. The specificity of experiments with an ECR source is related to the large choice of the charge and the atom of beams, the easy scan and high selectivity of the kinetic energy and the possibility to perform multi-coincidence measurements in event by event mode.

In this poster, we present experimental results on the fragmentation of DNA bases induced by impact of highly charged ions, Kr^{17+} (13 kV) and Xe^{23+} (10 kV). Multicharged ion beams delivered by the ARIBE facility allowed us to prepare charged molecules at low internal energy via electron capture process at large impact distances. By coincidence detection of the scattered projectile, the charged fragments and the ejected electron number, we were able to study the fragmentation dynamics and delayed dissociation processes. These results will be compared with the fragmentation patterns of DNA bases induced by singly charged ion beams using a novel experimental method, the so-called CIDEC (collision induced dissociation under energy control) [1-3].

References

[1] L. Chen, S. Martin, J. Bernard et R. Brédy, Phys. Rev. Lett. **98**, 193401 (2007)
[2] S. Martin, L. Chen, A. Salmoun, B. Li, J. Bernard, and R. Brédy, Phys. Rev. A **77**, 043201 (2008)
[3] S. Martin et al. Phys. Rev. A (2008)

EVIDENCE OF GIANT DIPOLE PLASMON RESONANCE IN ELECTRON SPECTRUM OF C_{60} AND BEAM INDUCED POLARIZATION

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Mechanisms of electron emission in collisions with clusters involving C_{60}-fullerene are governed by more complicated processes than in ion-atom collisions. The fullerenes are "small" particles with diameter ~10Å over which a large electron density similar to that of a solid is sampled. Fullerenes are known to exhibit collective excitation: *giant dipole plasmon resonance* (GDPR). Effect of GDPR on x-ray emission from fullerene and multiple ionization under heavy ion impact has been reported earlier [1-5]. However, a direct evidence of this process in fast ion-collisions was awaited. The plasmon excitation de-excite through emission of electrons of particular energy, which is characteristic of the plasmon frequency. This presents a unique possibility of observing the GDPR peak in the low energy electron spectrum of C_{60}. The electron energy due to the decay of GDPR-excited state is expected at ~10 eV (i.e. 20 eV- I_P, I_P=ionization potential). We measured the low energy (1-300 eV) e^- - DDCS spectrum from C_{60} in collisions with 4 MeV/u bare F ions at various angles. We observe a broad hump like structure near the expected GDPR peak position in all the electron spectra. The C_{60} DDCS spectra are different from the DDCS spectra of other atomic gaseous targets like Ne [Fig.1]. The low energy spectrum was collected with lot of precaution and spectrometer performance was verified by measuring expected spectral shapes from atomic targets.

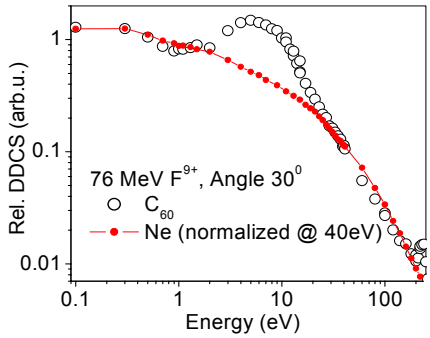

Fig.1 : Typical electron DDCS spectrum from C_{60} (o) and Ne.

We have also measured the angular distributions of the electrons. The electron emission (at ~10 eV i.e. at GDPR peak) is maximum in forward and backward direction w.r.t. to the projectile beam and a dip is observed at 90^0**.** This distribution is just opposite to the expected behaviour for atomic targets. The angular distribution suggests that the dipole oscillations are induced preferably along the projectile beam direction. This is for the first time that such an angular distribution of e-emission in plasmon decay in C_{60} or any type of clusters has been measured.

References

[1] T. LeBrun et al. Phys. Rev. Lett., 72, 3965 (1994)
[2] H Tsuchida, A Itoh, Y Nakai, K Miyabe and N. Imanishi, J. Phys. B 31, 5383 (1998).
[3]U. Kadhane et al. Phys. Rev. Lett. **90**, 093401 (2003)
[4] U. Kadhane et al. Phys. Rev. A (Rapd comm.) **75**, 041201 (R) (2007)
[5] A. H. Kelkar et al. J. Phys. B **40**, 2481 (2007) and Nucl. Instrm. Meth. B 256 114 (1007)

ANGULAR ANISOTROPY IN K-LL AUGER ELECTRON EMISSION FROM C_{60} AND CH_4 IN COLLISION WITH 4 MeV/u F^{9+}

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The energy and angular distributions of low energy electrons in ion-atom collisions are useful tool to identify various collisions mechanisms. We have shown that the low energy electron spectrum from C_{60} under the HCI impact reveals the evidence of the plasmon resonance peak (This HCI abstract book). It would the therefore interesting to check the angular distributions of the higher energy electrons produced in much low impact parameter collisions. Auger electron spectroscopy is widely used in atomic and molecular collision studies. High resolution Auger spectroscopy serve to identify the electronic configuration of the atomic species involved in the collisions. Also, the angular distribution of Auger electrons reveals the orientation and symmetry of the parent molecule as well as the polarization effects of the molecule during the collision. We have measured the K-LL Auger electron angular distribution from C_{60}, CH_4 and Ne in collisions with 4 MeV/u F^{9+} ions. The projectile beam is obtained from 14MV BARC-TIFR Pelletron accelerator and the secondary electrons were energy analyzed using an electrostatic hemispherical analyzer. We observe a K-LL Auger peak at 240 eV for C_{60} and CH_4 corresponding to Carbon K-LL, whereas the Ne K-LL Auger peak is detected at 740 eV. We observe that Auger electron angular distribution from C_{60} is highly anisotropic and peaks at forward and backward angles. Anisotropic behaviour was also observed for the case of CH_4 although its magnitude is much less compared to C_{60}. Contrary to this, Ne K-LL auger angular distribution is isotropic within experimental errors, which is, however, expected. One possible reason for this anisotropy in case of C_{60} could be the polarization of the valence electron cloud in the molecule by the highly charged projectile ions. The C_{60} molecule is known to be highly polarizable, which can lead to preferred axis of electron emission w.r.t. to the projectile beam direction. In order to check this we have also measured the angular distributions of the KLL Auger electrons induced by 6 keV electrons on Ne, N_2, and CH_4 and the distributions were found to be isotropic.

In addition, to the K-LL Auger electron peak due to single K-vacancy we have also identified the K-hypersatellite (2K-LL !) Auger line at an energy of ~280 eV arising due to double K-vacancy in the C-atoms. The intensity of this line is found to be approximately 10% of the K-LL line. The details will be provided.

LOW ENERGY CARBON ION IRRADIATION OF WATER ICES

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Ion processing plays an important role in the chemical and physical modification of ice surfaces in astrophysical environments. Magnetospheric ions surrounding the Gas Giants in the outer Solar System impinge upon and modify the icy satellite surfaces creating new chemical species, incorporating elements not originally present in the local ice composition.

$^{13}C^{+}$ and $^{13}C^{2+}$ ions were produced by an Electron Cyclotron Resonance ion source, accelerated by a low energy accelerator and were incident upon pure water ice samples. Modifications to the ice were measured using an FTIR spectrometer. The most significant modifications observed within the IR spectra were the growth of features corresponding to $^{13}CO_2$ and H_2O_2 and the decrease of features corresponding to H_2O. Additionally, a feature corresponding to 'dangling OH' bonds was seen to decrease, indicating a change in the porosity of the ice being irradiated. It was also interesting to note that no signature for ^{13}CO was observed at any stage during the experiments.

Figure 1 shows the formation of $^{13}CO_2$ as a function of ion fluence at kinetic energies of 2 (left) and 4 keV (right). It is clear that, at both energies, significantly different yields of $^{13}CO_2$ were observed with the two different ion charge states. This difference is believed to be a result of the additional potential energy depostited by the doubly charged ion during an electron capture event.

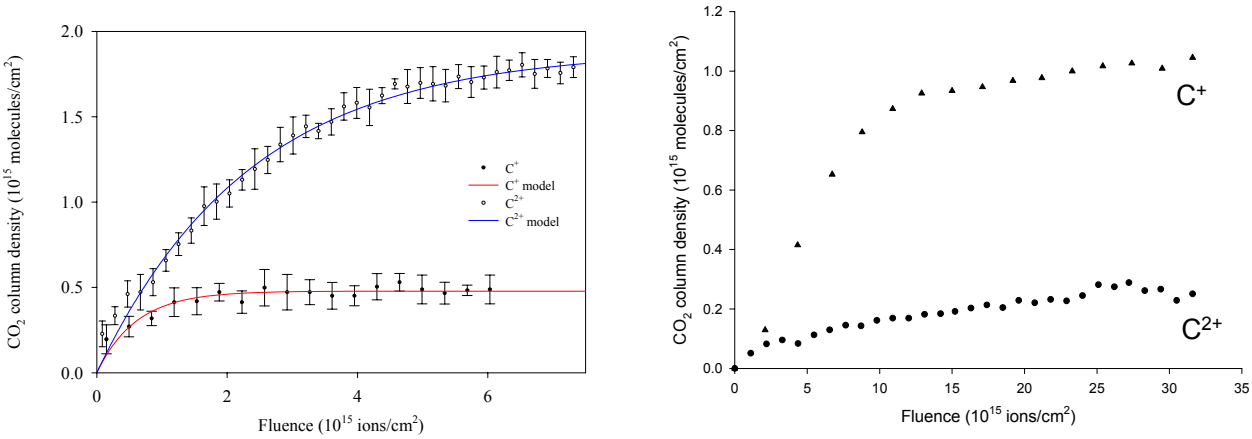

***Figure 1**: CO_2 growth at 2 (left) and 4 (right) keV. In both cases, the yield of CO_2 is significantly different for the two charge states.*

[1] Anita Dawes, Adam Hunniford, Philip D Holtom, Robin J Mukerji, Robert W McCullough and Nigel J Mason *Phys. Chem. Chem. Phys.* **9** 2886-2893 DOI: 10.1039/b618026d (2007)

OPTICAL EMISSION SPECTROSCOPY OF EXCITED ATOMS SPUTTERED ON A Ti SURFACE UNDER IRRADIATION WITH MULTICHARGE Ar IONS

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Optical emission spectroscopy of excited atoms was carried out in order to investigate the sputtering processes on solid surfaces under irradiation of slow multicharged ions. Many atomic lines of Ti I (neutral) and Ti II (single-charged ions) were observed in wavelengths from 250 to 750 (nm) with irradiation by Ar^{3+} (30 keV) on a Ti surface which was placed in a low pressure O_2 atmosphere as seen in Fig. 1.

Emission intensity of Ti I (520 nm) decreased monotonically with an increase of O_2 partial pressure, whereas that of Ti II (670 nm, a 2nd order wavelength of 335 nm) slightly increased as seen in Fig. 2. The difference in O_2-pressure between Ti I and II is considered to be due to the change of survival probabilities of sputtered Ti^* and Ti^{+*} atoms interacting with the oxygen-covered Ti surface. [1]

From a semi-logarithmic plot of emission intensity for the 670 nm spectrum as a function of distance from the surface, the mean velocity of the sputtered $Ti^*(3d^24s4p\ x^3G)$ in a normal direction parallel to the surface, e.g. $\langle v_\perp \rangle$, was determined. [2] As a result, $\langle v_\perp \rangle$ of Ti^* is rather large compared with $\langle v_\parallel \rangle$ of Al^* emitted from Al and Al_2O_3 surfaces interacting with Ar^{q+} (q = 3 − 8). [3]

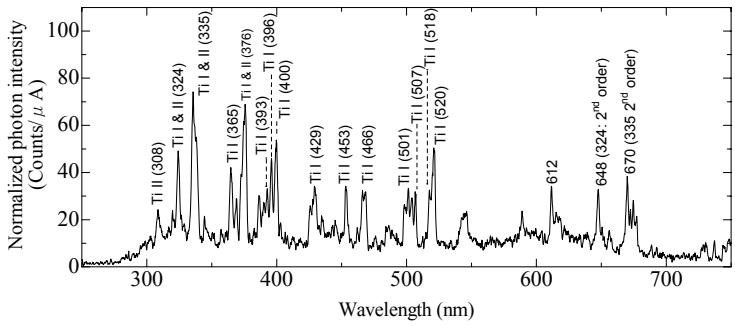

Fig. 1 Optical emission spectrum of excited atoms sputtered on a Ti surface interacting with Ar^{3+} (30 keV) ions.

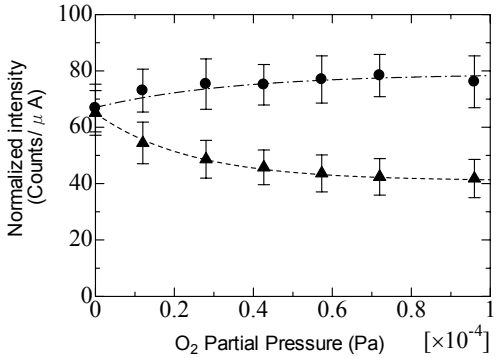

Fig. 2 Normalized emission intensity of ▲; Ti I (520 nm) and ●; Ti II (670nm, a 2nd order wavelength of 335 nm) spectra as a function of O_2 partial pressure.

References

[1] S. Tsurubuchi and T. Nimura, Surf. Sci. **513** (2002) 539.
[2] R. Walkup and Ph. Avouris, Surf. Sci. **157** (1985) 193.
[3] K. Motohashi, S. Tsurubuchi, H. Shimizu, K. Mochiji, H. Tanuma, and N. Kobayashi, Phys. Scr. **T73**, 329 (1997).

POTENTIAL ENERGY THRESHOLD FOR NANO-HILLOCK FORMATION ON CaF_2 BY IMPACT OF VERY SLOW, HIGHLY CHARGED IONS

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Upon impact on a solid surface the potential energy stored in slow highly charged ions is primarily deposited into the electronic system of the target. We present experiments with very slow (down to impact velocities as low as 0.03 a.u. or 30 eV/amu) highly charged xenon ions creating hillock-like topographic nanostructures on the surface of CaF_2(111) single crystals which are stable in air and non erasable by AFM scanning [1]. Surprisingly, these nanostructures closely resemble those created by swift heavy ions at a CaF_2 surface, while leaving deeper layers of the target undamaged. We find first unambiguous experimental evidence that potential energy alone is sufficient to cause these nano-sized hillocks. The observed dependence of the feature size on the kinetic energy of the projectile ions is very weak. A sharp and well-defined threshold of potential energy is required for the onset of nano-hillock formation [1,2].

Simulations of the dissipation of potential energy into the target material on the basis of an extended classical over-the-barrier model have been performed to facilitate the interpretation of the experimental findings [3]. The experimentally observed threshold of potential energy for hillock formation is linked to a solid-liquid phase transition.

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References

[1] A. S. El-Said, et al. NIM B 258 (2007) 167
[2] F. Aumayr, A. S. El-Said, W. Meissl, NIM B (2008), doi:10.1016/j.nimb.2008.03.106
[3] C. Lemell, et al., Sol. State Electr. 51 (2007) 1398

ELECTRON EMISSION FROM INSULATORS BOMBARDED WITH VERY SLOW HIGHLY CHARGED IONS

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Electron emission induced by impact of slow highly charged ions (HCI) on metallic surfaces has been studied extensively over the past 15 years [1]. The "classical-over-the-barrier" (COB) model [2] was very successful in modelling the formation of so-called "hollow atoms" in front of the surface and the subsequent emission of electrons due to Auger and other processes. Because of the finite hole mobility and differences in image charge potentials the response of insulator surfaces to slow HCI impact, however, is less well understood. We have recently used an electron statistics (ES) detector [3] to measure yields and number statistics of electrons emitted from (insulating) LiF(001) and CaF_2(111) surfaces bombarded by moderately slow (v < 1 a.u.) Ar^{q+} ($q \leq 18+$), Xe^{q+} ($q \leq 50+$), and Hg^{q+} ($q \leq 68+$) projectile ions under various impact angles [4]. The results show a clear deviation in the behaviour of potential electron emission as compared to metallic surfaces in this velocity regime. This deviation is explained by a strong sub-surface electron emission contribution from the insulating targets.

In this work we present electron yields from very slow Xe^{q+} impact on clean, single crystalline KBr(001), LiF(001) and CaF_2(111) surfaces, all of which have recently found to be susceptible to nanostructuring by single slow HCI impact [5] [6]. Charge states were varied between q = 10 and 44. Moderate heating of the targets was applied to counter any macroscopic charge-up during ion irradiation. We have constructed a new ES setup that was implemented into the deceleration station of the EBIT at the Forschungszentrum Dresden. Applying multiple electrical potentials, we first bend the ion beam (up to 70°) to hit a tilted target under normal incidence and then - with the same electrical field - collect close to 100% of the electrons emitted during the impact event. We have determined the true ion beam energy and its energy spread by applying a retarding field on the electron repeller aperture at the entrance of the chamber while monitoring the number of ions hitting the target. With this setup, we were able to measure electron yields for impact energies of less than 2 eV/amu up to 1.5 keV/amu, where a good agreement with previous data [4] for higher impat velocities was found. For the first time, electron yields from insulators have been obtained in the velocity regime close to the image-charge acceleration limit.

This work has been supported by Austrian Science Foundation FWF (P17449-N02) and by the European Project RII3\#026015. Transnational access to the Rossendorf ion beam facilities was provided through AIM (EU contract no. 025646).

References

[1] F. Aumayr, and HP. Winter, Springer Tracts in Modern Physics **225**, 79 (2007).
[2] J. Burgdörfer, and C. Lemell, Springer Tracts in Modern Physics **225**, 1 (2007).
[3] W. Meissl, *et al.*, Rev. Sci. Instrum. **77**, 093303 (2006).
[4] W. Meissl, *et al.*, e-J. Surf. Sci. Nanotech. **6**, 54 (2008).
[5] F. Aumayr, A. S. El-Said, W. Meissl, NIMB (2008) doi:10.1016/j.nimb.2008.03.106
[6] R. Heller, S. Facsko, R. A. Wilhelm, and W. Möller, submitted (2008).

SECONDARY-ION EMISSION FROM GaN(0001) AND DODECANETHIOL/Au(111) SURFACES IRRADIATED WITH Ar^{q+} (q = 3–6) AT GLANCING ANGLE

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Secondary-ion mass spectroscopic (SIMS) studies have been performed to investigate desorption or sputtering processes of various solid surfaces interacting with highly charged ions (HCIs). [1-2] To eliminate kinetic sputtering processes, we focused on glancing collisions between HCIs and surfaces. We recently developed an HCI-SIMS apparatus capable of detecting secondary ions, secondary electrons, and scattered atoms/ions simultaneously. This apparatus allows us to analyze solid surfaces in four different operating modes: 1) low-energy ion scattering spectroscopy (LEIS), 2) SIMS in coincidence with LEIS, 3) SIMS triggered by scattered neutral atoms, and 4) SIMS triggered by secondary electrons.

Figure 1 shows the experimental setup of the HCI-SIMS apparatus. Multichannel plates labeled D_1, D_2, and D_3 can detect secondary ions, scattered atoms/ions, and secondary electrons, respectively. The time of flight (TOF) of secondary ions is measured with the start signals of secondary electrons or scattered atoms/ions. The position y shown in Fig. 2 reflects the energy and charge-state dispersion of the scattered ions. The horizontal axis in Fig. 2 represents the TOF of secondary ions, measured from the difference between the arrival time of a secondary ion (T_1) and that of a scattered ion (T_2). Three arrows indicate the velocity (or energy) components of Ar^+ ions, which were scattered at three different lattice sites of GaN. This result suggests that protons were mainly emitted from three different lattice sites. [3] The preliminary results for a Dodecanethiol self-assembled monolayer (SAM) surface will also be presented.

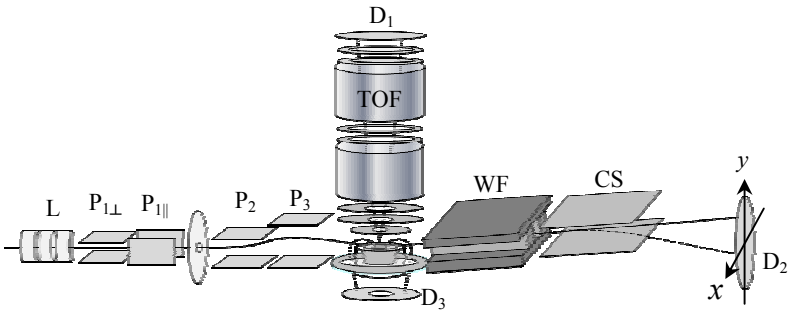

Fig. 1 Schematic illustration of a novel HCI-SIMS apparatus. L, electrostatic lens; P, parallel plates; TOF, time of flight analyzer of secondary ions; WF, Wien filter (velocity seperator) of scattered ions; CS, charge-state seperator of scattered ions; D_1, 2D position sensitive ion detector; D_2, 2D position sensitive ion/atom detector; D_3, electron detector

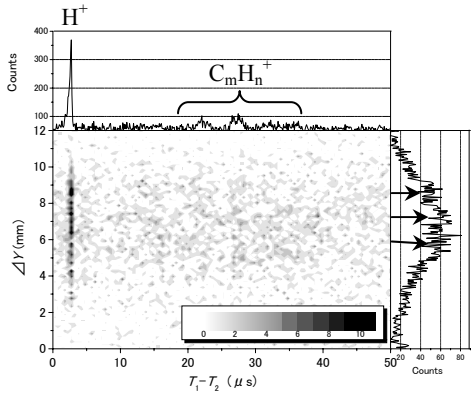

Fig. 2 Correlation map between TOF ($T_1 - T_2$) of secondary ions and displacement (Δy) of scattered Ar^+ in Ar^{6+} (15 keV)–GaN(0001) glancing collision.

References
[1] K. Motohashi and S. Tsurubuchi, Nucl. Instrum. Phys. B **264**, 15 (2007)
[2] K. Motohashi, S. Tsurubuchi, and A. Koukitu, J. Phys. Conf. Ser. **80**, 012015 (2007)
[3] K. Motohashi, J. Kor. Phys. Soc. (submitted).

SIMULATION OF ION GUIDING THROUGH NANOCAPILLARIES: ENERGY DEPENDENCE

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The transmission of highly charged ions (HCI) through insulating nanocapillaries at angles larger than the geometric opening angle has attracted much research interest in recent years. As HCIs are largely transmitted in their initial charge state, rather than being neutralized in a close collision with the capillary walls, the term "guiding" has been frequently used. The key to this process is the electrostatic deflection of HCI from the inner wall after a self-consistent charge-up. Numerous groups have studied this phenomenon employing capillaries of different geometry, material, and ion charge state. Comprehensive measurements of parameter dependences exist so far only for Polyethylene-terephthalate (PET) capillaries [1]. Recently, we have presented an theoretical treatment of HCI guiding through insulating nanocapillaries based on a calculation of classical trajectories in the electric field of a self-consistently charged capillary. A crucial aspect in our model is the charge transport on and into the inner walls. This invokes no free parameters but involves known material properties only. Within our approach, qualitative (and in part also quantitative) agreement with experiments employing PET capillaries could be found [2]. We will present simulations for PET capillaries with a diameter of 200 nm and analyze the dependence on the energy of incidence of HCI in the range of 2-9 keV. Comparison to recent experiments [1] serves as a further test of our model.

We will also analyze the recently observed transmission of electrons with an energy of several hundred eV through insulating PET nanocapillaries [3]. Contrary to the case of HCI, a significant inelastic component of the transmitted projectiles was observed. Consequently, transmission is not only established by deflection in (conservative) electrostatic fields alone. We have developed a model to simulate transmission of electrons through nanocapillaries which reproduces basic features of the experiment. Similarities and differences of electron and HCI guiding will be discussed.

References

[1] N. Stolterfoht, R. Hellhammer, J. Bundesmann, and D. Fink, Phys. Rev. A **77**, 032905 (2008).

[2] K. Schiessl, W. Palfinger, K. Tőkési, H. Nowotny, C. Lemell, and J. Burgdörfer, Phys. Rev. A **62**, 042902 (2005).

[3] S. Das, B. S. Dassanayake, M. Winkworth, J. L. Baran, N. Stolterfoht, and J. A. Tanis, Phys. Rev. A **76**, 042716 (2007).

Potential energy threshold of surface nanostructures formation by the interaction of slow Xeon ions on a HOPG surface

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The interactions between highly charged ions (HCIs) and surfaces are of importance not only for fundamental researches but also for potential applications. The possibility of exploiting the huge amount of potential energy stored in HCIs for nanostructure formation with a Scanning probe microscope (SPM) has attracted great attention. The slow HCIs could as a unique tool for the surface etching, the ultra-thin film growth and the nanostructure fabrication. Previous experiments have shown that the size of nano-dots depend strongly on the charge state but are independence of the velocity of the ions [1, 2]. However, the mechanism of the surface nanostructures formation is not well known in details and further systematic experiments are needed.

At the new experimental terminal for surface physics, the 320kV ECR Platform at IMP, Lanzhou, experiments on nanostructure formation irradiated by slow highly charged Xe^{q+} (q=15-29) ions on High Orientated Pyrolytic Graphite (HOPG) surface have been carried out. During the experiment, the pressure of vacuum chamber keeps below 10^{-9} mbar. The ions' velocity fix on 7.5×10^5 m/s and the fluxes of ions keep on 10^{10} ions/cm^2 in order to exclude other possible influences. In the tapping mode Atomic Force Microscope (AFM) image, the generation of the nano-sized hillocks protruding from the surfaces is probed. As shown in Fig. 1, the hillock-like nanostructure protruding from the HOPG surfaces can be observed only for Xeon ions with the charge state $q\geq27$ which is lower than the charge state threshold for nano-hillock formation by Xeon ions ($q\geq30$) on a CaF_2 (111) surface, and the height and the diameter of the nanostructure formation increase with the projectile ion charge state. The present results reveal a similarity between the nanostructure formation produced by slow HCIs and the track formation induced by the swift heavy ions [2, 3].

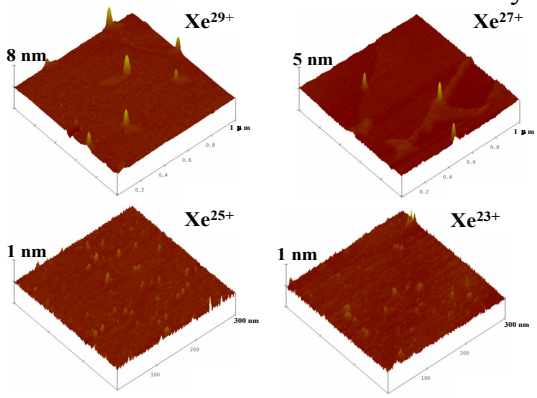

Fig. 1 AFM images of nanostructures formed by irradiation of slow Xe^{q+} (q=23, 25, 27, 29, v=7.5×10^5 m/s) ions on HOPG surfaces. Note the different lateral and vertical scales.

References

[1] Y.Yamazaki *et al*., J. Phys: Conf. Ser. 72 (2007) 012002
[2] A.S.El-Said *et al*., Nucl. Instr. and Meth. B 258, 167 (2007)
[3] J.Liu *et al*., Nucl. Instr. and Meth. B 212, 303 (2003)

ABSOLUTE SPUTTERING YIELDS FROM SOLID RARE GASES BY SINGLY- AND MULTIPLY-CHARGED ION IMPACT

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Interaction of slow multiply charged ions (MCIs) with a solid surface has been studied in past 20 years [1]. Most of the experimental studies, however, are limited to the metal and semiconductor surfaces, and very few are reported for the insulator surfaces. Rare gas solids have several characteristics very different from the other materials; small cohesive energy (e.g., 0.02 eV/atom for Ne), large band gap energy (e.g., 21.6 eV for Ne), long diffusion length of excitons (e.g., $\sim$ 200 nm for Ne), etc. We have studied the sputtering of atoms from the surface of rare gas solids by singly- and multiply-charged ion impact. The purpose of this study is to reveal qualitatively by observing the sputtered (desorbed) particles how such a large internal energy of MCI is consumed at the surface and/or in the bulk of very fragile rare gas solids.

Figure 1 shows total sputtering yields of solid Ne by Ar^{q+} ($q = 1, 4, 6$) impact as a function of the incident ion energy. Thickness of the solid Ne film is about 500 atomic layers. The results show surprisingly large sputtering yield even at relatively low incident energy, and that the yield is almost proportional to the incident ion energy.

The fact that no dependence on the charge state, i.e. potential energy, is observed in this energy region can be explained as follows; An exciton or an ion created in solid Ne induces the desorption of 1 - 5 atoms [2]. If we assume that all of the potential energy of the incident ion can be used to create excitons ($E_{\rm exciton} = 17.2$ eV) or ions ($E_{\rm g} = 21.6$ eV), the potential sputtering yield will be at most 100 even by Ar^{6+} (potential energy: 310 eV) impact, which is too small to be observed within the present experimental uncertainty.

Detail will be given at the conference.

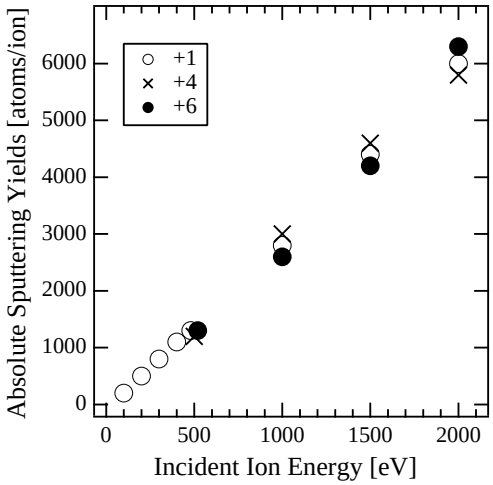

Figure 1: Absolute sputtering yield of solid Ne by Ar^{q+} ($q = 1, 4, 6$) impact as a function of the incident ion energy. Thickness of the sample film is about 500 atomic layers.

References

[1] for example, F. Aumayr and H. P. Winter, Phil. Trans. Roy. Soc. Lond. A**362**, 77 (2004), and references therein.

[2] T. Hirayama and I. Arakawa, J. Phys. Cond. Matt. **18**, S1563 (2006).

POTENTIAL SPUTTERING OF IONIC SPECIES FROM RARE GAS SOLIDS BY MULTIPLY CHARGED ION IMPACT

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Interaction of rare gas solids (RGS) with low energy photons and electrons were well studied in these two decades [1]. In these studies, creation of excitons and ions is found to play an important role in the desorption processes. Sputtering of ions from RGS by singly charged ion impact has been investigated by some groups [2, 3], however little report can be found by multiply charged ion impact. Here we report the results for the potential sputtering yields of ions from RGS by multiply charged ion impact.

Figure 1 shows mass spectra of ions sputtered by the impact of 1 keV Ar^+ and Ar^{7+} from solid Ne. Very large cluster ions up to cluster size n ~100 are observed (not shown in the figure). One can find that the intensity and size distribution for small clusters ($n \leqslant 3$) strongly depend on the charge state q of the incident ion, while almost no dependence on q has been observed for the large clusters ($n \geqslant 7$), suggesting that the kinetic sputtering is dominant for the desorption of large cluster ions.

Considering that the potential energy of Ar^+ (15.76 eV) is less than the creation energy of an exciton (17.1 eV) and an ion (21.6 eV) in solid Ne, we assume that only the kinetic sputtering occurs by Ar^+ impact, and estimate the potential sputtering yield Y_{PS}. The results (Fig. 2) show that Y_{PS} is proportional to the potential energy of the projectile ion, which suggests that all of the potential energy is consumed to create excitons and ions in the solid. Detailed discussion will be given at the conference.

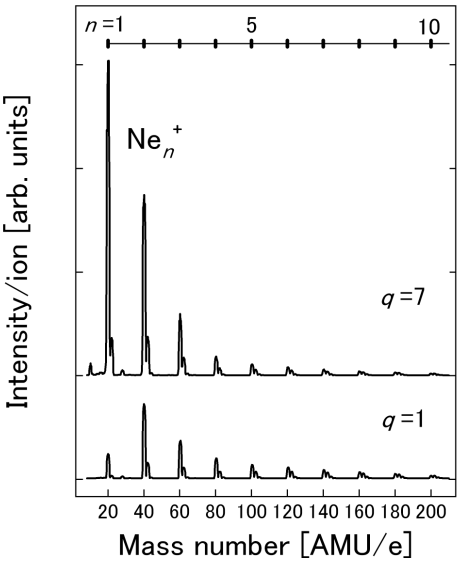

Fig. 1. Mass spectra of sputtered ions from the surface of the solid Ne by 1keV Ar^{q+} (q = 1, 7) impact. Thickness of the solid Ne is about 600ML.

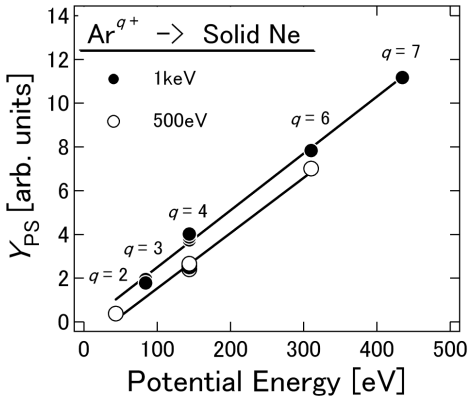

Fig. 2. Potential sputtering yields of ions sputtered by Ar^{q+} (q = 2, 3, 4, 6, 7) from the surface of solid Ne. Full and open circles correspond to 1 keV and 500 eV impact energy of incident ions, respectively.

References

[1] for example, T. Hirayama and I. Arakawa, J. Phys.: Cond. Matt. **18**, S1563 (2006) , and references therein.

[2] R.G. Orth, H.T. Jonkman, D.H. Powell and J. Michl, J. Am. Chem. Soc. **103**, 6026 (1981).

[3] K. Hiraoka, M. Watanabe, D. Eguchi, S. Okazaki and T. Sato, Rapid Commun. Mass Spectrom. **16**, 1016 (2002).

SECONDARY ION EMISSION FROM A KCl(001) SURFACE BY GRAZING-ANGLE INCIDENCE OF SWIFT IONS

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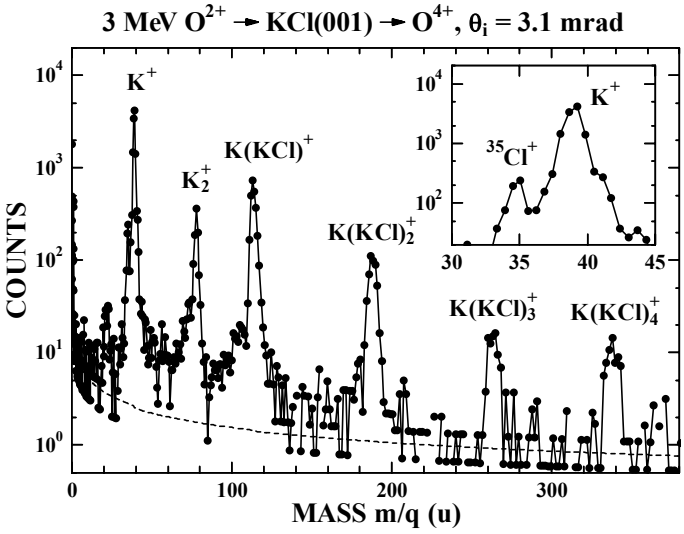
When energetic ions are incident on an atomically flat surface at a grazing angle, most of them are scattered around the angle of specular reflection. This phenomenon referred to as specular reflection of ions is favorable for studies on the ion-surface interaction because the ions are reflected in front of the surface atomic layer without the close collisions with the target atoms or the penetration inside. In addition, one can easily examine the dependence of the interaction on the distance from the surface by means of changing the angle of incidence [1,2].

In this paper, the yield and the mass distribution of positive-charged secondary ions emitted from a KCl(001) surface were measured along with the energy loss of the reflected ions, when MeV ions are incident on the surface at grazing angle θ_i ranging from 1 to 5 mrad. Single-charged secondary ions such as K^+, Cl^+, KCl^+, K_2^+ and small clusters, $K(KCl)_n^+$ (n = 1–4) were detected under the incidence of various MeV ions, 0.8 MeV He^+, 1.34 MeV Li^+, 2.1 MeV B^{2+}, 3 MeV O^{2+}, 1.5 MeV Si^{2+} and 6 MeV Si^{3+}. The total yield of the secondary ions increased with the angle θ_i regardless of kind of projectiles, while the energy loss of the reflected ions was almost independent of θ_i. The position-dependent production rate $P(x)$ of the secondary ions, i.e. the average number of secondary ions emitted per unit path length of a projectile traveling at a distance x from the outermost atomic plane, was derived from θ_i-dependence of the total yield. The production rate $P(x)$ is compared with the position-dependent stopping power $S(x)$ for the projectile at x. $P(x)$ shows an overlinear increase with $S(x)$ as $P(x) \sim S(x)^n$, but the index n varies from 1.4 to 2.6 depending on $S(x)$.

References

[1] Y. Fujii, K. Narumi, K. Kishine, K. Kimura, M. Mannami, Nucl. Instr. and Meth. B **67**, 82 (1992).
[2] K. Kimura, S. Ooki, G. Andou, K. Nakajima, M. Mannami, Phys. Rev. A **58**, 1282 (1998).



Example of mass spectrum of secondary ions from a KCl(001) surface under grazing-angle incidence of 3 MeV O^{2+} ions.

GUIDING OF VERY HIGHLY CHARGED IONS WITH A GLASS CAPILLARY

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Highly charged ions produced in an electron-beam ion trap, I^{q+}, $q = 10 \sim 50$, were transmitted through a tapered glass capillary, having diameter of 50 μm at the end. We found, for a particular beam current, there exists an optimum tilting angle of the capillary, in which a steady output of ions was observed, while for other smaller angles, the ion-counts exhibit first rise and gradual decay on the minutes time scale. In case of steady transmission, the charge state distribution was found to be slightly shifted towards the lower side.

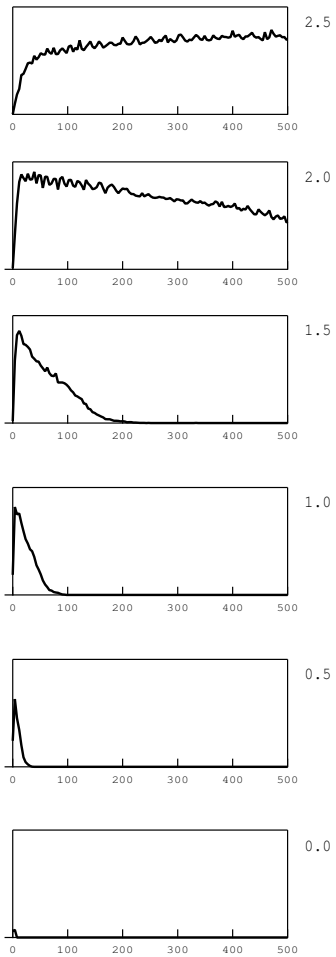

Figure 1: Time behavior of the transmitted highly charged ions. The numbers below the horizontal axes are time in seconds and the numbers at the right are tilt angles in degree.

STM OBSERVATIONS OF HIHGLY CHARGED ION IRRADIATED ALKANETHIOL MONOLAYERS

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Alkanethiols are long chain carbon molecules with a thiol group (-SH) at one end and a functional group at the other end. When these molecules are allowed to interact with a metal or semiconductor surface they form a stable monolayer with the thiol group covalently bonded to the substrate and the functional group forming a new surface. These structures are called self assembled monolayers (SAM) and have been the subject of intensive research recently due to their potential applications in functionally tailoring and nano-structuring surfaces [1]. We have used highly charged ions to irradiate alkanethiol SAM fabricated on flat gold surfaces. After irradiation scanning tunneling microscopy (STM) was used to observe the defects created in the SAM by highly charged ion impact.

Monolayers of the alkanethiol molecules 11-Mercaptoundecanoic acid, $HS(CH_2)_{10}COOH$, and Dodecanethiol, $HS(CH_2)_{11}CH_3$, were prepared on atomically flat Au(111) which was deposited as a thin film (200 nm) on freshly cleaved mica. The quality of the gold surface was confirmed by STM observations and the SAM formed by placing the clean gold samples into a 1 millimolar solution of the thiol in pure ethanol. Ar^{q+} (q = 7,8) ions generated by the high-Tc superconducting electron beam ion source (EBIS) located at RIKEN were used to irradiate the SAM surfaces under UHV with a typical ion dose of 10^9 ions/cm^2.

SAM surfaces were observed by STM before and after irradiation. Small craters in the SAM surface due to ion irradiation were observed. The density of these defects was approximately equal to the density of incident ions suggesting that individual ion impacts cause each defect. In most cases the defects were stable although under certain scanning conditions they could be made to disappear after several scans. For irradiation with Ar^{7+} ions at a kinetic energy of 14 keV the size distribution of the craters was found to be 2 – 4 nm, with an average depth of 0.2 nm. The nature of these defects is discussed in the light of complementary sputtering experiments from the same surfaces [2].

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References

[1] J. C. Love et al., Chem. Rev. **105** 1103 (2005)
[2] M. Flores et al., these proceedings

THEORY OF CRYSTAL-ASSISTED FREE-BOUND PAIR PRODUCTION BY RELATIVISTIC IONS

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When a relativistic ion enters a crystal, it feels the periodic field by crystal atoms. In ion's rest frame the periodic field is equivalent to a bunch of monochromatic photons. If the ion is sufficiently relativistic, these equivalent photons may cause pair production in which an electron is produced in a bound state of the relativistic ion while a positron is in a free-like state (Fig. 1). A theory for the same kind of process was reported by Kunashenko and Pivovarov [1]. Using the virtual photon method and the relativistic photoelectric cross section, we calculate the bound-free pair production rate as a function of the impact parameter. We compare our results with the theory using strong laser fields by Müller et al . [2].

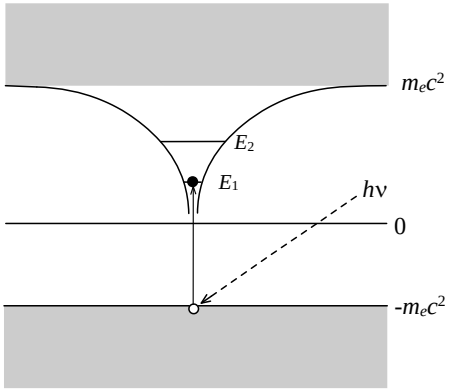

Fig. 1: Free-bound pair production

References

[1] Yu. P. Kunashenko, Yu. L. Pivovarov, Nucl. Instr. and Meth. B **119** (1996) 137.
[2] C. Müller, A. B. Voitkiv, and N. Grün, Phys. Rev. Lett. **91**, 223601 (2003)

Electron transfer proceess in ion neutralisation on nanoscale metal systems

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Nanoscale metal systems - supported clusters- play an important role in a number of applications including in particular heterogeneous catalysis, pigments etc. The properties of such systems and their interaction with atoms & molecules is thus of considerable interest. It is a well established fact that the size, shape and nature of support affect the properties of the nanoparticles and can play a crucial role in determining their use in a particular application. A considerable effort is being made to understand the various aspects that govern the properties of these systems, although a full understanding has not been achieved. The size effects have been discussed in terms of morphology and electronic structure and questions of the interaction with the substrate are addressed. It is thus interesting to investigate the evolution of electron transfer rates between ions and nanoparticles and follow their size dependence. Similarly recent theory (1,2) has also addressed the case of electron transfer on ultrathin films and the effect of quantization because of the finite thickness of the film.

Recently we have conducted experiments on Li neutralisation on Ag and Au clusters (3) supported on TiO_2, which have revealed a strong size dependence of the neutralization of Li^+ ions, which turns out to by several times more efficient on naoparticles of circa 3nm size. We are now extending these measurements to the case of Al_2O_3 support. In an attempt to understand these results we performed a study of Li^+ neutralization on (100) and (111) surfaces of bulk Cu, Ag and Au (4) for which in certain cases of very high workfunctions an anomalously high neutralisation was observed. In relation to these questions, recent theory indicates that resonant neutralization processes besides the workfunction, depend on such properties as positions of the surface states and bandgap (5). In order to attempt to highlight these we performed experiments for thin films for which the above characteristics evolve as a function of film size and thickness. Thus we studied Li^+ neutralisation on Ag submonolayer to multilayer films on Cu(111) and Au(111). Interestingly significant changes in neutralisation were however not observed.

These results will be presented and discussed.

References.

1. E. Yu. Usman, I. F. Urazgil'din, A. G. Borisov, and J. P. Gauyacq
Phys. Rev. B 64, 205405 (2001)
2. I.K. Gainullin, E.Yu. Usman and I.F. Urazgil'din. Nuclear Inst. and Methods B232, 2005, 22
3.A.R.Canario and V.A.Esaulov J.Chem Phys 124, 224710, (2006)
4. A.R. Canário, T.Kravchuk, V.A. Esaulov New J Phys 8 (2006), 227; H.Hamoudi, C.Dablemont and V.A.Esaulov submitted to Surf Science
5. A.R.Canario, A.G. Borisov, J.P. Gauyacq and V.A.Esaulov Phys. Rev. B **71**, 121401 (2005)
6. M.Wiatrowski, L. Lavagnino, and V.A. Esaulov Surface Science 601, (2007), L39; T.Kandasamy, L.Chen, C.Dablemont and V.A.Esaulov to be published

Density matrix description of resonant coherent excitation of swift highly charged ions in oriented crystals

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Experimental and theoretical studies on resonant coherent excitation (RCE) of channeled ions in crystals started about 40 years ago from pioneering works of V.Okorokov [1]. Unambiguous observation of *the Okorokov effect* by S.Datz group at Oak-Ridge and wide variety of RCE measurements performed recently by Tokyo collaboration have made main contribution to the present-day image of the RCE process [2].

Density matrix description [3,4] considers RCE ion as an open quantum system involved into coherent and incoherent interactions with the crystal medium. Systematic numerical calculations based on the generalized Master equation for density matrix show it as a good instrument for unified approach to charge state distribution of the RCE ions and the yield and angular distirbution of their characteristic X-ray radiation. Other RCE observables including metastable ion production in a usual RCE process [5] and Auger electron production in a doubly resonant process (dRCE) [6] were considered in the same theoretical approach and suggested for experimental observation. Following our long-time interest in the problem of alignment of excited ions in the RCE process we extend previous density matrix calculations [3,7,8] on this point by theoretical predictions for Stokes parameters of linear and circular polarization of the X-ray radiation from relativistic resonant coherently excited channeled ions.

Our current theoretical studies in the field [9] being closely correlated with main trends in the latest RCE experiments by the Tokyo group [10-13] concern also such novel aspects of the RCE process as its trajectory resolved characteristics and resonant coherent excitation of highly charged ions in non-channeling conditions. Corresponding calculation results and our seeing of general perspectives of further development of the density matrix approach in the RCE studies will be presented at the conference.

The work is supported by the Russian Foundation for Basic Research (grant 06-02-16367).

[1] V.V.Okorokov, JETP Lett. **2** (1965) 111; Yad. Phys. **2** (1965) 1009 [Sov. J. Nucl. Phys. **2** (1965) 719].
[2] D.Dauvergne, J.Phys.Conf .Ser. 58 (2007)25.
[3] V.V.Balashov, I.V.Bodrenko, Moscow University Physics Bulletin, **56** (2001) 33, N1.
[4] V.V.Balashov, I.V.Bodrenko, Phys.Lett. A **352** (2006) 129.
[5] V.V.Balashov, I.V.Bodrenko, NIM B **245** (2006) 52.
[6] V V Balashov, A A Sokolik , A V Stysin, JETP (in press).
[7] V.V. Balashov, I.V. Bodrenko, ICPEAC XIV, Rosario, Argentina, 2005; Book of Abstracts, Tu 133.
[8] V V Balashov, A A Sokolik, Optics and Spectroscopy **103** (2007) 761.
[9] V.V.Balashov, *Density matrix description of the RCE process* (lecture course), Tokyo Metropolitan University, Tokyo, April 3-24, 2008 (unpublished).
[10] C.Kondo, S.Masugi, Y.Nakano, et al., Phys.Rev.Lett. **97** (2006) 135503.
[11] Y.Nakano, S.Masugi, T.Muranaka, et al., J.Phys.Conf. Ser. **58** (2007) 395.
[12] C.Kondo, S.Masugi, T.Muranaka, et al., NIM B **256** (2007) 157.
[13] T.Azuma, Y.Takabayashi, C.Kondo, et al., Phys.Rev.Lett. **97** (2006) 145502.

UNEXPECTED DIFFERENCES BETWEEN KINETIC ENERGY RELEASE DISTRIBUTIONS FOR C_2^+-EMISSION FROM MULTIPLY CHARGED C_{60} AND C_{70} FULLERENES

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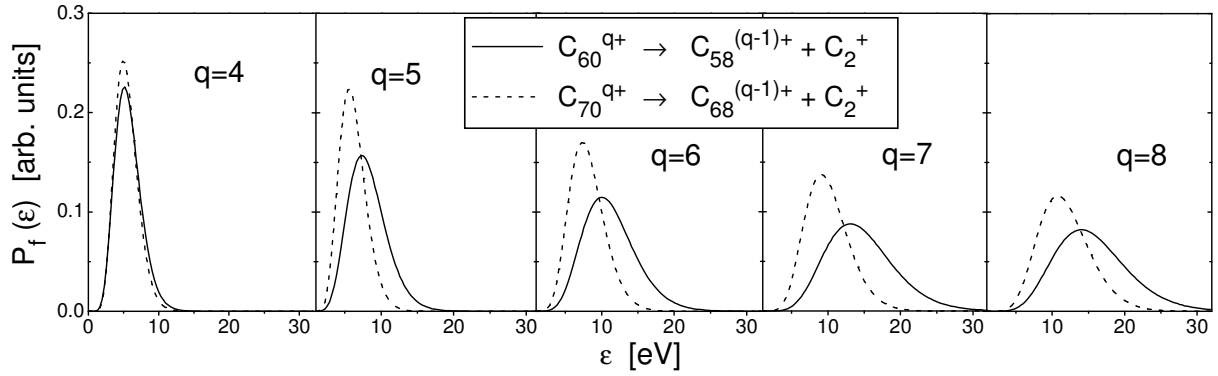
We have measured kinetic energy release distributions for asymmetric fission, $C_{60}^{q+} \rightarrow C_{58}^{(q-1)+} + C_2^+$ and $C_{70}^{q+} \rightarrow C_{68}^{(q-1)+} + C_2^+$, of multiply charged C_{60} and C_{70} fullerenes (q=4-8). The experimental technique involves a linear time-of-flight spectrometer with a position sensitive detector at the end. The kinetic energy distributions for the heavy fragments, $C_{58}^{(q-1)+}$ and $C_{68}^{(q-1)+}$, give corresponding two-dimensional position distributions on the detector which are reproduced by simulations including the initial thermal distributions in the target fullerene jets, the finite overlap volume of the jet and the ionizing pulsed beam of 57 keV Xe^{19+}-ions, the time delay between ionization and extraction, and kinetic energy release distributions of the form $P(\varepsilon) = a\varepsilon^k \exp(-k\,\varepsilon/\,\varepsilon_{max})$. Here, k = 8.5 for C_{60} and 10.0 for C_{70}, and $\varepsilon = \varepsilon_{max}$ is the kinetic energy release where $P(\varepsilon)$ has its maximum. The resulting $P(\varepsilon)$-distributions, using ε_{max} as a fit parameter, are very similar for C_{60} and C_{70} in the case of q=4 as can be seen in the figure below. For higher q, however, the C_{60}-distributions are significantly wider and peak at significantly higher ε-values than for C_{70} [1].



Further, we use a statistical model to describe the competitions between the asymmetric fission processes and evaporation processes in which a neutral C_2 unit is emitted. Relying on recent theoretical results for the dissociation energies for these two channels [2,3], and our experimental ratios which deviate significantly from zero and unity for q=4-6, we deduce semi-empirical fission barriers which compare favourably with recent theoretical results.

References

[1] N. Haag et al. submitted to J. Chem. Phys. 2008.
[2] S. Diaz-Tendero et al., J. Chem. Phys. 123, 184306 (2005).
[3] H. Zettergren et al., J. Chem. Phys. 127, 104308 (2007).

Hydrogen atoms sputtered by highly charged ions from a Si(111)-H surface

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During approach of highly charged ions on a surface, electrons in the small area of the surface, typically several nm^2, are sucked up, which causes the repulsive force by the charges of the ions and results in the explosion of surface atoms. This explosion is called Coulomb explosion and the sputtering by the Coulomb explosion is called potential sputtering.

Tona *et al.* [1] have measured sputtered atomic and molecular ions from a hydrogen terminated Si(111) surface by the bombardment of slow highly charged iodine ions. Sharp increases of the ionic species with the increase of the charge state q of the projectile were observed. In the case of proton, which dominated over the other ions, the emission yields increased as $q^{3.4}$ and reached 4.6 per incident ion at $q = 50$. On the other hand according to the morphological observations of the impact sites of highly charged iodine ions with $q = 50$, about 20 of the surface hydrogen could be sputtered by the single ion bombardment [2]. Therefore the large amount of sputtered particles was lost, which means loss of the information of sputtering processes.

We measured Lyα and Hα photons from the hydrogen atoms sputtered from a Si(111)-H surface by the impact of slow highly charged iodine ions quantitatively. Based on these measurements we will discuss the sputtering of atoms by slow highly charged ions from a surface.

References

[1] M. Tona, K. Nagata, S. Takahashi, N. Nakamura, N. Yoshiyasu, M. Sakurai, C. Yamada, and S. Ohtani, Surf. Sci. **600**,124(2006).

[2] Tona *et al.* to be submitted.

IMAGING DYNAMICS OF CHARGE-SELF-ORGANISATION IN GLASS CAPILLARIES: LATEST RESULTS AND PROSPECTIVES

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Multiply charged ion beam transmission through insulating capillaries is today a very active field of research [1]. Thanks to the work of several groups during the last five years, several features of this unexpected process have been evidenced. The open challenge is to understand and control the self-organized charging-up of the capillary walls which leads finally to the ion transmission. Up to now, the specific charge distribution on the inner surface, as well as the dynamics of the build-up, are still to be understood.

While capillaries usually studied are microscopic pore networks etched in different materials [2, 3], our concern is in macroscopic single capillaries made of glass. With a length of several centimeters and a diameter of a few micrometers at the exit, these capillaries have nevertheless the same aspect ratio as the etched pores (length/diameter ≈ 100). One of the leading goals of this research on single capillaries is to produce multi-charged ion beams with diameters smaller than a micrometer (nano-beams). Collimation by diaphragms is generally used to achieve this scale, but at the price of a drastic ion flow reduction. These glass capillaries offer the opportunity to use them as an ion funnel due to their amazing properties of guiding and focusing highly charged ion beams without altering neither their initial charge state nor the beam emittance (< 10^{-3}mm.mrad) [4,5]. However, the understanding of the underlying process is not complete and relies on models assuming charge patches distributed along the capillary [6] and which still need to be tested. Our latest observations concerning the dynamics of the charging-up process show that the 230keV Xe^{23+} transmitted beam is deflected back and forth several times as the outgoing current increases (Fig.1). This is in agreement with the picture of charge patches created sequentially along the capillary and thus deflecting the beam.

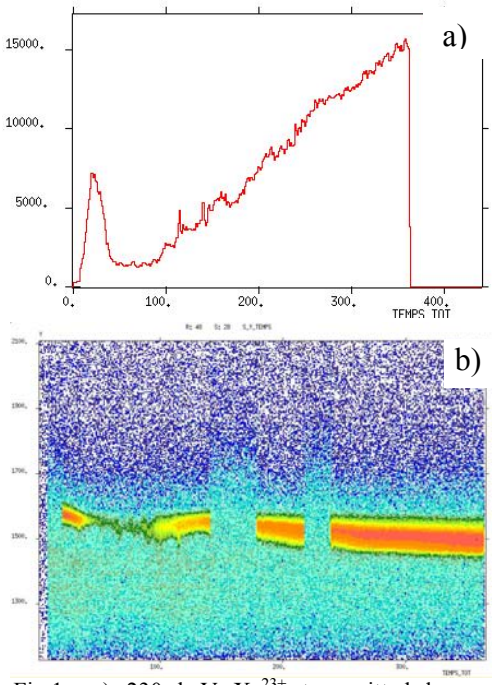

Fig.1 : a) 230 keV Xe^{23+} transmitted beam intensity as a function of time (1 channel = 20s) ; b) Horizontal position of the beam as a function of time (100 channels = 226μm).

These latest results together with near future projects concerning charge patch imaging will be presented at the conference.

References
[1] Y.Yamazaki, NIM B **258**, 139 (2007)
[2] N.Stolterfoht et al, Phys.Rev.Lett. **88**, 133201 (2002); N.Stolterfoht et al, Phys.Rev.A **77**, 032905 (2008)
[3] P.Skog et al, NIM B **258**, 145 (2007)
[4] T.Ikeda et al, Appl.Phys.Lett. **89**, 163502 (2006)
[5] A.Cassimi et al, Int.J.Nanotechnol. **5**, 809 (2008)
[6] K.Scheissl et al, NIM B **258**, 150 (2007)

A SYSTEMATIC STUDY OF THE 4d-GIANT RESONANCE IN Xe^{n+} (n = 0, 1~7)

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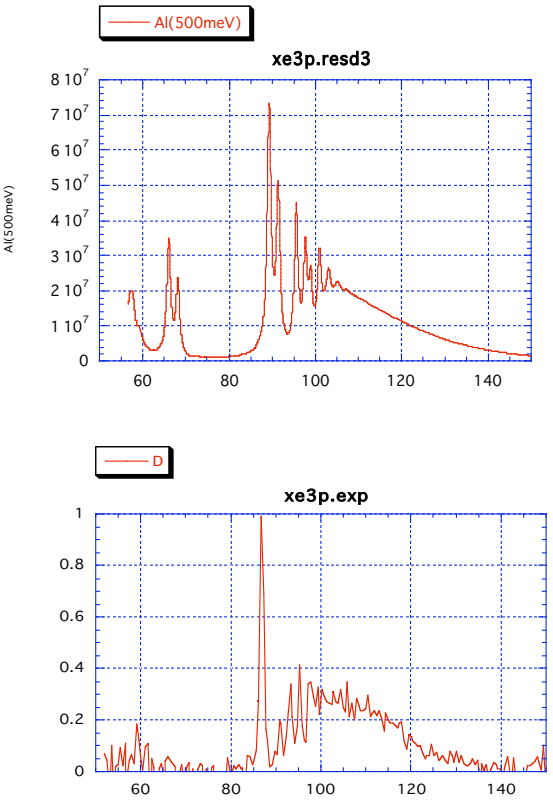
The 4d giant resonance structure that apperas in the photoabsorption spectra of process in heavy atoms and ions has been a subject of interest in atomic physics for a long time. [1, 2]. The broad resonance appeared is understood to be an effect of the double minimun final Hartree-Fock potenital for *f*-partial state and the electron-electron dynamic correlation. Generally speaking, the variation in shape and location of the 4d resonance structure for different heavy atoms and ions is due to differences in their respective final states. The initial states of these atoms or ions have relatively little effect on the the 4d resonance structures because the 4d levels are hardly affected by the outer shell electrons. Morever, it should be noted that a bound-free transition becomes possible due to the formation a short-range type efective potenital for the *f*-partial wave resulting from electron-electron correlation [2].

Using the density function theory[3] we calculated the photo-absorption cross section of the 4d-giant resonance of Xe and Xe^{n+}, where n = 1, 2,~ 7. For each species, the total spectrum, including discrete and continuum states[4]. The photo-absorption (ionization and excitation) cross section, $\sigma(\omega)$, as a function of energy ω (in atomic units) is given by the imaginary part of the dynamic polarizability $\alpha(\omega)$:

$$\sigma(\omega) = \frac{4\pi\omega}{c}\Im[\alpha(\omega)]. \qquad (1)$$

The dynamic polarizability in the presence of an external field $V^{ext}(\mathbf{r},\omega)$ is given in terms of $\chi^{IPA}(\mathbf{r}, \mathbf{r}', \omega)$ and a self-consistent field $V^{SCF}(\mathbf{r}',\omega)$. To obtain $V^{SCF}(\mathbf{r}',\omega)$, a set of integral equations which includes the exchange-corrected, self-energy-free potential is approximated by the local density approximation. Using this method we calculated 4d photoabsorption spectra for Xe^{n+} where n=0,1-7.

The upper figure on the right shows the calculated spectra of Xe^{3+} (resolution 500meV). The lower figure on the right shows the corresponding data [5]. Detailed discussion particularly on the global shapes of the absolute cross sections will be given in the symposium.



The upper fig. is calculated photoabsorption spectra for Xe^{3+} as a function of the photon energy in eV. The lower fig. shows the corresponding experimental one by Koizumi *et. al* [5]

References

[1] T. Hayaishi *et. al.* , J. Phys. B **17**, 3511 ('84).
[2] J. P. Connerade, J. E. Esteva, and R. C. Karnatak, *Giant Resonance in Atoms, Molecules and Solids* (Plenum, New York, '86).
[3] X. M. Tong *et. al,* Phys. Rev. A **55**,3406('97).
[4] P. Anderson *et. al,* J. Phys. B **34**, 2001('01)
[5] T. Koizumi, *et. al*, Phys. Scripta **T73**, 131 ('97)

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PHOTOIONIZATION OF HIGHLY CHARGED IONS IN AN ELECTRON BEAM ION TRAP BY SYNCHROTRON RADIATION

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Recent results achieved at the Free Electron Laser (FEL) at Hamburg, FLASH on the resonant excitation of Fe^{23+} ions by 49 eV photons [1] have shown that the combination of an electron beam ion traps (EBIT) with an FEL is a powerful method for investigating the interaction of VUV to x-ray radiation with highly charged ions (HCI). Photoionized ions generated within the trap volume by the photon beam are extracted after a suitable interaction time and guided behind the collector by an electrostatic 90° deflector towards a Wien-type velocity filter. A position sensitive microchannel plate detector is used to count the extracted ions in the different charge states with high efficiency. The preparation of the HCI target and the overlapping of the photon beam with it, as well as the diagnostics of the photoionized ions generated are sketched in Figure 1. Current experiments at the synchrotron facility BESSY are exploring now Fe an Ar ions in the photon energy range from 50 to 180 eV.

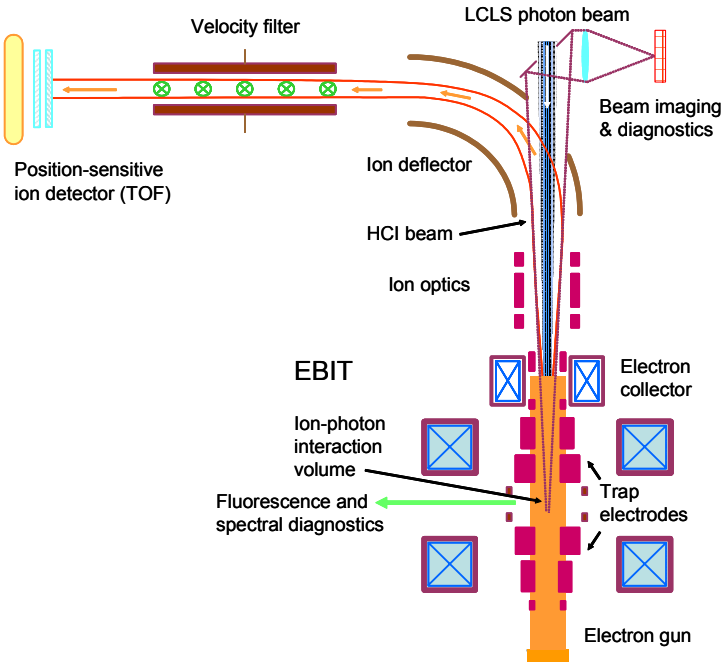

Fig. 1. Experimental setup for photoionization studies in an EBIT.

References

[1] S.W. Epp, J. R. Crespo López-Urrutia, G. Brenner, V. Mäckel, P. H. Mokler, R. Treusch, M. Kuhlmann, M. V. Yurkov, J. Feldhaus, J. R. Schneider, M. Wellhöfer, M. Martins, W. Wurth, and J. Ullrich, Phys. Rev. Lett **98**, 183001 (2007)

LOWLY IONIZED Ar AND Xe PLASMA DIAGNOSTICS AND MODELING

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Collisional-Radiative (C-R) models are needed both for non-equilibrium plasma diagnostics and for modeling. For diagnostics, non-intrusive emission spectroscopy allows for evaluation of the local electronic temperature and density; it also provides information on the constituents and the most important processes encountered in the plasma. For plasma modeling, a substantial amelioration of the codes is obtained by coupling the C-R statistical equations with the basic model equations [1].

We have developed and used various C-R models for diagnosing and modeling of Ar and Xe plasmas in existing propulsion [2] and fusion [3] devices. Moreover, the optical emission of Ar and Xe plasmas in dielectric barrier discharges was registered and compared with the theoretical spectra coming from our models [4]. C-R models containing the ground state and a number of excited levels of the ionized states were used previously for studying the I, II and III spectra of Ar and Xe. Multiplets of the IV and V spectra have also been included in our C-R models. Although these models were able to reproduce the more intense lines of the plasma, lesser lines were sometimes absent, because the corresponding configuration levels were not included in the model.

To improve the theoretical spectra, additional transition probabilities $A_{i,j}$ have been calculated and introduced in the models, as they play an essential role in emission spectroscopy, together with the excitation-desexcitation cross sections. Our calculations use a Coulomb Approximation (CbA) code [5] and the *ab initio* code contained within the SUPERSTRUCTURE package developed at University College [6]; the obtained data are compared with evaluated sets from NIST [7]. Special attention was given to transitions involving the lower metastable levels $1s^3/1s^5$ of the Ar and Xe ($4s$ and $6s$ configurations). Transitions involving the $4s - 4p$ and $4s - 5p$ multiplets of the Ar I and the $6s - 6p$ and $6s - 7p$ multiplets of the Xe I spectra are very important for various low temperature applications, as they often lead to the most intense Ar/Xe I visible lines.

References

[1] A. Dezairi, D. Saifaoui, K. Katsonis, M. Samir, M. Eddahby, Ch. Berenguer, ICPDP5 Conference, Azores (2008)
[2] K. Katsonis, J. Bonnet, D. Packan, Ch. Berenguer, R.E.H. Clark, M. Cornille, G. Maynard, IEPC Conference, Florence (2007)
[3] K. Katsonis, D. Zhang, Ch. Berenguer, R.E.H. Clark, M. Cornille, WEGA Team, EGAS 38 Conference, Ischia (2007)
[4] Ch. Berenguer, K. Katsonis, M. Cornille, M. Ganciu, C. Boisse-Laporte, SPPT23 Conference, Prague (2008)
[5] see D.R. Bates, A. Damgaard, *Phil. Trans. Roy. Soc. (London)* **A242** 101 (1949)
[6] W. Eissner, M. Jones, H. Nussbaumer, *Compt. Phys. Commun.* **8** 270 (1974)
[7] http://physics.nist.gov/cgi-bin/AtData/main_asd

EFFECTS OF DEBYE PLASMAS ON THE RESONANCE STATES OF HIGHLY STRIPPED TWO-ELECTRON IONS USING THE STABILIZATION METHOD*

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The effects of screened Coulomb potentials in atomic or molecular processes have become an active and relevant search topic in the recent years ([1-4], references therein). Recently, we have initiated resonance state calculations ([3-4], references therein) on different atomic and molecular systems under the influence of screened Coulomb potentials. In the present work, we investigate the resonance states of two-electron atoms, Mg^{10+} and Si^{12+} interacting with screened Coulomb potentials of the form : exp(-μr)/r, where μ is called the Debye screening parameter (μ=1/ λ_d, λ_d the Debye length). We employ highly correlated exponential basis functions, supported by a widely used quasirandom process [1,3] of the form $\varphi_i = r_1^L P_L(\cos\vartheta)\exp[-(\alpha_i r_1 + \beta_i r_2 + \gamma_i r_{12})] \pm$ exchange, for S-, P- states calculations, whereas for D-wave resonance calculations, we employ CI-type basis functions with certain approximations [4]. The stabilization method [5], a simple and powerful technique that needs only L^2 type basis functions, is used to extract resonance energies (E_r) and widths (Γ). We have obtained several doubly-excited *S*-, *P*- and *D*- waves resonance states of the proposed systems for each μ, below the *n*=2 thresholds of the respective two-body subsystems. In Fig.1, we present lowest S- and D-wave resonance widths of Mg^{10+} and Si^{12+} as functions of μ.

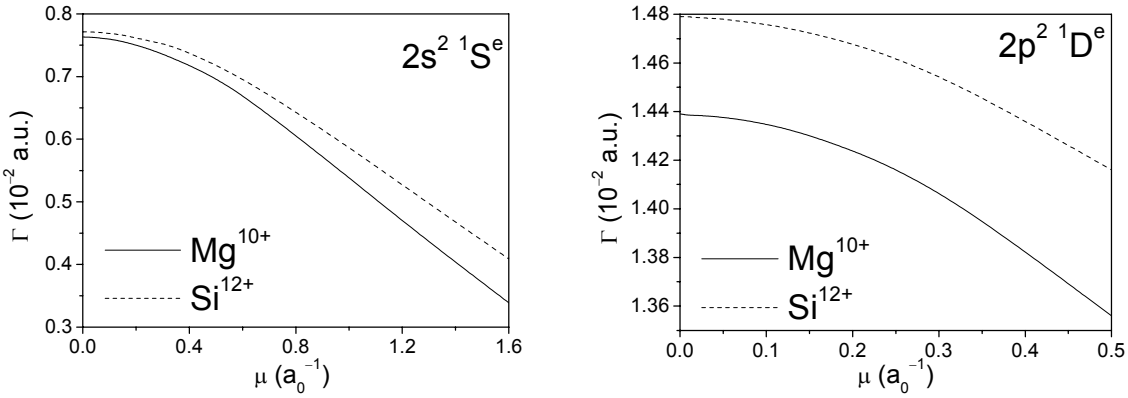

Fig. 1. Lowest S- and D- waves resonance widths of Mg^{10+} and Si^{12+} in terms of μ.

References

[1] S. Kar, Y. K. Ho, *Chem. Phys. Lett*. **424**, 403 (2006); **449**, 246 (2007); *Phys. Rev. A***77**, 022713 (2008); *Phys. Plasmas* **15**, 013301 (2008); *Phys. Lett. A* **372**, 4253 (2008); *JQSRT* **109**, 445 (2008).

[2] L Zhang, P. Winkler, *Chem. Phys*. **329**, 338 (2006); A.N. Sil, *et al. JQSRT* **109**, 873 (2008).

[3] S. Kar, Y. K. Ho, *Phys. Rev. E* **70**, 066411(2004); *Chem. Phys. Lett.* **402**, 544 (2005); *J. Phys. B* **39**, 2445 (2006); Phys. Rev. A **75**, 062509 (2007); **73**, 032502 (2006); **72**, 010703 (R) (2005).

[4] S. Kar, Y. K. Ho, *Phys. Scr.* **75**, 13 (2007); *Int. J. Quantum Chem.* **108**, 1492 (2008).

[5] V. A. Mandelshtam et al. *Phys. Rev. Lett.* **70**, 1932 (1993); S. S. Tan, Y. K. Ho, *Chin. J. Phys.* **35**, 701 (10997); S. Kar, Y. K. Ho, *J. Phys. B* **37**, 3177 (2004); *Euro. Phys. J. D* **35**, 453 (2005).

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PROBING ELECTRONS AND IONS IN STAGNATION LAYERS AT THE COLLISION FRONT BETWEEN COLLIDING LASER PRODUCED PLASMAS

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The domain of laser produced plasmas has been an active area of research since first studies in the 1960's and has spawned a wide range of applications such as Pulsed Laser Deposition [1], Inertial Confinement Fusion [2], Particle Accelerators [3], X-Ray lasers [4] and other light sources such as tin plasmas for EUV Lithography [5]. We have used an optical Nomarski laser interferometer to determine the evolution of the electron density profile for laterally colliding laser produced plasmas at early times in the plume life cycle (<100ns). We have also employed a framing camera and optical spectrometer coupled with a gated CCD (ICCD) to track ions with different charge states at the collision front between the two colliding laser produced plasmas in synchronisation with the electron density distributions. High time resolution has permitted us to observe the earliest phases of the plasma – plasma interaction. In particular we observe the formation of tightly confined structures in the electron density maps close in time to the optical emission from the optical emission from ion stagnation. We take this as the first signature of stagnation at the midplane.

References

[1] A Buzas et al., Jour. Phys. D - Appl. Phys., **41** 8 (2008)

[2] J Badziak et al., Plas. Phys. & Cont. Fus., **49** 12B 651-666 (2007)

[3] S S Bunalov et al., Med. Phys., **35** 5 1770 - 1776 (2008)

[4] Y Takemura et al., Jap. Jour. Appl. Phys., **47** 4 2275-2278 (2008)

[5] P Hayden et al., Jour. Appl. Phys., **99** 9 (2006)

TWO-PHOTON TRANSITIONS IN THE HE^+ ION EMBEDDED IN STRONGLY COUPLED PLASMAS*

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There has been considerable interests in the investigations of atomic processes for atoms/ions embedded in weakly coupled plasmas (Ref. [1] and references therein). In this work, we extend our investigations to study ions immersed in strongly coupled plasmas. Here, we report an investigation of two-photon transitions in the He^+ ions embedded in strongly coupled plasmas. We employ the Ion-Sphere (IS) Model [2] to simulate the plasmas effect on the embedded ions. The Hamiltonian of the system, with energy expressed in Rydberg units and Z=2, is

$$\left[-\nabla^2 + V(r)\right]\ \Psi(r) = E_0 \Psi(r) \tag{1}$$

with $$V(r) = -\frac{2Z}{r} + \frac{(Z-1)}{R}\left[3 - \left(\frac{r}{R}\right)^2\right] \quad \text{and} \quad R = \left[\frac{(Z-1)}{4\pi n_e/3}\right]^{1/3} . \tag{2}$$

Here, R is the radius of the IS sphere, and n_e is the number density of the electrons in the IS sphere. We use B-spline to represent the wave functions. The dimensionless transition amplitude, calculated using the pseudo state method and following the diplole selection rule, is given by

$$D_1 = \frac{1}{2}\sum_{np}\ \left[\frac{1}{E_{np} - E_i - \omega} + \frac{1}{E_{np} - E_f + \omega}\right] R_{1s}^{np} R_{2s}^{np} \ , \qquad \text{with} \qquad R_{ks}^{np} = \int_0^R dr r^3 \chi_{np} \chi_{ks} \, , \tag{3}$$

where χ_{ks} are the bound S-states and χ_{np} are the intermediate *P*-wave states; ω is the energy in Rydbergs for one of the two photons. E_i, E_f, and E_{np} are the energies for the initial *S*-state, final *S*-states, and the intermediate *P*-states respectively. In Figure 1, we present absorption coefficients $|D_1|^2$ for the 1*s*-2*s* and 1*s*-3*s* transitions for R=2.0 and 6.0 a.u., respectively. It is seen that resonant enhancement occurs in both cases, and a transparency frequency appears in the 1*s*-3*s* transition.

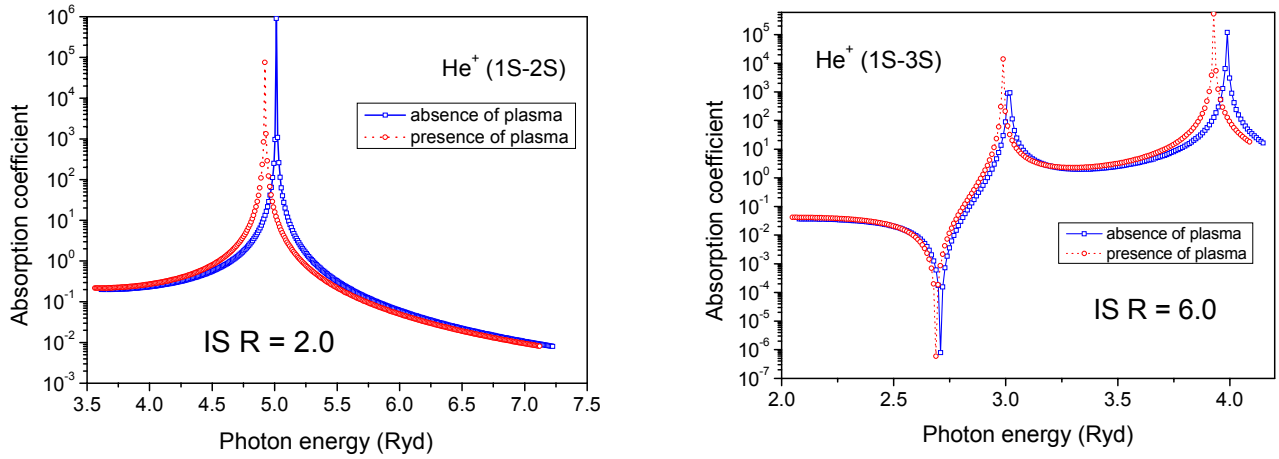

Fig. 1. Two-photon 1*s*-2*s* and 1*s*-3*s* transitions in the He^+ ion embedded in strongly coupled plasmas simulated by the Ion-Sphere model.

References

[1] L. B. Zhao and Y. K. Ho, *Phys. Plasmas* **11,** 1695 (2004); A.Yu and Y. K. Ho, *Phys. Plasmas* **12,** 043302 (2005); S. Sahoo and Y. K. Ho, *Phys. Plasmas* **13**, 063301 (2006); S. Kar and Y. K. Ho, *Phys. Plasmas* **15,** 013301 (2008).

[2] S. Ichimaru, *Rev. Mod. Phys.* **54**, 1017 (1982).

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ATOMIC PROCESSES OF DAMDE ON BIO-MOLECULES IRRADIATED BY XFEL

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The analysis of three-dimensional structure of single bio-molecules has lately attracted considerable attention for the application of x-ray free electron lasers (XFEL) [1, 2]. This analysis comes from diffraction patterns, which are produced from the irradiation of XFEL onto the bio-molecules. However, the x-ray flux required for this analysis is so large that the bio-molecules are damaged, that is, the atoms in the bio-molecules are more often ionized. This damage appears as noise for the analysis of the three dimensional structure. Therefore, it is indispensable to estimate the damage.

We treat C, N, O atoms which are the main elements of bio-molecules and some atomic processes such as photo-ionization, Compton scattering, Auger, electron impact ionization, and radiative transitions. The atomic data of Auger and radiarive transitions are shown in Ref. [3]. By the application of the atomic data of these processes to rate equations, we have calculated the change of electronic states or charge numbers as a function of times for various parameters such as x-ray flux, x-ray pulses, and wavelength of XFEL the size of bio-molecules .

Figures 1 (a) and (b) show the change of charge number of C as a function of time for the wavelength of 0.1 nm and 0.1 nm of XFEL, respectively. The x-ray flux, pulse of XFEL and the size of bio-molecules are 10^{22}/pulse/mm^2, 10 fs, and 20 nm, respectively. We have found that shorter wavelength produce smaller damage. In our presentation, we will show the results for various parameters and suitable parameters for the experiment of diffraction pattern of bio-molecules.

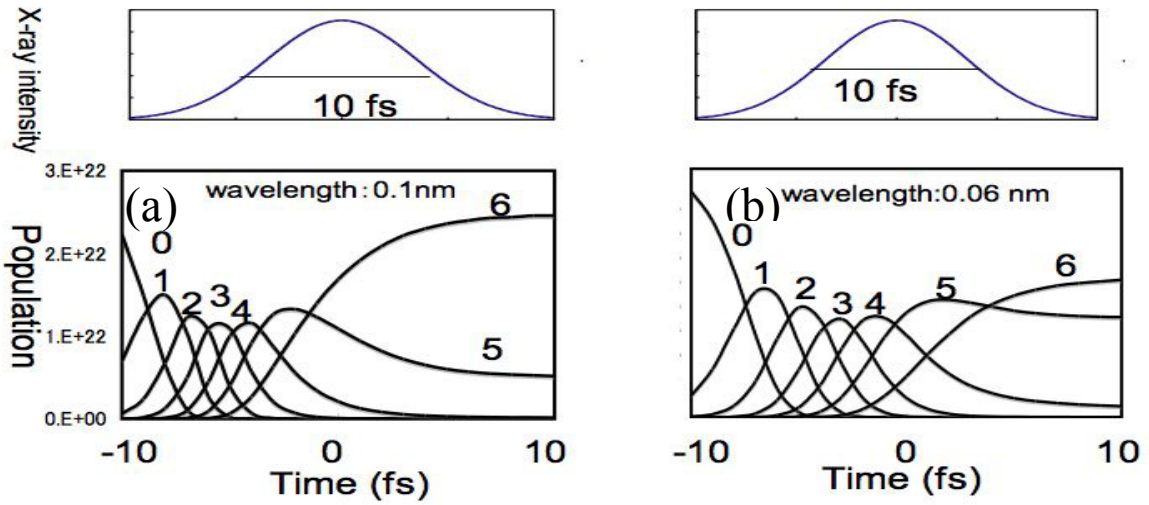

Figure 1 Population of charge number of C vs. time for the wavelengths of (a) 0.1 nm and (b) 0.06 nm, respectively.Upper figure shows the x-ray intensity. The pulse, flux of x-rays, and the size of bio-molecules are 10 fs, 10^{22} /pulse/mm^2, and 20 nm, respectively. The figures shown here are charge numbers.

References

[1] Neutze R, Wouts R, Spoel D, Weckert E, and Hajdu J, Nature, **406**, 752 (2000).
[2] Hau-Riege S P, London R ., Szoke A, Phys.Rev.E, **69**, 051906 (2004).
[3] K. Moribayashi, J. Phys.B, **41**, 085602 (2008).

Progress of Opacity Experiment on “Shengguang II” Laser Facility

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Abstract

The x-ray opacities of hot, dense plasmas have long been of interest due to their important and urgent need in studies of inertial confinement fusion (ICF), x-ray lasers and astrophysics. Theoretical calculations of opacities are quite complex and usually include numerous approximations. Therefore, experimental measurement of opacity is very important to verify the theoretical models. Many measurements of opacity with sample temperature of lower than 60eV had been done in laboratories during the past decades with the advent of high power laser. In recent years, a serials of opacity diagnostics have been developed at Research Center of Laser Fusion in China. The ninth laser beam has also been established on the “Shengguang II” eight-beam high power ns laser facility, which has duration of about 100ps and can be used as a short pulse backlighting beam in the opacity experiment. Two types of cavity(connical cavity called as type I target, and cylindrical cavity with foam baffle called as type II target) were designed to convert the eight-beam laser into x-ray radiation to efficiently heat the sample and to prevent the sample from irradiation of the reflected laser. The typical opacity experiments have been carried out on “Shengguang II” laser facility. It was shown that the sample temperature of about 95 eV has been reached using the type II target which is much higher than that using the type I target. The type II target can be further used in the opacity experiment for high temperature plasmas in future.

THEORETICAL AND EXPERIMENTAL RESEARCH OF ION CHARGE STATE EVOLUTION IN ELECTRON BEAM ION TRAP

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An Electron Beam Ion Trap (EBIT) is a device, which can be used both as a highly charged ion (HCI) source and as a HCI light source for various kind of research. As an ion source, it can basically provide ions of any possible charge state and of any element, for ion surface studies, for ion atom, ion electron, and ion photon collision studies. As a light source, EBITs can basically provide light from visible to X-ray region again from all charge states of all elements. A detailed understanding of the factors determining charge state distribution, ion temperatures etc. in an EBIT device are very important in planning experiments. Adjusting operating parameters such as electron beam energy, electron beam current, magnetic field strength, axial trapping potential, injection density and so on can be facilitated by such an understanding. This requires considerable knowledge of the numerous physical processes taking place in the trap region of an EBIT, such as ionization, recombination, charge exchange, heating, evaporative cooling and ion escape.

In this paper, we will discuss a theoretical simulation on charge state distribution and temperature evolution of the ions in an EBIT. The simulation took into account the main processes in EBIT: electron impact ionization of ions, radiative recombination, muticharge exchange between ions and neutral atoms, electron beam collision heating, ion-ion energy transfer, ion confining and ion escaping from the trap (including radial escape and axial escape), energy escaping from the trap due to the ion escaping, and electron beam space charge neutralization by traped positive ions. The simulations results showed sawtooth oscillation [1], sine oscillation [2] and more normal behaviour of the ion density evolution.

To test the theoretical simulation, experiments were designed and performed at Shanghai EBIT. The time dependent spectra of Xe and Kr ions with Xe-Kr gas mixture injection, and the time dependent spectra of Au ions with Au MEVVA injection were taken. Comparisons between the experimental and theoretical results will be presented and discussed in the paper.

References

[1]R. Radtke and C. Biedermann, Phys. Rev. A **67**, 032505 (2005).
[2]W. Hu *et al*, Can. J. Phys. 86, 321 (2008).

Simulation of electron beam in Shanghai EBIT

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Electron Beam Ion Traps (EBIT) are sophisticated devices capable of acting both as highly charged ion (HCI) light sources and ion sources. Because the HCIs produced in an EBIT are moving at much lower speed comparing with those produced in heavy ion accelerators, so much less bothered with Doppler shifts and spectral line broadening which is a very good character for spectroscopic research. Because of the flexibility in producing various ions with an EBIT, it is a very powerful tool for studies along iso-electronic and iso-nuclear-charge sequences to reveal the underlying physics behind many physical properties.

For the purposes of guiding operation of EBIT at optimum condition, we made simulations of the electron beam trajectories in Shanghai EBIT, with TRICOMP, a patch of codes from Field Precision Company. The electric and magnetic fields along the electron paths are calculated using finite-element method. Space charge effect and relativistic correction are considered during the simulation. A systematic study was made based on the simulation, for various operation conditions. Fig. 1 shows an example of the resulting intensity distribution of the electron beam in the central drift tube, with an electron beam of 6KeV, and 33mA confined by a magnetic field of 3T, the cathode temperature kT=0.1eV, and the cathode magnetic field Bc=0. The half width at half maximum of the relative current density distribution indicates a radius of about 30 micro meter for the electron beam. This result agrees with the result from a beam imaging experiment at the same condition. More results and discussions will be presented in the paper.

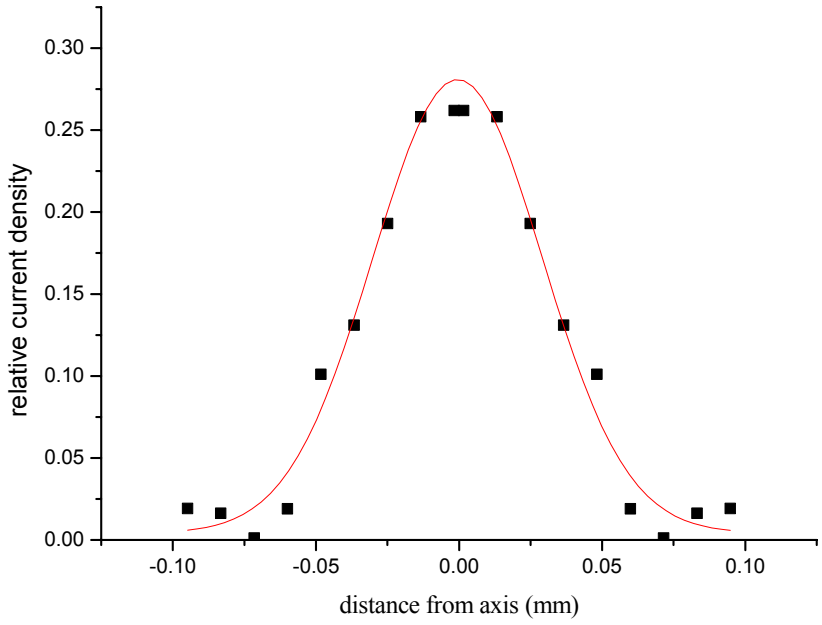

Figure 1 the electron beam current density versus beam radius

A tandem linear Paul trap as an ion source

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A linear Paul trap has been widely used for research. For examples, it is put into practical use as a mass spectrometer. By using laser cooled ions loaded in the trap, frequency standards[1] and quantum computers[2] are studied. Furthermore, the apparatus is used to study the motion of an ion plasma in a linear Paul trap which corresponds to beam dynamics of charged particles propagating through a periodic magnetic lattice[3,4]

Here, we investigated a possible application of a tandem linear Paul trap as an ion source. Compared with highly charged ion sources like electron cyclotron resonance ion source(ECRIS) and electron beam ion source(EBIS, EBIT), a tandem linear Paul trap is quite compact and inexpensive. It can generate ions without intense magnetic field and microwave.

The ion source is composed of three linear Paul traps. Each trap plays a role of generating ions, gate and mass filter. Argon ions were created in the trap by collisions with electrons emitted from an electron gun. The electron energy was $\sim$ 130 eV These ions pass through the gate as a pulsed beam. The filtered ion number is detected by Faraday cup. It was observed that Ar^{+} ions were produced about 6×10^{6}/pulse and Ar^{2+} ions 6×10^{4}/pulse. Confinement times were also measured to evaluate the ion production process

Also a tandem linear Paul trap has a possibility to be a nano-ion beam source. It is known that laser cooled ions form string crystals in a linear Paul trap containing several Ca^{+} ions. The ion crystals extracted from the trap can be a nano-ion beam with ultimately low emittance[5]. Furthermore, it is possible to produce and confine highly charged ions simultaneously with laser cooled Ca^{+} ions in a tandem linear Paul trap. The precise measurement of cold highly charged ions will be made easier with the use of a tandem linear Paul trap.

References

[1] D. J. Berkeland, J. D. Miller, J. C. Bergquist, W. M. Itano, and D. J. Wineland, Phys. Rev. Lett **80**, 2089 (1998).

[2] J. I. Cirac and P. Zoller, Phys. Rev. Lett. **74**, 4091 (1995).

[3] H. Okamoto and H. tanaka, Nucl. Instum. Methods Phys. Res. Sect. A **437**, 178 (1999).

[4] H. Okamoto, Y. Wada, and R. Takai, Nucl. Instum. Methods Phys. Res. Sect. A **485**, 244 (2002).

[5] M. Kano, S. Masuda, A. Ogata, K. Okabe, and H. Okamoto, J. Phys. Soc. Jpn. **73**, 760 (2004).

THE SPARC EBIT AT GSI; COMISSIONING AND FUTURE PLANS AT THE HITRAP BEAMLINE

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A small permanent magnet EBIT (Dresden EBIT [1]) has been installed at GSI to serve as an offline test ion source for the HITRAP project [2] and for use as a test setup for charge breeding explorations. The EBIT is named 'SPARC EBIT' as it will also be used as a test facility for instrumentation under development for the SPARC collaboration [3]. We describe some results of the initial conditioning of this source. X-ray spectra and TOF measurements confirmed the production of highly charged ions up to Ar^{18+} in the trap.

Charge breeding in the EBIT is also being investigated. Singly charged ions will be externally injected from a surface ion source and subsequently trapped in the EBIT and ionized. Simulations of the ion injection and extraction have been performed using SIMION. In the course of 2008 the EBIT will be transferred to the HITRAP beamline and will serve as an offline source for the various HITRAP experiments currently being prepared at GSI [4].

We also describe initial results from a program of atomic physics experiments designed to measure cross sections of charge changing reactions, i.e. ionization, dielectronic recombination, in the trap region via observations of the emitted x-ray spectra and charge balance of extracted ions.

References

[1] G. Zschomack et al., Rev. Sci. Instrum. **77** (2006) 30A904; http://www.dreebit.com
[2] Th. Beier et al. (Eds.), HITRAP Technical Design Report, GSI,Darmstadt, 2003, http://www.gsi.de/documents/DOC-2003-Dec-69-2.pdf;
T. Beier et al., Nucl. Instrum. and Meth. B **235** 473 (2005)
[3] Th. Stöhlker et al., Nucl. Instrum. and Meth. B **261**, 234 (2007)
[4] H-J. Kluge, W. Quint, D. F. A. Winters, J. Phys. Conf. Ser. **58**, 9 (2007)

DEVELOPMENT OF HIGH CURRENT ELECTRON BEAM ION TRAPS FOR CHARGE BREEDING OF RADIOACTIVE ION BEAMS

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Experiments with reaccelerated ion beams are planned in several rare isotope beam facilities. Radioactive rare isotope beams at energies ranging from a few hundreds of keV/amu to more than several MeV/amu are needed e. g. for studying key reactions related to nucleosynthesis in astrophysics, and the structure of nuclei far from stability. Rare isotopes produced by the interaction of powerful proton beams with heavy targets are normally extracted from the bulk by fast thermal and diffusion processes, yielding a cocktail of atoms which are subsequently ionized, mass selected and accelerated. Stripping those ions by means of foils allows raising their charge state before further acceleration steps. However, this method does not achieve optimum yields, and emittance can be rather poor, leading to severe ion losses. An additional step of charge breeding (e.g. in an electron beam ion trap) eliminates the need for conventional electron stripping with the corresponding detrimental effects on the efficiency and the collateral radioactive contamination problems. It also enables simpler accelerator design by aiming at well defined values of the *q/m* ratio, thus reducing its size and cost. A successful EBIS charge breeder for reacceleration has been demonstrated (REX-ISOLDE at CERN). The new generation of electron beam ion traps developed at the Max Planck Institute for Nuclear Physics in Heidelberg [1-3], one of which is undergoing testing in combination with a precision Penning trap for mass measurements at the ISAC facility (TRIUMF), and the future high current EBIT currently being developed in collaboration with the NSCL (MSU) will permit to further develop this method aiming at improving the yield and emittance of rare isotope beams and reducing the charge breeding time as far as needed for the study of short lived radioactive isotopes.

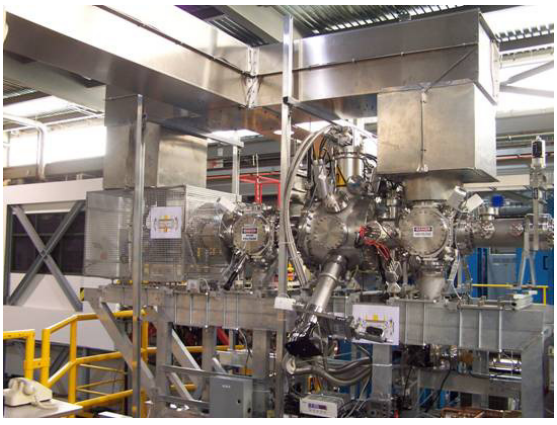

Fig. 1. The TRIUMF-EBIT installed at its stand in the TITAN facility.

References

[1] J. Dilling et. al, Nucl. Instrum. Methods B **204**(2003)492
[2] G. Sikler *et al.*, Eur. Phys. J. A **25**(2005)63
[3] J. Dilling *et al.*, Int. J. Mass Spec. **251**(2006)198

ELECTRON BEAM DENSITY DISTRIBUTION STUDIES USING AN PORTABLE SLIT IMAGING SLIT IMAGING SYSTEM AT THE SHANGHAI ELECTRON BEAM ION TRAP

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In an Electron Beam Ion Trap (EBIT), the density of the electron beam together with electron energy determines the rates of the main physical processes occurring in the trap region. The density of the electron beam is in turn determined by its size, profile and current. In this work, a portable slit imaging system was developed, and used to study the electron beam size and profile of the newly developed Shanghai EBIT. The fluorescence of the ion cloud in the EBIT were detected by a charge coupled device (CCD) sensitive to both visible light and X-rays rather than position sensitive proportional counter for higher resolution [1]. A large scale ray tracing was done for corrections of finite slit width of the slit imaging system and the finite pixel size of the CCD detector. A numerical de-convolution method was developed to analyze and reconstruct the electron beam density distribution in an EBIT.

FIG. 1 shows an image of the electron beam in the trap area recorded using the slit imaging system, at electron beam energy of 81 KeV and current of 80 mA under 3 T magnetic field. We attached a Be window to cover 2/3 of the surface of the CCD chip, and could get the image with only X-ray exposure and the image with both X rays and visible light exposure in a single run. In FIG. 1 the area above the arrow is from all wavelengths exposure, below the arrow is from pure X-ray exposure (from the part where the CCD was covered with the Be window). We can see clear difference both in width and intensity. The causes of the differences, as well as the inference of the fluorescence wavelength region on determination of the electron beam diameter, will be discussed in the paper.

The experiments were done at the electron energies of 100 keV, 81 keV, 50 keV, and 20 keV, with several different electron beam currents at each beam energy. The purpose was to study the energy and current dependence of the electron beam diameter, and hence the current density. The results will be displayed and discussed in the paper.

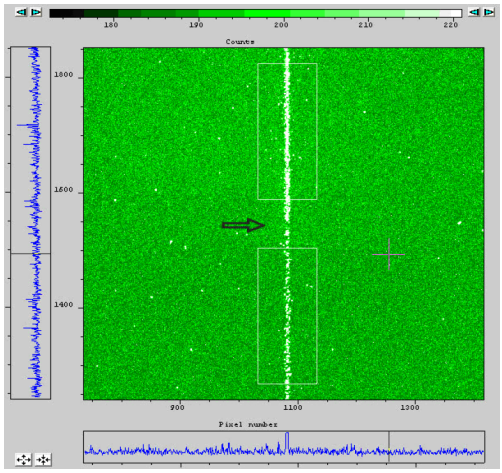

FIG. 1: An image of the ion cloud in the Shanghai EBIT taken using the slit imaging system, with an electron beam of energy of 81 keV and current of 80 mA.

References

[1] S. B. Utter, P. Beiersdorfer, J. R. C. L´opez-Urrutia, and K.Widmann, Nucl. Instr. and Meth. A 428, 276 (1999).

The multi-parameter data acquisition system at shanghai EBIT

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A multi-parameter data acquisition system (DAQ) for the collision platform has been established at shanghai EBIT. The system is based on VME modules; and fast electronics were used here. The software for the DAQ is written in C language. In the experiment, the multi-coincidence measurements are performed in event by event mode and all data is recorded in list mode. For the first application, a delay-line position sensitive detector [1] has been test with the electronic and DAQ. The signals from the MCP and delay-line are firstly amplified and discriminated by the fast amplifier and the constant fraction timing discriminator. And then the signals are sent to the TDC [2]. The results show that the total time resolution for the system is better than 1 ns and the dead time is shorter than 10 ns. All the tests show that the DAQ system is qualified for the future experiments.

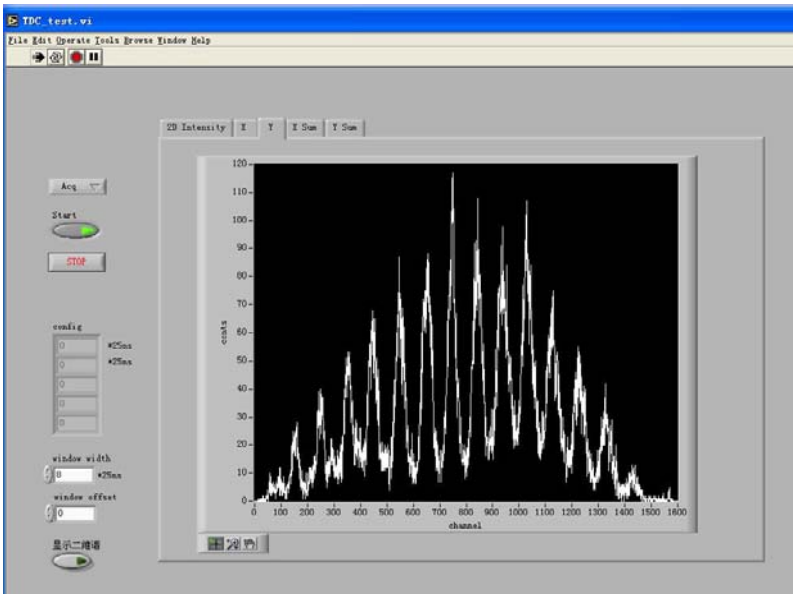

Fig. 1 The work space of the software, which shows the time of flight of each channel, and also the 2 dimensional information according to your command.

References

[1] O. Jagutzki, V. Mergel, K. Ullmann-Pfleger, *et al*, Proc. SPIE 3438 (1998) 322
[2] Mod. V1290A/N.32/16 Ch. Multihit TDC, User's Manual, Revision 6. CAEN

A Progress Report of 320 Kv Multi-Discipline Research Platform For Highly Charged Ions

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The interactions between highly charged ions and materials (atoms, molecules, clusters, surfaces, and bio-molecules, etc) have attracted more and more interests not only in fundamental researches but also in many application fields [1]. The low energy highly charged projectiles are usually provided by ECRIS, where their extraction voltage is below 50 kV. EBIS can provide even higher charge state ions but relatively low beam intensities. A dedicated beam-line for highly charged ions interaction with materials has been constructed at the Institute of Modern Physics (IMP) in Lanzhou, where the projectile energy is extended to 320q keV (where q is the projectile charge). The dynamical range of the projectile velocity will be from 0.1 a.u. to 2 a.u. covering electron capture dominant channel to ionisation dominant channel.

A permanent magnet ECR ion source which sits on the high voltage platform was constructed as shown in figure 1. The ion source can produce various charge states of atoms in the periodic table. The maximum high voltage applied to the platform is designed to 320kV. The beam lines are equipped with five experimental terminals [2]: for (1) surface studies, (2) atomic physics research (collision dynamics as well as spectroscopy with atomic or molecular target beams), (3) multi-purpose experimental terminal, the design is flexible and allows the external users to bring their own set-ups for experiments, (4) material science, and (5) biophysics searches, respectively.

The commissioning of the beam-line has been carried out successfully. Highly charged ions such as Ar^{13+} and Xe^{30+} has been provided for radiation damage studies and surface experiments. Presently the voltage applied to the platform has reached 200 kV.

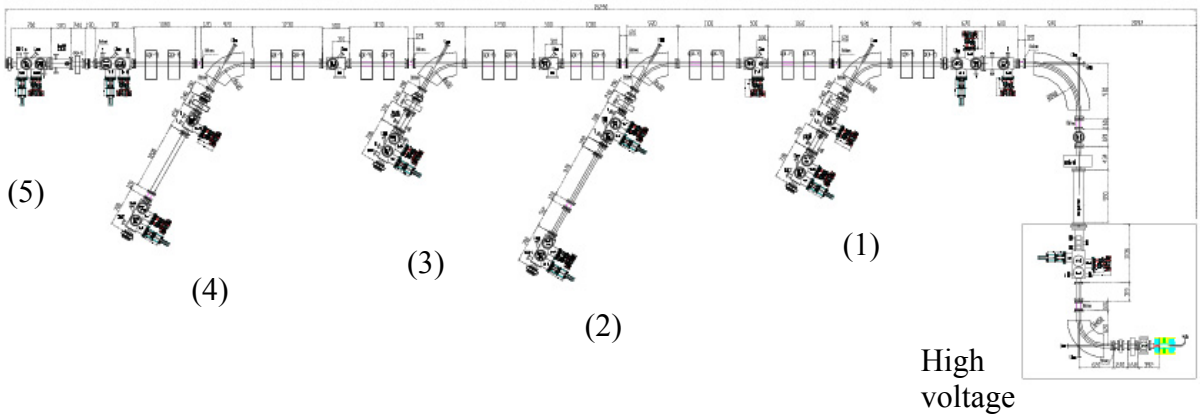

Fig. 1 layout of the high voltage platform and equipped experimental terminals

References

[1] H. Schmidt-boeking, et al., in AIP conference proceedings, 604, pp120
[2] L. T. Sun, H. W. Zhao, et al., Rev. Sci. Instr. 77 (2006)1
[3] X. Ma, X. L. Zhu, et al, Sciences in China (Series G) 38 (2008)1

Evolution of X-ray Calorimeter Spectrometers at the Lawrence Livermore Electron Beam Ion Trap

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High-resolution broadband, non-dispersive x-ray spectrometers have been under development for spaceflight since 1984. As an offshoot of the significant NASA investment in this technology, we have developed a series of calorimeter instruments for laboratory use and installed them at the Electron Beam Ion Trap (EBIT) facility at the Lawrence Livermore National Laboratory. Coupled with dispersive instruments at the facility, the calorimeter instruments have made significant contributions to our laboratory astrophysics program. Our laboratory astrophysics program involves benchmarking the spectral synthesis codes and the underlying atomic physics calculations that are used to model high-resolution x-ray spectra obtained with current and future x-ray observatories. The calorimeter instruments at EBIT have significantly enhanced our capabilities to study the physics of highly charge ions including broad band measurements of emission from charge exchange recombination and absolute cross sections for collisional excitation.

The first GSFC calorimeter instrument was installed at the EBIT facility in July of 2000 and has seen two major and a number of minor revisions since then. The performance of the instrument has significantly improved with time from the initial instrument that had a resolving power of ~500 at 6 keV, and essentially no quantum efficiency at energies above 20 keV, to the current instrument that has a resolving power of 1350 and 95% quantum efficiency at 6 keV, and a resolving power of 1800 and 32% quantum efficiency at 60 keV. The advances in resolution are especially apparent at lower energy, where, for example, O VII Kβ at 665 eV evolved from a distinguishable “shoulder” on the high-energy side of O VIII Lyα, to a well resolved line. These improvements have significantly increased the scientific yield of the calorimeter instrument at both high and low energies. We discuss the improvements in the instrument performance and the significant impact on the science yield at EBIT.

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THE MEVVA SOURCE ION INJECTION AT THE SHANGHAI EBIT

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A MEVVA ion source was installed to the Shanghai EBIT for metallic ion injection in July 2005. To achieve successful injection of lowly charged ions to the trap region of the Shanghai EBIT, two improvements have been done on the MEVVA source.

First is to improve the work efficiency of the MEVVA source. The performance of the original MEVVA source was unstable because of the loose installation of the cathode, trigger and the insulator between them. It was vacuum discharge between the cathode and trigger while the MEVVA source was running. We modified the construction of the trigger, guaranteed tight assembly of the MEVVA cathode, trigger and the insulator, and coated graphite on the insulator surface to reduce its insulation. Therefore the surface discharge, which is much more stable, would occur along the insulator's surface. In this way, the efficiency was improved to provide enough lowly charged ions for experiments.

Second is to improve the ion injection efficiency. The electron collector of the Shanghai EBIT is located between the MEVVA source and the trap region. The injected ions from the MEVVA source must find a way passing through the collector. The collector could be regarded as an einzel lens, and its potential, which is mainly determined by the electron beam energy, would affect remarkably the trajectories of the injected ions. To get better ion injection efficiencies, some parameters, including the potentials of the extractor and the einzel lens of the MEVVA source, should match appropriately with the electron beam energy. We simulated the ion injection processes under different electron beam energies by SIMION program, and got the appropriate parameters of the extractor and the einzel lens of the MEVVA source under different electron beam energies. These numerical results guided us to get better ion injection efficiency in the experiments.

With these two improvements, now we can achieve better ion injection efficiency with the MEVVA source. Some experimental results of Au ion injection under different electron beam energies will be shown and discussed in the report.

A POWER SAVING AND COMPACT ELECTRON BEAM ION SOURCE USING A PERIODIC PERMANENT MAGNET SYSTEM

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Collision physics of multiply charged ion has aroused an increasing interest in relation to the fields such as astrophysics, space science, radiation physics, and plasma physics. About ten years ago, we had made a power-saving and compact "Electron Beam Ion Source (EBIS)" named "micro-EBIS" using a ring permanent magnet [1]. The charge transfer cross sections of multiply charged neon and argon ions extracted from this micro-EBIS had been measured at keV energy region [2]. This ion source had been developed to more powerful tool by Motohashi *et al*. [3]. There is another method for electron beam focusing, that is "the use of alternating magnetic field. In the 1950s, this technique had already been applied to a travelling wave tube as a microwave amplifier. Becker *et al*. proposed a "mirrored EBIS" using this periodically arranged permanent magnet system (PPM) [4], but performance of their ion source was not clear. In this work, therefore, we have constructed more compact EBIS using the PPM.

The present PPM-EBIS was consisted of an electron gun, the PPM and ion-extracting assembly. The electron beam, emitted from a barium oxide (BaO) cathode of 2.0 mm in diameter, was accelerated with the electric potential deference V_a between an anode and cathode and can be extracted up to a few mA. The PPM was constructed five ring permanent magnets (Fe-Nd-B) of 15 mm inner diameter, 25 mm outer diameter and 3 mm thick with 2 mm thick pole pieces made of SUS430. Thus the magnetic period was 10 mm and the length of axitial ion drifting region was 27 mm. Average value of maximum magnetic flux densities along the central axis of the present PPM-EBIS was observed to be 0.24 T. First pass band for stable transmission of the electron bem will be achieved at $V_a > 3$ kV.

The vacuum system was evacuated with two turbo molecular pumps and residual gas pressure was about 6×10^{-7} Pa. Extracted ions were separated with a Wien filter and detected with a channel electron multiplier or a micro channel plate. The more detailed performance of this PPM-EBIS will be reported in this conference.

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References

[1] T. Kusakabe, T. Sano, Y. Yura, T. Osaka, Y. Nakajima, Y. Nakai, H. Tawara, M. Sasao, Phys. Scr. **T73**, 378 (1997).
[2] T. Kusakabe, Y. Miyamoto, R. Ishida, K. Itoh, N. Kuroyanagi, Y. Nakai, T. Shirai, Nucl. Instr. & Meth. **B 205**, 600 (2003).
[3] K. Motohashi, A. Moriya, H. Yamada, S. Tsurubuchi, Rev. Sci. Instrum. **71**, 890 (2000).
[4] R. Becker, H. Klein, W. Schmidt, IEEE Trans. Nucl. Sci. **NS-19**, 125 (1972).

DIAGNOSTICS OF THE HIGHLY CHARGED ION BEAM EXTRACTED FROM THE TOKYO-EBIT

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At the Tokyo-EBIT [1], highly charged ions (HCIs) such as bare I^{53+} and He-like Bi^{81+} can be produced and extracted. Fig.1 shows a typical charge state spectrum of extracted Bi ions obtained with a 60 keV electron beam. By using such a slow very highly charged ion beam, we have been studying not only interactions of HCIs with surfaces [2,3] but also the resonant process in the collisions between HCIs and electrons [4,5]. However, the intensity of the beam is not always enough for some experiments. For example, guiding of HCIs with a glass capillary needs an ion current of ~1pA or more to form a charged patch inside the capillary. However, since the charge-selected beam from the Tokyo-EBIT is not enough, an unselected beam is used for the capillary guiding experiments [6]. Thus it is important to increase the ion beam current for extending the experimental subjects can be done with the Tokyo-EBIT.

In this poster, we present the diagnostics of the highly charged ion beam extracted from the Tokyo-EBIT to clarify the problem which limits the ion current and to improve it. In particular, the emittance measurements for the very highly charged ion beams produced with electron energies of up to 100 keV are presented.

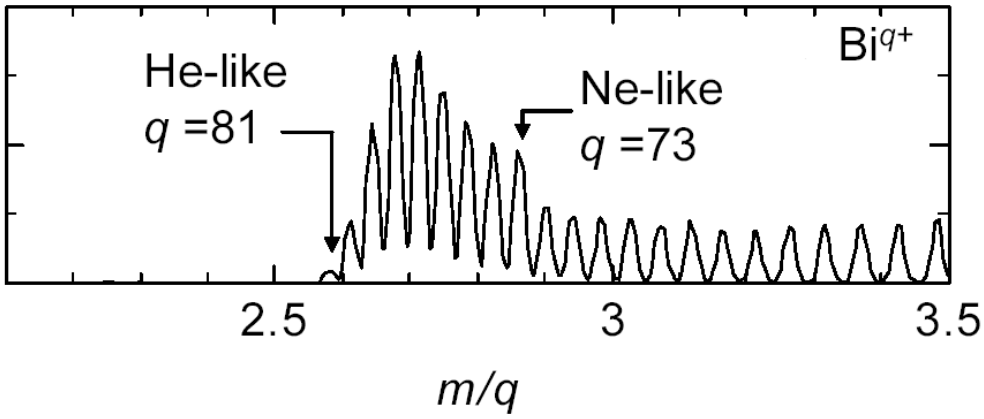

Fig.1. Typical charge state spectrum of highly charged Bi ion beam extracted from the Tokyo-EBIT at an electron energy of 60 keV.

References

[1] N. Nakamura et al., Phys. Scr. **T73** (1997) pp.362-364
[2] J. Sun et al., Phys. Rev. A **77** (2008) 032901
[3] M. Tona, Surf. Sci. **601** (2007) 723
[4] N. Nakamura et al., Phys. Rev. Lett. **100** (2008) 073203
[5] H. Watanabe, Phys. Rev. A 75 (2007) 012702
[6] A. Yamazaki et al., poster in this conference.

ENHANCEMENT OF SOFT X-RAY EMISSION FROM FS LASER PLASMA BY USING MIXTURE OF MOLECULE AND ATOMIC GASES AS CLUSTER JET TARGETS AND ITS APPLICATION FOR NANOSTRUCTURE IMAGING

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Using cluster targets allows reaching a very efficient fs laser pulses coupling with plasma. Such approach enables efficiently to produce very bright point plasma X-ray sources, to decrease the quantity of generated hot electrons and owing to the presence of debris. Unfortunately, only 10-30 % of expanded in supersonic nozzle gas could be aggregated in clusters. It means that between clusters, which good absorb laser energy and where plasma produced; also residual gas with enough high pressure presents and absorbs very efficiently soft X-ray radiation of plasma. Additional Soft X-ray radiation absorption also takes place in surrounding the laser interaction zone cold gas-cluster area. At the same time light atomic He gas has a very small absorption of soft X-ray radiation even when the density of this gas is enough high. Unfortunately pure He gas practically do not produce clusters during expansion in supersonic nozzle and it is impossible to produce intensive soft X-ray radiation using such gas. On the other hand, the presence of He gas helps clusterization of molecule gases. Obviously, it is very attractive to use the mixture of atomic He gas with some molecule gases for production of large size clusters target. Indeed, such gases combination will have the advantage of effective production of clusters due to the expansion of molecule gas in mixture with He gas and the advantage of the small absorption of soft X-ray generated in such cluster target, when it irradiates by fs laser pulses.

In this work we present the possibility of efficient production of CO_2 cluster targets by expanding mixture of 90% atomic He and 10% molecular CO_2 gases in the especially designed super-sonic nozzle. Irradiation of these clusters by a fs Ti:Sa laser pulses allows to enhance the soft X-ray radiation of He_β (665.7 eV) and Ly_α (653.7 eV) of Oxygen in 2-8 times compare with the case of using as targets pure CO_2 or N_2O clusters and reach values 2.8×10^{10} (~ 3 μ J) and 2.7×10^{10} (~ 2.9 μ J) ph/(sr · pulse), respectively. Nanostructure conventional soft X-ray images of 100 nm thick Mo foils in a wide field of view (cm^2 scale) with high spatial resolution (700 nm) are obtained using the LiF crystals as soft X-ray imaging detectors. The local inhomogeneities of soft X-ray absorption by the nanometer-thick films are measured with an accuracy of better than ± 3%. It was demonstrated that at the distance about 50 cm from such soft X-ray source the spatial coherence in the spectral range 1 – 5 nm is about 1 μm. Such spatial coherence was enough to obtain high quality phase-contrast soft X-ray imaging of different biological and nano films objects.

This work was supported by the grant-in Aid for Young Scientists (B) 918740254) and for Scientific Research on Specially Promoted Research (15002013) by MEXT. Also some part of investigations were supported by the RFBR (Projects No. 06-02-16174 and 06-02-72005-MNTIa) and by the RAS Presidium Program of Basic Researches No. 9.

NARROWBAND X-RAY SOURCE FOR APPLICATIONS IN MEDICINE

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Enhancing the efficiency of cancer radiotherapy and reducing the radiation side effects are two of the possible benefits of replacing conventional broadband radiation with narrowband radiation. In binary therapy ("dual targeting"), drugs containing high-Z atoms/nano-particles (e.g., platinum or gold) are made to preferentially concentrate in cancer cells, and then the radiation wavelengths are tuned to match the x-ray photoabsorption peaks (e.g., K-edge) of the heavy elements [1, 2]. Synchrotron facilities can provide the necessary x-ray beams, but are costly and impractical for routine therapy.

A new generation of EBIS/T devices may be a suitable alternative [3]. EBIS/T devices can produce beams of slow highly charged ions (HCI) that contain enormous potential energy. The ions can be easily transported to the vicinity of the body, where they radiate relatively mono-energetic X-rays [4].

In order to achieve the highest charge states with sufficient fluences for use in medicine, a better understanding of the EBIS/T ion trap dynamics may be required. We have analyzed some recorded EUV spectra [5] to estimate number of emitting ions in the trap for charge states up to 68+.

This work is supported by NIH-NIST Research Associate Program, National Research Council, USA.

References

[1] S. Corde, et al. Radiation Research, **158**, 763-770 (2002).

[2] M. C. Biston, A. Joubert,J. F Adam, H. Elleaume,S. Bohic, A. Charvet, F. Esteve, N. Foray, and J. Balosso, Cancer Research, **64**, 2317-2323 (2004).

[3] J. D. Gillaspy, J. M. Pomeroy, A. C. Perrella and H. Grube, J. Phy. Con. Ser. **58** 451-456, (2007).

[4] A. P. Kavanagh, J. D. Gillaspy, D. G. Hirst, M. H. Mendenhall, N. Nakamura, S. Ohtani, H Watanabe and F. J. Currell, J. Phy. Con. Ser. **58** 439-442, (2007).

[5] Yu. Ralchenko, I. N. Draganic, J. N. Tan, J. D. Gillaspy, J. M. Pomeroy, J. Reader, U. Feldman and G. E. Holland, J. Phys. B: At. Mol. Opt. Phys. **41**, 021003 (2008).

The atomic model of the Sn plasmas for the EUV sources

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We study the atomic processes in the EUV light sources for the next generation microlithography. We investigate the laser produced plasma (LPP) as well as discharge pumped plasma (DPP) EUV sources for the optimization of the target and pumping conditions, in order to obtain more than 180W of power in the 13.5nm wavelengh region (2%BW), with a high efficiency (≥3%) and small source size. We develop an atomic model of multiple charged ions based on the calculated atomic data using the Hullac code. We find from the dependence of the emission wavelength of multiply charge ions, that Sn is the most efficient source material, because the wavelength of the 4d-4f transition array is in the 13.5nm band and is almost constant over a wide range of charge states (8-12). We also find that the strong 4d-4f transition array is accompanied by satellite lines from multiply excited configurations, which produce the broad emission spectrum observed from high density plasmas. We improved the wavelength of major emission lines, after detailed comparison with measurement, which is carried out based on the charge exchange spectroscopy (CXS), in which the wavelength of resonance lines of each charge state is measured independently. We calculate the emissivity and opacity of the plasma using the collisional radiative model. The atomic states and transitions, which have significant effect on the charge state distribution and spectral structure, are determined using iterative calculations. Calculated opacity of a Sn plasma is found to agree with experiment [1], and the radiation hydrodynamics simulation using the present coefficients of radiative transfer is shown to reproduce experimental conversion efficiency and spectrum. The code calculation suggests the use of low density plasmas to obtain higher conversion efficiency, because the emission spectrum becomes narrower with the reduced satellite contribution, which is verified experimentally in a CO_2 laser pumped plasmas.

References

[1] S. Fujioka, et al., Phys. Rev. Lett. 95, 235004 (2005).

Posters B
(4 September)

Posters B (Thursday, 4 September)

a) Fundamental aspects, Structure and Spectroscopy

B-a01 EUV spectroscopy of highly charged iron ions with a low energy compact EBIT
Hiroyuki A Sakaue, Daiji Kato, Nobuyuki Nakamura, Etsushi Watanabe, Norimasa Yamamoto, Tetuya Watanabe

B-a02 Measurement of the $K\beta_2$ /$K\beta_1$ ratio for heliumlike krypton
M. F. Gu, P. Beiersdorfer, A. J. Smith, D. B. Thorn

B-a03 EBIT X-ray microcalorimeter measurements of the K-shell emission from heliumlike ions
P. Beiersdorfer, G. V. Brown, H. Chen, J. H. T. Clementson, M. F. Gu, S. M. Kahn, R. L. *Kelley, C. A. Kilbourne, F. S. Porter, D. B. Thorn, E. Traebert*

B-a04 Analysis of EUV spectra from highly charged iron ions with a compact EBIT
Norimasa Yamamoto, Hiroyuki Sakaue, Daiji Kato, Izumi Murakami, Takako Kato, Nobuyuki Nakamura, Etsushi Watanabe, Tetsuya Watanabe

B-a05 EUV spectroscopy of tin and xenon ions with a compact electron beam ion trap
Etsushi Watanabe, Hiroyuki A. Sakaue, Nobuyuki Nakamura

B-a06 Charge state selective EUV spectroscopy of HCI at very low collision energies in an electron beam ion trap
Thomas M. Baumann, Jose R. Crespo Lopez-Urrutia, Sascha W. Epp, Anastasia Gonchar, Zoltan Harman, Guiyung Y. Liang

B-a07 Measurement of the bound electron g-factor in highly charged ions by double resonance spectroscopy
W. Quint, D. L. Moskovkhin, W. Noertershaeuser, V. M. Shabaev, M. Vogel

B-a08 Energy levels and oscillator strengths for transitions in Fe XIV
Kanti M Aggarwal, T Kato, F P Keenan

B-a09 Electron shake off in the beta decay of trapped $^6He^+$ ions
Xavier Flechard, Gilles Ban, Claire Couratin, Dominique Durand, Etienne Lienard, François Mauger, Alain Mery, Oscar Naviliat-Cuncic, Daniel Rodriguez, Philippe Velten

B-a10 Stability of highly charged fullerene cations and anions
Fernando Martin, Henning Zettergren, Yang Wang, Manuel Alcami

B-a11 Relativistic light shifts in highly charged ions
O. Postavaru, Z. Harman, C. H. Keitel

B-a12 Multiconfiguration Dirac-Hartree-Fock method for the calculation of static electric dipole moment in the many-electron atoms
Erikas Gaidamauskas, Gediminas Gaigalas

B-a13 The influence of relativistic effect for the DR of many electron ion
Xiaoying Han, Yueming Li

B-a14 Study of inter sub-shell and inter shell electron correlations in 4d open-shell heavy atomic ions
Fumihiro Koike

B-a15 Accurate spectroscopy of excited levels in He-like uranium
Martino Trassinelli, Ajay Kumar, Heinrich F. Beyer, Paul Indelicato, Renate Märtin, Regina Reuschl, Carsten Brandau, Harald Bräuning, Sabrina Geyer, Alex Gumberidze, Sebastian Heß, Pawel Jagodzinski, Christophor Kozhuharov, Sergiy Trotsenko, Günter Weber, Thomas Stöhlker

B-a16 Two-photon decay in highly charged heavy ions: Spectral shape of the 2E1 ($2^1S_0 \rightarrow 1^1S_0$) in He-like tin
Sergej Trotsenko, Ajay Kumar, Andrej Volotka, Dariusz Banas, Heinrich Beyer, Harald Braeuning, Alexander Gumberidze, Siegbert Hagmann, Sebastian Hess, Christophor Kozhuharov, Regina Reuschl, Uwe Spillmann, Martino Trassinelli, Guenter Weber, Thomas Stoehlker

B-a17 Theoretical simulation of extreme ultraviolet spectra of tin in laser-produced plasmas
Maogen Su, Yuee Luo, Chenzhong Dong, Luyou Xie, Yanbiao Fu, Paddy Hayden, Lynn Gaynor, Gerry O'Sullivan, John White

B-a18 Visible spectroscopy with the Tokyo-EBIT
H.Watanabe, N. Nakamura, and S. Ohtani

B-a19 QED perturbation theory in calculating nuclear quadrupole moments and hyperfine structure parameters for Li-like mulricharged ions
Alexander V. Glushkov, Olga Yu. Khetselius, Elena P. Gurnitskaya , Denis E. Sukharev, Ludmila Lovett

b) Collisions with Electrons, Ions, Atoms and Molecules

B-b01 Electron impact ionization of ground-state and metastable Li^+ ions
Alexander Borovik, Igor Bray, Dmitry Fursa, Stefan Schippers, Alfred Müller

B-b02 Observation of higher order resonant electron recombination processes by highly charged krypton ions
Christian Beilmann, Zoltan Harmann, Jose R. Crespo Lopez-Urrutia, Volkhard Maeckel, Hiroyuki Tawara, Joachim Ullrich

B-b03 High resolution low-energy dielectronic recombination rate coefficients of beryllium-like germanium: QED test bench for two-valence-electron systems
Dmitry A. Orlov, Claude Krantz, Dietrich Bernhardt, Carsten Brandau, Jens Hoffmann, Alfred Müller, Ticia Ricsóka, Stefan Schippers, Andrey Shornikov, Andreas Wolf

B-b04 Low-lying dielectronic resonances of Fe XXII and Fe XVIII for accurate energy determination of autoionising Rydberg levels for boron- and fluorinelike cores
Claude Krantz, Dmitry A. Orlov, Jens Hoffmann, Ticia Ricsóka, Sándor Ricz, Stefan Schippers, Andreas Wolf

B-b05 Dielectronic recombination of Li- and Be-like xenon ions
Dietrich Bernhardt, Sebastian Boehm, Holger Knopp, Joerg Jacobi, Stefan Kieslich, Paul Mokler, Alfred Müller, Stefan Schippers, Wei Shi, Peter Beller, Fritz Bosch, Carsten Brandau, Christophor Kozhuharov, Fritz Nolden, Markus Steck

B-b06 Effective collision strengths for the electron impact excitation of Ni XVII
Claire Hudson, Patrick Norrington, Catherine Ramsbottom

B-b07 Dielectronic recombination into Mg-like ions
Izumi Murakami, Ulyana I. Safronova, Takako Kato

B-b08 Correlated strong-field dynamics and nuclear properties explored by resonant electron recombination with highly charged ions
Z. Harman, O. Postavaru, U. D. Jentschura, C. H. Keitel, W. Scheid, V. Maeckel, C. Beilmann, J. R. Crespo Lopez-Urrutia, H. Tawara, J. Ullrich, C. Brandau, C. Kozhuharov, Th. Stoehlker

B-b09 High precision measurement of the spectral width of the nickel-like molybdenum X-ray laser
Noboru Hasegawa, Tetsuya Kawachi, Akira Sasaki, HIroshi Yamatani, Maki Kishimoto, Momoko Tanaka, Yoshihiro Ochi, Masaharu Nishikino, Yuichi Kunieda, Hitoki Yoneda

B-b10 Electron ion collision studies at the Stockholm electron beam ion trap
S. Böhm, I. Orban, R. Schuch

B-b11 Investigating correlated high-field few-electron QED by means of dielectric recombination in $W^{69+...72+}$ ions
Volkhard Maeckel, Jose R. Lopez-Urrutia, Antonio J. Gonzalez-Martinez, Zoltan Harman, Hiroyuki Tawara, Joachim Ullrich

B-b12 Dielectronic recombination of Na-like S and Na-like Ar in the presence of external fields
I. Orban, S. Böhm, S. Trotsenko, R. Schuch

B-b13 Possibility of resonant capture of antiprotons by electron excitation in hydrogenlike ions
Michael Genkin, Eva Lindroth

B-b14 The enhancement effect in radiative recombination of bare uranium ions with cooling electrons
D. Banas, M. Pajek, Th. Stoehlker, H. Beyer, F. Bosch, C. Brandau, S. Chatterjee, M. Czarnota, A. Gumberidze, S. Hagmann, C. Kozhuharov, D. Liesen, P. Mokler, R. Reuschl, U. Spillmann, S. Tachenov, S. Trotsenko, P. Verma, D. Sierpowski, A. Warczak, S. Boehm, A. Mueller, E. Schmidt, J.-Cl. Dousse, J. Szlachetko

B-b15 Theoretical investigation on quantum interference effects between dielectronic recombination and radiative recombination for highly charged ions
Yinglong Shi, Jianjie Wan, Chenzhong Dong

B-b16 Resonance electron impact excitation and polarization of magnetic quadrupole line of neonlike Ba^{46+} ions
Jun Jiang, Chenzhong Dong, Luyou Xie, Jianguo Wang

B-b17 Isomer effect on ionization processes in collisions of 6-MeV/amu bare-ions with C_3H_6 molecules
Tomoharu Nakazato, Takashi Matsuo, Toshiyuki Kohno, Yumiko Ohno, Shin-ichi Watanabe, Takeshi Murakami

B-b18 State-selective differential cross sections for single, double electron capture in low energy He^{2+}-He collisions
Xiaolong Zhu, Xinwen Ma, Li Bin, Shaofeng Zhang, Wentian Feng, Huiping Liu, Lanfang Chen, Shiping Cao, Dongbin Qian, Dacheng Zhang

B-b19 Asymptotic theory for single and double electron capture in low - energy collisions of highly charged ions with molecules
Mykhaylo Khoma, Volodymyr Lazur, Ratko Janev

B-b20 Energy gain measurements of highly charged Xe ions in collisions with rare gas targets at 200 eV
Kunikazu Ishii, Yoko Inoue, Hidemi Ogawa

B-b21 Differential cross sections for single-electron capture by low-energy O_2^{2+} ions from Ne and O_2
Emanuel Y. Kamber

B-b22 Non-perturbative investigation of the interference effects in the ionization of H_2 by charged particle impact
Ladislau Nagy, Sándor Borbély, Katalin Póra

B-b23 A distorted wave model for electron ionization in collisions between clothed-ions and atomic targets
Juan Manuel Monti, Roberto Daniel Rivarola, Pablo Daniel Fainstein

B-b24 A full four-body continuum distorted wave - eikonal initial state model for ionization of He by ion impact
Juan Manuel Monti, Omar Ariel Fojón, Jocelyn Hanssen, Roberto Daniel Rivarola

B-b25 New classical CTMC approaches to A^{q+} + He processes
Francisco Guzmán, Luis Fernando Errea, Luis Méndez, Bernard Pons, Armando Riera

B-b26 A new MOTRIMS apparatus for high resolution measurements in ion-atom collisions and trapped atoms studies
Jeremy Blieck, Xavier Flechard, Amine Cassimi, Herve Gilles, Sylvain Girard, Dominique Hennecart

B-b27 Vacancy distribution of the X-ray satellite spectra of SiO_2 aerogel bombarded with calcium ions
Aneta Maria Gojska, Jacek Rzadkiewicz, Olga Rosmej, Marek Polasik, Katarzyna Slabkowska

B-b28 Complementary spectroscopy of tin ions by using ion beams and electron beams
Hayato Ohashi, Shintaro Suda, Hajime Tanuma, Shinsuke Fujioka, Hiroaki Nishimura, Katsunobu Nishihara, Takeshi Kai, Akira Sasaki, Hiroyuki A. Sakaue, Nobuyuki Nakamura, Shunsuke Ohtani

B-b29 Linear polarization studies for radiative electron capture transitions into highly charged uranium
Sebastian Hess, Harald Braeuning, Carsten Brandau, Sabrina Geyer, Maik Hegewald, Christophor Kozhuharov, Thomas Krings, Ajay Kumar, Renate Maertin, Brian O'Rourke, Davor Protic, Regina Reuschl, Uwe Spillmann, Martino Trassinelli, Sergej Trotsenko, Guenter Weber, Thomas Stoehlker

B-b30 One- and two- electron transfer to continuum in near-relativistic ion-atom collisions
Siegbert Hagmann, Muaffaq Nofal, Thomas Stoehlker, Andrej Surzhykov, Stefan Fritzsche, Doris Jakubassa-Amundsen, Benaceur Najjari, Alexander Voitkiv, Christophor Kozhuharov, Joachim Ullrich, Robert Moshammer, Alexander Gumberidze, Uwe Spillmann, Regina Reuschl, Sebasian Hess, Sergej Trotsenko, Fritz Bosch, Dieter Liesen, Reinhard Doerner, Hermann Rothard, Gaetano Lanzano, Enrico De Filippo

B-b31 Strong forward-backward asymmetry of H_2O ionic fragments by slow highly charged ions impact
Zoran Pesic, Rolf Hellhammer, Bela Sulik, Nikolaus Stolterfoht

B-b32 Investigation of the multiple electron scattering sequences in C^{n+} + Ar collisions
Karoly Tokesi, Bela Sulik

B-b33 Young type interference in electron emission frm H_2 and forward-backward asymmetry: A new approach
D Misra, S Chatterjee, Lokesh C Tribedi

B-b34 Interference patterns in spectra of electron ionization of heteronuclear HeH^+ targets in interaction with fast ion beams
Carmen Alejandra Tachino, Mariel Elisa Galassi, Fernando Martín, Roberto Daniel Rivarola

B-b35 Theoretical analysis of multiple ionization of Ar-ions in gas targets
Gerald Schenk, Tom Kirchner, Viatcheslav Shevelko

B-b36 High-resolution X-ray study of multiple ionization of Pd atoms by fast oxygen ions
M. Czarnota, D. Banas, M. Pajek, J.-Cl. Dousse, J. Hoszowska, Y.-P. Maillard, O. Mauron, M. Berset, P.A. Raboud, D. Chmielewska, J. Rzadkiewicz, Z. Sujkowski, M. Polasik, K. Slabkowska

B-b37 Radiative electron capture and subsequent radiative decay in collisions of U^{89+} ions with N_2
Jianjie Wan, Yongjun Wang, Xiaobin Ding, Chenzhong Dong, Xinwen Ma, Jacek Rzadkiewicz, Thomas Stohlker, Stephan Fritzsche

B-b38 Loss mechanism and lifetime of ions beam in HIRFL-CSRE
Yingli Xue, Xiaohong Cai, Deyang Yu, Caojie Shao, Fangfang Ruan, Dejun Qi, Mingwu Zhang, Wei Wang

B-b39 Investigation of multiple electron transfer in ion atom collisions
Ina Blank, Gabriel Hasan, Simone Götz, Terry Mullins, Wenzel Salzmann, Reinhard Morgenstern, Matthias Weidemüller, Ronnie Hoekstra

B-b40 Electron-impact excitation of $2p^5 3l \rightarrow 2p^5 3l'$ line emission of Fe XVII
Daiji Kato, Hiroyuki A Sakaue, Izumi Murakami, Takako Kato, Nobuyuki Nakamura, Shunsuke Ohtani, Norimasa Yamamoto, Tetsuya Watanabe

c) Interactions with Clusters, Surfaces and Solids

B-c01 Fragmentation of adenine induced by He^{2+} and F^{2+}
Xinwen Ma, Bin Li, Li Chen, Richard Bredy, Xiaolong Zhu, Huiping Liu, Shaofeng Zhang, Wentian Feng, Dongbing Qian, Dacheng Zhang

B-c02 Projectile q-dependence of single, double and multiple ionization and fragmentation of C_{60} under first ion-impact and influence of GDPR
Aditya Kelkar, Lokesh C. Tribedi

B-c03 Multiply charged ions within a fullerene cage: photoionization of $Ce@C_{82}^+$
Alfred Müller, Stefan Schippers, Mustapha Habibi, David Esteves, Jing-Cheng Wang, Ronald Arthur Phaneuf, David Kilcoyne, Alejandro Aguilar, Lothar Dunsch

B-c04 Absolute charge transfer and fragmentation cross sections in He^{2+} - C_{60} collisions
A. Rentenier, L. F. Ruiz, S. Diaz-Tendero, B. Zarour, P. Moretto-Cappelle, D. Bordenave-Montesquieu, A. Bordenave-Montesquieu, P. A. Hervieux, M. Alcami, M. F. Politis, J. Hanssen, F. Martin

B-c05 Potential and kinetic sputtering of molecular fragments from alkanethiols-SAMs due to HCI impact
Marcos I Flores, Brian E O'Rourke, Vladimir A Esaulov, Yasunori Yamazaki

B-c06 Guiding of argon ions trough PET nano capillary foils
Martin Kreller, Guenther Zschornack, Ulrich Kentsch

B-c07 Ion desorption from solid rare gases by singly- and multiply-charged ion impact
Takayuki Tachibana, Kentro Fukai, Tetsuo Koizumi, Takato Hirayama

B-c08 Formation of nano pits on the KBr (001) surface induced by single impact of slow highly charged ions
Rene Heller, Stefan Facsko, Richard Wilhelm, Wolfhard Möller

B-c09 X-ray emission in the interaction of slow H-like ions with a metal surface
Jian Sun, Hirofumi Watanabe, Masahide Tona, Tsutomu Watanabe, Nobuyuki Nakamura, Chikashi Yamada, Shunsuke Ohtani

B-c10 Guiding of slow highly charged ions through a thin gap between a pair of parallel glass plates
Tokihiro Ikeda, Yoshio Iwai, Takao M. Kojima, Shigeki Onoda, Yasuyuki Kanai, Kristina A. Vokhmyanina, Grigory P. Pokhil, Yasunori Yamazaki

B-c11 Collisions of ions with insulating surfaces: Charging and discharging dynamics
Nenad Bundaleski, Hocine Khemliche, Patrick Rousseau, Amine Cassimi, Laurent Maunoury, Philippe Roncin

B-c12 Charge-up dynamics in guiding slow highly charged ions through nano-capillaries
Patrik Skog, Hongqiang Zhang, Inna Soroka, Nadeem Akram, Kristina Vokhmyanina, Reinhold Schuch

B-c13 Investigation on a nano-structure on a hydrogen-terminated Si surface induced by individual HCI impacts
Masahide Tona, Makoto Sakurai, Hirofumi Watanabe, Jian Sun, Chikashi Yamada, Nobuyuki Nakamura, Shunsuke Ohtani

B-c14 Guiding effect of mediate and low energy electron-beam by quartz tube
Dejun Qi, Xiaohong Cai, Deyang Yu, Wei Wang, Yingli Xue, Fangfang Ruan, Mingwu Zhang, Caojie Shao

B-c15 Dynamic features of beam guiding by insulator capillaries: Incident energy dependence
Yasuyuki Kanai, Masamitsu Hoshino, Tokihiro Ikeda, Tadashi Kambara, R. Hellhammer, N. Stolterfoht, Yasunori Yamazaki

B-c16 Ion guiding through nanocapillaries in PET polymers with variable diameter
Nico Stolterfoht, R. Hellhammer, Bela Sulik, Zoltan Juhasz, Erwin Bodewits, Hong Dang, Ronnie Hoekstra

B-c17 Computation of dose distributions for heavy charged particles in theraputic applications
Houshyar Noshad

B-c18 Selective formation of multiply excited states by resonant coherent excitation
Yuji Nakano, Kenichi Metoki, Yasushi Takano, Atsushi Hatakeyama, Yoichi Nakai, Toshiyuki Azuma, Kenichiro Komaki, Yasunori Yamazaki, Eiichi Takada, Takeshi Murakami

B-c19 Solid-density plasma existed at initial stage of heavy ion track formation in solids
Sergey A. Pikuz Jr., Igor Yu. Skobelev, Igor V. Morozov, Alexander V. Lankin, Genry E. Norman

d) Interactions with Photons, Plasmas and Strong Field Processes

B-d01 Above-threshold two-photon transitions between bound states of multicharged hydrogen-like ions
Nikolay Leonidovich Manakov, Sergey Ivanovich Marmo, Sergey Aleksandrovich Sviridov, Sergey Aleksandrovich Zapryagaev

B-d02 Production of multiply charged ions from the 4d photoionization of Cs^+
Tetsuo Koizumi, Takao M Kojima, Mutsumi Sano, Naoki Watanabe

B-d03 X-ray absorption by highly charged ions in plasmas: Toward photo-pumping X-ray laser
Tetsuya Kawachi, Yoshiaki Kato

B-d04 Behaviour of impurity ions for radiation collapse in large helical device
Takako Kato, Izumi Murakami, Daiji Kato, Hisamichi Funaba, Kuninori Sato, Motoshi Goto, Byron Peterson, Norimasa Yamamoto

B-d05 Investigating the emission angle, charge and energy of ions produced from laser produced extreme ultraviolet sources
E Sokell, A O'Connor, P Dunne, P Hayden, O Morris, F O'Reilly, G O'Sullivan

B-d06 Electron temperature modifications by upgraded injection power of IBW heating system on HT-7 tokamak
Sarwar Sajjad, Xiang Gao, Bili Ling, Ti Ang

B-d07 Optimal pulse duration in laser-cluster interactions
Cornelia Deiss, Christophe Prigent, Emily Lamour, Jean-Pierre Rozet, Dominique Vernhet, Joachim Burgdörfer

B-d08 On the solution of the time dependent Dirac equation for hydrogen-like systems
Sølve Selstø, Jakob Bengtsson, Eva Lindroth

B-d09 QED theory of laser-atom and laser-nucleus interaction and multi-body dynamics in a strong laser field pulse
Alexander V. Glushkov

e) Production, Experimental developments and Applications

B-e01 Status of the g-factor experiment on highly charged calcium
W. Quint, K. Blaum, H.-J. Kluge, B. Schabinger, S. Sturm, A. Wagner, G. Werth

B-e02 HITRAP - a facility for precision experiments on heavy highly charged ions in extreme electromagnetic fields
W. Quint, Z. Andjelkovic, K. Blaum, G. Birkl, D. Bodewits, L. Dahl, F. Herfurth, R. Hoekstra, O. Kester, H.-J. Kluge, S. Koszudowski, C. Kozhuharov, G. Maero, W. Noertershaeuser, J. Pfister, U. Ratzinger, W. Salzmann, A. Schempp, D. Segal, A. Sokolov, Th. Stoehlker, R. Thompson, J. Ullrich, V. Varentsov, M. Vogel, G. Vorobjev, A. Warczak, M. Weidemueller, C. Weinheimer, D. F.A. Winters

B-e03 Re-trapping and cooling highly-charged ions
M. Hobein, S. Böhm, A. Solders, M. Suhonen, L. Yuwen, O. Kamalou, Sz. Nagy, G. Marx, R. Schuch

B-e04 Trapping of highly charged ions with an electrostatic ion trap
Alexandre Gumberidze, Paul Indelicato, Csilla Szabo, Dina Attia, Alexandre Vallette, S. Carmo

B-e05 X-ray spectroscopy characterization of Ar^{17+} produced by an ECRIS in the afterglow mode
Christophe Prigent, Emily Lamour, Jacques Merot, Bernard Pascal, Jean - Pierre Rozet, Martino Trassinelli, Dominique Vernhet, Jean - Yves Pacquet, Laurent Maunoury, Fabien Noury, Jean - Marc Ramillon

B-e06 Highly charged ion injector in terminal of tandem accelerator
Makoto Matsuda, Takamitsu Nakanoya, Kenichi Kutsukake, Susumu Hanashima, Suehiro Takeuchi

B-e07 Continuous beams of highly charged ions from the Dresden EBIS-A
Ulrich Kentsch, Frank Grossmann, Rene Heller, Vladimir P. Ovsyannikov, Guenther Zschornack, Martin Kreller

B-e08 A Si(Li) multistrip detector- an efficient compton polarimeter
Uwe Spillmann, Harald Braeuning, Sebastian Hess, Thomas Krings, Istvan Mohos, Davor Protic, Thomas Stoehlker

B-e09 The commissioning of the cooler storage ring HIRFL-CSR in Lanzhou
Jiawen Xia, Wenlong Zhan, Hushan Xu

B-e10 Development of multichannel Doppler tuned beam-foil X-ray absorption spectrometer at IUAC
Ranjeet Kumar Karn, Nissar Ahmad, Anjan Dutta, C. P. Safvan, T. Nandi and A. Roy

B-e11 Absolute detection efficiencies of an ion counting system with a channel-electron multiplier
Tetsuo Koizumi, Yuta Chihara

B-e12 Time resolved extreme ultraviolet tin spectra from laser produced plasmas
Patrick Hayden, Padraig Dunne, Gerry O'Sullivan, Eugene T. Kennedy, John T Costello

B-e13 Development and applications of electron beam ion source for nanoprocesses
Makoto Sakurai, Masahide Tona, Hirofumi Watanabe, Nobuyuki Nakamura, Shunsuke Ohtani, Toshifumi Terui, Shinro Mashiko, Hiroyuki A Sakaue

B-e14 Tin LPP source modelling for EUVL at 13.5 nm
John White, Padraig Dunne, Oran Morris, Fergal O'Reilly, Emma Sokell, Gerry O'Sullivan

B-e15 Angle-resolved studies of tin-based laser produced plasma EUV sources
Oran Morris, Paddy Hayden, Tom McCormack, Aodh O'Connor, Fergal O'Reilly, Gerry O'Sullivan, Emma Sokell, John White, Padraig Dunne

B-e16 Calculation of stability diagrams and ion trajectories in quadrupole ion trap with impulsional potential by matrix method
Alireza Doroudi

EUV SPECTROSCOPY OF HIGHLY CHARGED IRON IONS WITH A LOW ENERGY COMPACT EBIT

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Spectroscopic investigations of highly charged ions are very important not only for atomic physics but also for astrophysical and laboratory fusion plasmas. For example, the atomic data of highly charged iron ions with charge state around 10 are strongly needed for the spectroscopic diagnostics of the solar corona with the recently launched satellite Hinode. For spectroscopic studies of such moderately charged ions, we have recently constructed a compact electron beam ion trap (EBIT)[1]. The electron energy range of the present EBIT is 100-1500 eV, which is rather low compared to that of ordinary EBITs, and thus enabled us to downsize it. We have also developed a dedicated slitless spectrometer consisting of a 1200 lines/mm laminar-type replica diffraction grating and a back-illuminated CCD. The cross sectional view of the EBIT and the spectrometer is shown in Fig.1. It is possible to employ a slitless type of spectrometer because an EBIT represents a line source with a width of ~0.1 mm. Typical EUV spectra of highly charged iron ions are shown in Fig.2. As shown in this example, various charge state ions can be selectively produced with a narrow charge state distribution by adjusting the electron beam energy. Thus the charge state of unknown lines can be identified through such energy dependence measurements. On the other hand, the electron density dependence of line ratios, which are very important for plasma diagnostics, can be studied by changing the electron beam current at a fixed energy. First results of the new EBIT are presented.

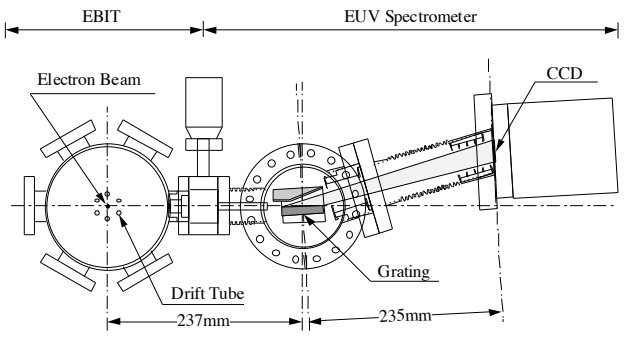

Fig.1 Cross sectional view of the EBIT and the spectrometer

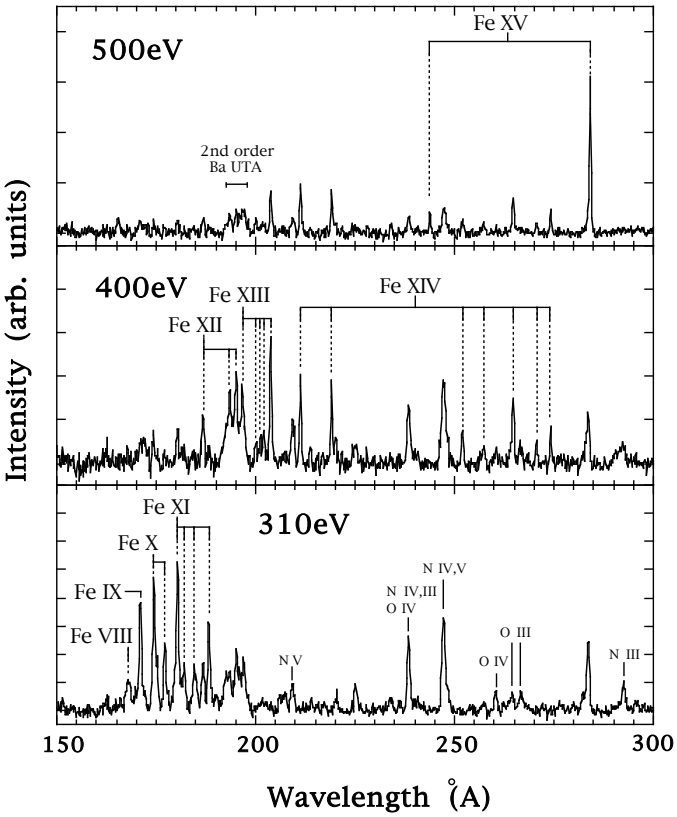

Fig.2 Typical EUV spectra of highly charged iron ions

References
[1] N. Nakanura et al., Rev. Sci. Instrum. (2008) in press.

MEASUREMENT of K_{β_2}/K_{β_1} RATIO FOR HE-LIKE KRYPTON

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In a previous measurement of intensity ratios of the $n = 3 \rightarrow 1$ intecombination line ($1s3p\ ^4P_1 \rightarrow 1s^2\ ^1S_0$, or K_{β_2}) to that of the resonance line ($1s3p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$, or K_{β_1}), it was shown that theoretical predictions underestimate the measured values for several ions with intermediate Z from magnesium to iron [1]. Among several reasons for the discrepancy, the effects of polarization of the emitted X-ray lines were mentioned as a possible cause, as the measurement was carried out on an electron beam ion trap, where the unidirectional beam creates linearly polarized light, and the X-rays were detected with crystal spectrometers, which have different reflectivities for the two polarized components. In this paper, we report the measurement of the K_{β_2}/K_{β_1} ratio of the He-like Krypton using an X-ray microcalorimeter and the electron beam ion trap SuperEBIT at Lawrence Livermore National Laboratory. The microcalorimeter is an energy dispersive device whose quantum efficiency is independent of the polarization degree of the X-ray photons. Although the linear polarization indirectly affects the measured ratio through the anisotropic factor due to the fact that the photons are detected in the direction perpendicular to the electron beam, such dependences are much weaker than those affecting the crystal spectrometers. We compare the measured K_{β_2}/K_{β_1} ratio with several theoretical predictions, and show that they underestimate the measured value, consistent with the previous results for lower Z ions from magnesium to iron.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

References

[1] A.J. Smith, P. Beiersdorfer, K.J. Reed, A.L. Osterheld, V. Decaux, K. Widmann, and M.H. Chen, Phys. Rev. A, **62**, 012704 (2000)

EBIT X-RAY MICROCALORIMETER MEASUREMENTS OF THE K-SHELL EMISSION FROM HELIUMLIKE IONS

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The K-shell emission from highly charged heliumlike ions has played an important role in EBIT spectroscopy since the first electron beam ion trap was put into operation. Early on, the spectra have been studied with high-resolution crystal spectrometers, and many of their properties have been determined during these measurements [1]. Together with the K-shell emission lines of hydrogenlike ions, the K-shell emission lines of heliumlike ions have also been used to set the wavelength scale in a variety of crystal spectrometer measurements of the transition energies of more complex spectra. Continuing the latter tradiation, we now use the K-shell emission of highly charged ions as calibration references to set the energy scale of the EBIT calorimeter spectrometer (ECS). The x-ray microcalorimeter [2] is used for measuring the complex x-ray emission from multiple shells over a broad energy range (typically 0.4 to 15 keV). Such emission may be produced, for example, by multi-electron ions from high-Z elements, such as W or Au, or by ion-atom collisions. In order to calibrate such a broad energy range, reference lines from multiple K-shell ions must be recorded.

Here we present an overview of the K-shell x-ray spectra measured with the ECS that fall into the energy regime between 400–14,000 eV. These include the more commonly studied K-shell spectra from heliumlike ions of noble gases (neon, argon, and krypton) and of the transition metals (e.g., iron, nickel). These also include the spectra of less studied heliumlike ions, inlcuding those of nitrogen, fluorine, silicon, sulfur, chlorine, and germanium.

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References

[1] P. Beiersdorfer, Can. J. Phys. **86**, 1 (2008).

[2] F. S. Porter, P. Beiersdorfer, K. Boyce, G. V. Brown, H. Chen, J. Gygax, S. M. Kahn, R. Kelley, C. A. Kilbourne and E. Magee, and D. B. Thorn, Can. J. Phys. **86**, 231 (2008).

ANALYSIS OF EUV SPECTRA FROM HIGHLY CHARGED IRON IONS WITH A COMPACT EBIT

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For the analysis of line spectra of astrophysical plasma and solar plasma, various analysis tools have been developed. However the most of the tools haven't been checked by applying the models to the laboratory plasma which can control plasma parameters. For developments of the analysis tool with high precision, selections of atomic data (wavelength (level energy), radiative transition probabilities, collisional excitation cross sections etc.) and constructions of the collisional-radiative model for spectral line analysis are important.

For these subjects, an equipment of a compact electron beam ion trap (EBIT). The compact EBIT can control electron temperature of 100 – 1500 eV and electron density around 10^{11} cm^{-3}. In this study, iron ions line spectra were measured by extreme ultraviolet (EUV) flat-field grating spectrometer (See a presentation by Sakaue et al. in this conference).

The iron ions line spectra were analyzed by constructing a new collisional-radiative model. An electron velocity distribution was taken to be a delta function for calculations of reaction rates corresponding to mono-energetic electron energy of the compact EBIT. In this paper, especially, electron density diagnostics by line intensity ratios around 10^{11} cm^{-3} were studied.

Our results in this paper are connected with applications to EIS (EUV Imaging spectrometer) observations of HINODE satellite which is solar observation satellite, and other X-ray/EUV observation satellites.

References

[1] N. Nakanura et al., Rev. Sci. Instrum. (2008), in press.
[2] N. Yamamoto et al., (2008), submitted

EUV SPECTROSCOPY OF TIN AND XENON IONS WITH A COMPACT ELECTRON BEAM ION TRAP

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Since an electron beam ion trap (EBIT) was originally developed for studying few-electron heavy ions to test fundamental quantum theories, almost all EBITs in the world have been designed to be operated with rather high electron beam energy (~10 keV or more). With such a high-energy electron beam, light and moderate elements are easily ionized to few-electron or bare ions. On the other hand, recently, spectroscopic studies of moderate charge state ions which still keep many electrons are attracting the attention of several areas. For example, to develop an EUV light source for the next-generation lithography, the atomic data of highly charged Sn and Xe ions with charge states around 10 are strongly needed [1,2]. For spectroscopic studies of such moderate charge state ions, we have recently constructed a compact EBIT [3].

In this paper, we present spectroscopic studies of highly charge Sn and Xe ions with the compact EBIT. Fig. 1 shows a typical spectrum of highly charged Xe ions. This high statistical quality spectrum has been obtained with an only 10-min exposure. This shows the high performance of the present EBIT. In the poster, the details of the new device are also presented.

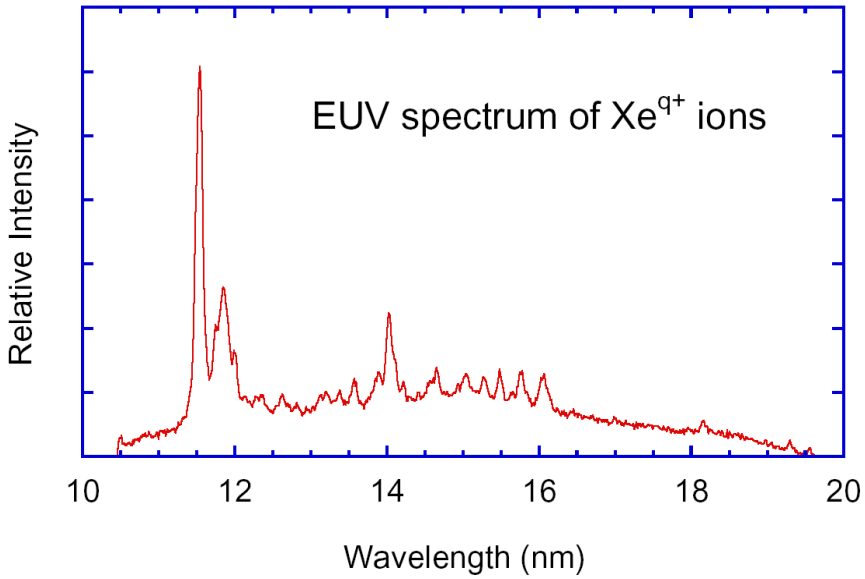

Fig.1. Typical EUV spectrum of highly charged Xe ions obtained with a recently constructed compact EBIT. The electron energy and current was 600eV and 10mA, respectively.

References

[1] G. O'Sullivan et al., AIP Conf. Proc. **771** (2005) 108.
[2] H. Ohashi et al., J. Phys.: Conf. Ser. **58** (2007) 235.
[3] N. Nakamura et al., Rev. Sci. Instrum. **79** (2008) 063104.

CHARGE STATE SELECTIVE EUV SPECTROSCOPY OF HCI AT VERY LOW COLLISION ENERGIES IN AN ELECTRON BEAM ION TRAP

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Emission spectra of HCI from xenon were recorded using the Heidelberg electron-beam ion trap (EBIT) and modelled theoretically. Transition wavelengths and probabilities were calculated using the multiconfiguration Dirac-Fock method. Electron impact excitation collision strengths were evaluated by large scale configuration interaction calculations. These predictions were used to solve the rate equations determining the population of different levels in thermal plasmas. Detailed results were given for low density plasmas at electron temperatures from 15 to 50 eV. Comparison of our theoretical model with our experimental emission spectra (see Fig. 1) obtained at beam energies as low as 40 eV proved to be a useful tool to analyze EUV emission properties of xenon plasmas. Similar experimental data for barium and iron ions were also obtained. A new high-resolution grating spectrometer has allowed further improving the quality of the data.

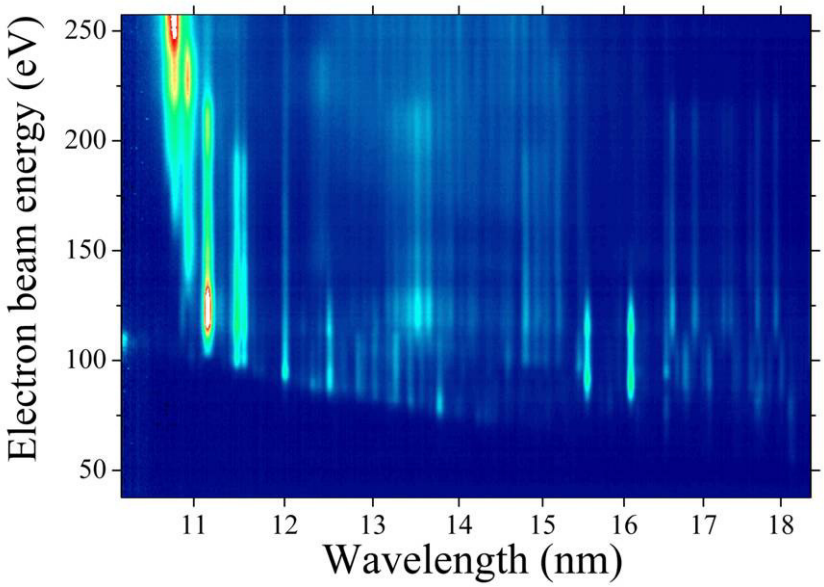

Fig. 1. Composite experimental map of the EUV emission spectra of xenon highly charged ions produced at different electron beam energies at the Heidelberg FLASH-EBIT

MEASUREMENT OF THE BOUND ELECTRON G-FACTOR IN HIGHLY CHARGED IONS BY DOUBLE RESONANCE SPECTROSCOPY

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Precise measurements of magnetic moments (g-factors) of free [1, 2] and bound electrons [3, 4] have opened possibilities to test quantum electrodynamics (QED) in free and bound systems, where strong fields are present, and to determine fundamental constants like the electron mass [5] and the fine-structure constant α [2,6]. Measurements of the electronic g_J-factor by use of the continuous Stern-Gerlach effect have been performed for the electron bound in hydrogen-like carbon $^{12}C^{5+}$ [3] and oxygen $^{16}O^{7+}$ [4]. They yield g_J = 2.001 041 596 3 (10)(44) for $^{12}C^{5+}$ and g_J = 2.000 047 026 0 (15)(44) for $^{16}O^{7+}$.

Here we present a double resonance technique [7] for the precise determination of the g-factor of the electron bound in heavy highly charged ions. With this technique, microwave transitions between the Zeeman sublevels of hyperfine states in hydrogen-like or lithium-like ions, which are confined in a cryogenic Penning trap, are induced. Such microwave transitions are probed by laser excitation to the upper hyperfine level and detection of optical fluorescence photons. This way, the g_F-factor of the highly charged ion is measured by laser-microwave double resonance spectroscopy. A combination of measured g_F-factors and the hyperfine transition frequency allows to simultaneously determine the electronic g-factor g_J and the nuclear g-factor g_I from one experiment, with essential input from theory. Thus, we introduce a stringent test of corresponding calculations in the framework of bound-state quantum electrodynamics in extreme electromagnetic fields and a possibility to determine nuclear magnetic moments in the absence of diamagnetic shielding.

Candidates for laser-microwave double resonance measurements are amongst others H-like and Li-like ions between lead and uranium, e.g. bismuth $^{209}Bi^{82+}$ and $^{209}Bi^{80+}$. Such experiments are planned at HITRAP, the ion trap facility for heavy highly charged ions at GSI, which is presently in the commissioning phase.

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References

[1] B. Odom, D. Hanneke, B. D'Urso and G. Gabrielse, Phys. Rev. Lett. **97,** 030801 (2006)

[2] D. Hanneke, S. Fogwell and G. Gabrielse, Phys. Rev. Lett. **100,** 120801 (2008)

[3] H. Häffner, N. Hermanspahn, H.-J. Kluge, W. Quint, S. Stahl, J. Verdu, G. Werth, Phys. Rev. Lett. **85,** 5308

[4] J. Verdu, S. Djekic, H. Häffner, H.-J. Kluge, W. Quint, S. Stahl, T. Valenzuela, M. Vogel, G. Werth, Phys. Rev. Lett. **92**, 093002 (2004)

[5] T. Beier, H. Häffner, N. Hermanspahn, S.G. Karshenboim, H.-J. Kluge, W. Quint, S. Stahl, J. Verdu, and G. Werth, Phys. Rev. Lett. **88**, 011603 (2002)

[6] V.M. Shabaev, D.A. Glazov, N.S. Oreshkina, A.V. Volotka, G. Plunien, H.-J. Kluge, and W. Quint, Phys. Rev. Lett. **96**, 253002 (2006)

[7] W. Quint, D.L. Moskovkhin, V.M. Shabaev, M. Vogel, submitted for publication

ENERGY LEVELS AND OSCILLATOR STRENGTHS FOR TRANSITIONS IN Fe XIV

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Emission lines of Fe XIV have been widely observed in a variety of solar and other astrophysical plasmas, and over a wide wavelength region varying from optical to extreme ultra-violet. The strongest observed forbidden transition is from the coronal green line ($3s^2$ 3p) $^2P^o_{1/2}$ - $^2P^o_{3/2}$ with the wavelength 5303 Å. Many of the line pairs are density and/or temperature sensitive, and hence provide useful information about physical conditions of the plasmas. However, to reliably analyse observations, atomic data are required for many parameters, including energy levels and radiative rates (A-values). Since experimental data are not available, particularly for the A-values, theoretical results are required.

Considering the importance of Fe XIV many calculations have been performed in the past, such as by Huang [1], Storey et al. [2], Safronova et al. [3], Gupta & Msezane [4], Froese-Fischer et al. [5], and Wei et al. [6]. However, most of these calculations are confined to transitions among the lowest 40 levels of the n = 3 configurations, although Gupta & Msezane and Wei et al. have also included some levels of the n = 4 configurations. Additionally, most of the available A- values are for the electric dipole (E1) transitions alone, whereas in the modelling and diagnostics of plasmas corresponding results are also required for other types of transitions, namely electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2). Therefore, the *aim* of the present work is not only to improve upon the earlier available calculations, but also to report a *complete* set of results for *all* transitions, which can be confidently applied in plasma modelling.

For our calculations we have adopted the GRASP (general-purpose relativistic atomic structure package) code, which is fully relativistic and is based on the jj coupling scheme. The n = 3 configurations generate 148 fine-structure levels. In addition, we have also included levels of the $3s3p4\ell$, $3s^24\ell$, $3s3p^55\ell$, and $3s^25\ell$ configurations. Energies for all these 332 levels and A- values among them for *all* types of transitions have been calculated. Furthermore, we have also calculated lifetimes for all levels. A complete set of all results, along with detailed comparisons, will be available during the conference.

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References

[1] K. N. Huang, At. Data Nucl. Data Tables **34**, 1 (1989)
[2] P. J. Storey, H. E. Mason, P. R. Young, Astron. Astrophys. Supl. **141**, 285 (2000)
[3] U. I. Safronova, M. Sataka, J. R. Albritton, W. R. Johnson, M. S. Safronova, Phys. Rev. **A 65**, 022507 (2002)
[4] G. P. Gupta, A. Z. Msezane, At. Data Nucl. Data Tables **89**, 1 (2005)
[5] C. Froese-Fischer, G. Tachiev, At. Data Nucl. Data Tables **92**, 607 (2006)
[6] H. L. Wei, H. Zhang, C. W. Ma, J. Y. Zhang, X. L. Cheng, Phys. Scr. **77**, 035301 (2008)

ELECTRON SHAKE OFF IN THE β DECAY OF TRAPPED $^6He^+$ IONS

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In the search of physics beyond the Standard Model, nuclear β decay is a unique and relatively easy-to-access laboratory to investigate the Weak Interaction. In particular, the possible contribution of exotic couplings can be evidenced through high precision measurements of unambiguously predicted properties like the β–ν angular correlation parameter a. In the case of ^{6}He decay (807 ms half-life), a deviation of a from the Standard Model value -1/3 would imply the existence of tensor currents, mediated by new gauge bosons called *leptoquarks*.

Using the low energy radioactive beam line of SPIRAL in GANIL, and a transparent Paul trap as a confinement device [1], the LPC-Trap experiment has been designed to measure this β–ν angular correlation parameter in the $^6He^+$ beta decay with an unprecedented precision. With the radioactive $^6He^+$ ions stored nearly at rest in a small volume defined by the driving RF field of a novel transparent Paul Trap, the decay products can be detected in coincidence, and the value of the correlation parameter a can be inferred from the recoiling ion time of flight. In a recent experiment, 10^5 decay coincidences between the beta particles and the recoiling $^6Li^{2+}$ ions have been measured, yielding a relative statistical uncertainty $\Delta a/a = 2\%$ [2]. The complete analysis of the recorded data requires accounting for many factors like the background contribution, temperature of the ions in the trap, the effect of the RF field, the response functions of the detectors, and the electron shake-off effect.

Concerning this last point, the probability of shake off ionization following the beta decay process has been recently calculated for recoiling $^6Li^{2+}$ ions as a function of their recoil energy, and found to be on the order of 2% [3]. However, this effect has never been investigated experimentally for $^6He^+$ radioactive ions. We present in this work the simulations of a new setup which makes use of the existing LPC-Trap experiment to measure precisely this ionization probability.

References

[1] D. Rodriguez et al., Nucl. Instrum. Methods A 565 (2006) 876-889.
[2] X. Fléchard et al., submitted to Phys. Rev. Lett.
[3] Z. Patyk, private communication

STABILITY OF HIGHLY CHARGED FULLERENE CATIONS AND ANIONS

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The most abundant fullerenes, C_{60} and C_{70}, and all the pure-carbon fullerenes larger than C_{70} synthesized so far follow, with no exception, the isolated-pentagon rule (IPR)[1-2]. Fullerenes containing adjacent pentagons (APs) are less stable due to the additional strain. Surprisingly, recent experiments have shown that a few endohedral fullerenes[3], for which IPR structures are possible, hence expected to be the most stable ones, are stabilized in non-IPR cages. These cages are either positively or negatively charged, depending on the character of electron acceptor or electron donor of the encapsulated species. It has been argued that this unexpected stability of charged non-IPR fullerenes is associated with electronic properties of the carbon cage, such as unusually large HOMO-LUMO gaps or bond resonance energies[4,5]. These properties might be related to a reduction of strain induced by the encapsulated species, but the ultimate reasons remain unclear.

By performing density functional theory calculations[6-8] on a large number of C_{60} and C_{70} derivatives with both IPR and non-IPR cages, we show that, apart from strain, the physical property that governs the relative stability of highly charged fullerenes is the charge distribution in the cage[9]. This charge distribution is controlled by the number and location of two different structural motifs, one electrofilic (the pentalene motif, i.e., the pairs of APs,) and the other one electrophobic (the pyrene motifs). APs are the preferential sites to host additional electrons, either by adding explicitly those electrons or by making the AP bonds to react (or both). On the contrary, when one electron is removed from the fullerene cage, the resulting positive charge locates in the pyrene motifs, not in the pyrene bonds but in the more aromatic bonds surrounding the latter. Thus by playing with the number and position of pyrene bonds it is possible to generate non-IPR fullerenes with strongly non uniform positive charge distributions. We show that, when AP and pyrene motifs are uniformly distributed in the cage and well separated from each other, stabilization of non-IPR endohedral and exohedral fullerenes, as well as pure-carbon fullerene anions and cations, is more the rule than the exception. This suggests that non-IPR charged fullerenes might be even more common than IPR ones, which can be relevant to interpret recent experiments in which highly charged fullerenes are produced in collisions with ions or in storage rings.

References

[1] H. W. Kroto, Nature 1987, 329, 529-531.
[2] K. M. Kadish, R. S. Ruoff and Eds, Fullerene: Chemistry, Physics and Technology, Wiley, New York, 2002.
[3] S. F. Yang, A. A. Popov and L. Dunsch, Angewandte Chemie-International Edition 2007, 46, 1256-1259.
[4] J. Aihara, Theor. Chem. Acc. 1999, 102, 134-138.
[5] J. Aihara, Chem. Phys. Lett. 2001, 343, 465-469.
[6] S. Díaz-Tendero, M. Alcamí and F. Martín J. Chem. Phys. 2003, 119, 5545-5557.
[7] G. Sánchez, S. Díaz-Tendero, M. Alcamí and F. Martín Chem. Phys Lett. 2005, 416, 14-17.
[8] S. Díaz-Tendero, M. Alcamí and F. Martín Phys. Rev. Lett. 2005, 95, 013401.
[9] H. Zettergren, M. Alcamí and F. Martín ChemPhysChem. 2008, 861-866.

RELATIVISTIC LIGHT SHIFTS IN HIGHLY CHARGED IONS

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We investigate the level structure of heavy hydrogenlike ions in laser beams. In heavy ions, the electrons are tightly bound by the Coulomb potential of the nucleus, which prohibits ionization even by strong lasers. However, interaction with the light field leads to dynamic shifts of the electronic energy levels. We apply a fully relativistic description of the electronic states by means of the Dirac equation. Interaction with the monofrequent laser field is treated by second-order time-dependent perturbation theory. Our formalism goes beyond the Stark dipole approximation and takes into account non-dipole effects of retardation and interaction with the magnetic field components of the laser beam. This allows one to extend the theoretical description of light shifts to strong laser fields, high frequencies – e.g., x-ray lasers –, and to the highest nuclear charges. The resulting level shifts are relevant for experiments at present and near-future laser systems like the FLASH [1] and the PHELIX [2] facilities.

References

[1] S.W. Epp, J.R. Crespo López-Urrutia, G. Brenner *et al.*, Phys. Rev. Lett. **98**, 183001 (2007)

[2] P. Neumayer, R. Bock, S. Borneis *et al.*, Laser and Particle Beams **23**, 385 (2005)

Multiconfiguration Dirac–Hartree–Fock method for the calculation of static electric dipole moment in the many-electron atoms.

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A non-zero permanent static electric dipole moment (EDM) of an atom, molecule, as well as any other composite or elementary particle is one of possible manifestations of parity (P) and time reversal (T) symmetry violations. The observation of EDM of a many-electron atom may be a very important step in searching for a new physics beyond the Standard model of elementary particles [1]. One of the main possible sources of EDM in the many-electron atoms is the scalar – pseudoscalar, nuclear Schiff moment interactions between the electrons and the nucleus and permanent electron EDM. This interactions mixes parity of atomic states and also induces the EDM of an atom. In the multiconfiguration Dirac–Hartree–Fock method atomic state function (ASF) is expanded as the linear combination of configuration state functions (CSF) with same parity, total angular momentum of electrons and one of it's projection [2]. The *P* and *T* symmetry violations (induced by *S* – *PS* interaction) include small admixture of other opposite parity and same total angular momentum (F) ASFs to the main ASF:

$$\widetilde{\Psi}(\gamma\nu JIFM_F) = a\Psi(\gamma\nu PJIFM_F) + \sum_{i=1}^{n} b_i \Psi(\alpha_i \nu(-P) J_i IFM_F).$$

Combining experimentally obtained limits of EDM with calculations the limit of *S* - *PS* interaction constant, nuclear Schiff momenta and electron EDM can be found. For these calculations we extended GRASP2K [3] package of the relativistic atomic structure calculations. This extension includes the programs for the interations and EDM operators matrix elements calculation.

References

[1] J.S.M. Ginges, V.V. Flambaum, Phys. Rep. **397**, 63 (2004)
[2] I. P. Grant, B. J. McKenzie, P. H. Norrington, D. F. Mayers, N. C. Pyper, Comput. Phys. Comm. **21**, 207 (1980)
[3] P. Jönsson, X. He, C. Froese Fischer,I.P. Grant, Comput. Phys. Comm. **177**, 597 (2007)

The influence of relativistic effect for the DR of many electron ion

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The influence of relativistic effect for the energy levels and dynamical process, e.g. DR process, of many electron system is the interesting objective theoretically and experimentally. The energy levels and DR cross sections of nickel-like Ta are respectively calculated by quasi-relativistic and relativistic methods. For the high-Z many electron system, the electron correlation and relativistic effects should be simultaneously treated adequately. By the comparisons of the two results, the influences of the relativistic effect for the energy levels and dynamical processes of many electron system are demonstrated in detail. This work will provide a useful criteria for the requirement of relativistic effects of many electron system.

STUDY OF INTER SUB-SHELL AND INTER SHELL ELECTRON CORRELATIONS IN $4d$ OPEN-SHELL HEAVY ATOMIC IONS

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Due to the unique structures of $N = 4$ open sub-shells in heavy atomic ions, we have a chance to observe an interesting correlation effect between $4p$, $4d$, and $4f$ orbital electrons, providing us with characteristic spectral structures of $4p - 4d$ and $4d - 4f$ optical transitions[1]. To gain an insight of this effect, which is originally pointed out by O'Sullivan and Faukner[2], we have carried out careful MCDF calculations[3] for $4d^q$ ($q = 0$ to 10) atomic ions with atomic numbers $Z = 48$ to 56. We show ,in Fig.1, the single electron atomic orbital energies for Sr-like atomic ions of $Z = 48$ to 56; we have made their MCDF optimizations including the bases up to $6p, 5d,$ and$5f$. The differences of orbital energies between $4p$ and $4d$ orbitals, and $4d$ and $4f$ orbitals coincide within the range of a few %. The $4p^6 4d^1 4f^1$ and $4p^5 4d^3 4f^0$ configurations may mix strongly, and the optical $4p - 4d$ and $4f - 4d$ transitions may take place coherently, providing us with quite a peculiar EUV emission spectrum. We may expect that the so called the effect of spectral narrowing and shift is quite common to the atomic specieds with the atomic numbers in the range $Z = 48$ to 56.

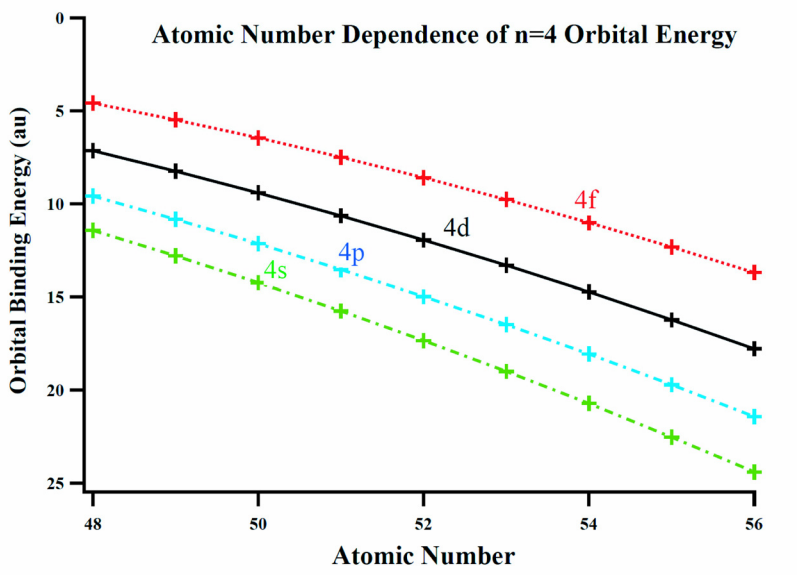

Figure 1: Atomic number Z dependence of the energies of $N = 4$ atomic orbitals. The calculated range of the atomic number is $Z = 48$ to $Z = 56$. Dotted curve: $4f$ orbital, Solid curve: $4d$ orbital, Dot-dashed curve in upper entry: $4p$ orbital, and Dot-dashed curve in lower entry: $4s$ orbital.

References

[1] G. O'Sullivan G et al 2006 *EUV Sources for Lithography Edited by V. Bakshi, SPIE Press Bellingham, Washinton, USA* 149

[2] O'Sullivan G, Faukner R 1994 *Opt. Eng.* **33**, 3978.

[3] Parpia F A, Fischer C F and Grant I P 1996 *Commpt. Phys. Commun.* **94** 249.

ACCURATE SPECTROSCOPY OF EXCITED LEVELS IN HE-LIKE URANIUM

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Electrons bound to a nucleus with a charge as high as Z=92 represent a unique probe of relativistic and Quantum Electrodynamics effects in the domain of strong fields. As compared to a one-electron and many-electron ions, heliumlike ions are the simplest multibody systems where the role electron-electron interaction in extreme conditions can be theoretically treated in a rigorous way. We present the first clear identification and highly accurate measurement of the intra-shell transition $1s2p\,^3P_2 \rightarrow 1s2s\,^3S_1$ of He-like uranium performed via X-ray spectroscopy. The present experiment has been conducted at the gas-jet target of the ESR storage ring in GSI (Darmstadt, Germany) where a Bragg spectrometer, with a bent germanium crystal, was mounted. A high systematic accuracy has been achieved making use of a differential measurement between He- and Li-like ions. With this method, it was possible to measure the $1s2p\,^3P_2 \rightarrow 1s2s\,^3S_1$ He-like U transition energy, at 4510 eV, with respect to the $1s^2 2p\ ^2P_{3/2} \rightarrow 1s^2 2s\,^2S_{1/2}$ Li-like U transition energy, at 4460 eV. First preliminary results of the data analysis will be presented.

TWO-PHOTON DECAY IN HIGHLY CHARGED HEAVY IONS: SPECTRAL SHAPE OF THE 2E1 ($2^1S_0 \rightarrow 1^1S_0$) IN HE-LIKE TIN

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The [1s2s] 2^1S_0 state of He-like ions decays to the ground state via two-photon electric dipole (2E1) transitions. The study of the spectral shape of this 2E1 decay mode in He-like ions is of interest due to its sensitivity to electron-electron correlations and relativistic effects [1]. In the present investigation, a novel experimental approach has been applied to study two-photon transitions in few-electron high-Z ions. Relativistic collisions of Li-like projectiles with low-dense gaseous matter were used to form the desired initial state [2], which allowed for a measurement of the undistorted two-photon spectral shape. The decay of the 2^1S_0 state in He-like tin was measured, following a successful earlier experiment with He-like uranium [3]. The continuum shape of the two-photon energy distribution was compared with fully relativistic calculations, which are Z-dependent. The preliminary results clearly show the best agreement with the relativistic calculations only in the region of correct nuclear charge thus confirming, for the first time, the sensitivity on Z. Detailed data analysis is still in progress.

References

[1] A. Derevianko and W.R. Johnson, Phys. Rev. A 56, 1288 (1997)
[2] Th. Stöhlker et al., Phys. Rev. A 57, 845 (1998)
[3] J. Rzadkiewicz et al., Phys. Rev. A 74, 012511 (2006)

THEORETICAL SIMULATION OF EXTREME ULTRAVIOLET SPECTRA OF TIN IN LASER-PRODUCED PLASMAS

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The emission of extreme ultraviolet (EUV) radiation from laser-produced tin plasmas is being studied extensively for its application in next generation semiconductor manufacturing technology. However, for pure Sn plasmas, the opacity is so high that 13.5 nm radiation emitted from deep within the plasma core is absorbed strongly during propagation through the surrounding plasma as it expands [1]. In addition, the spectrum of tin in the EUV range does not consist of sharp and well separated features, but a bright quasi-continuum band or unresolved transition array (UTA).

Extreme ultraviolet (EUV) emission spectra from laser-produced Sn plasmas have been experimentally investigated at different power densities in the 9.5-18 nm wavelength range. Experimental results indicate the presence of a broad reabsorption band and some pronounced dips because of opacity effects in the spectra. With increasing power densities, the reabsorption band shifts to the shorter wavelength side and the absorption dips become deeper.

Theoretical calculations using the Cowan code [2] show that the dips arise from the 4d-4f and 4p-4d transitions. Using detailed configuration accounting (DCA) with the term structures treated by the unresolved transition array (UTA) model [3], we analyze the opacity effects and simulate the spectra, as is indicated in figure 1. By comparing the results of the simulations with experiments, it can be concluded that the spectra from a pure Sn target contains both emission and absorption, with electron temperatures ranging from 28 to 15 eV, and electron densities from 5.0×10^{20} to $3.7\times10^{19}\,\mathrm{cm}^{-3}$, in going from the core to the outer plasma region.

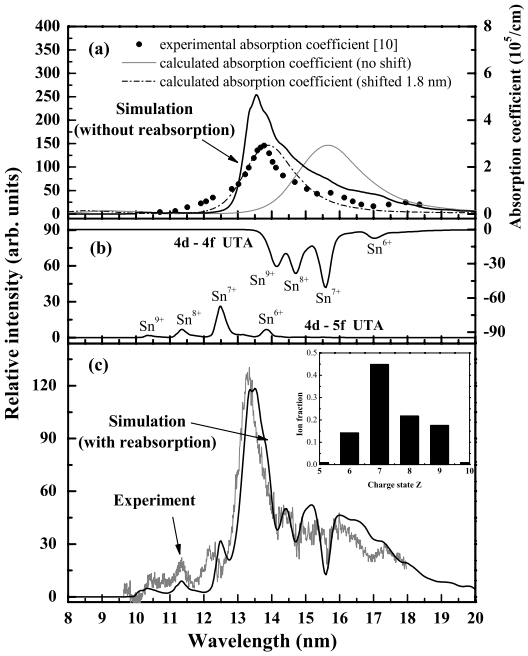

Fig. 1 Theoretical simulation and comparison of laser produced Sn spectrum.

References

[1] Y. Tao , S. S. Harilal, M. S. Tillack, K. L. Sequoia, B. O'Shay and F. Najmabadi, Optics Letters **31**, 2492 (2006).
[2] R. D. Cowan, The Theory of Atomic Structure and Spectra (University of California Press, Berkeley, 1981).
[3] J. Yan and J. M. Li. Chin. Phys. Lett. **17**, 194 (2000).

Visible spectroscopy with the Tokyo-EBIT

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Visible lines from highly charged ions, which can be used for diagnostics of plasmas, have been investigated extensively theoretically and experimentally. The investigations of the M1 transitions of Ti-like ions with EBIT are one of such examples [1].

Because W has been used as the plasma facing diverter wall due to the favorable physicochemical properties of this element, highly charged W ions exist in fusion plasmas for the sputtering of the diverter material. Therefore lines in the visible region from highly charged W ions can be one of the candidates for the diagnostics of fusion plasmas. Doron and Feldman [2] investigated theoretically visible and near UV transitions within N-shell ground state configurations of W. They showed that the intensity ratios of lines originating from transitions within the $4p^6 4d^5$ configuration of W^{33+} and $4p^6 4d^7$ of W^{31+} strongly depended on the electron density of plasmas. These lines could be used for diagnostics.

We have investigated visible lines from highly charged W ions with the Tokyo-EBIT. Since Doron and Feldman predicted that some lines arising from $4p^6 4d^k$ ground configurations could be observed in the range from 360 to 390 nm [2], our measurements were focused on the range from 350 to 400 nm and on the electron energy range from 1.1 to 1.7 keV. Several lines arising from highly charged W ions were observed in addition to the lines from lower charge state W ions.

References

[1] H. Watanabe, D. Crosby, F. J. Currell, T. Fukami, D. Kato, S. Ohtani, J. D. Silver, and C. Yamada Phys. Rev. A **63**,042513(2001).

[2] R. Doron and U. Feldman Phys. Scr. **64**,319(2001).

QED PERTURBATION THEORY IN CALCULATING NUCLEAR QUADRUPOLE MOMENTS AND HYPERFINE STRUCTURE PARAMETERS FOR LI-LIKE MULRICHARGED IONS

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Relativistic calculation of the spectra, hyperfine structure (hfs) parameters for heavy atoms and multicharged ions with account of relativistic, correlation, nuclear, QED effects [1,2] is carried out. Method is based on the gauge-invariant QED perturbation theory and generalized dynamical nuclear model [1]. The Fermi model has been used for modelling the distribution of charge in a nucleus. The results of the test calculation of the hyperfine structure parameters for H-like ion with nuclear charge Z=170 (plus derivatives of energy contributions on nuclear radius) are presented. A contribution of the relativistic, nuclear and radiative corrections is definitive one for H-like ion with Z=170. Calculation of the hfs parameters, splitting energies, constants (plus derivatives from energy contributions, the nuclear electric and vacuum-polarization potentials on nuclear radius) for Li-like ions with Z=20-100 is carried out. It is carried out an analysis of the inter-electron correlations, nuclear, radiative effects contributions, including an analysis of the role for nuclear effects contribution (core-polarization ones, which are induced by valent protons of a nucleus), temporal distribution of magnetization in a nucleus and high order QED corrections. As example table 1 contains data on hfs parameters $A=Z^3 g_I \overline{A}$, $B=\frac{Z^3 Q}{I(2I-1)}\overline{B}$ (cm^{-1}) for some Li-like ions.

nlj/Z		20	30	41	59	69	79	92
3s	$\overline{A}$	26 –03	29 –03	32 –03	43 –03	51 –03	63 –03	90 –03
4s	$\overline{A}$	15 –03	11 –03	14 –03	16 –03	19 –03	24 –03	36 –03
$2p_{1/2}$	$\overline{A}$	25 –03	30 –03	35 –03	46 –03	56 –03	71 –03	105 –02
$3p_{1/2}$	$\overline{A}$	81 –04	91 –04	09 –03	12 –03	16 –03	20 –03	31 –03
$4p_{1/2}$	$\overline{A}$	32 –04	37 –04	43–04	58 –04	72 –04	91 –04	11 –03
$2p_{3/2}$	$\overline{A}$	50 –04	55 –04	60 –04	65 –04	67 –04	71 –04	72 –04
	$\overline{B}$	9 –05	10 –04	11 –04	12 –04	13 –04	15 –04	17 –04
$3p_{3/2}$	$\overline{A}$	13 –04	14 –04	16 –04	18 –04	19 –04	21 –04	22 –04
	$\overline{B}$	31 –05	37 –05	41 –05	48 –05	51 –05	55–05	62 –05
$4p_{3/2}$	$\overline{A}$	62 –05	70 –05	77 –05	84 –05	89 –05	92 –05	10 –04
	$\overline{B}$	10 –05	12 –05	14 –05	18 –05	20 –05	22 –05	26 –05

References

[1] A.V.Glushkov, JETP Lett. **55,**108 (1992), A.V.Glushkov, L.N.Ivanov, Phys.Lett.A. **170**, 36 (1992); A.V.Glushkov, E.P. Ivanova, J.Quant. Spectr. Rad. Tr. (US) **36**,127 (1986); E.Ivanova, L.N.Ivanov, A.V.Glushkov, A.S.Kramida, Phys.Scr. **32,** 512 (1985); A.V.Glushkov, In: Low Energy Antiproton Phys. (AIP Serie) **796**, 211 (2005) ; J.Phys.CS. **11**,199 (2005);
[2] A..Glushkov, O.Khetselius etal, Nucl. Phys.A. **734**, e21 (2004); Phys.CS. **35**, 425 (2006); A. Glushkov etal, Recent Advances in Theory of Phys. and Chem. Systems, edited J.-P.Julien, J. Maruani, D.Mayuo, S.Wilson, G.Delgado-Barrio (Springer) **15**, 301 (2006); Ibid. **15**, 285 (2006).

ELECTRON IMPACT IONIZATION OF GROUND-STATE AND METASTABLE Li^+ IONS

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He-like systems are next in simplicity to H-like atoms and ions. Understanding their behavior in collisions is among the most fundamental problems in atomic physics. Although the first measurements on electron-impact ionization of He-like lithium ions have been performed a long time ago [1], satisfying theoretical treatment has become possible only recently. Benchmark-quality calculation have been published for ground state $Li^+(1s^2)$ [2] and metastable $Li^+(1s2s)$ ions [3]. The present investigation aimed primarily at providing high-quality experimental data on the electron impact ionization of ground state and metastable Li^+ ions and was accompanied by new calculations employing the converged coupled channel (CCC) method.

The crossed-beams technique was used to measure absolute cross sections in the energy range from near threshold to 1000 eV for electron impact ionization of Li^+ ions. By evaporating different parent materials into the ion source plasma, pure beams of ground-state or mixed beams of metastable and ground-state ions could be prepared. Fig. 1 shows experimental and theoretical data for ionization of ground-state Li^+. Almost perfect agreement is found between our experiments and the most recent theoretical calculations.

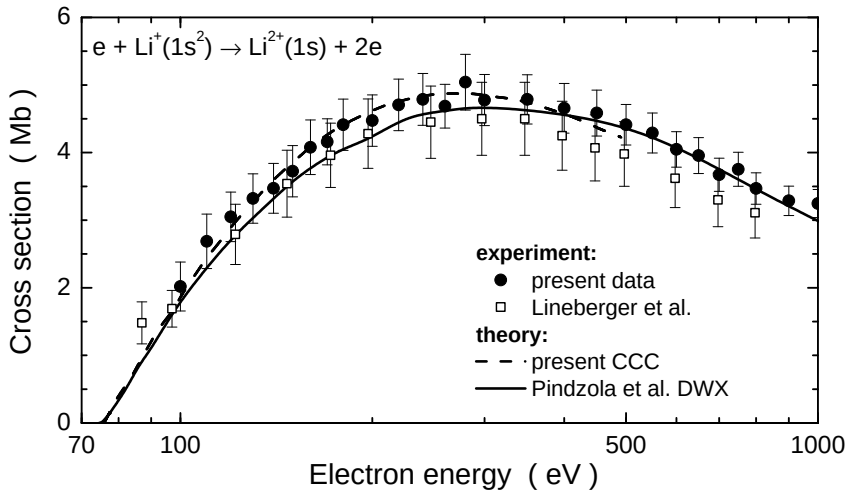

Figure 1: Electron impact ionization of $Li^+(1s^2)$: solid points and solid line represent the present experimental and theoretical results. Open squares are previous experimental data [1], the dashed curve shows distorted-wave with exchange (DWX) results from reference [2].

References

[1] W.C. Lineberger, J.W. Hooper, and E.W. McDaniel, Phys. Rev. **141**, 151-7 (1966)

[2] M. Pindzola et al., Phys. Rev. A**61**, 052712 (2000).

[3] J.C. Berengut et al., J. Phys. B: At. Mol. Opt. Phys. **40**, 1331-1336 (2007).

OBSERVATION OF HIGHER ORDER RESONANT ELECTRON RECOMBINATION PROCESSES BY HIGHLY CHARGED KRYPTON IONS

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By measuring resonant electron capture processes by highly charged ions, where the kinetic energy of the captured electron is transferred to bound electrons, atomic structure calculations can be tested stringently. These data are also relevant for plasma diagnostics applications. Many measurements of dielectronic recombination (DR) have been reported in recent years, see e. g. [1,2]. More detailed benchmarking of theory would results from the measurement of higher order resonant electron capture processes In the so called "trielectronic recombination" (TR) or "quadruelectronic recombination" (QR) resonances, two respectively three bound electrons are excited by the captured electron. Among the few reported related experiments, there exists an upper limit determination of the cross section for the TR-process in krypton [3] and also an observation of TR resonances in outer shells of Be-like chlorine at the Test Storage Ring [4]. We present the first observation of TR resonances including the K shell (*KL-LLL* TR) in highly charged krypton ions. Signatures of QR resonances

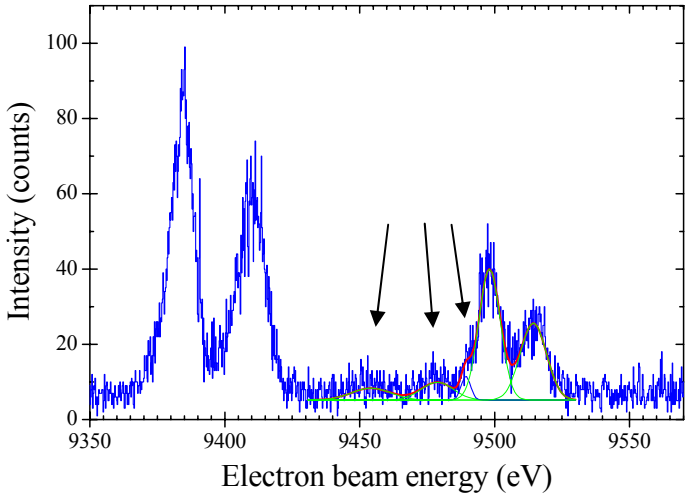

Fig. 1. Recombination of Kr HCI as a function of the electron beam energy. Mean peaks are due to C-like and N-like Kr. The weak features indicated by the two leftmost arrows were reproduced in several measurements and can be identified as the predicted TR of C-like krypton. The rightmost arrow appears at the position predicte for Be-like QR. The energy scale is preliminary.

have also been found for the first time (*KLL-LLL* QR). The excellent resolution achieved, has yielded more accurate data also for the DR resonances. These results have brought a further reduction of the uncertainty in the determination of the absolute resonance energies, and show good agreement with newest predictions of their values.

References

[1] A.J. González-Martínez *et al.*, Phys. Rev. Lett. **94** (2006) 203201
[2] Y. Zou, J. R. Crespo López-Urrutia and J. Ullrich, Phys. Rev. A **67** (2003), 043703
[3] M. Chevallier *et al.*, Phys. Rev. A **61** (2000), 022724
[4] M. Schnell *et al.,* Phys. Rev. Lett. **91** (2003) 043001

HIGH RESOLUTION LOW-ENERGY DIELECTRONIC RECOMBINATION RATE COEFFICIENTS OF BERYLLIUM-LIKE GERMANIUM: QED TEST BENCH FOR TWO-VALENCE-ELECTRON SYSTEMS

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High resolution measurements of low-energy dielectronic resonances of lithiumlike Sc^{18+}, performed at the Heidelberg TSR with a cold photoelectron target, allowed us to determine the $2s_{1/2}$-$2p_{3/2}$ transition energy in these systems with an accuracy of 4.6 ppm, less than 1% of the few-body effects on radiative corrections [1]. Following these studies we have investigated beryllium-like heavy ions with low-energy dielectronic resonances where QED corrections in atomic energy levels for a system with two valence electrons are promising for high accuracy tests. The dielectronic recombination (DR) of Ge^{28+} with a resonant capture of a free electron to the $9l$ Rydberg state accompanied by excitation of inner valence electrons from the $2s^2$ to the $2s2p(^1P_1)$ state was expected to show low-energy DR resonances below 0.2 eV.

The experiment at the TSR were carried out with different isotopes A=70, 73, 74 of beryllium-like Ge^{28+}. The MPIK tandem accelerator was used to inject ions of about 340 MeV kinetic energies into the storage ring with a typical ion current of few μA. The TSR's twin-beam electron facility was used for these measurements. Phase space cooling of ions was provided by an electron beam of high density (1.6×10^7 cm^{-3}) from the electron cooler. The cathode voltage of the cooler was kept constant, while the probe electron beam of low density (5.2×10^5 cm^{-3}) from the cryogenic photoelectron target [2] was used to measure DR spectra by scanning the electron energy. For these measurements the electron temperatures of the target beam were about 1.5 meV and 0.03 meV in the transverse and longitudinal direction, respectively. The details of the cryogenic photocathode target of the Heidelberg TSR are described elsewhere [2,3].

The DR measurements of beryllium-like Ge indeed revealed a series of sharp low–energy resonances in the range from about 100 meV up to 1.8 eV. The resonances can be assigned to capture of a free electron to the $9l$ Rydberg state accompanied by transition of a valence electron from the $2s^2$ to the 2s2p orbital forming a $^1P_1$ singlet state. Preliminary analysis shows that positions of low-energy resonances around 100 meV can be obtained with an accuracy of about 0.2 meV. The accurate calculations of Rydberg binding energies for these resonances is still required to derive a precise value of the $^1S_0$ -$^1P_1$ transition energy, which may give the opportunity to test QED corrections with high accuracy for atomic energy levels for two valence electron systems.

References

[1] M. Lestinsky, et. al., Phys. Rev. Let. **100**, 033001 (2008)
[2] D.A. Orlov, et. al., J.Phys.: Conf. Series **4**, 290 (2005)
[3] F. Sprenger, et. al., NIM A, **532**, 298 (2004)

LOW-LYING DIELECTRONIC RESONANCES OF FE XXII AND FE XVIII FOR ACCURATE ENERGY DETERMINATION OF AUTOIONISING RYDBERG LEVELS FOR BORON- AND FLUORINELIKE CORES

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We present high-resolution low-energy dielectronic recombination (DR) measurements of Fe^{21+} and Fe^{17+} performed at the Heidelberg Test Storage Ring (TSR) using the merged-beam technique.

Electron-ion recombination of L-shell ions has been studied at the TSR in the past as the dominant recombination process in interstellar plasmas [1, 2]. Besides their astrophysical relevance, such recombination processes provide an opportunity of testing atomic structure calculations of few-electron systems with multiple valence electrons.

The energy resolution of older datasets is limited by the former experimental setup at the TSR which involved only one electron cooler. This is especially true for the spectroscopically interesting low-energy part of the DR spectrum, at electron-ion collision energies below 1 eV. The setup has been improved by addition of an electron target, seperate from the existing electron cooler, which produces an ultra-cold electron probe beam employing a cryogenic photocathode [3, 4]. We were thus able to significantly improve the energy resolution of the DR measurements in the low-energy part of the spectra. In the case of Fe^{21+} the amount of individually resolved resonances is at least doubled compared to the previous measurement published in [2].

While former DR measurements on L-shell ions were focused on the absolute magnitude of the electron-ion recombination rate coefficient, our data provides a precise energy determination of low-energetic autoionising Rydberg levels with boron- and fluorinelike ionic cores, that could be used as a test bench in the process of extending existing precise atomic structure calculations for helium- and lithiumlike ions to systems with higher numbers of valence electrons.

References

[1] D. W. Savin *et al.*, Astrophys. J. Lett., **489**, 115 (1997)

[2] D. W. Savin *et al.*, Astrophys. J. Suppl. Ser., **147**, 421 (2003)

[3] F. Sprenger *et al.*, NIM A, **532**, 298 (2004)

[4] D. A. Orlov *et al.*, NIM A, **532**, 418 (2004)

DIELECTRONIC RECOMBINATION OF LI- AND BE-LIKE XENON IONS

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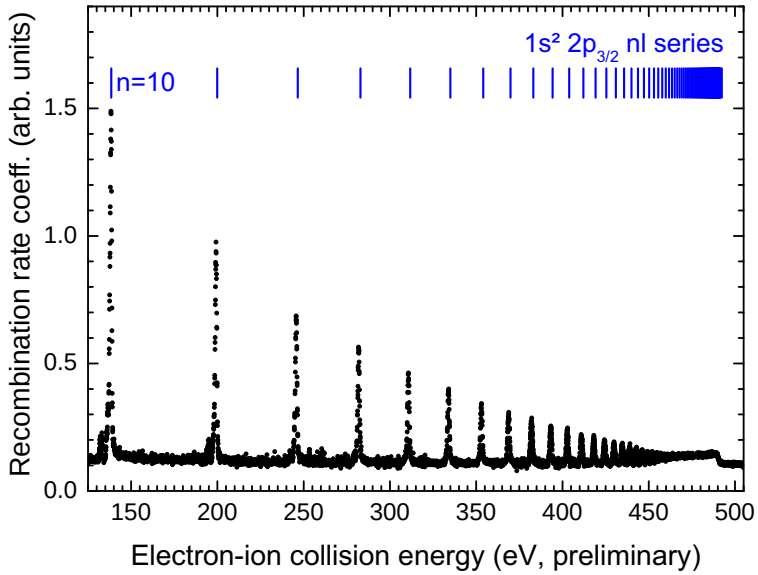
Dielectronic recombination (DR) of few-electron ions has evolved into a sensitive spectroscopic tool for highly charged ions. Recent experiments with Li-like ions clearly demonstrate that this collision spectroscopy is sensitive to 2nd order QED and to nuclear effects [1,2]. These studies exploit the fact that state-of-the-art theoretical methods treat few-electron systems with very high precision (see e.g. [3,4]).

With our present measurements of DR of Li-like $^{136}Xe^{51+}$ and Be-like $^{136}Xe^{50+}$ we aim at bridging the gap between low-charged systems such as F^{6+} [4] and highly charged ions such as U^{89+} [5]. At the same time xenon ions offer a broad distribution of naturally occurring isotopes with atomic mass numbers ranging from 124 to 136. This may be exploited in the future for studying isotope shifts of DR resonances and the extraction of nuclear charge radii [2]. The experiments were carried out by employing the electron-ion–merged-beam technique at GSIs heavy-ion storage ring ESR. The experimental collision energies ranged from 0 to ∼500 eV in the electron-ion center-of-mass frame. For both ions DR resonance spectra were obtained with high experimental resolving power (Fig. 1). Data analysis is in progress.



Dielectronic recombination of Li-like Xe^{51+}: In the displayed electron-ion collision energy range the DR spectrum exhibits a Rydberg series of $2p_{3/2}nl$ DR resonances associated with $2s_{1/2} - 2p_{3/2}$ core excitations. Individual nl resonance groups are resolved up to $n = 33$.

References

[1] M. Lestinsky et al., Phys. Rev. Lett. **100**, 033001 (2008)

[2] C. Brandau et al., Phys. Rev. Lett. **100**, 073201 (2008)

[3] Z. Harman et al., Phys. Rev. A **73**, 052711 (2006)

[4] M. Tokman et al., Phys. Rev. A **66**, 012703 (2002)

[5] C. Brandau et al., Phys. Rev. Lett. **91**, 073202 (2003)

EFFECTIVE COLLISION STRENGTHS FOR THE ELECTRON IMPACT EXCITATION OF NI XVII

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Ni XVII has recently been detected by the EIS instrument onboard Hinode [1]. The 249.18 Å line corresponding to the $3s^2\,{}^1S_0 - 3s3p\,{}^1P_1^o$ transition is analogous to the 284.16 Å transition of the iso-electronic Fe XV ion. Since this line is unblended, Young et al [1] indicate that it will be a useful probe of the hot cores of active regions.

Currently for this ion, there are no effective collision strength values available. Christensen et al [2] provide collision strengths at three incident electron energies using a Distorted Wave evaluation, and involving 16 fine structure levels. This method however does not include contributions from resonances, the presence of which can significantly enhance the maxwellian avergaed effective collision strengths and in turn greatly affect any diagnostics based on the data.

Therefore to provide a more accurate set of data, we have carried out a scattering calculation using the Dirac atomic R-matrix code (DARC), a method which does include contributions from resonances. The lowest 35 fine stucture levels have been included, having configurations $3s^2$, 3s3p, $3p^2$, 3s3d, 3p3d, $3d^2$ and the current evaluation considers partial waves up to $2J \leq 45$. Up to 52,000 energy points have been used to determine the detail in the collision strengths.

We mostly find good agreement in the background level of our collision strengths with the values from the Distorted Wave calculation of Christensen et al [2]. Collision strengths and effective collision strengths will be presented at the conference.

References

[1] P.R. Young, G. Del Zanna, H.E. Mason, et al, Publ. Astron. Soc. Japan **59**, S857-S864 (2007).

[2] R.B. Christensen, D.W. Norcross and A.K. Pradhan, Phys. Rev. A **34**, 4704-4715 (1986).

DIELECTRONIC RECOMBINATION INTO Mg-LIKE IONS

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Dielectronic recombination (DR) is important process governing ionization state of ions in various plasmas. Many theoretical and experimental studies on DR have been done for K-shell and L-shell ions, but not many for M-shell ions. Recently Netzer [1] and Kraemer et al. [2] suggested importance of M-shell Fe ions and the data needs for astrophysical plasmas such as photoionized plasma of active galactic nuclei. The solar observational satellite HINODE was launched in 2006 and has EUV Imaging Spectrometer (EIS) to observe the sun with EUV spectral lines of Fe M-shell ions [3]. Reliable data of total DR rate coefficient and state-selective DR rate coefficients are needed for determining ionization state of ions and level populations to estimate spectral line intensities.

Here we focus on DR process forming Mg-like ions. We have calculated energy levels, radiative transition probabilities, and autoionization rates for $1s^22s^22p^63l'nl$ (n =3-12, $l<n$) and $1s^22s^22p^64l'nl$ (n =4-7, $l<n$) states in Ti^{10+}, Fe^{14+} [4], Zn^{18+}, Se^{22+}, Kr^{24+}, and Mo^{30+} ions by using the Hartree-Fock-Relativistic method (Cowan code [5]). Autoionizing levels above three thresholds $1s^22s^22p^63s$, $1s^22s^22p^63p$, and $1s^22s^22p^63d$ are considered. Contributions from the excited states $1s^22s^22p^63l'nl$ with n >12 and $1s^22s^22p^64l'nl$ with n >7 to DR rate coefficients are estimated by extrapolation of all atomic characteristics. The state-selective and total DR rate coefficients are derived as a function of electron temperature. Figures 1 and 2 show the total DR rate coefficients of Kr and Zn ions. Contributions of high n states become important at Te >10eV.

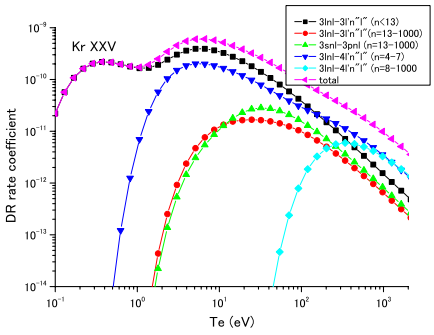

Fig.1 DR rate coefficient for Kr^{25+}.

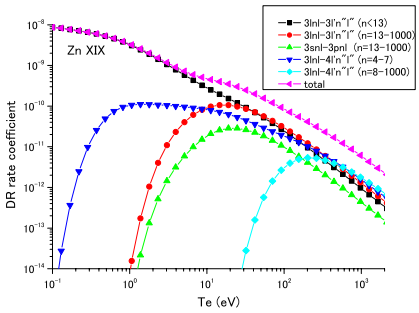

Fig.2 DR rate coefficient for Zn^{19+}.

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References

[1] H. Netzer, ApJ **604**, 551 (2004)
[2] S. B. Kraemer, G. L. Ferland, and J. R. Gabel, ApJ **604**, 556 (2004)
[3] J. L. Culhane, Solar Phys., **243**, 19 (2007)
[4] I. Murakami et al., NIFS-DATA-96 (2006); J. Phys. B, **39**, 2917 (2006)
[5] R. D. Cowan, *The Theory of Atomic Structure and Spectra* (Univ. of California Press, Berkeley, 1981)

CORRELATED STRONG-FIELD DYNAMICS AND NUCLEAR PROPERTIES EXPLORED BY RESONANT ELECTRON RECOMBINATION WITH HIGHLY CHARGED IONS

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In dielectronic recombination (DR), a free electron is recombined into an ion by resonantly exciting a bound electron. Dynamical and structural properties of highly charged ions have successfully be investigated by means of DR during the last decade. Also, it is one of the dominant atomic processes occurring in astrophysical and nuclear fusion plasmas, thus DR cross sections and spectra of x-rays emitted during the process yield indispensable information on a range of plasma properties.
We study the role of relativistic electron interaction and quantum electrodynamic effects in the strong binding fields of heavy nuclei in connection with experiments at the Heidelberg Electron Beam Ion Trap (EBIT) [1] and the Experimental Storage Ring of the GSI Darmstadt [2]. Current studies focus on DR resonance strengths and transition energies associated with the K-LL, K-LM and K-LN recombination channels in few-electron ions as heavy as W, Hg [1] and U [2]. Agreement between our calculations and the experiment is found only if the Breit contribution to the interaction of actively involved electrons is included in the theoretical model. The contribution of this relativistic correction to the total resonance strength amounts to 44% in the case of U [2]. Our investigations confirm the role of relativistic corrections to the electron interaction in a dynamical setting.
Furthermore, we investigate the higher-order resonant recombination process of trielectronic recombination (TR) in which two ionic electrons are simultaneously excited by nonlinear electron interaction. Our theoretical predictions for few-electron Kr ions have recently been confirmed by the first observation of KL-LLL TR using the Heidelberg EBIT [3].
Isotope shift measurements of low-lying dielectronic resonances, combined with atomic structure calculations, allow one to extract information on the nuclear charge distribution of the isotopes involved. We analyze the dependence of the electron interaction and QED contributions on the nuclear size and calculate mass shift terms to determine the change of the nuclear radius corresponding to the isotope shift in Li-like Nd measured with the ESR storage ring of the GSI [4]. This approach constitutes a new technique to determine nuclear radii.

References

[1] Z. Harman, I.I. Tupitsyn, A.N. Artemyev, *et al.*, Phys. Rev. A **73**, 052711 (2006); A.J. González Martínez, J.R. Crespo López-Urrutia, J. Braun, *et al.*, Phys. Rev. A **73**, 052710 (2006); V. Mäckel, Master's Thesis, Ruprecht-Karls-Universität Heidelberg, Germany (2006)

[2] C. Brandau, C. Kozhuharov, A. Müller, *et al.*, Rad. Phys. Chem. 75, 1763 (2006)

[3] C. Beilmann, Z. Harman, J.R. Crespo López-Urrutia, *et al.*, this volume

[4] C. Brandau, C. Kozhuharov, Z. Harman, *et al.*, Phys. Rev. Lett. 100, 073201 (2008)

HIGH PRECISION MEASUREMENT OF THE SPECTRAL WIDTH OF THE NICKEL-LIKE MOLYBDENUM X-RAY LASER

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In recent years, the advent of high-performance ultra short pulse lasers has made it possible to generate the high-brightness compact x-ray lasers [1-3] based on laser-produced plasmas. The gain media of the x-ray lasers are highly charged ions in high density plasmas. The precise knowledge about the wavelength and the spectral width of the lasing line is important for the applications of x-ray lasers, and especially for the spectral width, it is good benchmark of the atomic code because it depends on the electron collisional excitation and de-excitation rate coefficient. Only a few measurements of the spectral width of the laser line have been reported [4, 5], because the spectral width of the x-ray laser is so narrow that the required spectral resolution is quite high, *e.g.* $\Delta\lambda/\lambda \sim 10^{-4}$.

In this study, we took the nickel-like molybdenum x-ray laser ($4d\ ^1S_0$ - $4p\ ^1P_1$) as an example, and measure the spectral width by use of the high resolution spectrometer in order to compare it with a theoretical one. We obtained the spectral width of 20 mÅ at the wavelength of 18.9 nm ($\Delta\lambda/\lambda = 10^{-4}$). The details of the result of comparison the experiment result with the theoretical one are described in this conference.

References

[1] M. P. Kalachnikov *et al.*, Phys. Rev. A **57**, 4778 (1998).
[2] B. M. Luther *et al.*, Opt. Lett. **30**, 165 (2005).
[3] R. Keenan *et al.*, Proc. SPIE Vol. 5197, 213 (2003).
[4] J. A. Koch *et al.*, Phy. Rev. A 50, 1877 (1994).
[5] N. Hasegawa *et al.*, Jpn. J. Appl. Phys. Vol. 43, 2519 (2004).

ELECTRON ION COLLISION STUDIES AT THE STOCKHOLM ELECTRON BEAM ION TRAP

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A new laboratory for highly charged ions (HCI) has been build up at Stockholm University. An electron beam ion trap (S-EBIT) (3T magnet, <30keV electron beam) was installed and presently upgraded to a Super-EBIT version with 250 keV. It is used for in-trap spectroscopic and electron ion collision studies. In cooperation with Uppsala University an EUV-spectrometer has been mounted recently at the S-EBIT. S-EBIT is also used as an electron beam ion source. At one beam line an ion trapping system has been built up to cool HCI. These ions will be extracted into the ion trap SMILETRAP used for precision mass measurements[1]. Another beam line has been built up for measurements with nanocapillaries [2].
S-EBIT was used first in recombination studies of highly charged silicon and sulphur ions. X rays emitted from radiative recombination (RR) and dielectronic recomination (DR) and recorded in list mode as the electron beam energy was scanned. The recombination resonances can also be detected by counting the extracted ions of a certain charge state. This can be done using a photomultiplier detector after the charge state analyzing magnet. Another novel method is a time of flight detector mounted under zero degree which enables us to monitor several charge states simultaneously [3].

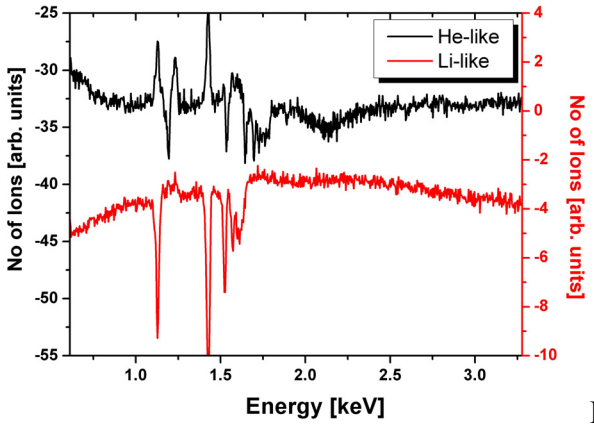

Figure 1. The recombination rate coefficients for He- and Li-like silicon ions measured with the TOF detector.

After the probing time during which the photons are measured the charge state distribution of the ions is recorded. As the electron energy is scanned and the electron ion collision energy matches a DR resonance the peak height of the charge state recombining decreases while the peak height of the adjacent next lower charge state increases. Figure 1 shows the integral over the peak of He- and Li-like silicon ions plotted against the collision energy. This technique can be combined with the one described in the paragraph above where the photons of the recombination process are measured. This will provide a more complete picture of the recombination processes. Silicon and sulphur are astrophysical abundant elements and accurate knowledge of the recombination process will help to improve theoretical methods used to model astrophysical plasmas.

References

[1] see contribution by M. Hobein et al.
[2] see contribution by P. Skog et al.
[3] S. Böhm, A. Enulescu, T. Fritioff, I. Orban, S. Tashenov, R. Schuch, Journ. Phys. **58**, 303, 2007

INVESTIGATING CORRELATED HIGH-FIELD FEW-ELECTRON QED BY MEANS OF DIELECTRIC RECOMBINATION IN $W^{69+...72+}$ IONS

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The study of dielectronic recombination (DR) in highly charged ions provides unique possibilities to explore relativistic correlation, quantum electrodynamic (QED) and nuclear size effects. Since deeply bound electrons experience extremely strong electromagnetic fields close to the nucleus, the the QED contributions to their binding energies become experimentally seizable. For tungsten ions (Z=74), QED contributions amount to roughly 100 eV. These effects can be estimated by accurately measuring the energies at which DR resonances occur.

In the present work, the KLL-DR resonances, where a free electron is captured by an ion into the L-shell while resonantly exciting a bound electron from the K-shell to the L-shell, were measured using the Heidelberg electron beam ion trap (EBIT). By slowly scanning the electron beam energy over the KLL-DR region between 39 keV and 44 keV and simultaneously monitoring the emitted x-rays, the DR resonance energies (see Fig. 1) of different charge states were determined relatively to the He-like resonances with a relative error as small as 3 eV at excitation energies of 40 keV. This high experimental accuracy allows one to test electron screening contributions to the QED corrections of self-energy and vacuum polarisation. A comparison with different predictions shows strong discrepancies for certain Li- and Be-like ion states while general agreement with other charge states is found. These results confirm earlier findings for mercury ($Hg^{75+...78+}$) DR measurements [1,2], highlighting the need for further investigations.

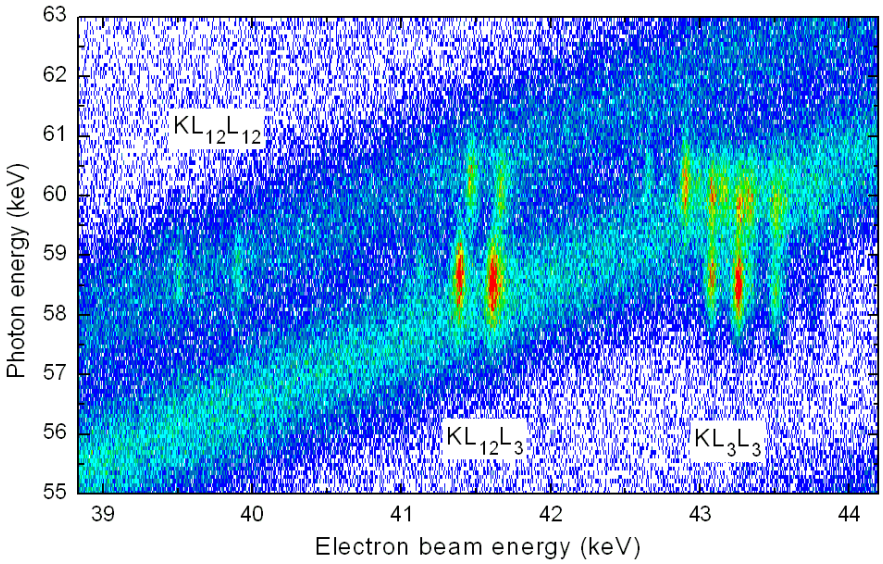

Figure 1: Scatter plot (photon counts as a function of electron beam energy and photon energy) showing the KLL DR resonances of $W^{69+...72+}$ ions which appear as distinct bright spots on top of the diffuse radiative recombination lines.

References

[1] A.J. González Martínez et al., Phys.Rev. A 73 (2006) 052710

[2] Z. Harman et al., Phys.Rev. A 73 (2006) 052711

DIELECTRONIC RECOMBINATION OF Na -LIKE S AND Na-LIKE Ar IN THE PRESENCE OF EXTERNAL FIELDS

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Dielectronic recombination (DR) is a resonant channel, in which recombination of a free electron and an ion takes place through an intermediate doubly excited state. DR is an important process governing charge-state distributions in astrophysical and laboratory plasma. External fields can enhance DR and can have important effects on various parameters of the plasma, e.g., can increase significantly the radiative cooling of magnetically confined fusion plasma.

Enhancements of DR by external fields were first suggested by LaGattuta et al. [1] and were experimentally verified by Muller et al. [2] in a crossed-beam experiment. DR in presence of external fields (DRF) was later studied at storage rings for Li-like ions [3, 4].

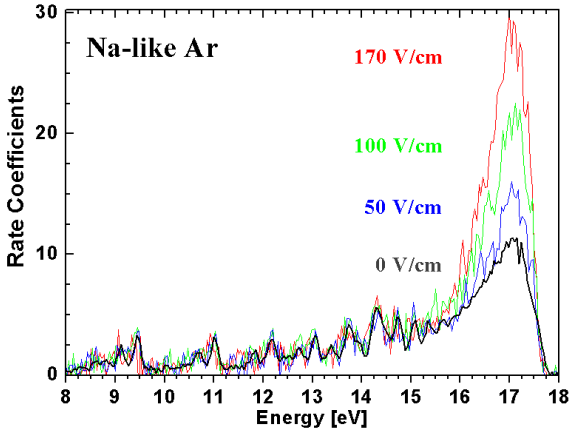

Fig. 1. Recombination spectra of Na-like Ar.

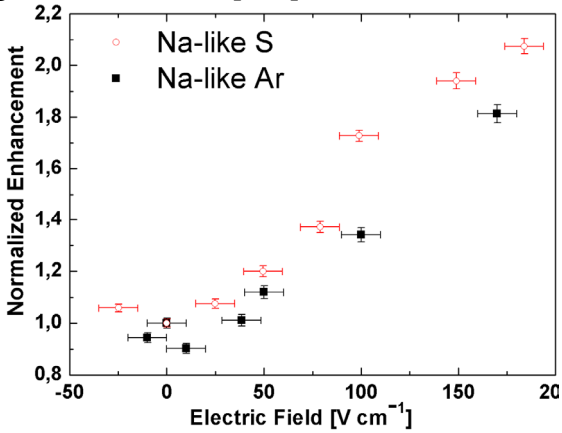

Fig. 2. Normalized enhancement coefficients.

We present preliminary results from the first storage-ring investigations of DRF, in spectra of astrophysically abundant Na-like ions. Recombination spectra of Na-like S^{5+} and Na-like Ar^{7+}, in the presence of motional electric fields ranging between 0 and 185 Vcm^{-1}, were measured at the CRYRING storage ring. In the electron cooler section of the storage ring, an electron beam was merged with the circulating ions over a distance of 80 cm. A motional electric field was created in the interaction region by inducing an angle between the 30 mT magnetic field guiding the electrons and the ion trajectory. Recombined ions were separated from the circulating beam in the first dipole magnet after the electron cooler. Field ionization at this dipole magnet hindered detection of ions recombined into high Rydberg states.

The recorded spectra (fig. 1) were integrated over the range affected by the external electric fields and the results were normalized to the 0 field case. An enhancement increasing with the electric field was observed for both ions, with enhancement factors of over 2 and 1.8, in case of Na-like S and Na-like Ar, respectively. Saturation was not reached yet, and as seen from the trend of enhancement vs. electric field (see figure 2), even higher enhancements are to be expected at stronger fields.

References

[1] K. LaGattuta *et al*. Phys. Rev. Lett. **51,** 558 (1983)
[2] A. Müller *et al*. Phys. Rev. Lett. **56,** 127 (1986)
[3] T. Bartsch *et al*. Phys. Rev. Lett. **79,** 2233 (1997)
[4] S. Böhm *et al*. Phys. Rev. A **65,** 052728 (2002)

POSSIBILITY OF RESONANT CAPTURE OF ANTIPROTONS BY ELECTRON EXCITATION IN HYDROGENLIKE IONS

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Exotic atoms are fascinating systems where the parameters determining the properties of ordinary matter can be tuned and investigated in completely new regimes. Since the early nineties the $He^+\bar{p}$ system has been studied intensively and has e.g. recently led to a significant improvement of the value for the electron-antiproton mass ratio. With the future facility FLAIR at GSI, cooled antiprotonic beams with an intensity much higher than available today will be provided which might open new possibilities for the production of antiprotonic exotic systems, as for example highly charged antiprotonic ions. Here we study the feasibility of resonant antiprotonic capture by highly charged hydrogenlike ions, a process that can be seen as the antiprotonic analogon of dielectronic recombination.

If, in an electron-ion collision, the energy of the antiproton is tuned such that the resonant condition is fulfilled, it can be captured into a bound orbit by simultaneous excitation of a target electron and thus form a doubly excited electron-antiproton state. This presents an additional channel to non-resonant capture of antiprotons by ions [1-3] where the energy is transmitted to an ejected target electron. The doubly excited state can subsequently decay by electron-, antiproton- or photon emission, and the rates for these processes will essentially determine the cross section for antiprotonic capture.

We have calculated the positions of the resonances and the rates for antiproton- and electron emission for a test case; Ca^{19+}. The full Hamiltonian is diagonalized on a B-spline basis, and complex scaling is used to handle the coupling to the continuum [4]. The numerical accuracy of the of the antiprotonic capture rates was tested through comparison between a second order complex rotation calculation and a Fermi Golden Rule calculation. Radiative decay rates were estimated in the dipole approximation with a first order perturbation theory approach.

Several groups of resonances were found in the region close to the $Ca^{19+}(1s)$ ionization threshold, arising from the configurations $(n_e, n_{\bar{p}}) = (2, 48), (2, 49), (3, 45)$ and $(4, 44)$. Electronic radiative transitions provide the dominant decay channel, and the antiproton ejection rate is found to be very sensitive to the total angular momentum of the resonances.

References

[1] J. S. Cohen, Phys. Rev. A **69**, 022501 (2004)

[2] K. Sakimoto, Phys. Rev. A **74**, 022709 (2006)

[3] K. Sakimoto, Phys. Rev. A **76**, 042513 (2007)

[4] J. L. Sanz-Vicario, E. Lindroth, N. Brandefelt, Phys. Rev. A **66**, 052713 (2002)

THE ENHANCEMENT EFFECT IN RADIATIVE RECOMBINATION OF BARE URANIUM IONS WITH COOLING ELECTRONS

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The "enhancement" effect, which was observed in radiative recombination (RR) of heavy bare ions with cooling electrons in storage ring experiments by observing recombined ions (see Ref. [1]), needs detailed experimental studies to be fully explained. Guided by this motivation, the radiative recombination of U^{92+} ions (23 MeV/u) with electrons was studied in a state-selective way by observing the emitted x-rays for relative electron energies in the range $E_{rel} = 0 - 1000$ meV. The x-rays emitted from the recombination process were measured by two germanium detectors placed close to 0° and 180° with respect to the ion beam direction. In this experiment the radiative recombination into low n-states was probed by observing the K-RR and L-RR x-rays, while the emitted Lyman and Balmer x-ray transitions, populated by the radiative cascades following decay of high Rydberg states, yielded information on the RR into high n-states.

From the the measured K-RR recombination rate for relative electron energies $E_{rel} = 0 - 1000$ meV the transverse electron beam temperature was derived allowing thus a determination of the recombination enhancement for the cooling condition ($< E_{rel} >= 0$ meV). The measured RR rates for the K-shell were compared with the relativistic calculations of the RR process. In this comparison a correction for a contribution from the two-step RR+RD process [2], namely the RR into high n-state followed by the radiative decay (RD) via the transition np-1s, was estimated. We demonstrate that in the present experiment an enhancement of the recombination of U^{92+} ions with cooling electrons for n=1 state was observed by comparing the K-RR data with the theoretical predictions. This is the first experimental observation of the recombination enhancement for the low n-state, which is important for explanation of the origin of the enhancement effect.

References

[1] W. Shi *et al.*, Eur. Phys. J. D15, 145 (2001).

[2] M. Pajek *et al.*, presented at the ICPEAC-2007 Conference.

THEORETICAL INVESTIGATION ON QUANTUM INTERFERENCE EFFECTS BETWEEN DIELECTRONIC RECOMBINATION AND RADIATIVE RECOMBINATION FOR HIGHLY CHARGED IONS

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The photorecombination (PR) process of a multiply charged ion with a free electron is traditionally described in terms of two distinct recombination mechanisms. The first is nonresonant or direct radiative recombination (RR), which is the inverse of the ordinary photoionization process, and the second corresponds to the two-step, resonant dielectronic recombination (DR) process. These two recombination mechanisms are usually treated as independent processes. It has been recognized, however, that the traditional description of RR and DR, as two independent, noninterfering processes, is not strictly permissible within the framework of a rigorous quantum-mechanical theory [1].

Indeed, more than 40 years ago, Fano [2] predicted the interference between transition amplitudes leading directly into the ionization continuum and those indirectly proceeding via a discrete intermediate resonant state. Several theoretical investigations have been carried out in pursuit of prominent manifestations of the quantum-mechanical interference between RR and DR. Asymmetrical PR cross-section profiles, which are characteristic spectral signatures of a prominent quantum-interference effect, have been observed firstly by Knapp *et al.* [3] for the PR of very highly charged uranium ions, and also have been detected for highly charged mercury ions by González Martínez *et al.* [4] recently.

Using a projection-operator and resolvent-operator approach [1], total cross section of electron-ion photorecombination processes are calculated for highly charged Hg^{75+} ion. This approach provides a unfied quantum-mechanical description of the combined electron-ion PR process, including radiative and dielectronic recombination as coherent, interfering components. The related energy levels, wavefunctions and transition data for B-like Hg ion have been obtained using GRASP92 package [5], component program REOSS99 [6] and AUGER [7], which is based on multiconfiguration Dirac-Fock method. The RR cross section calculated using our recent developed program RERR06 [8]. The present theoretical results show evident asymmetrical profile in the $KL_{12}L_3$ DR resonant region.

References

[1] M. Zimmermann, N. Grün, W. Scheid, J. Phys. B **30**, 5259 (1997)

[2] U. Fano, Phys. Rev. **124**, 1866 (1961)

[3] D. A. Knapp, P. Beiersdorfer, M. H. Chen *et al.*, Phys. Rev. Lett. **74**, 54 (1995)

[4] A. J. González Martínez, J. R. Crespo López-Urrutia, J. Braun *et al.*, Phys. Rev. Lett. **94**, 203201 (2005)

[5] F. A. Parpia, C. Froese Fischer, I. P. Grant, Comput. Phys. Commun. **94**, 249 (1996)

[6] S. Fritzsche, C. Froese Fischer, C. Z. Dong, Compt. Phys. Commun. **124**, 340 (2000)

[7] S. Fritzsche, H. Aksela, C. Z. Dong *et al.*, Nucl. Instrum. Methods B **205**, 93 (2003)

[8] J. J. Wan, C. Z. Dong, C. C. Sang *et al.*, J. Phys: Confer. Ser. **58**, 367 (2007)

RESONANCE ELECTRON IMPACT EXCITATION AND POLARIZATION OF MAGNETIC QUADRUPOLE LINE OF NEONLIKE BA^{46+} IONS

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When the highly charged ions are excited by electron beam or more generally by electrons with an anisotropic velocity distribution, the excited state populations for the magnetic sublevels may be in a nonstatistical way. Then, the radiation emitted from these unequally populated sublevels to a lower level may be strongly polarized. The degree of polarization depends on the extent of deviation from the statistical populations of excited magnetic sublevels. In the present work, a new rapid and accurate fully relativistic Distorted program has been developed, based on the Zhang's method[1] and the Grasp92[2], Ratip [3] and REIE [4] packages, for calculating the specific magnetic sublevel excitations including both the direct and resonance excitation contributions. As an example, the electron impact excitation processes of neonlike Ba^{46+} ions were studied systematically, and the polarization degree of the magnetic quadrupole line is obtained and compared with the experimental measurements[5]. Our results shown that the $4l5l'$ resonant series have larger contributions on the electron impact excitation cross sections which were enhanced more than two times compared with the direct excitation when the impact energy in the range of 5keV to 5.2keV, and the polarization changes from -22% to 4% in this energy range. However, the $4l6l'$ and $5l5l'$ resonant series have small contributions to the excitation cross sections, but they make the polarization of the M2 line changes evidently. Our results are found to be in excellent agreement with the experimental results[5].

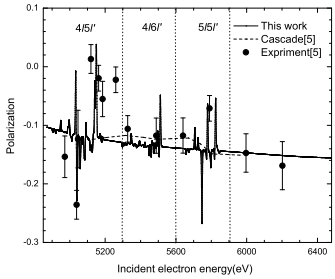

Figure 1: Linear polarization degree of neonlike Ba^{46+} M2 line $(2p_{3/2}^{-1}3s_{1/2})_2 \rightarrow 2p^6\ J = 0$ as a function of the incident electron energy.

References

[1] H. L. Zhang, *et. al.* Phys. Rev. A **41**, 198 (1990), Phys. Rev. A **66**, 042704 (2002)

[2] F. A.Parpia, C. F. Fischer and I. P. Grant, Comput. Phys. Commun **94**, 249 (1996)

[3] S. Fritzsche *et al.*, Nucl. Instr. and Meth. in Phys. Res. B **205**, 93 (2003)

[4] J. Jiang, C. Z. Dong, L. Y. Xie, *et. al.* Chin. Phys. Lett. **24**, 691 (2007)

[5] E. Tak*á*cs, E.S. Meyer, J.D. Gillaspy, J.R. Roberts, *et. al.* Phys. Rev. A **54**, 1342 (1996).

ISOMER EFFECT ON IONIZATION PROCESSES IN COLLISIONS OF 6-MEV/AMU BARE-IONS WITH C_3H_6 MOLECULES

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We have been studying ionization of hydrocarbon molecules in 6-MeV/amu fully stripped-ion impact through measurements of gross ionization cross sections and relative intensities of individual secondary ions. In the present study, the target was chosen to be hydrocarbon isomers, C_3H_6 propylene and $(CH_2)_3$ cyclopropane to study the effect of molecular structure on the ionization and subsequent fragmentation processes. The experiment was carried out using the 6-MeV/amu-H^+, He^{2+}, -C^{6+}, -Ne^{10+}, and -Ar^{18+} projectiles provided by the Heavy Ion Medical Accelerator in Chiba (HIMAC) of the National Institute of Radiological Sciences.

The gross ionization cross sections were measured with the parallel-plate-condenser method [1]. The reproducibility of the cross sections was within 2%. The cross sections of cyclopropane were found to be 2-3% larger than those of propylene for all projectiles studied here. On the contrary, the electron impact experiments for isomer hydrocarbons showed quite different features; the cross sections for propylene were reported to be larger than those for cyclopropane (roughly 2-3%) [2]. Unfortunately, no comparable data exists in the ion impact, and the cause of such discrepancies is not clear at present.

Figure 1 shows the secondary ion spectra measured for propylene and cyclopropane . It should be noted that the most prominent peak is the parent molecular $(CH_2)_3^+$ ion in cyclopropane, whereas the $C_3H_5^+$ ion predominates the $C_3H_6^+$ ion in propylene, indicating an isomer effect in fragmentation. Doubly charged molecular ions, such as $C_3H_6^{2+}$, $C_3H_5^{2+}$, $C_3H_4^{2+}$and $C_3H_3^{2+}$, were apparently produced in these molecules.

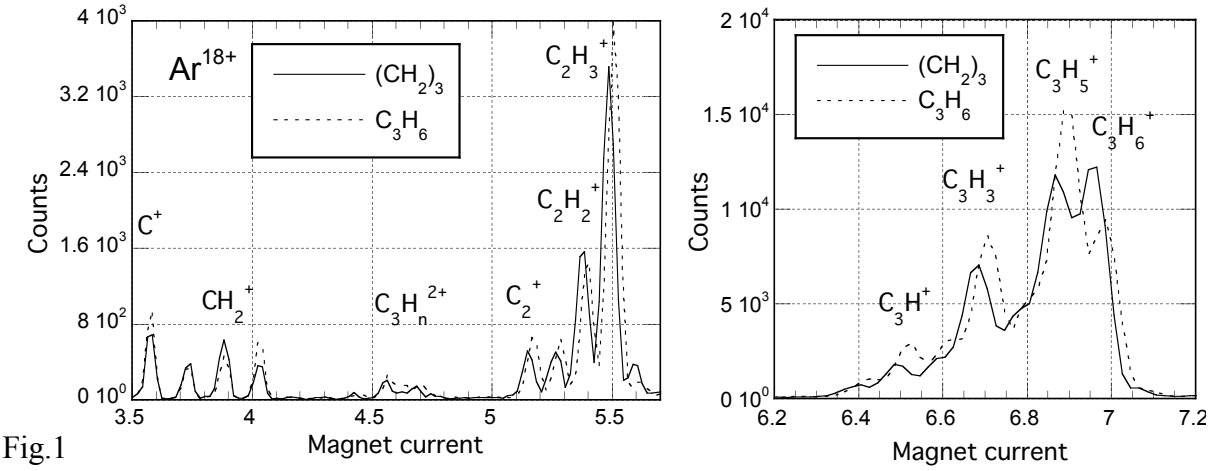

Fig.1

References

[1]T. Matsuo, T. Kohno, et al., Phys. Rev. A, 60, 3000-3007, 1999.

[3]H. Nishimura and H.Tawara, J. Phys. B: At. Mol. Opt. Phys. 27, 2063-2074, 1994.

STATE-SELECTIVE DIFFERENTIAL CROSS SECTIONS FOR SINGLE, DOUBLE ELECTRON CAPTURE IN LOW ENERGY HE^{2+}-HE COLLISIONS

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For 20-40 keV He^{2+} on He collisions, we have measured state-selective single and double electron capture cross sections and differential cross sections in projectile scattering angle by the Cold Target Recoil Ion Momentum. Absolute state-selective angular differential cross sections are obtained for electron capture into ground state and excited states of projectiles. It is found that the single electron capture into the L shell is a dominant reaction channel, and double electron capture into ground state is by far dominant in the incident energy range. The single electron capture into the excited states occur at a smaller distances than the ground state capture. Figure 1 shows the energy dependence of state-selective capture cross sections, where results are compared with Fritsch's calculation [1] and other experimental results [2]. Figure 2 shows the state-selective angular differential cross sections. More results for double electron capture will be presented at the conference.

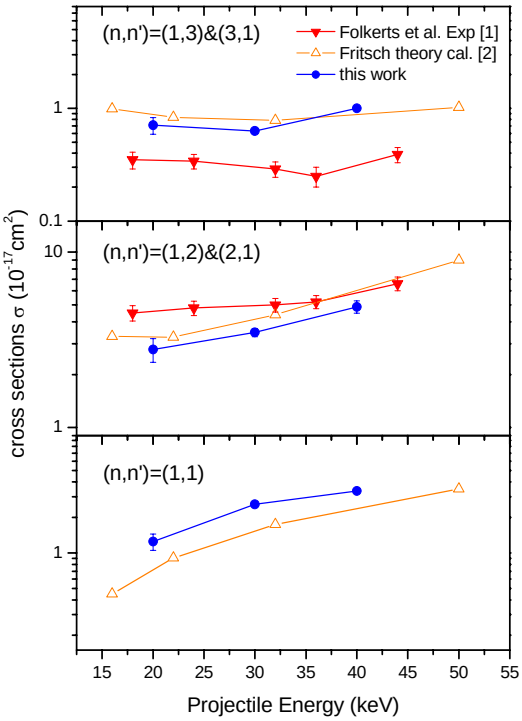

Fig. 1 State-selective cross sections for 20, 30 and 40 keV He^{2+} on He single electron capture.

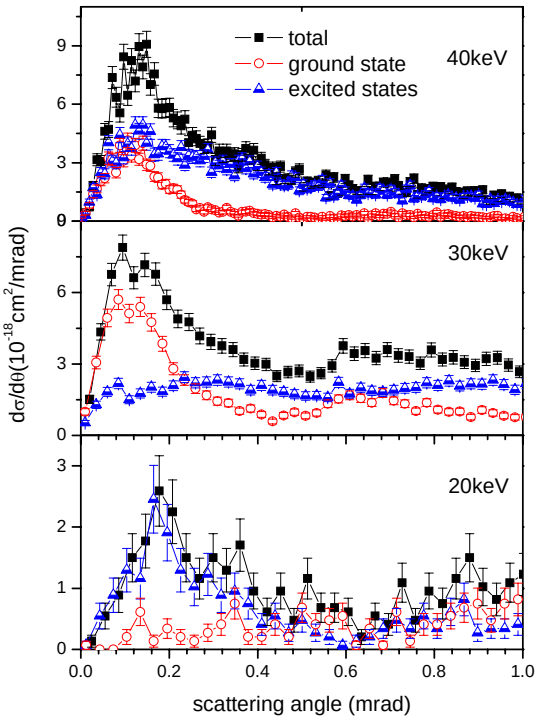

Fig. 2 Scattering angle distribution for 20, 30 and 40 keV He^{2+} on He single electron capture.

References

[1] Folkerts H O , Bliek F W, Meng L et al. J. Phys. B: At. Mol. Opt. Phys. **27**,3475(1994)
[2] Fritsch W, J. Phys. B: At. Mol. Opt. Phys. **27**, 3461(1994)

ASYMPTOTIC THEORY FOR SINGLE AND DOUBLE ELECTRON CAPTURE IN LOW – ENERGY COLLISIONS OF HIGHLY CHARGED IONS WITH MOLECULES

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The collision processes of highly charged ions B^{Z_b+} with molecules $\mathrm{A}_2^{(Z_a-2)+}$ have recently attracted considerable interest in view of their observed role in generation the X–ray and EUV radiation in the cometary atmospheres interacting with the solar wind [1a] and in certain astrophysical environments [1b], and in the cooling of divertor plasmas of magnetic fusion devices [1c]. In the present work we shall employ the asymptotic method [2] to study the electron–exchange interactions and the dynamics of corresponding inelastic low–energy collision processes in the $\mathrm{A}_2^{(Z_a-2)+}$ + B^{Z_b+} collision system, where Z_a and Z_b are the effective charges of the molecular core $\mathrm{A}_2^{Z_a+}$ and of the ion B^{Z_b+}. We study the most important one- and two–electron exchange processes in this collision system:

- nondissociative single electron captures (NDSEC):

$$A_2^{(Z_a-2)+}(e_1,e_2) + B^{Z_b+} \rightarrow A_2^{(Z_a-1)+}(e_2) + B^{(Z_b-1)+}(e_1); \tag{1}$$

- two–electron capture (TEC):

$$A_2^{(Z_a-2)+}(e_1,e_2) + B^{Z_b+} \rightarrow A_2^{Z_a+} + B^{(Z_b-2)+}(e_1,e_2); \tag{2}$$

- single electron capture with simultaneous target excitation:

$$A_2^{(Z_a-2)+}(e_1,e_2) + B^{Z_b+} \rightarrow A_2^{(Z_a-1)+^*}(e_2) + B^{(Z_b-1)+}(e_1). \tag{3}$$

The method of deriving the asymptotic form of one–electron three–centre wave function of the quasi-molecules $\mathrm{A}_2^{Z_a+} + \mathrm{B}^{(Z_b-2)+}$ and $\mathrm{A}_2^{(Z_a-2)+} + \mathrm{B}^{Z_b+}$ in different regions of configuration space is described. Obtained results are used to calculate the asymptotically exact one– and two–electron exchange interactions (nonadiabatic couplings) responsible for one–electron capture (1) and two–electron processes (2) and (3), respectively. The obtained analytical results on electronic couplings are used for close–coupling calculations of the total and state-selective n–, ℓ–resolved cross sections of one- and two–electron capture processes in the $\mathrm{He}^{2+} + \mathrm{H}_2$ collision system in energy range 0.1 – 50 keV/amu.

References

[1] (a) T. E. Cravens, Science **296**, 1042 (2002); (b) R. Lallement, Astron. and Astrophys. **422**, 391 (2004); (c) R. K. Janev, Contemporary Phys. **46**, 121 (2005)

[2] M.I. Chibisov, R.K. Janev, Phys. Rep. **166**, 1 (1988); V.Yu. Lazur, M.V. Khoma, R.K. Janev, Phys. Rev. A. **73**, 032723 (2006)

ENERGY GAIN MEASUREMENTS OF HIGHLY CHARGED Xe IONS IN COLLISIONS WITH RARE GAS TARGETS AT 200 eV

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Experimental study of collision dynamics of multiply charged Xe and Sn ions with atoms and molecules at low energies below 1 a.u. is important not only in atomic physics but also in various applied fields. Especially, charge transfer processes involving Xe and Sn ions in their plasmas have attracted attention for the developments of strong EUV light sources for new lithography techniques. In the Xe or Sn plasmas, these ions always capture electron(s) and de-excite with emitting photons (sometimes EUV) or electrons. Therefore knowledge of charge transfer and decay scheme of these ions in plasma is needed for the development of strong EUV source. However it is difficult to understand not only those energy levels including their excited states but also charge transfer process, since multiply charged heavy ions such as Xe^{q+} and Sn^{q+} (q around 10) still have many electrons.

In this work, we have measured energy gain spectra of Xe^{q+} with rare gas targets for the charge state around ten at 200 q eV. The experiment was performed using Mini-EBIS ion source at Nara Women's University [1]. Multiply charged Xe ions extracted from the Mini-EBIS were mass-analyzed by electro-magnetic analyzer and collided with the effusive target gas at the collision cell. Then projectile ions after the collision were analyzed by a parallel plate energy analyzer, detected by Position sensitive detector and recorded into PC.

We have compared the measured energy gain spectra with theoretical energy levels of projectile ion after the charge transfer. Here we have used calculated energy levels of excited Xe ions by Kagawa et al [2]. The dominant charge transfer processes are predicted as following,

$$\begin{aligned} Xe^{9+} + He &\rightarrow Xe^{8+}(4d^8 4f^1 5s^1, 4d^8 5s^1 5p^1) + He^+, \\ Xe^{10+} + He &\rightarrow Xe^{9+}(4d^7 4f^2, 4d^8 5s^1, 4d^8 5d^1) + He^+, \\ Xe^{11+} + He &\rightarrow Xe^{10+}(4d^6 4f^2, 4d^7 5d^1) + He^+. \end{aligned}$$

For q = 9-11, Xe^{q+} ions dominantly capture electron into $Xe^{(q-1)+}$(n = 4, 5), although predicted energy levels of projectile after charge transfer by using classical over barrier model are much higher [3]. Detailed results and discussions including results for another target species and calculation by classical over barrier model will be presented at the conference.

References

[1] K. Ishii, Y. Inoue, H. Ogawa, A. Itoh and N. Sakamoto, J. Phys. Conf. Ser. **58**, 275 (2007).

[2] T. Kagawa, private communication

[3] A. Niehaus, J. Phys. B: At. Mol. Phys. **19**, 2925 (1986).

DIFFERENTIAL CROSS SECTIONS FOR SINGLE-ELECTRON CAPTURE BY LOW-ENERGY O_2^{2+} IONS FROM Ne and O_2

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Electron capture processes by multiply charged molecules are of importance not only in hot astrophysical and terrestrial plasmas but also in low-temperature plasmas. The O_2^{2+} ions are of particular interest due to their potential influence on the properties of the ionosphere and their involvement in many atmospheric and astrophysical phenomena. In the present work, state-selective differential cross sections for non-dissociative single-electron capture processes in low-energy collisions of O_2^{2+} recoil ions with Ne and O_2 at an impact energy of 100 eV and scattering angles between 0^o and 6^o have been studied using a differential energy-gain spectrometer [1], capable of measuring simultaneously the energy-gain and the scattering angle of projectile products in ion-atom/molecule collisions. Our results show clear evidence of the presence of metastable states in the incident O_2^{2+} ion beam.

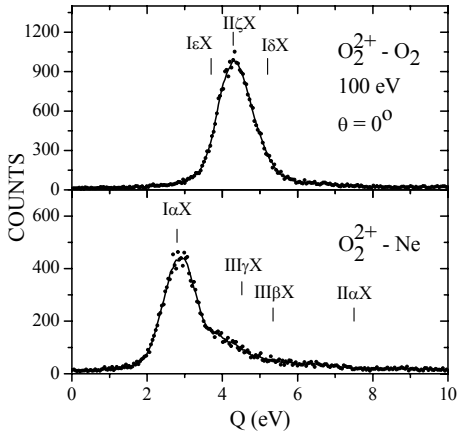

Figure 1: Translational energy-gain spectra for single-electron capture by 100 eV O_2^{2+} ions from O_2 and Ne at 0^o scattering angle. The designations I, II, and III represent, respectively, the ground, first, and second electronically excited states of O_2^{2+}; α, β, γ, represent the ground and subsequent electronically excited states of O_2^+ ion; X, represents the ground state of the target product.

In O_2^{2+} - O_2 system, the observed spectrum shows that the dominant exit channel (peak IIζX) is due to capture by low-lying metastable state (A $^3\Sigma_u$) of the O_2^{2+} ions into the (c $^4\Sigma_u$) state of O_2^+. In O_2^{2+} - Ne collision, the dominant peak correlates with single-electron capture from ground state ($^1\Sigma_g^+$) of O_2^{2+} ions into X $^2\Pi_g$ (peak IαX) state of O_2^+, while the unresolved structure on the higher-energy side of the dominant peak is due to capture from the metastable state O_2^{2+} (W $^3\Delta_u$) ions into a $^4\pi_u$ and A $^4\pi_u$ excited states of the O_2^+ product ions, in agreement with the other measurements at 6 keV [2]. The energy-gain spectra are interpreted qualitatively in terms of the reaction windows, which are calculated using the Landau-Zener model and the extended version of the classical over-the-barrier model. Additional measurements of differential cross sections will be presented.

References

[1] S. Yaltkaya, E. Y. Kamber and S. M. Ferguson, Phys Rev A **48**, 382 (1993).
[2] M. Hamdan and A.G. Brenton, Chem. Phys. Lett. **164**, 413 (1989).

NON-PERTURBATIVE INVESTIGATION OF THE INTERFERENCE EFFECTS IN THE IONIZATION OF H_2 BY CHARGED PARTICLE IMPACT

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The interference effects in the double differential ionization cross section of H_2 was studied both theoretically [1] and experimentally [2]. It is shown by Rodríguez et. al. [3], that theoretical models developed for the ionization of the atomic systems by intense ultrashort laser pulses can be applied with success to study the ionization by charged particle impact in the case of distant collisions. Based on these results in this work the Volkov and MSSFA (momentum space strong-field approximation) models [4], developed for the over the barrier ionization, are applied to study the ionization of the hydrogen molecule by charge particle impact. By employing the Volkov and MSSFA we are able to study separately the influence of the two-center initial wave function and of the two-center Coulomb potential on the interference effects. Beside these non-perturbative approaches, calculations are also performed using a perturbative, impact parameter method [1]. The interference effects are analyzed in the angular distribution of the ejected electrons in the collisional plane for fixed impact parameter at different molecular axis orientations. The sharp minima in the Volkov angular distributions presented on Figure 1 are clear evindence of the destructive interference, which appears due to the two-center inital state wave function. The electron ejection angle integrated sprectra are also analyzed and the influence of the interference is discussed.

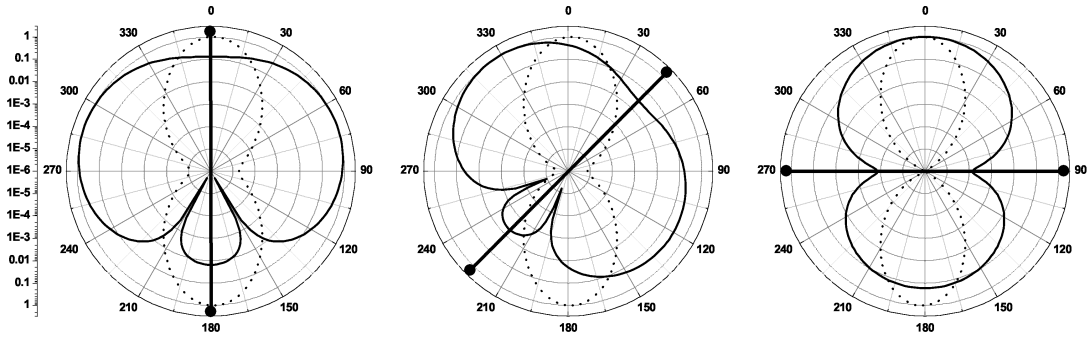

Figure 1: The angular distribution of the electrons ejected in the collisional plane with 65 eV ejection energy, for fixed impact parameter (4 a.u.) of the 68 MeV/u Kr^{33+} projectile, for different molecular axis orientations. Solid line - Volkov results, Dotted line - impact parameter method. The presented distributions are normalized to maximum value.

References

[1] L. Nagy, L. Kocbach, K. Póra, J. P. Hansen, J. Phys. B: At. Mol. Opt. Phys. **35**, L453 (2002).

[2] N. Stolterfoht et. al., Phys. Rev. Lett. **87**, 023201 (2001).

[3] V. D. Rodríguez, P. Macri, R. Gayet, J. Phys. B: At. Mol. Opt. Phys. **38**, 2775 (2005).

[4] S. Borbély, K. Tőkési, L. Nagy, Phys. Rev. A **77**, 033412 (2008).

A DISTORTED WAVE MODEL FOR ELECTRON IONIZATION IN COLLISIONS BETWEEN CLOTHED-IONS AND ATOMIC TARGETS

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The Continuum Distorted Wave - Eikonal Initial State (CDW-EIS) model has been used with success to describe electron ionization of atomic targets by bare ions [1]. The interest of the present work is to extend the CDW-EIS model to the case of dressed projectiles, where some electrons are initially bound to the ion. A three-body approximation is proposed [2], where in the entry channel the initial target state is distorted by an eikonal phase corresponding to the long distance interaction between the screened projectile and the active target electron. The projectile electrons are assumed to remain as frozen during the collision, so that model potentials are used [3-4] in order to describe the short range interaction between the projectile and the active electron. In the exit channel a product of a plane wave and two wave functions (corresponding to the continua of the active electron in the asymptotic projectile and residual targets fields) is proposed. Double differential spectra are analyzed as a function of the final energy and angle of the emitted electron. In particular two different effects previously observed in the binary encounter region: i) an increasing of its height at forward emission angles as the number of the projectile electrons increases [5] and, ii) a double structure appearing in a narrow band, at larger emission angles, which was attributed to a rainbow effect [6-7], are investigated.

References

[1] N. Stolterfoht, R. D. DuBois and R. D. Rivarola, Electron Emission in Heavy Ion-Atom Collisions, Springer, Berlin (1997) and references therein.
[2] P. D. Fainstein, V. H. Ponce, R. D. Rivarola, J. Phys. B **21**, 287 (1988).
[3] A. E. S. Green, D. L. Sellin and A. S. Zachor, Phys. Rev. **184**, 1 (1969).
[4] R. H. Garvey, C. H. Jackman and A. E. S. Green, Phys. Rev. A **12**, 1144 (1975).
[5] P. Richard, D. H. Lee, T. J. M. Zouros, J. M. Sanders and J. L. Shinpaugh, J. Phys. B **23**, L213 (1990).
[6] C. O. Reinhold, D. R. Schultz and R. E. Olson, J. Phys. B **23**, L591 (1990).
[7] C. O. Reinhold *et al.*, Phys. Rev. Lett. **66**, 1842 (1991).

A FULL FOUR-BODY CONTINUUM DISTORTED WAVE - EIKONAL INITIAL STATE MODEL FOR IONIZATION OF He BY ION IMPACT

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Electron ionization of atomic targets produced in collisions with bare ions is usually studied using three-body distorted wave approximations. The three considered bodies are the incident projectile, the residual target and the *active* electron (the electron to be ionized as a consequence of the collision). The other electrons, the *passive* ones, are assumed to remain as frozen in their initial orbitals during the reaction (see for example Ref. [1]). Four-body distorted wave models were also introduced to investigate ionization of dielectronic targets ([2-3]). Correct boundary conditions were preserved in both the entry and exit channels but only the *active* electron was considered to be distorted by the projectile.
In order to avoid any asymmetric description of the target electrons we consider both of them as *active* electrons in a four-body Continuum Distorted Wave - Eikonal Initial State (CDW-EIS) approximation. Thus, the initial bound state is distorted in the entry channel by two eikonal phases associated with the interaction of the projectile with each one of the target electrons. These phases correspond to an approximated description of the projectile-target electrons continuum states for large enough collision velocities. As we are here interested in ionization-excitation processes the residual bound wave function is distorted by a projectile-residual target electron eikonal phase as in the single-electron excitation Symmetric Eikonal (SE) approximation [4] and the emitted electron is considered to move in the combined fields of the projectile and residual target as in the single-electron ionization CDW-EIS model [5]. The use of four-body representations where the two electrons are considered as *active* ones, allows the study of the influence of *static* and *dynamical* electron correlation on multiple differential and total cross sections. The case of a bare ion impacting on a He target will be presented in the conference.

References
[1] P. D. Fainstein, V. H. Ponce, R. D. Rivarola, J. Phys. B **21**, 287 (1988).
[2] D. Belkic, J. Phys. B **30**, 1731 (1997).
[3] D. Belkic, Nucl. Instr. Meth. B **124**, 365 (1997).
[4] G. R. Deco, P. D. Fainstein and R. D. Rivarola, J. Phys. B **11**, 213 (1986).
[5] D. S. F. Crothers and J. F. McCann, J. Phys. B **16**, 3229 (1983).

NEW CLASSICAL CTMC APPROACHES TO A^{q+} + He PROCESSES

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Any small perturbation in the classical stable Helium atom produce unphysical autoionization that prevents any classical dynamical study. Previous attempts [1,2,3] have required barrier potentials to limit the electron energy.

In a first approach we consider two sets of N classical electron trajectories, whose evolution obey the Hamilton equations in the full Hamiltonian. Each classical electron of one set feels the average repulsion due to the classical electrons of the other set. This is combined with the smoothing of the evaluation of the classical electronic repulsion by assuming that each electron can be described by gaussian functions centred on the position of the corresponding electrons [4].

The initial electronic densities, have been obtained from a microcanonical distribution that takes into account the electrostacic field created by the other set of electrons, that is also a microcanonical distribution. Initial distribution can evolve, before the projectile starts the collisions, under the influence of the actual He atom to describe more accurately the exact ones. A second approach employs N couples of electrons that evolve under model potentials exerted by the other electron both in the target and projectile, through a time-dependent parameter that represent the number of core electrons.

Results will be presented at the conference.

References

[1] C.L. Kirschbau and L. Wilets, Phys. Rev. A **21,** 834, (1980)
[2] J.S. Cohen, Phys. Rev. A **54,** 573, (1996)
[3] V.J. Montemayor and G.S. Schiwietz, Phys. Rev. A **40,** 6223, (1989).
[4] A. Donoso and C. C. Martens, J. Chem. Phys **116,** 10598 (2002)..

A NEW MOTRIMS APPARATUS FOR HIGH RESOLUTION MEASUREMENTS IN ION-ATOM COLLISIONS AND TRAPPED ATOMS STUDIES

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MOTs (magneto-optical traps) and COLTRIMS (cold target recoil ion momentum spectroscopy) are two of the most fruitful experimental techniques developed these last decades in atomic, molecular, and optical (AMO) physics. Laser cooling and trapping of atomic samples in a MOT is now a first step for many exciting and innovating experiments: among well known examples, one can find Bose-Einstein condensate formation and superfluidity studies, electromagnetically induced transparency, photoassociation, quantum information, etc. On the other hand, the COLTRIMS technique has proven to be very powerful for mapping the dynamic of ion-atom/molecule and photon-atom/molecule collisions. Based on the measurement of the full momentum vector of the charged target fragments, the COLTRIMS technique gives access to the dynamic of the projectile-target interaction. Quite recently, several groups merged both MOTs and COLTRIMS techniques by using trapped atoms as a cold target for the COLTRIMS methodology [1]. This new development, called MOTRIMS, added several advantages to the standard technique: the very low temperature of the target (on the order of 100 μK) does not limit the resolution in recoil momentum, and the MOT provides an additional set of atomic species such as alkali atoms. These atoms can be easily optically pumped with lasers and allow measurements with different initial states of the target (including aligned or oriented states).

A new MOTRIMS apparatus has been built at the LPC-CAEN, and recently tested with a beam of 2 keV Na^+ projectiles colliding a trapped Rb target. In this work, we demonstrate the capability of the setup to provide, with a very high signal over background ratio, fully differential cross sections in scattering angle, initial state, and final state of the system. We also detail features that had not been described previously in the literature: an extraction of the recoil ions transverse to the ion beam axis, and a fast switch for the MOT magnetic field. Future possibilities for the setup, including the target orientation and the electron detection will be presented at the conference.

References

[1] B.D. DePaola, R. Morgenstern, and N. Andersen, in *Advances in Atomic, Molecular and Optical Physics,* Vol. 55, p. 139, edited by E. Arimondo, P. Berman, C. Lin (Academic Press, 2007)

VACANCY DISTRIBUTION OF THE X-RAY SATELLITE SPECTRA OF SiO_2 AEROGEL BOMBARDED WITH CALCIUM IONS

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The Si x-ray spectra of the low-density SiO_2 aerogel target indicated with Ca^{6+} ions with initial energy of 11.4 MeV/u were measured with a high spectral and spatial resolution along 80% of the ion beam stopping path [1]. The $K\alpha L^0$ diagram and $K\alpha L^n$ (n=1-5) satellite lines (appearing in these spectra as a result of the radiative deexcitation of multiply ionized atomic states) were observed. The $K\alpha L^n$ x-ray satellite lines were resolved from the parent diagram lines and the energy shifts were determined [2]. From the relative intensities of satellites, the population of the primary KL^n vacancy configurations (at the moment of collision) were deduced by taking into account the intra-atomic rearrangement processes occurring before the K x-ray emission. Assuming that the L-shell vacancy can be produced in near-central collisions by two uncorrelated processes: direct ionization and electron capture of the target L-shell electron into the K-shell of the projectile, the L-shell ionization probabilities were deduced by means of statistical considerations. The experimental values were compared with the results of theoretical semi-classical (SCA) and geometrical model (GM) calculations. It was found that both theoretical models overestimate the experimental L-shell ionization probabilities. Moreover, for each projectile energy the significant enhancement of the KL^0 vacancy configuration was observed in measured spectra. The possible influence of the delta electrons appearing in stopping processes as well as chemical environment of the stopping media on the shape of the K x-ray spectra will be discussed.

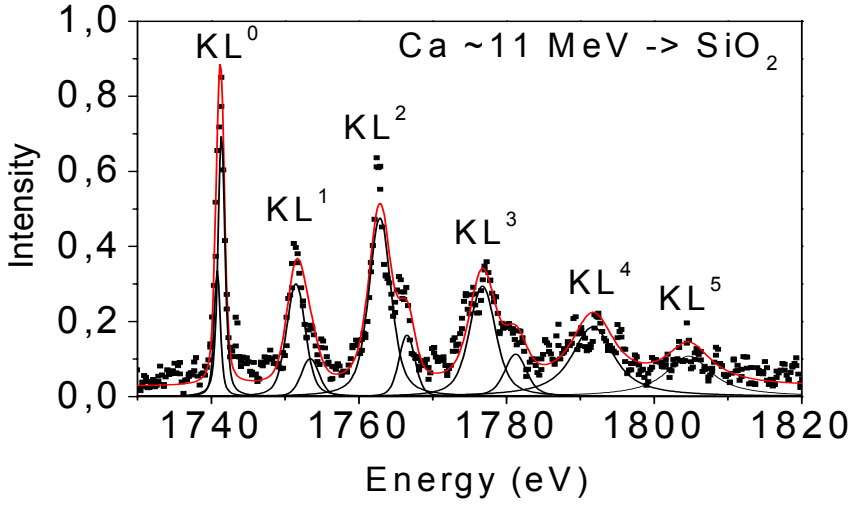

Fig. 1. High resolution spectrum of low-density SiO_2 aerogel induced by Ca projectiles for 0.5 mm (11.4 MeV/u). Results of the simplified fitting procedure is also shown (solid lines).

References
[1] O. N. Rosmej et al., PRA **72,** 052901 (2005)
[2] J. Rzadkiewicz et al., High Energy Density Physics **3,** 233 (2007)

COMPLEMENTARY SPECTROSCOPY OF TIN IONS BY USING ION BEAMS AND ELECTRON BEAMS

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Sn plasmas have been studied for the EUV (extreme ultraviolet) lithography using the light of the wavelength around 13.5 nm. Theoretical calculations suggested that not only the resonance lines but also the satellite lines, corresponding to the transitions between the excited states, of Sn ions contributed to the 13.5 nm emission.

To provide the spectroscopic data on the multiply charged Sn ions, we have measured EUV spectra of the emission following the charge transfer collisions of the Sn ions with rare gas targets in the charge exchange spectroscopy (CXS). In this method, we can select the charge states of the emitting ions, because the single-electron capture is dominant in collisions of highly charged ions. We, however, can not distinguish between the resonance lines and the satellite lines in the observed spectra. On the other hand, in the electron beam ion trap (EBIT), the ions are excited by the electron impact, and most of the emission from the ions are resonance lines. In this apparatus, the ionic charge can be controlled by the electron energy. But, generally speaking, a couple of charge states exist in the trap at the same time. In this study, we have measured the emission spectra of multiply charged Sn ions in the EUV region both with the CXS and the EBIT, and discussed those complementary results.

The CXS experiments have been performed with a 14.25 GHz electron cyclotron resonance (ECR) ion source in Tokyo Metropolitan University. The EBIT in the University of Electro-Communication has been operated with extremely low electron energies as this device to produced moderately charged ion. The emission spectra were measured by using the same grazing-incident spectrometer equipped with a liquid nitrogen cooled CCD camera.

The spectrum observed in collisions of Sn^{15+}-He and that observed in the EBIT with the electron beam energy of 312 eV are shown in Figure 1. Both of the spectra have a common strong emission line at 13.3 nm, and we considered it to be a resonance line of Sn^{14+}. We also suggest that the emissions between 13.5 and 14.3 nm are satellite lines corresponding to the 4d-4f transitions by the comparison with the theoretical calculations. The complementary research using the different experimental methods is significantly effective to study the spectroscopic properties of multiply charged ions.

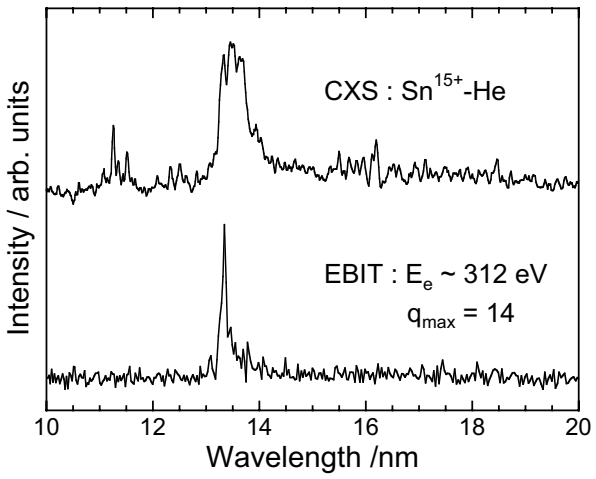

Figure 1: EUV emission spectra in collisions of Sn^{15+}-He and in EBIT.

LINEAR POLARISATION STUDIES FOR RADIATIVE ELECTRON CAPTURE TRANSITIONS INTO HIGHLY CHARGED URANIUM

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The recent advances in the development of energy, time and position sensitive 2D microstrip detectors [1] opens up new possibilities for the investigation of physical processes producing linearly polarized X-rays. We present new measurements of Radiative Electron Capture (REC) into the K- and L- shells of highly charged Uranium ions at the Experimental Storage Ring of the GSI facility in Darmstadt, Germany.

For the experiment, a stored beam of cooled bare Uranium ions with 96.6 MeV/u beam energy was crossed with a hydrogen gas target. The preliminary data analysis shows a strong linear polarization for the KREC transition into bare Uranium at an angle of 90 degrees with respect to the ion beam. In contrast to this, at 35 degrees, a strong depolarization has been observed. This is in agreement with theoretical descriptions and measurements [2, 3], predicting an increased importance of higher order multipole processes leading to a strong depolarization of the emitted light.

References

[1] D. Protić, T. Krings, IEEE Transactions on Nuclear Science **50**, (2003)

[2] S. Tashenov, Th. Stöhlker, et al., Physical Review Letters **97**, (2006)

[3] A. Surzhykov, S. Fritzsche, Th. Stöhlker et al., Radiation Physics and Chemistry **75**, (2006)

ONE- AND TWO- ELECTRON TRANSFER TO CONTINUUM IN NEAR-RELATIVISTIC ION-ATOM COLLISIONS

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Observing the different electron transfer to continuum channels in fast ion-atom collisions permits to study the dynamics of ionization as well as of radiative and non-radiative capture very close to threshold; it is therefore a test of unparalleled sensitivity for first order theories.

Theories for electron transfer to the continuum, however, have encountered considerable difficulties to take into account the intrinsic many-electron processes in the capture channel which have been seen in slow collisions, but which persist surprisingly also in very fast collisions. This may partially be attributed to large momentum transfers involved and thus collision systems are mostly not in the realm of first order perturbation theories. For this reason we have studied simultaneously competing electron transfer processes, like radiative (RECC) and non-radiative electron capture to continuum (ECC) in the relativistic domain where one or two active electrons are involved; additionally, the projectile electron loss to continuum (ELC) channel permits to comparatively study in the same collision the dynamics of ionization very close to threshold.

We have studied these electron transfer processes in forward electron emission in two systems of different projectile Compton profile, $U^{88+} + N_2$ and $Sn^{47+} + N_2$ collisions using the forward electron spectrometer at the supersonic jet-target of the ESR storage ring. We report first results for differential cross sections and compare with available theories.

STRONG FORWARD-BACKWARD ASYMMETRY OF H_2O IONIC FRAGMENTS BY SLOW HIGHLY CHARGED IONS IMPACT

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Fragmentation of molecules subsequent to the interaction with ions has been studied intensively in the last decade [1]. If the projectile is fast that the interaction time is orders of magnitude smaller than the dissociation time, the collision can be considered as a two-step process [2]. On the other hand, for slow ($v < 1$ a. u.), highly charged projectiles the energy and angular distribution of fragments is determined by the energy and momentum transferred from the projectile, in addition to the energy gained by the repulsive dissociation of the molecule [3].

We present the results of the fragment ion spectroscopy studies of water molecules subsequent to impact of highly charged 1-220 keV Xe^{q+} ions (q=10, 15 and 22). We observed a strong forward-backward asymmetry in the emission of the ionic fragments. For example, the ion yield in the forward direction is almost completely suppressed for the impact of below 10 keV Xe^{22+} ions. These results are compared with our previous studies of water fragmentation induced by $He^{1,2+}$ and $Ne^{(3-9)+}$ ions [1, 4, 5]. For projectiles with low charge state, the final kinetic energy is apparently determined by the related Franck-Condon transition. In order to guide the interpretation of the experimental data, we performed a classical trajectory simulation within the framework of a Coulomb Explosion model wherein a satisfactory agreement is achieved. Finally, the integrated cross sections over all fragmentation channels are compared with results of the semiempirical scaling law deduced from a multi-electron capture model [6].

References

[1] N. Stolterfoht *et al.*, Advanc. in Quantum Chem. **52**, 149 (2007) and references therein
[2] B. Siegmann *et al.*, J. Phys. B: At. Mol. Opt. Phys. **34**, L587 (2001)
[3] C.R. Feeler *et al.*, Phys. Rev. A **60**. 2112 (1999)
[4] P Sobocinski *et al.*, J. Phys. B: At. Mol. Opt. Phys. **39**, 927 (2006)
[5] Z. D. Pešić *et al.*, J. Phys. B: At. Mol. Opt. Phys. **37**, 1405 (2004)
[6] N Selberg *et al.*, Phys. Rev. A **54**. 4127 (1996)

INVESTIGATION OF THE MULTIPLE ELECTRON SCATTERING SEQUENCES IN C^{N+} + AR COLLISIONS

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Multiple electron scattering in low and intermediate energy ion-atom and ion-molecule collisions may contribute to the emission of fast, high energy electrons. It manifests itself in the structures of the double differential electron spectra [1,6]. In such processes, an electron is repeatedly scattered by the ionic cores of the projectile and the target, and it gains energy in every encounter with the projectile. This mechanism is often referred to as Fermi-shuttle acceleration [4]. Fast electrons have been identified from double, triple and quadruple scattering by the projectile and target cores [4]. The effect is the most pronounced in collisions of dressed heavy projectiles and heavy target atoms. These systems are particularly challenging theoretically to describe at a level of the double differential electron emission cross sections. So far, no quantum calculations were carried out at such a complexity. For modeling these collisions, classical trajectory Monte-Carlo (CTMC) calculations have been performed for many collision systems. Surprisingly, a general quantitative agreement has been found compared with the experimental data [5,6] in intermediate energy collisions. This fact allows us to identify multiple scattering events in a classical sense, by analyzing the calculated individual particle trajectories. Moreover, it has been found that the cross section of multiple scattering sequences is dramatically increases towards lower projectile velocities.

In this work, we present a systematic theoretical study of the electron emission from collisions of carbon ions at 60 keV energies with argon atoms. In the Monte Carlo simulation the electron emission yield is calculated separately for the contribution from the target and projectile ionization. On the basis of the present calculations we suggest some experiments to be performed in this energy region, to separate and identify target and projectile multiple scattering contributions to the fast electron spectrum. Moreover, we present the principles of a random sampling analysis of the individual CTMC trajectories to identify and determine the contribution of multiple scattering sequences.

References
[1] S. Suarez et al., Phys. Rev. Lett. 77 (1996) 474.
[2] U. Bechtold et al., Phys. Rev. Lett. **79** (1997) 2034
[3] G. Lanzano et al., Phys. Rev. Lett. **83** (1999) 4518.
[4] B. Sulik et al., Phys. Rev. Lett. **88** (2002) 073201.
[5] T. Ricsóka et al., Nucl. Instr. Meth. B **235** (2005) 397
[6] B. Sulik and K. Tőkési, Adv. Quant. Chem. **52** (2007) 253.

YOUNG TYPE INTERFERENCE IN ELECTRON EMISSION FRM H_2 AND FORWARD-BACKWARD ASYMMETRY: A NEW APPROACH

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The coherent electron emission from the inversion-symmetric homonuclear diatomic molecule H_2, carry the signature of the Young type interference effect under fast ion and photonic collisions. Although it was predicted about forty years back it was first observed in fast ion-molecule collisions a few years back by Stolterfoht et al. [2]. Since the double differential cross section (DDCS) varies over several orders of magnitudes in an energy range of few hundred eV, it is difficult to observe a small variation in the DDCS spectrum owing its steep variation. Therefore, to observe the oscillatory structure, the ratio of H_2-to-2H cross sections, are used which are either obtained theoretically [2] or in an experiment with atomic H [3]. We have recently reported [4] an independent way of obtaining the interference structure by using the forward backward asymmetry parameter of electron DDCS. This method does not need any input from the theoretical model calculations and neither requires a complementary experiment with atomic H. Bare C (6MeV/u) and F (4 MeV/u) ions were available from the BARC-TIFR Pelletron accelerator at TIFR. The experiments were carried using low pressure H_2 gas. Energy and angle resolved electrons were detected, using a hemi-spherical electrostatic analyzer, at several forward and backward angles between 20^0 and 160^0. The difference in the oscillation frequency for the forward and backward angles causes the oscillation in the forward backward asymmetry parameter which is also reproduced by the molecular CDW-EIS calculation[4,5]. A model calculation based on Cohen-Fano model joined together with the frequency difference in forward-backward angles, fits the spectrum well. The ratio of frequency in 160^0 and 20^0 was about 1.8. Since this study does not need any atomic target, can be applied for other diatomic molecular targets: a step forward towards the study of Young type interference in ionizations of molecule. Besides first order interference the re-scattering of the electron from the second atom can give rise additional oscillatory structure in the electron spectrum. Such second order effect was first predicted by Stolterfoht et al.[6] for GeV energy collision. We provide here here the evidence of frequency doubling of the oscillations in ionization of H_2 in collisions with 4 MeV/u bare F ions. We believe the present experimental data provides strong support for the evidence of a higher frequency component in interference oscillations as predicted in [6].

References:

1. H. D. Cohen and U. Fano, Phys. Rev 150, 30 (1966).
2. N. Stolterfoht et al., Phys. Rev. Lett., 87, 023201 (2001).
3. D. Misra, U. Kadhane, Y.P. Singh, L. C. Tribedi, P.D. Fainstein and P. Richard, Phys. Rev. Lett. 92, 153201 (2004).
4. D. Misra, A. Kelkar, U. Kadhane, Ajay Kumar, L. C. Tribedi, and P.D. Fainstein, Phys. Rev. A-Rapd comm.. 74, 060701(R) (2006).
5. M.E. Gallasi, R.D. Rivarola, P.D. Fainstein and N. Stolterfoht, Phys. Rev A **66**, 052705 (2002).
6. N. Stolterfoht et al., Phys. Rev. A. 69, 012701 (2004).

INTERFERENCE PATTERNS IN SPECTRA OF ELECTRON IONIZATION OF HETERONUCLEAR HeH^+ TARGETS IN INTERACTION WITH FAST ION BEAMS

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Coherent electron emission from diatomic molecular targets provokes the presence of interference patterns in the corresponding spectra of electron ionization. This effect was theoretically predicted more than fourty years ago for the case of photoionization [1]. At the beginning of the present century, oscillations appearing in double differential cross sections were measured by the first time for impact of fast multiply charged heavy ions on H_2 targets [2], confirming the existence of the physical effect. This was an incentive for further active experimental and theoretical research, not only for photon and ion beams but also for electron beams (for a brief review, see Ref. [3]), in all cases considering homonuclear targets.

In the present work, we investigate the possible existence of the effect when a *heteronuclear* HeH^+ molecule is ionized by a fast ion beam. It could be associated with the interference two-slit Young experiment, but where the two orifices have different dimensions. Vibration and rotation of the molecule are considered to be produced in times much larger than the collision time, so that their influences on the studied reaction are neglected. In particular, the internuclear axis is assumed to remain as *frozen* during the ionization reaction. The orbital of each one of the target electrons in the fundamental state of HeH^+ is described by a linear combination of Gaussian functions centred on the positions of the nuclei of the molecule. It allows us to investigate the ionization process within a two-effective centre approximation (TEC; see Ref. [4]), where two effective coulombic continuum functions (associated with each one of the molecular centres) are chosen to describe the interaction of the ejected electron with the residual target in the exit channel. The dynamics of the reaction is analyzed using the Continuum Distorted Wave – Eikonal Initial State model (CDW-EIS), so that the influence of the projectile on the emitted electron is also taken into account. Moreover, into the straight line version of the impact parameter approximation, the interaction of the projectile with the nuclei of the molecule can be easily included [4] when differential cross sections are studied as a function of the momentum transfer.

The initial bound electron wavefunction presents a strong monocentric character. The electrons are placed mostly around the alpha particle but however they have a smaller probabilitity to remain at the proximities of the proton center. This relatively weak two-centre behaviour is the origin of the presence of interference patterns in differential cross sections. Results corresponding to different collision systems will be presented at the conference.

References

[1] H. D. Cohen, U. Fano, Phys. Rev. **150** (1966) 30.
[2] N. Stolterfoht *et al.*, Phys. Rev. Lett. **87** (2001) 023201.
[3] R. D. Rivarola, Nucl. Instr. Meth. B **261** (2007) 161.
[4] M. E. Galassi, R. D. Rivarola, P. D. Fainstein, Phys. Rev. A **70** (2004) 032721.

THEORETICAL ANALYSIS OF MULTIPLE IONIZATION OF AR-IONS IN GAS TARGETS

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Current activities at accelerator facilities, e.g., in the framework of the FAIR project at GSI require precise knowledge of electron stripping cross sections for fast highly-charged ions in gas targets. As a first step toward the goal of providing cross section data for lowly-charged uranium ions from the MeV/amu to the GeV/amu regime we have considered electron loss from sixfold and eightfold argon ions in helium and argon gases at around 10 MeV/amu. Our calculations are based on a mean-field description of the electron dynamics and the nonperturbative basis generator method [1] for orbital propagation.

In the case of Ar^{6+} ions we find that a considerable fraction of electron loss is due to ionization from the L-shell (see figure). Consequently, Auger processes can contribute to multiple electron loss. We have taken them into account on the basis of a statistical model introduced recently [2] and find that they indeed have a major influence on the final charge-state distributions of the ions. Furthermore, we argue that antiscreening, i.e., the ionization of a projectile electron due to a direct interaction with one of the target electrons does play a role. It is not unlikely that both processes are also important for the uranium ions of interest at GSI [3].

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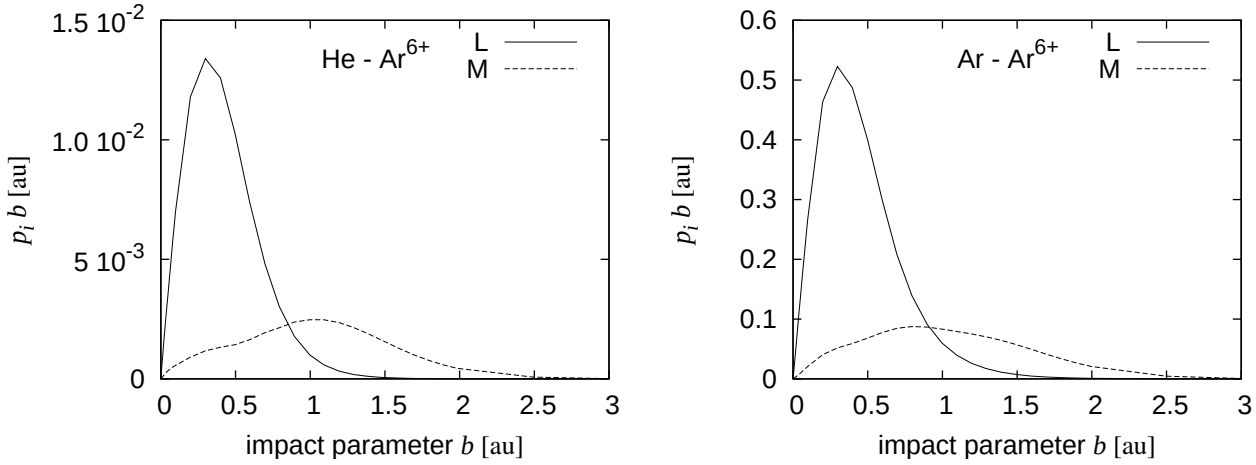

Figure 1: Ionization probabilities $p_i(b)$, weighted with the impact parameter b and number of electrons of the respective shell.

References

[1] O.J. Kroneisen *et al.*, J. Phys. A **32**, 2141 (1999)

[2] T. Spranger and T. Kirchner, J. Phys. B **37**, 4159 (2004)

[3] R.E. Olson *et al.*, J. Phys. B **37**, 4539 (2004)

HIGH-RESOLUTION X-RAY STUDY OF MULTIPLE IONIZATION OF Pd ATOMS BY FAST OXYGEN IONS

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In high-resolution measurements of the x-rays excited in collisions of heavy ions with atoms the complex x-ray satellites, corresponding to the multi-vacancy configurations present in the moment of X-ray emission, are observed. In this way a high resolution measurements of the X-ray satellites give thus access to study the dynamics of multiple ionizations. In particular, the ionization probabilities for the L- and M-shells can be derived from the measured x-ray spectra of multiply ionized atoms.

In the present paper a high-resolution x-ray spectra of Pd L$\alpha_{1,2}$ x-ray transitions excited by O^{6+} ions of energy 279 MeV [1] is discussed, which were measured by a high resolution von Hamos crystal spectrometer having energy resolution of about 0.6 eV. The measured x-ray spectra, showing both the M-shell satellite and L-shell hypersatellite x-ray transitions, were interpreted in terms of the multi-configuration Dirac-Fock (MCDF) calculations. In this way the ionization probabilities for L- and M-shell were obtained for the moment of x-ray emission, which were further compared with the semiclassical (SCA) calculations of the ionization probabilities. Since the ionization probabilities are calculated for the moment of collision, they were corrected for the vacancy rearrangement processes taking place between the moments of collision and x-ray emission. The SCA calculations, which were performed using relativistic hydrogenic (SCA-HYD) and self-consistent Dirac-Hartree-Fock (SCA-DHF) wave functions, indicate strong effect of the realistic description of the electronic wave function for the L- and M-shell. A systematic comparison of the SCA-DHF/SCA-HYD calculations will be discussed in details.

References

[1] M. Czarnota *et al.*, Nucl. Instr. and Methods B 205, 133 (2003)

RADIATIVE ELECTRON CAPTURE AND SUBSEQUENT RADIATIVE DECAY IN COLLISIONS OF U^{89+} IONS WITH N_2

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The radiative electron capture (REC) in collisions of U^{89+} ions with N_2 target molecules [1-4] has been studied theoretically, along with the subsequent radiative deexcitation (RD) spectra. In this study, the REC cross sections and photon energies for the capture into the levels of the $1s^22snl$ ($2\leq n\leq 9$, $0\leq l\leq 6$) configurations, starting from the $1s^22s$ ground configuration of the U^{89+} ions, have been calculated for the first time by applying the newly-developed program RERR06. This program is based on the RATIP package [5] and includes the contributions of all required multipole transitions. The REC spectra were generated by using the cross sections and the Compton profile of the N_2 molecule. When compared with new experiments at GSI [4], the calculated REC spectra are in good agreement with the observations. Furthermore, by combining the cross sections from above together with the computation of the transition probabilities among the lowest 147 levels of Be-like U^{88+} ions in the $1s^22snl$ configurations ($2\leq n\leq 9$, $0\leq l\leq 6$), the RD spectra from the subsequent decay has been simulated using both the multi-step model and coupled rate equations. The results were found in good agreement with the experimental spectra.

References

[1] Th. Stöhlker, H. Geissel, H. Irnich *et al.*, Phys. Rev. Lett. **73**, 3520 (1994)
[2] Th. Stöhlker, C. Kozhuharov, P. H. Mokler *et al.*, Phys. Rev. A **51**, 2098 (1995)
[3] X. W. Ma, Th. Stöhlker, H. F. Beyer *et al.*, Nuclear Physics Review **19**, 131 (2002)
[4] J. Rzadkiewicz, Th. Stöhlker, D. Banaś *et al.*, Phys. Rev. A **74**, 012511 (2006)
[5] S. Fritzsche, J. Electron Spectroscopy and Related Phenomena **114-116**, 1155 (2001)

LOSS MECHANISM AND LIFETIME OF IONS BEAM IN HIRFL-CSRE

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Ion	Energy (MeV/u)	τ_{rr}/s	τ_r/s	τ_t/s	τ_{total}/s
C^{6+}	50	3.77×10^{3}	1.91×10^{5}	1.79×10^{2}	1.71×10^{2}
	100	4.17×10^{3}	8.73×10^{5}	7.68×10^{2}	6.48×10^{2}
	200	5.02×10^{3}	3.66×10^{6}	3.03×10^{3}	1.89×10^{3}
	300	5.94×10^{3}	7.55×10^{6}	6.28×10^{3}	3.05×10^{3}
	400	6.95×10^{3}	1.16×10^{7}	1.00×10^{4}	4.10×10^{3}
	500	8.03×10^{3}	1.52×10^{7}	1.39×10^{4}	5.09×10^{3}
Ar^{18+}	50	3.54×10^{2}	5.62×10^{4}	5.52×10^{2}	2.15×10^{2}
	100	3.90×10^{2}	1.39×10^{5}	1.41×10^{2}	1.04×10^{2}
	200	4.70×10^{2}	8.00×10^{5}	7.98×10^{2}	2.96×10^{2}
	300	5.57×10^{2}	2.24×10^{6}	2.22×10^{3}	4.45×10^{2}
	400	6.51×10^{2}	4.42×10^{6}	4.48×10^{3}	5.68×10^{2}
	500	7.52×10^{2}	7.02×10^{6}	7.42×10^{3}	6.83×10^{2}
Xe^{54+}	50	33.8	1.39×10^{5}	1.40×10^{2}	27.2
	100	37.3	2.99×10^{5}	3.05×10^{2}	33.2
	200	44.9	7.12×10^{5}	7.43×10^{2}	42.3
	300	53.2	1.24×10^{6}	1.33×10^{3}	51.1
	400	62.2	1.87×10^{6}	2.07×10^{3}	60.4
	500	71.9	2.57×10^{6}	2.95×10^{3}	70.2
U^{92+}	50	10.9	3.38×10^{4}	35.3	8.3
	100	12.0	6.45×10^{4}	67.7	10.2
	200	14.5	1.34×10^{5}	1.42×10^{2}	13.1
	300	17.1	2.18×10^{5}	2.32×10^{2}	16.0
	400	20.0	3.17×10^{5}	3.40×10^{2}	18.9
	500	23.2	4.30×10^{5}	4.65×10^{2}	22.1

Table 1. $\tau_{rr}(s)$, $\tau_r(s)$, $\tau_t(s)$ and $\tau_{total}(s)$ are the partial and total lifetimes resulting from interaction with electrons in e-cooler, residual gas, internal nitrogen gas jet target, respectively.

HIRFL-CSRe is the experimental ring of the Cooler-Storage-Ring system HIRFL-CSR [1] in Lanzhou. The lifetime of highly charged ions (HCIs) beam in HIRFL-CSRe mainly depends on the interaction between HCIs and residual gas molecules, electron in e-cooler and internal target atoms/molecules. The main processes include the single, multiple Coulomb scattering and charge exchanges between HCIs and residual gas molecules; radiative recombination, which occurs in the interaction of HCIs beam with cooling electrons; and Coulomb scattering and charge exchange in the collision between HCIs and internal target atoms/molecules.

The loss mechanism and lifetime of ions beam in collisions with residual gas (3.0×10^{-11} mbar, 85% H_2, 15% N_2), internal target(N_2:5.0×10^{12}atoms/cm^2) and electrons in e-cooler (5×10^{7} electrons/cm^3) in HIRFL-CSRe were studied, and the partial beam lifetimes resulting from various loss mechanisms and the total beam lifetimes of 50-500MeV/u $^{12}C^{6+}$, $^{36}Ar^{18+}$, $^{132}Xe^{54+}$ and $^{238}U^{92+}$ stored in HIRFL-CSRe were calculated (see table 1).

The calculations indicate that the charge exchanges between HCIs and the internal target, and radiative recombination with the electrons in e-cooler restricted the beam lifetime considerably. For heavy beams such as $^{132}Xe^{54+}$ and $^{238}U^{92+}$, the radiative recombination with the electrons in e-cooler is the main loss mechanism.

References

[1] J. W. Xia, W. L. Zhan, B. W. Wei , et al. Nucl. Instr. and Meth. A**488**, 11 (2002).

INVESTIGATIO OF MULTIPLE ELECTRON TRANSFER IN ION ATOM COLLISIONS

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Double-electron transfer in collisions of highly charged ions on atoms leads to the creation of doubly excited (nln'l') projectile states. In most studies noble gases, in particular He, or H_2 have been used as electron donors, which implies the capture of two equivalent electrons. As a general finding two distinct population processes, namely mono-electronic and dielectronic processes are found to be responsible for the population of either near symmetric (n'~n) or asymmetric (n'>>n) configurations.

In mono-electronic transitions the electrons are transferred independently one at a time. This process is called uncorrelated or sequential double capture (SDC). In dielectronic transitions the two electrons are captured simultaneously. For two-electron capture from He it has been shown that the population of asymmetric (n'>>n) final states cannot be described when assuming independent electron transfer, i.e. a mono-electronic transition. Hence this dielectronic transition process is called correlated double capture (CDC). Near symmetric configurations (n'~n) on the other hand can be populated by uncorrelated double capture.

In contrast to transfer of two equivalent electrons studies on two-electron capture of nonequivalent electrons are rather scarce. Alkali atoms are ideal target systems to study capture of two nonequivalent electrons. The main double capture process is the transfer of the valence electron and one of the inner-shell electrons. The question is whether here symmetric and asymmetric nln'l' configurations are also populated via distinct mechanisms.

We have performed the experiments using a magneto-optically trapped Na target and recoil ion momentum spectroscopy (MOTRIMS). Figure 1 shows an example of the recoil momentum spectra obtained. One clearly sees that different configurations can be resolved. But most remarkably one sees that in particular the 3l3l' states and the 3ln'l' states with n'>5 get populated, while the 3l4l' configurations seems to be not populated at all. As for Na one starts with an asymmetric initial state (…2p3s) the 3l3l' configurations in O^{4+} are expected to be populated by CDC while the 3ln'l' states with n'>5 are populated via SDC.

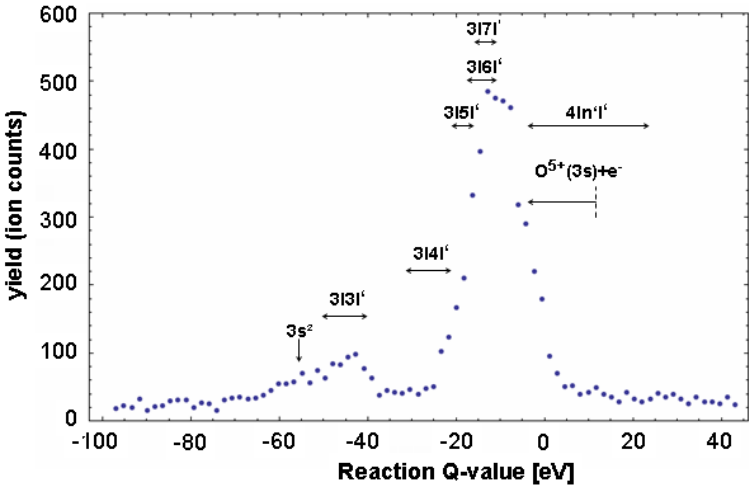

Figure 1: Q-value spectrum of Na^{2+} recoils resulting from O^{6+} + Na(3s) collisions at an energy of 8.625 keV/amu. Double capture states of O^{4+} are indicated as well as the onset for transfer ionization.

Electron-impact excitation of $2p^5 3l \rightarrow 2p^5 3l'$ line emission of Fe XVII

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We present theoretical investigations on $2p^5 3l \rightarrow 2p^5 3l'$ line intensities of Fe XVII excited by electron-impact. These lines of the extreme ultraviolet wavelengths appeared in solar flares [1] and beam-foil spectra [2]. Most of the lines were identified with good confidence [2-4]. Among them, Fe XVII 204.6 Å and 254.8 Å lines, $2p^5 3p\ (^1S_0) \rightarrow 2p^5 3s\ (3/2, 1/2)_1$ and $\rightarrow 2p^5 3s\ (1/2, 1/2)_1$, respectively, have the electric-dipole branching ratio close to unity. The two lines have therefore been predicted to have almost the same intensities [5].

Recently, solar coronal emission lines were observed by means of the Extreme Ultraviolet Imaging Spectrometer on *Hinode* satellite. It was reported [4] that measured intensities of the two lines differed by a factor of 2.5. Even though the unexpectedly large difference in the two intensities can be ascribed to blending of other ion lines and some calibration issues, the measured intensities can not be reconciled with atomic data of the CHIANTI code. Thus, we undertook careful studies on atomic processes relevant to those line emissions for a better understanding.

In the present studies, besides electron-impact excitation from the ground state of Fe XVII, i.e. $2p^6\ (^1S_0)$, other atomic processes to make population of the upper level are also examined, e.g. the inner-shell ionization excitation of Fe XVI: $2p^6 3s \rightarrow 2p^5 3l + e$, the dielectronic recombination of Fe XVIII: $e + 2p^5 \rightarrow 2p^4 3s3l \rightarrow 2p^5 3l + h\nu$. We evaluate published data for electron-impact cross sections of the processes concerned, and also conduct calculations of the distorted-wave Born and the isolated-resonance approximations. Based upon the cross sections, we analyze population kinetics of the $2p^5 3l$ levels.

The present work is supported by the NIFS/NINS project of Formation of International Network for Scientific Collaborations.

References

[1] K.P. Dere, Astrophys. J. **221**, 1062 (1978)
[2] J.P. Buchet et al., Phys. Scr. **31**, 364 (1985)
[3] C. Jupén, Mon. Not. R. Astr. Soc. **208**, short communication 1 (1984)
[4] U. Feldman, G.A. Doschek, and J.F. Seely, Mon. Not. R. Astr. Soc. **212**, 41 (1985)
[5] G.A. Doschek, U. Feldman, and A.K. Bhatia, Phys. Rev. A **43**, 2565 (1991)
[6] H.P. Warren, U. Feldman, and C.M. Brown (private communications)

FRAGMENTATION OF ADENINE INDUCED BY HE^{2+} AND F^{2+}

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The damages of the cellular DNA induced ionizing radiation are not produced by the mere direct impact of the primary high-energy particles, also are caused by secondary species generated by the primary ionizing radiation. Thus, it is important to understand the ionization mechanisms as well as the energy deposition at the molecular level. Several studies involving low energy electrons or protons colliding with DNA or RNA bases have shown that the dissociation of the molecule can occur well below the ionization energy threshold [1]. There are also few studies on fragmentation of biomolecular target or DNA bases induced by slow highly charged ions [2].

An experiment was performed using 30 keV He^{2+} impact on adenine at the new built beamline. Adenine ($C_5H_5N_5$) is one of the DNA bases, whose structure is shown in figure 1. In the experiment the biomolecular ions and its fragment ions produced in collisions were extracted by electric field and then detected by MCP detector in coincidence with scattered projectiles. The ion detecting system has the multi-hit function and records all the charged fragments produced in one collision. A total time-of-flight spectrum is shown in figure 2. The emission of light ions such as H^+, CNH_2^+ can be identified, and the corresponding peaks are marked in the spectrum. The successive loss of neutral CNH from parent bimolecular ion can also be tracked from the TOF spectrum, namely, the decay chain: $(C_5N_5H_5)^+ \xrightarrow{CNH} (C_4N_4H_4)^+ \xrightarrow{CNH} (C_3N_3H_3)^+ \xrightarrow{CNH} (C_2N_2H_2)^+$. There are also other fragmentation patterns in the spectrum. Presently correlation analysis is being under performance.

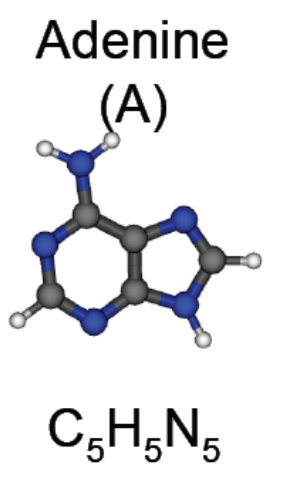

Fig.1 structure of Adenine molecule

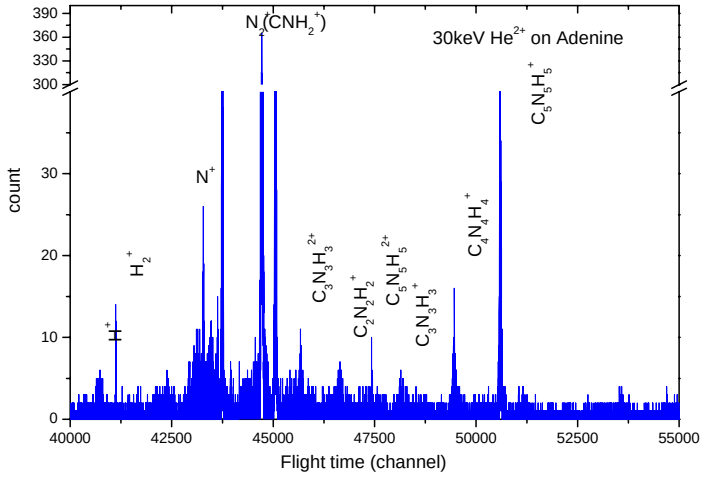

Fig 2. Total TOF spectrum recorded for 30 keV He^{2+} on Adenine

References

[1] B. BoudaÏffa, P. Cloutier, D. Hunting, M. A. Huels, L. Sanche. *Science* **287**(2000), 1658
[2] F Alvarado, S. Bari, R. Hoekstra, and Th Schlathölter. *J. Chem. Phys.* **127**(2007), 034301

Projectile q-dependence of Single, double and multiple ionization and fragmentation of C_{60} under first ion-impact and influence of GDPR

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Ionization and fragmentation studies of C_{60} fullerene provide useful insights about the energy transfer mechanisms in C_{60}-heavy ion collisions. The recoil ion spectra carries finger prints of various energy deposition, excitation and relaxation channels such as swift ionization, evaporation, multi-fragmentation etc. We shall present here our measurements of ionization and fragmentation cross sections of C_{60} in collisions with 3 MeV/u C, F and Si ions. The recoil ions were detected using time of flight technique. We have measured the absolute ionization cross sections of single, double and multiply charged ions of C_{60}. The ionization yields were found to increase linearly as a function of projectile charge state *q* (as shown earlier in ref [1-6]). The linearity was well reproduced by the GDPR model in case of single and double ionization up to q~9 (i.e. for C and F ions). For these ions the triple ionization yields were found to be independent of q. This indicates the prominence of giant excitations in single and double ionization of C_{60}. Then higher charge state ions such as Si^{q+} (q=6-14) were used and it was found that single, double and even triple ionization cross sections show almost linear dependence on q (for q>9) and the slopes were closely reproduced by the GDPR model. The behaviour of single ionization was also compared with CDW-EIS model for C-atom, which was modified to include the electron density (only approximately) effects of C_{60}. However, the CDW theory predicts a non-linear dependence of ionization yield on the projectile charge state *q*.

We have also studied the behaviour of multi-fragmentation ion yields as a function of *q*. The total multi-fragmentation yield increases linearly with projectile *q*, where as the fragmentation to total-recoil-ion yield ratio saturates at high-q of projectile. This can be understood in terms of equilibration of energy partitioning between nuclear and electronic degrees of freedom. The fragment ion mass distribution is usually modeled as power law of the type $\sim n^{-\lambda}$ (n=no. of atoms in a fragment) Different values of λ have been quoted in literature for different systems. We observe that the value of λ varies from 0.8 for low charge state projectiles to 2 for high q_p projectiles. The values of λ are often related to the amount of energy loss to the system. The odd-even oscillations in the fragmentation mass distribution are well known for C_{60} and have been observed earlier. We have also compared the over all mass distribution of C_{60} recoil ions with a parameterized bond percolation model. The model was found to fit well to data for different *q* by suitable adjustment of the bond breaking probability parameter. Details of the experiment and discussion of various results will be presented.

References

[1] U. Kadhane et al. Phys. Rev. Lett. **90**, 093401 (2003)
[2] U. Kadhane et al. Phys. Rev. A **75**, 041201 (R) (2007)
[3] A. H. Kelkar et al. J. Phys. B **40**, 2481 (2007)
[4] A. H. Kelkar et al. Nucl. Instrm. Meth. Phys. Res. B 256 114 (1007)
[5] A. H. Kelkar et al. J. Phys. Conf. Ser. **80**, 012009 (2007)
[6] A. H. Kelkar et al. J. Phys. Conf. Ser. **80**, 012010 (2007)

MULTIPLY CHARGED IONS WITHIN A FULLERENE CAGE: PHOTOIONIZATION OF Ce@C_{82}^+

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The concept of an atom residing inside a ball shaped C_n molecule fascinates both chemists and physicists. Due to the high electron affinity of the carbon sphere, encapsulated metal atoms typically donate electrons to the fullerene cage to stabilize the endohedral complex. A Ce atom within a C_{82} sphere, for example, is expected to be triply charged, so that the whole endohedral fullerene can be described as $Ce^{3+}@C_{82}^{3-}$.

With the goal to investigate possible differences in the behaviour of free and of caged atomic ions exposed to ultraviolet radiation, photoionization of $Ce@C_{82}^+$, C_{82}^+ and of atomic Ce^{q+} ions ($q = 2, 3, 4$) were conducted using the merged-beams technique with monochromatized synchrotron radiation. Significant redistribution of oscillator strengths associated with excitation of the Ce 4d-shell could be observed when switching from free atomic Ce ions to their caged counterparts. The Ce 4d contribution to photo double ionization $Ce@C_{82}^+$ at around 125 eV is clearly seen in Fig.1.

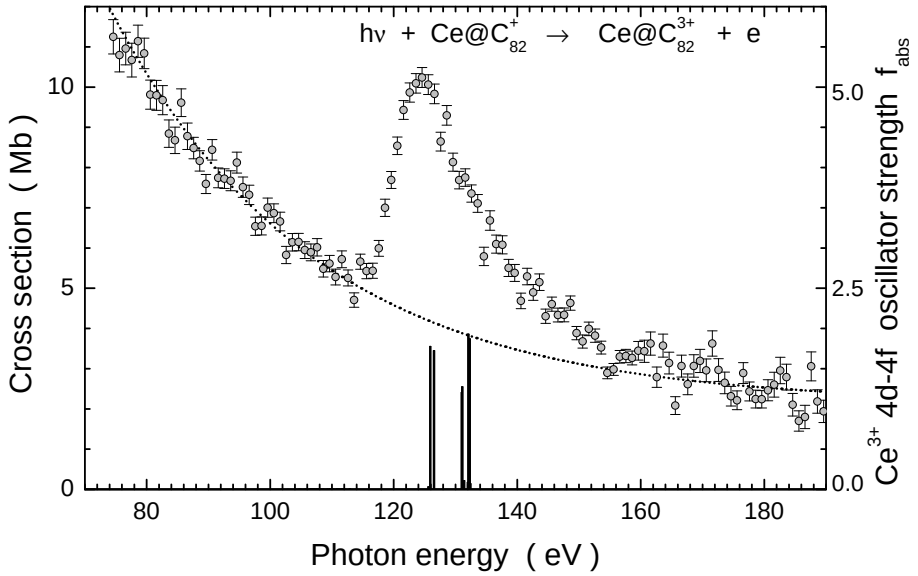

Figure 1: Experimental cross sections (circles with statistical error bars) for double ionization of $Ce@C_{82}^+$ ions by monochromatized VUV photons. The dotted line is a fit to the "backround" below the Ce 4d contribution. The vertical bars correspond to the scale on the right and show the distribution of oscillator strengths for absorption by 4d-4f transitions in Ce^{3+}, calculated by using the Los Alamos Atomic Physics Codes Package.

ABSOLUTE CHARGE TRANSFER AND FRAGMENTATION CROSS SECTIONS IN He^{2+} - C_{60} COLLISIONS

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We consider the collision of $^4He^{2+}$ ions with C_{60} in the region of impact energies 0.1-250 keV, in which charge transfer is the dominant process and the resulting neutral, singly and doubly charged C_{60} preferentially decays by emission of neutral C_2 molecules [1-3]. At these impact energies, all electronic processes (electron capture, ionization, excitation) are much faster than fragmentation [4]. Thus, fragmentation can be considered as a postcollisional process in which the energy deposited by the collision in C_{60} is transferred to the nuclear (dissociative) degrees of freedom. Therefore, the mass spectrum associated with charge transfer in ion-C_{60} collisions is determined by two parameters: (i) the charge transfer cross sections $\sigma_{\rm CT}$ and (ii) the collision energy deposit $E_{\rm dep}$. The former determines the proportion of the different C_{60}^{q+} ions produced in the collision and the latter the ensuing fragmentation. Both quantities are not easy to determine either theoretically or experimentally. This is due to the large number of active electrons and nuclear degrees of freedom involved, which implies the detection in coincidence of many particles and makes fully quantum dynamical theoretical approaches unfeasible.

In this work [5] we report on absolute measurements and theoretical calculations of charge transfer cross sections in He^{2+} + C_{60} collisions at low impact energies. The experimental and theoretical cross sections are in reasonable agreement with each other, thus reinforcing the quantitative value of our predictions. The measurements cover a wide range of impact energy (3-250 keV) and make use of multicoincidence techniques to separate the different fragmentation channels. The theory explains the various charge transfer mechanisms and provides the energy deposit that eventually leads to fragmentation. We have found that the cross sections for the formation of He^+ and He^0 are comparable in magnitude, which cannot be explained by the sole contribution of pure single and double electron capture but also by contribution of transfer-ionization processes that are important even at low impact energies. The results show that multifragmentation is only important at impact energies larger than 40 keV; at lower energies, sequential C_2 evaporation is the dominant process.

[1] S. Martin, L. Chen, A. Denis, R. Bredy, J. Bernard, and J. Desesquelles, Phys. Rev. A **62**, 022707 (2000)

[2] S. Matt, R. Parajuli, A. Stamatovic, P. Scheier, T. D. Märk, J. Laskin, and C. Lifshitz, Eur. Mass Spectrom. **5**, 477 (1999)

[3] L. Chen, S. Martin, J. Bernard, and R. Brédy, Phys. Rev. Lett. **98**, 193401 (2007)

[4] C. Bréchignac, P. Cahuzac, B. Concina, J. Leygnier, L. F. Ruiz, B. Zarour, P.-A. Hervieux, J. Hanssen, M. F. Politis, and F. Martín, Phys. Rev. Lett. **89**, 183402 (2002)

[5] A. Rentenier et al, Phys. Rev. Lett. 100, 183401 (2008)

POTENTIAL AND KINETIC SPUTTERING OF MOLECULAR FRAGMENTS FROM ALKANETHIOLS-SAMs DUE TO HCI IMPACT

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Self-assembled monolayers (SAMs) are ordered molecular assemblies formed by the adsorption of an active surfactant on a solid surface. SAMs provide a convenient, flexible, and simple system with which to tailor the interfacial properties of metal, metal oxides and semiconductors [1]. The alkanethiols are one kind of molecules used to build SAMs. These molecules are constituted by the ligand group (sulfur), the alkane chain $(CH_2)_n$ and the terminal functional group (X), see figure 1.

In this work, we employ HCI to study the desorption of positive molecular fragments from two different alkanethiol SAMs on gold surfaces: MUA and DDT, $X = COOH$ and CH_3 respectively. The SAMs are bombarded with pulsed Ar^{q+} beam ($5 < q < 9$) with kinetic energies 5-20keV. The desorbed positive molecular ions were detected and analyzed from TOF spectra, from which the masses and yields of secondary ions were obtained [2]. A complementary scanning tunneling microscopy study has also been performed with HCI on identical SAM surfaces [3].

For both surfaces the mass spectra are proton peak dominated and the intensity is larger in MUA compared to DDT. In principle the protons come from the terminal groups due to their exposed positions which make them vulnerable to being ejected, but there is also possibly a contribution from the alkane chain. Molecular ions from the chain and terminal group plus chain fragments are also observed. Additionally, both spectra show a similar peak distribution due to the chain. The molecular peaks (e.g.$(CH_2)_n^+$) decrease monotonically with increasing cluster size from n=3. It is found that peak yields for heavier mass fragments are largely independent of the charge state of incident ions.

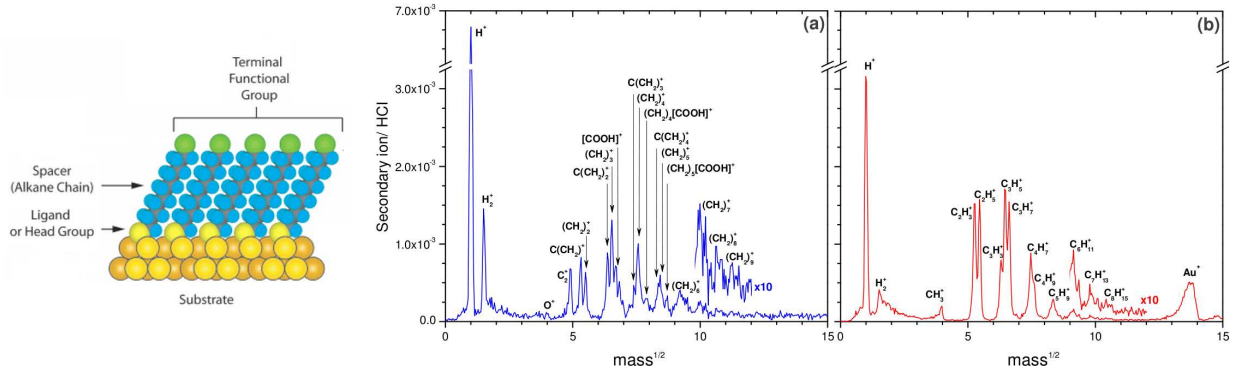

Figure 1: Left: Scheme of Alkanethiol-SAMs, from Love et al. [1]. Right: Mass spectra of secondary molecular ions emitted from SAMs surfaces (a) MUA and (b) DDT irradiated with Ar^{9+} at 18keV.

References

[1] Ulman, Chem. Rev. **96** (1996) 1533; Love et al., Chem. Rev. **105** (2005) 1103.

[2] Hamza et al., J. Vac. Sci. Technol. **A17** (1999) 303; Schenkel et al., Phys. Scrip. **T80** (1999) 73.

[3] O'Rourke et al., these proceedings.

Guiding of Argon ions trough PET nano capillary foils

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The transmission of charge state separated slow argon ions through nano capillaries with an aspect ratio of 1/100 in insulating polyethylene terephthalate (PET) polymers was investigated on argon ions with different charge states from Ar^{1+} up to Ar^{16+}. A beam of slow argon ions was extracted from an ion source of the Dresden EBIS-A type [1]. The experiments were performed with a beam line featuring an ion deceleration system [2]. With it the ion guiding of projectiles of different kinetic ranging from 600eV up to 9.6 keV has been studied.

For tilted capillaries, the ions are guided along the capillary axis, as shown for several ions in previous experiments [3]. In the following he guiding power as defined in [4] as well as the divergence angle of the transmitted ion beam have been studied in dependence on the initial ion charge state and the ion energy for Argon ions.

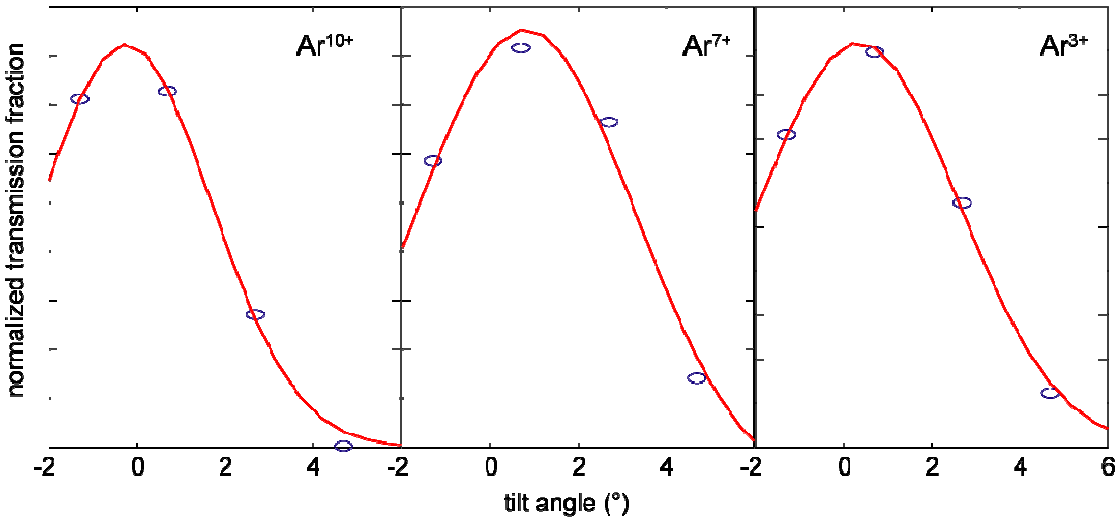

Figure 1: The measured (blue circle) and fitted (red line) transmission of Argon ions in dependence on the tilt angle of the capillary foil at a kinetic energy of q times 600 eV is shown. The guiding power is 2.7±0.5 for Ar^{10+}, 3.5±0.5 for Ar^{7+} and 3.2±0.5 for Ar^{3+}.

The guiding power and the divergence angle of the transmitted ion beam were measured in dependence on the charge state at a constant deceleration voltage. Both values are independent on the charge state as shown in Figure 1. An increasing guiding power with increasing charge state at a constant ion energy is expected.

The work was supported by the Deutsche Forschungsgemeinschaft (project No. ZS 14/9-1), by the EFRE fund of the EU and by the Freistaat Sachsen (projects No. 12321/2000 and 12184/2000).

References

[1] http://www.dreebit.com
[2] F.Grossmann, e.a.; Nuclear Instruments and Methods in Physics Research, **B256**,565 (2007)
[3] Allen, F. I., e.a; Nucl. Instrum. Methods Phys. Res. B ***244***, 323-326 (2006)
[4] R. Hellhammer, e.a.; Nucl. Instrum. Methods Phys. Res. B **258**, 159 (2007)

ION DESORPTION FROM SOLID RARE GASES BY SINGLY- AND MULTIPLY-CHARGED ION IMPACT

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Over the past few decades, a considerable number of studies has been conducted to the interaction of slow multiply charged ions (MCIs) with a solid target [1]. Because the MCI internal energy (sum of the ionization potential) can be consumed in the target surface, desorption mechanism for certain target shows strong dependence on the charge state of the projectile. However, little is known about the effect of MCI impact for condensed gas targets. In this work, we will discuss the internal energy contribution to ion desorption from the rare gas solids, on the basis of measurements of the mass spectrum and the kinetic energy distribution of the desorbed ions by singly- and highly-charged ion impact.

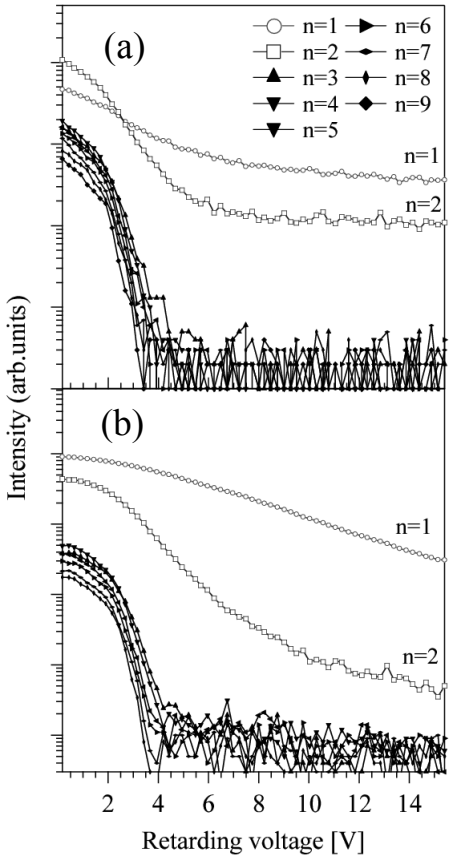

Figure 2. Retardation plots of desorpbed Ne_n^+ (n=1-10) from solid Ne (500ML) by (a) Ar^+ impact and (b) Ar^{6+} impact.

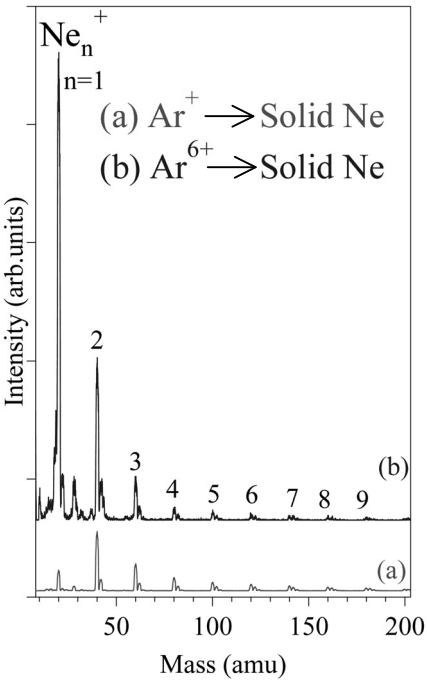

Figure 1. Mass supectra of desorpbed ions from solid Ne (500ML) by (a) Ar^+ impact and (b) Ar^{6+} impact.

Mass spectrum of desorbed ions from solid Ne by 1.0 keV Ar^+ impact is shown in Fig. 1(a). The ions desorbed surface were detected by a quadrupole mass spectrometer (QMS). The peaks of Ne^+ and the cluster ions, Ne_n^+, with a cluster size n from 2 to 19 were observed. The largest cluster size was limited by the range of QMS. We also measured the mass spectrum by 1.0 keV Ar^{6+} impact (Fig. 1(b)). Compared with singly charged ion impact, the desorbed Ne_n^+(n=1,2) intensities were increased.

Kinetic energy distribution of the desorbed ions was analyzed by placing a retarding field energy analyzer of a 4-grid type in front of the entrance of QMS. Retardation plots of desorbed Ne_n^+ (n=1-9) from the surface of the solid Ne impacted by (a) Ar^+ and (b) Ar^{6+} are shown in fig. 2. The results indicated that the energy distributions of Ne_n^+(n=1,2) strongly depend on the charge state of the projectile. We suggest that the effect of MCI impact contributes most to desorption of Ne^+ and small cluster ions.

References

[1] F. Aumayr, and HP. Winter, Phil. Trans. Roy. Soc. Lond. A **362,** 77 (2004), and references therein

Formation of Nano Pits on the KBr (001) Surface Induced by Single Impact of Slow Highly Charged Ions

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In recent years investigations of the potential energy dissipation of slow highly charged ions (HCI) on solid surfaces have brought out many new interesting phenomena, e.g. hollow atom formation, enhanced sputter yields, and potential electron emission [1].
The rapid release of the potential energy of a HCI produces a highly excited electronic system in the surface comparable to the excitation by high power ultra-short laser pulses or swift heavy ions [2]. This far from equilibrium state is known to induce various changes in the topography of insulating surfaces on a nanometer scale. Hence, HCIs are considered to be a promising tool for nano structuring and analysis [3]. However, the underlying detailed microscopic mechanisms, especially on atomically flat surfaces, are less investigated so far.
Therefore, we have studied the interaction of slow (300 eV/amu) highly charged Xe ions with the KBr (001) surface. The individual impact of such projectiles induces nanometer size pit-like structures on the surface. Thereby, the pit formation ability and the pit volume are found to depend strongly on the projectiles initial charge state and their kinetic energy. From complementary high fluence irradiations evidence is found that the pit formation is associated with the agglomeration of electronic defects induced by the potential energy dissipation into complex centers (X-centers).

References

[1] F. Aumayr, P. Varga, and H. P. Winter, Int. J. Mass Spec. 192, 415 (1999)
[2] E. Akcoltekin et al., Nature Nanotechnology 2, 290 (2007)
[3] F. Aumayr, and H. P. Winter, e-J. Surf. Sci. Nanotech. 1, 171 (2003)

X-RAY EMISSION IN THE INTERACTION OF SLOW H-LIKE IONS WITH A METAL SURFACE

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We measured x-ray spectra to study the hollow atom below the surface in the interaction of H-like ions with the metal surface by the coincidence measurement with secondary electrons emitted. We will present the measurement of the x-ray spectra and the x-ray yields. It is found that the x-ray yields of the K shell for the hollow atom become larger than the atom. The x-ray yields represent the filling probability of a vacancy in the K shells being filled by x-ray transitions in competition with Auger processes for the K shell hole. Since the filling probability through Auger transition straightforwardly with the number of spectator electrons, x-ray yields would increase with decreasing the number of the spectator electrons in outer shell. By the measurement of K x-ray fluorescence yields we will discuss the deexcitation of the hollow atom below the surface. Figure 1 shows a typical x-ray spectrum from the hollow atom. The projectile is H-like I^{52+} ions and the target is cobalt.

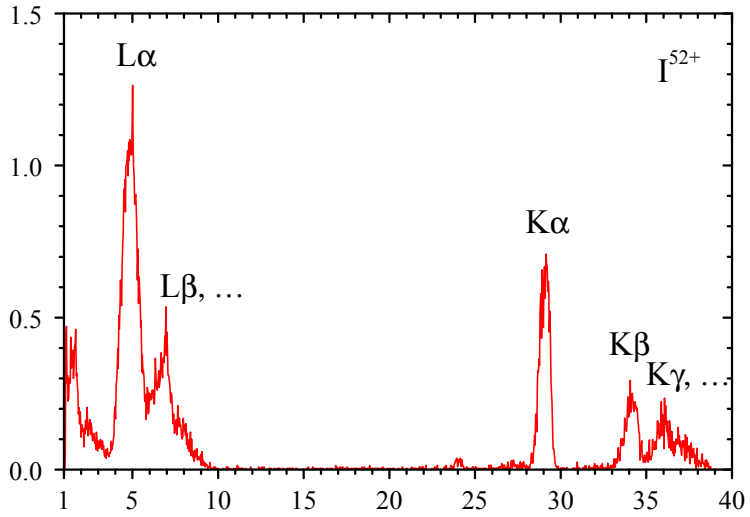

Figure 1: X-ray spectrum for collisions of H-like I^{52+} ions with a Co surface.

GUIDING OF SLOW HIGHLY CHARGED IONS THROUGH A THIN GAP BETWEEN A PAIR OF PARALLEL GLASS PLATES

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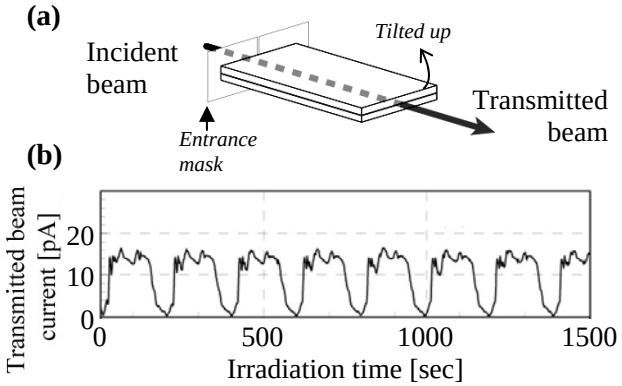
Interaction of slow highly charged ions (HCI) with insulator multi-capillaries has recently been intensively studied experimentally as well as theoretically. One of the most prominent features is a so-called guiding effect, a transportation of slow HCIs along the capillary axis keeping their initial charge states even when the capillary axis was tilted against the beam direction. The fact that most of the guided ions keep their initial charge suggests that the ions do not touch the inner wall of the capillaries during transportation, i.e., an amazingly well-tuned electric field is automatically formed in each capillary. In other words, a self-organized charge-up of the inner wall plays an important role in realizing the guiding effect. We have developed a method to produce a micro-/nano-sized HCI beam with a tapered single glass capillary based on the guiding effect [1-3]. The glass capillary has a possibility to realize modification in a small area on the surface, micropatterning of nanodots and element-sensitive microscopy using HCI beams.

In order to provide a nanobeam as a tool using the glass capillary, stability of the transmission is required. The stability is expected to be sensitive to the balance between the charge-up and the discharge on the inner wall. We have employed a thin gap between a pair of parallel glass plates, which is easy to understand the irradiated position on the inner wall (Fig. (a)).



The transmitted beam currents through the gap (0.1 mm) were measured for several incident currents of 104 keV Ar^{8+} beams. Figure (b) shows the transmitted beam current as a function of the irradiation time and a repetition with precise structure. The incident beam was stable and monitored to be 5. 9 nA at the entrance mask. When the incident current was varied, the frequency of the repetition changed. The frequency of the repetition was well-proportional to the incident currents ranging from 4 to 15 nA. It means that the reconstruction and the decay of the charge-up on insulator surface can be well-arranged. We will report the incident current dependence of the frequency and a model describing the glass surface conductivity based on the strength of the charge on the surface.

References

[1] T. Ikeda, et al., Appl. Phys. Lett. **89**, 163502 (2006)
[2] T. Ikeda, et al., J. Phys. Conf. Ser. **58**, 68 (2007)
[3] T. Ikeda, et al., J. Phys. Conf. Ser. **88**, 012031 (2007)
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COLLISIONS OF IONS WITH INSULATING SURFACES: CHARGING AND DISCHARGING DYNAMICS.

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Guiding and focussing of keV to MeV ions by insulator micro-capillaries offers exciting perspectives for the production of low divergence micro-sized beams and a fine spatial control over the irradiated zone. Such high quality beams may find applications in surface nano- structuring. A spectacular demonstration of the effective use of a tapered capillary is the direct injection of ions inside a living cell [1]. The guiding effect results from the local charging of the capillary inner wall, so this effect depends only on the charging dynamics of the insulating material.
Finding the best material for these applications requires that the charge induced processes are well understood. For that purpose, we have studied the dynamical behaviour of charge deposition and beam deflection on well defined planar geometry where the exact number of charges left on the surface as well as the time dependant beam deflection can be monitored. Depending on surface composition, temperature and structure, discharging time constant vary by orders of magnitude giving rise to different characteristic behaviour.
We have also performed numerical simulations that, besides giving access to the field distribution above the surface plane, point to the importance of the intensity distribution within the incident beam.

[1] Y. Iwai, T. Ikeda, TM. Kojima, et al., App. Phys. Lett. **92** , 023509 (2008)

CHARGE-UP DYNAMICS IN GUIDING SLOW HIGHLY CHARGED IONS THROUGH NANO-CAPILLARIES

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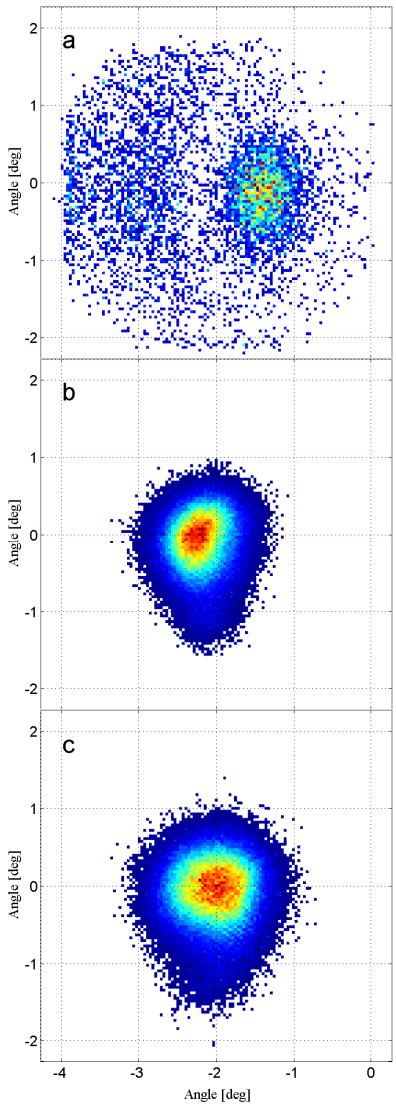
Experiments have shown that Slow Highly-Charged Ions (HCI) are transmitted, without change of their charge, through insulating nano-capillaries even when the capillary membranes are tilted by angles much larger than the angle given by the aspect ratio, i.e. the ions are guided, when the capillary membrane is not geometrically open to the incident ion-beam [1-3]. This is explained by charge patches, deposited in a self-arranged pattern, on the inside of the capillary walls [1-5].



We have studied the time dependence of charge-up by two-dimensional distribution of 7 keV Ne^{7+}-ions guided through SiO_2-capillaries. The transmitted ion angular distributions after different amounts of incident charge deposited on the membrane at tilt angle -2º during charging-up of the capillaries are shown in Fig. 1. The ions start to be seen at -1.4º (top) after 21 nC, the centroid moves to the left to -2.2º after 105 nC (middle), and the steady state is reached at -2º (bottom) after 356 nC. This is interpreted by successive build-up of three charge patches that guide the ions on zig-zag trajectories through the capillaries. The angular distributions are broadened with forming further charge patches and the amount of deposited charge in the charge patch at the capillary exit.

Fig. 1.
Two-dimensional images of the transmitted Ne^{7+}-ion distributions after different amounts of incident charge on the membrane during charging-up of the SiO_2 capillaries. top: after 21 nC, middle: after 105 nC, bottom: after 356 nC.

References

[1] N. Stolterfoht *et al.* Phys. Rev. Lett., **88** 133201 (2002)
[2] G. Vikor *et al.* , NIM B 233, 218 (2005)
[3] M. B. Sahana *et al.* Phys. Rev. A **73**, 040901 (2006)
[4] P. Skog *et al.* , NIM B 258 (1), 145-149, (2007)
[5] K. Schiessl *et al.* Phys. Rev. A **72**, 062902 (2005).
[6] R. T. R. Kumar *et al.* Nanotechnology **16** 1697–1700 (2005).

Investigation on a Nano-Structure on a Hydrogen-Terminated Si Surface Induced by Individual HCI impacts

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We have investigated properties of the interaction of slow highly charged ions (HCI) with a hydrogen terminated Si (Si-H) surface. Iodine HCIs (I^{q+}) having high q (up to naked ion, i.e., q=53) were produced in the Tokyo-EBIT and were incident onto a Si-H surface. During irradiation, emission yields for various kinds of secondary particles (e.g., secondary ions, photons, and so on) were measured with a coincidence technique. After irradiation, furthermore, a HCI-irradiated Si-H surface was observed by a scanning tunnelling microscope (STM). Figure 1 shows a typical STM image of a Si(100)-(2×1)-H surface induced by a I^{50+} impact. The sample was exposed to oxygen gas (partial pressure:$\sim 1\times10^{6}$ Pa, base pressure:1×10^{8} Pa) during irradiation (irradiation time: ~2 hours). We can note that a nano-structure indicated by a white arrow is at around the centre in addition to the atomic structure of the Si-H surface. We consider that the impact site includes Si-O bonds formed by a surface-chemical reaction that O atoms are attached to dangling bonds created after removing a large amount of hydrogen atoms by "potential sputtering". We will discuss the physical and chemical properties of the structures.

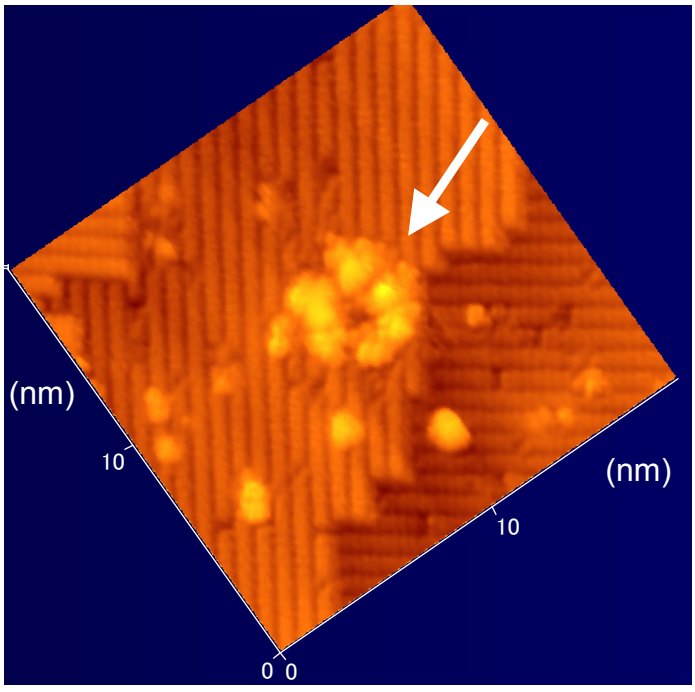

Figure 1. Nano-strucrue on Si-H surface incuced by a I^{50+} HCI impact.

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GUIDING EFFECT OF MEDIATE AND LOW ENERGY ELECTRON-BEAM BY QUARTZ TUBE

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The study on interaction between charged particle and capillary has attracted lots of attention during these few years, especially after the guiding phenomen of HCI through multi-channel PET capillary was reported by N. Stolterfoht *et. al*.[1] in 2002. After that, a serious of experimental and theoretical research had been done for investigating this guiding effect in more details. To the best of our knowledge, so far, all of the researches in or related to this area were focused on using weak beam current and micro-sized capillary. In this works, we investigated the guiding effect of low energy electron beam with strong beam current by a cylindrical bended macro-sized quart tube.

Electron beam was injected into a quart tube with 15° bended angle, its inner and outer diameter are 2.3mm and 4.5mm respectively. To overcome the limitation that PSD can not work under strong beam intensity, a position sensitive faraday cup was developed and used to detect the electron beam transmitted through the quartz tube, and the distribution of transmitted beam current on each channel of the Faraday cup was acquired. The faraday including sixteen channels, each one of them is 2.3mm width and 1.5mm high.

We found that, similar to those cases of micro-sized capillary, guiding effect also exist on the process of interaction between electron beam and macro-sized insulator tube which was also due to the self-organized charge-up effect above the inner wall of the insulator tube. The incident electrons can not pass through along the axis of the quart tube with 15° angle, while the self-organized charged-effect above the inner of the quart tube stop these electrons from hitting on the inner wall directly and "guided" them to transmit through the quart tube (see fig1). While compared to previous works, the result of our experiment indicated a fact that the guiding ability of the tube is proportion to the incident beam intensity, which, did not yet reported so far. We conclude that this was due to the impact generated by the big area of the inner wall of the insulator tube.

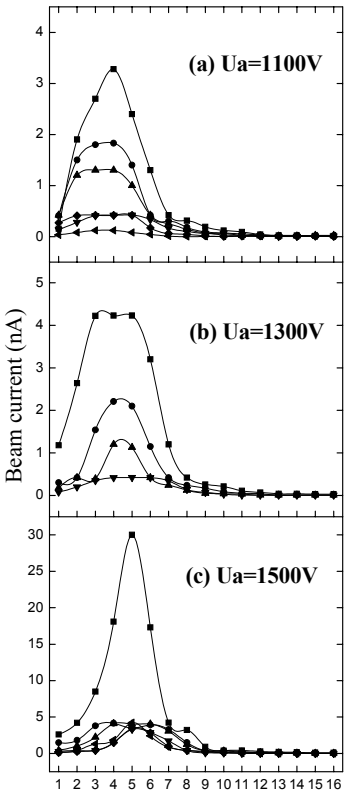

Fig 1. Distribution of beam current

References

[1] N. Stolterfoht, J. H. Bremer, R. Hoffmann, et al. Phys. Rev. Lett. **88**, 133201 (2002).

DYNAMIC FEATURES OF BEAM GUIDING BY INSULATOR CAPILLARIES: INCIDENT ENERGY DEPENDENCE

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The electric property of insulator surfaces can be used to guide slow ions along the axis of an insulator capillary.[1, 2] Qualitatively, this guiding process can be explained as the deflection of ions by charge patches produced on the capillary surface by the preceding ion-surface collisions.[1, 3] Here, we present experimental results indicating the relationship between the growth of the charge patches and the dynamic behavior of the guided ions.

Experiments were carried out at RIKEN with 3.5 -7 keV Ne^{7+} ions from a 14.5 GHz ECR ion source. [4, 5] A polyethylene terephthalate (PET) foil was attached to the target holder and rotated. The PET foil included capillaries with a length of 10 μm and a diameter of 200 nm. The capillary density was 4 $\times 10^6$ capillaries/cm^2.A two-dimensional position-sensitive detector (PSD) was used to measure the transmitted ions.

Results for 3.5 - 7 keV Ne^{7+} are shown in Fig. 1. The PET capillary was tilted by 2.8° with respect to the beam direction. The transmitted intensities and deflection angles of the beams were plotted as functions of the charge deposited at the foil surface. The deflection angles changed along the tilt direction in accordance with the intensity evolution. Although this behavior seems to be a general feature for the beam guiding effect [4, 5, 6, 7], a detailed study has not been done.

The increase in deflection angle with the intensity evolution in Fig. 1 may be attributed to the growth of a charge patch at the entrance region of the capillary. Moreover, the decrease in deflection angle after the maximum in Figs. 1 (a) and (b) may be attributed to the growth of another charge patch in the capillary. It is noted that this oscillatory behaviour of the deflection angle along the tilt direction was clearly observed at low energies of 3.5 and 4.9 keV, and was not clear at 7 keV, as shown in Fig. 1.

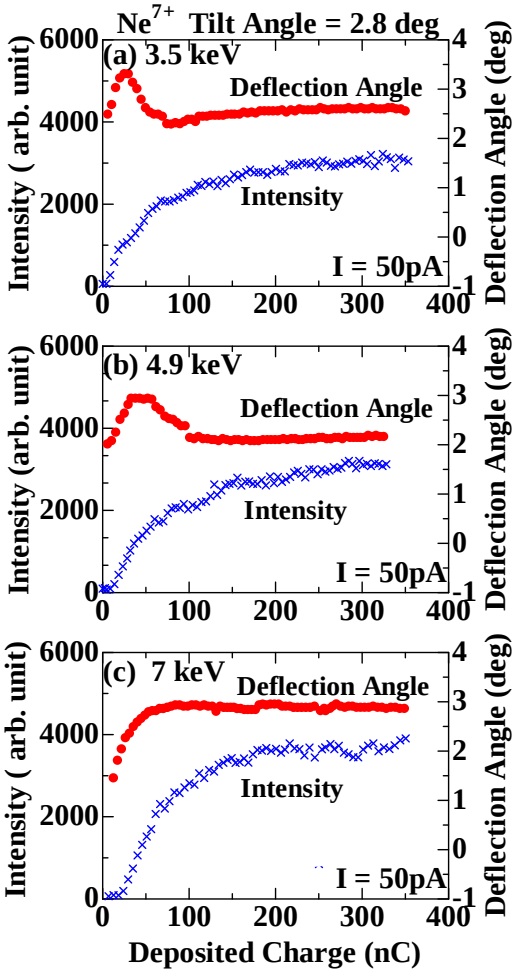

Fig. 1 Deflection angle and intensity evolution of transmitted, 3.5, 4.9, and 7 keV Ne^{7+} ions as functions of charge deposited at PET foil.The deflection angle was deduced from the peak position at the PSD

References

[1] N. Stolterfoht *et al.*, Phys. Rev. Lett. **88**, 133201 (2002).
[2] T. Ikeda *et al.*, Appl. Phys. Lett. **89**, 163502 (2006).
[3] K. Schiessl *et al.*, Phys. Rev. A **72**, 062902 (2005).
[4] Y. Kanai *et al.*, NIM B **258**, 155 (2007).
[5] N. Stolterfoht *et al.*, Phys. Rev. A **76**, 022712 (2007).
[6] N. Stolterfoht *et al.*, NIM B **225**, 169 (2004).
[7] M. Fürsatz *et al.*, J. Phys. Conf. Series **58**, 319 (2007).

ION GUIDING THROUGH NANOCAPILLARIES IN PET POLYMERS WITH VARIABLE DIAMETER

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Recent studies [1] reported on guided ion transmission through capillaries in insulating poly-ethylene terephthalate (PET) polymers, i. e. the main fraction of ions is transmitted through the capillary in its incident charge state. The guiding phenomena can be understood by the charge deposition of the incident ions at the inner wall of the capillaries in a self-organizing manner. For a tilted foil the deposited charge in the entrance region increases until the electrostatic field is sufficiently high for a deflection of the ions towards the direction of the capillary exit. Due to the increasing interest in this subject, several laboratories have started investigations of capillary guiding [2-6].

In this work we performed measurements using the apparatus available at the ECR beam line of KVI in Groningen. We studied capillaries with diameters of 100, 200, 300, and 400 nm as shown in Figure 1.. The capillary density of $4x10^6$ cm^{-2} and the projectile was 3 -keV Ne^{7+}. The tilt angle of the capillaries was varied from 0° to 11°. The tilt angle dependence of the total ion yield I can be fitted by a Gaussian function (Fig. 1).

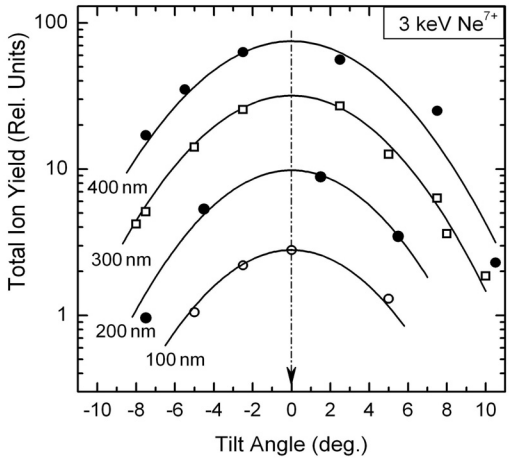

Figure 1: Total intensity of the emission profiles as a function of the tilt angle for different diameters of the capillaries. The solid lines are Gaussian fits.

The Gaussian fit allows for the determination of the *guiding angle* ψ_c, for which the intensity of the transmission profiles drops as $I(\psi_c)/I(0) = 1/e$. The guiding angle is a measure for the guiding power, which represents the capability of the capillaries to guide the ions. From the width of the Gaussian functions (Fig. 1) we determined the guiding angle for 100, 200, 300, and 400 nm capillaries. The guiding angle was found to vary within a relatively small range of 5° - 6° (in disagreement with previous preliminary studies [7]). From the new observation we conclude that the field in the entrance region is similar for all capillary diameters studied. This conclusion is unexpected, since the geometry of the capillaries changes considerably with varying diameter. The results are interpreted in terms of model calculations

REFERENCES

[1] N. Stolterfoht *et al.*, Phys. Rev. Lett., **88**, 133201 (2002), Phys. Rev. A **76**, 022712 (2007), ibid **77**, 032905 (2008), and references therein
[2] K. Schiessl *et al.*, Nucl. Instrum. Methods 232, 228 (2005) and Phys. Rev. A, 72, 062902 (2005).
[3] M. B. Sahana, *et al*., Phys. Rev. A **73**, 040901(R) (2006).
[4] S. Mátéfi-Tempfli, *et al.*, Nanotechnology, **17**, 1 (2006).
[5] A. R. Milosavljević *et al.*, Phys. Rev. A **75**, 030901(R) (2007)
[6] S. Das *et al.*, Phys. Rev. A, 76, 042716 (2007).
[7] N. Stolterfoht et al., Surface and Coating Technology 196, 389 (2005)

COMPUTATION OF DOSE DISTRIBUTIONS FOR HEAVY CHARGED PARTICLES IN THERAPUTIC APPLICATIONS

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Proton and carbon ion tracks in muscle tissue were determined using the Monte Carlo method employed in Ref. [1]. The lateral dose distributions in the Bragg peak and the isodose curves were computed for a point-like beam as well as a pencil beam of protons and carbon ions in radiation therapy. Total dose deposited in the tissue were also obtained, and comparisons were made with the experimental values reported in the literature [2]. The computer program written for this purpose is able to analyze some problems in heavy charged particle therapy.

References

[1] H. Noshad, N. Givechi, Rad. Meas. **39**, 521 (2005).
[2] M. Goitein, R. Gentry, A. M. Koehler, J. Radiat. Oncol. Biol. Phys. **9**, 259 (1983).

SELECTIVE FORMATION OF MULTIPLY EXCITED STATES BY RESONANT COHERENT EXCITATION

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Multiply excited states attract great interests for the test of theories involving the strong electron correlations. Especially, investigation of triply excited Li or Li-like ions has progressed significantly in recent years. However, the triply excited Li-like system of heavier ions can be formed only by the atomic collisional processes such as electron capture to the outer shell since the synchrotron radiation is not applicable. Here we demonstrate a novel method for the formation of selective multiply-excited states of heavy ions.

We utilized three-dimensional resonant coherent excitation (3D-RCE) [1] of energetic heavy ions in a crystal, in which the traveling ions are resonantly excited through the interaction with the periodic crystal fields. With the use of ions at relativistic velocity, the available transition energy of RCE rises up to the x-ray region which enables us to excite the inner shell electron of highly-charged heavy ions. Since the oscillating field consists of numerous frequency components, the double resonance of RCE can be realized by adopting two of them simultaneously to the resonance.

We excited the two $1s$-electrons of He-like Ar^{16+} and Li-like Ar^{15+} into the $n = 2$ orbitals by successive 3D-RCEs of different harmonics. The energy diagrams are shown in Fig. 1(a) and (b). The double resonance conditions are satisfied by independently adjusting two rotating angles of the thin Si crystal keeping the ion velocity constant, which is a significant advantage over the previous 2D-RCE method [2]. The experiment was performed at the heavy ion medical accelerator in Chiba (HIMAC) with the $\sim$ 400MeV/u ions. We observed the charge state distribution of the ions emerging from the crystal together with the emitted x-ray yields and their polarization. In both cases, our result provided clear evidence that the multiply excited states are formed in the crystal.

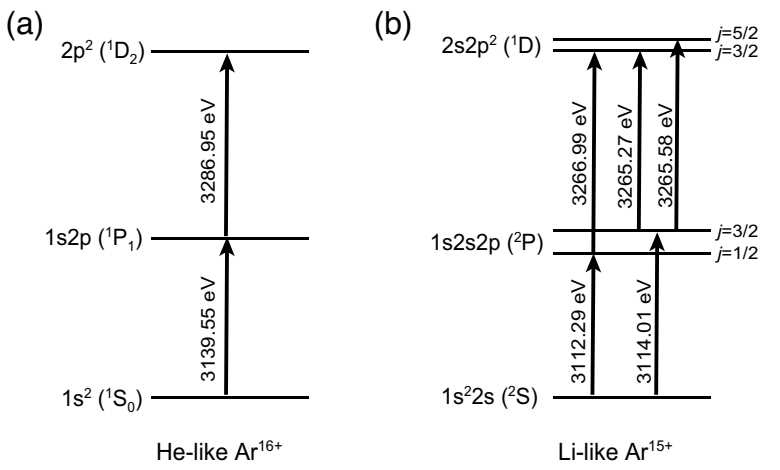

Figure 1: The level diagram of double electron excitation of (a) He-like Ar^{16+} and (b) Li-like Ar^{15+}.

References

[1] C. Kondo *et al.* Phys. Rev. Lett. **97**, 135503 (2006)

[2] Y. Nakano *et al.* J. Phys. Conf. Ser. **58**, 359 (2007)

SOLID-DENSITY PLASMA EXISTED AT INITIAL STAGE OF HEAVY ION TRACK FORMATION IN SOLIDS

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The processes undergo in solids immediately after excitation by single fast ions with energy of 0.1–1.0 GeV are considered. We analyze and discuss X-ray spectra of excited target atoms (Si and Al) were measured in [1,2]. It is shown the regularly used model of multiple collisional excitation of insulated target atom does not provide the correct simulation for relative intensities of K-shell dielectronic satellites spectral lines.

To describe the X-ray spectra we suggest to use specially developed model of time-depended collision-radiative kinetics, which takes into account every relaxation process caused by target ion collisions with free electrons in dense matter. The time of raditation for registered spectra is about 10 fs, thus its represent the data for the matter parameters inside the track on so short timescale after initial excitation in collision with projectile ion. Further, the molecular dynamics modeling was applied to confirm the times of Maxwell distribution establishment and recombination processes are in the range of 1 and 100 fs, respectively. It is allow to consider the matter inside the heavy ion track as non-equilibrium solid density plasma on the timescale of X-ray spectra radiation (tens of fs).

Based on that, the plasma model was developed and used for experimental spectra simulation. The spectral measurements were done with spatial resolution along projectile ion stopping range, so the evolution of plasma parameters in depends on projectile energy was investigated. The temperature of free electrons in the central part of swift ion track was considered as free parameter during the simulation. According to the comparison with experimental data, the values of electron temperature in the range of 10-50 eV were obtained and the plasma model was verified successfully.

The results and using of plasma model approach are well-promising to be applied in considerations for the next stages of heavy ion track relaxation and latent track formation.

References

[1] S.A. Pikuz Jr, V.P. Efremov, O. Rosmej et al., J. Phys. A **39**, 4765 (2006)

[2] O.N. Rosmej, S.A. Pikuz Jr., A.D. Fertman et al., Phys.Rev. A **72**, 052901 (2005)

ABOVE-THRESHOLD TWO-PHOTON TRANSITIONS BETWEEN BOUND STATES OF MULTICHARGED HYDROGEN-LIKE IONS

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Recent advances in production of an intense coherent x-ray radiation, either from free electron lasers or from high-order harmonics of optical laser radiation, open the possibility of experimental measurements of elastic and inelastic (Raman-like) x-ray scattering involving inner shells in heavy atoms or multicharged ions. Major difficulty in theoretical description of such processes is the summation over intermediate states of the electron in a Coulomb continuum after absorption of above-threshold photon (which energy $\hbar\omega$ exceeds the binding energy of an initial bound state, $\hbar\omega > |E_0|$). The well-known standard Sturmian expansions for the Dirac Coulomb Green Function (CGF) cannot be used for this case, since they give convergent Sturmian series for the transition amplitude only for below-threshold photons (with $\hbar\omega < |E_0|$). We show that the use of generalized Sturmian expansions for Dirac CGF (involving a free (arbitrary) parameter α, cf. Ref. [1]) leads to well-convergent Sturmian series for relativistic two-photon matrix elements in the above-threshold region after proper choice of the complex parameter α. For nonrelativistic problems, high efficiency of generalized Sturmian expansions for CGF of the Schredinger equation in numerical calculations of above-threshold processes was demonstrated in Ref. [2]. As the illustration of developed techniques for treatment of relativistic two-photon above-threshold transitions, we present high-precision results for the (electric-dipole) dynamic polarizability of ground state of H-like ions with $Z < 137$ (Z is the nuclear charge) over a wide interval of above-threshold photon energies. Our techniques may be useful also for high-precision calculations in quantum electrodynamics of bound states in a strong Coulomb field.

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References

[1] A.A. Krylovetsky, N.L. Manakov, S.I. Marmo, Zh. Eksp. Teor. Fiz., **119**, 45 (2001) [Sov. Phys.-JETP, **92**, 37 (2001)]
[2] N.L. Manakov, S.I. Marmo, S.A. Sviridov, Zh. Eksp. Teor. Fiz., **132**, 796 (2007) [Sov. Phys.-JETP, **105**, 696 (2007)]

PRODUCTION OF MULTIPLY CHARGED IONS FROM THE 4d PHOTOIONIZATION OF Cs^+

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There has been great interest in systematic studies of 4d photoabsorption of atoms with increasing ionization along with isoelectronic sequence. However, very little is known experimentally on photoabsorption for ionic species. The 4d photoabsorption spectrum of Cs^+ has been measured by Cummings and O'Sullivan[1] with the dual-laser-produced plasma (DLP) technique. However, because of absorption saturation the shape of the 4d giant resonance could not be deduced in their experiment. In this paper, we present the relative photoion yield spectra of Cs^{2+} and Cs^{3+} from a Cs^+ target within the 4d giant resonance region with an ion-photon merged-beam apparatus. The experimental set-up was the same as that described in Koizumi *et al* [2]. The measurements were done using the monochromatic photon beam from a high-resolution spherical grating monochromator in the BL-16B beam line at the Photon Factory for High Energy Accelerator Research Organization (KEK-PF).

Figure 1 shows the total ion spectrum below 90 eV with higher resolution ($E/\Delta E \approx 800$). Some prominent discrete peaks are observed. These peaks are assigned to 4d-np,nf transitions from the theoretical study by Sato *et al*[3]. Above 90eV, a broad 4d giant resonance peak is observed clearly for Cs^{3+} spectrum. It is worth noting that some window type resonances appear around at 100eV. Detail comparison between present data and the theoretical study will be given at the conference.

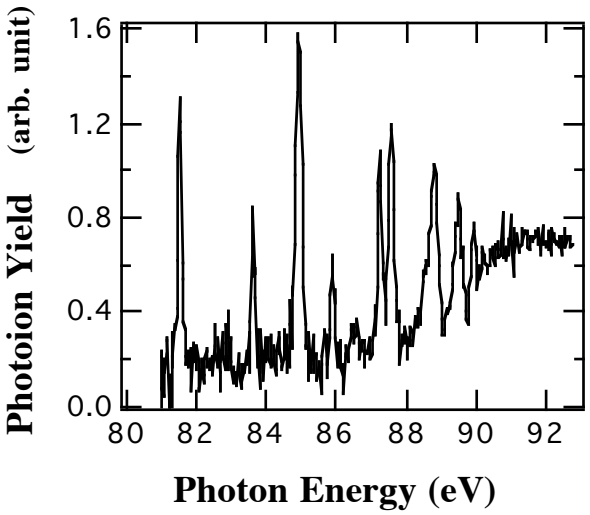

Fig. 1. Sum of Cs^{2+} and Cs^{3+} yield from Cs^+ target with higher energy resolution. ($E/\Delta E \approx 800$).

References

[1] A. Cummings and G. O'Sullivan, J. Phys. B**30**, 5599 (1997).
[2]T. Koizumi, Y. Itoh, M. Sano, M. Kimura, T.M. Kojima, S. Kravis, A. Matsumoto, M. Oura, T. Sekioka and Y. Awaya, J. Phys. B**28**, 609 (1995).
[3]M. Sato, X. M. Tong, and T. Watanabe, Phys. Scr. T**92** 338(2001).

X-RAY ABSORPTION BY HIGHLY CHARGED IONS IN PLASMAS: TOWARD PHOTO-PUMPING X-RAY LASER

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In the photo-pumping x-ray laser scheme, spectral line emission from particular ions is absorbed by different element ions to create the population inversion in the latter. The success of this scheme as an x-ray laser depends upon exact spectral matching between the emission line and the absorption line. The widths of the spectral lines of ions in plasma, that are due mainly to the Doppler broadening and the Stark broadening, are typically $\sim \Delta\lambda/\lambda < 0.01\%$. Therefore high resolution spectroscopic studies are required to find appropriate pair of the "emitter" and "absorber" ions. Indeed, in the early 1990s, the atomic physics group at the Lawrence Livermore National Laboratory (LLNL) has determined the accurate wavelengths of many spectral lines of highly charged ions by use of the electron beam ion trap (EBIT) [1, 2]. The data obtained by the EBIT group, in collaboration with the x-ray laser specialists at LLNL, was used to find the candidate pairs of ions for photo-pumping x-ray lasers.

The scheme using "emitter" ions and "absorber" ions has a technical difficulty: the emitter and the absorber ions should be located as close as possible so that the pumping emission reaches to the absorber ions efficiently. At the same time, the electron temperature should be high for the emitter to increase the emissivity of the ions, whereas the lower temperature is preferred for the absorber ions to avoid the "thermal" population in the lower lasing level, which reduces the amplification gain. This implies that the use of "emitter" and "absorber" ions in different kinds of plasmas is not practical under usual laser irradiation geometry [3].

In this presentation, we propose the use of Kα line from solid target as the emitter coupled with the laser-produced plasma as the absorber. We take aluminum Kα line (0.833816 nm) and resonance line $2p^6$-$2p^5 4d$ $(2p_{1/2}, 4d_{3/2})_1$ of neonlike zinc ions (0.83400 nm) as an example and calculate the excited level population of the neonlike zinc ions by use of an Monte-Carlo simulation code. The calculated result shows that substantial amplification gain in the transition of $3p$-$4d$ line at a wavelength of 3.5 nm can be generated in this scheme.

Reference

[1] J. Nilsen, P. Biersdorfer, et al., "Measurement of the Ly-α Mg resonance with the $2s \rightarrow 3p$ Ne-like Ge line", Phys. Rev. A 50: 2143-2149 (1994).

[2] S. R. Elliott, P. Biersdorfer, B. J. MacGowan, and J. Nilsen, "Measurements of line overlap for resonant spoiling of x-ray lasing transitions in nickel-like tungsten", Phys. Rev. A 52: 2689-2692 (1995)

[3] Y. Kato and T. Kawachi, "Prospect of Laser-Driven X-Ray Lasers for Extension to Shorter Wavelengths.", Progress in Ultrafast Intense Laser Science IV, Springer Series in Chemical Physics , Vol. 91, Eds. Yamanouchi, K.; Becker, A.; Li, R.; Chin, S.L. (2008) (in press).

BEHAVIOUR OF IMPURITY IONS FOR RADIATION COLLAPSE IN LARGE HELICAL DEVICE

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Impurities have an important effect on energy balance and particle transport in plasmas and play a key role for many plasma properties. This is normally the case in fusion plasmas, astrophysical plasmas and industrial plasmas. For simulation or modeling of plasmas we would like to know the absolute values of ion and electron densities, electron temperature, radiation power etc. In order to study the behavior of impurities quantitatively, spectroscopic measurements are very useful. We are studying plasma diagnostics with the use of spectroscopy. In this paper we discuss the behavior of impurities as deduced from EUV spectra measured in laboratory fusion plasmas in the LHD (Large Helical Device).

Radiation collapse in such fusion machines is related to the problems of the density limit and the threshold temperature [1]. It is also related to a balance between input power and radiation power output. Radiation collapse is thought to occur when the electron density increases, the electron temperature decreases and so the radiation loss increases significantly. However this scheme is not studied well quantitatively. Recently the effect of electric field on radiation collapse has been discussed. In order to investigate how and why plasmas collapse, we measure the impurity emission spectra.

In this paper we try to make a quantitative study of radiation collapse using spectroscopic measurement of carbon ion lines of C III, C IV and C V from LHD plasmas. We estimate the time dependent electron temperatures from the intensity ratios of spectral lines from C V and C III using a collisional-radiative model for the carbon ions. We find that the intensity ratios of C V are affected by recombination at the end of plasma. We will describe a time dependent model for carbon ions. We will also compare the radiation collapse caused by radiation from other elements such as neon, iron and xenon.

References

[1] B.J. Peterson et al, (2006) Plasma Fusion Research, **1**, 45

INVESTIGATING THE EMISSION ANGLE, CHARGE AND ENERGY OF IONS PRODUCED FROM LASER PRODUCED EXTREME ULTRAVIOLET SOURCES.

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With the ongoing miniaturisation of microprocessors in accordance with Moore's law, the physical limits of current photolithography employing deep ultraviolet radiation (λ =193 nm), are being reached. Laser produced plasma sources of radiation are one of the favoured candidates for the production of the 13.5 nm radiation required for Extreme Ultraviolet Lithography (EUVL) manufacture of features at the 32 nm node and beyond [1]. The choice of wavelength for EUVL is based on the availability of Mo/Si multilayer mirrors which have a 70% reflectivity at 13.5 nm [2]. Tin (Sn) and xenon (Xe) are both potential EUVL source materials as they emit strongly at the required wavelength [3,4]. Both Sn and Xe target materials emit energetic ions which can damage and greatly reduce the reflectivity of real world optics thus hindering any commercial application. It is therefore important to characterise the charge state, energy and angle of emission of ions emanating from laser produced plasmas that might be utilised in EUV lithographic applications.

The properties of ions emitted from tin based laser produced plasmas have been investigated using a spherical sector energy analyser. The analsyser was used to determine the charge states and energies of ions emitted from the plasmas. The detection efficiency of the analyser has been absolutely calibrated using an Electron Cyclotron Resonance Ion Source. Angular discrimination was achieved using a custom built optical system which could be rotated in relation to the spherical sector energy analyser, whilst maintaining a normal angle of incidence for the laser pulse with respect to the target [5]. The optical system provides angular measurement, with a 1 degree accuracy, over a range from 20 – 85 degrees to the normal incident direction of the laser. The tin plasmas were generated using a Nd:YAG laser operating at 1064 nm with a full width half maximum pulse duration of 7-9 ns. Tin charge states from SnII to SnX, with energies / charge ratios spanning 0.2 – 3.2 keV, over a range of angles (20, 30, 40, 45, 50, 60, 70, and 80 degrees) were analysed.

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References

[1] International Technology Roadmap for Semiconductors (ITRS) – www.sematech.org.
[2] Hayden *et al*, Microelectronic Eng, 83 699-702 (2006).
[3] Bowering *et al*, J. Appl. Phys., Vol 95, 16 (2004).
[4] Hayden *et al*, J. Appl Phy ., Vol 99, 093302 (2006).
[5] Morris *et al*, J. Phys. Conference Series, Vol 58, 391-394 (2007).

Electron Temperature Modifications by Upgraded Injection Power of IBW Heating System on HT-7 Tokamak

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Abstract:

The enhanced local and globalized electron heating has been achieved by recently upgraded ion Bernstien waves (IBWs) heating system in deuterium plasmas on HT-7 tokamak. The maximum capability of injection power of the system has been enhanced from 350 kW to 600 kW (15-30 MHz) for better and active control of current density and pressure profiles, and for discovering the new aspects of plasma heating for good particle and energy confinement. A new quadruple T-type ion Bernstein waves (IBWs) coupling antenna has also been installed, mounted in the toroidal direction on low field side in this scenario. Both on-axis and off-axis electron heating has been investigated. In the present study, the electron-heating mode was experimented by varying IBW injection power, and the investigated results are demonstrated. The enhancement in direct electron heating via electron Landau damping (ELD) from IBWs has been observed, and the bulk electron temperature showed a significant rise with a heating factor, $\Delta(T_e \times n_e)/P_{rf}$, up to 9.3×10^{19} $eV\ m^{-3} kW^{-1}$ at central electron density (n_e) 3.7×10^{19} m^{-3}. A good particle confinement has been achieved at the IBW injection power of 550 kW at frequency of 27 MHz and at toroidal magnetic field of 1.92 T. The enhancement and modifications observed in electron temperature and other plasma profiles are discussed under various plasma conditions at higher IBW injection powers. Improvement in energy confinement has also been observed in this regime.

Keywords: IBW heating; electron cyclotron emission; electron temperature.

PACS: 52.55.Fa, 52.50.Qt, 52.35.Hr.

OPTIMAL PULSE DURATION IN LASER-CLUSTER INTERACTIONS

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The study of the interaction of intense short laser pulses with clusters has received much attention during the last decade [1]. The ions and quasi-free electrons in the cluster form a "nano-plasma" of solid density, where the electrons are efficiently heated by the combined fields of the laser and the surrounding particles [2,3]. Electron-impact ionization produces highly charged ions as well as inner-shell vacancies, which are at the origin of X-ray radiation. As a fraction of the electrons leaves the cluster, a net positive charge is left behind and the cluster begins to expand before disintegrating completely in a Coulomb explosion.

The size of the system and the multitude of mechanisms at play provide a challenge for the theoretical description of the interaction. Due to the large number of atoms ($N > 10000$) in a cluster, a full ab-initio simulation still seems impractical. We therefore opt for an open effective mean-field approach, in which many-particle effects are included via stochastic processes. The roles played by different effects such as cluster polarization, surface disintegration, and microscopic atomic dynamics (elastic electron-ion scattering, electron-impact ionization etc.) can thus be studied.

The measurement of the 3.1 keV characteristic K-shell X-ray radiation emitted from argon clusters [4] provides an excellent experimental tool to gain insight into the dynamics of the interaction on the short time-scale of the irradiating laser pulse ($\tau > 60\,\mathrm{fs}$). High resolution X-ray spectroscopy gives access to the charge state distribution of the highly charged cluster ions Ar^{q+} with $q > 12$.We achieve good quantitative agreement between the simulated and experimental absolute X-ray yields, and the ionic charge-state distributions are also well reproduced at high laser intensities.

By varying the pulse duration, additional information on the interplay between ionic and electronic dynamics during the cluster explosion process can be gained. One highlight is the existence of an optimum pulse duration that maximizes the X-ray yield at constant laser pulse energy. We give an interpretation of this effect different from the previously invoked nanoplasma resonance [5].

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References

[1] U. Saalmann, Ch. Siedschlag, and J.M. Rost, J. Phys. B **39** R39 (2006).

[2] C. Deiss et al., Phys. Rev. Lett. **96**, 013203 (2006).

[3] C. Deiss and J. Burgdörfer, Jour. of Phys. Conf. Ser. **88** 012036 (2007).

[4] E. Lamour et al., Nucl. Instr. and Meth. B **235** 408 (2005).

[5] T. Ditmire et al., Phys. Rev. A **53** 3379-3402 (1996).

On the solution of the time dependent Dirac equation for hydrogen-like systems

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The time dependent Dirac equation for a hydrogen-like system exposed intense electromagnetic radiation is solved numerically by expanding the wave function in eigenstates of the Hamiltonian. These eigenstates are obtained by diagonalizing the Dirac Hamiltonian on an exponential grid. As the field parameters (field strength and frequency) increases, both magnetic and relativistic effects become important. Furthermore, for higher nuclear charges, relativistic effects are important even for relatively weak fields. The need for a non-dipole and relativistic treatments is investigated by direct comparison with the corresponding predictions of the Schrödinger equation in the dipole approximation.

Even for fields far below the threshold for pair-creation, negative energy states may still play a role during the interaction. The possible influence of such states is studied by propagating the wave function in field dressed states, which are obtained by diagonalizing the full Hamiltonian. In order to minimize the number of basis states needed, complex scaling has been applied. This scaling also facilitates the calculation of ionization rates.

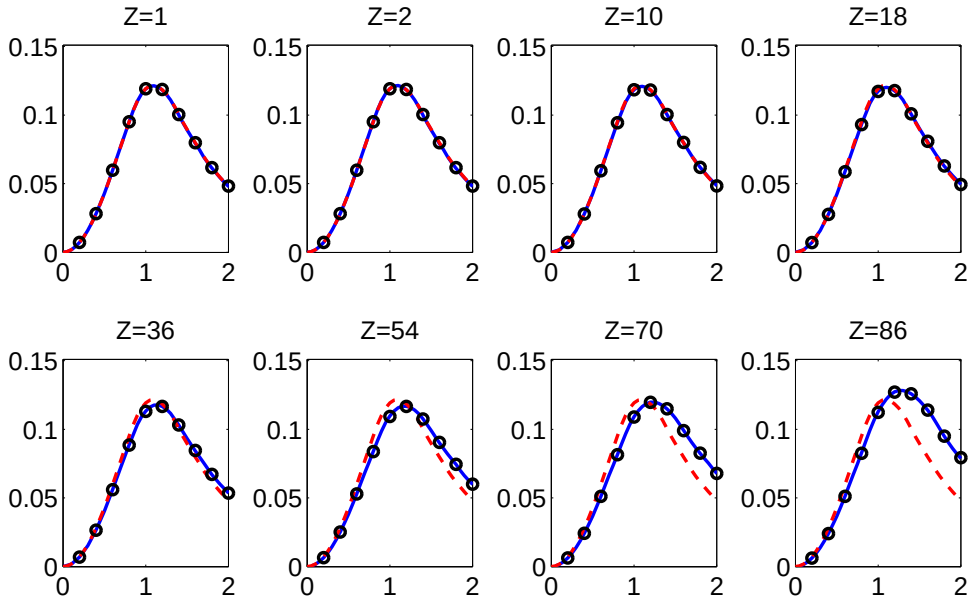

Figure 1: Ionization rates for hydrogen-like systems of different nuclear charges Z exposed to monochromatic laser light of frequency $\omega = 1.0\,Z^2$ a.u.. The electric field strength E_0, given in atomic units, is scaled with Z^3. The blue, full curve corresponds to the Dirac equation in the dipole approximation, the circles are obtained without the dipole approximation, and the red, dashed curves, which are the same for all Z, stem from the Scrhödinger equation in the dipole approximation.

QED THEORY OF LASER-ATOM AND LASER-NUCLEUS INTERACTION AND MULTI-BODY DYNAMICS IN A STRONG LASER FIELD PULSE

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QED theory is developed for studying interaction of atoms and nuclei with an intense and superintense laser field. Method bases on a description of system in the field by the k- photon emission and absorption lines. The lines are described by their QED moments of different orders, which are calculated within Gell-Mann & Low adiabatic formalism [1]. The analogous S-matrix approach is developed for consistent description of the laser-nucleus interaction. We have studied the cases of single-, multi-mode, coherent, stochastic laser pulse shape. An account for stochastic fluctuations in a field effect is of a great importance. Results of the calculation for the multi-photon resonance and ionization profile in Na,Cs, Yb, Gd atoms are presented. It is also studied the phenomenon of the above threshold ionization. Efficiency of method is demonstrated by QED perturbation theory calculations for the two-photon ionization cross-sections for extended photon energy range (including above-threshold ionization) in Mg. Comparison with the R-matrix calculation of Luc-Koenig et al is given. There is considered a phenomenon of the Rydberg stabilization of the H atom in a strong laser field and estimated the rate of transition between the stabilized Rydberg state (n=40,m=2; E~10(8)V/cm) and ground state, when it's possible the radiation of photons with very high energy (short-wave laser amplification). DC strong filed Stark effect for atoms, including atoms in plasma, Rydberg atoms and confined systems is studied within new quantum approach, based on the operator PT [1]. The zeroth order Hamiltonian, possessing only stationary states, is determined only by its spectrum without specifying its explicit form. We present here the calculation results of the Stark resonances energies and widths for a number of atoms (H, Li, Tm,U etc.) and for a whole number of low-lying and also Rydberg states. We discovered and analyzed the weak field effect of drastic broadening of widths of the Letokhov-Ivanov re-orientation decay autoionization resonances in Tm etc. Developed approach can be naturally applied to studying the Stark effect in confined systems, including quantum wells, quantum dots etc, where especially interesting effects may occur. Modelling nuclear ensembles in a super strong laser field provides opening the field of nuclear quantum optics and is carried out in our work too. The direct interaction of super intense laser fields in the optical frequency domain with nuclei is studied and the AC Stark effect for nuclei is described within the operator perturbation theory and the relativistic mean-field (RMF) model for the ground-state calculation of the nucleus [2]. We find that AC-Stark shifts of the same order as in typical quantum optical systems relative to the respective transition frequencies are feasible with state-of-the-art or near-future laser field intensities.

References

[1] A.V.Glushkov, L.N.Ivanov, Phys.Lett.A. **170**, 36 (1992); J. Phys. B : At. Mol. Opt. Phys. **26**, L379 (1993) ; Preprints of ISAN N1-3AS, Troitsk-Moscow (1994) ; A.V.Glushkov et al, J.Phys.CS.**11**, 188 (2005); J.Phys.CS.**35**, 420 (2006).
[2] A.V.Glushkov, In: Low Energy Antiproton Phys., AIP Serie. **796**, 205 (2005); A.V.Glushkov et al, Nucl. Phys.A. **734**, 21 (2004); Int. Journ. Quant.Chem. **99**, 879 (2004); **99**, 936 (2004); **104**, 496 (2005);); **104**, 512 (2005);); **104**, 562 (2005); Europ. Phys. Journ. ST **160**, 195 (2008); Frontiers in quantum systems in chemistry and physics (Springer). **18**, 541 (2008).

STATUS OF THE G-FACTOR EXPERIMENT ON HIGHLY CHARGED CALCIUM

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Measurements of the anomalous magnetic moment of the electron bound in hydrogen-like ions have proven to be highly sensitive tests of corresponding calculations based on bound-state quantum electrodynamics. The calculations of the g-factors of the electron bound to hydrogen-like carbon and oxygen and their corresponding measurements performed by the collaboration of GSI and the University of Mainz [1,2] agreed within nine significant digits.

Presently, a triple Penning trap experiment on highly charged calcium is prepared (Fig. 1) [3,4], which is expected to yield a precision on the level of 10^{-9} for the electronic g-factor of $^{40,48}Ca^{17,19+}$. This experiment makes use of a cryogenic in-trap electron-beam ion source (EBIS) at T = 4 K, where the charge breeding of the ions is performed by electron-impact ionization [5].

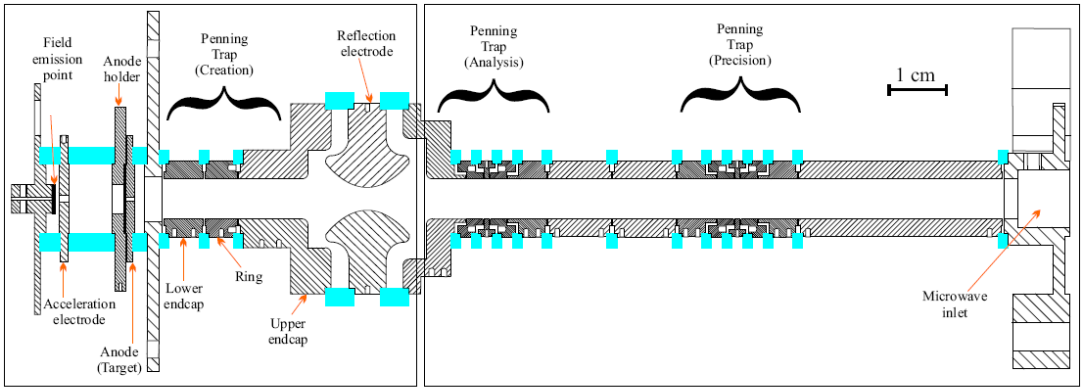

Fig. 1 Experimental setup including the EBIS for charge breeding, the analysis trap for spinflip detection, and the precision trap for the measurement of the eigenfrequencies of a single ion.

The electron source is based on a single field emission point (FEP) made from tungsten. The emission of an electron current of some nA up to 100 nA is achieved by applying a voltage between the FEP and an extraction electrode. The electron beam is reflected several times between a reflector and the FEP until it widens up and hits the target, which consists of graphite with a layer of calcium. Atoms from the target get ionized by electron impact and are trapped in the centre of the EBIS. For recording a mass spectrum, the electric trapping potential is ramped to bring the ions into resonance with an electronic detection circuit. After charge breeding the ions are transported either to the analysis trap or the precision trap. The precision trap has a homogeneous magnetic field for precise measurement of the eigenfrequencies of the stored ion. In the analysis trap the magnetic field is inhomogeneous for the detection of the spin direction. We report on new results regarding successful charge breeding tests in the EBIS and commissioning of the analysis and precision traps.

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References

[1] H. Häffner et al., Phys. Rev. Lett. **85**, 5308 (2000)
[2] J. Verdu et al., Phys. Rev. Lett. **92**, 093002 (2004)
[3] M. Vogel et al., Nucl. Instr. Meth. **B 235**, 7-16 (2005)
[4] B. Schabinger et al., J. Phys. Conf. Ser. **58**, 121 (2007)
[5] J. Alonso et al., Rev. Sci. Instr. **77**, 03A901 (2006)

HITRAP – A FACILITY FOR PRECISION EXPERIMENTS ON HEAVY HIGHLY CHARGED IONS IN EXTREME ELECTROMAGNETIC FIELDS

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HITRAP is an ion trap facility for heavy highly charged ions at GSI [1-3]. Commissioning is expected for autumn 2008. HITRAP (Fig.1) uses the GSI relativistic ion beams, the Fragment Separator FRS, if required, for production of radionuclides, the Experimental Storage Ring ESR for electron cooling and deceleration to 4 MeV/u, a combination of an interdigital H-mode (IH) structure with a radiofrequency quadrupole structure for further deceleration to 6 keV/u and a Penning trap for accumulation and cooling. Finally, ion beams with low emittance are delivered to a large variety of atomic physics experiments. Transferred to and stored in an ion trap kept at 4 K, a trapped and point-like sample is realized. Such a situation allows for highest accuracy from the experimental as well as from the theoretical point of view. For the most ambitious case, U^{92+}, we expect to load the cooler trap every 10 seconds with 10^5 ions.

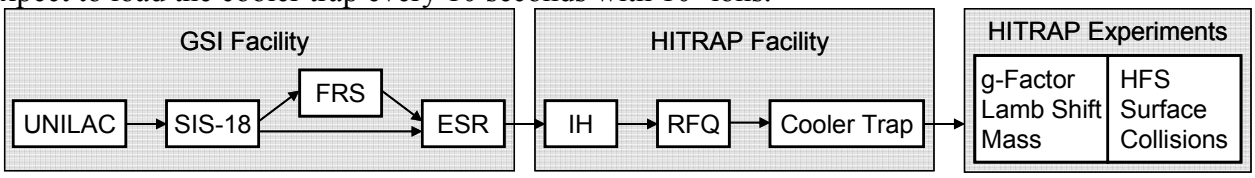

Fig. 1. The HITRAP facility under construction at GSI.

With this novel technique of deceleration, trapping and cooling of highly charged ions, atomic physics studies on slow highly charged ions up to uranium U^{92+} interacting with photons, atoms, molecules, clusters, and surfaces will become possible. In addition to collision studies, high-accuracy atomic physics experiments on trapped or slow HCI will be a significant part of the atomic physics program of the HITRAP facility.

Sensitive tests of quantum electrodynamics (QED) for bound electrons in the strongest electromagnetic fields available in the laboratory for extended periods of time will be performed by measuring the g-factor of the bound electron, the binding energies of a single or of few electrons including the Lamb shift, or the hyperfine structure (HFS) of a stable isotope of an element in different high charge states with utmost accuracy. The results for stable isotopes are then compared with state-of-the-art QED calculations. If the QED effects are under control so that they are calculable with sufficient accuracy or if they can be almost eliminated by measuring the same nuclear quantity in different charge states, the results can be used also to address questions in metrology, in nuclear physics and particle physics.

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References

[1] T. Beier et al., Nucl. Instr. Meth. **B 235**, 473 (2005)
[2] F. Herfurth et al., Int. J. Mass Spectr. **251,** 266 (2006)
[3] F. Herfurth et al., Hyp. Int. **173,** 93 (2006)

Re-trapping and Cooling Highly-Charged Ions

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Presently, a trapping system for cooling highly-charged ions that were extracted from the new Stockholm electron-beam ion trap (S-EBIT) is being set up at AlbaNova (Fig.1). The experiment aims at production of low temperature (emittance) highly-charged ions at very low energy for injection into the precision trap of SMILETRAP II. As a first step the Penning-type cooling trap with deceleration and acceleration system, which facilitates the injection and extraction, was brought into position and successfully tested. Ions can be created either externally, i.e., in the ion sources S-EBIT or SMILIS, or internally by transmitting a 4 kV electron beam through the trap to ionize rest gas. The segmented centre electrode allows for rf-excitation for cleaning the cooling trap from unwanted ions. Currently, a pepper-pot emittance meter is being installed to monitor the emittance of trapped ions in real-time.

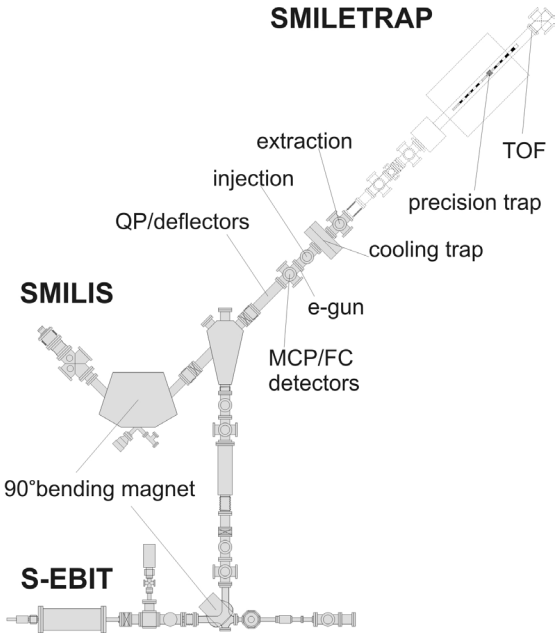

Fig.1 Layout of the HCI facility at AlbaNova.

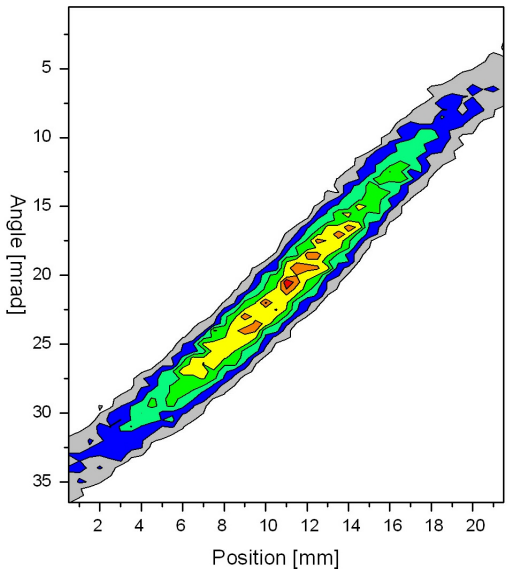

Fig.2 Emittance of Ar^{16+} ions trapped for 100 us.

From S-EBIT and SMILIS two ion species, highly-charged and low charged ions (e.g. S^{14+} or Ar^{16+} and He^{+}) could be injected sequentially and stored simultaneously in the cooling trap. The emittance of the trapped ions was measured (Fig.2), which will be used for optimizing the evaporation of the light ions to cool the highly-charged ions in the cooler trap. For the primary ions, emittances in the order of a few mm·mrad and energy spreads of few qeV were measured. It is expected that these values will be reduced and highly charged ions of 0.1 qeV energy spread can be extracted as pure ion beam.

TRAPPING OF HIGHLY CHARGED IONS WITH AN ELECTROSTATIC ION TRAP

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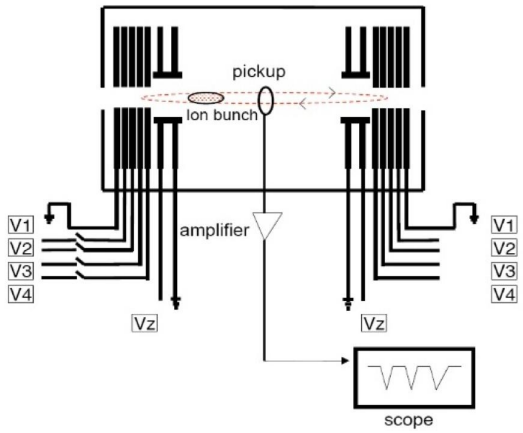
Following a design from the Weizmann Institute [1], an electrostatic trap has been constructed and attached to the beam line of "SIMPA" (Source d'ions Multichargés de Paris) an Electron Cyclotron Resonance (ECR) ion source at LKB (Laboratoire Kastler Brossel) and INSP (Institut des Nano Sciences de Paris). This attempt is the first one to use this type of ion trap for trapping highly charged ions that can give a unique opportunity to measure the life times of metastable states in highly charged ions in the millisecond time range, in a mostly field free design. The electrostatic ion trap is composed of two coaxial electrostatic mirrors, working for charged particles in the same way as a Fabry-Perot interferometer works for light in the optical regime. The figure bellow shows a schematic of the ion trap.



Schematics of the electrostatic ion trap; V1 to V4 are the trap high-voltage electrodes, Vz with the grounded electrodes build an Einzel lens for beam focusing on both ends of the trap.

The central region of the trap between the two mirrors is essentially field-free. With the help of a pick up electrode in the linear center of the trap we have proved trapping for tens of milliseconds in the case of a variety of high charge states of O, Ar, Kr and Xe ions (up to O^{5+}, Ar^{13+}, Kr^{21+} and Xe^{20+}). Using a low (<20 V) radio frequency voltage with frequencies close to the oscillation frequency of the ions in the trap we were able to observe trapping times up to 50 ms. Running the ion trap in the so called "bunching" or synchronization mode [2] in the time domain of the pickup signal we observed a strange oscillation on the millisecond scale superposing the ion oscillation in the trap on the microsecond scale. With computer simulations using and modifying the one-dimensional model presented in [2] we try to explain the observed oscillations by looking at the behavior of a test ion close to a bunch of ions in the trap.
With the use of a digital vector signal analyzer to observe the oscillation frequency of the ion packet we have obtained preliminary results, that confirm of the possibility of using this ion trap as a mass spectrometer [3] with a resolution of 10^{-4} or better, that could be used to study highly charged radioactive ion beams.

References

[1] D. Zajfman, O. Heber, L. Vejby–Christensen, et al. Phys. Rev. A **55**, R1577 (1997)
[2] H. B. Pedersen, et al. Phys. Rev. A **65**(4) 042704 (2002)
[3] H. B. Pedersen, D. Strasser, S. Ring, et al., Phys. Rev. Lett. 87, 055001 (2001).

X – ray spectroscopy characterization of Ar^{17+} produced by an ECRIS in the afterglow mode

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The afterglow operation mode in the Electron Cyclotron Resonance Ion Source (ECRIS) has been mostly developed in view of applications as beam-injector of high energy (> MeV/A) accelerators. Indeed it can provide a pulsed beam of highly charged ions (HCI) of much higher instantaneous current than in a continuous mode. It is also of big interest for atomic physics experiments making direct use of H-like and even bare ions in the low energy regime (i.e. a few keV/q). However, control of pulse widths, optimization of the operation conditions and measurements of bare or H-like ions currents are not a trivial matter. Especially for those HCI of medium Z (like argon), a complete characterization of the ion beams delivered in the afterglow mode is needed, since currents range around a few nAe or lower and possible contamination by ions having close m/q ratio may occur. Therefore, classic measurement techniques are almost useless, and to overcome this problem, we make use of more sophisticated X-ray spectroscopy techniques. Having Ar^{q+} ions of a few hundred of keV impinging on a thin carbon foil, we have been able to characterize, for the first time, the production of Ar^{17+} delivered in the afterglow mode by the SUPERSHYPIE ion source of GANIL[1]. Indeed, the K X-ray emission comes from the deexcitation of projectile atomic states populated by charge transfer from the target (single or multiple capture processes occur) and provide, through its energy, a clear signature of both the atomic number **and** the charge state of the emitting projectile. A characteristic K X-ray line at 3.1 keV has been observed, allowing for a precise identification and quantification of the Ar^{17+} ion beam extracted from the plasma explosion when the HF is off, and transported along the beam line of ARIBE[2] to finally impinge on a thin carbon target. Recording x ray emission in coincidence with the HF signal, we are able to measure the temporal structure of the beam in the range of several ms with a time resolution less than one μs.

1 : Grand Accélérateur National d'Ions Lourds.
2 : French acronym for "accelerator dedicated to low energy ions"

HIGHLY CHARGED ION INJECTOR IN TERMINAL OF TANDEM ACCELERATOR

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Electron cyclotron resonance ion source(ECRIS)s are able to produce intense beams of highly charged positive ions, of which charge states are higher than those obtained from charge stripping by carbon foil at the high voltage terminal of tandem accelerators. It is possible to increase beam intensity, beam energy and beam species by utilizing an ECRIS in a tandem accelerator [1]. A 14.5GHz all permanent magnet ECRIS has been installed in the high voltage terminal of the vertical and folded type 20UR Pelletron tandem accelerator at Japan Atomic Energy Agency at Tokai.

The high voltage terminal is in a severe environment, i.e. it is filled with the pressurized insulation gas of 5.5 atm and itself is held at a voltage of 20MV at maximum. The characteristics of withstanding high pressure and electrical discharges are indispensable to the in-terminal ion injector. The components of the injector; ion source, beam line devices, power supplies and vacuum components, have been confirmed to be pressure-resistant. A control system with optical fibers and circuits were designed to prevent damages from electrical discharges, and these electrical devices were heavily shielded. For the reason that ion pumps do not work for inert rare gases, a turbo molecular pump and a rotary pump were newly developed for the use in the high pressure gas. The exhaust gas from the pumps was designed to accumulate in a closed vessel. Even when failure occurs, the pumping system can keep high vacuum.

Highly charged ions of Ne, Ar, Kr and Xe are accelerated from new injector. The rare gas ions have been available, and the intensities were increased from 10 times as much as those before. Xe ion energy reached 400MeV, and the accelerator has become the only accelerator that provides beams in a wide energy range of 20~500MeV. In addition, the beam quality has greatly improved because neither the energy spread nor beam divergence are caused by the carbon foil.

These highly charged ions with wide energy have been applied for atomic collision research [2] and so on.

References

[1] M. Matsuda et al., Heavy Ion Accelerator Technology,65(1998)
[2] K. Kawatsura et al., these abstracts

Continuous beams of Highly Charged Ions from the Dresden EBIS-A

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We report on investigations of continuous ion beam extraction from the Dresden EBIS-A and compare these results with extraction experiments from the Dresden EBIT. Both ion sources are room-temperature EBIS/T with comparatively low magnetic compression fields (600 mT and 250 mT, respectively) /1/. In the case of the Dresden EBIS-A the presented experiments are done at a beam line as described in /2/. We show that integral currents of some µA can be extracted at electron beam currents of about 100 mA and at a working gas pressure of some 10^{-9} mbar. The charge state distribution of the extracted ions in dependence on the working gas pressure, the electron energy and the electron beam current was investigated to optimize the ion output current.

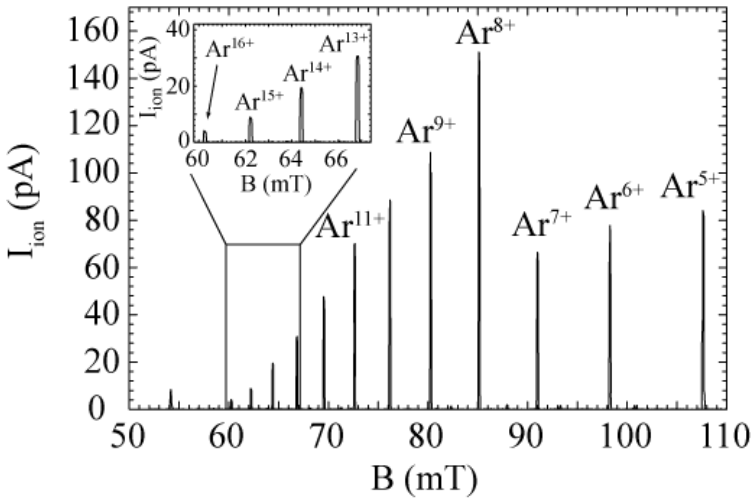

Figure 1
Spectrum of extracted Argon ions measured with the Dresden EBIS-A at an electron energy of 18 keV, an electron beam current of 64 mA and an Argon gas pressure of $3x10^{-9}$ mbar

As an example we extracted maximum DC ion beam currents of 3 nA H_2^+, 6 pA Ar^{16+} and 150 pA Ar^{12+} as well as 300 pA Xe^{14+}, 10 pA Xe^{30+} and 0.6 pA Xe^{44+}, respectively. The spectrum of an argon ion extraction experiment is shown in Fig. 1. We would like to point out that the ion output is very dependent on the selected source operation parameters.

Furthermore, the ion output currents in dependence on the axial trap depth were studied and the radial trap depth of the electron beam was measured to be 25 V for a 30 mA electron beam in the Dresden EBIT and to be 150 V for a 100 mA electron beam in the Dresden EBIS-A. Both values are in good agreement with the calculated radial beam potentials.

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References

/1/ for details see http://www.dreebit.com
/2/ F.Grossmann, R.Heller, M.Kreller, U.Kentsch, S.Landgraf, V.P.Ovsyannikov, M.Schmidt, F.Ullmann, G.Zschornack; Nuclear Instruments and Methods in Physics Research, B 256, 565, 2007

A Si(Li) MULTISTRIP DETECTOR – AN EFFICIENT COMPTON POLARIMETER

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Polarisation of x-rays coming from recombination processes induced by collisions of heavy and highly charged ions at relativistic energies with electrons or low-density gaseous targets provides a unique insight into the dynamics of charge particles in extreme strong and temporally short electromagnetic fields.
Detailed knowledge of this field has, besides atomic physics itself, a great relevance for plasma- and astrophysics. Due to the observed physical processes one may summarize that one finds significant effects on the linear polarisation of the emitted x-rays in the energy regime between 50 keV and 500 keV [1,2]. Making use of the Compton process which is sensible to the electric field vector of the incoming photon we can address this problem. For photon energies above ~150 keV we have already proven the high sensitivity on linear polarisation of a planar 2D-Ge(i) micro strip detector [3] used as a Compton polarimeter [4]. To have access to the energy regime between 50 keV and 150 keV which is very important for studies of electron ion recombination processes at the ESR of the GSI facility at Darmstadt we developed as a Si(Li) polarimeter. As a rule of thumb one can say that a Compton polarimeter is well suited for an energy if the photo and the Compton cross section is approximately of the same size for a particular detector material. Using silicon for the detector crystal makes the polarimeter due to the lower Z of the material more efficient as Compton scatterer than germanium at lower energies. In addition, the relatively low-Z of silicon leads to a significant reduction of the width of the Compton profile, which is important for imaging applications based on the Compton effect.
Based on advances in the development of large-volume Si(Li) orthogonal strip detectors [5] a two dimensional planar Si(Li) strip detector was built. The key part of the polarimeter is a large-volume 7 mm thick double-sided Si(Li)- strip detector mounted in a cryostat attached to a commercial dewar. The detector crystal itself consists of the Li-drifted silicon bulk which holds a boron-implanted p^+-contact on one side and a thin Li-diffused n-contact. Plasma etched strip structures (2 x 32 strips each 2 mm wide and 64 mm long) provide the position resolution. The strip structures on both sides of the crystal are orientated orthogonally. To reduce distortions of the electric field applied to the crystal due to the limited size of the detector it is surrounded by an 8 mm wide guard ring. The 64 preamplifiers are placed inside the detector housing close to the detector crystal. We will report on first laboratory results which document the good energy resolution below 2 keV and the uniform efficiency of the system.

References

[1] A. Surzhykov, S. Fritzsche, Th. Stöhlker, Phys. Lett. A 289 (2001) 213
[2] Th. Stöhlker, et al., Physica Scripta. Vol. T110, 384-388 (2004)
[3] D. Protic, Th. Stöhlker, T. Krings, I. Mohos, U. Spillmann, IEEE 52, 3194-3198 (2005)
[4] U. Spillmann, et al., GSI scientific report 2005
[5] D. Protić, E. L. Hull, T. Krings and K. Vetter, IEEE 52, 3181-3185, Dec. 2005

THE COMMISSIONING OF THE COOLER STORAGE RING HIRFL-CSR IN LANZHOU

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HIRFL-CSR is a multi-purpose cooler-storage-ring system in the National Laboratory of Heavy Ion Research (HIRFL) In Lanzhou, China [1] including a main ring (CSRm), an experimental ring (CSRe), and a radioactive beam line (RIBLL2) connecting the two rings. The two existing cyclotrons SFC (K=69) and SSC (K=450) of the HIRFL are be used as its injectors. Heavy ion beams in an energy range of 8–30 MeV/u from the HIRFL will be accumulated, cooled and accelerated to the energy of 1100 MeV/u ($^{12}C^{6+}$) and 500 MeV/u ($^{238}U^{72+}$) in the main ring, and then extracted to produce secondary beams (radioactive ion beam or highly charged heavy ions). The secondary beams will be accepted by and stored in the experimental ring for internal-target experiments or for high-precision spectroscopy with beam cooling. The experimental ring CSRe can accept highly charged ions with energies up to 750 MeV/u ($^{12}C^{6+}$) and 500 MeV/u ($^{238}U^{92+}$). The double-ring-system provides flexibility in the production of highly charged ions and of radioactive ion beams, thus offering opportunities for nuclear physics and atomic physics research.

In January 2007 electron cooling in CSRm was successfully finished and the carbon ions up to 1.6mA (corresponding to the ion number of 8×10^9) have been accumulated by using cooling stacking. The multiple multi-turn injection (MMI) was successfully done for $^{12}C^{6+}$, $^{36}Ar^{18+}$ and $^{129}Xe^{27+}$(Fig.1). In October 2007 the 7MeV/u $^{12}C^{4+}$ provided by SFC have been accumulated and accelerated to 660MeV/u in CSRm and then extracted fast to RIBLL II. The 660MeV/u $^{12}C^{6+}$ transferred through RIBLL II was injected into CSRe and reached an intensity of 15mA (1.56×10^{16}pps) in CSRe.

The first two physics experiments were successfully carried out in December 2007. In one of the experiments a Be target of 5 mm was installed at the primary target position of RIBLL II, secondary beams such as ^{34}Cl, ^{32}S and ^{30}P and so on were produced and injected into CSRe which was set in the isochronous mode. The masses of the stored secondary ions could be determined from the revolution time spectrum of the ions. The mass resolution of 10^{-5} was obtained (Fig.2).

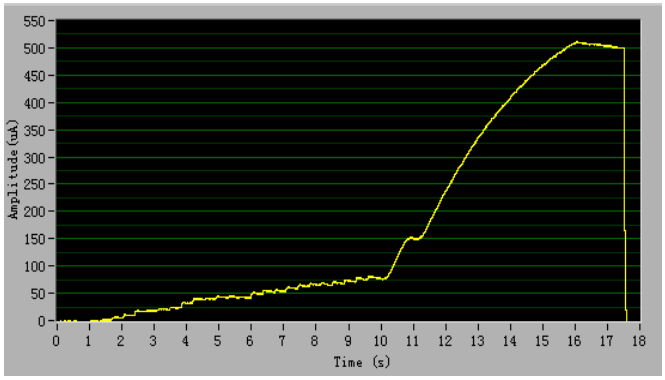

Fig. 1 Multiple multi-turn injection for 2.9 MeV/u $^{129}Xe^{27+}$

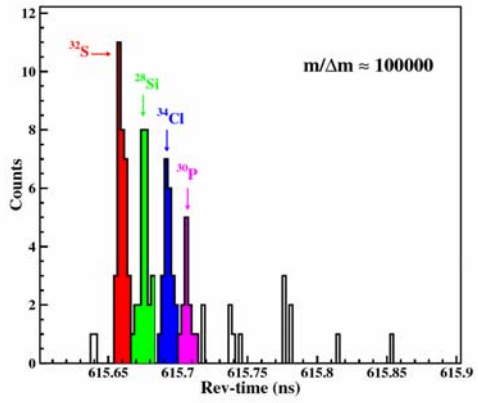

Fig. 2 Mass measurement in CSRe in ischronous mode

References

[1] J. W. Xia et al., Nucl. Instr. Meth. A488 (2002) 11

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Development of Multichannel Doppler Tuned Beam-Foil X-Ray Absorption Spectrometer at IUAC

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Since decades beam foil time of flight technique serves as a versatile tool to measure the lifetime of different energy levels, which can be applied in principle to any charge state. Due to limitation in resolution of available energy dispersive solid state detectors (resolution ~150 eV at 5.9 keV), this technique does suffer from inherent cascading and blending problems. In order to minimize these problem and spectroscopically resolve the satellite line from the parent line, a high resolution, multichannel Doppler Tuned Spectrometer (DTS) [1, 2] setup coupled with lifetime measurement setup has been developed in general purpose scattering chamber (GPSC) at IUAC.

In most beam-foil experiments, the Doppler effect produces unwanted distortion of emission spectra. But DTS utilizes the Doppler shift as a function of angle of emission from the beam as a dispersive element. When the foil-excited beam emits a photon of energy E_0, will be Doppler shifted and appears at energy $E(\theta)$ to a stationary detector. The relation between Doppler shifted energy $E(\theta)$ and rest energy E_0 can be given by

$E(\theta) = E_0 / \gamma(1 - \beta \cos\theta)$ Where γ and β has their usual meaning and v is the velocity of the post foil beam and θ is the angle of detection of photon with the beam axis. An absorber foil is placed between target foil and the detector (proportional counter), which has an absorption edge energy, E_{AB}, near the rest mass energy E_0. The angle is tuned in such a way that absorption edge energy just coincide with the Doppler shifted energy $E(\theta)$, a dip appears in the spectrum due to the absorption of x-ray by absorber foil. Differentiation of this spectra contains the high resolution feature.

For this setup, a Position Sensitive Proportional Counter (PSPC), having position resolution of 350 μm in the linearity range of 140 mm and the energy resolution of ~22% at 5.9 keV of Fe x-ray, has been developed to use as a detector for multi channel DTS. Further an attempt has been made to energetically resolve M1 transition ($1s2s\ ^3S_1 - 1s^2\ ^1S_0$), M2 transition ($1s2p\ ^3P_2 - 1s^2\ ^1S_0$) in He-like Fe and its satellite M2 transition ($1s2s2p\ ^4P_{5/2} - 1s^22s\ ^2S_{1/2}$) in Li-like Fe and measure the lifetime of corresponding levels. The details of such setup along with preliminary results will be presented.

References:

[1] R W Schmieder, Rev. Sci. Instrum. **45**, 687 (1974).

[2] J. Robert Huddle and J. R. Mowat, Nuc. Inst. Meths **202** (1982) 343.

ABSOLUTE DETECTION EFFICIENCIES OF AN ION COUNTING SYSTEM WITH A CHANNEL-ELECTRON MULTIPLIER

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Absolute detection efficiencies of an ion counting system have been examined for Li^+, Rb^+, Cs^+, Ar^+, and Ar^{2+} ions as a function of incident ion impact energy. The incident ion energy ranges from 0.5 to 6.0 keV. Figure 1 shows schematic diagram of an ion counting system and a detection efficiency measurement set-up. The ion counting system consists of a converter plate (SUS), an electro-static lens system, and a channel type secondary-electron-multiplier (SEM:Channeltron 4139S). A surface-ionization type ion source employed for singly charged alkali ions, and an ECR ion source for Ar^+ and Ar^{2+}. The incident ions hit the converter plate, and then the secondary electrons emitted from the converter accelerate to the SEM. The output signals from the SEM are counted with a conventional ion counting electronics. The absolute detection efficiency D is defined as

$$D = \frac{eN_{\mathrm{SEM}}}{I_f} \qquad , \qquad (1)$$

where N_{SEM} is the total counting signal from the SEM (count/sec), I_f the ion current measured at the Faraday cup, and the e elementary charge.

Figure 2 shows the absolute detection efficiencies for Ar^+ and Ar^{2+} as a function of the ion impact energy. The detection efficiency increases with the ion energy, and reaches 1.0 above 5keV. For all ions examined in this study, the detection efficiency is about 1.0 as far as the ion energy is larger than 5 keV. Charge state dependence is not so large for Ar^+ and Ar^{2+}. This means that the kinetic emission mechanism dominates the secondary electron emission in this energy region.

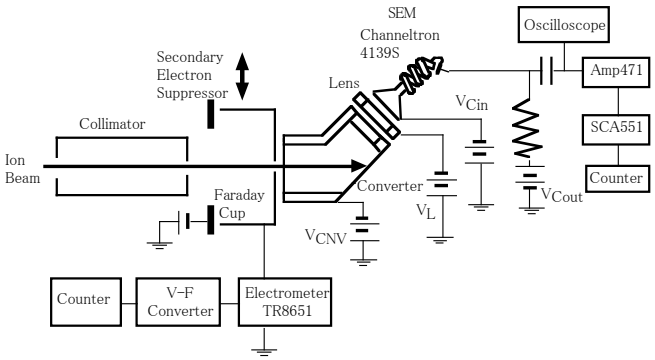

Fig.1. Schematic diagram of an ion counting system and a detection efficiency measurement set-up.

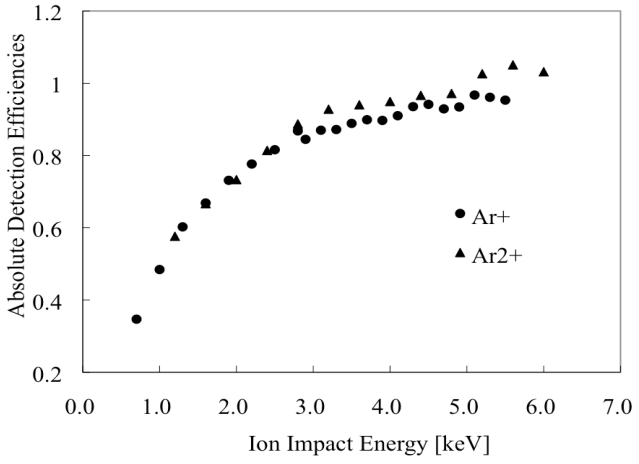

Fig. 2. The absolute detection efficiencies for Ar^+ and Ar^{2+} as a function of the ion impact energy.

Time resolved extreme ultraviolet tin spectra from laser produced plasmas

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Radiation at 13.5 nm is currently of great interest to the semiconductor manufacturing industry – driven to meet Moore's law [1] (*i.e.* a doubling of feature density every two years). Traditionally optical lithography has been at the forefront of the required feature size reduction, due to the decreasing wavelength of the light sources used. However, to make further progress new lithography techniques are needed, with extreme ultraviolet lithography (EUVL) the most promising candidate [2]. The 13.5 nm wavelength is determined by the availability of highly reflective ($\sim$70%) molybdenum/silicon multilayer mirrors with a 2% bandwidth centred at 13.5 nm [3]. Although beta tools are currently in use, a suitable light source for high volume manufacturing has not yet been developed.

The current preferred sources for EUVL are tin [4], lithium [5] and xenon [6]. Atomic and plasma physics show that laser produced plasmas, with electron temperatures of 30 to 70 eV, containing tin can emit brightly in the desired bandwidth. This emission can be ascribed to overlapping 4d subshell atomic transitions ($4p^6 4d^n \rightarrow 4p^5 4d^{n+1} + 4d^{n-1}4f + 4d^{n-1}5p$) from adjacent Sn ions (Sn^{7+} to Sn^{12+}), which merge to form an unresolved transition array (UTA) [7].

Here we present time resolved spectra of this UTA, in the 9–18 nm region. The plasmas under investigation are formed from a pure tin bulk target, by focussing a 500 mJ, 16 ns FWHM, laser pulse from a Q-switched Nd:YAG laser to a power density of $\sim 10^{11}$ $\mathrm{Wcm^{-2}}$ on to the target. The radiation emitted is collected by a toroidal mirror and imaged onto the 20 μm entrance slit of a McPherson 2.2 m grazing incidence spectrograph, equipped with a 1200 groove/mm grating, giving a spectral resolving power of $\sim$1000. The detector consists of a 40 mm microchannel plate, which is coupled via a coherent fibre optic bundle to a 1024 pixel photodiode array. The microchannel plate can be gated to a shutter speed of $\sim$5 ns.

The resulting time and spectrally resolved spectra are compared with atomic structure calculations, performed with the Cowan suite of codes [8], to determine the dominant ion stage as function of time.

References

[1] G. E. Moore, Electronics **38**, 114 (1965)

[2] V. Baskshi, *EUV Sources for Lithography*, SPIE Press, Bellingham (2007)

[3] S. Bajt *et al.*, Proc. SPIE **4506**, 65 (2001)

[4] P. Hayden *et al.*, J. Appl. Phys. **99**, 093302 (2006)

[5] A. Nagano *et al.*, Applied Physics Letters **90**, 151502 (2007)

[6] Y. Ueno *et al.*, Appl. Phys. Lett. **90**, 191503 (2007)

[7] J. White *et al.*, J. Appl. Phys. **98**, 113301 (2005)

[8] R. Cowan, *The Theory of Atomic Structure and Spectra*, University of California Press, Berkeley (1981).

Development and applications of Electron Beam Ion Source for Nanoprocesses

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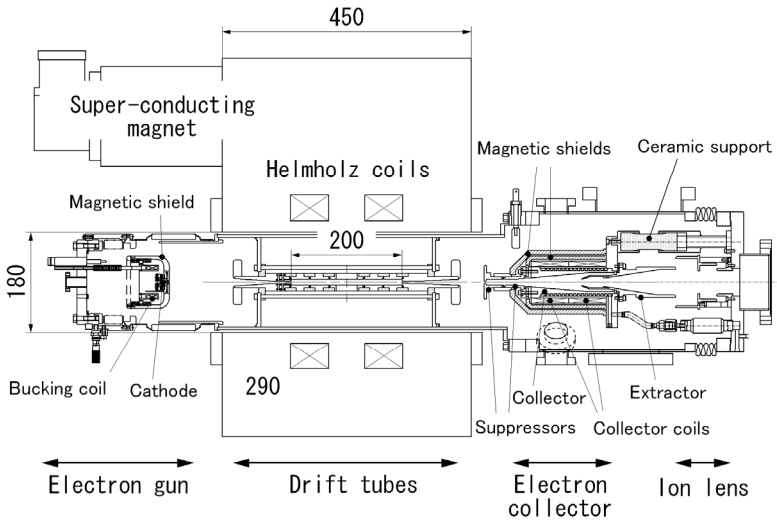
The interaction of slow HCI with solid surfaces is useful for 'nanoprocess'; the modification, activation, machining and analysis in nanometer scale. An electron beam ion source, 'Kobe EBIS' has been developed for the application of HCIs to nanoprocesses. The EBIS uses a commercial superconducting magnet (3T) cooled by a closed-cycle refrigerator. The schematic diagram of the EBIS is shown below. The design and tentative performance is described on the literature [1,2]. The EBIS is installed in the beamline for the experiments of the irradiation of sample with HCIs and scanning tunneling microscopy (STM) observations of irradiated sample surfaces.

The STM observation of the surface of highly oriented pyrolytic graphite irradiated with Ar^{11+} ions illustrated that the fluence of HCI in the order of $10^{13}/cm^2$ is accessible with the present EBIS. We have also developed an apparatus to process a sample with periodically arranged traces of HCI irradiation using a mask with small holes (the diameter < 100nm) made of a thin film of Si_3N_4.

References

[1] M. Sakurai, F. Nakajima, T. Fukumoto, N. Nakamura, S**.** Ohtani and S**.** Mashiko, J. Phys. Conf. Ser. **2**, 52-56 (2004).

[2] M.Sakurai, M. Tona, S. Takahashi, H. Watanabe, N.Nakamura, N. Yoshiyasu, C. Yamada, S. Ohtani, H.A.Sakaue, Y. Kawase, K. Mitsumori, T. Terui, and S. Mashiko, Nucl. Instr. Meth. B**257**, 297-300 (2007).



Schematic diagram of Kobe EBIS

TIN LPP SOURCE MODELLING FOR EUVL AT 13.5 nm

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Because of the large number of transitions and complexity of the $4p^6 4d^n - 4p^5 4d^{n+1} + 4p^6\ 4d^{n-1}4f$ unresolved transition array (UTA) responsible for 13.5 nm emission in Sn plasmas, as well as the computationally intensive nature of radiation transport calculations, statistical methods can be used to estimate the spectral profile [1]. Increasing laser power density initially shows increased in-band UTA brightness though emission eventually decreases as the dominant ion stages move beyond the open 4d subshell species responsible for the UTA emission. [2].

The impact of wavelength λ and power density ϕ on ion distribution and electron temperature is calculated for a Nd:YAG (λ = 1064 and 355 nm) and CO_2 (λ = 10600 nm) laser plasmas. The laser power densities, ϕ, are chosen to keep $\lambda^2\phi$ constant, thus keeping the electron temperature constant in the Collisionally Radiative Equilibrium CRE rate equations [3]. (The 355-nm laser is included to highlight the emission dependence on electron density, primarily three-body recombination, and gives greatly reduced Sn^{10+} and Sn^{11+} ion populations, the main emitters at 13.5 nm.) The theoretical intensity shows an increase for the CO_2 laser produced plasma, where the in-band summed oscillator strength is 13.4% greater at 32 eV and 2.7% greater at 36 eV [4].

The influence of reduced electron density in the CO_2 LPP (~ 1/100, where $n_e \propto 1/\lambda^2$) is considered in a 1-D radiation transport model. Plasma opacity is less in the lower electron density CO_2 plasma, resulting in less absorption and a brighter source. A more than 2-fold increase in conversion efficiency is predicted for the CO_2 laser over that attainable with the Nd:YAG, close to the experimentally observed values [5]. The 2-D RMHD code Z* [6] models emission in an optically thick tin LPP. The implicit Eulerian-Lagrangian code solves MHD, ionization kinetics with radiation transport and uses an average atom model to account for all possible states and transitions. Optimum 4-4 in-band emission occurs primarily from the plasma core at an electron temperature of 30-40 eV [7]. However the core emission is reduced by absorption in the colder wings because of the high absorption cross section of lower stage ions.

References:

[1] G. O'Sullivan and R. Faulkner, Opt. Eng. **33**, 3978, 1994.
[2] P. Hayden *et al*. J. Appl. Phys. **99**, 093302, 2006.
[3] D. F. Colombant and D. G. Tonon, J. Appl. Phys. **44** (8), 3524–3537, 1973.
[4] J. White *et al*. Appl. Phys. Lett. **90**, 181502, 2007.
[5] Y. Tao and M. S. Tillack, Sematech EUV Source Workshop, Vancouver, May, 2006.
[6] S. Zakharov, V.G. Novikov, and P. Choi, *EUV Sources for Lithography*, editor Vivek Bakshi, Publ., SPIE, 2006.
[7] J. White *et al*. Appl. Phys. Lett. 92, 151501, 2008.

ANGLE-RESOLVED STUDIES OF TIN-BASED LASER PRODUCED PLASMA EUV SOURCES

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The proposed use of laser-produced plasmas (LPPs) for EUV. lithography is dependent on a range of factors, including collectable source power and the debris levels emitted by the source. Ions that are emitted from these plasmas will cause significant damage to the optical components in a projection lithography system. One further issue is the level of out-of-band (OOB) radiation, residing outside the narrow extreme ultraviolet band, emitted by the plasma, as this has the potential to cause flare in the wafer plane, leading to a loss of feature resolution.

In this study *three* of the key laser plasma source parameters have been investigated, ion emission from laser plasmas, in-band radiation at 13.5 nm and out-of-band radiation.

We have performed time of flight (TOF) analysis to determine the intensity of ion distribution from tin based LPP for a range of charged tin ions (Sn^{1+}–Sn^{9+}). The source reported here is a plasma formed on a planar bulk tin target by pulses from a Neodymium Yttrium Aluminium Garnet (Nd:YAG) laser delivering 500 mJ per pulse in a time of 7 ns (full-width half-maximum intensity) at the fundamental wavelength of 1064 nm. The laser pulse was focused to a power density of 4 x 10^{11} W/cm^2, close to the value at which the conversion efficiency to in-band radiation at 13.5 nm is a maximum. The plasma formation occurred on a custom made optical system, which could be rotated with respect to the detector so TOF analysis could be preformed at various angles of emission, while maintaining a normal angle of incidence for the laser pulse with respect to the target. The detector used was an energy sector analyser (ESA), which is a well-characterised diagnostic capable of measuring ion energy and discriminating by charge state. Analysis was performed on ions of various charge states, with energy/charge state ratios ranging from 3 keV to 50 eV, for angles of emission from the plasma ranging from 90 to 15 degrees.

Out-of-band (OOB) radiation was also measured over a range of angles between 25 and 85 degrees with respect to the target normal, for six energy bands typically 100 nm wide centred between 200 and 1000 nm. The intensity of the radiation was measured using an absolutely calibrated filter/photodiode combination. The emission was found to be dominated by radiation in the band centred on 214 nm. An $I(\theta) \propto \cos^{\alpha}(\theta)$ approximation was fitted to the angular distribution of the radiation summed over all energy bands, yielding a value for α of 0.23 ± 0.02.

Extreme ultraviolet (EUV) spectra were recorded from a similar plasma were also recorded over a range of angles between 20 and 90 degrees from the target normal. Absolute intensity measurements are presented of both the 2% band centred on 13.5 nm and the total radiation emitted by the plasma between 10 and 18 nm. The in-band intensity is seen to be relatively constant out to an angle of 60 degrees from the target normal, beyond which it drops off quite steeply. The spectra at wavelengths greater than 13.5 nm are strongly influenced by self-absorption by ions ranging from 6^+ to 10^+.

CALCULATION OF STABIL ITY DIAGRAMS AND ION TRAJECTORIES IN QUADRUPOLE ION TRAP WITH IMPULSIONAL POTENTIAL BY MATRIX METHOD

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Despite of the long history of the calculation of the stability of ion motion in radio-frequency quadrupole fields, since about 80 years ago it has remained of interest for several new areas of mass spectrometry. These include the use of higher stability regions[1], application of resonant excitation, and the use of non-sinusoidal trapping voltages[2]. The most general differential equation describing ion motion is the Hill equation. We first discuss the solution of this equation by matrix methods [3] and then calculate the ion trajectories and the first stability region and higher stability regions by employing an impulsional potential of the form $V_0 \cos(\Omega t)/(1-k\ \cos(2\Omega t))$ with (0.0<k<1).We also discuss the fractional resolution $m/\Delta m$ of the confined ions.

[1] P. H. Dawson, B. Yu, Int. J. Mass Spectrum. Ion proc. 56, 41-50 (1984);
Z. Du, D. J. Douglas, N. V. Konenkov, J. Anal. Atom. Spectrum. 14, 1111-1119(1999).
[2] A. Doroudi et al Int. J. Mass. Spec. 247, 61-66 (2005).
[3]N. V. Konenkov, M. Sudakov, J. Am. Soc. Mass Spectrum. 13, 597-613 (2002).

HCI 2008 Time Table

Sunday	Monday (1 Sep)	Tuesday (2 Sep)	Wednesday (3 Sep)	Thursday (4 Sep)	Friday (5 Sep)
	chair: Y.Yamazaki	*chair: E.Lindroth*	*chair: R.Hoekstra*	*chair: to be announced*	*chair: F.Martín*
	9:00 opening	9:00 S.Schippers	9:00 T.Watanabe	9:30 G.O'Sullivan	9:00 R.Moshammer
	9:20 B.A.Huber	9:45 X.Zhu	9:45 P.Beiersdorfer	10:15 A.Ya.Faenov	9:45 K.Moribayashi
	10:05 L.Chen	10:05 C.Beilmann			10:05 Y.K.Ho
	10:25 coffee	10:25 coffee	10:05 coffee	10:35 coffee	10:25 coffee
	chair: A.Cassimi	*chair: to be announced*	*chair: F.J.Currell*	*chair: J.R.Crespo López-Urrutia*	*chair: H.Cederquist*
	11:00 W.Meissl	11:00 T.J.M.Zouros	10:30 R.Hutton	11:00 A.Surzhykov	11:00 S.Yoshida
	11:30 R.Heller	11:30 M.Frankel	11:00 K.Kubiček	11:30 K.Yao	11:30 C.Prigent
	11:50 C.A.Hunniford	11:50 Y.Itoh	11:30 O.Yu.Andreev	11:50 M.Andersson	11:50 L.C.Tribedi
	12:10 T.Hirayama	12:10 Z.D.Pešić			12:10 H.Zettergren
	12:30 lunch	12:30 lunch	11:50 lunch	12:10 lunch	adjourn
	chair: Y.Zou	*chair: J.Burgdörfer*		*chair: D.Vernhet*	
	14:30 L.Labzowsky	14:30 K.Motohashi		14:00 T.Ishikawa	
	15:15 M.Hobein	15:00 H.Lebius	13:00-22:00 Excursion + Dinner	14:30 Y.Nakano	
	15:35 S.Ohtani	15:30 N.Bundaleski		14:50 V.Balashov	(SPARC)
Registration+Reception 17:00-20:00 *Harmonia* /UEC	16:30 Tokyo-EBIT Lab tour	16:00-18:00 Poster A	Hotel Mt. Fuji	15:30-17:30 Poster B	

Review Lecture	6
Progress Report	8
Local Report	2
Selected Topics	23