

RESEARCH ARTICLE

View Article Online
View Journal | View IssueCite this: *Org. Chem. Front.*, 2024,
11, 690Received 23rd October 2023,
Accepted 4th December 2023

DOI: 10.1039/d3qo01749d

rsc.li/frontiers-organic

Asymmetric copper-catalyzed alkynylallylic dimethylation†

Si-Yuan Luo,^{a,b,c} Guo-Qiang Lin^{a,b} and Zhi-Tao He^{b,c,d}

A feasible protocol for Cu-catalyzed asymmetric alkynylallylic dimethylation is developed with the discovery of tetramethyldiaminomethane as a new, stable and convenient surrogate of dimethylamine. A series of enantioenriched 1,4-enynes are constructed in reasonable yields, high regioselectivities and moderate to good enantioselectivities. Mechanistic experiments show that the tertiary amine works as a nucleophile directly followed by the release of the expected dialkylamine unit, different from the conventional primary and secondary amines with the cleavage of a proton as the nucleophile. DFT calculations elucidate the origin of regio- and enantioselectivity for the present transformation.

Introduction

Transition metal-catalyzed η^3 -substitution reactions have been widely used for the construction of different stereogenic centers.^{1–6} In particular, since the pioneering work of van Maarseveen⁷ and Nishibayashi⁸ groups, Cu-catalyzed propargylic substitution has emerged as a reliable strategy to introduce C–N,^{9–16} C–O,^{17–20} C–C^{21–29} and C–S^{30,31} bonds vicinal to an alkyne unit stereoselectively. In this case, a propargylic leaving group is required to be prepared for the following generation of a critical Cu-allenylidene intermediate. However, when a leaving group is located at a remote position to the alkyne unit, such a motif is generally not considered a potential substrate for propargylic substitution. Recently, Fang,³² Xu³³ and our group^{34,35} independently demonstrated the concept of Cu-catalyzed remote propargylic substitution reactions. In these studies, an olefin^{32–34} or aryl unit³⁵ was used to link the alkyne unit and the γ -leaving group, and the reactive alkene-tethered or dearomatization-induced Cu-allenylidene intermediate was smoothly formed to induce the expected substitution. In particular, our group³⁴ and Xu³³ sequentially described the first asymmetric alkynylallylic substitution processes, in which both S_N2' and *in situ* substitution models were shown to be feasible

to form chiral 1,4-enyne products and spirocycles, respectively. However, the substrate scope and reaction models are heavily limited to the use of common nucleophiles. Thus, the discovery of new applications and the establishment of efficient catalytic systems suitable for the less developed remote propargylic substitution reactions are highly desired.

The chiral dimethylamino unit exists widely in bioactive molecules, such as rivastigmine,³⁶ which is used to treat Alzheimer's disease, and the tetracycline family including tetracycline, doxycycline and tigecycline, a series of broad-spectrum antibiotics³⁷ (Scheme 1a). Based on our previous work,³⁴ we envisioned that with dimethylamine as the nucleophile, Cu-catalyzed asymmetric alkynylallylic substitution might provide a novel and valuable route to construct chiral 1,4-enynes bearing a dimethylamino stereocenter. The vicinal olefin and alkyne units could further be transformed into a series of functional groups, thus largely broadening the application potential of this methodology. However, dimethylamine is gaseous at room temperature and usually stored in special solvents, which limits the convenient use of this reagent and also influences the efficiency of the corresponding transformation (Scheme 1b). Therefore, the identification of different and efficient surrogates of the dimethylamine nucleophile is critical to realize the expected alkynylallylic dimethylation reaction. Here, we discovered that tetramethyldiaminomethane³⁸ worked as a novel and reliable precursor of dimethylamine and enabled enantioselective Cu-catalyzed alkynylallylic dimethylaminations to construct valuable chiral 1,4-enynes³⁹ (Scheme 1b). A variety of 1,4-enynes bearing a dimethylamino stereocenter were constructed in good yields and moderate to good enantioselectivities. Mechanistic experiments and DFT calculations elucidated the origin of regio- and enantioselectivity and revealed that tetramethyldiaminomethane first participated in the reaction as a neutral

^aState Key Laboratory of Chemical Biology, Shanghai Institute of Organic Chemistry, University of Chinese Academy of Sciences, Shanghai, 200032, China.

E-mail: hezt@sioc.ac.cn

^bSchool of Physical Science and Technology, ShanghaiTech University, Shanghai, 201210, China

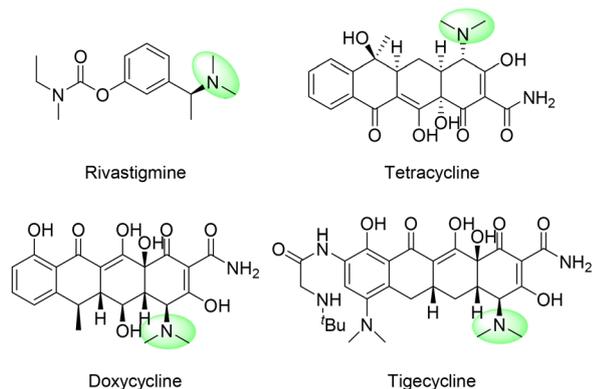
^cState Key Laboratory of Organometallic Chemistry, Shanghai Institute of Organic Chemistry, University of Chinese Academy of Sciences, Shanghai, 200032, China

^dSchool of Chemistry and Materials Science, Hangzhou Institute for Advanced Study, University of Chinese Academy of Sciences, Hangzhou 310024, China

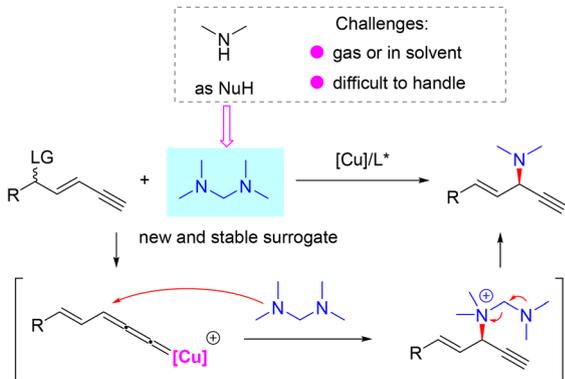
†Electronic supplementary information (ESI) available. See DOI: <https://doi.org/10.1039/d3qo01749d>



a. Selected drugs containing dimethylamino stereocenter



b. This work: Cu-catalyzed asymmetric alkynylallylic dimethylaminations



Scheme 1 Representative drugs with dimethylamino stereocenters and our design.

tertiary amine nucleophile and then released the dimethylamino unit from the ammonium intermediate.

Results and discussion

We initiated the reaction with racemic 1,3-enyne **1a** as the electrophile and tetramethyldiaminomethane (**2a**) as a new dimethylamine source under copper(I) catalysis (Table 1). A set of PyBox ligands which were proven to be efficient for stereocontrol in the previous alkynylallylic substitutions^{32–34} were evaluated first. When **L1** was used, the reaction proceeded smoothly, providing **3a** in a total 42% yield, 75:25 er and 2.5:1 rr (entry 1). Other PyBox ligands showed similar reactivity and stereocontrol effects to **L1** as the ligand (entries 2–5). However, when **L6** was used as the ligand, **3a** was obtained in a high yield and good stereoselectivity, *i.e.*, 94% yield, 19:1 rr and 91:9 er (entry 6). When the solvent was changed to EtOH or DCM, obvious erosion of the yield and enantioselectivity of **3a** was observed (entries 7 and 8). Reducing the loading of the ligand led to a slight increase in the enantioselectivity, reaching 93:7 er (entry 9). The evaluations of reaction temperature were unfavourable to the regio- and enantioselectivity of **3a** (entries 10–12). In addition, when OBoc as the leaving group in **1a** was changed to OAc, the alkynylallylic amination pro-

Table 1 Optimization of the reaction conditions^a

Entry	L*	Yield (%)	rr	er
1	L1	42	2.5:1	75:25
2	L2	39	1:1	77:23
3	L3	34	1.2:1	81:19
4	L4	58	15:1	73:27
5	L5	45	1.9:1	54:46
6	L6	94	19:1	91:9
7 ^b	L6	66	13:1	86:14
8 ^c	L6	21	>20:1	56:44
9 ^d	L6	90	>20:1	93:7
10 ^{d,e}	L6	72	10:1	91:9
11 ^{d,f}	L6	79	>20:1	90:10
12 ^{d,g}	L6	55	11:1	87:13
13 ^{d,h}	L6	55	>20:1	90:10
14 ^{d,i}	L6	68	3.8:1	79:21

L1, R = Me
L2, R = *i*Bu
L3, R = Cy
L4, R = Ph

L5

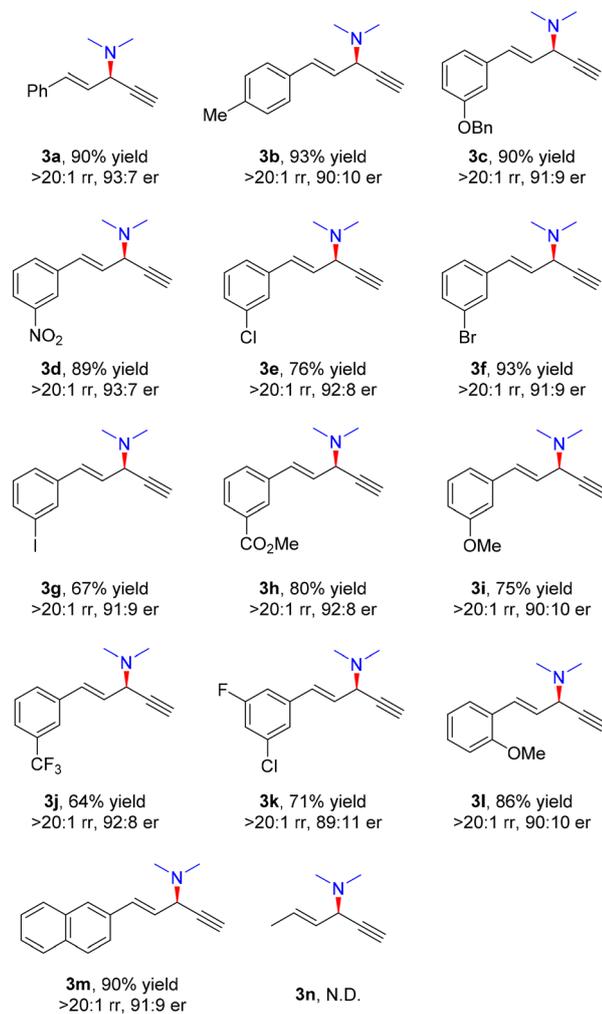
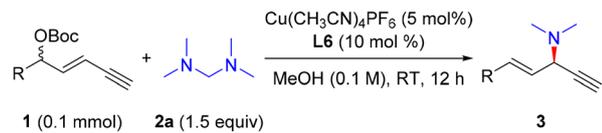
L6

^a The reactions were carried out on a 0.1 mmol scale. The yields and rr values were determined by crude ¹H NMR. The er values were determined by HPLC analysis. ^b EtOH as the solvent. ^c DCM as the solvent. ^d **L6** (10 mol%) was added. Isolated yield. ^e The reaction temperature was –20 °C. ^f The reaction temperature was –10 °C. ^g The reaction temperature was 60 °C. ^h OAc was used instead of OBoc as the leaving group. ⁱ Dimethylamine was used as the nucleophile.

ceeded with lowered efficiency and stereocontrol (entry 13). Thus, the optimal conditions for alkynylallylic substitution were identified as the combination of 1,3-enyne **1a** (1 equiv.), nucleophile **2a** (1.5 equiv.), Cu(MeCN)₄PF₆ (5 mol%) and **L6** (10 mol%) in MeOH (0.1 M) at room temperature for 12 h. In this context, when dimethylamine in methanol solution was used directly as the nucleophile, a heavily decreased yield, regioselectivity and enantioselectivity of **3a** were observed (entry 14).

With the optimal conditions in hand, we investigated the scope of 1,3-enyne electrophiles for this remote propargylic dimethylation reaction and the results are summarized in Scheme 2. Various electron-rich and electron-deficient functional groups at the *para*- or *meta*-positions of aryl-substituted 1,3-enynes **1** showed high compatibility with the substitution. For example, alkoxy, nitril, halide, and ester moieties were well tolerated in the reaction, providing the corresponding di-

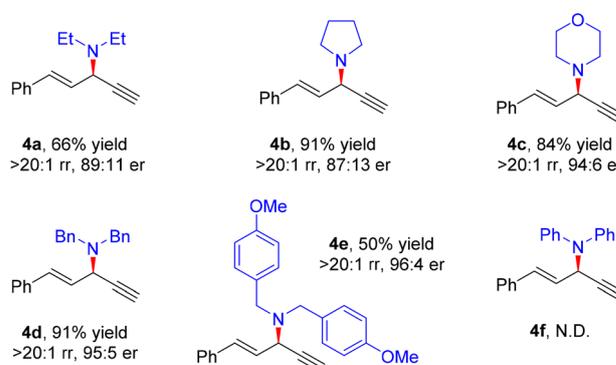




Scheme 2 The scope of electrophiles. The reactions were carried out on a 0.1 mmol scale. Isolated yields. The rr values were determined by ^1H NMR. The er values were determined by HPLC analysis.

methylamination products in 64–93% yields with generally >20:1 rr and >90:10 er (**3b–3j** and **3m**). Notably, substrates that are prone to cross-coupling reactions also yielded amination products smoothly (**3f** and **3g**). Multi-substituted aryl enyne was also a suitable electrophile for the transformation (**3k**). In addition, 1,3-enyne bearing an *ortho*-methoxy unit afforded **3l** in 86% yield, >20:1 rr and 90:10 er. However, alkyl-derived enyne as the electrophile failed to undergo the alkynylallylic dimethylation reaction (**3n**).

After demonstrating the feasibility of the remote propargylic dimethylation with this novel dimethylamine source, we further explored the application potential of this protocol with other amine nucleophiles and the results are summarized in Scheme 3. A set of secondary amine sources as the surrogates



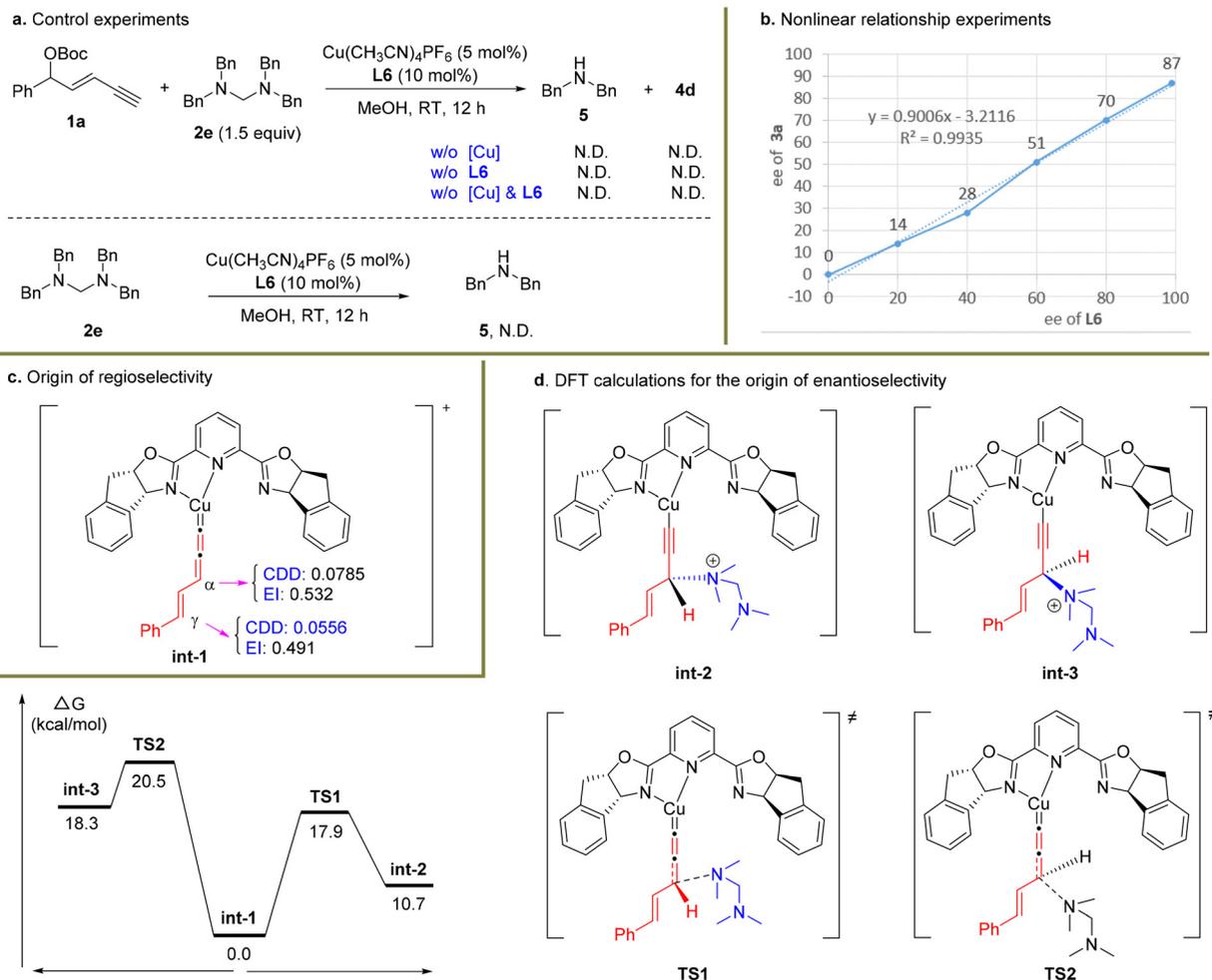
Scheme 3 The scope of amine precursors. The reactions were carried out on a 0.1 mmol scale. Isolated yields. The rr values were determined by ^1H NMR. The er values were determined by HPLC analysis.

of dimethylamine, pyrrolidine and morpholine were suitable for the alkynylallylic substitution, furnishing the corresponding products **4a–4c** in high yields, >20:1 regioselectivity and up to 94:6 er. This strategy was also applicable to the introduction of different diarylmethyl amines, and the corresponding products **4d** and **4e** were obtained in 95:5 and 96:4 er, respectively. The absolute configuration of **4d** was determined to be (*R*)-**4d** based on the same reported compound.^{34a} However, the introduction of the diarylamine moiety *via* this route did not work (**4f**).

To figure out the potential reaction mechanism, a set of mechanistic studies were conducted (Scheme 4). As it was unclear whether the nucleophile **2a** underwent the substitution *via* the *in situ* release of dimethylamine or serving as the tertiary amine nucleophile first and then releasing the dimethylamine unit, several control experiments were carried out with **2e** as the substrate (Scheme 4a). When the reaction was conducted under standard conditions without a Cu catalyst or ligand or Cu/ligand, no product **4d** was formed in these cases. In particular, dibenzylamine **5** was not detected. When electrophile **1a** was not used under the standard conditions, no dibenzylamine **5** was observed similarly. These facts indicated that the *in situ* generation of **5** from **2e** might be unfavourable under the present reaction system, and tertiary amine **2e** might directly work as the nucleophile.³⁸

Next, a nonlinear relationship experiment showed a linear curve between the enantiopurity of chiral ligand **L6** and that of the product **3a** (Scheme 4b). This result suggested that mono-copper/**L6** as the catalyst might be involved in the enantio-determining step. Based on this fact, DFT calculations were conducted to uncover the origin of regio- and enantio-selectivity for the alkynylallylic amination reaction. Both the condensed dual descriptor (CDD) and electrophilicity index (EI) were determined for the optimized structure of **int-1**

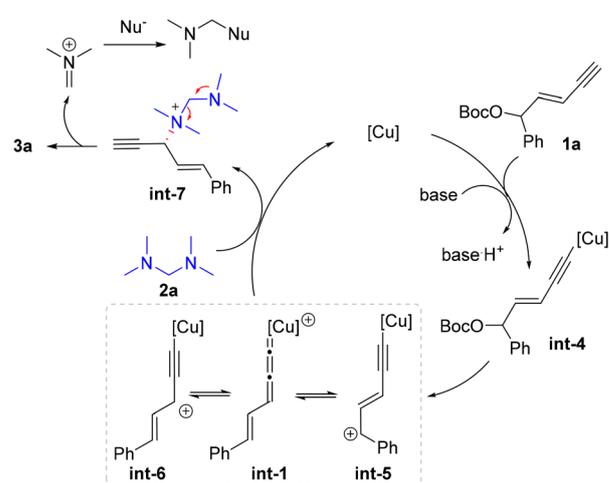




Scheme 4 Preliminary mechanistic studies. BP86/def2tzvp/SMD(methanol)//B3LYP-D3(BJ)/6-31g*/SDD was used for DFT calculations.

(Scheme 4c).^{40,41} The relatively larger CDD and EI data for the α -carbon center than those for the γ -carbon center showed that the α -carbon center is more electrophilic than the γ -carbon center. This is consistent with the observed preferred nucleophilic attack at the α -carbon position. Finally, calculations were conducted to uncover the energy profile of enantioselective substitution processes (Scheme 4d). It was obvious that the *Re*-face nucleophilic attack occurred *via* **TS1** with only 17.9 kcal mol⁻¹ while the *Si*-face nucleophilic attack *via* **TS2** was 20.5 kcal mol⁻¹. Therefore, the (*R*)-configuration for the formed stereocenter was observed in the present transformation.

Based on the above experimental and computational results, the proposed catalytic cycle is described in Scheme 5. The enyne substrate **1a** first reacted with the copper catalyst in the presence of a base to give alkyne copper intermediate **int-4**, which sequentially generated the Cu-allenylidene intermediate **int-1** and tautomers **int-5** and **int-6** *via* the cleavage of the leaving group. Then an outer-sphere nucleophilic attack by tertiary amine **2a** occurred to provide ammonium salt **int-7**, which then released product **3a** and regenerated the Cu cata-



Scheme 5 Proposed mechanism.

lyst. The released dimethylaminium might be further captured by potential nucleophiles in the reaction systems, such as methoxide.^{38,42}



Conclusions

In summary, we have established a feasible protocol for an asymmetric alkynylallylic dimethylamination reaction with the use of tetramethylmethanediamine as a new dimethylamine source. The novel protocol features reasonable functional group compatibility, high regioselectivity and moderate to good enantioselectivity. Different from the commonly used primary and secondary amines as nucleophiles with the cleavage of a proton, mechanistic experiments support the involvement of the tertiary amine as a neutral nucleophile directly followed by the release of dialkylamine. DFT calculations further elucidate the origin of regio- and enantioselectivity for the alkynylallylic substitution reaction.

Author contributions

Z.-T. H. conceived the project. S.-Y. L. conducted the experiments and calculations. Z.-T. H. and G.-Q. L. supervised the project. Z.-T. H. and S.-Y. L. co-wrote the manuscript with feedback from all authors. Yuan-Xiang Yang is acknowledged for checking some results.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We acknowledge the National Natural Science Foundation of China (22371292 and 22071262), the Natural Science Foundation of Ningbo (2023J036), the Shanghai Municipal Committee of Science and Technology (22ZR1475200), and the Shanghai Institute of Organic Chemistry for financial support.

References

- L. Süsse and B. M. Stoltz, Enantioselective formation of quaternary centers by allylic alkylation with first-row transition-metal catalysts, *Chem. Rev.*, 2021, **121**, 4084–4099.
- G. Li, X. Huo, X. Jiang and W. Zhang, Asymmetric synthesis of allylic compounds via hydrofunctionalisation and difunctionalisation of dienes, allenes, and alkynes, *Chem. Soc. Rev.*, 2020, **49**, 2060–2118.
- R. J. Detz, H. Hiemstra and J. H. Van Maarseveen, Catalyzed propargylic substitution, *Eur. J. Org. Chem.*, 2009, 6263–6376.
- Y. Miyake, S. Uemura and Y. Nishibayashi, Catalytic propargylic substitution reactions, *ChemCatChem*, 2009, **1**, 342–356.
- D.-Y. Zhang and X.-P. Hu, Recent advances in copper-catalyzed propargylic substitution, *Tetrahedron Lett.*, 2015, **56**, 283–295.
- K. Sakata and Y. Nishibayashi, Mechanism and reactivity of catalytic propargylic substitution reactions via metal-allylidene intermediates: a theoretical perspective, *Catal. Sci. Technol.*, 2018, **8**, 12–25.
- R. J. Detz, M. M. Delville, H. Hiemstra and J. H. Van Maarseveen, Enantioselective copper-catalyzed propargylic amination, *Angew. Chem., Int. Ed.*, 2008, **47**, 3777–3780.
- G. Hattori, H. Matsuzawa, Y. Miyake and Y. Nishibayashi, Copper-catalyzed asymmetric propargylic substitution reactions of propargylic acetates with amines, *Angew. Chem., Int. Ed.*, 2008, **47**, 3781–3783.
- C. Zhang, Y.-H. Wang, X.-H. Hu, Z. Zheng, J. Xu and X.-P. Hu, Chiral tridentate *P,N,N* ligands for highly enantioselective copper-catalyzed propargylic amination with both primary and secondary amines as nucleophiles, *Adv. Synth. Catal.*, 2012, **354**, 2854–2858.
- G. Hattori, K. Sakata, H. Matsuzawa, Y. Tanabe, Y. Miyake and Y. Nishibayashi, Copper-catalyzed enantioselective propargylic amination of propargylic esters with amines: copper-allylidene complexes as key intermediates, *J. Am. Chem. Soc.*, 2010, **132**, 10592–10608.
- R. J. Detz, Z. Abiri, R. I. Griel, H. Hiemstra and J. H. Van Maarseveen, Enantioselective copper-catalyzed propargylic substitution: synthetic scope study and application in formal total syntheses of (+)-anisomycin and (-)-cytoxazone, *Chem. – Eur. J.*, 2011, **17**, 5921–5930.
- T. Mino, H. Taguchi, M. Hashimoto and M. Sakamoto, Copper-catalyzed asymmetric propargylic amination of propargylic acetates with amines using BICMAP, *Tetrahedron: Asymmetry*, 2013, **24**, 1520–1523.
- M. Shibata, K. Nakajima and Y. Nishibayashi, Enantioselective intramolecular propargylic amination using chiral copper-pybox complexes as catalysts, *Chem. Commun.*, 2014, **50**, 7874–7877.
- D.-Y. Zhang, L. Shao, J. Xu and X.-P. Hu, Copper-catalyzed asymmetric formal [3 + 2] cycloaddition of propargylic acetates with hydrazines: enantioselective synthesis of optically active 2-pyrazolines, *ACS Catal.*, 2015, **5**, 5026–5030.
- Z.-T. Liu, Y.-H. Wang, F.-L. Zhu and X.-P. Hu, Enantioselective copper-catalyzed formal [4 + 2] cycloaddition of o-aminophenol derivatives with propargylic esters for synthesis of optically active 3,4-dihydro-2H-1,4-benzoxazines, *Org. Lett.*, 2016, **18**, 1190–1193.
- W. Guo, L. Zuo, M. Cui, B. Yan and S. Ni, Propargylic amination enabled the access to enantioenriched acyclic α -quaternary α -amino ketones, *J. Am. Chem. Soc.*, 2021, **143**, 7629–7634.
- K. Nakajima, M. Shibata and Y. Nishibayashi, Copper-catalyzed enantioselective propargylic etherification of propargylic esters with alcohols, *J. Am. Chem. Soc.*, 2015, **137**, 2472–2475.
- R.-Z. Li, H. Tang, K.-R. Yang, L.-Q. Wan, X. Zhang, J. Liu, Z. Fu and D.-W. Niu, Enantioselective propargylation of polyols and desymmetrization of meso 1,2-diols by copper/boronic acid dual catalysis, *Angew. Chem., Int. Ed.*, 2017, **56**, 7213–7217.



- 19 R.-Z. Li, D.-Q. Liu and D.-W. Niu, Asymmetric *O*-propargylation of secondary aliphatic alcohols, *Nat. Catal.*, 2020, **3**, 672–680.
- 20 Y. Hou, Z. Zhang, X. Sun, Z. Yang, Y.-X. Luan and P. Tang, Copper-catalyzed enantioselective trifluoromethoxylation of propargyl sulfonates, *Angew. Chem., Int. Ed.*, 2023, **62**, e202218919.
- 21 P. Fang and X.-L. Hou, Asymmetric copper-catalyzed propargylic substitution reaction of propargylic acetates with enamines, *Org. Lett.*, 2009, **11**, 4612–4615.
- 22 F.-L. Zhu, Y. Zou, D.-Y. Zhang, Y.-H. Wang, X.-H. Hu, S. Chen, J. Xu and X.-P. Hu, Enantioselective copper-catalyzed decarboxylative propargylic alkylation of propargyl beta-ketoesters with a chiral ketimine *P,N,N*-ligand, *Angew. Chem., Int. Ed.*, 2014, **53**, 1410–1414.
- 23 W. Shao, H. Li, C. Liu, C. J. Liu and S.-L. You, Copper-catalyzed intermolecular asymmetric propargylic dearomatization of indoles, *Angew. Chem., Int. Ed.*, 2015, **54**, 7684–7687.
- 24 K. Tsuchida, Y. Senda, K. Nakajima and Y. Nishibayashi, Construction of chiral tri- and tetra-arylmethanes bearing quaternary carbon centers: copper-catalyzed enantioselective propargylation of indoles with propargylic esters, *Angew. Chem., Int. Ed.*, 2016, **55**, 9728–9732.
- 25 Q. Wang, T.-R. Li, L.-Q. Lu, M.-M. Li, K. Zhang and W.-J. Xiao, Catalytic asymmetric [4 + 1] annulation of sulfur ylides with copper-allenylidene intermediates, *J. Am. Chem. Soc.*, 2016, **138**, 8360–8363.
- 26 K. Zhang, L.-Q. Lu, S. Yao, J.-R. Chen, D.-Q. Shi and W.-J. Xiao, Enantioconvergent copper catalysis: in situ generation of the chiral phosphorus ylide and its Wittig reactions, *J. Am. Chem. Soc.*, 2017, **139**, 12847–12854.
- 27 J. Song, Z.-J. Zhang and L.-Z. Gong, Asymmetric [4 + 2] annulation of C1 ammonium enolates with copper-allenylidenes, *Angew. Chem., Int. Ed.*, 2017, **56**, 5212–5216.
- 28 H.-D. Qian, Z.-H. Li, S. Deng, C. Yao, H.-M. Xiang, G. Xu, Z.-Q. Geng, Z. Wang, L. Chen, C. Liu, C. Zhu, X. Qi and H. Xu, Catalytic asymmetric vinylogous and bisvinylogous propargylic substitution, *J. Am. Chem. Soc.*, 2022, **144**, 15779–15785.
- 29 F. Gong, X. Meng, S. Lan, J. Liu, S. Yang and X. Fang, Asymmetric semipinacol rearrangement enabled by copper-catalyzed propargylic alkylation, *ACS Catal.*, 2022, **12**, 12036–12044.
- 30 J. E. Gomez, A. Cristofol and A. W. Kleij, Copper-catalyzed enantioselective construction of tertiary propargylic sulfones, *Angew. Chem., Int. Ed.*, 2019, **58**, 3903–3907.
- 31 X. Gao, Y.-L. Xiao, S. Zhang, J. Wu and X.-G. Zhang, Copper-catalyzed enantioselective trifluoromethylthiolation of secondary propargyl sulfonates, *CCS Chem.*, 2021, **3**, 1463–1471.
- 32 S. Niu, Y. Luo, C. Xu, J. Liu, S. Yang and X. Fang, Copper-catalyzed γ -allylic substitutions using stabilized nucleophiles, *ACS Catal.*, 2022, **12**, 6840–6850.
- 33 H.-H. Kong, C. Zhu, S. Deng, G. Xu, R. Zhao, C. Yao, H.-M. Xiang, C. Zhao, X. Qi and H. Xu, Remote enantioselective [4 + 1] annulation with copper-vinylidene intermediates, *J. Am. Chem. Soc.*, 2022, **144**, 21347–21355.
- 34 (a) J.-S. Ma, H.-Y. Lu, Y.-W. Chen, W.-C. Zhao, Y.-Z. Sun, R.-P. Li, H.-X. Wang, G.-Q. Lin and Z.-T. He, Copper-catalyzed convergent regio- and enantioselective alkynylallylic substitution, *Nat. Synth.*, 2022, **2**, 37–48; (b) J. H. van Maarseveen, Copper for alkynylallylic substitution, *Nat. Synth.*, 2023, **2**, 11–12.
- 35 Y.-Z. Sun, Z.-Y. Ren, Y.-X. Yang, Y. Liu, G.-Q. Lin and Z.-T. He, Asymmetric Substitution by Alkynyl Copper Driven Dearomatization and Rearomatization, *Angew. Chem., Int. Ed.*, 2023, **62**, e202314517.
- 36 M. Rosler, R. Anand, A. C. Sain, S. Gauthier, Y. Agid, P. D. Bianco, H. B. Stahelin, R. Hartman and M. Gharabawi, Efficacy and safety of rivastigmine in patients with Alzheimer's disease: international randomized controlled trial, *Br. Med. J.*, 1999, **318**, 633–638.
- 37 (a) D. Schnappinger and W. Hillen, Tetracyclines: antibiotic action, uptake, and resistance mechanisms, *Arch. Microbiol.*, 1996, **165**, 359–369; (b) A. N. Sapadin and R. Fleischmajer, Tetracyclines: nonantibiotic properties and their clinical implications, *J. Am. Acad. Dermatol.*, 2006, **54**, 258–265; (c) G. A. Pankey, Tigecycline, *J. Antimicrob. Chemother.*, 2005, **56**, 470–480.
- 38 Y. Zhou, Y. Xie, L. Yang, P. Xie and H.-M. Huang, Copper-catalyzed aerobic oxidative amination of arylboronic acid with aminal under base-free conditions, *Tetrahedron Lett.*, 2013, **54**, 2713–2716.
- 39 H.-Y. Lu and Z.-T. He, Catalytic asymmetric synthesis of 1,4-enynes, *Chin. Chem. Lett.*, 2023, **34**, 108105–108115.
- 40 T. Lu and F. Chen, Multiwfn: A Multifunctional Wavefunction Analyzer, *J. Comput. Chem.*, 2012, **33**, 580–592.
- 41 T. Lu and Q. Chen, Realization of conceptual density functional theory and information-theoretic approach in Multiwfn program, in *Conceptual Density Functional Theory*, ed. S. Liu, Wiley-VCH, 2022, pp. 631–647.
- 42 (a) B. E. Love, Facile synthesis of *N*-dialkylaminomethylsubstituted heterocycles, *J. Org. Chem.*, 2007, **72**, 630–632; (b) R. R. Khairullina, B. F. Akmanov, R. V. Kunakova and A. G. Ibragimov, Synthesis of amino sulfides in the presence of rare-earth and transition metal catalysts, *Russ. J. Org. Chem.*, 2012, **48**, 902–907.

