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DFT study on the *E*-stereoselective reductive A³-coupling reaction of terminal alkynes with aldehydes and 3-pyrroline[†]

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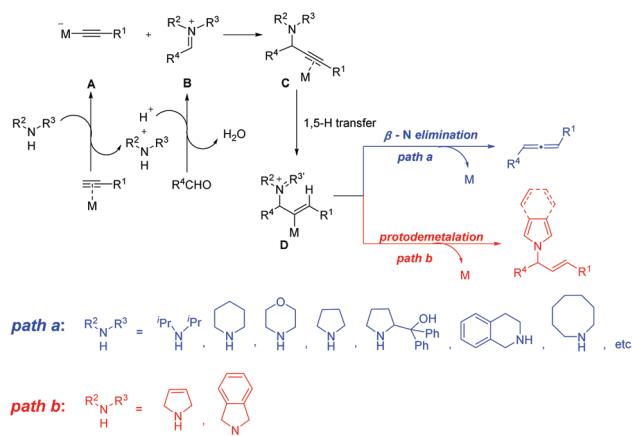
The mechanism of the Cu(i)-catalyzed reductive A³-coupling reaction of terminal alkynes with aldehydes and 3-pyrroline for the synthesis of *E*-allylic amines has been studied by DFT calculations. The calculations suggest that the pathway selectivity is determined by the activation energy difference between β -N elimination and protodemetalation from the iminium intermediate (**INT7**) formed via the rate-limiting 1,5-H transfer of the CuBr-coordinated propargylic amine (**INT4**). The stepwise intermolecular protodemetalation assisted by 3-pyrroline or water cluster proceeds more efficiently than β -N elimination, resulting in the formation of an allylic amine instead of an allene as the final product. Notably, the aromatization of the azacycle (formed from 3-pyrroline) is an essential driving force for the preference of the allylic amine products. In addition, the formation of a hydrogen bond between the hydroxyl group of the terminal alkyne and the migrating hydrogen stabilizes the transition state of the 1,5-H transfer step, thus, increasing the reaction reactivity.

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Introduction

Metal-catalyzed three-component coupling of an alkyne, an aldehyde and an amine (A³-coupling) is a straightforward protocol for preparing propargylic amines,¹ which serve as the key intermediates for the synthesis of many organic compounds.² Mechanistically, the A³-coupling involves the reaction of the *in situ* generated metal alkynylide species **A** with the iminium ion **B** that is *in situ* generated from the condensation of an aldehyde with an amine, resulting in the formation of the metal-coordinated propargylic amine **C**, which undergoes 1,5-H transfer to afford the iminium intermediate **D** (Scheme 1). Subsequent β -N elimination would produce the allene product (path a in Scheme 1).³ This mechanism has been supported by our detailed theoretical studies.^{3c} It is worth noting that the amine in these reactions can be diisopropylamine,^{2f} dicyclohexylamine,^{2g} morpholine,^{2h} pyrrolidine,^{2i,k,n} diphenylprolinol,^{2j,m} tetrahydroisoquinoline,^{2l} azocane,^{2o} and so on. Interestingly, *E*-allylic amines were obtained unexpectedly when terminal alkynes and aldehydes were treated with 3-pyrroline or isoindoline in the presence of

copper(i) (path b in Scheme 1).⁴ We presumed that the *E*-allylic amine is afforded through the protodemetalation process after the generation of the iminium intermediate **D**. Deuterium-labeling experiments have been performed to confirm that the β -position proton of *E*-allylic amines came from the azacycle and the α -position proton came from the proton in the ambient environment (Scheme 2).⁴ Here, we sought to investi-

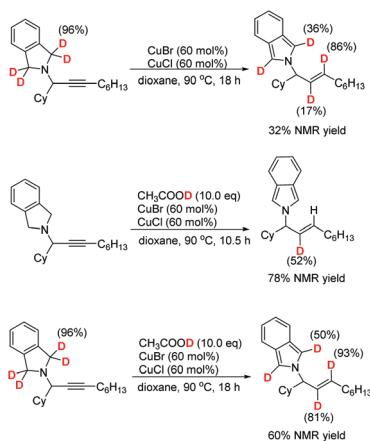


Scheme 1 (a) A general mechanism for the metal-catalyzed A³-coupling reaction followed by 1,5-H transfer and β -N elimination affording an allene (ATA reaction). (b) Reductive A³-coupling for the synthesis of *E*-allylic amines.

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Scheme 2 Deuterium-labeling experiments.

gate the detailed reaction mechanism of this Cu(i)-catalyzed⁵ reductive A³-coupling reaction, as well as the crucial role of 3-pyrroline or isoindoline. The origin of the different chemoselectivity of the afforded allylic amine or allene was also discussed.

Computational methods

DFT calculations were carried out using the Gaussian 09 software.⁶ M06-2X,⁷ including Grimme's D3 dispersion corrections, was employed to performed geometry optimizations. The LANL2DZ⁸ basis set in conjunction with the LANL2DZ pseudopotential⁹ was used for Cu and Br atoms, while the 6-31G(d,p)¹⁰ basis set was used for the other atoms. Geometry optimizations were fully carried out. Harmonic vibration frequency calculations were conducted at the same level of theory to verify the stationary points to be the minima (no imaginary frequency) or saddle points (one imaginary frequency). Intrinsic reaction coordinate (IRC)¹¹ calculations were performed to confirm the connection of the transition structures with their corresponding reactants and products. The single point energies and solvent effects in toluene ($\epsilon = 2.37$) were computed with M06-2X-D3/SDD¹²-6-311++G(d,p) basis sets by using the SMD¹³ solvation model. The solution-phase Gibbs free energy was used in the present discussions. The calculations were carried out on the exact compounds applied experimentally: 2-methylbut-3-yn-2-ol (1), cyclohexanaldehyde (2) and 3-pyrroline (3) with copper(i) bromide as the catalyst (Scheme 3).



Scheme 3

Results and discussion

The A³-coupling reaction proceeds initially from the sp C-H activation of the terminal alkyne **1** by the metal catalyst and the condensation of cyclohexanaldehyde **2** with 3-pyrroline **3**, affording the ion pair **Int3**, which consists of copper alkyne-*l*ide anion **Int1** and iminium cation **Int2**. This process leads to an energy increase of 4.0 kcal mol⁻¹, accompanied by the loss of one molecule of water. The subsequent electrophilic attack of iminium **Int2** on the copper attached C¹ *via* **TS1** requires an energy barrier of 10.1 kcal mol⁻¹, providing the propargyl amine-CuBr complex **Int4**. Subsequent isomerization of **Int4** to **Int5**, affording the precursor for 1,5-H transfer, in which CuBr and the amino group are in the *trans* position, is endergonic by 7.4 kcal mol⁻¹ relative to **Int4**.

With the envelope conformation of the pyrrolidine moiety in **Int5**, there are two axial hydrogen atoms (H¹ and H² in Fig. 1) in perfect orientation for transfer to the C² atom. The six-membered cyclic transition state for the 1,5-H transfer has been located as **TS2_1** and **TS2_2** for the transfer of H¹ and H² atoms, respectively. The free energy barrier for 1,5-H¹ transfer is calculated to be 27.7 kcal mol⁻¹ (**TS2_1** relative to **Int4**), which is lower by 1.8 kcal mol⁻¹ than that for the 1,5-H² transfer (**TS2_2**), due to the fact that H¹ is closer than H² to the C² atom (2.80 Å *vs.* 3.03 Å). Hence, **TS2_1** is more favorable, leading to the formation of *N*-allylic iminium-CuBr intermediate **Int6_1**, during which a σ bond between Cu(i) and C1 is formed. Subsequent isomerization of **Int6_1** by single-bond rotation produces the more stable species **Int7**, which is exergonic by 3.6 kcal mol⁻¹ relative to **Int6_1**. The 1,5-H transfer step features the highest free energy barrier of the whole profile (27.7 kcal mol⁻¹, **TS2_1**), and may, thus, be rate determining.

From iminium intermediate **Int7**, there are two alternative pathways: one is β-N elimination to produce the allene product (path a in Fig. 2), and the other is the protodemetalation process to afford the allylic amine (path b in Fig. 2). The optimized transition structure for path a has been located as **TS3** and **TS4**, in which the C-N and C-Cu bonds break simultaneously. The *cis* elimination from **Int7** proceeds through **TS3**, which requires an energy barrier of 24.9 kcal mol⁻¹ (**TS3** relative to **Int7**). However, the *trans* elimination through **TS4** is much easier with a barrier of 14.3 kcal mol⁻¹. The precursor for **TS4** is **Int8**, which is provided through the single-bond rotation of **Int7**. Thus, we consider that the β-N elimination should be in a *trans* manner through **TS4**, which needs to overcome a free energy barrier of 14.3 kcal mol⁻¹ to afford **Int9**. Finally, allene 5 is released from **Int9**, with an overall exergonity of 19.2 kcal mol⁻¹ (relative to **Int7**).

An alternative pathway from allyl iminium-CuBr intermediate **Int7** is the protodemetalation process to afford the allylic amine (path b in Fig. 2), which is the only product obtained experimentally. The direct intramolecular protodemetalation of **Int7** proceeds through a concerted five-membered cyclic transition structure (**TS5**), in which the deprotonation of the alkyl hydrogen (H³) adjacent to the N atom and

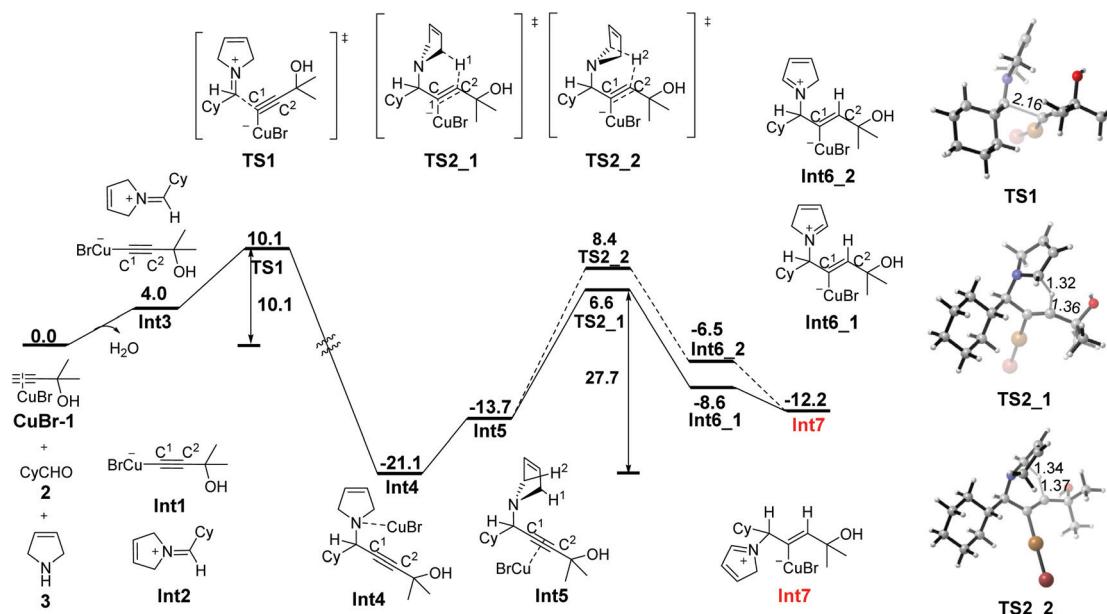


Fig. 1 Free energy profile (ΔG in kcal mol^{-1}) for the formation of the propargylic amine and the subsequent 1,5-H transfer. Bond lengths are given in angstroms.

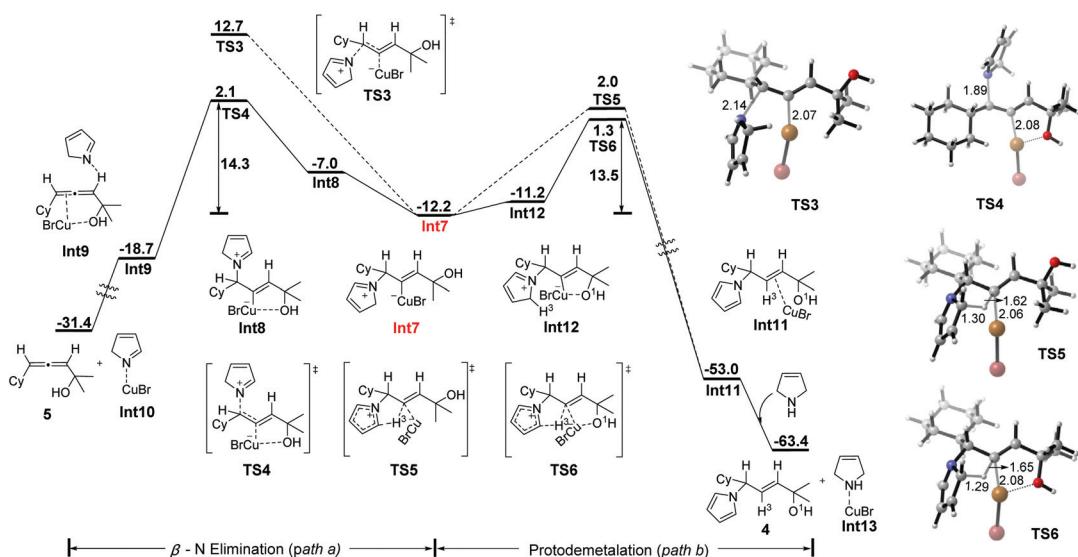


Fig. 2 Free energy profile (ΔG in kcal mol^{-1}) for either intramolecular protodemetalation or β -N elimination from Int7. Bond lengths are given in angstroms.

protodemetalation of CuBr take place simultaneously, leading to the CuBr-coordinated allylic amine **Int11**. This process is computed to be exergonic ($\Delta G = -40.8 \text{ kcal mol}^{-1}$) and requires a $14.2 \text{ kcal mol}^{-1}$ activation barrier (TS5 relative to **Int7**). However, **Int7** can isomerize to a less stable species **Int12** ($1.0 \text{ kcal mol}^{-1}$ higher in energy than **Int7**) through single-bond rotation with the hydroxyl group coordinating to the Cu atom ($d(\text{Cu}\cdots\text{O}) = 2.41 \text{ \AA}$). **Int12** may serve as the precursor for the protodemetalation process as well, which also proceeds through a concerted five-membered cyclic transition

structure (TS6). TS6 needs to overcome a free energy barrier of $13.5 \text{ kcal mol}^{-1}$, which is lower in energy by $0.7 \text{ kcal mol}^{-1}$ than TS5 ($14.2 \text{ kcal mol}^{-1}$), leading to **Int11** as well. Thus, we consider that TS6 is preferable to TS5 for the direct intramolecular protodemetalation of **Int7**. The final step of this process involves the release of the product allylic amine **4** through CuBr coordinated to another 3-pyrroline molecule, which is calculated to be exergonic by $10.4 \text{ kcal mol}^{-1}$ (relative to **Int11**) due to the strong coordination ability of nitrogen with CuBr.

The abovementioned computational results show that the direct protodemetalation is preferred over β -N elimination both kinetically and thermodynamically, indicating that an allylic amine should be obtained as the major product. However, in the experiment, allylic amines are obtained as the only products, and allenes are not observed at all. We do not think that the free energy difference of 0.8 kcal mol⁻¹ could account for the exclusive formation of allylic amines. In addition, deuterium-labeling experiments confirm that the β -position proton of allylic amines may come from not only the azacycle but also the moisture in the ambient environment (Scheme 2).⁴ Hence, the stepwise protodemetalation assisted by other molecules is taken into account. When one molecule of water is taken into consideration,¹⁴ the single bond C²–C³ in **Int7** rotates to facilitate the hydrogen bond formation between the hydroxyl group and the H⁴ in water, leading to the formation of the complex **Int14**, in which three hydrogen bonds take shape with water [$d(\text{O}^2\cdots\text{H}^3) = 2.23$ Å, $d(\text{O}^1\cdots\text{H}^4) = 1.96$ Å, $d(\text{Br}\cdots\text{H}^5) = 2.73$ Å] (Fig. 3). The deprotonation process of **Int14** involves the abstraction of the proton H³ from the azacycle by water and the subsequent protonation of the hydroxyl group, affording the intermediate **Int15**, in which the protonated hydroxyl group is stabilized by the hydrogen bond formed with water. This deprotonation process, accompanied by the aromatization of the azacycle of **Int14**, requires a free energy barrier of 8.1 kcal mol⁻¹ (TS7, relative to **Int7**). Isomerization of **Int15** to **Int16** facilitates the subsequent protodemetalation process, which takes place intramolecularly through a concerted five-membered cyclic transition state (TS8). TS8 is calculated to be higher in electronic energy by only 1.8 kcal mol⁻¹ than **Int16**. However, when the thermal correction and the solvent effect are taken into account, TS8 is slightly lower in free energy than intermediate **Int16**, indicating that the water-assisted protodemetalation could proceed with almost no barrier to afford the CuBr-coordinated allylic

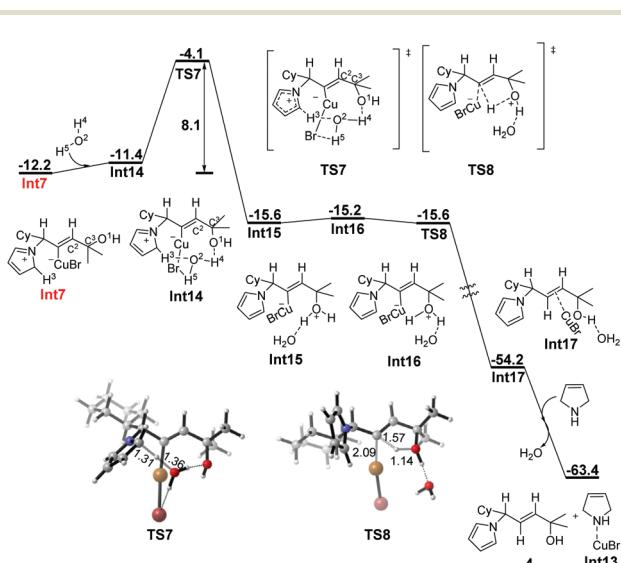


Fig. 3 Free energy profile (ΔG in kcal mol⁻¹) for H₂O-assisted stepwise protodemetalation of **Int7**. Bond lengths are given in angstroms.

amine **Int17**. Finally, the product allylic amine **4** can be obtained by the coordination of CuBr to another 3-pyrroline molecule.

When the water cluster, modeled by three molecules of water, is taken into account, a similar energy profile is obtained, which is shown in Fig. 4. The water cluster assisted deprotonation requires to overcome a lower energy barrier of 5.2 kcal mol⁻¹. Different from the one water molecule assisted pathway, the subsequent protodemetalation takes place in an intermolecular way with an energy barrier of 4.2 kcal mol⁻¹.

Calculations show that the presence of water (or water cluster) turns the direct concerted protodemetalation into a reversible stepwise deprotonation–protodemetalation process, which requires a much lower free energy barrier in total. Obviously, water (or the water cluster) may act as a proton shuttle in this process, making the protodemetalation process more kinetically favorable.

Interestingly, when an additional 3-pyrroline was taken into account as the proton shuttle, another kinetically favorable pathway of the stepwise deprotonation–protodemetalation process was discovered (Fig. 5). All efforts to locate the hydrogen-bonding complex of 3-pyrroline with **Int7** were unsuccessful. When the N atom of 3-pyrroline approaches the proton H³ of the azacycle of **Int7**, the abstraction of H³ takes place immediately, indicating that the deprotonation process of **Int7** requires no barrier in the presence of 3-pyrroline. The abstraction of the proton H³ from **Int7** produces **Int21**, which is exergonic by 24.5 kcal mol⁻¹, accompanied by the aromatization of the azacycle. The subsequent protodemetalation takes place intermolecularly by the protonated 3-pyrroline through **TS11** with an energy barrier of 2.3 kcal mol⁻¹, affording the more stable CuBr-coordinated allyl amine **Int22**. Finally, the coordination of CuBr with 3-pyrroline releases allylic amine **4** to com-

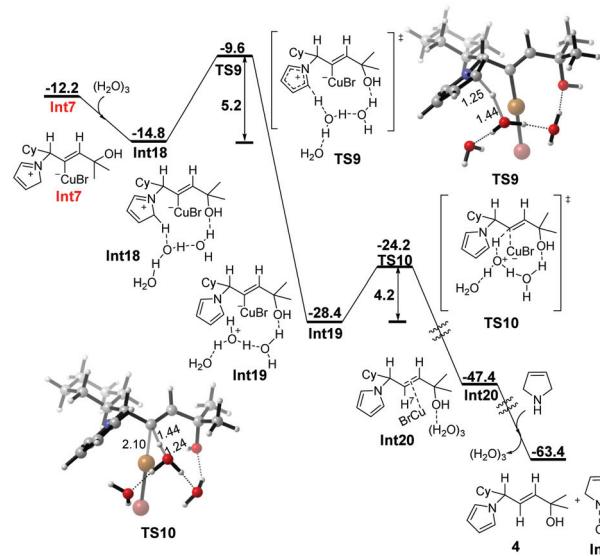


Fig. 4 Free energy profile (ΔG in kcal mol⁻¹) for water cluster-assisted stepwise protodemetalation of **Int7**. Bond lengths are given in angstroms.

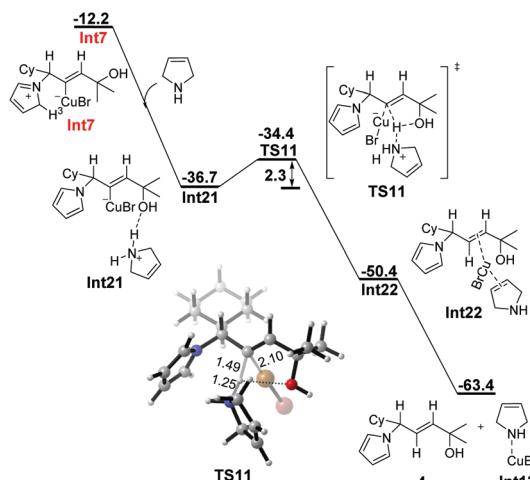


Fig. 5 Free energy profile (ΔG in kcal mol^{-1}) for 3-pyrroline-assisted stepwise protodemetalation of **Int7**. Bond lengths are given in angstroms.

plete the whole process. Thus, an extra 3-pyrroline molecule could also act as the proton shuttle to change the concerted protodemetalation process to a stepwise deprotonation–protodemetalation process. But different from the water (or water cluster) involved pathway, the rate-limiting step of the 3-pyrroline assisted process is the protodemetalation step with an activation barrier of only 2.3 kcal mol^{-1} .

The propargylic alcohol **1**, as one of the reactants, may also act as a proton shuttle to assist the protodemetalation process (Fig. 6). The computed potential energy surface is qualitatively similar to that of the one water molecule assisted pathway, but with more energy demanded in the deprotonation step, which needs to overcome an activation barrier of 10.1 kcal mol^{-1}

(**TS12**). The following protodemetalation proceeds intramolecularly with an energy barrier of 1.8 kcal mol^{-1} .

The normal terminal alkynes with no hydroxy group present relatively lower reactivities in the experimental studies.⁴ For example, when using 1-octyne under the standard reaction conditions, the *E*-allylic amine was also formed with a lower yield (20% NMR yield), accompanied by 70% NMR yield of the propargylic amine.⁴ The effect of the hydroxyl group in 2-methylbut-3-yn-2-ol (**1**) was further rationalized by DFT calculations on comparison with the 1-octyne-participated system.¹⁵ The computed potential energy surfaces are qualitatively similar to those of the 2-methylbut-3-yn-2-ol (**1**)-involved system, but with more free energy demanded in the rate-limiting 1,5-H transfer step [28.8 kcal mol^{-1} (**TS15_1**) vs. 27.7 (**TS2_1**)], which is in accordance with the experimental observations. As shown in Fig. 7, the hydrogen bond, formed

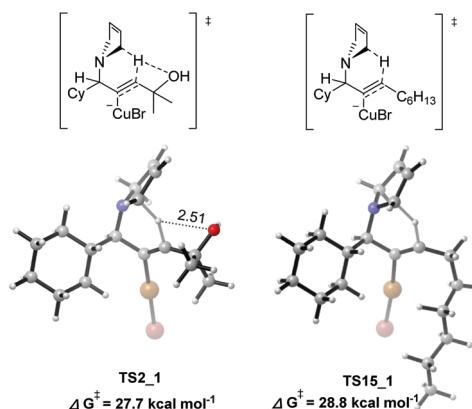


Fig. 7 Optimized transition structures for 1,5-H transfer. Bond lengths are given in angstroms.

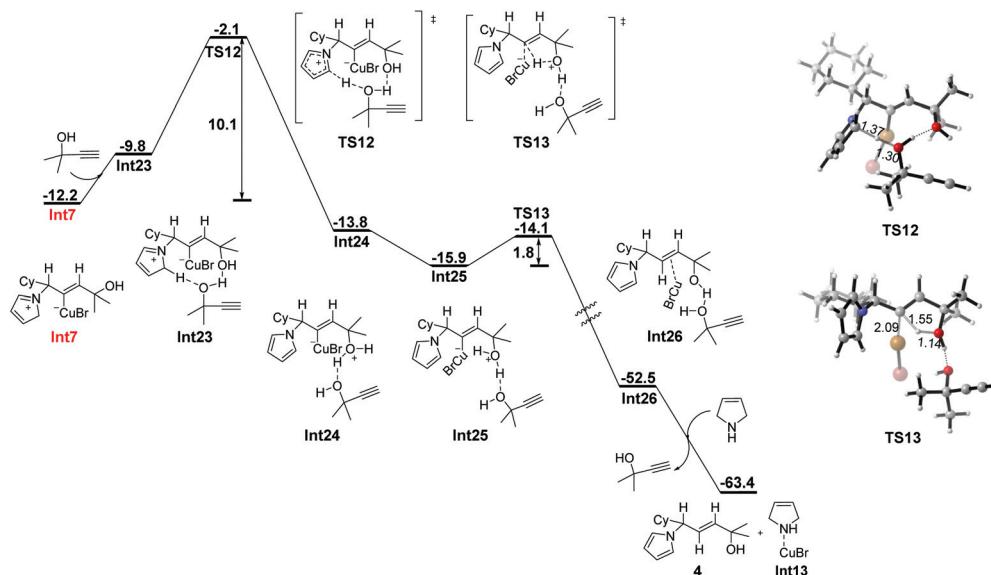


Fig. 6 Free energy profile (ΔG in kcal mol^{-1}) for propargylic alcohol-assisted stepwise protodemetalation of **Int7**. Bond lengths are given in angstroms.

Table 1 Activation energies (ΔG in kcal mol⁻¹) for the processes from **Int7**

Protodemetalation						
Assisting species	None ^a	H ₂ O	(H ₂ O) ₃			β -N Elimination
Deprotonation	13.5	8.1	5.2	No barrier	10.1	14.3
Protodemetalation		No barrier	4.2	2.3	1.8	

^a The protodemetalation proceeds in a concerted manner.

between the hydroxyl group and the migrating hydrogen [$d(\text{O}\cdots\text{H}) = 2.51 \text{ \AA}$] in **TS2_1**, facilitates the 1,5-H transfer, resulting in the enhanced stability of **TS2_1**.

Conclusions

The activation energies for the stepwise deprotonation–protodemetalation process of **Int7** assisted by different species are presented separately in Table 1, together with the energy barrier of the β -N elimination process. It is obvious that the direct intramolecular pathway without the aid of other species is unfavorable, owing to the high energy demand of 13.5 kcal mol⁻¹. The presence of different assisting species makes the concerted intramolecular process an irreversible stepwise deprotonation–protodemetalation process, reducing the activation barrier significantly. Among the four assisting species, 3-pyrroline shows the highest activity in the deprotonation step owing to the relatively strong basicity of the N atom. Once the rate-limiting 1,5-H transfer completes, the deprotonation–protodemetalation process takes place immediately with the aid of 3-pyrroline to afford the final allylic amine product. It is noteworthy that without 3-pyrroline (or isoindoline) in the reaction system, other species, such as water cluster, could also act as the proton shuttle to assist the protodemetalation, which is in agreement with the observation in deuterium-labeling experiments (Scheme 2). Significantly, the aromatization of the azacycle is the essential driving force for the protodemetalation process.

The pathway selectivity is determined by the activation energy difference between β -N elimination and the protodemetalation from the intermediate **Int7** formed *via* the 1,5-H transfer. Consistent with the experimental observations, with 3-pyrroline, protodemetalation is favored over β -N elimination by 12.0 kcal mol⁻¹ (14.3 kcal mol⁻¹ *vs.* 2.3 kcal mol⁻¹), leading to the overwhelming formation of the allylic amine product. However, all the other amines listed in Scheme 1, other than 3-pyrroline and isoindoline, completely reverse the pathway selectivity, providing allenes as the final products. Due to the lack of the driving force arising from the aromatization of the azacycle, the protodemetalation of the intermediate **D** (Scheme 1) is rather difficult. Therefore, β -N elimination

becomes the favorable pathway for the classical ATA reactions using the amines except 3-pyrroline or isoindoline.

In summary, the mechanism of this Cu(i)-catalyzed reductive A³-coupling reaction affording *E*-allylic amines was investigated by DFT calculations in detail. The calculations disclose that 3-pyrroline (or isoindoline) serves not only as a reactant but also as a shuttle in a proton relay to assist the protodemetalation step, resulting in the production of an allylic amine other than an allene. Importantly, the calculations reveal the factors governing the selectivity: the aromatization of the azacycle (formed from 3-pyrroline or isoindoline) is the essential driving force for the preference of the allylic amine products. Furthermore, we also discovered that formation of a hydrogen bond with the migrating hydrogen to facilitate the rate-determining 1,5-H transfer step is the key role of the hydroxyl group in the terminal alkyne substrate in the reactivity.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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