Monday 25 September 2023 - Friday 29 September 2023

Schloss Bückeburg

ECTI

7th European Conference on Trapped Ions

Book of Abstracts

Welcome Note

We are delighted to welcome you to Bückeburg for the 7th European Conference on Trapped Ions (ECTI). The conference, often described as the “family gathering of ion-trappers” embodies its spirit by bringing together the international ion-trapping community. It serves as a platform to discuss the whole breadth of topics of the community, including quantum computing, simulations and sensing, precision measurements, optical clocks, molecular ions and more.

This year, our gathering takes place in Schloss Bückeburg, the ancestral seat of the House of Schaumburg-Lippe. The castle, which today comes in the Baroque style, looks back on more than 700 years of history. We believe that its historic charm provides the ideal backdrop to cultivate engaging discussions and foster scientific interaction

Despite having space for 250 participants, the conference quickly reached its capacity due to overwhelming demand. With registrations filling up swiftly, we’ve seen an incredible level of interest that speaks to the vibrant engagement of our community, ensuring a truly rewarding conference ahead. The program includes 33 invited talks, 14 hot topic talks and 112 posters. On Wednesday afternoon, we have planned three different social activities that offer an opportunity for casual scientific exchange, followed by the conference dinner in Schloss Bückeburg. On Thursday, we look forward to welcoming Reinhard Werner, professor at Leibniz University in Hannover, as a speaker for the evening talk. During this session, he will offer us his unique insights into the topic of last year’s Nobel Prize, shedding light on “The End of the Classical World”. After the main program of the conference on Friday, we invite you to visit the laboratories of either Leibniz University Hannover or Physikalisch-Technische Bundesanstalt in Braunschweig.

We wish you a motivating and inspiring week and hope you enjoy the conference

Nils Huntemann, Tanja E. Mehlstäubler, Christian Ospelkaus, Ekkehard Peik, Piet O. Schmidt, Fabian Wolf

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We would like to thank for the generous support of the conference by our sponsoring partners, which has played a crucial role in bringing ECTI to fruition. We appreciate your contributions that have allowed us to maintain low registration costs. By doing so, you have ensured that a wider range of participants can engage in this exchange of ideas and knowledge.

In addition to our industrial sponsoring partners we acknowledge the financial support provided by DQ-mat, Quantum Frontiers and QVLS-Q1 as well as organizational support through QVLS e.V.

Program Overview

Time	Monday 25.9.2023	Tuesday 26.9.2023	Wednesday 27.9.2023	Thursday 28.9.2023	Friday 29.9.2023
09:00-09:30	Arrival	Hammerer	Barrett	Müller	Leibfried
09:30-10:00		Akerman	Huang	Monz	Patterson
10:00-10:30		Lucas	Keller	Moses	V. C. Schmidt
10:30-11:15		Coffee (Oxford Ionics)	Coffee (QUDORA)	Coffee (Laseroptik)	Coffee
11:15-11:45		Gerritsma	Blumenthal	Home	Sturm
11:45-12:15		Pfau	Ozawa	Reiter	Berger
12:15-12:45	Welcome Lunch & Introduction	Gleyzes	A. Schmidt	Hilder	Roussy
12:45-14:15		Lunch	Lunch	Lunch	Lunch package
14:15-14:45	Linke	Smorra	Excursion	Jayich	Labtours PTB/LUH
14:45-15:15	Roos	Hot Topics: Kovalenko, Filzinger, Toscano		Hot Topics: Pinkas, Zhang, Wild	
15:15-15:45	Cetina				
15:45-16:30	Coffee (QUARTIQ)	Coffee (TechnoSystem)		Coffee (QUARTIQ)	
16:30-17:00	Northup	Crespo López-Urrutia		Koelemeij	Shuttle to HAJ
17:00-17:30	Hot Topics: DeBry, Eschner, Navickas	Hot Topics: Brewer, Wu, Mallweger		Grinfeld	
17:30-18:00				Hot Topics: Alighanbari, Goncalves	
18:00-19:30	Dinner	Dinner		Dinner	
19:30-21:30	Poster	Poster	Conference Dinner	Evening Lecture: Werner	

Contents

Tuesday Poster Session 157

Monday invited

Monday invited / 21

Digital Quantum Simulation and Symmetry Protection with Trapped Ions

Autor Norbert Linke[1]

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Our quantum computer consists of a chain of trapped 171Yb+ ions with individual Raman beam addressing and individual readout. This fully connected system can be configured to run any sequence of single- and two-qubit gates, making it in effect an arbitrarily programmable digital quantum computer. The high degree of control can be used for digital, but also for analog and hybrid quantum simulations.

Noisy operations influence all quantum computing applications and in the absence of fault-tolerant encoding, different mitigation strategies are being investigated. We recently simulated the real-time dynamics of a lattice gauge theory in 1+1 dimensions, i.e., the lattice Schwinger model, and report the comparison of different error mitigation strategies for this application [1].

The motional modes of trapped ions are a quantum computing resource that can be used for efficient operations. We present results on pairwise-parallel entangling gates applied using two sets of motional modes simultaneously, showing a significant error reduction in an example Ising-model simulation. We also describe progress towards an analog-digital hybrid quantum simulation of the Yukawa model, proposed in [3], that employs motional modes along multiple directions.

[1] N. H. Nguyen et al., PRX Quantum 3, 020324 (2022)
[2] D. Zhu et al., Science Advances 5, 10 (2019)
[3] Z. Davoudi et al., Phys. Rev. Research 3, 043072 (2021).

Monday invited / 96

Quantum simulation and sensing experiments with large ion crystals

Autor Christian Roos[None]

Co-Autoren: Helene Hainzer ; Dominik Kiesenhofer ; Artem Zhdanov ; Matthias Bock ; Tuomas Ollikainen ; Johannes Franke ; Florian Kranzl ; Manoj Joshi ; Rainer Blatt ; Raphael Kaubrügger ; Luca Arceci ; Christian Kokail ; Rick van Bijnen ; Torsten Zache ; Peter Zoller ; Sean Muleady ; Ana-Maria Rey

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In this talk, I will present experiments carried out with long ion strings and planar ion crystals with engineered long-range spin-spin interactions. In a first experiment, we variationally prepare low- and high-energy states of a nearest neighbor Heisenberg spin chain. Subsequently, measurements are carried out to learn the entanglement Hamiltonian describing subsystems of the spin chain that show a transition from an area-law to a volume-law of entanglement [1]. In a second experiment, we demonstrate the use of finite-range entangling interactions for creating squeezed states [2]. When going to interaction times where the squeezing parameter fails to detect entanglement, we observe Schrödinger cat-like states. The experiment can be extended to planar ion crystals stored in a monolithic, microfabricated linear ion trap [3]. After preparing the out-of-plane modes of crystals with up to 105 ions close to the ground state by EIT cooling, we induce long-range spin-spin interactions mediated by these modes and observe the build-up of spin-spin correlations and squeezing.

[1] M. K. Joshi, C. Kokail, R. van Bijnen et al, arXiv: 2306.00057

[2] J. Franke et al., arXiv: 2303.10688, to appear in Nature

[3] D. Kiesenhofer, H. Hainzer et al., PRX Quantum 4, 020317 (2023)

Monday invited / 131

Quantum Computing and Simulations with Long Ion Chains

Autor Marko Cetina[1]

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To apply today's quantum hardware to challenging problems, we need to efficiently use native interactions while minimizing the effects of noise. While operations on trapped ion qubits can be first-order resilient to noisy electric fields, deep computations with long ion chains suffer from high axial temperatures. To counter this, we employ sympathetic cooling in $^{171}\mathrm{Yb}^{+}$-$^{172}\mathrm{Yb}^{+}$ chains. To speed up digital computations and simulations, we developed a new class of quantum gates based on state-dependent squeezing. To speed up analog simulations, we leverage individual addressing of spins. We prepare near-ground states of the long-range 1D XY model, which break the U(1) symmetry of the underlying Hamiltonian, resulting in long-range off-diagonal order.

Monday invited / 129

Co-trapping an ion and a nanoparticle in a two-frequency Paul trap

Autor Tracy Northup[None]

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Coupling a spin qubit to a mechanical system provides a route to prepare the mechanical system's motion in nonclassical states, such as a Fock state or an entangled state. Such quantum states have already been realized with superconducting qubits coupled to clamped mechanical oscillators. We are interested in achieving an analogous coupling between a spin and a levitated oscillator — namely, a silica nanoparticle in a linear Paul trap — in order to take advantage of a levitated system's extreme isolation from its environment. In this case, we envision an atomic ion as the spin qubit.

I will present recent steps in this direction: First, we have adapted techniques originally developed for trapped atomic ions, including detection via self-interference and sympathetic cooling, for the domain of nanoparticles [1,2]. Second, we have confined a nanoparticle oscillator in ultra-high vacuum and obtained quality factors above 10¹⁰, evidence of the particle's extreme isolation from its environment [3]. Finally, we have trapped a calcium ion and a nanoparticle together in a linear Paul trap, taking advantage of a dual-frequency trapping scheme.

1. L. Dania, K. Heidegger, D. S. Bykov, G. Cerchiari, G. Arenada, T. E. Northup, *Phys. Rev. Lett.* **129**, 013601 (2022)
2. D. S. Bykov, L. Dania, F. Goschin, T. E. Northup, *Optica* **10**, 438 (2023)
3. L. Dania, D. S. Bykov, F. Goschin, M. Teller, T. E. Northup, arXiv:2304.02408

Monday Hot Topics

Monday Hot Topics / 28

Experimental quantum channel discrimination using metastable states of a trapped ion

Autoren Kyle DeBry[1]; Jasmine Sinanan-Singh[2]; Colin D. Bruzewicz[3]; David Reens[3]; May E. Kim[3]; Matthew P. Roychowdhury[3]; Robert McConnell[3]; Isaac L. Chuang[2]; John Chiaverini[3]

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One of the hallmarks of quantum mechanics is the impossibility of perfectly distinguishing non-orthogonal states. Extending this to the task of discriminating among quantum channels (such as unitary evolution or projective measurements) reveals a far richer problem, where seemingly non-orthogonal channels can sometimes be distinguished with certainty with only a few queries of the channel. Using quantum signal processing-based algorithms, we present experimental demonstrations of accurate and unambiguous single-shot discrimination between three quantum channels using a single trapped $^{40}Ca^{+}$ ion. The three channels cannot be distinguished unambiguously using repeated single-use queries, the natural classical analogue, but coherently interleaving the channel queries with quantum signal processing operations enables us to fashion targeted response functions to extract information about the channel. We develop techniques for using the 6-dimensional $D_{5/2}$ state space for this quantum information processing task, implementing protocols to discriminate among the quantum channel analogues of two data encodings commonly used in classical radio communication. These demonstrations achieve discrimination accuracy exceeding 99%, with inaccuracy entirely attributable to known experimental imperfections.

Monday Hot Topics / 136

Entanglement distribution, teleportation, and QKD over a 14-km urban fiber link

Autor Jürgen Eschner[1]

Co-Autoren: Stephan Kucera [2]; Elena Arenskötter [2]; Christian Haen [2]; Meiers Jonas [2]; Tobias Bauer [2]; Christoph Becher [2]

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The application of existing telecom fiber infrastructure for quantum communication protocols enables efficient development of quantum networks [1]. It also entails multiple challenges, since existing infrastructure in an urban region is often underground or paired with the electrical overhead power line, and prone to environmental influences which cause fluctuations in polarization mode dispersion, photon travel times, and polarization dependent loss.
Here, we present the characterization and application of a 14.7 km long deployed fiber link in the Saarbrücken urban area as a quantum channel. The link connects our ion trap laboratory on the campus of the Saarland University with a receiver station on the campus of the University of Applied Sciences, with a point to point distance of 5.5 km. It comprises 1278 m of overhead cable and several patch stations. An efficient polarization correction scheme is employed, following the technique of [2], to ensure high-fidelity transmission of single-photon polarization qubits.
As elementary quantum network protocols, entanglement distribution and quantum-state teleportation [3] from a 40Ca+ ion quantum memory are demonstrated, both utilizing a bright, high-fidelity entangled photon pair source and polarization-preserving quantum frequency conversion [4].
As a perspective we report on the status of a demonstration of device-independent quantum key distribution [5] over this fiber link, using atom-photon entanglement generated in single-photon emission from 40Ca+ ions [6].

[1] H. Kimble, Nature 453, 1023–1030 (2008).
[2] F. Hocke, Diploma thesis, TU Munich (2007)
[3] E. Arenskötter et al., arXiv:2301.06091 (2023)
[4] E. Arenskötter et al., NPJ Quantum Inf. 9, 34 (2023)
[5] R. Schwonnek et al., Nat Commun 12, 2880 (2021)
[6] M. Bock et al., Nat Commun 9, 1998 (2018)

Monday Hot Topics / 93

Analogue quantum simulation of molecular vibronic spectra with a trapped ion

Autor Tomas Navickas[None]

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The analogue simulation of a quantum chemical system is challenging using conventional computers, particularly in strong vibronic (vibrational and electronic) coupling regimes when the Born-Oppenheimer approximation breaks down. The vibronic terms in Hamiltonians representing ultrafast molecular dynamics can be efficiently simulated on quantum systems with coupled internal states and bosonic modes [1]. We can use this mapping to recast basic molecular dynamics onto our 171Yb+ ion system. The radial motional modes of the ion behave as the vibrational modes of the molecule, while the necessary molecular interactions are implemented using a pair of Raman beams carrying multiple frequency tones.

We implemented the analogue quantum simulation in a proof-of-principle experiment to reconstruct molecular spectra. We found the quality of the simulations were limited by the dephasing of the motional modes. The source of dephasing was found to be the voltage noise of the radio-frequency trapping field. By implementing amplitude noise filtering and feedback, we improved radial mode coherence times from ~1 ms to more than ~30 ms. This enabled us to compute the 1-dimensional Franck-Condon spectra of an SO2 molecule [2] and demonstrate geometric phase effects in molecular dynamics [3].

[1] Analog quantum simulation of chemical dynamics. Ryan J. MacDonell, Claire E. Dickerson, Clare J. T. Birch, Alok Kumar, Claire L. Edmunds, Michael J. Biercuk, Cornelius Hempel and Ivan Kassal, Chem. Sci., 2021,12, 9794-9805
[2] Predicting molecular vibronic spectra using time-domain analog quantum simulation. Ryan J. MacDonell, Tomas Navickas, Tim F. Wohlers-Reichel, Christophe H. Valahu, Arjun D. Rao, Maverick J. Millican, Michael A. Currington, Michael J. Biercuk, Ting Rei Tan, Cornelius Hempel, Ivan Kassal, arXiv:2209.06558
[3] Direct observation of geometric phase in dynamics around a conical intersection. Christophe H. Valahu, Vanessa C. Olaya-Agudelo, Ryan J. MacDonell, Tomas Navickas, Arjun D. Rao, Maverick J. Millican, Juan B. Pérez-Sánchez, Joel Yuen-Zhou, Michael J. Biercuk, Cornelius Hempel, Ting Rei Tan, Ivan Kassal, arXiv:2211.07320

Tuesday invited

Tuesday invited / 102

Bugs & Features of Quantum Correlations in Ion Crystals and Clocks

Autor Klemens Hammerer[None]

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Coulomb crystals, formed by cold trapped ions, represent a leading platform for realizing quantum processors, simulators, and constructing optical atomic clocks. The coupling between collective motion and internal degrees of freedom, resulting in quantum correlations, plays a pivotal role in achieving and enhancing these applications. However, at times, these quantum correlations can also manifest as bugs, unexpectedly complicating seemingly simple tasks. In this talk, I will present illustrative examples of both phenomena.

A bug associated with quantum correlations arises from the difficulty in transferring the well-established sideband thermometry method, designed for single ions, to cold Coulomb crystals without sacrificing accuracy due to the complex dynamics of many interacting particles. To address this challenge, I will present a systematic solution that can be applied to crystals of any size, eliminating computational bottlenecks. The successful application of this method for thermometry on cold crystals, including a 1D chain of 4 ions and a 2D crystal of 19 ions, has yielded promising results.

Conversely, a distinctive feature of quantum correlations is their potential, in principle, to enhance the stability of atomic clocks. Utilizing controlled quantum dynamics beyond spin-equilibrated states, ion traps offer a myriad of possibilities for creating specially designed correlated states and measurements. In this presentation, I will discuss the specific requirements in frequency metrology and present optimized protocols tailored for ion clocks.

Although these topics may seem distinct, they are conceptually and theoretically interconnected as both fall within the domain of estimation theory. This presents an opportunity to underscore the practicality of the available methodology and conceptual framework by utilizing these two specific applications in cold Coulomb crystals as illustrative examples.

Tuesday invited / 208

Entanglement and dynamic decoupling in multi-ion clock

Autor Nitzan Akerman[1]

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Trapped ions are ideal systems for optical atomic clocks and precision tests of fundamental physics. However, the quantum projection noise of the single ion imposes a limit on its stability. Multi-ion optical clock has an obvious potential to improve clock stability. However, their operation has so far been impeded due to the challenges of controlling the various inhomogeneous shifts that are typical to ion traps. Recently dynamic decoupling and quantum state engineering were proposed to tackle some of these challenges. In this talk, I will present the status of our Sr+ ion clock at WIS. I will then report our recent progress in implementing a clock of two-isotope in an entangled state that is magnetic insensitive. In addition, a dynamic decoupling scheme which suppresses the quadruple and Zeeman shift in a multi-ion clock.

Tuesday invited / 110

Quantum networking and computing with trapped ions

Autor D Lucas[None]

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I will describe recent work at Oxford on quantum networking applications using trapped-ion qubits. Our apparatus consists of two independent ion traps, separated by 2 metres, linked via a single-photon optical fibre interface. We can generate high-fidelity (>90%) entanglement between trapped-ion qubits, one stored in each trap, at high speed (up to 200 entanglement events per second). Using this setup we have made demonstrations of several quantum technological applications in the areas of cryptography, metrology and information processing [1,2,3].

Firstly, we achieved a full implementation of a “device-independent” QKD protocol [1]; that is, the generation of a shared secret key between Alice and Bob, reliant only on their possession of a pair of entangled particles - entanglement which no eavesdropper can share [4]. Secondly, we demonstrated entanglement-enhanced frequency comparison of two optical atomic clocks [2], with precision approaching the Heisenberg limit (the ultimate measurement precision allowed by quantum mechanics). Recently, we have added robust quantum memory to our network [5], which has enabled a demonstration of verifiable blind quantum computing [3]; that is, the ability of a “client” to run and verify a simple protocol on the “server’s” quantum processor, without the server being able to see the client’s data or algorithm.

[1] D.P.Nadlinger et al., Nature 2022.
[2] B.C.Nichol, R.Srinivas et al., Nature 2022.
[3] P.Drmota et al., arXiv 2023.
[4] A.Ekert, Phys.Rev.Lett. 1991.
[5] P.Drmota et al., Phys.Rev.Lett. 2023.

Tuesday invited / 193

Buffer gas cooling of trapped ions using ultracold atoms

Autor Rene Gerritsma[1]

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I will discuss the ups and downs of buffer gas cooling of trapped ions in the ultracold regime [1-3]. I will focus on attainable temperatures, collision energies and possible issues such as spin exchange and relaxation during atom-ion collisions [4] as well as trap-assisted complexes that can arise after an atom-ion collision [5]. I will discuss the prospects of using the system to explore polaronic physics in an ultracold gas. Furthermore, I will present some results in quantum chemistry that we obtained some time ago when we immersed an ion into a cloud containing Li2 dimers [6,7]. These results are of interest when considering charged impurity physics in the BEC to BCS crossover regime in a fermionic spin mixture. Moreover, they highlight the possibilities offered to study quantum chemistry in the system.
[1] H. Hirzler et al., Phys. Rev. A 102, 033109 (2020).
[2] E. Trimby et al., New Journal of Physics 24, 035004 (2022).
[3] T. Feldker et al., Nature Physics 16, 413–416 (2020).
[4] H. Fürst et al., Phys. Rev. A 98, 012713 (2018).
[5] H. Hirlzer et al., Phys. Rev. Lett. 130, 143003 (2023).
[6] H. Hirzler et al., Phys. Rev. Research 2, 033232 (2020).
[7] H. Hirlzer et al., Phys. Rev. Lett. 128, 103401 (2022).

Tuesday invited / 91

A molecular bond between ions and Rydberg atoms

Autor Tilman Pfau[None]

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Atoms with a highly excited electron, called Rydberg atoms, can form unusual types of molecular bonds. The bond differs from the well known ionic and covalent bonds not only by its binding mechanism, but also by its bond length ranging up to several micrometres. We report the observation a new type of molecular bond based on the interaction between the ionic charge and a flipping induced dipole of a Rydberg atom with a bond length of several micrometres [2]. We measure the vibrational spectrum and spatially resolve the bond length and the angular alignment of the molecule using a high-resolution ion microscope [1]. As a consequence of the large bond length, the molecular dynamics is slow and can be directly observed under the microscope [3]. These results pave the way for future studies of spatio-temporal effects in molecular dynamics, e.g., beyond Born-Oppenheimer physics, and more generally on (ionic) impurities in quantum gases.

References
[1] C. Veit et al. Phys. Rev. X 11, 011036 (2021).
[2] N. Zuber et al. Nature 5, 453 (2022).
[3] Y. Zou, et al. PRL 130, 0230020 (2023)

Tuesday invited / 85

Circular Rydberg Atoms of Strontium

Autor Sébastien Gleyzes[1]

Co-Autoren: Léa Lachaud [1]; Baptiste Muraz [1]; Jean-Michel Raimond [1]; Michel Brune [1]

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Rydberg atoms arrays are one of the most promising platforms for quantum simulation. Alkali ground-state atoms, trapped in optical tweezers, are arranged into a well-defined arbitrary geometry before being transferred into low-angular momentum Rydberg states using laser pulses. Once in a Rydberg level, the atoms interact with each other through the dipole-dipole coupling, which enables to simulate the dynamics of arbitrary Hamiltonians [1,2].
However, the relatively short lifetime (in the 100 µs range) of low-angular momentum Rydberg atoms currently limits either the number of atoms or the duration of the simulation. Longer lifetimes can be obtained by switching to high-angular momentum Rydberg states, like the circular states [3], but observing the spin dynamics over a long timescale requires trapping the low-laser-intensity-seeking alkali Rydberg atoms using complex hollow beam geometries [4].
This is one of the reasons that motivated many groups to develop Rydberg experiments with alkaline-earth or alkaline-earth-like elements. Rydberg states of divalent atoms have an optically active ionic core that can be used to manipulate the atoms. If, for laser-accessible Rydberg states, the optical excitation of the ionic core leads to the fast auto-ionization of the atom, the auto-ionization rate exponentially decreases as the angular momentum of the Rydberg electron increases. This opens the way to use the ionic core electron transitions to image, trap or cool alkaline-earth circular states.
During the last few years, we have developed a new experiment to prepare and manipulate circular states of strontium. We have demonstrated that it possible to use the ionic core transition to slow down a beam of strontium circular atoms by using a counter-propagating 422nm laser beam. We have also shown that the residual electrostatic interaction between the ionic core and the Rydberg electrons opens the way to manipulate the state of the Rydberg electron using laser beams resonant with ionic core transitions, or to encode the state of a Rydberg atom with a given n onto one of the magnetic sublevels of the metastable state 4d3/2. This opens the way to state-selective fluorescence imaging of circular states [5].

[1] Barredo, D. et al, Nature 561, 79 (2018).
[2] Ebadi, S. et al, Nature 595, 227 (2021).
[3] Nguyen, T. L. et al, PRX 8, 011032 (2018).
[4] R.G. Cortiñas et al, PRL 124, 123201 (2020)
[5] A. Muni et al, Nat. Phys. 18, 502 (2022)

Tuesday invited / 137

A roadmap for proton-antiproton precision measurements

Autor Christian Smorra[None]

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Precision measurements of fundamental properties of protons and antiprotons constitute stringent tests of the fundamental interactions. Comparisons of their charge-to-mass ratios and magnetic moments have been used to constrain potential violations of CPT invariance, asymmetric particle-antiparticle dark matter couplings, and antiproton gravitational anomalies.

The BASE collaboration has established or improved these limits in the recent years, and I will report the latest measurement results. Future improvements are challenging and require new experimental techniques to achieve significant progress in the sensitivity to new interactions. Therefore, I will also present our efforts on developing a transportable antiproton trap, and a sympathetic cooling method for protons/antiprotons based on image-current coupling to laser-cooled ions.

Tuesday invited / 206

X-raying highly charged ions with synchrotrons and free-electron lasers

Autor José R. Crespo López-Urrutia[1]

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Strong ionizing radiation fields are ubiquitous in astrophysical environments. There, atomic matter appears mainly as highly charged ions (HCIs), which dominate radiation transport and plasma dynamics. Their spectroscopic signatures provide information on the composition, temperature, density, turbulence, and velocity of plasmas, e. g. those surrounding stars, X-ray binaries, active galactic nuclei, as well as those filling galaxy clusters and the intergalactic medium. The abundance and electronic properties of iron HCl make their X-ray transitions key to our understanding of these plasmas. The Ne-like Fe XVII is very interesting because it survives up to very high temperatures. The oscillator strengths of its transitions have puzzled observers, theorists, and laboratory astrophysicists for nearly fifty years. A series of experiments with electron beam ion traps at X-ray sources have finally confirmed advanced atomic structure calculations by steady improvements in resolution and signal-to-noise ratio. Their agreement in the range of a few percent is important for plasma diagnostics and astrophysics. The hopefully successful launch this August of XRISM, an X-ray space telescope equipped with a high-resolution X-ray microcalorimeter, will provide a wealth of X-ray data of unprecedented quality. The benchmarked advanced theory methods used to interpret our laboratory data will be very useful for analyzing the upcoming data streams and will enhance the scientific return from this mission and the upcoming Athena X-ray observatory.

Tuesday Hot Topics

Tuesday Hot Topics / 70

Super-Poissonian light from indistinguishable single-photon emitters

Autoren Artem Kovalenko[1]; Daniel Babjak[1]; Lukáš Lachman[1]; Lukáš Podhora[1]; Petr Obšil[1]; Tuan Pham[2]; Adam Lešundák[2]; Ondřej Číp [2]; Radim Filip[1]; Lukáš Slodička[1]

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Trapped ion crystals consisting of many individual photon emitters offer an ideal platform for the exploration of a wide range of fundamental quantum emission scenarios. We present the implementation of a new optical emission regime in which photons scattered incoherently from different ions collectively contribute to the observation of photon bunching and super-Poissonian photon number variance.

The second-order coherence of light has been explored in the experiment comprising a linear Paul trap with large crystals of Ca^+ ions. We realized the scattering geometry where light from many independent emitters – trapped ions can be collected into a single detection spatial mode with overall efficiency sufficient for the observation of photon-photon correlations. The correlations are measured using a Hanbury-Brown and Twiss detection setup with single-photon counting modules for a broad range of ion numbers ranging from a single to up to several hundred. The corresponding normalized intensity correlations at a zero-time delay gradually increase from sub-Poissonian to super-Poissonian values for single ion and large Coulomb crystals, respectively. We provide evidence that the indistinguishability of scattering contributions to a single detection mode provides the fundamental resource for photon bunching and, consequently, for the increased variance of the photon number above the Poissonian level. The realized experimental tests in the opposite - spatially multi-mode regime prove that the photon distinguishability is crucial for the feasibility of direct observation of nonclassical sub-Poissonian character in the limit of a large number of independent and mutually incoherent single-photon emitters. We develop a unified description of the corresponding measurements of photon correlations from a large, but fixed number of non-interacting and phase-randomized single-photon emitters.

Tuesday Hot Topics / 88

New limits on variations of the fine-structure constant and ultralight dark matter

Autoren Melina Filzinger[1]; Sören Dörscher[None]; Richard Lange[None]; Joshua Klose[None]; Martin Steinel[2]; Erik Benkler[None]; Ekkehard Peik[None]; Chistian Lisdat[None]; Nils Huntemann[2]

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The 171Yb+ ion features two narrow optical transitions: an electric octupole (E3) transition as well as an electric quadrupole (E2) transition. Because they have a large differential sensitivity to the fine structure constant α, its possible variations can be probed by comparing the transition frequencies at various positions in spacetime. We find improved bounds on a linear temporal drift of α, as well as its coupling to the gravitational potential of the sun, from a long-term optical clock comparison [1,2].

Additionally, the couplings of so-called ultralight bosonic dark matter (m « 1 eV/c^2) to standard model particles would lead to coherent oscillations of constants, with an oscillation frequency corresponding to the Compton frequency of the dark matter mass [3]. We conduct a broadband dark-matter search by comparing the frequency of the E3 transition to that of the E2 transition, and to that of the 1S0 ↔ 3P0 transition in 87Sr. We find no indication for significant oscillations in our experimental data. Consequently, we put limits on oscillations of the fine-structure constant and thus improve existing bounds on the scalar coupling of ultralight dark matter to photons for dark-matter masses of about 1E−24 to 1E−17 eV/c^2 [2]. Couplings to quarks and gluons can also be investigated with optical frequency ratio measurements by considering the effect an oscillating nuclear charge radius would have on electronic transitions [4].

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Tuesday Hot Topics / 9

Trapping and sympathetic cooling of conformationally selected ions

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The different effective dipole moment of conformational isomers allows for their spatial separation by means of electrostatic deflection, enabling their individual reactivity to be investigated [1]. Recently, the conformer-specific polar cycloaddition of dibromobutadiene (DBB) with trapped propene ions has shown that both *gauche* and *s-trans* DBB conformers display capture-limited reaction rates [2]. The reaction was found to occur through both a concerted and a stepwise reaction mechanism, despite the spatial rearrangement of atoms necessary in *s-trans* DBB for the latter to take place. These results were obtained by selectively aiming the molecular beam containing either one of the two conformers at a static target of propene ions embedded within a laser-cooled Coulomb crystal of calcium ions. In order to gain further control over the reaction partners, we also wish to select the conformational isomer of the ionic reactant.

Here, we demonstrate for the first time the sympathetic cooling of different conformational isomers within a Coulomb crystal, setting the scene for fully conformationally selected ion–molecule reaction studies. Following the successful isomer-selective ionisation and loading of the two *meta*-aminostyrene conformers into Coulomb crystals of trapped and laser-cooled calcium ions, we now aim to investigate their isomer-specific reactivity.

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Tuesday Hot Topics / 61

Towards optical clocks based on highly charged ions for precision tests of fundamental physics and improved frequency standards

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Optical clocks based on highly charged ions (HCIs) offer several promising avenues for the study of physics beyond the standard model. Among these are searches for time variation of the fine structure constant, $\dot{\alpha}/\alpha$, ultralight scalar dark matter, and tests of quantum electrodynamics (QED) [1]. Due to level crossings occurring in high charge states, narrow linewidth optically accessible transitions with a high sensitivity to $\dot{\alpha}/\alpha$ are predicted in systems such as Pr^{10+} [2]. We plan to create HCIs, including Pr^{10+}, in a compact electron beam ion trap (EBIT) and then transfer them to a cryogenic radiofrequency (rf) Paul trap where quantum-logic spectroscopy (QLS) will be performed. In this talk, I will present an update on HCI production in the newly developed CSU EBIT and recent results on precision spectroscopy on $^9Be^+$ in our first-generation room temperature rf trap. In addition, I will present an update on the development of a Ba^{4+} quantum-logic clock for use as an improved optical frequency standard [3] and a recently established dark optical fiber link between CSU and the NIST-WWV clock ensemble located in Fort Collins, CO.

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Tuesday Hot Topics / 23

Quantum Control of Motional States in Mixed-Species Trapped Ion Crystals

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Motional modes of ions trapped in the same potential are often used to transfer information between ions, for example in quantum logic spectroscopy or Molmer-Sorensen gates. Good motional control is crucial for high-fidelity operations; as many modes as possible should be cooled to near the ground state. Unfortunately, in some crystals, due to geometrical constraints on the apparatus or low participation of the cooling ions in certain modes, it is difficult to perform rapid, efficient cooling of all motional modes.

Furthermore, each motional mode of a trapped-ion chain implements a harmonic oscillator, enabling the study of bosonic qubits on this platform. A significant barrier to this avenue of exploration is photon recoil; since both motional and atomic ion states are usually distinguished by state dependent fluorescence, it is difficult to non-destructively extract information about the state of motional modes.

To overcome both these issues, we have developed a technique, whereby oscillating potentials are applied to trap electrodes to directly, coherently, and rapidly parametrically couple two modes of motion. We use this coupling to demonstrate both cooling of difficult-to-cool modes, as well as non-destructive, repetitive readout of a single motional mode in a three-ion crystal in which the middle ion is a different species from the other two. In this presentation, I will describe these results, as well as the use of repetitive readout to stabilize the lowest two Fock states of a motional mode, and other related experiments.

Tuesday Hot Topics / 105

Non-destructive characterization of phonon number states using the Autler-Townes effect and using composite pulse sequence

Autoren Marion Mallweger[1]; Murilo Henrique De Oliveira[2]; Boyan Torosov[3]; Robin Thomm[1]; Harry Parke[1]; Natalia Kuk[1]; Gerard Higgins[4]; Nikolay Vitanov[3]; Romain Bachelard[2]; Celso Jorge Villas-Boas[2]; Markus Hennrich[1]

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Quantum technologies employing trapped ion qubits commonly rely on the motional state of the ion. Motional states can not only be used for entanglement operations but also for example to store quantum information or can act as a tool for logic spectroscopy. Hence, a precise knowledge about the motional state of the ion is often required.
In this work we present two novel methods to measure phonon number states in a non-destructive manner. We demonstrate both techniques using a single trapped $^{88}Sr^{+}$ ion.
The first method relies on the Autler-Townes effect that arises when two levels are strongly coupled while being probed from a third level. If the two levels are coupled on a motional sideband transition, then the magnitude of the Autler-Townes splitting depends on the phonon number state. This novel technique provides a robust and efficient way of measuring motional states of an ion. It can even be applied to perform single shot measurements of phonon number states in a non-destructive way.
The second method uses an ultra-narrowband composite pulse sequence for efficient detection of the ions' motional state. It is based on a pulse sequence with optimized relative phases forming a narrow excitation profile. We characterize this technique for multiple pulse sets. This technique can even be used outside the Lamb-Dicke regime, making it a versatile tool for phonon characterization.

Wednesday invited

Wednesday invited / 143

A lutetium frequency reference.

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Singly ionized lutetium ($^{176}\mathrm{Lu}^{+}$) has a unique level structure that provides multiple clock transitions. In combination with hyperfine averaging, two of these transitions ($^1S_0$ – $^3D_1$ & $^1S_0$ – $^3D_2$) present both a long lifetime and low sensitivity to the electromagnetic environment, which allows high performance clock operation on both transitions. Recently we have demonstrated clock comparison on the $^1S_0$ – $^3D_1$ at the low 10^{-18} level limited by clock stability, with an error budget that supports the capability to go well beyond 10^{-18}.

The relative ease at which we are able to establish agreement between two independent frequency references is attractive both for applications and establishing a laboratory frequency reference. We discuss the advantages that lutetium offers with an emphasis on the unique possibilities afforded by the existence of two transitions within the one system. In particular, a frequency ratio measured within the one system provides an independent metric that can validate performance claims made on a single transition.

Wednesday invited / 73

Ca^+ Optical clocks with Systematic Uncertainties at the E-18 level

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Here our progress on the Ca+ ion optical clocks for the last few years will be reported, including both the laboratory clocks and the transportable clock.
A cryogenic Ca+ clock at the liquid nitrogen environment is built, with the blackbody radiation (BBR) shift uncertainty greatly suppressed, and improvements made with other systematic uncertainties, the overall systematic uncertainty of the clock is evaluated as 3.0E-18[1].
The Ca+ clock at room temperature is also improved. The systematic uncertainty of the room temperature clock was at the E-17 level, limited by the BBR shift uncertainty [2]. To lower the BBR shift uncertainty, the precise measurement of the differential scalar polarizability through of the clock transition is taken [3], and the active liquid-cooling scheme is adopted, combined with the precise temperature measurement with 13 temperature sensors [4]. The BBR field temperature uncertainty is then evaluated as 0.4 K, corresponding to a BBR shift uncertainty of 4.6E-18, then the overall systematic uncertainty of the room temperature clock is evaluated as 4.9E-18 [4].
Clock frequency comparison between the room temperature clock and the cryogenic clock is taken for testing the systematic shift uncertainty evaluations, and the two clocks show an agreement at the 10-18 level after the systematic shift corrections: With the systematic shift corrections, the frequency difference between the two clocks is measured as 1.8(7.5) × 10-18, the overall uncertainty includes a statistic uncertainty of 4.9 × 10-18 and a systematic uncertainty of 5.7 × 10-18 [4].
Besides the laboratory clocks mentioned above, a transportable Ca+ ion clock is also built, with an uncertainty of 1.3E-17 [5]. With the comparison between the transportable clock and the laboratory clock, a demonstration of geopotential measurement with clocks has been made [5]. Recently, a 35-day-long absolute frequency measurement is taken, with improvements made such as the increase of the uptime rate to 91.3 %, the uncertainty of the absolute frequency measurement is further reduced to 3.2E-16 [6].

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Wednesday invited / 112

High-Accuracy Optical Clock Based on ^{115}In^{+} / ^{172}Yb^{+} Mixed-Species Coulomb Crystals

Autoren Jonas Keller[1]; Tabea Nordmann[1]; Hartmut Nimrod Hausser[1]; Nishant Bhatt[1]; Ingrid Dippel[1]; Moritz von Boehn[1]; Tanja E. Mehlstäubler[1]

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Optical clocks based on mixed-species Coulomb crystals promise reductions of both statistical and systematic uncertainties beyond the state of the art.

We operate an optical clock based on the combination of ^{115}In^{+} (clock) and ^{172}Yb^{+} (auxiliary) ions, which we have identified as a candidate for multi-clock-ion operation with 10^{-19} level systematic uncertainties [1,2].

Our approach uses short linear chains (~10 ions), in which the permutation of species is actively controlled to ensure efficient and reproducible sympathetic cooling conditions [3]. The systematic uncertainty is currently evaluated as 2.5×10^{-18} for operation with a single In^{+} clock ion, which yields an instability of $\sigma_y = 1.6 \times 10^{-15}/\sqrt{t}$ [4]. The clock has participated in local and international comparisons, and operation with up to four clock ions has been demonstrated.

Besides its use for sympathetic cooling, mixed-species operation also allows the reduction of systematic uncertainties. Fluorescence from the ^{2}S$_{1/2}$ to ^{2}P$_{1/2}$ cooling transition in Yb^{+} is used for excess micromotion compensation during clock operation. Uncertainties of the differential polarizability and the ^{3}P$_0$ g factor of In^{+} can be reduced using interleaved interrogation of different transitions in the mixed-species system. These measurements can reduce the frequency uncertainty contributions due to black-body radiation and the 2nd-order Zeeman shift from their respective current values close to 1×10^{-18} by more than an order of magnitude each.

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Wednesday invited / 42

Visible Light Photonic Integration for Atom and Quantum Science

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Visible light photonic integration will enable compact, low weight, and reliable quantum and atomic sensing systems. In this talk we will review the latest advances in the ultra-low loss silicon nitride integration platform and heterogeneous integration, that enable quantum systems on chip (QSOC). Various technologies supported include visible light and ultra-narrow linewidth lasers, modulators, laser noise measurement, frequency stabilization circuits and reference cavities, beat-note detection, spectroscopy locks, and atom trap and cooling beam emitters. We will also talk about current integration and QSOCs for cold atom 3D-MOTs, trapped ions, and the potential for future neutral atom trapping.

Wednesday invited / 71

Towards High-Precision Spectroscopy of the 1S−2S Transition in He+

Autor Akira Ozawa[1]

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The energy levels of hydrogen-like atoms can be precisely described by bound-state quantum electrodynamics (QED). The frequency of the narrow 1s-2s transition of atomic hydrogen has been measured with a relative uncertainty below 10^{-14}. When combined with other spectroscopic measurements of hydrogen and hydrogen-like atoms, the Rydberg constant and the proton charge radius can be determined. Comparing the physical constants extracted from different combinations of measurements serves as a consistency check for the theory. Hydrogen-like He+ ion is yet another interesting spectroscopy target for testing QED. Due to their charge, He+ ions can be held near-motionless in the field-free environment of a Paul trap, providing ideal conditions for high precision measurement. Interesting higher-order QED corrections scale with large exponents of the nuclear charge, which makes this measurement much more sensitive to these corrections compared to the hydrogen case. We are currently setting up an experiment to perform precise spectroscopy of the He+ 1S−2S transition. The main challenge of the experiment is that driving the 1S−2S transition in He+ requires narrow-band radiation at 61 nm. This lies in the extreme ultraviolet (XUV) spectral range where no continuous wave laser sources exist. Our approach is

to use two-photon direct frequency comb spectroscopy with an XUV frequency comb. The XUV comb is generated from an infrared high power frequency comb using intracavity high harmonic generation. The spectroscopy target will be a small number of He^+ ions, which are trapped in a linear Paul trap and sympathetically cooled by co-trapped Be^+ ions. In this talk, we will present our recent progress in developing XUV frequency comb and Paul-trap for high-precision spectroscopy of He^+ 1S–2S transition.

Wednesday invited / 51

The PUMA Experiment: Investigating Short-lived Nuclei with Antiprotons

Autor Alexander Schmidt[None]

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The antiProton Unstable Matter Annihilation (PUMA) experiment is a nuclear physics experiment at CERN which will determine the ratio of protons to neutrons in the nuclear density tail based on the peripheral annihilation of low-energy antiprotons, providing a new observable to test nuclear structure theory. As the annihilation conserves the total charge, the annihilated nucleon can be identified by detecting all charged pions produced in the annihilation process with a detection system comprised of a time-projection chamber and a plastic scintillator barrel. Here, the charge identification is performed by determining the curvature in a 4T field of a solenoid. This magnetic field is also used for trapping and storing antiprotons in an extreme high vacuum at the Antimatter Factory of CERN as the only facility providing low-energy antiprotons. There, measurements with stable ions will be performed to investigate the evolution of the proton-to-neutron ratio along isotopic chains. The ions are provided by an offline ion source beamline, which can supply isotopically pure and bunched beams by implementing a multi-reflection time-of-flight spectrometer and a Paul trap. Following the purification, the ions are overlapped with antiprotons in the PUMA Penning trap, which is surrounded by the detection system. Besides the research with stable ions at the Antimatter Factory, due to the sensitivity to the nuclear density tail, this approach is particularly interesting for nuclei with a high proton-to-neutron asymmetry, i.e. short-lived nuclei such as halo nuclei and nuclei with a thick neutron skin. To perform measurements with such short-lived nuclei, the full PUMA experimental setup can be disconnected from its beamline at the Antimatter factory after antiproton accumulation and transported to the ISOLDE facility of CERN.

This talk will give an overview over the different subsystems of the experiment and present their current status.

Thursday invited

Thursday invited / 145

Concepts for Fault-Tolerant Quantum Computing with Trapped Ions

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Quantum computers hold the promise to efficiently solve some computationally hard, classically intractable problems. Unfortunately, unavoidable noise limits the capabilities of current noisy intermediate-scale quantum (NISQ) devices. In my talk, I will first introduce basic concepts of topological quantum error correcting codes and quantum fault-tolerance, which is imperative to prevent errors from spreading uncontrollably through the quantum register. I will in particular discuss most modern fault-tolerant protocols that led to the first realisation of a universal set of logical quantum gates with trapped ions. Furthermore, I will highlight promising alternative approaches towards error-corrected quantum processors, based e.g. on code-switching, quantum machine-learning (so-called quantum auto-encoders) or new autonomous measurement-free, yet fully-fault-tolerant error correction protocols. Finally, I will outline promising pathways to scale up current trapped-ion architectures towards scalable, error-corrected trapped-ion quantum computers.

Thursday invited / 219

Experimental fault-tolerant quantum computation with trapped ions

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Quantum computation at scale requires methods to address the accumulation of errors. Fault-tolerant quantum computing building on top of (i) sufficiently small error rates, (ii) suitable encoding of quantum information across multiple qubits, and (iii) carefully chosen interactions to limit error propagation, allow one to increase the system size without increasing the error rates in the encoded system. In this presentation, building upon theoretical concepts, experimental approaches for fault-tolerant quantum computing with trapped ions, their characterisation, and implementation will be addressed.

Thursday invited / 24

Benchmarking Quantinuum's Second-Generation Quantum Processor

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One of the main challenges facing large-scale quantum computing is scaling systems to more qubits while maintaining high fidelity operations. In this talk, I will describe our efforts at Quantinuum in scaling trapped-ion quantum computers based on the quantum charge-coupled device architecture. We recently released our second-generation machine, which has a race-track shaped ion trap. The new system incorporates several technologies crucial to future scalability, including electrode broadcasting, multi-layer RF routing, and magneto-optical trap loading, while maintaining, and in some cases exceeding, the gate fidelities of our first-generation system. We initially released the system with 32 qubits, but future upgrades will allow for more. I will describe the thorough set of benchmarking experiments we performed to characterize the system, as well as present a selection of recent results of quantum circuits that have been run on the system.

Thursday invited / 200

Quantum control and transport in a micro fabricated Penning trap.

Autoren Jonathan Home[1]; Shreyans Jain[1]; Tobias Saegesser[2]; Pavel Hrmo[1]; Daniel Kienzler[2]; Martin Stadler[1]

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I will describe experimental work on the control of ions in a micro fabricated surface-electrode Penning trap. The work is motivated by the possibility to realise micro-trap arrays for quantum computing, sensing and simulation, without being restricted by the complications introduced by high-voltage RF fields for trapping. At a trapping height of 152 micron, we have trapped beryllium ions and cooled all motional modes to the ground state, observing heating rates as low as 0.1 quanta per second at 2.5 MHz trap frequency. Using in-sequence switching, we demonstrate the ability to trap ions while isolating the electrodes from all voltage sources. By translating the ion in 3-dimensions over >100 micron range, we use the ion as a field sensor for electric and magnetic fields in a flexible manner. Our work provides and characterizes a range of elements of a unit-cell for a Penning trap QCCD architecture for scalable quantum computing and simulation.

Thursday invited / 170

Multi-qubit gates for bosonic logical qubits in trapped ions

Autor Florentin Reiter[1]

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Bosonic codes comprise a paradigm for quantum computing and quantum error correction where quantum information is encoded in continuous degrees of freedom such as modes of radiation or motion. In particular, Gottesman-Kitaev-Preskill (GKP) codes [1] are promising candidates for bosonic quantum information processing, in which quantum error correction has recently been demonstrated both in superconducting circuits [2] and trapped ions [3]. In order to embed such encodings into larger systems, gates between multiple encoded qubits are required.
We present techniques for the realization of two-qubit gates on GKP codes with finite energy [4]. Here we observe that operations designed for ideal infinite-energy codes create undesired effects when applied to physically realistic states. We demonstrate that these can be mitigated using local error-correction protocols. In addition, we propose finite-energy gate implementations which largely avoid the need for further correction.

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Thursday invited / 127

Scalable Trapped-Ion Quantum Computers from Trap Fabrication to User Interface

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Trapped-ion quantum technology is one of the most promising candidates for the realization of scalable quantum processors. To address individual ions and perform high-fidelity two-qubit entangling gates in a linear segmented Paul trap, we dynamically employ register reconfiguration operations to place specific qubits in a laser interaction zone in combination with addressing of sub registers. Efficient operation of scalable systems requires not only microfabricated ion traps and custom control electronics, but also a software stack including a convenient user interface such as Qiskit.
After a short introduction to shuttling- and addressing-based trapped-ion quantum computer architectures, we present a new trap fabrication facility recently setup in Mainz, required for fast prototyping of complex trapping devices. This clean room facility is specialized in the production of complex 3D microfabricated ion traps and fits to the demands of iterative and generative ion trap developments within weeks instead of months.
Additionally, details about our latest quantum computing hardware and software stack are going to be presented. Building on the experience of manually compiled shuttling and operation sequences, such as in the realization of an error correction building block [3], a software framework was implemented to fully automize this compilation process. This allows external users to execute quantum algorithms including hybrid computation, parametrized gates, in-sequence measurements and feedback, without detailed knowledge of the hardware backend.

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Thursday invited / 229

Radium clocks

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We are developing optical clocks based on radium. Though unstable it has potential for low instability clocks as radium's high mass reduces sensitivity to leading systematic uncertainties. The wavelengths needed for a radium clock are in relatively photonic technology friendly parts of the spectrum, making it appealing for a robust and compact optical clock. The nuclear instability is an asset to address the recently posed question: do atoms age? This could be addressed by running a clock for time scales comparable to an isotope's half-life and looking for drift in the clock transition's frequency. We have realized a clock with radium-226 (1600 y half-life). We'll discuss laser cooling and trapping of radium-224 (3.6 d half-life) and radium-225 (15 d half-life) and progress towards making clocks with these isotopes. Radium-225 is appealing as it has a nuclear spin of 1/2 which makes it less sensitive to magnetic field noise than spin zero isotopes.

Thursday invited / 81

Solving a 9σ discrepancy between hyperfine theory and experiment in trapped HD^+ ions

Autoren Dmitrii Kliukin[1]; Roya Ahemeh[1]; Thijmen Klijn Velderman[1]; Kjeld Eikema[1]; Jean-Philippe Karr[2]; Jeroen Koelemeij[1]

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Previously we have carried out Doppler-free laser vibrational spectroscopy of trapped, laser-cooled HD^+ molecular ions with a relative uncertainty of a few parts per trillion (ppt) [1]. Combined with accurate theoretical predictions and other recent precision measurements, our HD^+ data can potentially improve the literature value of the electron's relative atomic mass from 29 ppt to 18 ppt [2]. Surprisingly, the Doppler-free spectroscopy also revealed a large (8.5 kHz, or 9σ) deviation between the observed and theoretically predicted hyperfine structure. In order to resolve the 9σ discrepancy, we are currently performing electron spin resonance spectroscopy of various hyperfine transitions in HD^+ to measure the hyperfine structure with a target uncertainty of 0.1 kHz. The results should allow establishing whether the discrepancy stems from proton-electron, deuteron-electron, or spin-rotation interactions, and/or from an extraordinarily large yet overlooked systematic effect in the previous experiments.

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Thursday invited / 144

Orbitrap Mass Spectrometry

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In a special class of ion traps, referred as isochronous traps, stored ions make oscillations with their frequencies independent of orbital parameters such as injection energy, coordinates, and angles. A well-known example of an isochronous ion trap is an ion cyclotron resonance (ICR) cell that utilizes the property of a constant frequency of Larmor precession in a uniform magnetic field. The frequencies are nevertheless dependent on the ions' mass-to-charge ratios (m/z) in a certain way, which allows precise ion mass measurements. However, generation of a strong magnetic field needs large and expensive superconductive magnets. As a response to this challenge, pure electrostatic isochronous ion traps may be adopted for mass spectrometry.

It is well known that an electrostatic field provides no stationary stable equilibrium for charged particles. Nevertheless, ions may be effectively confined in their motion. The idea of orbital charged particle confinement dates back to 1923 when Kingdon proposed trapping positive ions revolving around a negatively charged filament [1]. This approach was further developed by Knight [2] who proposed the quadro-logarithmic electrostatic field $\varphi = const(z^2 - \frac{r^2}{2} + r_m^2 ln\frac{r}{r_m})$,generated by a negatively charged wire and a pair of positively charged conical caps. The Knight's trap offered enhanced trapping time, and it was first reported that the harmonicity of oscillations along the axis z might be employed to separate trapped ions by their mass-to-charge ratios.

The further advance required a drastic precision improvement of the quadro-logarithmic potential. The use of specially machined electrodes, whose shapes followed the equipotential lines, keeps the trapped ions coherent on millions of oscillations. A combination of induced-current detection and the Fourier transform signal processing generates precise mass spectra for any analyte ion mixture. The Orbitrap(tm) analyzer is now a heart of the whole family of mass-spectrometric equipment with the resolving power up to one million.

Despite of the micron-range manufacturing, an orbital ion trap is to be thoroughly balanced to compensate for the residual field perturbations. Our

presentation describes challenges of the aberration corrections and fanciful space-charge effects.

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Thursday Hot Topics

Thursday Hot Topics / 41

Trap-assisted bound states and emergence of chaos in ultracold atom-ion collisions

Autor Meirav Pinkas[1]

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A hybrid system combining ultracold atoms and ions can be a valuable tool for studying the properties of atom-ion collisions in the ultracold regime. In free space, atoms and ions cannot be bound in an elastic binary collision due to energy and momentum conservation. However, since the ion is strongly trapped, the trap can couple the center-of-mass and relative motion and lead to a short-lived bound state. By measuring the spin-exchange of Sr^+ and Rb as a function of energy and magnetic field, we estimate the binding energy and lifetime of the bound state and compare it to a classical molecular dynamics simulation. Numerical simulations also suggest that the bound states would appear both in harmonic and time-dependent ion traps.
In addition, our simulations show that in collisions of Rb and harmonically trapped Sr^+ ion, the lifetime of the bound state has a significant sensitivity to the initial conditions. A closer look shows self-similarity on different scales and fractal behavior. This chaotic behavior persists when the ion is in a Paul trap under experimental parameters. Further, Chaos leads to a molecular lifetime distribution that has a power-law tail of long-lived events, which might be observed experimentally. The emergence of chaos in the classical description of atom-trapped-ion collisions suggests that chaos might also be visible in the quantum limit, for example, as a Wigner-Dyson distribution of resonances.

Thursday Hot Topics / 75

Quantum metrology for symmetry violation searches in molecular ion systems

Autor Chi Zhang[1]

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Precision measurements of time-reversal (T) symmetry violation in molecular systems provide stringent tests of new physics beyond the Standard Model. Recent measurements of the electron's electric dipole moment (eEDM) in both neutral molecules [1] and molecular ions [2] have excluded a broad parameter space of T-violating leptonic physics at energy scales up to ~10 TeV. To improve the measurements further, it would be advantageous to trap molecules in stationary traps and apply quantum-enhanced metrology methods. However, for molecular ion systems, contemporary eEDM searches are conducted in non-stationary rotating traps, since an external electric field is needed to polarize the molecules.

I will present our recent proposal [3] of measuring the eEDM using entangled molecular ions without an external electric field. We propose to polarize the molecules by preparing a superposition of opposite parity states, where the orientation of the molecule is oscillating. We show that in a system of two (or more) oscillating molecules, the eEDM can be observed as a coupling between two entangled spin states within a decoherence-free subspace. Furthermore, the eEDM sensitivity scales linearly with the entangled molecule number, thereby offering Heisenberg-limited sensitivity beyond the standard quantum limit, while the susceptibility to electromagnetic fields remains mitigated.

Importantly, our method does not require an electric field to polarize the molecular ions. As a result, it is compatible with quasi-stationary ion traps, such as the linear Paul trap, in which a powerful toolbox of precision spectroscopy and quantum metrology has been developed.

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Thursday Hot Topics / 109

Reactive tunneling and vibrational quenching collisions in a cryogenic multipole trap

Autor Robert Wild[1]

Co-Autoren: Markus Nötzold [1]; Malcolm Simpson [1]; Christine Lochmann [1]; Tanja Rahim [1]; Sruthi Purushu Melath [1]; Thuy Dung Tran [2]; Barry Mant [3]; Jan Franz [4]; Francesco Gianturco [1]; Roland Wester [1]

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Quantum tunneling reactions play an important role in chemistry when classical pathways are energetically forbidden [1]. Binary collisions of atomic with molecular hydrogen belong to the most fundamental molecular systems and are simple enough to be theoretically investigated using first-principle calculations. The rate of the tunneling reaction $H_2 + D^- \rightarrow H^- + HD$ has been calculated [2] but has until now lacked verification. Here we present high-sensitivity measurements of the reaction rate carried out in a cryogenic 22-pole ion trap. A deviation of the reaction rate from linear scaling, which is observed at high H_2 densities, can be traced back to previously unobserved heating dynamics in radiofrequency ion traps. Our measured value agrees with quantum tunneling calculations, serving as a benchmark for molecular theory and advancing the understanding of fundamental collision processes [3].

Further work has focused on inelastic collisions of C_2^-, which has been proposed as a candidate for laser cooling due to the existence of multiple stable electronic states. We have demonstrated vibrational state control of C_2^- via a novel scheme that uses optical pumping in conjunction with inelastic collisions of H_2 and measured the vibrational quenching rate [4]. Additionally, we precisely determined the proposed laser-cooling transitions of C_2^-. We resolve the spin-rotation splittings and use it to perform accurate thermometry in our newly-developed wire trap [5].

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Thursday Hot Topics / 95

First laser spectroscopy of a rovibrational transition in the molecular hydrogen ion H_2^+

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The molecular hydrogen ion H_2^+ is the simplest molecule. This iconic system has been the subject of innumerous theoretical studies, from the earliest days of quantum mechanics [1] until today, culminating in highly precise predictions of its level energies [2]. Comparisons of these predictions and measured vibrational transition frequencies would offer excellent opportunities in fundamental physics that go beyond the results achieved with the related molecule [3, 4]: a direct determination of the proton-electron mass ratio and the proton's charge radius. Furthermore, achieving precision spectroscopy of H_2^+ is an essential prerequisite for a future CPT test that compares H_2^+ with its antimatter counterpart [5, 6].
In this work we report the first vibrational laser spectroscopy of H_2^+, between low-lying rovibrational levels of para-H_2^+ [7]. We employed sympathetically laser-cooled and trapped H_2^+ ensembles. A first-overtone electric-quadrupole (E2) transition [8, 9] was driven by a unique 10^{-13}-level optical frequency metrology system reliably delivering Watt-level laser power at 2.4μm. Both hyperfine components were measured. We determined the spin-averaged rovibrational transition frequency with 3×10^{-8} fractional uncertainty, finding agreement with the predicted value. By using HD^+ as a test molecule, we also show that E2 spectroscopy is possible with 1×10^{-12} uncertainty. This demonstrates that E2 transitions are suitable for precision spectroscopy of molecular ions and that determining m_p/m_e spectroscopically with accuracy competitive with mass spectroscopy is a realistic prospect.
This work has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 786306, "PREMOL").
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Thursday Hot Topics / 57

Development of a technique for sympathetically cooling positrons using laser-cooled Beryllium ions compatible with antihydrogen formation

Autor Maria Goncalves[None]

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ALPHA works with trapped antihydrogen atoms to investigate some of its properties and compare it to its matter counterpart, hydrogen. These atoms are created by slowly mixing antiprotons and positrons in one of our Penning-Malmberg traps. There is strong evidence that positron temperature before mixing greatly influences the number of trappable antihydrogen atoms. [1]

Using laser ablation, a plasma of singly-charged Beryllium ions is formed. It is then trapped in the ALPHA-2 apparatus and laser-cooled. Mixing the laser-cooled $^{9}Be^{+}$ ions with a dense positron plasma sympathetically cools the positrons, having achieved a positron temperature of 6.8 ± 0.5K, as opposed to positrons cooling by cyclotron radiation which reach around 20K. [2] However, the work quoted in [2] does not explore the cooling of positrons under the inhomogenous magnetic field caused by the octupole, a necessary component for the trapping of antihydrogen. This inhomogeneity typically causes the expansion and heating of plasmas. [3]

We present the development of a technique that allows for sympathetic cooling of positrons using laser-cooled $^{9}Be^{+}$ compatible with antihydrogen formation. This includes installation of new hardware allowing for axial laser cooling of plasmas, novel implementation of Strong Drive Regime Evaporative Cooling (SDREVC) in ions allowing for enhanced reproducibility of number and size of $^{9}Be^{+}$ plasmas and e+/$^{9}Be^{+}$ mixing studies and optimization.

This will allow ALPHA to study the effect of lower positron temperatures in the formation of trappable antihydrogen, hopefully yielding a higher trapping rate.

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[2] C. J. Baker *et al.*, Nat Commun **12**, 6139 (2021)

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Thursday Evening Lecture

Evening Lecture / 5

The end of the classical world: The 2022 Nobel Prize in Physics

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Friday invited

Friday invited / 68

Quantum Logic Control of a Single Molecular Ion

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An amazing level of quantum control is routinely reached in modern experiments with atoms, but similar control over molecules has been an elusive goal. A method based on quantum logic spectroscopy [1] can address this challenge for a wide class of molecular ions [2,3]. We have now realized many basic aspects of this proposal.

In our demonstrations, we trap a calcium ion together with a calcium hydride ion (CaH+) that is a convenient stand-in for more general molecular ions. We laser-cool the two-ion crystal to its motional ground state and then drive Raman, mm-wave or vibrational overtone transitions in the molecular ion. Laser-based transitions in the molecule can deposit a single quantum of excitation
in the motion of the ion pair when a motional "sideband" is driven. We can efficiently detect this single quantum of excitation with the calcium ion, which projects the molecule into the final state of the sideband transition, a known, pure quantum state.

The molecule can be coherently manipulated after preparation by a first projection, and after attempting a transition, the resulting molecular state can be read out by another quantum logic state detection. We demonstrate this by driving Rabi oscillations between different rotational states [4, 5, 6] and by entangling the molecular ion with the logic ion [7]. Transitions in the molecule are either driven by a single, far off-resonant continuous-wave laser, by a far-off resonant frequency comb or a frequency comb resonant with a certain vibrational overtone transition. This makes the approach suitable for quantum control and precision measurement of a large class of molecular ions. Controlled transitions to excited vibrational levels open avenues to precise characterization of the electronic ground state potential surface and to coherent dissociation along a specific bond.

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Friday invited / 54

A general method for single molecule infrared spectroscopy

Autoren David Patterson[1]; Aaron Calvin[2]; Scott Eierman[2]; Merrell Brzezck[2]; Lincoln Satterthwaite[2]

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We demonstrate a novel single molecule action-spectroscopy technique that is compatible with high precision measurement. The method is generally applicable to a wide range of polyatomic molecular ions, and promises spectral resolution comparable to state of the art quantum logic methods, with significantly less stringent experimental overhead. The method is an extension of the recent ensemble "Leak Out Spectroscopy" work in the Schlemmer group, extended to single molecular ions and laser-cooled samples. Our recent single-molecule tagging spectroscopy results will also be presented. Progress towards extending this technique to include chiral recognition of single molecules will be discussed. Adaptations of this technique will prove useful in a wide range of precision spectroscopy arenas, including the search for parity violating effects in chiral molecules.

Friday invited / 97

Molecular ion studies at the Cryogenic Storage Ring (CSR)

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Modern space and Earth-based telescopes like JWST and ALMA are able to provide us with increasingly detailed insight into the molecular composition of interstellar space. These instruments are able to identify the different species and determine their abundance. However, information on the processes of formation and destruction of molecules in this environment is still needed. Laboratory experiments with the ability to mimic interstellar medium (ISM) conditions are essential to investigate these mechanisms. Furthermore, the spectroscopic identification can be limited by the absence of reliable spectroscopy data for many molecular ions at low internal excitation.
The Cryogenic Storage Ring (CSR) at the Max-Planck-Institut für Kernphysik, Heidelberg [1] enables such spectroscopy and reaction studies. Inside its experimental chambers, which can be cooled down to 4K, residual gas densities down to 1000 cm^{-3} and a very strong suppression of the black-body radiation field can be achieved. At such conditions ions can be stored up to hours. Provided they have a permanent dipole moment, molecular ions will cool down to their lowest ro-vibrational states. The stored ion beam can then be overlapped with well-defined beams of possible reactants found in the ISM, namely photons, electrons and neutral atoms. As a result, the properties and reaction rates for the creation and destruction of these molecules can be studied in detail under ISM conditions.
This talk will summarize the various experimental features of the CSR like a low-energy electron cooler [2], a newly build reaction microscope, and a facility for ion-neutral collision measurements [3]. Technical developments like the recently implemented isochronous mass spectrometry mode [4] will be outlined. Furthermore, a number of molecular ion projects are currently ongoing or have recently been concluded. These include laser experiments with Al_4^- and CCH_2^- as well as studies involving the electron cooler with CH^+ [5,6], OH^+ and TiO^+ [7]. Selected highlights of these projects will be presented.

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[7] N. Jain et al., J. Chem. Phys., 158, 144305 (2023)

Friday invited / 166

Precision Penning trap experiments for fundamental physics

Autor Sven Sturm[1]

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Experiments with single ions confined in a Penning trap enable access to a broad range of observables that are of fundamental importance for our understanding of fundamental physics. In the magnetic field of the trap, the cyclotron frequency of an ion can be determined with unique precision and gives direct access to the charge-to-mass ratio. Furthermore, we have access to the gyromagnetic gfactor via a measurement of the (Larmor) spin precession frequency. This way, we have determined a number of fundamental parameters, such as the electron, proton, neutron and deuteron atomic masses with leading precision. This way, in our new generation experiment ALPHATRAP we have recently measured the g-factor of highly charged, hydrogenlike ¹¹⁸Sn. A comparison to a precise prediction by quantum electrodynamics (QED) allows probing the validity of QED in extreme electric fields, in the order of 10¹⁵ V/cm. The ability to unambiguously and non-destructively determine the internal state of a single ion gives us access to systems that were previously difficult to handle, such as the molecular hydrogen ions. Currently, we are performing spectroscopy on HD⁺ and soon H₂⁺ . The development of the necessary toolbox will be a seminal step towards a possible future spectroscopy of the antimatter equivalent, anti-H₂⁻ , which could enable a unique test of charge-parity-time (CPT) reversal symmetry. Furthermore, by crystallizing two ions simultaneously in one trap we have achieved a leap of two orders of magnitude on the precision frontier. With this new technique, we have recently determined the isotopic effect of the g-factor in hydrogenlike neon ions, at 13 digits precision with respect to g and are consequently sensitive to previously invisible contributions, such as the QED recoil, and can set limits on hypothetical new physics such as dark matter mediated couplings.
Currently, we are designing a novel experiment, LSym (Lepton Symmetry Experiment), that will allow storing a single positron and cooling it to the ground state of motion. Then, using a similar coherent difference technique will enable comparing the spin precession of electron and positron with 14 digits precision, which would yield a very stringent test of CPT in the lepton

sector.

Friday invited / 174

Probing P,T-violation with molecules in high charge states

Autoren Carsten Zülch[None]; Konstantin Gaul[None]; Robert Berger[1]

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Polar molecular ions in extreme charge states have the potential to merge advantages that highly-charged *atomic ions* and neutral *polar molecules* offer, when performing precision tests of fundamental physics. As we have discussed in Ref. 1, one can expect to benefit from enhanced relativistic effects and compressed level structures on the one hand and large internal fields with considerable enhancements of P,T-odd effects on the other hand in specifically tailored molecular ions.

In this talk, general trends in the stability of highly-charged molecules are outlined, level structures and their dependence on the charge state in iso-electronic sequences of diatomic molecules [2] are presented and sensitivities to various sources that induce a violation of parity (P) and time-reversal (T) symmetry are discussed.

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Friday invited / 213

Probing TeV-scale physics in an ion trap

Autor Tanya Roussy[1]

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We recently placed a new limit on parity-violating physics with a unique tabletop experiment which combines trapped molecular ions, rotating bias fields, orientation-resolved detection, and over a dozen lasers. In this talk I will give an overview of our measurement and methods for probing new physics at energy scales exceeding the reach of the LHC.

Monday Poster Session

Monday Poster / 224

Towards Fast Coherent Transport and Reconfiguration Operations on Microfabricated X-Junction Ion Traps with Integrated Current Carrying Wires

Autoren Sahra Kulmiya[None]; Petros Zantis[1]; Martin Siegele-Brown[1]; Samuel Hile[1]; Sebastian Weidt[2]; Winfreid Hensinger[1]

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Trapped ions have proved to be a promising way of realising a large-scale quantum computer. They allow for simple reproducibility and modular architectures which is crucial for a scalable, universal quantum computer. Our blueprint for a trapped-ion based quantum computer outlines operating with global microwave (MW) fields to dress the ground-state hyperfine manifold of 171Yb+ ions [1]. By applying individually controlled static (DC) voltages, ions can be effectively shuttled around and between modules, while modulated radio-frequency (RF) signals are utilised to facilitate quantum logic gate operations [2].

Borrowing knowledge from the semiconductor industry, we have produced microfabricated ion traps with embedded current-carrying wires (CCWs) which provide a controllable, high magnetic field gradient [3]. This allows spin-motion coupling which allows more accurate energy measurements to be performed on the motional sidebands and track the heating rate of the ion which is very important for measurements of gate infidelities and characterizing transport and reconfiguration protocols.

Our approach towards scalability and quantum algorithm implementation involves physically transporting ions across the surface trap. The shuttling operations need to be as fast as possible to speed up quantum computation, as well as adiabatic, to preserve the ions' motional state. By simulating trapping potentials and ion dynamics, we investigate various candidate transport and reconfiguration protocols on our X-junction trap. We examine and compare different tools for simulating the potentials, including BEM and FEM based methods, and test them against experimental observations, with the aim of achieving precise and accurate control potentials..

Monday Poster / 44

Source of negative ions for matter-antimatter studies

Autoren Lukasz Klosowski[1]; Mariusz Piwinski[2]; Marek Teske[1]

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Forming antiprotonic atoms and their investigation is one of the goals of the AEgIS project at CERN. An intermediate stage of such an experiment is preparing a set of negative, atomic ions, co-trapped with antiprotons in a Penning trap. Such anions must be delivered in a single pulse, which requires an efficient, well-controlled, pulsed source of the ions.
Since attachment of electrons to neutral atoms is forbidden by momentum and energy conservation, the production of anions must be achieved via electron-molecule dissociative attachment process, enhanced by some shape or Feschbach resonance effects.
In the presentation, we will show our newly designed source of negative ions using electron collisions with iodine molecules inside a linear Paul trap. Details of the source construction and operation will be discussed as well as the electron dissociative attachment phenomenon. Additionally, the results of the numerical simulations of the source performance will be presented.

Monday Poster / 152

A Trapped Ion Computing Platform with Software-Tailored Architecture for Quantum co-design

Autoren Marissa Donofrio[None]; Jacob Whitlow[1]; Tianyi Chen[1]; Samuel Phiri[1]; Leon Riesebos[2]; Junki Kim[3]; Brad Bondurant[1]; Jungsang Kim[1]; Kenneth Brown[1]

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A full-stack approach to quantum computing requires collaborative design and integration between layers, from the algorithms and programming language to the qubit-specific hardware. The Software-Tailored Architecture for Quantum co-design (STAQ) team focuses on demonstrating quantum advantage on an ion trap platform developed at Duke University. This poster will discuss recent progress and results regarding the project's goals of realizing a 32-qubit quantum computer with all-to-all connectivity and a fully integrated vertical stack, using the system in-house to address computer engineering and software challenges, and making the system accessible to collaborators through an easily programmable software interface.

Monday Poster / 116

Programmable XY-type interactions on trapped ions: parallel Ising-type interactions mediated via the same motional-modes

Autoren Nikhil Kotibhaskar[1]; Chung-You Shih[1]; Sainath Motlakunta[1]; Anohony Vogliano[1]; Hahn Lewis[1]; Yu-Ting Chen[1]; Rajibul Islam[1]

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The Mølmer–Sørensen (MS) scheme has facilitated Quantum Simulation of Ising-type ($J^x_{ij}\sigma^i_x\sigma^j_x$) interacting-spin-systems, leveraging collective motional-modes of ions. However, only a few experiments explored more complex models, like XY models that can simulate novel many-body systems such as superfluids and spin-liquids. Existing protocols used modified MS schemes that are only valid stroboscopically, restricted in their programmability, and break down for long times. We propose and experimentally demonstrate that the application of two spin dependent forces, applied at frequencies that are close but non-degenerate, can mediate parallel Ising interactions required for XY-type models ($J^x_{ij}\sigma^i_x\sigma^j_x + J^y_{ij}\sigma^i_y\sigma^j_y$) with independent control over the J^x_{ij} and J^y_{ij} terms [1]. This scheme inherits the programmability and scalability of MS Ising interactions and can be readily implemented in existing setups.

[1] N. Kotibhaskar, C.-Y. Shih, S. Motlakunta, A. Vogliano, L. Hahn, Y.-T Chen, and R. Islam Programmable XY-type couplings through parallel spin-dependent forces on the same
trapped ion motional modes, (2023), arXiv:2307.04922

We acknowledge financial support from UWaterloo, NSERC Discovery grant, NFRF, CFREF, and the Ontario Govt.

Monday Poster / 117

Development of X-junctions and robust transport protocols for an ion-trap based quantum computer

Autoren Axel Hoffmann[1]; Brigitte Kaune[2]; Teresa Meiners[2]; Rodrigo Munoz[3]; Florian Ungerechts[2]; Christian Ospelkaus[4]

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One of the challenges of ion-trap based quantum computers is their scalability. With an increasing number of qubits and parallelization of computation junctions and ion transport become necessary. A surface quantum charged coupled device architecture is a promising approach to tackle this challenge. Storage registers are needed for temporarily storing ions inbetween excecuting individual gate operations.
We report on the development of an X-junction and on our current X-junction design. Additionally, we show results of the development of ion transport protocols for implementing robust and reproducible ion transport for our surface-electrode trap chip.

Monday Poster / 26

Deltaflow.Control: A distributed control system architecture for large-scale ion trap and cold atom quantum computing

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A dedicated control system is pivotal for sophisticated experiments in atomic, molecular and optical (AMO) physics. In particular, large-scale ion-trap and neutral atom quantum computing will require some of the most complex control systems ever built. These will need to support measurement-heavy workflows, fast feedback with tight latency constraints, and be scalable in hardware and software. Here, we present the architecture of Deltaflow.Control, an FPGA-based control system designed with large-scale error-corrected quantum computing in mind. Its distributed architecture pushes processing out to all system components, reducing latency of feedback and feedforward loops. Modular atomic control units (ACUs) enable multi-tone generation of phase-coherent pulses with sub-nanosecond accuracy. We show bottleneck-free execution of instructions on all channels with scalability to multiple FPGAs and larger heterogeneous systems. Finally, we present an intuitive and deterministic programming model and a user interface for quick control, tune up and experiment orchestration crucial to saving time in the lab and enabling further advances. Our goal is to provide a powerful control system that can handle the growing list of requirements for error-corrected, large-scale quantum computing.

Monday Poster / 153

Prospects of dark-matter searches via correlation spectroscopy of I_2^+ and Ca^+

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The nature of dark matter (DM) and its interaction with the Standard Model (SM) is one of the biggest open questions in physics nowadays. Ultralight DM coupling to the SM induces oscillations in fundamental constants that are detectable by comparing clocks with different sensitivities to DM. Vibrational transitions of molecular clocks are more sensitive than electronic transitions of optical atomic clocks when considering DM that couples to the SM's strong sector. Here, we propose the iodine molecular ion, I_2^+, as a sensitive detector for DM that couples to the QCD part of the SM. The iodine's dense spectrum allows us to tune its transition frequency to that of an optical atomic clock (Ca^+) and perform correlation spectroscopy between the two clock species. With this technique, we project a few-orders-of-magnitude improvement over the most sensitive clock comparisons performed to date.

Monday Poster / 14

How to wire a 1000-qubit trapped ion quantum computer

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One of the most formidable challenges of scaling up quantum computers is that of control signal delivery. Today's small-scale quantum computers typically connect each qubit to one or more separate external signal sources. This approach is not scalable due to the I/O limitations of the qubit chip, necessitating the integration of control electronics. However, it is no small feat to shrink control electronics into a small package that is compatible with qubit chip fabrication and operation constraints without sacrificing performance. This so-called "wiring challenge" is likely to impact the development of more powerful quantum computers even in the near term.

In this work, we address the wiring challenge of trapped-ion quantum computers. We describe a control architecture called WISE (Wiring using Integrated Switching Electronics), which significantly reduces the I/O requirements of ion trap quantum computing chips without compromising performance. Our method relies on judiciously integrating simple switching electronics into the ion trap chip – in a way that is compatible with its fabrication and operation constraints – while complex electronics remain external. To demonstrate its power, we describe how the WISE architecture can be used to operate a fully connected 1000-qubit trapped ion quantum computer using ~ 200 signal sources at a speed of $\sim 40 - 2600$ quantum gate layers per second.

Monday Poster / 119

Controlling trapped-ion motional modes for precision measurement*

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Motional modes of trapped ions have been shown to be a useful tool for quantum sensing, making use of time reversal protocols. This application requires the ability to prepare well-defined motional states with high fidelity. Many of these states can be generated from motional ground states without the use of laser fields. We report our results in generating one-mode and two-mode squeezed states using parametric excitation. These operations help to create motional state interferometers and can be used to achieve sensitivities approaching the Cramér-Rao bound. We present an implementation of an SU(1,1) interferometer using one and two motional modes of a 40Ca+ ion in a Paul trap, and compare the performance to the more traditional SU(2) Mach-Zender interferometer. To characterize the input and output motional states of the interferometers, the ions' motion is coupled to internal 'spin' states, which are distinguishable through spin-dependent fluorescence. The calculation of the Fisher information from experimental data can be used to quantify the phase sensitivity that we can achieve in our setup.
*We acknowledge support from NSF through the Q-SEnSE Quantum Leap Challenge Institute, Award #2016244.

Monday Poster / 83

A setup for co-trapping an atom and a molecule

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Traditionally, molecules were considered too complicated for coherent quantum control. Recent molecular-ion-trapping developments enabled trapping, ground-state cooling, high-fidelity state detection, precision spectroscopy, coherent manipulation, and atom-molecule entanglement. Nowadays, molecule diversity and the variety of molecular degrees of freedom open new research directions that are impossible with atoms. Investigating the quantum properties of molecular ions and manipulating their unique characteristics may lead to new quantum-information applications. Here, we present our work toward building a quantum-logic apparatus for co-trapping N_2^+ and Ca^+ to create qubits encoded in the molecule's nuclear-spin-isomer degree of freedom.

Monday Poster / 8

Native qudit entanglement in a trapped ion quantum processor

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An attractive proposition to extend the capabilities of quantum information systems is to fully utilise their high-dimensional Hilbert space. The internal electronic structure of trapped atomic ions offers a natural way to encode information not just in a two-level system, but in a high-dimensional qudit instead. One of the challenges of this approach is to achieve high fidelity interactions between them. We experimentally demonstrate a native qudit entangling gate between two $^{40}\mathrm{Ca}^{+}$ ions in up to 5 dimensions by exploiting a novel generalization of the light-shift gate. We achieve gate fidelities of $99.6(1)\%, 98.7(2)\%, 97.0(3)\%, 93.7(3)\%$ for dimensions of $d = 2, 3, 4, 5$ respectively. This gate is able to generate genuine qudit entanglement in a single application which makes it scale favorably with dimension in terms of calibration overheads compared to previous approaches.

Monday Poster / 56

Demonstration of a universal two-qubit register for a QCCD-based quantum processor

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Single-qubit rotations and a two-qubit entangling gate form a universal set of quantum logic gates[1]. In this work, we realize such a two-qubit computational register that is compatible with the quantum charge-coupled device (QCCD) architecture. Quantum logic operations are implemented using embedded microwave conductors. Single-qubit gates in two-ion crystals are performed by addressing each ion individually with a micromotion addressing technique[2]. The single-qubit gate infidelity of individually addressed ion is characterized using a randomized benchmark protocol of $3.8(4) \times 10^{-3}$. The entanglement operation is implemented using a Mølmer-Sørensen type interaction, where we measure an infidelity approaching 10^{-3} using partial state tomography[3]. Finally, we characterize the quantum processor in a computational context using the cycle benchmarking protocol[4]. We present a partial analysis of the discrepancy of the above results.

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Monday Poster / 165

Coupling trapped ions to a mechanical oscillator

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Ultracold trapped ions in linear radiofrequency traps are well-established and highly controllable quantum systems with a variety of applications in fields such as precision spectroscopy, cold chemistry, quantum information and optical clocks. Nanomechanical oscillators are highly sensitive objects for the development and implementation of technologies in miniaturized devices. Their nanoscopic size makes them excellent candidates for the study of physics on the border of classical and quantum physics and highly susceptible to very weak forces. This property makes nanomechanical oscillators excellent measuring probes with high sensitivities that enabled the development of devices such as atomic force microscopes.
This project is aimed at the implementation of an ion-nanowire hybrid system to explore new methods of trapped ion state preparation, manipulation and readout via the mutual interaction of its constituents. A charged Ag2Ga nanowire is positioned in close proximity to the trapped ions such that they experience a strong mutual Coulomb interaction. Here, we demonstrate the excitation of the axial ion motion in the classical regime and experimentally determine the coupling between pairs of trapped ions and the mechanical oscillator.

Monday Poster / 6

Integrated photonics in ion traps for scalable quantum information processing

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The integration of photonic components in surface electrode traps is a promising approach for scalable quantum computing with trapped ions [1]. Integrated photonics enables efficient delivery of laser light to the trap chip. Beams can be tightly focused on the ions, reducing power requirements, and a given configuration of laser fields can be reliably reproduced in different zones of the trap. It allows for full in-fiber manipulation of light all the way from the source to the ions, which compactifies the experimental setup and makes it less prone to instabilities and drifts. Integrated optics can be used to shape the spatial mode of the laser field, creating engineered laser-ion interactions for enhanced quantum operations.

Here we report on the last years of research endeavors on integrated photonics at ETH Zurich. We focused on surface traps equipped with integrated waveguides and diffractive optput couplers made of silicon nitride, carrying light at 729 nm to address the quadrupole $4S_{1/2} \rightarrow 3D_{5/2}$ transition in $^{40}\mathrm{Ca}^{+}$ ions. Additional waveguides are used to deliver repumper light at 866 nm and 845 nm.
We demonstrated the first two-qubit entangling gate controlled by integrated light in a trap with one 729 integrated beam addressing multiple ions [2].
In our current design, two integrated laser beams coherently interfere at the ion location forming a passively phase-stable standing wave. We characterized the spatial structure of the light field and the optical performance of the device using one trapped ion as a probe [3]. Such a structured light field can be used to enhance the fidelity of entangling gates [4] and generate state-dependent optical potentials in a novel way.
Finally, we explore the use of such devices for scalable multizone quantum operations. We implemented real-time control of the trapping potential, which allowed for loading multiple ion crystals, splitting and shuttling them along the trap axis, and for simultaneous control of ions in different trap zones.

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Monday Poster / 169

Observation of spin-tensor induced topological phase transitions of triply degenerate points with a trapped ion

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Topological transitions between different types of triply degenerate points are experimentally observed with a trapped ion. Recently, the remarkable discovery of topological semimetals with triply degenerate points in Fermionic systems provides an avenue for exploring new types of quasiparticles beyond quantum field theory. Such triply degenerate points are naturally characterized by high-rank spin-1 tensors, but not previously observed experimentally. Here, by simulating the electron momentum in solids with a spin-1 trapped ion system, we observe the topological transitions between triply degenerate points with different monopole charges and elucidate the crucial roles played by the spin tensors. We develop a measurement technique that reveals the role of geometric rotations connected to the famous Berry flux. Our work demonstrates the versatile controllability of multi-level ion for high-spin physics and paves the way to explore novel topological phenomena therein.

Monday Poster / 50

Cold hybrid electrical-optical ion trap

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Abstract Advances in research such as quantum information and quantum chemistry require subtle methods for trapping particles (including ions, neutral atoms, molecules, etc.). Here we propose a hybrid ion trapping method by combining a Paul trap with optical tweezers. The trap combines the advances of the deep-potential feature for the Paul trap and the micromotion-free feature for the optical dipole trap. By modulating the optical-dipole trap synchronously with the radio frequency voltage to counteract the alternating electrical potential in the trap center, the micromotion temperature of a cold trapped ion can reach the order of nK while the trap depth is beyond 300K. These features will support a stable cold collision process between an ion and an atom in the S-wave scattering regime and trap the reacted ion molecule in the cold hybrid system, which will facilitate cold ion molecule and cold quantum chemistry research. Additionally, this will enable the investigation of new reaction pathways and reaction products in the cold regime, which are important for the study of cold chemistry. It will also provide a unique platform for probing the interactions between the ions and the surrounding neutral particles.

Monday Poster / 163

Sympathetic cooling, cold chemistry, and spectroscopy of CaH+ molecular ions

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Molecular ions exhibit a rich internal structure attributed to their vibrational and rotational degrees of freedom. However, at room temperature, the rotational energy level populations are widely distributed due to black body thermalization, and the numerous decay pathways make direct laser cooling of molecules challenging at best, and impossible at worst. Therefore, we aim to demonstrate a novel technique for the sympathetic cooling of molecular ions by first sympathetically Doppler cooling molecular ions (CaH^+) with co-trapped atomic ions (Ca^+) and then sympathetically cooling the internal degrees of freedom to the rovibrational ground state with neutral atoms (K) in a 3D MOT [1, 2]. This experimental setup also facilitates the study of chemical reactions between these species at a fundamental level. We have observed photon-mediated charge exchange between Ca^+ and K and characterized the reaction channels [3], and we have obtained preliminary evidence of charge exchange between CaH^+ and K. To demonstrate sympathetic internal cooling, it is essential to probe the internal state of the molecular ions. For this purpose and precision spectroscopy applications, we have employed Resonance Enhanced Multi-Photon Dissociation (REMPD) method to conduct vibronic and rovibronic spectroscopy of CaH^+ in previous studies [4], and our ongoing efforts involve extending this technique to rotational spectroscopy of CaH^+. The control over chemical reactions along with rotational spectroscopy will allow us to demonstrate sympathetic ground state cooling of CaH^+.

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Monday Poster / 171

An ion trap with integrated metal-clad fiber microcavity

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We designed an ion trap with integrated fiber cavities for enhanced coupling between single ion and photons. We fabricated the fiber electrodes covered with metal except for the light-through region by a series of processes including etching, CO_2 laser ablation, lithography, magnetron sputtering, stripping, and electroplating. Its metallic part can be used both to provide the voltage required to trap the ion and to conduct the charge generated during UV photoionization. We simulated the trapping potential and built a validation device with similar structure. We have now successfully captured $^{138}\mathrm{Ba}^{+}$ ion using the validation device.

Monday Poster / 43

Optical tweezers for trapped ion quantum simulations

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Trapped ion crystals offer a natural platform for quantum simulation. They have shown great advantages with regards to other systems, such as long coherence times (~ hours), fidelities and fully connected interactions. However, limited control over the interactions between the ions constrains the range of accessible Hamiltonians.
In our expermeint, we plan to combine trapped ions with microtraps in the form of optical tweezers.
These additional potentials will allow us to manipulate the phonon mode spectrum and thereby control the spin-spin interactions of the ions in a Paul trap. We will use a high power 1030nm laser far detuned from any transition in Yb+. The tweezers will be produced by a spatial light modulator and focused on the ions to a waist of a few µm with a high NA objective. With the right tweezer pattern [1], we can then use the system to study various Hamiltonians of interest, for example, Hamiltonians on a kagome lattice [2] in 2D ion crystals.
Furthermore, in one dimensional ion chains optical tweezers can be combined with oscillating electric fields in order to realize two-qubit geometrical phase gates [3]. This has the advantage that it does not require ground state cooling of the ions and works even in very long ion chains, as the electric field couples to all ions equally.
The current experimental status as well as steps taken to align the tweezers on the ions will be presented.

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Monday Poster / 106

High-precision isotope shift measurements in highly charged ions

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Highly charged ions (HCI) have long been proposed for the application in optical clocks due to their extreme atomic properties. This allows for tests of fundamental physics and promises a systematic uncertainty that can compete with the state-of-the-art [1]. However, their application as frequency references has long been impeded by the megakelvin temperatures at which HCI are typically produced and stored. In our work, this is overcome by extracting HCI from a plasma and transferring them to a cryogenic linear Paul trap. There, a single HCI is sympathetically cooled using singly-charged Be+ ions, enabling quantum logic spectroscopy with Hz-level resolution [2] which paved the way to optical clock operation. The evaluation of the experimental setup yielded a systematic uncertainty of 2×10^{-17}, comparable to many other optical clocks. As a demonstration, the frequency of the electric dipole-forbidden transition in Ar^{13+} was compared to the well-known octupole transition in $^{171}\mathrm{Yb}^{+}$. The derived absolute frequency and isotope shift ($^{36}\mathrm{Ar}^{13+}$ vs $^{40}\mathrm{Ar}^{13+}$) are compared to the best previous result, providing an improvement by eight and nine orders of magnitude, respectively. For the first time, this has enabled to resolve the QED nuclear recoil in a many-electron system [3]. The applied techniques are universal and can easily be transferred to other HCI species. Recently, we demonstrated this by performing measurements of Ca^{14+}, where we investigated the isotope shift of the transition frequency and the excited-state g-factor. These results will be used to test fundamental physics and search for new physics [4, 5].

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Monday Poster / 20

Realizing coherently convertible dual-type qubits with the same ion species

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Trapped ions constitute one of the most promising systems for implementing quantum computing and networking. For large-scale ion-trap-based quantum computers and networks, it is critical to have two types of qubit: one for computation and storage, and another for auxiliary operations such as qubit detection, sympathetic cooling and entanglement generation through photon links. Previously, it was assumed that such frequency-separated dual-type ion qubits have to be implemented in hybrid systems of two ion species. For hybrid systems, apart from the experimental complexity of trapping and cooling two ion species and the lower mixed-species gate fidelity than the same-species case, it is also challenging to control the fraction and the positioning of each qubit type in many-ion crystals. Moreover, the mass mismatch between the ion species makes it very difficult to realize sympathetic cooling and high-fidelity gates with the transverse phonon modes.
In this work we experimentally realize dual-type qubits that are coherently convertible to each other with the same species of 171Yb+ ions. We encode the qubits into two pairs of clock states of the 171Yb+ ions, and achieve microsecond-level conversion rates between the two types with one-way fidelities of 99.5% using bichromatic narrowband laser beams at wavelengths of 411 nm and 3,432 nm. We further demonstrate that operations on one qubit type, including sympathetic laser cooling, single-qubit gates and qubit detection, have crosstalk errors less than 0.06% on the other type, which is below the best-known error threshold of ~1% for fault-tolerant quantum computing using the surface code.
Coherent conversion between different qubit types allows us to dynamically tune the fraction and positioning of each qubit type on demand in many-ion crystals during computation, which is highly desirable for efficient sympathetic cooling and quantum error correction in large-scale systems. In addition, the capability of fast and high-fidelity qubit type conversion indicates that entangling gates between different qubit types can be performed in exactly the same way as for gates with the same qubit types,

hence eliminating the challenging requirement for mixed-species high-fidelity gates. The demonstrated below-threshold crosstalk errors between the dual types of qubits, together with their fast high-fidelity coherent conversion, opens up prospects of wide applications in large-scale quantum computing and quantum networking.

Monday Poster / 27

Digital-analog simulation of quantum field theories with trapped ions

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Quantum simulation area promising approach for understanding the dynamics governed by quantum field theories in the strong coupling regime. However, a lot of qubits and gates are required due to the presence of bosons in these models. Taking advantage of the available bosonic degrees of freedom in the quantum system can potentially help with this problem. In this talk, we propose a scheme to perform quantum simulation of field theories where the fermions are mapped to qubits and the bosons are mapped to the vibrational modes of the ion chain. We apply this hybrid method to the Yukawa model and the Schwinger model and numerically compare the qubit counts and gate counts with the digital method. We also show preliminary data for the Yukawa model with two staggered sites performed on a trapped ion quantum simulator.

Monday Poster / 11

Maximizing temporal quantum correlation by approaching an exceptional point

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Quantum correlations, both spatial and temporal, are the central pillars of quantum mechanics. Over the last two decades, a big breakthrough in quantum physics is its complex extension to the non-Hermitian realm, and dizzying varieties of novel phenomena and applications beyond the Hermitian frame work have been uncovered. However, unique features of non-Hermitian quantum correlations, especially in the time domain, still remain to be explored. Here, for the first time, we experimentally achieve this goal by using a parity-time (PT)-symmetric trapped-ion system. The upper limit of temporal quantum correlations, known as the algebraic bound, which has so far not been achieved in the standard measurement scenario, is reached here by approaching the exceptional point (EP), thus showing the unexpected ability of EPs in tuning temporal quantum correlation effects. Our study, unveiling the fundamental interplay of non-Hermiticity, nonlinearity, and temporal quantum correlations, provides the first step towards exploring and utilizing various non-Hermitian temporal quantum effects by operating a wide range of EP devices, which are important for both fundamental studies and applications ofquantum EP systems.

Monday Poster / 89

Spontaneous emission error characterization and improvements for quantum simulation and sensing in a Penning trap

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We theoretically examine the effects of spontaneous emission at high magnetic fields for multi-qubit entangling operations on large ion crystals, and compare different gate types, laser beam detunings and polarizations, magnetic field strengths, and ion species. We show that the current configuration in the Penning trap at NIST is approximately ideal for light-shift (LS) gates in $^9Be^+$ ions. The Molmer-Sorensen (MS) gate is of interest as well since it may have superior phase stability and allow simulations and sensing using three-dimensional crystals with up to $\sim 10^5$ ions. We demonstrate that the MS gate for $^9Be^+$ has similar predicted error rates due to spontaneous emission with our current magnetic field strength, and that both gates can be improved by detuning farther from resonance and using higher laser intensities. Furthermore, for both gates, we compare error rates at lower magnetic field strengths with those for our current field of 4.5 T and examine the dependence of the error rates on the fine structure splitting. These calculations show that for fixed detunings, the errors in the LS gate with our current laser beam geometry worsen significantly for both lower magnetic fields and heavier ions. Conversely, the error rate for the MS gate for a given detuning shows approximately no dependence on the magnetic field, and increases more slowly with fine structure splitting than that for the LS gate.

Another approach to improving errors due to spontaneous emission is the use of parametric amplification (PA) to amplify the strength of the spin-dependent optical dipole force that couples the spin and motional states of the ion [1]. We implement PA with a RF drive nearly resonant with twice the axial center-of-mass mode frequency of a two-dimensional crystal in a Penning ion trap and characterize the strength of the PA through the generation of motional squeezing. We theoretically discuss the potential improvements in employing PA for sensing small displacements and

generating spin-squeezed states in the presence of realistic motional dephasing.

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*Supported by DOE, Office of Science, NQIS Research Center QSA, AFOSR grant FA9550-20-1-0019, and DARPA ONISQ.

Monday Poster / 177

An integrated approach to beat note locking of lasers

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Trapped-ion based quantum computers rely on frequency and phase locked lasers to perform experiments. Conventionally, this requires the use of bulky RF electronics that hinder scalability as well as inject noise into the system. In this poster, I will discuss the performance of a frequency/phase locking PCB that we have designed to allow for a more efficient and compact beat-note laser-locking solution. I will present data on the locking performance of a 370 nm laser which we use for state initialization, detection and cooling of Ytterbium 171. The PCB is cost effective and easily reproduced, which is advantageous for scalability. The design also allows for multiple channels per board, meaning multiple lasers can be locked using this integrated approach. This is particularly useful for systems with multiple ion species where many lasers need to be locked.

Monday Poster / 17

Progress towards long-range entanglement of $^{40}Ca^{+}$ ions in a surface-electrode trap with an integrated fiber Fabry-Perot cavity.

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Remote entanglement using a quantum network has applications in distributed quantum computation, long-range quantum sensing, and secure quantum communication. Trapped ions present unique advantages as the quantum repeater node of a quantum network due to the ability to precisely prepare, control, and manipulate each qubit, perform high fidelity operations between qubits, and maintain superposition states for extended times. Here I present our new effort to create a long-range quantum network of $^{40}Ca^{+}$ ions. Ions will be trapped in a surface electrode trap, with an integrated fiber-based optical cavity that collects the flying qubits into an optical fiber. The system operates at cryogenic temperatures to reduce ion motional heating from the dielectrics in the cavity and for fast iteration of ion trap and cavity designs. The cavity uses micromirrors that are fabricated on a 2'' wafer, singulated, and attached to the tip of a single-mode optical fiber. These micromirrors have demonstrated scattering loss less than 1 ppm at telecom wavelengths, supporting a finesse above 1 million over a range of radius of curvatures from 100 μm to 1 m.

Monday Poster / 19

Ultrafast Spin-Motion Control In Trapped-Ion System By Resonant Laser Pulses

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Ultrafast spin-phonon entanglement based on SDKs provides an approach to realize fast entangling gates with intrinsic robustness and scalability for trapped ion quantum computing. Such SDKs so far have been implemented on a nanosecond timescale by off-resonant Raman transitions where each laser pulse is split into a sequence of perturbation pulses with carefully designed temporal patterns.

Here we demonstrate the spin-phonon entanglement with SDKs on a hyperfine qubit using resonant laser pulses. In our scheme, complicated pulse shaping and splitting are avoided. Compared with the earlier proposal for resonant pulses on optical qubits, our scheme uses hyperfine qubits and thus has advantages on qubit coherence time. Then by applying two pulses from opposite directions, each with half the pulse area, we obtain the desired SDK in 80 ps, which is faster than the previous results by more than an order of magnitude. It removes the need to engineer the pattern of a sequence of perturbation pulses and is less vulnerable to noise, simplifying the approach to large-scale trapped-ion quantum computing based on fast quantum gates with SDKs. Finally, we present a two-qubit gate scheme based on the new SDKs' scheme which can achieve a high fidelity in theory thus can be a building block for the large-scale trapped ion quantum computing in future.

Monday Poster / 172

High resolution vibrational spectroscopy of molecular hydrogen ions and its application in fundamental physics

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As the simplest molecules, molecular hydrogen ions (MHIs) are calculable, with ab initio theory reaching uncertainties for the prediction of transition frequencies only a factor of 10 larger than those achieved for the hydrogen atom [1]. They thus offer great potential for the extraction of fundamental constants as well as for tests of QED and search for BSM physics.
We present an overview of recent our experiments on HD^+, most notably the single-photon spectroscopy of a fourth overtone vibrational transition [2]. From this, a value for the combination of fundamental constants $\mu/m_e = m_p m_d/(m_p + m_d)m_e$ can be extracted, which is in reasonable agreement with mass spectrometry experiments in Penning traps [3-6]. Moreover, because the latter measurements rely on the classical motion of baryon-containing particles, while in MHI spectroscopy the quantum mechanical motion of the two nuclei is intrinsic, the agreement can be regarded as a test of the quantum behaviour of charged baryons. We show that a related test can be obtained by comparing the ratios of vibrational frequencies with the corresponding ab initio prediction.
Similar to previous measurements on MHIs [7-9], a test of physics beyond the Standard Model of particle physics is undertaken by probing for a hypothetical fifth force between the two nuclei. No evidence is found.
We also present ongoing work: high-accuracy spectroscopy of electric-quadrupole transitions in MHIs [10] as well as the current status of a single-ion trap apparatus [11]. These developments pave the way towards higher accuracy and less-studied MHI species.
This work has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 786306, "PREMOL").
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Monday Poster / 49

Dark resonances as local probes

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In this work we show theoretically and experimentally how to use dark resonances emerging from coherent population trapping (CPT) in a multi-level lambda-type system as local electric field and temperature probes. To do this, we include a third laser to the system to avoid optical pumping effects. We find that the nature of the dark resonances can be either preserved or affected by the additional laser depending on its optical power and polarization. We performed experiments with a single trapped calcium ion in a ring-shaped Paul trap using its S1/2-P1/2-D3/2 level system. We show that the obtained spectra can be used as a vectorial beam polarimeter allowing us to measure the electric field at the position of the ion in any spatial direction. Finally, we present an application of CPT spectra to perform single ion thermometry to be used to study heat transport in ion chains and out-of-equilibrium systems like 2D ion crystals.

Monday Poster / 92

A silicon-based microfabricated surface-electrode ion trap with integrated capacitors for modular quantum computing

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We have built a microfabricated surface trap with integrated chip capacitors for quantum computation and simulation experiments. The trap features two loading zones at both sides for isotope selection and a central quantum operation region. We fabricate a series of parallel plate capacitors on chip with each capacitance around 800 pF to shunt the pick-up RF noise to the ground. The trap is attached on top of the capacitor chip and then standardized on a 100-pin CPGA architecture.

We have successfully trapped Yb+ ions on this surface trap. After optimization of trapping parameters, the lifetime of a single ion is up to several hours. The heating rate is around 200 quanta per second while the trap center is about 108 microns above the chip surface and the secular frequency is about 2.1 MHz.

Monday Poster / 10

Scalable DC control of ion traps

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In order to scale trapped ion quantum computing from small lab experiments to industrial quantum computers, large ion traps will need to contain integrated electronics. Integrated electronics minimizes the number of voltages passed into the cryostat as the number of feed-throughs is limited. This reduces the complexity as well as the heat load on the cryostat. Here, I want to present the Infineon strategies on integrated electronics to enable the control of a large number of DC electrodes with few input lines. The fundamental idea is to employ multiplexing to use the same DAC voltages on different parts of the trap. As stray fields require different offsets for different parts of the trap, I will show different ways how to passively add offsets within the multiplexing structure. In addition, results of our first cryogenic DC multiplexing chip and an outlook on the next generation will be presented.

Monday Poster / 114

High-fidelity transport of trapped-ion qubits in a multilayer array

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Chip-based trapping technology has emerged as a promising approach for multi-dimensional quantum simulations and entanglement using individually controllable trapped ion qubits arrays. Previous studies have demonstrated successful local control, inter-site coupling, and floquet-engineered couplings in such architectures[1-3]. Here we present the extension of the existing toolbox by introducing tools from the QCCD architecture[4], enabling deterministic transport of a single trapped ion qubit across a three-dimensional landscape. We also showcase the preservation of quantum coherence in the electronic degrees of freedom throughout the transport process[5]. Additionally, we address technical limitations, such as anomalous heating through Argon-ion bombardment and challenges related to the dephasing of motional and electronic degrees of freedom[6].

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Monday Poster / 45

Sideband Thermometry on Ion Crystals

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Being a prospective platform for quantum computing and metrology, Coulomb crystals of ultracold trapped ions currently reach sizes of hundreds of individual particles. Such systems require high level of control over their motional temperature in order to account for the second-order Doppler shift in atomic clocks and implement high-fidelity entangling gates in quantum computers. However, the existing ion crystal thermometry tools struggle to provide an accurate temperature estimation for large ground-state cooled Coulomb crystals, either focusing only on the symmetric center-of-mass vibrational mode of motion or neglecting the involved spin-spin correlations between the trapped ions. To resolve the arising thermometry bottleneck, we consider the many-body dynamics of an ion crystal, arising when motional sideband transitions are driven in a near ground-state regime. In the single ion case, thermometry methods based on the motional sidebands are widely used and are thus of interest in the ion crystal case. The conducted study of the single-ion case from the Fisher Information prospective gives us some valuable insights for extending the approach further towards ion crystals. In our work we account for entanglement created between the ions in a Coulomb crystal to derive a new reliable temperature estimator, insensitive to the number of ions, and field-test in experiments with 4- and 19-ion crystals done by our colleagues from PTB Braunschweig and University of Innsbruck.

Monday Poster / 59

Surface-electrode ion traps for QCCD architectures

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We summarize Quantinuum's progress in research and development of surface-electrode ion traps for QCCD quantum computing architectures. This includes additional information about the racetrack trap in the commercially available H2 computer as well as design and experimental progress towards 2D ion trap grids planned for next-generation commercial computers.

Monday Poster / 53

Advanced technologies for ion trap systems

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Trapped ion systems will require large complex ion trap geometries with fast shuttling between zones and integrated photonics to address the large number of ions in the system. Here, we highlight our recent efforts on all three fronts. We discuss our optimization efforts to shuttle ions at high speeds with low excitation in our recently fabricated multi-junction ion trap. Furthermore, we detail recent results utilizing photonic optical modulators to manipulate the quantum state of an ion.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

Monday Poster / 178

Trapped ion quantum engineering platforms

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Ion trap experiments have evolved drastically over the last decades. The surge in quantum computing, communication and metrology projects led to an increased demand for more advanced ion traps and control systems.

We established a rapid prototyping facility at University of Mainz to meet the fabrication requirements of highly advanced three-dimensional ion traps, like 3D glass structuring, precise alignment of structures, metal coating and eventually the integration of micro-optical components.

We will present a two-layer segmented linear ion trap, fabricated in this facility with selective laser-induced etching of 4-inch fused silica wafers followed by PVD gold-coating, wafer dicing and sub ▯m-precision die bonding. Upgrades will be made in the coming months to allow for electroplating, laser polishing and UHV compatible assembly of micro-optical components.

We are also building up 9 experiments for testing and operation of such ion traps, which feature titanium vacuum vessels intended for XHV pressures, high-performance mu-metal shielding, high NA optics for individual addressing of ions in linear crystals. All experiments will be equipped with custom rackmount multi-AWG electronics for ion register reconfiguration and Raman gate operations, laser systems and compact optical components.

We will present our newly developed experimental control system in more detail. The system is scalable to a large number of qubits, performs all real-time and near-real-time operations and features self-calibration and auto-alignment procedures. With this system we aim for a simple and reliable 24/7 user access for our quantum computing experiments.

Monday Poster / 101

VUV laser spectroscopy of trapped Th ions

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There is strong interest in laser spectroscopy of trapped Th ions because of the low-energy (8.3 eV) isomer that exists in 229Th [1]. With an energy that is accessible for laser excitation, this nuclear resonance is attractive as the reference of an optical clock that combines high accuracy with a strong sensitivity for effects of new physics that may be sought in frequency comparisons with atomic clocks [2].

As a step towards laser excitation of 229Th we have developed a tunable vacuum-ultraviolet (VUV) laser source based on four-wave frequency mixing in xenon. Using seed radiation from two contin-uous-wave lasers, the system allows for precise control of the VUV frequency. Tunable in the wave-length range 148-155 nm, the source produces pulses of 6-10 ns duration with up to 40 μJ energy and is coupled via a vacuum beamline to a linear RF ion trap. In a first implementation of VUV laser spectroscopy of trapped Th+ ions we excite three previously unknown resonance lines to electronic levels in the vicinity of the 229Th isomer energy. An analysis of the lineshape is used to estimate the linewidth of the VUV radiation to be about 6 GHz, dominated by phase noise that is enhanced in harmonic generation and in the four-wave mixing process.

Trapping of 229Th ions in charge states 1+, 2+ and 3+ has been demonstrated with the ions produced in laser ablation from solid 229Th targets [3,4], but the efficiency of the method decreases substantially with increasing charge. In preparation of experiments with laser-cooled 229Th3+ ions we have developed an apparatus for the trapping of Th3+ recoil ions from the alpha decay of 233U. The ion source in a helium buffer gas cell is linked to a linear RF trap in ultrahigh vacuum, where the ions are cooled sympathetically by laser cooled 88Sr+ ions. 88Sr+ has been selected as the coolant ion because of its convenient laser cooling transitions and because its charge to mass ratio is similar to that of 229Th3+, so that Coulomb crystals are produced where the two species are closely coupled.

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Monday Poster / 122

Native 3-body interactions for quantum annealing with trapped ions

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Using quantum annealing algorithms to solve optimization problems represents a promising path to achieving a practical quantum advantage in the NISQ era. Problems of interest are typically formulated as a quadratic unconstrained binary optimization (QUBO) and then encoded into a spin glass Hamiltonian with two-body spin interactions.

Recently the inclusion of higher-order terms into the formulation of optimization problems (PUBO's) has garnered much interest due to the promise of increased ressource effiency and potential speedups.

We study examples of relevant optimization problems that are naturally formulated as PUBO's and calculate the associated ressource savings when solving them using quantum annealing protocols with three-body spin interactions. Specifically we show that one can save up to an order of magnitude in for the encoding required logical qubits as compared to a QUBO formulation for certain problems like 3SAT.

We propose and discuss different approaches to engineer these higher-order interactions within a trapped ion quantum computer. These schemes are feasible to implement on current hardware and allow quantum annealing algorithms to solve larger optimization problems with relevance to industry.

Monday Poster / 150

Integrated Current-Carrying Wires on a Planar Ion Trap to Produce a Magnetic Field Gradient.

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The combination of the entangling Mølmer–Sørensen gate and single qubit rotations
is a well-established method to realise a universal set of quantum gates using trapped ions. Implementing this gate scheme using global microwave fields can further the scaling prospects of this quantum computing platform, by reducing the complexity of the laser system required. [1]

Our approach uses current carrying wires embedded in the planar ion trap chip to generate the magnetic field gradient needed to achieve spin-motion coupling driven by long-wavelength radiation. [2] [3] This novel chip design has the potential to improve gate speed and fidelity, and simultaneously alleviate some of the limitations in scaling trapped-ion quantum computers. [4] Here we describe the design of the integrated gradient generating structure and discuss the use of frequency scans on the Zeeman states to characterise the geometry of the magnetic field. Additionally, time scans on the motional sidebands of these states are used as verification of these measurements. We also outline the dominant noise contributions in this system, and measure the coherence of a dressed hyperfine state qubit in such a gradient.

The techniques used for characterisation of the current carrying wires overlap with the ones we implement for coherent control in our systems. Dynamical decoupling techniques, automated calibrations and empirically motivated simulations based on Bayesian optimisation can further improve our results and lead to higher fidelity quantum gate operations.

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Monday Poster / 22

Heating Effects for Wigner Ion Crystals and Experimental Realization of Multi-ion Sympathetic Cooling

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Trapped ions are one of the leading platforms in quantum information science. And a trapped-ion Wigner crystal is a suitable platform for a controlled study of the solid-liquid phase transition with its unprecedented resolution of individual atomic ions. We study the melting dynamics of a linear chain of 174Yb+ ions, which is initially cooled to the Doppler temperature and is then periodically heated and detected by a focused laser beam. We achieve controlled melting of the ion chain and observe nontrivial effects over the chain under localized heating. These explorations have deepened our understanding of the solid-liquid phase transition in ion crystals and insights into energy transport problems in low-dimensional systems. Additionally, it provides guidelines for extending the lifetime of large ion crystals and conducting large-scale sympathetic cooling. Here, we also report experimental realization of multi-ion sympathetic cooling on a long ion chain using a narrow cooling beam focused on two adjacent ions, and optimize the choice of the cooling ions according to the collective oscillation modes of the chain. By cooling a small fraction of ions, cooling effects close to the global Doppler cooling limit can be achieved. This experiment therefore demonstrates an important enabling step for quantum information processing with large ion crystals.

Monday Poster / 203

Towards Entanglement-Enhanced Metrology with Trapped Ions

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Single-ion optical atomic clocks have reached fractional uncertainties of 1 part in 10^{-18} [1], but reaching this level of uncertainty requires long averaging times. Using n uncorrelated ions, the same uncertainty could be obtained n times quicker. If these n ions could be placed in an entangled state however, speed-ups beyond this standard quantum limit are in principle possible with the potential to produce results up to n^2 times faster [2].

We trap strings of ^{88}Sr^{+} ions in a microfabricated monolithic linear rf trap with a three-dimensional electrode geometry [3]. This design provides 7 operation zones, plus a separate loading zone, each of which can hold ions in a deep potential well with low heating rates. The trap design and vacuum package provide a high degree of optical access available on both sides of the chip wafer.

To perform entanglement-enhanced metrology the ionic clock/qubit transition is driven by a laser that possesses two important properties: an extremely narrow linewidth around a stable optical carrier, and a low level of noise power at frequencies a motional trap frequency detuned from the optical carrier. We have realised a high power ultrastable 674 nm laser for the optical qubit in ^{88}Sr^{+} based on a commercial Titanium-Sapphire laser system. We have measured Allan deviation at the 1 Hz level out to beyond 100 s averaging time and frequency noise below a white noise level of a few $\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ out to 10 MHz from the carrier.

We have recently performed our first entangling operations on pairs of trapped ions, using a Molmer-Sorensen interaction on the optical transition to generate a maximally entangled state with initial fidelities of 96%. The steps required to produce larger entangled states and use them for entanglement-enhanced metrology will also be covered.

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Monday Poster / 147

Toward dipole-phonon quantum logic with optimized sideband cooling

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The dipole-phonon interaction (DPI) between the permanent dipole of a diatomic molecular ion and the secular oscillation of the ion chain manifests as a Jaynes-Cummings-type interaction. When combined with quantum logic, this interaction can enable state preparation and measurement of quantum information encoded within a molecular ion [1,2]. Here, we report on our progress toward observing the DPI with a CaO+-Ca+ ion chain. To that end, we have demonstrated sympathetic sideband cooling to the ground state of motion and preservation of the motional state after adiabatic ramping of the secular frequency, which are both necessary prerequisites for the search for the DPI [3]. Moreover, we outline an experimental plan for observing the interaction despite low qubit subspace population at room temperature. Additionally, to improve the efficiency of the search for the DPI, we implement a comparative analysis of continuous and optimized pulsed sideband cooling and demonstrate the results experimentally with a Ca ion [4].

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Monday Poster / 72

Quantum error supresion by weak measurement reversal with current trapped-ion devices

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In the long-term, fault-tolerant (FT) quantum information processing is the central promise to demonstrate a quantum advantage for practical problems. However, in the current era of Noisy-Intermediate Scalable Quantum (NISQ) devices, low distance quantum error-correcting (QEC) codes and quantum error mitigation methods pave the way to today's quantum reliable hardware. Unlike QEC techniques, error mitigation methods allow mitigation of the effect of noise with no or fewer hardware overhead.

Trapped-ions lie among the most promising platforms for several applications of quantum technology. High-fidelity state preparation, measurement, and single-qubit rotations with trapped-ions have already been demontrated whilst entangling errors remain the major bottleneck. Increasing the fidelity of two-qubit gates is crucial for exploiting maximally-entangled states which are an important resource across several modalities of quantum information processing. However, due to imperfections during or after the entangling gates used to prepare such states, the amount of entanglementdecreases and their quality as a resource gets degraded.

Amplitude damping is an important mechanism of decoherence that is common to many atom-based platforms that can affect entangled states. For example, the T1-time sets the ultimate decoherence limit for trapped-ions optical qubits when all other sources of technical noise are suppressed. It can become relevant for trapped-ion hyperfine or Zeeman qubits when using two-photon Raman transitions via auxiliary excited states, or in Rydberg-atom quantum processors where several spontaneous emission decay channels limit the two-qubit gate fidelities. We introduce in [1] a low-overhead protocol to reverse this degradation by partially filtering out amplitude damping noise. In [1], we present two trapped-ion schemes for the implementation of a non-unitary probabilistic filter against amplitude damping noise, which can protect any maximally-entangled pair from spontaneous photon scattering during or after the two-qubit trapped-ion entangling gates. This filter can be understood as a protocol for single-copy quasi-distillation, as it uses only local operations to realise a reversal operation that can be understood in terms of weak measurements.

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Monday Poster / 13

Experimental violation of the Leggett-Garg inequality in a three-level trapped-ion system

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Quantum mechanics has overturned people's traditional cognition, and the superposition contradicts the fact that objects in our daily life are always in a certain state. Leggett and Garg proposed the Leggett-Garg inequality (LGI) to verify the existence of macroscopic superposition states. Classical systems are limited by LGI, while quantum systems may violate LGI. LGI provides an observable criterion for whether a system possesses quantum properties, which provides us a way to experimentally find the boundary between the quantum world and the classical world or to study whether there is a boundary between quantum and classical.

We conduct experimental research on LGI based on a trapped-ion system. The specific research content is as follows: Different measurement methods can produce different results for LGI in quantum systems. We conducted experimental tests on LGI in a three-level system under the Lüders and the von Neumann state update rules. We employed the model of a large spin precessing in a magnetic field and obtained the largest experimental observation value under this model to date. The maximum observed value of the Leggett-Garg correlator under the von Neumann state update rule is K3 = 1.739 ± 0.014, which demonstrates a violation of the Lüders bound by 17 standard deviations and is by far the most significant violation under the specific model. Based on the three-dimensional LGI experimental research, we propose an experimental scheme for the four to six-dimensional LGI based on a trapped-ion system. The method used in our experiment could also be used in other multilevel experiments in the trapped-ion system.

Monday Poster / 164

Laser cooling and shuttling of trapped ions in strongly inhomogeneous magnetic fields

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We demonstrate that $^{40}Ca^{+}$ ions confined in a segmented linear Paul trap can be laser cooled in the presence of a strongly inhomogeneous magnetic field created by two permanent ring magnets. The magnetic field gradients of 800 to 1600 G/mm give rise to a highly position-dependent Zeeman shift on the energy levels of the trapped ions. Efficient laser cooling is demonstrated using two 397 nm cooling lasers with appropriate wavelengths and polarisations and one 866 nm repump laser. The obtained Coulomb crystals are found to exhibit similar secular temperatures compared to those trapped in absence of the magnetic field. The position dependency of the Zeeman effect can be used to create a map of the magnetic field and to estimate the mismatch between the eletric and magnetic field centres.

This work forms the basis for developing a hybrid trapping system that consists of an RF ion trap and a magnetic trap to study cold collisions with longer interaction times between particles compared to beam experiments. Such a system is currently under development in our lab. It will incorporate a cryogenic shield which increases the trap lifetime of the moelcules. Efficient shuttling of the ions to the magnetic trap centre by synchronously varying the electric potentials of the ion trap has alraedy been implemented, even in the presence of the strongly inhomogeneous magnetic fields. These findings could open new possibilities for quantum science experiments that employ trapped ions in inhomogeneous magnetic fields.

Monday Poster / 48

Electron cooling of trapped highly charged ions

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HITRAP is a facility for deceleration of large bunches of highly charged ions (HCI) produced online by the GSI accelerator. It consists of an ion transport beamline from the accelerator, an IH-structure and an RFQ for deceleration down to several keV/q, as well as a Penning-Malmberg trap for ion cooling down to sub-eV energies.

The linear deceleration stages reduce the ion energy from 4 MeV/u to 500 keV/u and to 6 keV/u respectively, resulting in a slow, but hot ion bunch mixed with non-decelerated components. Customized detectors separate then the energy components, while an electrostatic beamline guides the slow ions to the ion trap, which is the final cooling stage.

The trap is operated in a nested configuration, where the electrons are stored simultaneously with the HCI. The ions transfer their energy by Coulomb interaction to the electrons, which in turn continuously dissipate energy by synchrotron radiation from their circular motion in the trap's magnetic field. The alignment of the ion trap was achieved by projecting the magnetron motion of the stored electron plasma onto a position sensitive detector, which proved to be a crucial step.

Recently, the cooling process was demonstrated by storing about 10^5 highly charged argon ions together with about 10^9 electrons. The HCI were produced by an EBIT and transported at 4 keV/q, while the electrons came from a photocathode source with an initial energy of 200 eV. Depending on parameters such as ion energy, electron density and trap configuration, the ions transferred most of their energy to the electrons within a few seconds of storage.

In addition to describing the first electron cooling of HCI, this talk will also present the status of the HITRAP facility and some of the associated experiments.

Monday Poster / 15

Realization of cross-talk avoided trapped-ion quantum network node with one ion species

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Quantum network is of great importance to the development of quantum communication, quantum computation and quantum metrology. With photon interference, separate quantum nodes can be entangled to build large-scale quantum information processor. However, its scaling up is facing with the challenge of quantum memory decoherence from photonic interfaces. To avoid disturbance, in trapped ion system, people are using two species of ions to work as the memory and communication qubits respectively, which at the same time boubled the complexity of the platform. Here, we use dual type qubits in one ion species to avoid crosstalk, which almost bring no increment to the system complexity. The $^2S_{1/2}$ clock state of $^{171}\mathrm{Yb}^+$ is used to generate ion-photon entanglement with the spontaneously emitted 369.5 nm single photon, working as the communication qubit, while the $^2F_{1/2}$ state works as the memory qubit. Within the time of a successful ion-photon entanglement generation, the information stored in memory qubit shows a fidelity of 83.56%, that about 14% of the infidelity comes from conversion and SPAM lose, and 3% from decoherence. In this way, we generate ion-photon entanglement successfully and prove that the entanglement attempts dose not effect the information stored in memory qubit.

Monday Poster / 12

Precisely Measuring the Potential of a Surface Electrode Ion Trap

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Accurately measuring the potential generated by electrode of a Paul trap is of great importance for either precision metrology or quantum computing using ions in a Paul trap. For a rectangular shaped electrode, we find a simple and highly accurate parametric expression of the spatial field distribution. Using this expression, a method based on multi-objective optimization is presented to accurately characterize the spatial field strength due to the electrodes and also the stray electric field. This method allows to utilize many different types of data for optimization, such as the equilibrium position of ions in a linear string, trap frequencies and the equilibrium position of a single ion, which therefore greatly improves the model accuracy. The errors of predicted secular frequencies and average ion position are less than 0.5 micron and 1.2 micron respectively, better than the ones predicted by existing method.

Monday Poster / 55

Tests of fundamental physics via precision spectroscopy with Yb⁺ ions

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Trapped-ion quantum sensors have become highly sensitive tools for the search of physics beyond the Standard Model. We present our recent measurements on the test of local Lorentz -invariance (LLI) with a single Yb+ ion [1] and isotope shift measurements for the search of the fifth force mediated by a potential dark matter boson [2,3].
In the attempt to unify all fundamental forces at the Planck scale, it is suggested that spontaneous breaking of Lorentz symmetry would occur. In the framework of Standard Model Extension [4], such violation would lead to energy shifts of atomic states with non-spherical electron orbitals. With high-precision spectroscopy of such states in a Michelson-Morley type experiment, we search for violation of LLI. With this method, we constrained the symmetry breaking coefficients at the 10⁻²¹ level. These results represent the most stringent test of this type of violation in the combined electron-photon sector.
Astronomical observations [6,7] hint towards the existence of dark matter. However, the origin and composition of it are still unknown. Theoretical proposals suggest a dark matter boson coupling the neutrons and electrons in an atom, mediating the fifth force. This coupling would lead to an additional Yukawa-like potential, giving a small shift in energy levels. To distinguish this shift from the less accurately calculated nuclear effects (eg. field shift and mass shift), isotope shift measurements and King plot analysis have been used. We follow the same analysis as in Ref. [8], and with the improved accuracy by factors of 10 to 100 for the measured transitions, we hope to shine light into the observed nonlinearity of the King plot in ytterbium.

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Monday Poster / 76

Demonstration of a low-crosstalk double-side addressing system in a high optical access and XHV bladetrap

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We've designed and built a high-pass optical bladetrap, with the ability to achieve NA=0.66 in two laser directions and NA=0.37 in the other two. This bladetrap has excellent performance: the vacuum can reach 7*10^-17 Torr at room temperature, and the Q value of helical can reach 280. Combined with optical and electronic scheme, we demonstrate a low-crosstalk optical double-side addressing scheme and implement MS gate based on symmetrically-configured acousto-optic deflectors (AODs). We employ two 0.4 NA objective lenses in both arms of the Raman laser and obtain a beam waist of 0.93±0.03 μm, resulting in a Rabi rate crosstalk as low as 6.32 × 10−4 when the neighboring ion separation is about 5.5 μm, and realize a 2-qubit MS Gate with fidelity>90%. These technologies combined together provides a promising platform for quantum computing, simulation and networking.

Monday Poster / 18

Quantum Networking with a Metastable Sr+ Qubit

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The Strontium ion is an ideal candidate for medium-distance quantum networking due to an atomic transition at 1.1 μm, a wavelength compatible with existing fiber optic infrastructure. This transition eliminates the need for lossy photon conversion processes, allowing for direct remote entanglement on the kilometer scale. We report on current progress towards ion-photon entanglement in a Strontium ion trap system, including design and construction of the high numerical aperture imaging system for photon collection. The final qubit states in our photon-generation scheme lie in the $D_{3/2}$ level and differ by $\Delta m_j = 2$. We show results from readout of the metastable state with an extended probabilistic detection method without shelving. Additionally, we discuss work towards building a microwave vortex antenna for directly driving this dipole-forbidden transition.

Monday Poster / 99

A Neural Network Assisted 171Yb+ Quantum Magnetometer

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A versatile magnetometer must deliver a readable response when exposed to targets fields in a wide range of parameters. In this work, we experimentally demonstrate that the combination of a $^{171}\mathrm{Yb}^{+}$ atomic sensor with adequately trained neural networks enables the characterization of target fields in challenging scenarios. In particular we estimate parameters of radio frequency (RF) driving fields with large shot noise, including the limiting case of continuous data acquisition with single-shot measurements, and in regimes where the magnetometer delivers a response that significantly departs from the standard harmonic behavior.

Monday Poster / 47

Electron-ion collision with optically controlled quantum state

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Electron-atom collision experiments are widely used to study the structure of bombarded objects. The experimentally determined scattering amplitudes associated with measured cross-sections complement the data obtained in spectroscopic studies. The measurement usually involves the bombardment of the target with a monochromatic electron beam and the detection of non-scattered or scattered electrons. While such experiments are relatively simple to perform with neutral targets, ions are an experimental challenge. Therefore, there is a lack of experimental data (particularly cross-sections) concerning the collisions of electrons with singly charged ions.

In our recent paper [1] we showed that it is possible to measure integral cross-sections for electron-ion collision using a set of ions in a Paul trap. Moreover, the proposed experimental method enabled the determination of the cross-sections for various quantum states of the collision target. The technique's disadvantage was the measurements' relatively low energetic resolution.
One of the goals of such studies is to observe narrow structures in the cross-section functions, related to the formation of autoionizing states during the collisions. It is required to increase the energy resolution of the measurements to make it possible, which is related to the precise control and guidance of the electron beam.
We present a new apparatus using a monochromatic electron beam introduced along the axis of the ion trap, which will overcome described problems. Details of the experimental setup and methodology will be discussed.

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Monday Poster / 176

Quantum simulation of conical intersections using trapped ions

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Conical intersections (CIs) are an ever-present phenomenon in chemistry and molecular physics that mark the crossing of energy levels on an adiabatic potential energy surface (PES). Around such intersections, the Born-Oppenheimer approximation breaks down and the coupling between electronic and nuclear coordinates becomes important. Thus, efficiently simulating the dynamics in the vicinity of CIs is an important and open problem. Another notable phenomenon is the geometric phase that accumulates when a wave function loops around CIs on a PES. Such a phase depends only the direction of travel and the solid angle encompassed by the loop with respect to the CI and can have non-trivial effects on the dynamics of the molecule. Meanwhile, trapped atomic ions have proven to be a robust platform for performing quantum simulations of molecules. Manipulation of the internal states and the motion is made possible by light-matter interactions using lasers. These can be mapped to the internal states and nuclear parameters of simple molecules. With this tool, we present a scheme for engineering a CI in trapped ions systems and demonstrating controllable geometric phase interference by using an appropriate initial state and adiabatic evolution. The final state will have a characteristic shape marked by interference between parts of the wave function that took different paths around the CI. Finally, we will present experimental measurements of the spatial distribution and compare the results to numerical calculations.

See paper preprint:

Whitlow, Jacob, et al. "Simulating conical intersections with trapped ions." arXiv preprint arXiv:2211.07319 (2022).

Monday Poster / 46

Quantum gates with trapped ions and optical tweezers.

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Optical tweezers offer new opportunities to control and manipulate trapped ions with applications in quantum information processing. Two techniques to implement quantum logic gates have been theoretically developed in our group. These are based on qubit state-dependent potentials delivered by optical tweezers in combination with either electric fields [1], or strong polarization gradients in the tweezer waist [2,3]. An oscillating electric field can excite the modes of ions pinned by optical tweezers [1]. The proposed gates may offer key benefits such as infrastructural simplification – the light only has to be supplied from one direction - and enhanced long-ranged interactions between the ion qubits.

We present the ongoing development to realize these gates experimentally in the lab. Specifically, the design and construction of a microfabricated ion trap and UHV setup, and the optimization of a programmable UV tweezer array. Photon scattering in the tweezer can be suppressed using Laguerre-Gaussian tweezer modes generated by our spatial light modulator.

Monday Poster / 74

Advances in Penning trap ion imaging and control for quantum sensing and simulation

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Coherently manipulated crystals of ions in a Penning trap are a promising candidate for near-term quantum simulation of complex many-body phenomena and the search for dark matter using quantum sensing [1]. At the University of Sydney, we developed a Penning trap to perform such experiments with crystals containing hundreds of beryllium ions [2]. This contribution introduces this system and two major technical innovations supporting these applications. First, we have implemented a high bandwidth time-correlated single-photon-counting camera, which allows efficient single-ion detection in 2D ion crystals, a prerequisite to investigate spatial correlations in many-body quantum systems. Ion positions are localised using an artificial neural network. We achieve a spin-state detection fidelity of 94(2)% [3]. Next, we describe a laser beam delivery system based on compact piezo-actuated optical mirrors, which allow an efficient beam-position tuning inside the room-temperature bore of a superconducting magnet. This system enables in situ maximization of the ratio of coherent spin-spin interaction strength to spontaneous emission in laser-mediated interactions. Using this system, we demonstrate long-range entanglement with a variable coupling strength.

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[2] H. Ball et al., Rev. Sci. Instrum. 90, 053103 (2019)
[3] R. N. Wolf et al., arXiv:2303.10801

Monday Poster / 220

Progress on trap-integrated qubit control and readout for scalable trapped ion quantum computing

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The integration of qubit control and readout elements into microfabricated surface-electrode ion traps offers potential advantages for scaling to larger trapped-ion systems. We report progress on two efforts in this direction. First, we present measurements of improved trap-integrated superconducting photon detectors for qubit fluorescence readout. The detectors are shielded from the trap rf, enabling operation in a fully functional trap at temperatures up to 6 K, and should be suitable for high-fidelity readout of trapped Ca^+ ions. Second, we describe progress towards a mixed-species architecture based on laser-free quantum logic operations driven using trap-integrated current-carrying electrodes. We combine an entirely laser-free "data" species ($^{25}Mg^+$), which encodes quantum information in hyperfine states, with a co-trapped auxiliary "helper" species ($^{40}Ca^+$) that provides sympathetic cooling and quantum-logic-based state preparation/readout of the data ions. Only low-power resonant lasers are required for the helper species, making the architecture compatible with trap-integrated waveguides for laser light delivery across many trap zones. All operations on the data ions, and some on the helper ions, are driven using magnetic fields and magnetic field gradients generated by currents in the trap electrodes. This architecture eliminates memory errors/readout crosstalk from stray data qubit laser light, offers the potential for extremely low data qubit SPAM errors, and should enable high-fidelity, individually-addressable laser-free single-qubit and two-qubit operations carried out in parallel across many trap zones in the quantum CCD architecture.

Monday Poster / 125

Sympathetic cooling of a Be+ ion by a Coulomb crystal of Sr+ ions: a test bed for taming antimatter ions (GBAR)

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We present here an experiment focusing on the extension of sympathetic cooling techniques to the unfavourable case of large mass ratios between the two ionic species involved and for ions injected from outside the trap. This study is essential to the success of ambitious projects such as the GBAR (Gravitational Behaviour of Antihydrogen at Rest) project aiming to study the free fall of a antihydrogen atom prepared at rest [1] or non-destructive detection of singly-charged heavy molecules [2].

We develop a testbed experiment to study this process with 88Sr+ (the laser-cooled ion) and 9Be+ (the sympathetically cooled ion).The possibility of optically addressing the Be+ ion gives the advantage to perform thermometry measurements. Thus, cooling Be+ will enable us to control the initial energy of the ion launched in the target trap. This will allow us to measure for the first time the capture dynamics of a light ion by a Coulomb crystal, and to follow its cooling over several decades (typically from 10000K to mK). We will compare these measurements with numerical simulations [3].

Sr+ ions are also used to validate the trapping and cooling conditions and test the transport protocols of a single ion from one trapping zone to another. A method for characterizing the initial energy of an ion on arrival in the target trap has been developed (via Doppler recooling). Comparison with injection simulations showed good agreement between the calculated and measured kinetic energies. In a second phase, thanks to the Be+ cooling laser, it will be possible to cool a single Be+ ion and transport it with controlled kinetic energy to the second trapping zone, already loaded with a

Sr+ Coulomb crystal. Thermalization via Coulomb interaction will then be studied.

The method chosen to quantify the kinetic energy loss of the Be+ ion is based on measurement of the laser-induced fluorescence rate at resonance, which produces no laser cooling or heating on the oscillating ion. Spectroscopic measurements on the Be+ ion will be used to develop temperature diagnostics and cooling protocols for the GBAR experiment.

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[2] C. Champenois, et al. Non-destructive detection method of charged particles without mass limitation. EP20150767557 (2015)
[3] N. Sillitoe et al, JPS Conf. Proc (2017)

Tuesday Poster Session

Tuesday Poster / 162

A novel control system architecture for quantum computing

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Sinara is an open-source, open-hardware control system specifically created for quantum applications that is currently operational in numerous global laboratories. Its design is based on ribbon cable connections linking a controller with peripheral modules. This seemingly uncomplicated and economical method, however, has raised concerns about system reliability, thermal management, and effective monitoring. As quantum technologies evolve beyond their exclusively experimental phase, it becomes imperative for control systems to offer a higher level of dependability in their hardware platforms. In this poster, we introduce an innovative system architecture named DI/OT, based on the Compact PCI-Serial standard, a product of collaborative development with CERN. Our objective with this new architecture is to facilitate smoother system maintenance, enhance reliability, and broaden its applicability beyond quantum physics applications.

Tuesday Poster / 207

Laser cooling and trapping of short-lived radium ions

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Radium-225 (nuclear spin 1/2) is a particularly appealing candidate for optical clocks and testing fundamental symmetries due to its accessible electronic structure and heavy, octupole deformed nucleus. We demonstrated the first laser cooling of short-lived $^{224}\mathrm{Ra}^{+}$ (3.6 day half-life) and $^{225}\mathrm{Ra}^{+}$ (15 day half-life) ions which are loaded into linear Paul traps by a two-step photoionization process. We observed the $7s\ ^2\mathrm{S}_{1/2} \rightarrow 7d\ ^2\mathrm{D}_{5/2}$ clock transition in $^{224}\mathrm{Ra}^{+}$ and $^{225}\mathrm{Ra}^{+}$. This work was done with an effusive oven source based on the decay of longer-lived thorium atoms, which is expected to provide a useful supply of radium atoms over several thorium half-lives. We will measure the absolute transition frequencies of the electronic transitions needed for laser cooling and operating an optical clock with both short-lived isotopes. In parallel efforts, we are measuring the hyperfine structure of $^{225}\mathrm{Ra}^{+}$ and developing an orthotropic oven to produce a more efficient radium source. In following work we will produce and trap radium molecules which have enhanced sensitivity to tests of fundamental symmetries.

Tuesday Poster / 201

Continuous lasing and atom number self-regulation of strongly coupled atoms in a high finesse cavity

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Superradiant lasers are a promising path towards realising a narrow-linewidth, high-precision and high-bandwidth active frequency reference [1]. They shift the phase memory from the optical cavity, which is subject to technical and thermal vibration noise, to an ultra-narrow optical atomic transition of an ensemble of cold atoms trapped inside the cavity. Our previous demonstration of pulsed superradiance on the mHz transition in ⁸⁷Sr [2,3] achieved a fractional Allan deviation of 6.7·10⁻¹⁶ at 1s of averaging. Moving towards continuous-wave superradiance promises to further improve the short-term frequency stability by orders of magnitude. A key challenge in realizing a cw superradiant laser is the continuous supply of cold atoms into a cavity, while staying in the collective strong coupling regime.
We demonstrate continuous loading and transport of cold ⁸⁸Sr atoms inside a ring cavity, after several stages of laser cooling and slowing. We further describe the emergence of regimes of collective continuous lasing of the atoms on the 689nm 7.5kHz transition in ⁸⁸Sr, 7x narrower than the cavity linewidth, and pumped by the cooling lasers via inversion of the motional states. The lasing is supported by self-regulation of the number of atoms inside the cavity that pins the dressed cavity frequency to a fixed value over a range of more than 3MHz of applied cavity frequency. In the process up to 80% of the original atoms are expelled from the cavity. We also show how the interplay between different cooling lasers leads to the emergence of several distinct zones of lasing.
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[2] M. A. Norcia et al., Science Advances 2, e1601231 (2016)
[3] M. A. Norcia et al., PRX 8, 021036 (2018)

Tuesday Poster / 194

QuMIC - Towards a cryogenic ion trap with integrated microwave generator

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Ion traps are a promising candidate for a scalable quantum computer [1]. A major challenge is the integration of qubit control into the device.
With the microwave near-field approach [2], qubit control realized by microwave conductors that are integrated into the ion trap naturally scale with the trap itself.
However, the microwave signal generation currently takes place outside of the vacuum chamber in which the ion trap is located.
The QuMIC project researches and develops novel highly integrated BiCMOS chips at high frequencies and their hybrid integration with quantum electronics like ion traps.
This approach enables the scalability of a quantum computer to a large number of qubits and a drastic reduction in the number of required high-frequency lines, which also benefits the cooling capabilities of the cryostat used to cool down the ion trap to around 4 K.
We describe the setup of a cryogenic ion trap apparatus for rapid testing of traps, such as the ion traps with integrated microwave sources developed for QuMIC.
We discuss the operating principle of the microwave generator and the planned impedance matching network.
Finally, we will report on the current status of the project.

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[2] Ospelkaus et al., Phys. Rev. Lett. 101, 090502 (2008)

Tuesday Poster / 182

4K Cryogenic platform for the characterisation and development of cryogenic trapped-ion quantum computing technologies

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When considering the design of a trapped-ion quantum computer, a key aspect that emerges is the required operating temperature. Indeed, several advantages can be gained by operating trapped ion systems at low temperatures [1]. For example, cryogenic ion-trap systems boast of enhanced vacuum conditions, leading to increased ion lifetime; lower motional heating rates, increasing both ion lifetime and two-qubit gate fidelity; reduced power dissipation and noise from electronics; and the ability to use superconductors. As such, it is reasonable to suspect that the first large-scale trapped ion quantum computers may also operate under cryogenic temperature conditions.
In this work, an experimental system is presented that acts as a test bench for temperature-controlled trapped ion experiments at cryogenic temperatures. The system uses a Gifford-McMahon cryocooler and feedback-controlled heaters to simulate liquid helium (4.2 K) and liquid nitrogen (77 K) operating conditions with a high temperature stability (e.g. <5 mK recorded at a 9 K over a period of 24 hours). In addition, an ultra-low vibration interface mechanically isolates the cryocooler from the vacuum chamber, resulting in a reduction of vibration amplitude to <15 nm in all axes (dominant peaks at 50 Hz and 100 Hz). The system is designed to harbour a surface ion trap, with successful trapping achieved on multiple trap designs. Thus, offering a platform to characterise and develop technologies for cryogenic trapped-ion quantum computing directly using trapped ions. Examples of these technologies include: a novel cryogenic vario-coupling resonator design for generation of trapping radio-frequency voltages, a cryogenic low-power atomic oven and cryogenic microwave delivery. Additionally, cryopumping enables fast turn-around times for experiments, with ultra-high vacuum achieved in less than a day after opening the system for modification; compared to a typical 3 weeks when baking room-temperature systems. Finally, the low-noise characteristics of

the cryogenic system make it an excellent platform for high-fidelity two-qubit microwave gate experiments. Notably, noise intrinsic to experimental hardware can be investigated with reduced interference from the environment, e.g. motional decoherence due to heating of the ion.

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Tuesday Poster / 63

Observation of an interaction between two parallel ion chains in a surface-electrode trap towards nanofriction studies

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We study two parallel ion chains in a surface-electrode trap with an RF electrode configuration creating a double-well potential in order to establish a nanofriction model. One of the nanofriction models is Frenkel-Kontorova (FK) model which has close similarities to two parallel ion chains. The FK model is composed of a chain of classical particles which are harmonically coupled to the nearest neighbors and are subject to a periodic external potential. In the case of the FK model consisting of a finite chain, a phase transition takes place with the increase of the periodic potential when particle distances are incommensurate with the potential period. It is shown theoretically that the incommensurate has translational invariance. This is called the Aubry-type transition, where friction force vanishes. Several types of implementation of the nanofriction model with trapped ions have been demonstrated, for example, ion chains in optical lattices and zig-zag ion chains. It is reported that two parallel ion chains are a quantum system which is suited to emulate FK model. The final goal of our study is to observe the Aubry-type transition with two parallel ion chains. However, the interaction between two chains of ions has yet to be observed.
As the first step, we plan to observe interactions which are dependent on the distance of the two chains of ions. These are evaluated with the vibrational normal mode frequency of each ion chain. As the inter-chain distance is shortened, it can be shown that the degeneracy in the vibrational normal mode frequency of each ion chain is resolved under a threshold. There are three RF electrodes in our trap. Two outer ones are driven with a common RF voltage and supply radial confinement. The central one located between them is driven with another RF voltages to modify the confinement to a double—well shape. We can experimentally control the distance between the ion chains by varying the RF voltage ratio. We have stabilized RF voltages to reduce the fluctuation of the inter-chain distance. To measure

the frequency of ion chains, we apply an additional RF voltage to one of the DC electrodes, sweep its frequency around the normal mode frequency, and observe the ion image. When resonance phenomena occur, the amplitude of the ion motion becomes larger than that of the case of off-resonance. In this poster presentation, we will discuss how to control two parallel ion chains and the result of frequency measurements.

Tuesday Poster / 126

Single-Setting Quantum State Characterization

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A cornerstone of all quantum technology is the reliable characterization of the underlying building blocks, in particular the prepared quantum states. The standard approach for this task is to perform local Pauli measurements and from that estimate the quantities of interest. As the system size grows, however, the number of measurement bases to consider grows exponentially. We show that this challenge can be overcome by implementing symmetric informationally complete (SIC) POVMs on a trapped-ion quantum processor. While SIC POVMs are non-projective and cannot be implemented in a qubit, we make use of additional states within each ion to locally extend the Hilbert space from two to four dimensions, where SIC POVMs can be measured directly. This approach thus enables full quantum state characterization with a single, fixed measurement setting independent of the system size and with negligible experimental overhead. Combining the SIC POVM measurements with classical shadows enables the efficient estimation of arbitrary linear and nonlinear properties of quantum states orders of magnitude faster than standard methods. We demonstrate this potential by performing online tomography of an eight-qubit state in real time.

Tuesday Poster / 94

A segmented-blade ion trap with biasing rods

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We report the numerical simulation, fabrication process, and characterization of a segmented-blade trap with biasing rods [1, 2]. Our homemade trap consists of two radio frequency blades, dc blades with ten separate electrodes, and two biasing rods for compensating the ions' micromotion. We explore the effect of the rods on the trap potential and the influence of trap misalignment. The trap fabrication process is presented, including laser machining of an alumina substrate, metal deposition, and gold electroplating. We characterize the properties of both the bulk and surface of the substrate. An X-ray diffraction measurement reveals that the substrate is an alpha-alumina sintered above 1,200 degrees Celsius; the loss tangent is directly measured to be ~0.01 near 20 MHz; and we obtain the surface roughness of the polished substrate 20~30 nm. In this ion-trap device, we demonstrate the trapping of laser-cooled ytterbium ions successfully. We finally show our recent experimental results on the nonlinear motion of the ions and outline future research directions.

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Tuesday Poster / 154

Towards quantum logic spectroscopy of heavy few-electron ions

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Highly charged ions (HCI) feature an enhanced sensitivity to fundamental physics while many systematic effects from external perturbations are highly suppressed [1]. They are therefore excellent systems to test our understanding of nature and to realize novel high-accuracy optical atomic clocks.

Recently, quantum logic spectroscopy (QLS) of a fine-structure transition in a medium-light HCI of intermediate charge state [2] and the operation of an optical clock based on this transition [3] have been demonstrated. Even more extreme systems are heavy HCI in their highest charge-states (e.g. hydrogen-like or lithium-like ions) which offer narrow, laser-accessible transitions in their hyperfine structure (e.g. 1019.7 nm in $^{207}Pb^{81+}$) and the strongest electromagnetic fields that are accessible in a lab. On top of that, the small number of bound electrons allows for an accurate calculation of their atomic structure. However, they are not yet available for QLS due to the missing combination of a source for heavy HCI and a suitable experiment. State of the art is collinear laser spectroscopy at a heavy-ion storage ring, reaching an uncertainty level of 10^{-5} [4].

This contribution will report on a unique and versatile spectroscopy platform being set up at the HITRAP facility of the GSI Helmholtz Center for Heavy Ion Research to establish QLS for frequency metrology of heavy and simple ions. This will allow to improve the state-of-the-art uncertainty by many orders of magnitude, ultimately enabling unprecedented tests of fundamental physics and searches for physics beyond the Standard Model. The major challenges concerning the production and preparation of these ions as well as establishing a sufficiently low background pressure to prevent charge exchange reactions will be discussed.

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PhD openings available!

Tuesday Poster / 167

Digital simulation of a 1D spin chain in qudits

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Digital quantum simulation is an exciting near-term application of NISQ quantum devices. The re-programmable digital approach allows them to emulate a wide range of interesting materials, such as topological matter or large molecules, that have proven too complex to understand using classical physics and standard computation. Digital simulation combines the tool-set of quantum information with high performance gate-based evolution [1], enabling the use of quantum control and error mitigation protocols designed for gate-based algorithms [2, 3]. The high fidelities and long coherence times of trapped ion systems make them an excellent candidate to demonstrate digital quantum simulation.

Here we will demonstrate the quantum simulation of a topological spin chain on a trapped-ion quantum processor. In this work, we utilize qudits to directly simulate higher-dimensional spin systems in nature. We generate the spin chain sequentially using an ancilla qubit [4] and verify the expected properties of the state. In particular, we probe error-robust edge modes that arise due to topological symmetry in our material, and study the correlations and entanglement behaviour between qudits.

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Tuesday Poster / 123

Investigating entanglement structure on a programmable trapped ion quantum simulator

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Trapped ions are one of the leading candidates for performing quantum simulation, computation, and precision measurements. Entanglement in simulation experiments plays a crucial role in generating exciting quantum many-body states and distinguishes these experimental systems from their classical counterparts. Investigating entanglement in many body systems is extremely valuable to reveal underlying physics, however, investigating it in an experimental platform with a large number of particles is challenging. In our recent work, we investigated entanglement structure on a 51-ion programmable quantum simulator while variationally preparing the ground and excited states of the iconic 1D XXZ Heisenberg model and employing a sample-efficient entanglement Hamiltonian tomography method. We learn a reduced quantum state of 20 qubits in the middle of our 51-ion chain. To our knowledge, this is the largest quantum state reconstruction reported in the literature.

Tuesday Poster / 121

Investigating interference with phononic bright and dark states

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Interference underpins some of the most unusual and impactful properties of both the classical and quantum worlds, from the highest powered lasers down to the level of single photons. However, with regards to light-matter coupling, neither the usual classical nor quantum descriptions of interference can sufficiently explain why some states of light couple to matter while others do not. In this work a new description of interference, based on the formation of bright and dark states, is investigated experimentally. We employ a single trapped ion, whose electronic state is coupled to two of its motional modes in order to simulate a multi-mode light-matter interaction. We observe the emergence of phononic bright and dark states for both a single phonon and a superposition of coherent states. The collective dynamics of these systems demonstrate that a description of interference based solely on bright and dark states is sufficient to explain the light-matter coupling of any initial state in both the quantum and classical regimes.

Tuesday Poster / 25

Addressing individual ions with microwaves

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Microwave driven operations offer a scalable approach to trapped ion quantum computing, with cheap and reliable components; stable phase and amplitude control; and potentially higher fidelity gates. However, whilst laser beams can be focussed onto individual ions, the centimeter-wavelength of microwaves requires alternate techniques to address individual qubits. Here, we experimentally demonstrate new ion addressing techniques for both single- and two-qubit gates.

For two-qubit gates, we demonstrate the effective focusing of a spin-dependent force through the spatially varying microwave phase of a dynamical decoupling drive. For addressed single qubit gates, we utilize the spatial variation in microwave amplitude in a 4-pulse scheme. For the latter, parallel randomized benchmarking on two ions yields an average error of 3.4×10^{-5} per logical gate. Both methods demonstrate strong potential for microwave-driven addressed gates — far below error-correction thresholds — in registers of tens of ions confined within a single potential well.

Tuesday Poster / 202

Cold highly charged ions in a Paul trap with superconducting magnetic shielding

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Highly charged ions (HCI) offer promising candidate species for searches of physics beyond the Standard Model and next-generation optical atomic clocks. In the CryPTEx-SC experiment, we store HCIs in a cryogenic linear Paul trap that simultaneously functions as a superconducting radio-frequency resonator filtering the trap drive [1].
The HCIs are produced in a compact electron beam ion trap and then injected into and sympathetically cooled by a Coulomb crystal of Be^+ ions. Subsequently removing ions until a single Be^+ cooling ion and a single HCI are left enables quantum logic spectroscopy towards frequency metrology and qubit operations with a great variety of species.
We present Be^+ microwave spectroscopy measurements characterizing the magnetic shielding properties of the resonator trap built from superconducting niobium that almost fully encloses the stored ions [2].
While cooling the resonator trap down through its transition temperature into the superconducting state, a quantization magnetic field applied at this time becomes persistent and the trap becomes shielded from subsequent external electromagnetic fluctuations.
Using a magnetically-sensitive hyperfine transition of Be^+ as probe, we measure the fractional decay rate of the stored magnetic field to be at the 10^{-10} s^{-1} level. Ramsey interferometry and spin-echo measurements yield coherence times of over 400 ms without active field stabilization, demonstrating excellent passive shielding of magnetic field noise at frequencies down to DC, producing a suitable environment for precision ion spectroscopy.

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Tuesday Poster / 211

Quantum frequency conversion of Ba-138 single photons for long-distance quantum networking

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While prime candidates as nodes in long-distance quantum networks, trapped ions do not typically emit photons at telecommunications wavelengths. Quantum frequency conversion (QFC) allows trapped ions to connect with other nodes of a long-distance quantum network by frequency downconverting ion-emitted visible and near-IR photons to telecommunications wavelengths [1-3]. Polarization-preserving QFC has previously been used to convert near-IR single photons from a trapped Ca-40 ion to the telecommunications O-band [4]. Here, we report our progress towards a two-stage, polarization-preserving QFC setup to convert 493-nm single photons from a trapped Ba-138 ion to the telecom O-band. We separately transmit converted photons over 11 km of in-ground optical fiber.

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Tuesday Poster / 135

Single 40Ca+ ion-based quantum repeater cell - experimental demonstration and perspectives

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The quantum repeater cell according to [1] is a basic building block for a quantum repeater [2], that allows one to overcome the distance limitations of direct transmission in a future quantum internet [3]. We demonstrate the implementation of a quantum repeater cell based on two free-space coupled 40Ca+ ions trapped in a single linear Paul trap. Photons emitted by each ion create ion-photon entanglement [4] and are coupled to two separate single-mode fibers. The ion-photon entanglement is generated in an asynchronous manner by driving one ion independently of the other. Distant photon-photon entanglement is finally obtained through entanglement swapping [6], by applying a Mølmer–Sørensen quantum gate [5] between the ions and subsequently projecting the two ions. We characterize the asynchronously generated ion-photon entanglement and the photon-photon entanglement achieved by the protocol and discuss the scaling of this implementation.
Furthermore, we present the status of a new ion trap setup with integrated cavity, designed to increase the probability and rate of photon emission. Finally, we discuss the use of short excitation pulses to increase the photon purity for its use in a photonic Bell state measurement.

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Tuesday Poster / 156

Status of the aluminium ion clock at PTB

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Optical atomic clocks based on a single aluminium ion reach a record fractional frequency stability below 10^{-18}. This outstanding precision allows for applications like relativistic geodesy on the cm-level and helps to tighten the bounds for physics beyond the standard model. Here, we present the newest results of the aluminium ion clock with an systematic uncertainty of 1.1×10^{-18}. This uncertainty is estimated using calcium as a sensor. Besides mapping out the environment of the ion, calcium is also used for cooling and readout of the aluminium clock state. This is necessary since cooling and detection of aluminium at its cooling transition at $167\,\mathrm{nm}$ is not feasible. The employed quantum logic readout needs two narrow line laser at $1069\,\mathrm{nm}$ and $729\,\mathrm{nm}$. We stabilise both laser onto one reference cavity with a dual wavelength coating. Here, we present the characterisation of this resonator with emphasis on the cross correlation between the lasers. The cavity shows a relative frequency stability of the $729\,\mathrm{nm}$ laser of 1×10^{-14} and for the $1069\,\mathrm{nm}$ laser of 4×10^{-15}. Besides the stability of the resonator, we show first stability measurements of the aluminium clock by measuring it against the silicon cavity at PTB.

Tuesday Poster / 115

Adiabatic Rapid Passage of Phonons in Trapped Ion Crystals

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In a recent demonstration of the quantum charge coupled device (QCCD) trapped ion architecture [1], circuit time is dominated by cooling operations. Some motional modes of a multi-ion crystal are cooled inefficiently due to the geometry of the cooling lasers and the coupling of the mode to the sympathetic coolant ion species, requiring as much as 1 ms to cool to the ground state, whereas others can be cooled in just a few us. Previous work has shown that motional quanta can be transferred from mode to mode by modulating electric fields that couple those modes at their difference frequency [2,3]. While useful for transferring population out of hard-to-cool modes, this technique can be hampered by filters meant to suppress high frequency noise on the electrodes that control the trapping potential, and is sensitive to drifts in the mode frequency or drive amplitude. We propose a method that extends this technique by a process analogous to adiabatic rapid passage, where we directly control the trapping potentials to create an avoided crossing that we sweep through to transfer population with quasi static voltages. Using this method, we demonstrate full population transfer out of motional modes with transfer times that are over an order of magnitude smaller than the time it would take to directly cool those modes to the ground state .

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Tuesday Poster / 187

Quantum Simulation of Oscillatory Unruh Effect with Superposed Trajectories

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A detector moving with relativistic accelerated trajectory would experience Unruh effect and raise both detector excitation and particle creation in the accelerated frame, despite being in a vacuum in the rest frame. We simulate such an effect in the case of the detector oscillating in a cavity with a laser-controlled trapped ion. The simulation could be extended to superposed quantum trajectories, leading to coherent interference of excitation. Our demonstration reveals the Unruh's prediction regarding particle creation by non-inertial motion, as well as the novel coherent effects in quantum field theory relating to quantum gravity.

Tuesday Poster / 103

Experimental setup for trapped Rydberg ions in cryogenic environment

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Trapped Rydberg ions combine the advantages of ion trapping and tunable and long-range Rydberg interactions. They enable entangling operations over longer distances and are great candidates for performing fast and scalable entangling gates.

Working with Rydberg ions is promising but also challenging. It is so mostly due to the need to address transitions with UV lasers and relatively frequent loss of ions during the measurement sequence. Since the Rydberg states lie very close to continuum, black-body radiation (BBR) can lead to double ionization of singly-charged ions. Once it happens, the ion can no longer be controlled or detected and reloading of ions into the trap is necessary. To prevent that, the trap can be placed in the cryogenic environment, greatly diminishing the magnitude of BBR.

To be able to address and detect the fluorescence signal with a single-ion resolution, a high NA objective is required. We present a custom-made refractive objective consisting of two bi-aspherical lenses with NA reaching up to 0.34. The design allows for high resolution detection of $^{88}Sr^{+}$ ions by collection of 422 nm fluorescence light and precise addressing with 674 nm, 243 nm and 305 nm laser beams. The compact design with 41 mm outer diameter and 35 mm tube length allows for placement in the vicinity of the trap itself - inside the cryogenically cooled region. Besides the optical part, the overall design of the experimental setup will be discussed.

Tuesday Poster / 185

A quantum perceptron gate and a classical Toffoli gate with microwave-driven trapped ions

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Direct implementation of multi-qubit gates with three or more qubits circumvents decomposition into two-qubit operations, effectively reducing the required depth of quantum circuits. Using the inherent all-to-all coupling in a trapped ion quantum computer, we experimentally realize classical Toffoli and perceptron gates with three microwave-driven hyperfine qubits using 171Yb+ ions. The classical Toffoli gate can be used to efficiently implement arithmetic operations, such as a half-adder. The perceptron gate, when nested with other perceptrons, can be used as universal approximator. Both, the perceptron and Toffoli gates are implemented by a continuous microwave driving field, while the qubits' coherence is protected by pulsed dynamical decoupling. In case of the perceptron, a dressing field applied to the target qubit is adiabatically ramped down. We report the implementation of a two-layer neural network using successive perceptron gates. For the Toffoli gate, the target qubit is controlled by two control qubits and a top hat microwave pulse. 171Yb+ ions are stored in a linear Paul trap exposed to a permanent magnetic field gradient. Using MAgnetic Gradient Induced Coupling (MAGIC), all-to-all coupling in the qubit register is achieved while the qubits can be individually addressed by microwave radiation.

Tuesday Poster / 65

Telecom-Wavelength Quantum Repeater Node Based on a Trapped-Ion Processor

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A quantum repeater node is presented based on trapped ions that act as single-photon emitters, quantum memories, and an elementary quantum processor. The node's ability to establish entanglement across two 25-km-long optical fibers independently, then to swap that entanglement efficiently to extend it over both fibers, is demonstrated. The resultant entanglement is established between telecom-wavelength photons at either end of the 50 km channel. Finally, the system improvements to allow for repeater-node chains to establish stored entanglement over 800 km at hertz rates are calculated, revealing a near-term path to distributed networks of entangled sensors, atomic clocks, and quantum processors.

Tuesday Poster / 80

The stacked-ring ion guide and the MR-TOF MS developed for the NEXT experiment

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The NEXT experiment [1] is currently being built at the AGOR facility in Groningen. NEXT aims to study Neutron-rich EXotic, heavy nuclei around N=126 and in the transfermium region which are produced in multinucleon Transfer reactions. Precision mass spectrometry and decay spectroscopy will be used to characterize these nuclei.

The target-like transfer products are pre-separated from the primary beam and lighter projectile-like products within the magnetic field of a superconducting solenoid magnet. They are slowed down by use of a gas catcher. A continuous and divergent beam of low energy ions is extracted from the gas catcher which has to be transformed to well-focused bunches of ions with keV energy suitable for time-of-flight mass measurements. For this purpose, a new ion guide consisting of a stack of ring electrodes has been developed where deviation in a radio-frequency duty cycle is introduced to transport the ions along the ion guide and produce ion bunches [2]. A recently designed multi-reflection time-of-flight analyzer [3] will be used for isobaric separation and mass measurements.

At the moment, the custom-made ion guide and MR-TOF mass spectrometer (MR-TOF MS) are being commissioned and its performance has been studied using an alkali ion source. In this contribution, the first tests of the setup will be presented and discussed.

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Tuesday Poster / 64

A network of trapped-ion quantum computers

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Trapped ions are a leading platform for quantum computing due to their long coherence time, high level of control over internal and external degrees of freedom, and the natural full connectivity between qubits. Single and multi-qubit operations have been performed with high fidelity (>99.9%), enabling the demonstration of small universal quantum computers (approx. 10 atoms). However, scaling up to larger sizes remains a challenge. In our experiment, we aim to demonstrate the first operational and fully controllable two-node quantum computer, where each node consists of small-scale quantum processors connected via photonic entanglement. We use two ion trap systems to confine mixed chains of Strontium and Calcium ions. 43Ca+ has excellent qubit coherence properties, while 88Sr+ has a convenient internal structure for generating photonic entanglement. Single 422 nm photons emitted by the Strontium ion are used to generate remote entanglement. We recently achieved a remote Strontium-Strontium entanglement fidelity of 96.0(2)% at a rate of 100 entangled events/s, along with an average CHSH violation of 2.65.

In this talk, I will present our latest results using this elementary quantum networks, including the implementation of a long-lived (>10s) memory qubit into our mixed-species trapped-ion quantum network nodes [1]; and how to use one of these nodes to implement simple instances of Blind Quantum Computing [2].
Furthermore, I will present the demonstration of secure quantum communications between the nodes of our network, certified by continuous violation of the CHSH inequality (DIQKD), and the demonstration of the first quantum network of entangled optical atomic clocks.

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Tuesday Poster / 79

Towards implementing quantum logic spectroscopy for (anti-)proton g-factor measurements

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Comparisons of fundamental properties of matter and antimatter provide stringent tests of CPT symmetry [1]. Throughout the past years, measurements of proton and antiproton g-factors in Penning traps have been carried out with outstanding precision, setting new constraints on CPT violating effects of the SME [2,3]. However, these experiments rely on time consuming particle cooling and state detection schemes based on image current detection (see e.g. [3]),
currently limiting measurement sampling rate and accuracy.
To overcome these limitations, we develop new cooling and state readout techniques following a proposal by Heinzen and Wineland [4,5]. In our approach, we want to couple an (anti-)proton to a laser (ground-state) cooled $^9\mathrm{Be}^+$ using free-space Coulomb-coupling in a double-well potential. This should allow to ground-state cool the (anti-)proton and detect its spin state by means of a quantum-logic inspired readout protocol [6].
In this contribution, we present the basic concept of our approach as well as latest advances of our experiment on resolved axial sideband cooling and fast adiabatic transport of a single $^9\mathrm{Be}^+$, which are mandatory steps towards implementing quantum-logic spectroscopy.

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Tuesday Poster / 190

Monolithic Miniature 3D Linear Trap for Cavity Integration

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Scalability represents an ongoing challenge for the trapped ion quantum computing platform. The photonic interconnect architecture was proposed to address the scalability issue using trapped ions [1]. The efficiency of the architecture relies on the remote entanglement rate between different nodes. The figures of merit of the architecture are the entanglement generation rate and fidelity of this entanglement. To this end, the cavity-mediated photon generation scheme has demonstrated great potential. By reducing the cavity length, the increased ion-cavity coupling is estimated to result in two orders of magnitude improvement over the current record for remote entanglement rate [2]. Despite the potential for such improvement, the introduction of the cavity in a trapped ion system is hindered by stray charges accumulated on the dielectric mirror surfaces [3], the increased heating rate due to the dielectric materials [4] and the distortion of trapping potential [5]. These detrimental effects from the cavity necessitate a miniature trap to shield it sufficiently. We present our recent progress in developing a monolithic miniature 3D linear trap that integrates a miniature optical cavity and can serve as a building block for a scalable trapped ion quantum processor. Fabricated with selective laser-induced etching has allowed for a monolithic design with virtually no misalignment of the electrodes where we have successfully trapped single ions. This work is supported by JST Moonshot R&D Grant No. JPMJMS2063 and MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) Grant No. JP-MXS0118067477.

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Tuesday Poster / 87

Unveiling the frontier of antiprotonic atom synthesis using trapped anions

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Exotic atoms, formed by substituting one or more of their constituents—electrons, protons or neutrons—with others of the same electric charge, have played a pivotal role in studying the fundamental interactions in nature. Antiprotonic exotic atoms, containing at the same time matter and antimatter can be used to test matter-antimatter asymmetries, one of the unresolved questions in modern physics. The advancements in ion trapping technology unlock novel possibilities for controlled synthesis and manipulation of these exotic systems directly within traps.

Antiproton Deceleration (AD) and Extra Low Energy Antiproton (ELENA) rings at CERN are the world's only source of abundant, low-energy antiprotons appropriate for synthesis, manipulation ad studies of antimatter.

At the Antimatter Experiment: Gravity, Interferometry, Spectroscopy (AEgIS) up to 3.7×10^6 of antiproton particles are trapped and utilized to study of antihydrogen atoms. The experiment uses pulsed production mechanism by merging cold antiproton plasma with Rydberg-excited positronium (Ps*) cloud and the subsequent charge exchange: $\overline{p} + Ps^* \rightarrow H^* + e^-$.

Anionic molecules can be trapped and cooled down in the Penning-Malmberg traps of the AEgIS experiment together with antiprotons. After neutralization and Rydberg excitation of the anions $A^- \rightarrow A^*$ a cold antiproton replaces an electron of the outermost atomic orbital, leading to synthesis of the exotic atom: $\overline{p} + A^* \rightarrow \overline{p}A^* + e^-$. Previously, exotic atoms were created by injection of MeV antiprotons into bulk gaseous or solid materials. The result has been an instantaneous ejection of orbital electrons and consecutive antiproton annihilation on the nuclear surface without the possibility of a detailed study of the full process.

In our approach, we aim to achieve a controlled exotic atom formation, in a cold, near static system. By using heavy and mid-heavy ions we will extend the lifetime, magnify and diversify observable processes: orbital electron ejection, surface annihilation and nuclear fragment formation. In our method, we will be able to perform measurements at every stage of the process, from Auger cascade and fluorescent spectroscopy of ejected electrons to measurement of half-life of Highly Charged Ions and nuclear hyper-fine structure after nuclear fragmentation.

Tuesday Poster / 69

Mixed qubit types in registers of individually addressed trapped barium ions

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Registers of different qubit types, where one qubit type is insensitive to the other's light fields, are a promising avenue for scaling the quantum information processing capabilities of trapped-ion systems [1]. This approach mitigates scattering errors and allows for advanced qubit control schemes by enabling partial projective measurements, mid-circuit measurements, and in-sequence cooling.

Barium is particularly well suited for realizing mixed qubit type registers: using just a single atomic species, qubits can be implemented in both barium's ground level and its long-lived (~ 30 s) metastable level. Additionally, qubit transitions within both the ground and the metastable level manifolds can be driven using the same laser wavelength at 532 nm, leading to a significantly reduced experimental overhead.

In our experiment, we use $^{137}\mathrm{Ba}^{+}$ ions with a nuclear spin of $3/2$. The resulting hyperfine structure allows for the implementation of magnetically-insensitive 'clock' qubits.
We present an all-fibre system capable of single-ion addressing in large qubit registers by utilizing a laser-written waveguide device. Using a trapped ion as a light-field sensor, we characterize the performance of the addressing system by measuring the Stark shifts induced by the individual beams and observe $< 10^{-3}$ crosstalk between neighbouring channels.
We further demonstrate simultaneous manipulation of ground-level and metastable-level qubits and present post-selection schemes that enhance the fidelity of state preparation and effectively identify and eliminate population leakage errors.

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Tuesday Poster / 60

Photon-mediated entanglement of co-trapped atomic barium ions

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Long chains of trapped ions are a leading platform for quantum information processing, but their control suffers from spectral crowding and excess motional heating when chains grow too long. One proposal to access larger Hilbert spaces and thus more computational power is to entangle ions in separate traps via photonic interconnects. Previous demonstrations have used 0.6 NA objectives to entangle ytterbium [1] and strontium [2] ions or optical cavities to entangle calcium ions [3]. Here, we make use of an RF Paul trap surrounded by two in-vacuo 0.8 NA aspheric lenses to entangle co-trapped barium ions. The higher NA increases the efficiency of our photonic interconnects and the presence of two high-NA imaging systems in a single vacuum chamber will allow this system to be integrated as the middle node in a three-node quantum network.

*This work is supported by the ARO with funding from the IARPA LogiQ program, the NSF STAQ Program, the DOE Quantum Systems Accelerator, the ARO MURI on Modular Quantum Circuits, the AFOSR MURI on Quantum Transduction, the AFOSR MURI on Interactive Quantum Computation and Communication Protocols, and the ARL Center for Distributed Quantum Information. This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant No. DGE 2139754.

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Tuesday Poster / 196

Towards cavity quantum electrodynamics with Barium ions

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We report our plans and progress towards implementing a cavity quantum electrodynamics system with Barium ions. With Barium ions' strong S-P dipole transition at 493 nm, we can expect much stronger ion-cavity coupling than achievable with infrared transitions in Barium as well as in other atomic species. This can be exploited for high-fidelity light-atom entanglement generation and state readout in the dispersive regime. However, so far, cavity QED experiments with ions utilizing S-P transitions have suffered from high optical losses and in-vacuo degradation of mirror coating leading to poor performance of the optical cavities [1]. However, this has not been established for the wavelength that we are concerned with, 493 nm. This wavelength is of particular interest since 1) it is the longest wavelength for a S-P transition among all major ionic species, and 2) the in-vacuo degradation of mirrors has not been observed at wavelengths beyond 550 nm [2]. As a first step towards cavity QED with Barium ions, we are testing coated highly reflective mirrors in vacuum.

To test possible degradation, we have built a Fabry-Perot cavity using mirrors that are highly reflective at 493 nm and placed it in a vacuum chamber. The chamber is maintained at a pressure of 10^{-8}mBar. We are testing degradation by two different mechanisms that are known from previous studies. The first mechanism is the diffusion of oxygen from the mirror surface in vacuum over time [3]. We have observed no such degradation over the past year. The second mechanism is laser induced damage of the mirror surface under continuous exposure to laser light in vacuum [4]. To study this we lock the cavity in vacuum to the laser resonance and record the cavity finesse after prolonged exposure. We measure the finesse at regular intervals to check for degradation. As we do not expect nonlinear optical effects to play a role, the total integrated optical power is the quantity of interest. The experiment is in progress, and we will report up-to-date results at the conference. We will also report the design for our envisioned ion trap-cavity system with Barium ions.

This work is supported by JST Moonshot R&D Grant No. JPMJMS2063.

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Tuesday Poster / 104

Laser cooling of molecular anions for sympathetic cooling of antiprotons

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The Antimatter Experiment: Gravity, Interferometry, Spectroscopy (AEGIS) at CERN utilizes cold antiproton beams from the Antimatter Decelerator to

study gravitational effects on antihydrogen beams. The pulsed production of Rydberg excited antihydrogen is achieved through a charge exchange reaction between laser-excited Rydberg positronium and cold antiprotons. This same technique is now being adapted for creating cold antiprotonic atoms through charge exchange with Rydberg excited atoms within the trap. At present, the antiprotons are sympathetically cooled by co-trapped electrons, which can reach temperatures down to tens of K. However, to achieve much lower plasma temperatures, laser cooling is required. Antiprotons can be sympathetically cooled using a laser-cooled species with a negative charge. Among various anions studied, the diatomic molecular anion C2- emerges as a promising candidate due to its well-known level scheme, absence of hyperfine structure, and high Franck-Condon factors. Simulations indicate that laser-cooled C2- could enable antiprotons to reach millikelvin temperatures within the Penning-Malmberg trap at AEGIS. This would pave the way for the novel formation of Super Rydberg antiprotonic atoms for precision QED studies and cold antihydrogen for measuring the influence of gravity on antimatter.
A proof-of-principle setup at CERN has been successful in generating pulsed beams of C2- molecules and trapping them in a Paul trap. Ongoing spectroscopic measurements aim to investigate the ro-vibronic ground state fraction post pulsed production, followed by the first photodetachment cooling of the molecular anion. Subsequent studies will explore non-destructive cooling methods, such as Sisyphus cooling, necessary for sub-K sympathetic cooling of the antiprotons.

Tuesday Poster / 186

Microwave-double dressed entangling gate with trapped 171Yb+ ions

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Entangling gates are an essential buliding block of any quantum processor, ideally working at high speeds in a in a robust and scaleable manner. Microwave-driven trapped-ion gates present promising features in terms of scalability and stability of the driving field. Experimentally, limited fidelity values are mostly attributed to the use of magnetic field sensitive states, which make qubits vulnerable to magnetic noise sources. Here we present a promising Mølmer- Sørensen type entangling gate based on a continuous dynamical decoupling technique [1]. We implement a double dressing field scheme, using a single microwave field per ion.

The gate is implemented on trapped 171Yb+-ions in a static magnetic gradient of 19 T/m and an inherent all-to-all coupling based on the Magnetic Gradient Induced Coupling (MAGIC) scheme [2]. Here, we show first experimental results of these fast entangling gates that take a few hundred microseconds. This is an order-of-magnitude improvement in gate time compared to our previous entangling gate results. These are achieved without siginficant modifications of the trapping parameters and the magnetic field gradient as compared to previous gate realizations [2, 3].

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Tuesday Poster / 58

Differential polarizability measurements using a ^{171}Yb^{+}-^{88}Sr^{+} dual-species optical clock

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The currently most accurate frequency standards based on optical transitions have reached fractional systematic uncertainties on the order of 1×10^{-18}, enabling sensitive tests of fundamental physics [1]. The Stark shift induced by room temperature blackbody radiation (BBR) in many cases causes the largest shift from the unperturbed transition frequency and limits the systematic uncertainty of the optical clock. For the ^{171}Yb^{+} clock the BBR shift evaluation is limited to the low 10^{-18} range by the knowledge of the differential polarizability $\Delta\alpha$ of the electric octupole (E3) transition at infrared wavelengths, if radiofrequency (rf) traps with small and homogeneous rf heating are used to confine the ion [2].

Measurements of $\Delta\alpha$ based on the Stark shifts from deliberately applied laser radiation are limited to a fractional uncertainty of about 1% due to the accuracy of optical power meters and imaging properties. For ^{40}Ca^{+} and ^{88}Sr^{+} [3] ions, however, the static differential polarizability $\Delta\alpha_{\mathrm{dc}}$ has been determined with high accuracy from the specific trap drive frequency at which the micromotion induced second-order Doppler and Stark shift cancel each other. This is possible, because for both ions the clock transition features a negative $\Delta\alpha_{\mathrm{dc}}$. Employing this high accuracy, we can use ^{88}Sr^{+} as an in-situ sensor to evaluate the temperature rise from rf losses of an ion trap with low thermal conductivity with 1 K uncertainty [4]. This allows us to determine the unperturbed frequency ratio of the ^{88}Sr^{+} and ^{171}Yb^{+} clock transitions to a fractional uncertainty of 2.3×10^{-17} and to infer the ^{88}Sr^{+} absolute frequency [4].

To enable frequency uncertainties on the 10^{-19} level for ^{171}Yb^{+}, we aim to transfer the uncertainty of Δα from ^{88}Sr^{+} to^{171}Yb^{+} through measuring the light shift induced by a 10 µm CO2 laser beam for 88Sr+ and the two clock transitions of ^{171}Yb^{+}. To minimize the polarizability uncertainty of ^{88}Sr^{+} at

10 μm, we investigate the dynamic behavior of $\Delta\alpha$ by measuring its zero-crossing around 1540 nm.

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Tuesday Poster / 100

Toward precision spectroscopy of trapped chiral molecular ions for fundamental physics

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The success of trapped molecular ion precision spectroscopy in eEDM searches motivates the extension of the platform to more complicated polyatomic species to test the Standard Model (SM) and search for new physics.

The prediction that weak force parity violation (PV) breaks the symmetry between the left and right-handed chiral molecules has eluded detection for decades in a field dominated by neutral species. Crucially, comparison between the two chiralities of the molecule isolates all PV interactions, which arise from the SM and beyond. Despite the potential, the lack of theory on chiral molecular ions makes it challenging to select a species to initiate the experiment. Importantly, the ideal candidate, must be prepare-able at internally cold temperatures and have efficient detection avenues.

We have found several intriguing candidates, the most promising of which is CHDBrI+. Using ab initio theory, we predict a ~2 Hz shift between L and R molecules for the C-H bend vibrational transition at 9 um, where the transition's linewidth is >10x narrower than the shift [1, 2]. CHDBrI+ has reasonable wavelengths for cold preparation through state-selective, near-threshold photoionization of neutral CHDBrI and is also promising for detection via photodissociation [1].

Our plan is to extract the PV signature from a mixed chirality ensemble of trapped CHDBrI+, using vibrational Ramsey spectroscopy that is embedded within the 3-wave mixing (3WM) framework [3]. So far 3WM has been demonstrated using microwaves to separate molecules according to their handedness using asymmetry of the chiral molecules' transition dipole moment components. We propose to extend these ideas to differential precision spectroscopy between the two chiralities, which is critical to suppress noise and sources of systematic uncertainty.

We will discuss our progress in this young experiment.

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Tuesday Poster / 209

Next-generation quantum computer system with long chains of trapped ions

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Trapped ions are a leading platform for quantum computers, with their high level of programmability and lack of idle decoherence mechanisms. Here, we present progress on building a state-of-the-art quantum computer with full control of up to 32 $^{171}Yb^{+}$ ion qubits on a Sandia Phoenix ion trap chip. We measure the heating rate as a function of trap axial frequency and manage sources of electric field noise that affect entangling fidelity. We measure a hyperfine qubit coherence time of >2 seconds, which is mainly limited by magnetic field noise from Helmholtz coils. We measure the chamber pressure to be $1.3(2)\times10^{-11}$ Torr from the switching of an ion in a weak double well potential. We use 355-nm individually addressed Raman beams to implement unitary rotations, and characterize SPAM errors and motional coherence from Raman operations. The hardware upgrades compared to previous systems should lead to better fidelity gates and expand the complexity of physics and quantum circuits that can be run on the quantum processor.

Tuesday Poster / 77

Ion matter-wave interferometry in a nearly circular potential for a gyroscope application

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Sensors based on the wave nature of a massive particle are expected to be one of the next generations' high-performance sensing technologies. Atoms and ions are ideal for such use since they give us the capability to control their quantum states using optical means precisely. A Laser-cooled ion in an ion trap is an important platform for quantum sensing due to its ideally isolated condition and trap stability and controllability.
We aim to develop a gyroscope using a matter-wave interference of an ion. The ion trap gyroscope, whose feasibility has been theoretically discussed by Campbell and Hamilton[1], requires the interferometry between the states of a clockwise-rotating and a counter-clockwise-rotating wave packet of an ion in a two-dimensional isotropic potential. This is a matter-wave version of a Sagnac interferometer.
Although the concrete scheme of the ion Sagnac interferometer is clear, there are several technical challenges to realizing it. First, we need to realize a matter-wave interference of an ion in the multi-dimensional motion. We have realized the three-dimensional ion matter-wave interference by applying the momentum kick onto the ion along the direction diagonal to all the fundamental axes of the trap[2]. Second, the non-adiabatic trap potential displacement is essential to increase the interference area for the gyroscope operation. The direction of the potential displacement must be perpendicular to the momentum kick. We developed the method to realize the non-adiabatic trap potential displacement as large as 10 microns[3]. Third, the trap potential needs to be circular to realize a closed trajectory of an ion after a number of rotations inside the trap for the two-dimensional matter-wave interference. We experimentally investigated how the trap potential gets deformed under the fine-tuning of the trap frequencies from careful trap frequency measurements and calculations of the trap potential. Recently, we constructed a whole experimental setup on a rotatable optical table to rotate the entire system with an angular velocity of up to 2 degrees per second. In the presentation, we will discuss the detail of our results.

Tuesday Poster / 113

Progress towards Integration of a High Finesse Optical Cavity with an Individually-Addressed Trapped Ion Chain

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Trapped ion chains are a promising architecture for the development of quantum computers and quantum simulators owing to their high connectivity, high-fidelity gate operations, and long coherence times. Scaling up to many qubits is challenging as adding more ions to each chain increases its susceptibility to electric fields, slows down the gate operation and increases errors due to thermal motion.
While separate chains have been successfully connected by shuttling, for many ions this approach has large time and architectural overheads. Our design integrates a near-confocal optical cavity with a silicon micro-fabricated surface electrode ion trap with a focus on reproducibility for exploring a different approach to scaling. We aim to use a high-finesse optical cavity in order to create a fast, coherent, photonic interface between ion chains [1]. This may allow the entanglement of individual spatially separated qubits within one single trap with rates above 10 kHz. The high entanglement rates offer a means to connect multiple independent logical qubits on one trap. Further scaling is possible by using two-photon protocols, potentially employing superradiance, to connect independent cavity-based modules.
By using the cavity mode to form an optical lattice, we can suppress the motion of ions along the axial direction. This may allow individual addressing and controlled spin-spin interactions in chains of up to a hundred ions, with applications to quantum simulation, including that of lattice gauge theories.

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Tuesday Poster / 155

Creation of entangled coherent states with the motional degrees of freedom of a trapped ion

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The motional degree of freedom of a trapped ion system has been studied as a conveyor of quantum information in the context of continuous variable quantum computing (CVQC) [1,2]. Theoretical and experimental studies concerning quantum information processing with the motional degrees of freedom include phonon sampling [3,4], and encoded qubits [5]. In this work, we experimentally create the entangled coherent state (ECS) of the form $|\alpha\rangle \ |\beta\rangle + \ |-\alpha\rangle \ |-\beta\rangle$ with a single ion and study its characteristics. The quantum state has previously been realized in other quantum systems such as photons and microwave resonator cavities [6,7], and this work represents its first implementation in a trapped ion system. The ECS is created by simultaneously driving spin-dependent force on the two principal axes of the ion, and then projecting its spin state, which disentangles the spin degree of freedom from the entangled motional states [8,9]. Afterwards, we observe a periodic modulation in the phonon number parity of one of the two entangled modes and confirm that it matches the theoretically predicted pattern where the parity information disappears when the two modes are strongly entangled. We expect the generation of the ECS to facilitate the study of CVQC in trapped ion systems.

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Tuesday Poster / 107

Orientational melting of a two-dimensional ensemble of charged particles

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A system of confined charged particles undergoes crystallization at sufficiently low temperature, forming self-organized structures in which each particle is spatially localized. However, when particles in a two-dimensional plane are confined by an isotropic potential, there is no preferential orientation of the crystal, and thermal fluctuations lead to the delocalization of particles in circular trajectories. Following this orientational melting of the crystal, the particles remain localized radially and delocalized in the angular direction. Orientational melting of a mesoscopic crystal is a change of configuration that is similar to a phase transition in a macroscopic system, but it is not universal as it depends on the specific properties of the system, e.g. the exact number of particles.

We report on the experimental observation and characterization of orientational melting in a two-dimensional crystal of trapped Ba+ ions [1].

The specific geometry of our trap [2] makes it possible to continuously change the arrangement of the ions from a one-dimensional string to a two-dimensional crystal while keeping the ions always in a two-dimensional plane. We observe that orientational melting occurs under conditions that strongly depend on the number of particles, and find excellent agreement with the results of a Monte Carlo simulation, which we use to estimate the temperature of the ions at which melting occurs. Additionally, we are able to locally inhibit melting by adding a single impurity with a different mass. Interestingly, for a sufficiently large number of ions two or more concentric rings are populated, and the rings can exhibit independent dynamics.

Our experiment paves the way to accessing quantum regimes for delocalized strongly-interacting particles, and in particular for the coherent control of the rotational state of the ions [3] by entangling it to the ions' internal state.

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Tuesday Poster / 118

Towards a long-chain trapped ion quantum simulator with in-situ mid- circuit measurement

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Here, we report on the development of a large-scale quantum simulator with programmable individual control of more than 50 $^{171}\mathrm{Yb}^{+}$ ions in a segmented 'blade trap' system. The trap allows high NA optical access from four directions and will include high fidelity and low crosstalk in-situ state measurement and reset of individual ions [1]. Our custom monolithic optical breadboards are engineered to provide long-term stability. Through optimized vacuum engineering and extensive outgassing tests, the vacuum system is optimized for long ion storage times. Preliminary tests show a measured pressure of <8E-13 mbar, lower than most existing room temperature ion traps. This system will allow us to perform a wide range of quantum information processing experiments, like exploring measurement-based quantum phases of spin Hamiltonians to hybrid digital-analog quantum algorithms.

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We acknowledge financial support from UWaterloo, CFREF, NSERC Discovery grant, NFRF and the Ontario Govt

Tuesday Poster / 130

Measurement of the Damping Resistance of Laser Cooled 9Be+ Ions using Image Current Detection

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Co-Autoren: collaboration) (BASE ; Peter Micke ; Christian Will ; Hüseyin Yildiz ; Fatma Abbass ; Bela P. Arndt ; Jack A. Devlin ; Stefan Erlewein ; Markus Fleck ; Julia I. Jäger ; Barbara M. Latacz ; Daniel Schweitzer ; Gilbertas Umbrazunas ; Elise Wursten ; Klaus Blaum ; Yasuyuki Matsuda ; Andreas Mooser ; Wolfgang Quint ; Anna Soter ; Jochen Walz ; Christian Smorra ; Stefan Ulmer

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At the proton g-factor experiment in Mainz we have recently succeeded in sympathetically cooling a single proton by laser-cooled 9Be+ ions stored in a separate Penning trap. Here, the coupling between both ion species is mediated by image currents induced in a common RLC circuit. Uniquely, our setup combines laser cooling and fluorescence detection of the 9Be+ ions with image current detection of the proton and the 9Be+ ions. Using this setup, we were able to measure the laser-induced damping resistance using image currents. In this contribution, we present a map of the damping resistance as a function of laser frequency and laser power. Further, we relate the measured damping resistance to the measured fluorescence intensity and compare the results to theoretical predictions.

Tuesday Poster / 139

Tensor-Network Assisted Quantum Algorithms for Quantum Simulations

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Quantum simulations stand out as a particularly promising application of quantum computers. The noisy intermediate-scale quantum (NISQ) devices pave the way for the development of fault-tolerant quantum computers. However, the presence of noise and decoherence in current noisy quantum devices necessitates the use of hybrid quantum algorithms based on low-depth circuits to achieve promising results. In this context, the initialization of quantum algorithms with a suitable initial ansatz becomes crucial. Tensor network methods, well-established techniques for classical simulations of quantum many-body systems, offer a valuable approach to enhance state preparation in quantum algorithms. In this presentation, we demonstrate how tensor network methods can improve the performance of a specific quantum algorithm. By using these methods to prepare an optimized ansatz and feeding it into the algorithm, we show significant enhancements in the results obtained.

Tuesday Poster / 90

Design of Molecular Cluster Dynamics through Digital Quantum Simulation on a Trapped Ion Quantum Computer

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Electronic excitation of molecular clusters are the microscopic dynamics governing the efficacy of both photovoltaic cells and photosynthetic reaction centers, as well as those emerging technologies that lie in between. In most cases, accurately capturing the behavior of such systems requires understanding not only the electronic excitations, but also the dynamics of the vibrational degrees of freedom, to which they are coupled. Simulating the dynamics of such an expansive Hilbert space is a prime application of quantum computers. In this work, we experimentally simulate the transfer of an electronic excitation along a chain of macromolecules under a variety of conditions using a trapped-ion-based quantum computer. Our approach begins by using the relatively accessible spectroscopic data of an isolated macromolecule, pseudoisocyanine, as the input to a hybrid quantum-classical optimization algorithm which creates a digitally prepared wavefunction describing that macromolecule. Thereafter, we use an ab initio model to track the dynamics of a cluster of three macromolecules. We perform these simulations for a variety of different inter-molecular couplings by varying the relative angle between the molecules in the cluster, providing proof of principle for ab-initio design of molecular clusters with tailored excitation transfer rates.

Tuesday Poster / 159

Detection of micromotion using direct dc potential scan and Rabi oscillation

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Detecting and minimizing the micromotion in an ion trap system is crucial for precise control of the quantum states and suppression of heating. For this purpose, several methods have been reported, such as measuring fluorescence amplitude at the rf frequency, optimizing the optical sideband spectrum, minimizing ion displacement while alternating between different trap depths, and employing parametric excitation at the rf frequency [1-3]. In this work, we will present a simple but highly applicable method for micromotion detection using Raman beatnote-driven Rabi oscillation combined with dc potential scanning. Similar to the resolved-sideband spectroscopy method, this method exploits changes in absorption rate when the phase of the transition laser that the ion experiences is modulated by the ion's micromotion in the direction of the laser momentum. However, instead of obtaining the fluorescence spectrum, fluorescence is measured against scanned dc voltages, or the electric fields at the ion. The consequent profile follows a Bessel-like curve, which is predicted by the Bessel expansion of the modulation of the transition field. Without requiring the whole spectrum which demands many shots of measurement, the proposed method only requires 10-20 shots versus dc voltage scan, at the carrier transition or any of the sideband transitions. A demonstration using the Raman carrier transition and the first-order sideband transition will be presented, where the sensitivity of the measurement appears to be at the equivalent level to previously reported levels in practical operations. Also, a demonstration of an application for long-term monitoring of the stray field at the ion using the proposed method will be presented, along with additional measurements using other conventional methods. In addition to its accessibility, the method eliminates the need to undermine the trap stability, which is frequently encountered in conventional detection methods when diminishing the intensity of a laser or modulating the electric potential.

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Tuesday Poster / 111

Spin squeezing and entanglement generation in two-dimensional ion crystals with up to 105 ions

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Linear strings of trapped ions in radio-frequency traps are a well-established platform for quantum simulation of magnetism. However, linear strings feature some drawbacks, among them difficulties in scaling the system size beyond 50 ions or the inability to investigate spin models in more than one dimension where many exotic quantum phenomena are expected to manifest. Here we present our novel ion trap apparatus which is capable of trapping and coherently manipulating two-dimensional ion Coulomb crystals of up to 105 $^{40}Ca^{+}$ ions. In the first part we will briefly present techniques to cool and control large planar ion crystals as well as some experiments to characterize their properties. We find that rf-induced heating and melting due to background collisions are no obstacles for quantum simulation experiments. We characterize the trapping potentials as well as the spatial crystal configurations by an analysis of crystal images and prove that we are able to mitigate configuration changes to realize stable confinement of large crystals. Furthermore, we show that precise control of the crystal orientation allows for minimizing micromotion seen by the out-of-plane motional modes similar to the level achieved in linear strings, and demonstrate simultaneous preparation of all 105 modes close to the motional ground state by means of electromagnetically induced transparency cooling [1]. In the second part we present global coherent manipulation of a ground-state Zeeman qubit – in which we encode the spin - by means of Raman transitions. Employing bichromatic Raman beams enables coupling of the spin state to the out-of-plane motional modes and the realization of the long-range transverse-field Ising model. To assess the performance of our quantum simulator and to prove multi-partite entanglement we implement a recently developed protocol to create spin-squeezed states, a valuable tool in quantum-enhances metrology [2]. Despite not having infinite-range interactions at hand, we show that

operating the simulator in the power-law XY regime yields an evolution being well-approximated by the one-axis twisting model. This enables the creation of highly-squeezed states with Wineland parameters of more than 8dB for up to 105 particles and unambiguously verifies multi-partite entanglement in planar ion crystals.

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Tuesday Poster / 128

2D ion trap architectures for enhanced qubit connectivity

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Ion traps are a promising platform to host a quantum information processor. However, on the road to producing a functional quantum computer, scaling up to hundreds of ions is a challenge.
The established usage of 1D arrays of ion qubits limits connectivity to low ion numbers, thus restricting the quantum advantage.
In this work we develop an ion trap architecture where independent ion strings are located in distinct lattice sites in a 2D array, greatly enhancing connectivity. Conventionally, coupling between ion strings in separate sites, or wells, is realized by first merging them into a single well. We demonstrate an alternate method of ion coupling in which separate wells are brought close but are not merged [1]. This is performed along two orthogonal directions: One direction (axial) is achieved through control of DC voltages, and the other (radial) through control of RF fields.
I will review the principles of such a shuttling-based architecture and motivate the advantages of keeping ions in separate trapping sites. For example, the more-than-linear scaling of coupling strength with number of ions per chain makes well-to-well coupling viable for reasonable gate times. Moreover, for ion strings in separate wells there exists an out-of-phase mode of oscillation that is inherently insensitive to electric field noise, thus exhibiting lower heating rates but retaining the same high coupling strength as that of the in-phase mode. This makes this mode a good candidate for implementing quantum gate operations.
To investigate these advantages, we have developed two microfabricated surface traps, a linear trap designed for DC shuttling based well-to-well coupling, and another consisting of two parallel linear traps designed for RF shuttling.

With the first, we present axial coupling of ion crystals of up to 6 ions per site, and measure coupling rates up to 60 kHz, allowing gate times < 20 μs. Furthermore, we demonstrate a reduction of heating rate of the out-of-phase mode of oscillation by almost an order of magnitude with respect to the in-phase mode. With the second trap, we demonstrate and characterize radial shuttling of arrays of up to 3 ions. These results provide an important insight into the implementation of fully controllable 2D ion trap lattices, and pave the way to the realization of two dimensional logical encoding of qubits.

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Tuesday Poster / 120

Fabrication of trapped ion microchips for microwave-based quantum computers

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We present the fabrication of trapped ion microchips integrated with the key features required to realise a scalable architecture for a modular microwave trapped-ion quantum computer. In our approach for ion trap quantum computing [1], high currents of up to 15 A generate large local magnetic field gradients at the ion position which, together with global microwave and RF fields, enable the implementation of high-fidelity quantum gates [2].
In order to enable such high currents within the quantum computing microchip, we fabricated surface ion trap microchips with current-carrying wires (CCWs) integrated into the silicon substrate. With the developed chips, currents up to 13 A can be applied continuously, resulting in a simulated magnetic field gradient of 144 T/m at the ion position, which is 125 μm from the trap surface. The low resistivity of the CCWs allows for a power dissipation of 1 W for 10A and 3 W for 13 A at a base temperature of 38 K for the CCWs including the compensation coils [3].
Our ion trap architecture is also modular, which means that arbitrary numbers of modules can be connected via electric fields to allow ion transport between individual modules. The key technique for this approach is aligning modules with respect to each other, requiring protruding electrodes at the edge of each module. For this purpose, silicon undercuts have also been fabricated at the edges of the developed chips. We have successfully fabricated such a chip, which has been used for coherent ion transport between two quantum computing modules [4-5]. We are currently working on integrating vias for inner segmented electrodes and atomic ovens.

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Tuesday Poster / 184

Isotope Shift Measurements of Ca+ in a Trapped Ion Quantum Computing Platform

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We present our preliminary findings regarding the measurement of the isotope shift in the $4s\,^2S_{1/2} \rightarrow 3d\,^2D_{5/2}$ transition within pairs of even isotopes of Ca^+. We perform the measurement by co-trapping the isotope pairs in a single well produced by a micro-fabricated segmented ion trap. Our method showcases a significant advancement in accuracy, enhancing the precision of the isotope shift measurement by two orders of magnitude compared to previous experiments. Furthermore, we address various systematic effects that gain importance within this elevated accuracy range. The resulting precision of our measurements can serve not only as a reference point for evaluating theoretical isotope shift calculations but also paves the way for exploring New Physics: by combining our measurements with at least one isotope shift measurement of a different transition, new energy bounds for a potential 5th force between neutrons and electrons may be established. Additionally, our experiment underlines how the ongoing technical progress in trapped ion quantum computing contributes to the domain of precision measurements.

Tuesday Poster / 199

Modular variable laser cooling for efficient entropy extraction

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I will present work on laser cooling a trapped-ion oscillator based on sequences of spin-state dependent displacements followed by spin repumping. For a thermal state with mean occupation $\bar{n} \gg 1$ the method attains a reduction of 0.632 of the initial thermal oscillator occupation for two repumps of the spin state. We demonstrate the motion using a single calcium ion, and illustrate its advantages and limitations. To increase robustness to imperfections, we have recently been working to implement the method spin-state dependent displacements with laser pulses of very different intensity, requiring integrating phase tracking into our FPGA hardware to work in real-time for flexible sequence generation and deployment. We will also present an overview of upgrades to the control system underlying all the experiments in the ETH Zurich group.

Tuesday Poster / 78

Towards ultrafast spectroscopy with trapped molecular ions and photodissociation of CaOH+

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Trapped atomic ions are one of the most promising platforms for quantum simulation and computation. Our project focuses on their application in quantum logic spectroscopy to investigate the rovibrational structure of various molecular ions co-trapped with atomic ions, as demonstrated experimentally on diatomic molecular ions such as CaH^+ and N_2^+. Utilizing femtosecond laser pulses, we aim to explore ultrafast intramolecular dynamics in polyatomic molecular ions. The collective motion of the ion crystal will be prepared in a non-classical state to measure the net momentum transfer from the pump and delayed probe pulses to the molecular ion. The evolution of vibrational excitations inside a single polyatomic molecule can then be studied. Our goal will be to advance our understanding of quantum phenomena in molecular systems, especially in complex molecules of chemical or biological importance.

While constructing the experimental setup, we also measure the photodissociation threshold of $CaOH^+$ molecules. The molecules are generated via chemical reactions between trapped Ca^+ ions and water molecules which are introduced into the experimental chamber using a gate valve. Following the reaction, photodissociation threshold are measured by applying laser pulses of tunable wavelength to dissociate the “dark” molecule back to a “bright” Ca^+ ion.

Tuesday Poster / 198

Cryogenic trapped-ion system and quantum control of quantum harmonic oscillators

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We present our experimental progress on the control and application of the vibrational modes with a cryogenic trapped Calcium ions system. We implement a segmented four-blade Paul trap in a closed-cycle 4 K cryostat, achieving a heating rate of 8 phonon/s at a trap frequency of 1.1 MHz. We utilize this setup and entangle two vibration modes with reservoir engineering, and obtain a stable two-mode squeezed state along two axes. Along the squeezed axes, we demonstrate simultaneous estimation of two displacements with up to 6.9(3) dB and 7.0(3) dB improvement over the standard quantum limit, respectively. Our demonstration may have various applications, including quantum sensing, quantum imaging, and other fields that require precise measurements of multiple parameters.

Tuesday Poster / 191

Advances in state-preparation, cooling and state detection of N2+ molecular ions

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Manipulation of single trapped molecules on the quantum level has gained notable interest in recent years. Their complex energy-level structure with rotational and vibrational degrees of freedom provides a plethora of transitions with various properties but also presents challenges toward molecular state initialisation, manipulation and readout. Building on the methods known for trapped atomic species, for the state readout, we follow a quantum-logic protocol that uses a single co-trapped atomic ion as a probe for the molecular state [1]. We implemented EIT cooling of an atomic-molecular two-ion string to investigate how the state-readout fidelities are affected by the populations of different motional modes of the two-ion crystal. We are also implementing precision-spectroscopic measurements on a narrow infrared quadrupole transition of the nitrogen molecular ion N_2^+ referenced to the Swiss primary frequency standard at METAS in Berne via an optical fibre link. The present method paves the way for the implementation of molecular qubits with excellent coherence properties, for establishing new frequency standards in the mid-IR regime, for investigating state-to-state dynamics of chemical reactions, and for exploring beyond-standard-model physics by tracking a possible temporal variation of fundamental constants.

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Tuesday Poster / 7

Feedback Cooling the Motion of a Trapped Ion

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The inherent quantum nature of single trapped ions makes them promising candidates for the experimental realization of qubits, the fundamental building blocks of quantum computers. In order to harvest the potential that trapped ions posses, it is necessary to not only have precise control over an ion's quantum state but also over its motional state. Doppler cooling is commonly deployed to dampen the thermal motion of an ion inside the trapping potential down to the Doppler limit. Additional cooling methods are, however, necessary to further reduce the ion motion beyond this Doppler limit, so as to achieve more efficient interaction of light and the ion [1, 2]. Feedback cooling can be used to actively dampen the ion's motion by monitoring the momentary displacement of the ion and applying a corresponding feedback signal in real time [3]. This is achieved in our setup by trapping the single ion inside a deep parabolic mirror using a stylus-like trap [4], enabling us to collect most of the emitted fluorescence light due to the large solid angle coverage. An imaging system is used to image the ion onto a knife edge. The signals of single-photon detectors behind this edge are then used to discern the ion's motion in combination with a lock-in amplifier to subsequently extract and provide the feedback signal. The ion motion is observed to be reduced using a spectrum based method [3] and an imaging based method [5].

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Tuesday Poster / 134

Ion-cavity node engineering for scalable networked quantum computing

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Networked architectures provide a route to freely-scalable quantum computation with trapped ions, with entanglement between ions in remote nodes mediated by the coherent production, interference and projective measurement of single photons. Two-node networks have provided proof-of-principle demonstrations but have been limited in the rate of entanglement achieved, and many further hurdles remain on the route to large-scale networked quantum computation.

To approach equivalency with local, phonon-mediated entangling operations, network photons must be generated near-deterministically and at high rate, most readily achieved via integration of a high-finesse optical cavity. The use of microcavities to enhance photon production has long been recognised as essential to success of scalable quantum networks, but the development of systems of sufficiently high performance and reliability remains a considerable challenge.

In Oxford, we are tackling this problem from multiple angles. To commission and operate a multi-node computational architecture will require ion trap system of vastly greater simplicity and reliability than currently available, enabling nodes capable of long-term autonomous operation. We are therefore working to improve the manufacturing precision and operational reliability of our traps, cavities and other subsystems. In parallel we aim to improve the intrinsic robustness of the photon production and entanglement schemes utilised, to minimise the detrimental impact of residual imperfections in system manufacture and environmental control.

I will present technical progress towards creating a multi-node quantum network, providing illustrative examples of the engineering efforts underway across our group. Here, I will focus on a selection of methods for complex 3D trap microfabrication, optical cavity integration, microlens arrays for laser delivery and fluorescence collection and high-efficiency compact atomic sources.

Tuesday Poster / 223

Integrated ion traps for quantum metrology and information

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Chip-based ion traps are a versatile platform for quantum technologies. Our established ion traps for optical clocks enable controlling systematic frequency uncertainties at the 10^-19 level [1, 2]. Currently, we are developing ion traps with integrated optics. Integrated optics improve the robustness against vibrations, make the traps scalable to large numbers of ions, and help to compactify the setup for portable optical clocks. With photonic design beam profiles can be generated that, combined with improved pointing stability, enable the excitation of forbidden transitions in trapped ions [3]. Together with our partners from Cornell University and ETH Zurich, we are working on ion traps with integrated waveguides for quantum metrology.
In our projects with partners from German industry, we are developing chip-based traps with integrated micro-optics, as well as traps with integrated waveguides for quantum information processing. To reach optimal performance in metrology, we pay attention to heat management and rf properties. Our aim is to employ the traps in portable optical clocks for geodetic measurements on earth and in space [4].

[1] J. Keller et al., Phys. Rev. A, 99, 013405 (2019)
[2] T. Nordmann et al., Rev. Sci. Instr., 91, 111301 (2020)
[3] A. A. Peshkov et al. ANNALEN DER PHYSIK 2300204 (2023)
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Tuesday Poster / 230

Studies of Highly Charged Ion Ensembles in the ARTEMIS trap and Direct Mass Measurements of Radio-nuclides at SHIPTRAP at GSI, Germany

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Penning traps are high-precision tools for mass spectrometry and spectroscopy experiments. Two such experiments based on Penning traps at the GSI Helmholtz Centre for Heavy Ion Research are: ARTEMIS and SHIPTRAP. The ARTEMIS Penning trap experiment aims to measure the magnetic moment of an electron bound to heavy, highly charged ions using the laser-microwave double-resonance spectroscopy technique with 10^{-9} level of accuracy. These high-precision g-factor measurements would be the most stringent test of QED in the limits of extreme electromagnetic fields of the nucleus. $^{40}\mathrm{Ar}^{13+}$ is the first candidate for these high-precision measurements followed by $^{209}\mathrm{Bi}^{82+}$. In order to perform the double-resonance spectroscopy, a pure cooled cloud of Ar^{13+} ions needs to be prepared in the spectroscopy trap of ARTEMIS.

The SHIPTRAP mass spectrometer enables high-precision measurements of superheavy and exotic nuclei with rather short half-lives of about 200\,ms and above. These mass measurements are performed using the phase-imaging ion-cyclotron-resonance technique. This talk will present the studies of highly charged argon ions produced in ARTEMIS and high-precision mass measurements of radio-nuclides obtained from the recoil-ion sources: $^{225}\mathrm{Ac}$ and $^{223}\mathrm{Ra}$, installed in the cryogenic gas cell of SHIPTRAP.

Tuesday Poster / 217

A Cryogenic System for Rapid Ion Trap Characterization

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Trapped ions are promising qubit systems for quantum information processing due to their long coherence times and high gate fidelities. Current scalable trap design efforts rely on 2D surface traps, which are challenged by shallow trap depths and sensitivity to electric field noise. We built a cryogenic system aimed at efficient, iterative prototyping of scalable 3D-printed ion traps. These traps will be fabricated with sub-micron precision using a method based on two-photon polymerization. We have first used a 2D surface trap to calibrate our system. We demonstrated resolved sideband cooling to the motional ground state and measured axial motional heating rates for a single $^{88}Sr^{+}$ ion. We will replicate these measurements and test single and multi-qubit operations using 3D-printed traps, which can be rapidly installed and characterized in our system.

Tuesday Poster / 108

Electronic control of trapped ion qubits

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Electronic control methods, where quantum gates are implemented without lasers, hold great potential for trapped-ion quantum computing due to their low fundamental errors and the ease of scalability. In this work, we demonstrate a new electronic control method, where addressed single-qubit rotations are implemented by localized AC electric fields, generated by trap electrodes. We demonstrate theoretically and experimentally how this tool enables local single-qubit control in a multizone trap, using only small voltages and existing trap structures. Finally, we discuss how electronic control techniques enable large-scale integration of trapped-ion quantum computers with scalable fabrication processes.