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Asymmetric construction of non-activated C-SCF_3 stereocenter *via* copper-catalyzed hydroallylation of SCF_3-alkenes

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ABSTRACT

Fluorinated motifs are prevalent in both pharmaceuticals and agrochemicals. The incorporation of fluorine-containing moieties to drug candidates has emerged as a potent strategy for lead optimization in pharmaceutical research and development. While extensive research has been devoted to constructing molecules that incorporate a trifluoromethylthio (SCF_3-) group on a stereogenic carbon, the synthesis of trifluoromethylthiolated alkanes featuring a SCF_3-substituted stereogenic carbon at non-activated site remains understudied. Herein, we report a Cu-catalyzed regio- and enantioselective hydroallylation of 1-trifluoromethylthiolated alkenes. Important to the process is the regio- and enantioselective Cu-H insertion to SCF_3-substituted alkene to form chiral α-SCF_3 alkyl copper intermediates, outcompeting unproductive insertion to the coupling partner, and eventually proceed to afford optically active homoallylic trifluoromethylthiolated products.

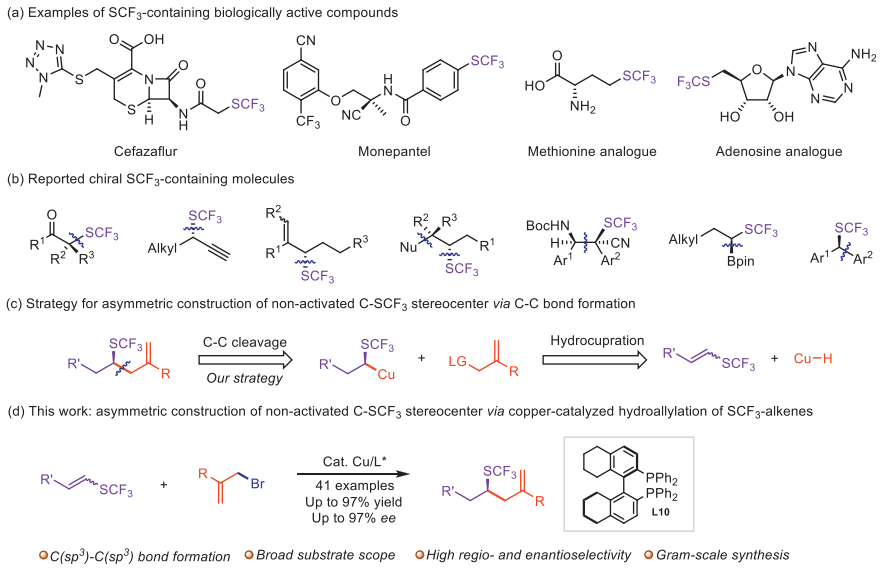
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Chirality is an intrinsic characteristic of nature and pervades the biological systems [1–3]. Most organic molecules that comprise living organisms are chiral. Living systems have a strong chiral recognition ability, contributing to distinct physiological properties of different enantiomeric forms of biologically active molecules. Accordingly, the idea of incorporating chiral motifs in target compound has profoundly affected the modern pharmaceutical industry, and represents a major theme in drugs design and discovery [4–7]. Meanwhile, the adoption of fluorine or fluorinated motifs into drug design has been continuing to expand, facilitated by an ever-increasing understanding of 'fluorine effects' on physicochemical properties and efforts to efficient syntheses of novel fluorinated molecules [8–25]. However, most fluorine-containing molecules used in drugs so far are normally achiral compounds, with majority found as fluorinated or fluorine-containing functionalized arenes. The drug-like molecules installed with fluorinated stereocenters are still relatively rare, possibly due to the lack of highly efficient and enantioselective synthetic methods for preparation of single enantiomers to meet the requirement of FDA's policy. The past several decades have witnessed the rapid development of novel synthetic methodologies for enantioselective construction of fluorinated or fluorine-containing functionalized stereocenters to make chiral fluorine-containing bioactive molecules [26–35]. However, most protocols provide only settlements to construct chiral centers at activated sites, such as benzylic, allylic, propargyl positions, or α-position of carbonyl groups and heteroatoms, and the rational construction of non-activated stereocenters featuring fluorine or fluorinated functional groups remains extremly challenging.

The trifluoromethylthio group (SCF_3), characterized by its strong lipophilic and electron-withdrawing nature, could remarkedly improve the metabolic stability and transmembrane permeability of drug molecules [36–38], making it an attractive functional group for drug design and development. For instance, Cefazaflur is a parenteral cephalosporin antibiotic administered *via* injection [39–49], and Monepantel is specifically marketed for veterinary applications (Scheme 1a). While most reported methods focused on the synthesis of trifluoromethylthioated arenes [50], the asymmetric construction of C(sp^3)-SCF_3 stereocenter were less explored with known approaches predominantly centered on activated sites [51–81], including α-position adjacent to carbonyl groups or heteroatoms, benzylic, allylic and propargyl position (Scheme 1b). To resolve these issues in asymmetric synthesis of SCF_3-containing molecules and deliver the construction of C(sp^3)-SCF_3 stereocenter at non-activated carbon centers in enantioconvergent synthesis of diverse trifluoromethylthiolated compounds, we reason a

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Scheme 1. SCF_3-containing biologically compounds and stoichiometric or catalytic asymmetric synthesis of stereocenters bearing the SCF_3 group.

conceptually divergent route might address these challenges. Considering the presence of sulfur atom in a SCF_3 group of SCF_3-alkene could potentially controll the regioselectivity of CuH-catalyzed hydrocupration process, we posited that this *in-situ* generated alkyl-copper intermediate could further react with a alkyl coupling partner for construction of trifluoromethylthiolated carbon center at a non-activated site (Scheme 1c). Notably, employing chiral ligated copper catalyst might contribute to a 'chiral pocket' for subsequent $C(sp^3)$-$C(sp^3)$ coupling [82–85], constructing C-SCF_3 stereocenter at non-activated site *via* copper-catalyzed three-component hydrofunctionalization of SCF_3-alkenes

Taking this hypothesis driven design into practice (Scheme 1d), we report copper-catalyzed asymmetric hydroallylation of 1-trifluoromethylthioalkenes for enantioselective synthesis of trifluoromethylthiolated carbon center at non-activated site. Excellent regioselective and enantioselective control, good functional group tolerance, and mild reaction conditions are demonstrated in this protocol, providing facile syntheses of optically pure allyl SCF_3-containing compounds. Given that trifluoromethylthiolated chiral centers could serve as key structural motifs, this method offers a convenient approach to SCF_3-containing drug-like molecules and agrochemicals.

We commenced our study by using trifluoromethylthiolated alkene **1a** and exo-alkene **2a** as starting materials, with PMHS as the hydrogen source, CsOPiv as additive, and $Cu(OAc)_2$ (10 mol%) as the catalyst in 1,4-dioxane at 25 °C (Fig. 1). Given the critical role of chiral ligands in controlling enantioselectivity and catalytic activity, we first optimized various types of chiral ligand, including nitrogen-based ligands, N,P-based ligands, mono and disphosphine (**L1-L6**) where we observed relatively better reactivity when using biphenyl disphosphine ligands (**L6**), giving moderate yield and enantioselectivity. Further optimization of chiral biphenyl disphosphine ligands indicated that H8-BINAP (**L10**) could provide expected product in 55 % yield with 81 % *ee*. Lowering reaction temperature offered improved enantioselectivity with comparable yield (Table 1, entry 1). Considering the low freezing point of 1,4-dioxane, we sought to test alternative solvents. Screening revealed that aromatic and ether solvents performed well, with diethyl ether yielding the product with 87 % *ee* at −10 °C (Table 1, entry 3). Continuing optimization of other parameters showed that using CuCN could achieve higher yields and *ee* values and lowering the temperature furnish the product in higher enantioselectivity but decreased yield. To address this issue, extending the reaction time emerged as an effective strategy. Indeed, we conducted the reaction with CuCN at −20 °C for 72 h to access the expected product in a yield of 85 % and an *ee* values of 92 % (Table 1, entry 7) while other additives or hydrogen sources did not lead to further improvements (Table 1, entries 8–11).

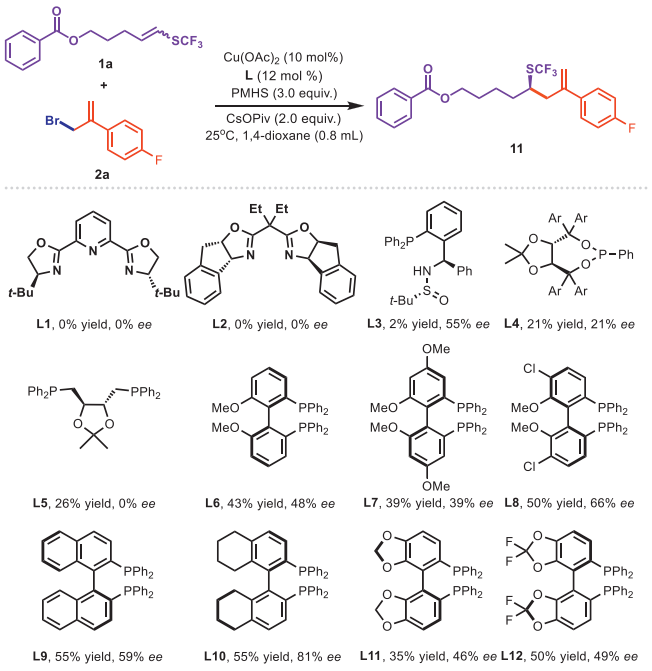
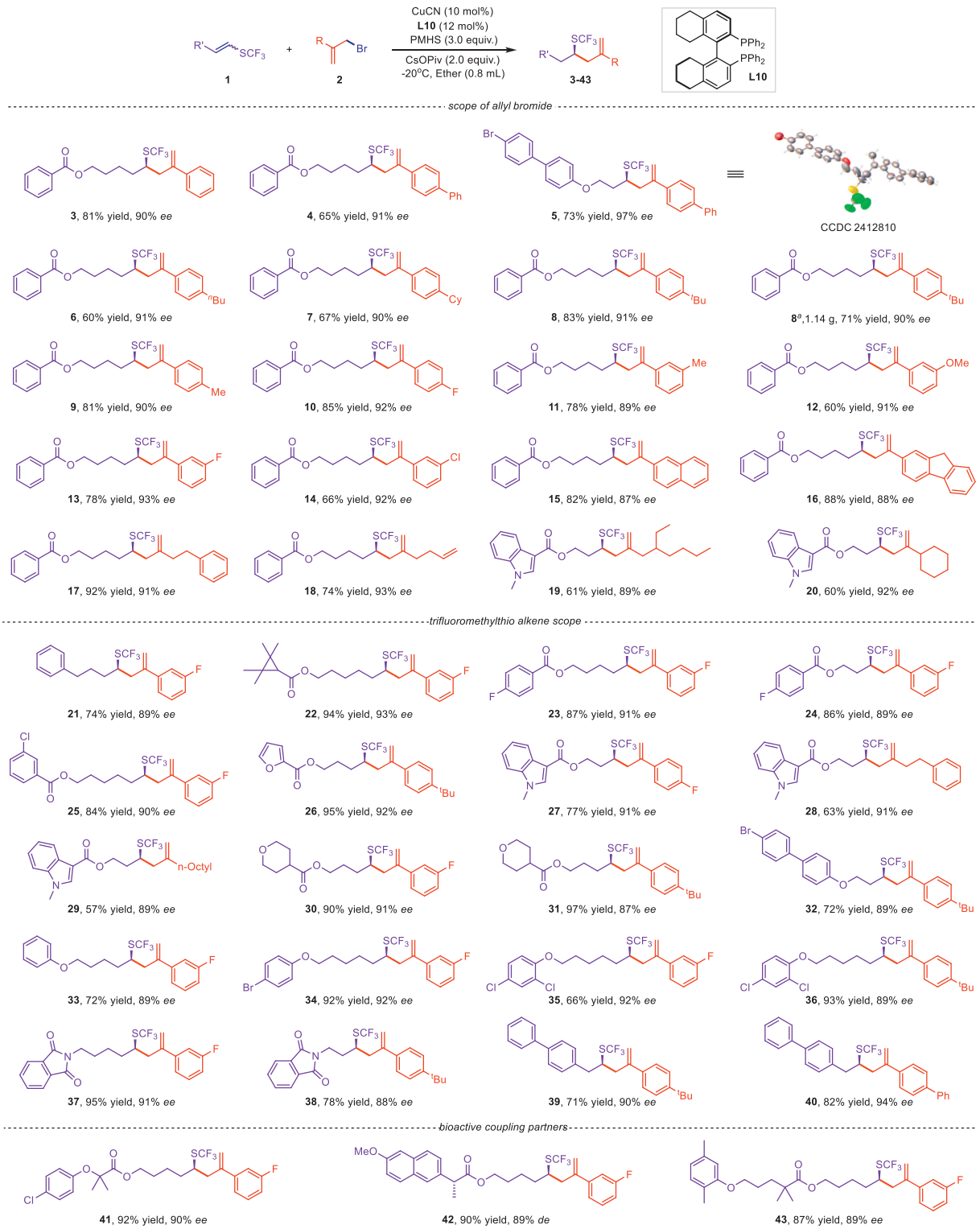


Fig. 1. Ligand screening.

With the optimized conditions in hand, we sought to investigate substrate generality of our protocol (Scheme 2). First, a series of aryl-substituted allylic bromides were found to be well compatible with this catalytic system. When the aryl *para*-position was substituted with bulky groups such as phenyl (**4**, **5**), cyclohexyl (**7**), and *tert*–butyl (**8**), the reactions maintained at least 90 % *ee* values, with product **5** having an impressive 97 % *ee*. It is worth noting that the gram-scale synthesis under standard conditions successfully produced the desired product without appar-



Scheme 2. Copper-catalyzed regio- and enantioselective hydroallylation of 1-trifluoromethylthioalkenes. Isolated yields were given. [a] Gram-scale synthesis.

Table 1
Copper-catalyzed hydroallylation of SCF_3-alkenes: optimization of conditions.[a]



Entry	Cu cat.	Temp (°C)	Solvent	Yield (%)[b]	*ee* (%)[c]
1	$Cu(OAc)_2$	10	1,4-Dioxane	45	82
2	$Cu(OAc)_2$	−10	Benzene	45	79
3	$Cu(OAc)_2$	−10	Ether	49	87
4	$Cu(OAc)_2$	−10	Diglyme	27	84
5	$CuBr_2$	−10	Ether	70	89
6	CuCN	−10	Ether	72	89
7[d]	CuCN	−20	Ether	85	92
8[d]	CuCN	−30	Ether	75	92
9[d,e]	CuCN	−20	Ether	0	–
10[d,f]	CuCN	−20	Ether	45	79
11[d,g]	CuCN	−20	Ether	84	92

[a] Reaction conditions: **1a** (0.1 mmol, 1.0 equiv.), a **2a** (0.2 mmol, 2.0 equiv.), [Cu] (10 mol%), Ligand (12 mol%), PMHS (3.0 equiv.), CsOPiv (2.0 equiv.), 1,4-dioxane (0.8 mL), Ar.
[b] Yield was determined by ^{19}F NMR spectroscopy using $PhCF_3$ as an internal standard; numbers in parentheses were yields of isolated products.
[c] The *ee* values were determined by HPLC on a chiral stationary phase.
[d] The reaction was carried out for 72 h.
[e] LiOPiv was used as the additive.
[f] Cs_2CO_3 was used as the additive.
[g] Trimethoxysilane was used as the hydrogen source.

ent loss of enantioselectivity, thereby demonstrating the practicality of this method. The reaction was unaffected by electron-donating (**9**) or electron-withdrawing groups (**10**). Similarly, when the aryl *meta*-position was substituted with electron-donating (**11**, **12**) or electron-withdrawing groups (**13**, **14**), high yields and excellent enantioselectivities were showcased. Additionally, polycyclic aryl group (**15**, **16**) did not interfere with the reaction. Having explored aryl substituents, we turned our attention to alkyl chain-substituted allylic bromides. Satisfyingly, both small (**17**, **18**) and bulky alkyl substituents (**19**, **20**) were well tolerated by the reaction system.

Next, we explored the functional group tolerance of 1-trifluoromethylthiolated alkenes. As shown in Scheme 2, various types of 1-trifluoromethylthiolated alkenes underwent hydroallylation smoothly, yielding the desired products (**21–40**) with excellent enantioselectivities, including aliphatic chain (**21**), stained ring system (**22**), substituted arenes (**23–25**) and alkyl chains with ether (**36**) and amide (**37**, **38**) functionalities. Notably, the reactions proceeded smoothly regardless of the alkyl chain length (**23**, **24** and **37**, **38**) and the presence of heteroaromatic groups (**26–29**), or halogen substituents (**32**, **34**, **35**, **36**) indicated excellent compatibility. Of particular importance is that 1-trifluoromethylthioalkenes bearing aryl conjugated systems exhibited exceptional regioselectivity, furnishing products in high yields and excellent enantioselectivities without detectable isomers (**39**, **40**). This phenomenon may be attributed to the electron-donating effect of the sulfur atom, in favor of Cu-H insertion positioning copper adjacent to trifluoromethylthiolated carbon.

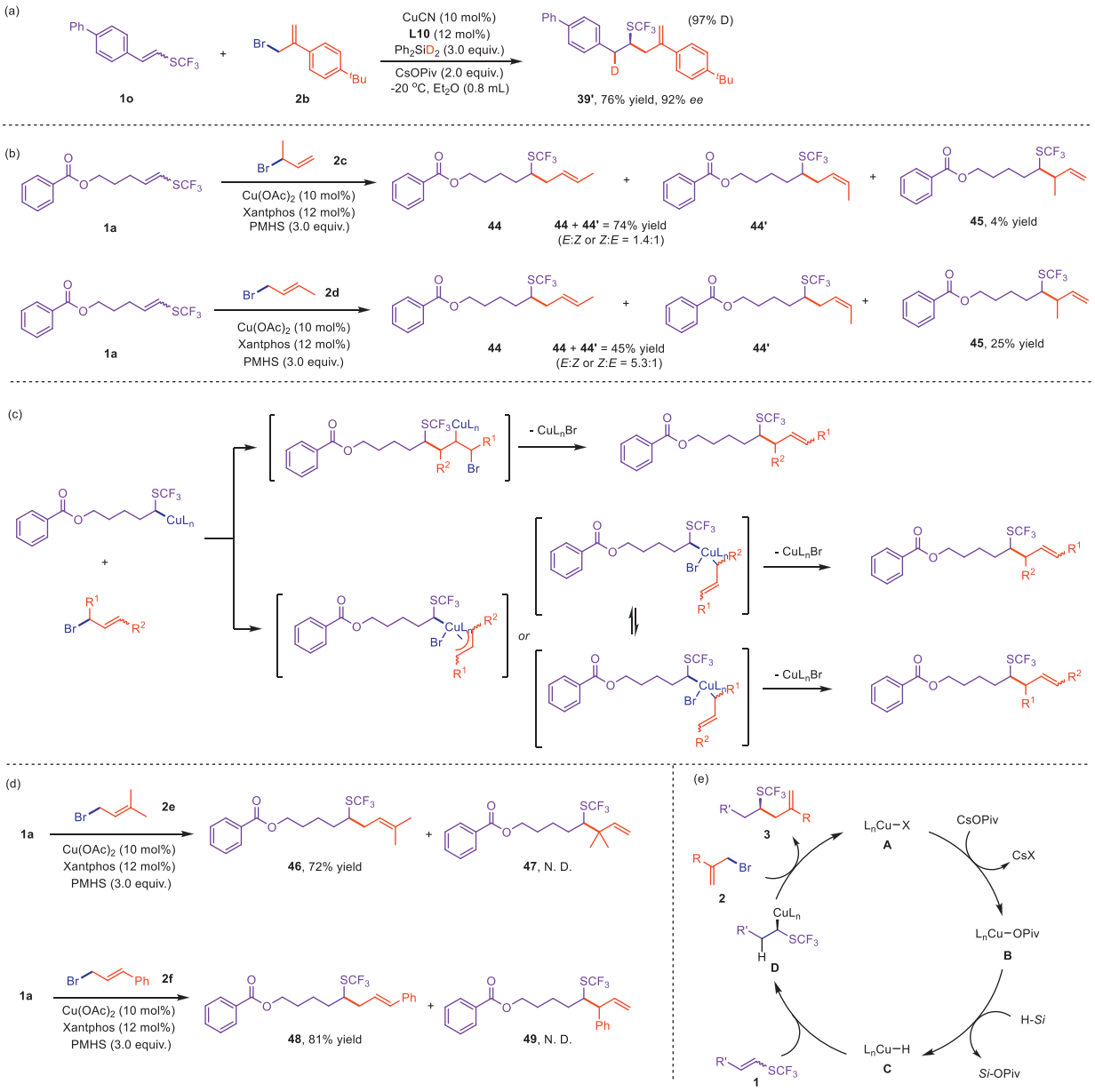
Encouraged by these exciting results, we proceeded to perform late-stage asymmetric modifications on biologically active molecules, such as *clofibric acid* (**41**), *naproxen* (**42**), and *gemfibrozil* (*Lopid*, **43**). All modifications resulted in excellent yields and good enantioselectivities, highlighting the substantial potential of this method to efficiently construct chiral trifluoromethylthiolated derivatives of pharmaceuticals or drug candidates.

To gain deeper insights into the reaction mechanism of this system, we subsequently carried out a series of mechanistic experiments. Firstly, using Ph_2SiD_2 for asymmetric catalysis successfully synthesized deuterium-labeled chiral product **39′** (Scheme 3a). The result indicates that the copper hydride species **A** is formed from hydrosilane, ultimately transferring hydride to 1-SCF_3 substituted alkene to form an alkyl copper intermediate. Next, we investigated the hydroallylation step (the transition from **D** and **2** to **A** and product in Scheme 3e). Under non-diastereoselective conditions, we tested regioisomeric allylic bromides 3–bromo–but-1-ene (**2c**) and (*E*)-1-bromobut-2-ene (**2d**) using the Xantphos ligand (Scheme 3b). The branched allylic bromide **2c** reacted with **1a** to yield linear products **44** and **44′** in 74% yield, along with 4% of the branched product **45**.

Products **44** and **44′** could be generated either through an S_N2'-type addition-elimination mechanism or *via* the formation of π-allyl or π-en-σ-yl copper intermediates, whereas **45** can only be produced through the latter pathway. On the other hand, the linear allylic bromide **2d** reacted with **1a** to yield linear products **44** and **44′** in 45% yield, which can only be formed *via* π-allyl or π-en-σ-yl copper intermediates. Additionally, rapid *E*:*Z* (*syn*/*anti*) isomerization resulted in the formation of *Z*-isomers. Although the mechanism for the 25% branched product **45** remains unclear, it is evident that the reaction primarily proceeds through the formation of π-allyl or π-en-σ-yl copper intermediates (Scheme 3c). Furthermore, when steric hindrance increased, such as allylic bromides **2e** and **2f**, the reaction exclusively proceeded through the formation of π-allyl or π-en-σ-yl copper intermediates, followed by reductive elimination at more accessible spatial positions, yielding the corresponding linear hydroallylated products **46** and **48** (Scheme 3d). Notably, the choice of allylic substrate has a significant impact on the reaction efficiency. When the leaving group is a carbonate, acetate, or phosphate, the hydroallylation product is not observed at all. Allylic chlorides can yield the desired product but with lower yields compared to bromides. In fact, due to high reactivity of allylic bromide and β-elimination followed by Cu-H inserstion to allylic bromide side reactivity, allylic bromides are rarely used in known hydroallylation reactions. Benefited from strong electron-withdrawing effect of SCF_3 on alkene components, the nucleophilic copper-hydride is prone to inserting to the alkenes that are more electron deficient, precluding unproductive insertion to allylic bromide, contributing to the excellent regioselectivity of Cu–H insertion into substrate **1a** in followed by the participation of allylic bromide **2a** to form π-allyl or π-en-σ-yl copper species. Given that allylic bromides are more reactive in forming π-allyl or π-en-σ-yl copper species compared to chlorides and the unproductive metal hydride insersion would be circumvented, higher reactivities with allylic bromide could also correlate to these the mechanistic studies, indicating that the formation of π-allyl or π-en-σ-yl copper species is the predominant pathway (Scheme 3c).

Based on the collective experimental results, we propose a possible reaction mechanism as shown in Scheme 3e. Initially, the *in situ* formed ligated copper complex LnCu-X (**A**) undergoes salt metathesis with the base CsOPiv to form the LnCu-OPiv species (**B**). Next, copper hydride **C** was furnished by σ-bond metathesis with the hydrosilane. Under the influence of the strong electron-withdrawing nature of the SCF_3 group, the double bond of 1-trifluoromethylthioalkene **1** inserts into the Cu–H bond with high regio- and enantioselectivity, yielding the α-SCF_3 alkylcopper intermediate **D**, followed by coupling with allylic bromide **2** *via* a possible π-allyl or π-en-σ-yl copper intermediate, to give homoallylic trifluoromethylthiolated products and ligated copper.

In conclusion, we have successfully developed an asymmetric construction of homoallylic trifluoromethylthiolated alkanes featuring C-SCF_3 stereocenter at non-activated site *via* copper-catalyzed hydroallylation of SCF_3-substituted alkenes. The asymmetric Cu



Scheme 3. Mechanistic investigation.

catalysis effectively controls the chirality at the α-position adjacent to the SCF_3 group, without the proximal directing heteroatoms. Comprehensive experimental studies also indicate that the reaction involves with the formation of π-allyl or π-en-σ-yl copper intermediates for subsequent coupling process. This transformation provides a robust and efficient method for synthesizing SCF_3-containing chiral molecules with potential for pharmaceutical synthesis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Wei-Cheng Zhao: Writing – original draft, Validation, Methodology, Investigation, Data curation. **Yan He:** Writing – original draft, Validation. **Chen-Hui Jiang:** Validation. **Peng Liu:** Validation. **Qian Gao:** Validation. **Duo-Duo Hu:** Writing – review & editing, Writing – original draft, Supervision, Methodology. **Xi-Sheng Wang:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Investigation, Funding acquisition, Data curation.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.cclet.2025.111487.

References

[1] J. Patocka, A. Dvorak, J. Appl. Med. 2 (2004) 95–100.
[2] L.A. Nguyen, H. He, C. Pham-Huy, Int. J. Biomed. Sci. 2 (2006) 85–100.
[3] N. Chhabra, M.L. Aseri, D. Padmanabhan, Int. J. Appl. Basic Med. Res. 3 (2013) 16–18.
[4] M. Eichelbaum, A.S. Gross, Adv. Drug Res. 28 (1996) 1–64.
[5] S.W. Smith, Toxicol. Sci. 110 (2009) 4–30.
[6] N. Chhabra, M.L. Aseri, D. Padmanabhan, Int. J. Appl. Basic Med. Res. 3 (2013) 16–18.
[7] H. Alkadi, R. Jbeily, Infect. Disord. Drug Targets 18 (2018) 88–95.
[8] K. Müller, C. Faeh, F. Diederich, Science 317 (2007) 1881–1886.
[9] S. Purser, P.R. Moore, S. Swallowb, V. Gouverneur, Chem. Soc. Rev. 37 (2008) 320–330.
[10] J. Wang, M. Sánchez-Roselló, J.L. Aceña, et al., Chem. Rev. 114 (2014) 2432–2506.
[11] E.P. Gillis, K.J. Eastman, M.D. Hill, D.J. Donnelly, N.A. Meanwell, J. Med. Chem. 58 (2015) 8315–8359.
[12] N.A. Meanwell, J. Med. Chem. 61 (2018) 5822–5880.
[13] H. Mei, J. Han, S. Fustero, et al., Chem. Eur J. 25 (2019) 11797–11819.
[14] M. Inoue, Y. Sumii, N. Shibata, ACS Omega 5 (2020) 10633–10640.
[15] B.M. Johnson, Y.Z. Shu, X. Zhuo, N.A. Meanwell, J. Med. Chem. 63 (2020) 6315–6386.
[16] Y. Yu, A. Liu, G. Dhawan, et al., Chin. Chem. Lett. 32 (2021) 3342–3354.
[17] J. Li, W. Xi, S. Liu, et al., Chin. Chem. Lett. 33 (2022) 3007–3011.
[18] N. Meng, Y. Lv, X. Zhao, W. Wei, Chin. Chem. Lett. 32 (2021) 258–262.
[19] R. Wang, J. Xu, J.X. Li, et al., Chin. Chem. Lett. 34 (2023) 108490.
[20] D.S. Deng, S.Q. Tang, Y.T. Yuan, et al., Chin. Chem. Lett. 35 (2024) 109417.
[21] L. Yang, Y. Li, M. Jiang, et al., Chin. Chem. Lett. 35 (2024) 109512.
[22] C.C. Wu, B.L. Wang, J.B. Liu, et al., Chin. Chem. Lett. 28 (2017) 1248–1251.
[23] X.J. Song, Y. Shao, X.G. Dong, Chin. Chem. Lett. 22 (2011) 1036–1038.
[24] X. Chen, Z. Zhu, S. Liu, Y.H. Chen, X. Shen, Chin. Chem. Lett. 33 (2022) 2391–2396.
[25] H. Wang, Y. Xie, Y. Zhou, N. Cen, W. Chen, Chin. Chem. Lett. 33 (2022) 221–224.
[26] T.D. Beeson, D.W.C. MacMillan, J. Am. Chem. Soc. 127 (2005) 8826–8828.
[27] M. Marigo, D. Fielenbach, A. Braunton, A. Kjærsgaard, K.A. Jørgensen, Angew. Chem. Int. Ed. 44 (2005) 3703–3706.
[28] D. Cahard, X. Xu, S. Couve-Bonnaire, X. Pannecoucke, Chem. Soc. Rev. 39 (2010) 558–568.
[29] S. Lectard, Y. Hamashima, M. Sodeoka, Adv. Synth. Catal. 352 (2010) 2708–2732.
[30] C.Y. Huang, A.G. Doyle, J. Am. Chem. Soc. 134 (2012) 9541–9544.
[31] R.J. Phipps, F.D. Toste, J. Am. Chem. Soc. 135 (2013) 1268–1271.
[32] N.A. Cochrane, H. Nguyen, M.R. Gagne, J. Am. Chem. Soc. 135 (2013) 628–631.
[33] X. Yang, R.J. Phipps, F.D. Toste, J. Am. Chem. Soc. 136 (2014) 5225–5228.
[34] S.Y. Lee, S. Neufeind, G.C. Fu, J. Am. Chem. Soc. 136 (2014) 8899–8902.
[35] X. Jiang, M. Gandelman, J. Am. Chem. Soc. 137 (2015) 2542–2547.
[36] A. Leo, C. Hansch, D. Elkins, Chem. Rev. 71 (1971) 525–616.
[37] C. Hansch, S.H. Unger, A.B. Forsythe, J. Med. Chem. 16 (1973) 1217–1222.
[38] C. Hansch, A. Leo, R.W. Taft, Chem. Rev. 91 (1991) 165–195.
[39] G.W. Counts, D. Gregory, D. Zeleznik, M. Turck, Antimicrob. Agents Chemother. 11 (1977) 708–711.
[40] N. Aswapokee, H.C. Neu, Antimicrob. Agents Chemother. 15 (1979) 444–446.
[41] N.J.W. Straathof, B.J.P. Tegelbeckers, Hessel V, X. Wang, T. Noël, Chem. Sci. 5 (2014) 4768–4773.
[42] K. Jouvin, C. Matheis, L.J. Goossen, Chem. Eur. J. 21 (2015) 14324–14327.
[43] S. Alazet, T. Billard, Synlett 26 (2015) 76–78.
[44] X.-H. Xu, K. Matsuzaki, N. Shibata, Chem. Rev. 115 (2015) 731–764.
[45] S. Barata-Vallejo, S. Bonesi, A. Postigo, Org. Biomol. Chem. 14 (2016) 7150–7182.
[46] M. Zhao, X. Zhao, P. Zheng, Y. Tian, J. Fluorine Chem. 194 (2017) 73–79.
[47] A.-L. Barthelemy, E. Magnier, G. Dagousset, Synthesis 50 (2018) 4765–4776.
[48] C. Ghiazza, T. Billard, A. Tlili, Chem. Eur. J. 25 (2019) 6482–6495.
[49] Y. Huang, M. Zhang, Q. Lin, Z. Weng, Synlett 32 (2021) 109–118.
[50] L. Liao, X. Zhao, Acc. Chem. Res. 55 (2022) 2439–2453.
[51] X. Wang, T. Yang, X. Cheng, Q. Shen, Angew. Chem. Int. Ed. 52 (2013) 12860–12864.
[52] T. Bootwicha, X. Liu, R. Pluta, I. Atodiresei, M. Rueping, Angew. Chem. Int. Ed. 52 (2013) 12856–12859.
[53] M. Rueping, X. Liu, T. Bootwicha, R. Pluta, C. Merkens, Chem. Commun. 50 (2014) 2508–2511.
[54] X.L. Zhu, J.H. Xu, D.J. Cheng, et al., Org. Lett. 16 (2014) 2192–2195.
[55] Q.H. Deng, C. Rettenmeier, H. Wadepohl, L.H. Gade, Chem. Eur. J. 20 (2014) 93–97.
[56] B.L. Zhao, D.M. Du, Org. Lett. 19 (2017) 1036–1039.
[57] M. Li, X.S. Xue, J.P. Cheng, ACS Catal. 7 (2017) 7977–7986.
[58] H. Zhang, X. Leng, X. Wan, Q. Shen, Org. Chem. Front. 4 (2017) 1051–1057.
[59] M.Y. Jin, J. Li, R. Huang, et al., Chem. Commun. 54 (2018) 4581–4584.
[60] F. Gelat, T. Poisson, A.T. Biju, X. Pannecoucke, T. Besset, Eur. J. Org. Chem. 2018 (2018) 3693–3696.
[61] M.A. Hardy, H. Chachignon, D. Cahard, Asian J. Org. Chem. 8 (2019) 591–609.
[62] V. Capaccio, M. Sicignano, R.I. Rodriguez, G. Della Sala, J. Aleman, Org. Lett. 22 (2020) 219–223.
[63] M. Sicignano, R.I. Rodriguez, V. Capaccio, et al., Org. Biomol. Chem. 18 (2020) 2914–2920.
[64] A. Eitzinger, J.F. Briere, D. Cahard, M. Waser, Org. Biomol. Chem. 18 (2020) 405–408.
[65] A. Eitzinger, J. Otevrel, V. Haider, et al., Adv. Synth. Catal. 363 (2021) 1955–1962.
[66] X. Liu, R. An, X. Zhang, J. Luo, X. Zhao, Angew. Chem. Int. Ed. 55 (2016) 5846–5850.
[67] J. Luo, Y. Liu, X. Zhao, Org. Lett. 19 (2017) 3434–3437.
[68] J. Luo, X. Liu, X. Zhao, Synlett 28 (2017) 397–401.
[69] X. Liu, Y. Lang, J. Ji, J. Luo, X. Zhao, J. Am. Chem. Soc. 140 (2018) 4782–4786.
[70] J. Luo, Q. Cao, X. Cao, X. Zhao, Nat. Commun. 9 (2018) 527.
[71] J. Xu, Y. Zhang, T. Qin, X. Zhao, Org. Lett. 20 (2018) 6384–6388.
[72] T. Qin, Q. Jiang, J. Ji, J. Luo, X. Zhao, Org. Biomol. Chem. 17 (2019) 1763–1766.
[73] Q. Jiang, X. Zhao, Chin. J. Org. Chem. 41 (2021) 443–454.
[74] X. Gao, Y.L. Xiao, S. Zhang, J. Wu, X. Zhang, CCS Chem. 3 (2021) 1463–1471.
[75] Q. Wang, T. Nilsson, L. Eriksson, K.J. Szabo, Angew. Chem. Int. Ed. 61 (2022) e202210509.
[76] J. Zhou, Q.F. Zhang, W.H. Zhao, G.F. Jiang, Org. Biomol. Chem. 14 (2016) 6937–6941.
[77] L. Xu, H. Wang, C. Zheng, G. Zhao, Adv. Synth. Catal. 359 (2017) 2942–2948.
[78] Z. Zhang, Z. Sheng, W. Yu, et al., Nature Chem. 9 (2017) 970–976.
[79] H. Kondo, M. Maeno, K. Sasaki, et al., Org. Lett. 20 (2018) 7044–7048.
[80] D.D. Hu, T.M. Nie, X. Xiao, et al., Angew. Chem. Int. Ed. 63 (2024) e202400308.
[81] Y. Kojima, Y. Nishii, K. Hirano, Angew. Chem. Int. Ed. 63 (2024) e202403337.
[82] Y.M. Wang, S.L. Buchwald, J. Am. Chem. Soc. 138 (2016) 5024–5027.
[83] J.T. Han, W.J. Jang, N. Kim, J. Yun, J. Am. Chem. Soc. 138 (2016) 15146–15149.
[84] J. Lee, S. Torker, A.H. Hoveyda, Angew. Chem. Int. Ed. 56 (2017) 821–826.
[85] Y. Kojima, M. Miura, K. Hirano, ACS Catal. 11 (2021) 11663–11670.