

Mechanism of Cu-catalyzed iododeboronation: A description of ligand-enabled transmetalation, disproportionation, and turnover in Cu-mediated oxidative coupling reactions

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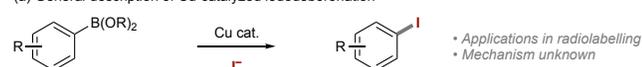
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ABSTRACT: We report a combined experimental and computational study of the mechanism of the Cu-catalyzed arylboronic acid iododeboronation reaction. A combination of structural and DFT analyses has allowed determination of the identity of the reaction pre-catalyst and the first complete description of the catalytic cycle. Key findings include a rationale for ligand stoichiometry related to key turnover events – the ligand facilitates transmetalation via H-bonding to an organoboron boronate generated in situ and ligand loss/gain is integral to the key oxidative events. These data provide a framework for understanding ligand effects on these key mechanistic processes, which underpin several classes of Cu-mediated oxidative coupling reactions.

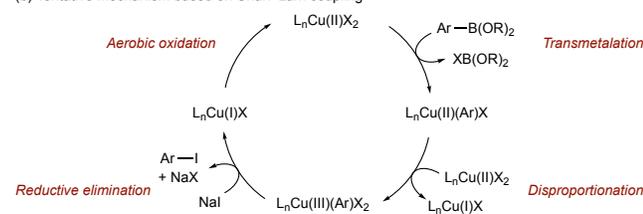
Introduction

Cu-catalyzed iododeboronation of aryl boronic acids using iodide is a useful reaction for the synthesis of aryl iodides (Scheme 1a).¹⁻⁴ More importantly, this reaction accommodates iodide radioisotopes providing products that have important applications within in vivo imaging and radiotherapy.⁵⁻⁹

(a) General description of Cu-catalyzed iododeboronation



(b) Tentative mechanism based on Chan–Lam coupling



Scheme 1. (a) General representation of Cu-catalyzed iododeboronation. (b) Tentative description of the iododeboronation reaction.

There are several reported methods for Cu-catalyzed iododeboronation, each with subtle variations in copper source, ligand, and associated reaction conditions.¹⁻⁴ Related copper-catalyzed or -mediated halodeboronation reactions, such as the equivalent fluorination reaction, also operate with similar reaction conditions.¹⁰⁻¹³ This general reaction class therefore has broad applications across synthetic chemistry and specific applications in bio-facing fields.

Very limited mechanistic information is available on the halodeboronation reaction in general, with a tentative mechanistic description of the iododeboronation largely based on the framework of the Chan–Lam reaction (Scheme 1b).¹⁴⁻¹⁷ This

proposed mechanism involves transmetalation of the arylboronic acid to Cu(II), giving a Cu(II)(aryl) species, followed by disproportionation to Cu(III), and anion exchange/reductive elimination to give the aryl iodide product and Cu(I). Aerobic reoxidation of Cu(I) to Cu(II) closes the cycle.

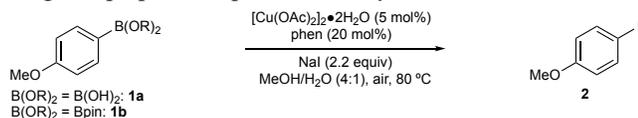
Despite the importance and influence that ligand stereoelectronics exert on redox processes at metal centers, robust identification of intermediate ligand structure and speciation states remains a general problem in Cu-mediated oxidative catalysis. This renders the study of key mechanistic events, such as transmetalation, disproportionation, and oxidative turnover, difficult to understand and, therefore, control through rational catalyst design.

The main knowledge in this area arises from several key studies of catalytic reactions. Hartwig identified a Cu(III) intermediate in solution and proposed a mechanism for transmetalation of arylboronic acid pinacol (ArBpin) esters in a fluorodeboronation reaction using an F⁺ reagent, with ligands proposed for this key intermediate and event.¹¹ Stahl,^{15,16} Watson,^{17,18} and Schaper^{19,20} proposed ligand sets for related Chan–Lam etherification and amination reactions, with broadly similar descriptions of rate-limiting transmetalation.²¹ Computational analysis of Chan–Lam amination reactions have aligned closely, although with some differences in the interpretation of the rate-limiting event.²² While integral to many Cu-based oxidative coupling reactions, there is limited information on the disproportionation event or oxidative turnover.

Here we report a detailed mechanistic description of the Cu-catalyzed iododeboronation reaction using a combination of structural, spectroscopic, and computational analyses. For the first time, this includes an assessment of ligand structure at all stages of the proposed catalytic cycle. More broadly, this analysis has provided insight into the transmetalation, disproportionation, and oxidative turnover events that underpin many Cu-mediated oxidative coupling reactions.

Results

Synthesis and characterization of Cu complexes. For our analysis, we selected a catalytic iododeboronation system reported by Gouverneur using $\text{Cu}(\text{OAc})_2$ and 1,10-phenanthroline (phen) as the catalyst/ligand system and NaI as the requisite source of iodide (Scheme 2).⁷ Based on these conditions, we sought to prepare complexes that may be formed in situ.



Scheme 2. Model iododeboronation system used in this study.

Treatment of $[\text{Cu}(\text{OAc})_2]_2 \cdot 2\text{H}_2\text{O}$ with phen delivered the monomeric complex $[\text{Cu}(\text{OAc})(\text{phen})_2]\text{OAc}$ (**[3]OAc**)²³ or the dimeric complex $[\text{Cu}(\text{OAc})_2(\text{phen})_2]_2 \cdot \mu\text{-H}_2\text{O}$ (**4**)²⁴ (Scheme 3a). Recrystallization of **[3]OAc** in CH_2Cl_2 fortuitously led to formation of $[\text{Cu}(\text{OAc})(\text{phen})_2]\text{Cl}$ (**[3]Cl**) (Scheme 3c). Treatment of $[\text{Cu}(\text{OAc})_2]_2 \cdot 2\text{H}_2\text{O}$ with phen under halodeboronation reaction conditions (NaI, MeOH/ H_2O) led to formation of $[\text{Cu}(\text{I})(\text{phen})_2]\text{I}$ (**[5]I**) (Scheme 3d).²⁵ Crystalline material from the reaction mixture of an iododeboronation reaction of **1a** conducted under an inert atmosphere was isolated and determined to be the dimeric complex $[\text{Cu}(\mu\text{-I})(\text{phen})_2]$ (**6**) (Scheme 3e).²⁶

Discussion

Identification of reaction-relevant Cu complexes. To elucidate the function of reaction components and identify reaction-relevant Cu complexes, $[\text{Cu}(\text{OAc})_2]_2 \cdot 2\text{H}_2\text{O}$ was first treated with NaI; however, no reaction or denucleation of the paddle-wheel was observed by EPR spectroscopy (not shown, see Fig. S12).

We therefore hypothesized that the reaction initiates by formation of a $\text{Cu}(\text{II})(\text{phen})_n$ complex. Treatment of $[\text{Cu}(\text{OAc})_2]_2 \cdot 2\text{H}_2\text{O}$ with phen (2 equiv) and analysis by EPR spectroscopy showed formation of a complex with a spectrum consistent with that of **[3]OAc** and less consistent with **4** (Figure 1). This suggested that **[3]OAc** was the dominant species arising from reaction-relevant Cu:phen stoichiometry (1:2).

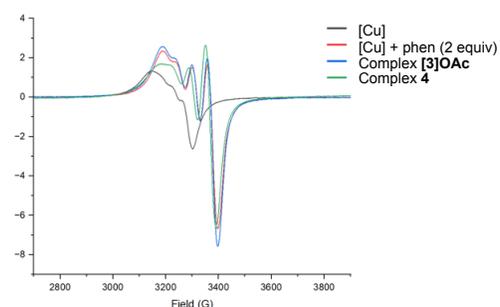
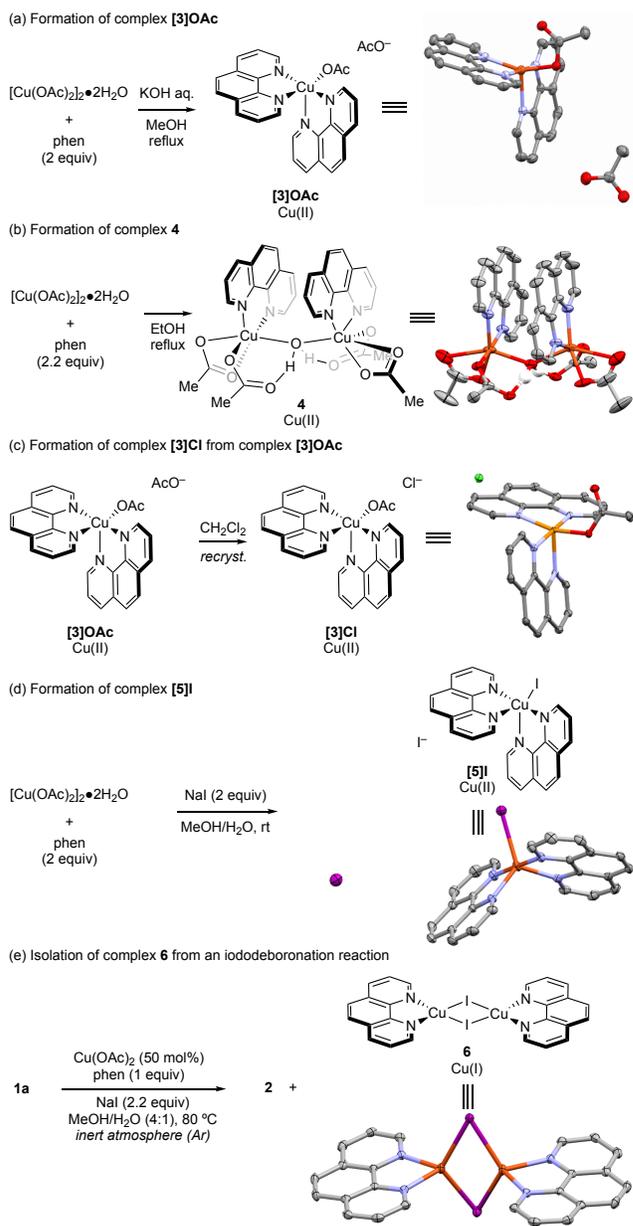


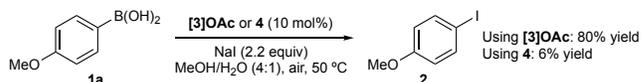
Figure 1. Overlaid EPR spectra for $[\text{Cu}(\text{OAc})_2]_2 \cdot 2\text{H}_2\text{O}$ (black), complex **[3]OAc** (blue), complex **4** (green), and the proposed in situ formation of through complexation of **[3]OAc** by treatment of $[\text{Cu}(\text{OAc})_2]_2 \cdot 2\text{H}_2\text{O}$ with phen (2 equiv) (red). Solvent = MeOH/ H_2O (4:1). $[\text{Cu}] = [\text{Cu}(\text{OAc})_2]_2 \cdot 2\text{H}_2\text{O}$.

Using pre-formed **[3]OAc** or **4** in the iododeboronation reaction of **1a** delivered the expected product **2**, indicating reaction relevance and catalytic competency (Scheme 4); however, while **[3]OAc** exhibited catalytic turnover, **4** did not.



Scheme 3. Formation of Cu complexes 3-6.

Note that to avoid complications in data analysis, **1a** was used to avoid off-cycle inhibitory processes that are associated with release of pinacol from reactions using ArBpin (i.e., **1b**; see ESI for control experiments).¹⁷ In addition, while it is possible to prepare $\text{Cu}(\text{II})(\text{phen})_3$ complexes,²⁷ these are not readily accessible under conditions relevant to the iododeboronation process and, as such, were discounted from this study.



Scheme 4. Competency of **[3]OAc** and **4** in the iododeboronation of **1a**. Yields determined by ¹H NMR using an internal standard.

Treatment of $[\text{Cu}(\text{OAc})_2]_2 \cdot 2\text{H}_2\text{O}$ with phen and NaI and analysis by EPR spectroscopy revealed a solution structure consistent with complexes **[3]OAc** and **[3]Cl**, with the observation of increased line broadening, and which were significantly different

to the spectrum of **[5]I** (Figure 2). Based on these data, we propose the formation of **[3]I** in situ, which subsequently proceeds to **[5]I** via further anion metathesis. Attempts to isolate **[3]I** were unsuccessful – all attempts led to isolation of **[5]I**.

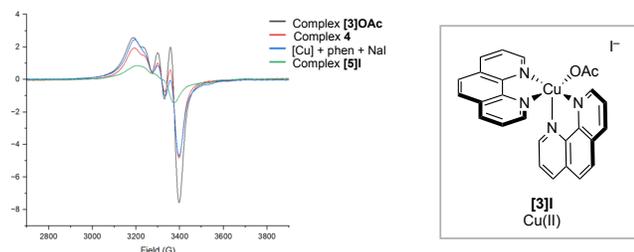
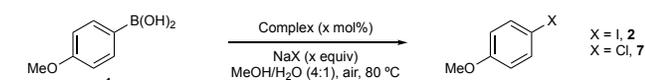


Figure 2. Overlaid EPR spectra for compound **[3]OAc** (black), complex **4** (red), complex **[5]I** (green), and the proposed in situ formation of **[3]I** through reaction of $[\text{Cu}(\text{OAc})_2] \cdot 2\text{H}_2\text{O}$ with phen (2 equiv), and NaI (2 equiv) (blue).

Use of complexes **[3]Cl** and **[5]I** in halodeboronation reactions was informative (Table 1). Stoichiometric **[3]Cl** delivered only 16% of the expected chloroarene product **7** while stoichiometric **[5]I** delivered quantitative conversion to **2** (entries 1 and 2). Similar effects were observed when using catalytic **[3]Cl** and **[5]I** in the presence of NaCl and NaI, respectively (entries 3 and 4): poor conversion was observed with **[3]Cl** but **[5]I** was competent. Interestingly, using NaI as the halide source, **[3]Cl** was catalytically competent and delivered exclusively the iododeboronation product **2** (**7** not observed) despite the presence of 10 mol% chloride (entry 5). The reciprocal reaction using **[5]I** with NaCl delivered iododeboronation commensurate with the presence of 20 mol% iodide (from 10 mol% **5**) as expected, but low levels of chlorodeboronation despite the presence of excess chloride (entry 6). These data suggest that (i) **[3]Cl** and **[5]I** are catalytically competent, (ii) complex **[3]⁺** is likely a key on-cycle species and exists in equilibrium with, or is a precursor to, **[5]⁺**, and (iii) iodide transfer is more efficient than chloride. This latter point begins to impact upon understanding of halodeboronation in general, in particular aligning with the more difficult fluorodeboronation process.¹⁰⁻¹³

Table 1. Halodeboronation competency and halide effect of complexes **[3]Cl** and **[5]I**.



Entry	Complex (loading)	NaX (equiv)	Yield (product) ^a
1	[3]Cl (1 equiv)	---	16% (7)
2	[5]I (1 equiv)	---	>99% (2)
3	[3]Cl (10 mol%)	NaCl (2.2)	20% (7)
4	[5]I (10 mol%)	NaI (2.2)	83% (2)
5	[3]Cl (10 mol%)	NaI (2.2)	67% (2)
6	[5]I (10 mol%)	NaCl (2.2)	16% (2) 17% (7)

^aYields determined by ¹H NMR using an internal standard.

In situ reaction monitoring and sequential addition of reagents showed productive reactivity was only observed with the addition of NaI prior to **1a** (not shown, see ESI S24, S25), suggest-

ing transmetalation occurs after formation of complex **[3]I**. Attempts to identify Cu(II)(aryl) complexes were unsuccessful, consistent with transmetalation being rate-limiting as indicated for other reactions in this class, e.g., Chan–Lam processes.¹⁴

We hypothesized that Cu(I) complex **6** was produced following reductive elimination of the product from a Cu(III) intermediate. This complex was notable due to the 1:1 Cu:phen ratio, which implied loss of one phen ligand from the proposed intermediate **[3]⁺**. To enable catalysis, **6** would require oxidation to Cu(II) in the presence of air (the terminal oxidant used in the iododeboronation process). Oxidation of CuOAc under air was therefore monitored by UV-Vis (Figure 3a) and in the presence of other reaction-relevant additives. Oxidation was not observed in air or in the presence of NaOAc or substrate **1a**. B(OH)₃, which has been effective in promoting oxidation in Chan–Lam amination reactions, also had no effect;¹⁷ however, addition of phen (Cu:phen = 1:2) and AcOH was effective at promoting the oxidation. The effect of AcOH is consistent with previous observations in Chan–Lam reactions.¹⁵⁻¹⁷ The dependence on a Cu:phen ratio of 1:2 for catalyst turnover was shown by the direct use of 10 mol% **4**, when a yield of 6% was obtained. When an additional equivalent of phen was included (with respect to Cu loading), this enabled catalytic turnover, resulting in a 70% yield (Table S5). The effect of phen stoichiometry on oxidation has been notable: oxidation of [Cu(phen)I] required an 18 h reflux, compared to [Cu(phen)₂I], where oxidation was achieved within 20 mins at 70 °C.²⁸ Heating to a minimum of 30 °C was also required for oxidation to occur (Fig. S9), with a reaction yield of 9% (i.e., one catalytic cycle) at room temperature and 70% at 30 °C (Table S2). Moreover, the EPR spectrum of the oxidation in the presence of phen was consistent with that of the proposed **[3]I** (Figure 3b).

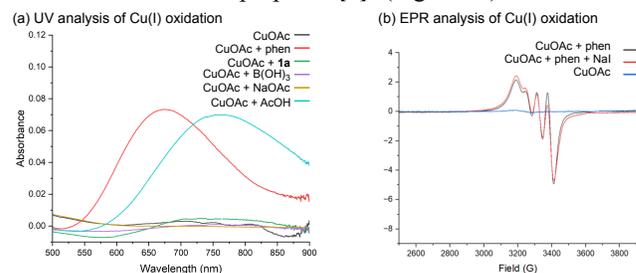


Figure 3. (a) Oxidation of CuOAc in air and in absence/presence of reaction components. (b) EPR spectra of oxidation of CuOAc + phen/NaI under air.

The above data indicated that ligand speciation, specifically relating to phen stoichiometry, varied during the reaction and Cu required one or two phen for specific mechanistic events. To shed more light on this issue and to clarify the details of the iododeboronation reaction mechanism we turned to DFT calculations (Figure 4).²⁹

The geometry computed in solution for the $[\text{Cu}(\text{phen})_2\text{OAc}]^+$ cation, **[3]⁺**, displays a distorted square-pyramidal geometry ($\tau = 0.28$ ³⁰) with an axial N-donor and a κ^1 -OAc ligand (Cu–O distances = 2.01 Å/2.70 Å), similar to the cation in the solid state structure of **[3]OAc** ($\tau = 0.42$, Cu–O = 2.00/2.64 Å²³). A variety of alternative precursor species were also assessed: 6-coordinate $\text{Cu}(\text{phen})_2(\text{OAc})_x(\text{X})_{2-x}$ (X = I, OAc; x = 0–2); cationic $[\text{Cu}(\text{phen})_2(\text{X})(\text{S})]^+$ (S = MeOH, H₂O) and mono-phen 4-coordinate $\text{Cu}(\text{phen})(\text{OAc})_x(\text{I})_{2-x}$ (see ESI for details). Of these the most accessible was $\text{Cu}(\text{phen})(\text{OAc})_2$ ($\Delta G = +3.1$ kcal/mol) while OAc/I exchange in **[3]⁺** to give 5-coordinate

[Cu(phen)₂I]⁺ (**5**)⁺ was endergonic by 5.4 kcal/mol. The computed geometry of **5**⁺ is trigonal bipyramidal ($\tau = 0.90$) in good agreement with the solid-state structure of **5**I ($\tau = 0.85$). Similar speciation studies identified [Cu(phen)₂Ph]⁺, **8**⁺, as the most stable Cu-aryl intermediate formed upon transmetalation (where Ph was used as the prototypical aryl group). **8**⁺ exhibits a distorted square-pyramidal geometry with an axial N-donor ($\tau = 0.37$). Cu(phen)₂(I)Ph, **9**, lies only 0.8 kcal/mol above **8**⁺ suggesting it would be readily accessible in solution. Loss of a phen ligand from **9** to form Cu(phen)(I)(Ph) is disfavored ($\Delta G = +7.5$ kcal/mol).

Having identified **3**⁺ and **8**⁺ as the most likely precursor and intermediate formed in the transmetalation step, we turned to the details of that process. The most accessible computed profile is shown in Figure 4a, where the acetate present in solution engages **1a** to deliver the cognate boronate.³¹ This first binds to **3**⁺ via a hydroxyl substituent to give **Int(3⁺-8⁺)1** at +11.5 kcal/mol. Dissociation of the Cu-bound acetate ligand then forms **Int(3⁺-8⁺)2** (+7.4 kcal/mol) from which the Cu-N¹ phen arm decoordinates to form **Int(3⁺-8⁺)3** (+15.3 kcal/mol), which features a strong H-bond with the Cu-bound OH of the boronate (N¹...H¹ = 1.62 Å, see also Figure 4d for the computed structure and atom labelling). This places the Ph group adjacent to a vacant site at Cu (Cu...C¹ = 2.40 Å) from which Ph group transfer can readily occur via **TS(3⁺-8⁺)** with an additional barrier of only 6.6 kcal/mol. All Cu-N bonds lengthen slightly in this transition state to accommodate the transferring phenyl group while the N¹...H¹ shortens further to 1.56 Å. The initial Cu-phenyl intermediate, **Int(3⁺-8⁺)4** (+11.1 kcal/mol), retains the B(OH)₂(OAc) side-product via Cu-O and OH...N interactions. Dissociation of this species with re-coordination of the free phen arm then forms **8**⁺ at +5.2 kcal/mol. Transmetalation therefore occurs with an accessible overall barrier of 21.9 kcal/mol, but is endergonic by 5.2 kcal/mol. This is consistent with the non-observation of any Cu-aryl species when the reaction is performed in the absence of a halide source.³²

Retention of the weakly bound κ^1 -N-phen ligand in **TS(3⁺-8⁺)** is important as in its absence the overall barrier for an equivalent mono-phen pathway increases to 34.4 kcal/mol. Alternative transition states were also located in which MeOH or H₂O solvent molecules act as H-bond acceptors to the boronate with similar overall computed barriers of 22.0 kcal/mol and 22.8 kcal/mol, respectively. Elongation of the Cu-N¹ distance was far less marked in these cases (ca. 2.53 Å) and IRC calculations indicated direct formation of **8**⁺ with expulsion of AcOB(OH)₂ (i.e., no intermediate equivalent to **Int(3⁺-8⁺)4** was located). Other pathways, including those in which HO⁻ was considered as base, proved higher in energy; in addition, transmetalation with PhBpin gave a higher overall barrier of 26.9 kcal/mol (see ESI for full details).

Once **8**⁺ is formed, iodide can readily add to give Cu(phen)₂(Ph)(I), **9** from which reductive elimination of PhI could in principle occur. However, this process would form a Cu(0) species and was shown to be thermodynamically inaccessible ($\Delta G = +18.1$ kcal/mol). Instead we propose **9** undergoes disproportionation with a further equivalent of **3**⁺ to form Cu(I) species [Cu(phen)₂]⁺, **10**⁺, and a Cu(III) species, Cu(phen)(I)(OAc)Ph, **11** (Figure 4b).

11 is the lowest of four low-spin square-pyramidal Cu(III) isomers that all lie with 4 kcal/mol; all these structures are at least

17 kcal/mol less stable when computed as a high-spin triplet. Ph-I bond forming reductive elimination from **11** then proceeds with a minimal barrier of 1.1 kcal/mol to form an initial η^2 -PhI complex at +10.5 kcal/mol (see Figure 4c). Dissociation of the PhI product forms Cu(phen)(OAc), **12**, at which AcO⁻/I⁻ substitution and dimerization yields [Cu(μ -I)(phen)]₂ **6**, at -7.9 kcal/mol.

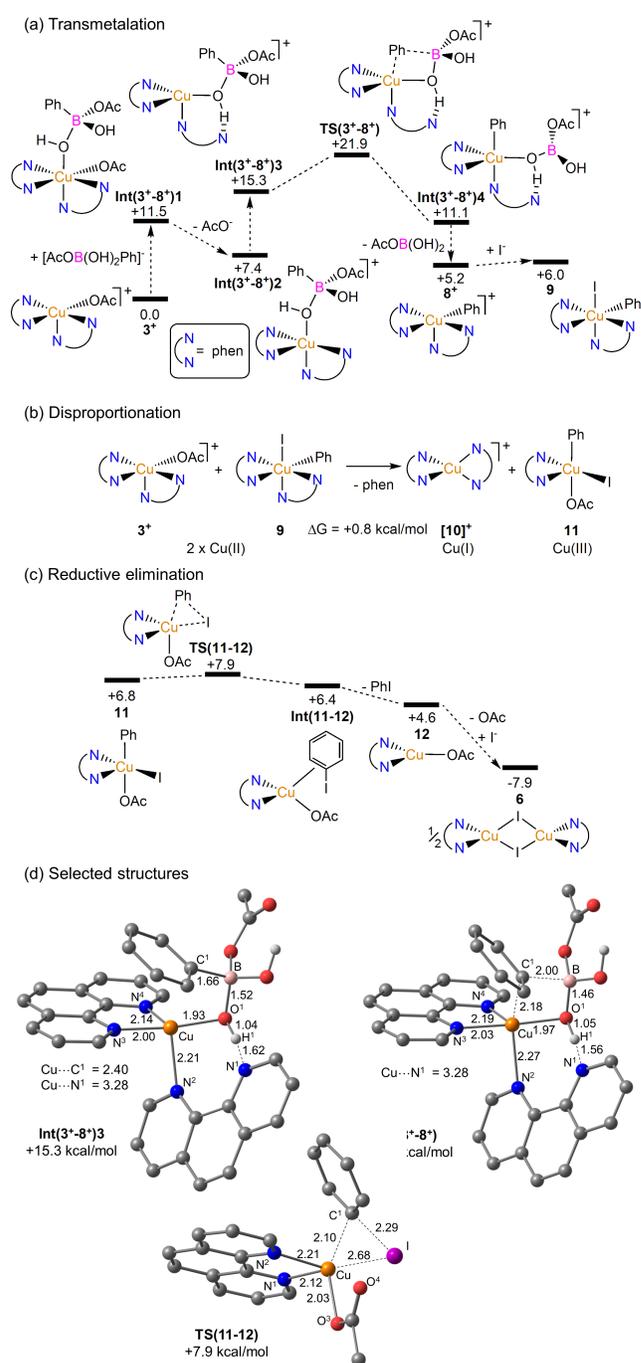
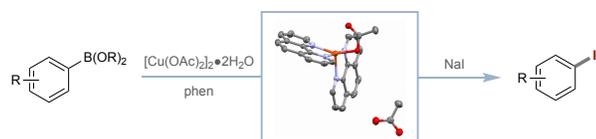


Figure 4. Computed reaction profiles (free energies, kcal/mol) for: (a) The transmetalation step linking **3**⁺ to **8**⁺ and **9** with AcO⁻ as base; (b) Disproportionation of Cu(II) intermediates **3**⁺ and **9**; and (c) Reductive elimination from Cu(III) intermediate **11**. (d) Selected computed geometries with key distances in Å and non-hydroxy H atoms omitted for clarity. See ESI for alternative pathways considered.

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Table of Contents artwork



active catalyst species identified • ligand-controlled transmetalation • turnover events rationalized