

Cite this: *Chem. Sci.*, 2025, 16, 21548 All publication charges for this article have been paid for by the Royal Society of ChemistryReceived 22nd September 2025
Accepted 9th October 2025

DOI: 10.1039/d5sc07347b

rsc.li/chemical-science

Copper-catalyzed stereospecific methoxyboration of styrenes enabled by oxygen umpolung with acetal-based peroxides

Kiyosuke Fujiwara,^{†a} Shogo Nakamura^{†a} and Koji Hirano *^{ab}

An oxygen-umpolung-enabled, regioselective and stereospecific copper-catalyzed methoxyboration of styrenes with diborons and acetal-based methyl peroxide has been developed. The use of designed peroxide enables the otherwise difficult two-electron redox event under the borylcopper catalysis, thus delivering the corresponding oxyborated products with high stereospecificity. Combined with the stereospecific post functionalizations of the boron moiety, the copper catalysis can provide facile access to the stereochemically defined, functionality-rich alkyl ether derivatives ubiquitously found in bioactive molecules and functional materials.

Introduction

Organoboron compounds are ubiquitous and indispensable in modern organic synthetic chemistry because the C–B bonds can be selectively and stereospecifically converted to various C–C and C–heteroatom bonds under specific conditions, which are particularly useful for convergent synthesis of complex molecules such as bioactive molecules and natural products.¹ Moreover, several organoboron compounds themselves are important targets with unique biological activities.² Accordingly, the development of synthetic methods for functionality-rich and stereochemically defined organoboron compounds is one of long-standing research subjects in the synthetic community. Among numerous reported protocols, the borylative difunctionalizations of readily available and simple alkene substrates are highly attractive from the synthetic point of view. There are many successful reports of diboration, silaboration, carboboration, stannylation, and aminoboration.^{1,4,3} However, the catalytic simultaneous addition of oxygen and boron atoms, namely, oxyboration and alkoxyboration, still remains underdeveloped. In particular, the stereoselective and/or stereospecific variants are unmet challenges. In 2015, Shimizu, Kanai, and co-workers reported the copper-catalyzed oxyboration of terminal alkenes with bis(pinacolato)diboron (pinB–Bpin) and 2,2,6,6-tetramethylpiperidine 1-oxyl (TEMPO; Scheme 1a).⁴ While the regioselectivity was divergently controlled by the suitable choice of ancillary ligands, the reaction process involved the carbon radical intermediates and only employed terminal alkenes, thus not focusing the stereochemistry

(diastereoselectivity) of the reaction. More recently, Xiong and Zhang developed the copper-catalyzed *anti*-selective oxyboration of β -substituted styrenes (Scheme 1b), where similar carbon-centered radical species are involved and a mixture of *syn*- and *anti*-diastereomers are initially formed, but stereochemical mutation process occurs *via* the selective reverse reaction of *syn*-isomer to the starting styrene.⁵ As a result, the corresponding *anti*-product was selectively formed in a stereoconvergent manner. Although this strategy allowed for the stereoselective preparation of oxyboration product with high *anti*-stereochemistry, the opposite isomer, *syn*-oxyboration product, cannot be obtained. Moreover, the overall process is stereoconvergent, and both (*E*)- and (*Z*)-styrenes are converted to the same *anti*-isomers. Thus, the stereospecific process, in which the (*E*)- and (*Z*)-styrenes are selectively converted to the corresponding *syn*- and *anti*-products, respectively (or *vice versa*), is not achieved yet but in high demand.

Meanwhile, our group recently focused on polarity inversion (umpolung) concept of oxygen⁶ and developed the highly stereospecific hydroalkoxylation of styrenes with hydrosilanes and designed acetal-based peroxides.⁷ The unique two-electron redox character of peroxides enabled the net hydroalkoxylation with perfect stereospecificity under copper hydride catalysis. During the continuing interest in this chemistry, we here report a copper-catalyzed methoxyboration of styrenes with pinB–Bpin and acetal-based methyl peroxide (Scheme 1c). The use of peroxide promotes the two-electron redox process rather than the previously observed one-electron redox process, thus leading to the high stereospecificity, which is difficult to achieve by other means.

Results and discussion

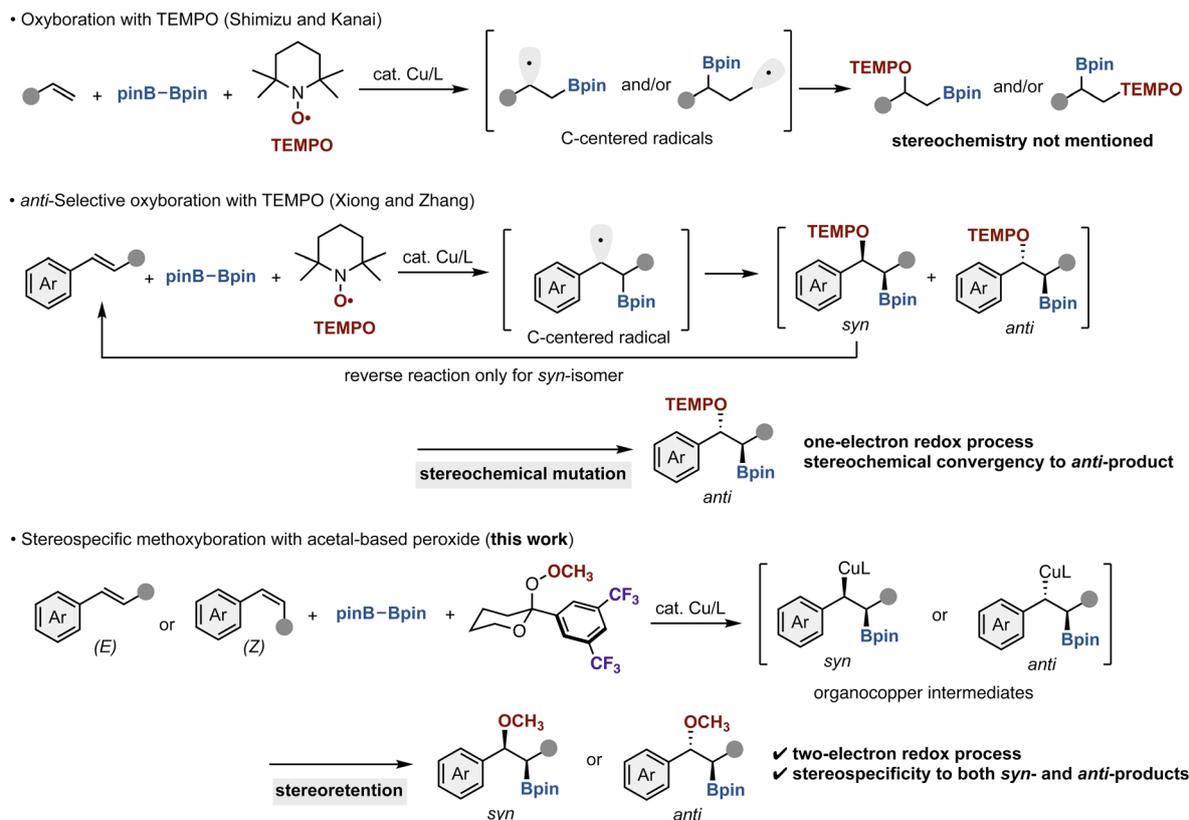
Our optimization studies commenced with (*E*)- β -methylstyrene [(*E*)-**1a**], pinB–Bpin, and 3,5-(CF₃)₂C₆H₄-substituted acetal-based peroxide **2**, which was optimal in the previous

^aDepartment of Applied Chemistry, Graduate School of Engineering, Osaka University, Suita, Osaka, 565-0871, Japan. E-mail: k_hirano@chem.eng.osaka-u.ac.jp

^bInnovative Catalysis Science Division, Institute for Open and Transdisciplinary Research Initiatives (ICS-OTRI), Osaka University, Suita, Osaka, 565-0871, Japan

[†] These authors equally contributed to this work.





Scheme 1 Stereochemistry in copper-catalyzed oxyboration of alkenes.

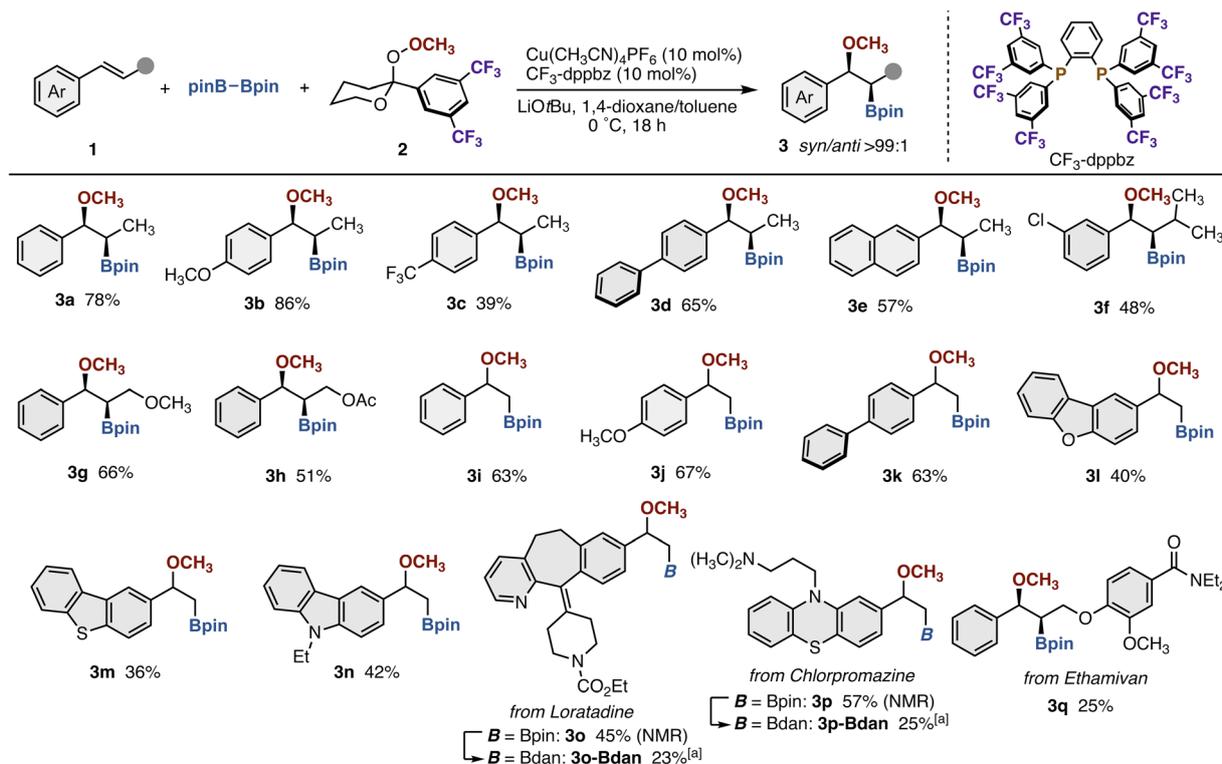
hydroalkoxylation,^{7a} to identify the suitable catalyst system (Table 1). In an early experiment, treatment of (*E*)-**1a** (0.10 mmol), pinB-Bpin (2.5 equiv.), and **2** (1.5 equiv.) in the presence of Cu(OAc)₂/dppbz (10 mol%) and LiOtBu (2.0 equiv.) in 1,4-dioxane at room temperature for 18 h afforded the desired methoxyborated product **3a** in 11% yield (entry 1). The yield was low, but the exclusive *syn*-stereochemistry was observed, thus suggesting the operation of two-electron redox system. This intriguing result prompted us to examine the effects of bidentate dppbz ligands⁸ in more detail. In the cases using *para*-substituted dppbz derivatives, almost negligible effects on the reaction efficacy were observed, regardless of electronic nature of substituents (entries 2 and 3). On the other hand, the introduction of electron-withdrawing groups at the *meta*-position significantly improved the yield of **3a** with maintenance of high *syn*-selectivity (entries 4 and 5), particularly with CF₃-dppbz proving to be optimal, while less influences were observed with the electron-donating substituents (entries 6–8). In addition, the corresponding monodentate phosphine, P[3,5-(CF₃)₂C₆H₃]₃, provided **3a** in only 2% yield (entry 9), thus suggesting that both the strong electron-withdrawing and bidentate chelating nature of CF₃-dppbz are essential for the reaction. Investigation of other reaction parameters such as copper catalyst precursor, solvent, and reaction temperature revealed that the yield of **3a** further increased to 82% (78% isolated yield) with the Cu(CH₃CN)₄PF₆ catalyst and 1,4-dioxane/toluene (1:1, v/v) mixed solvent system at 0 °C (entry 10). Moreover, the choice

of substituents at the anomeric position of acetal-based peroxide **2** was also critical. The reaction proceeded to some extent when using methyl-, butyl-, and simple phenyl-substituted peroxides (entries 11–13). On the other hand, the introduction of electron-withdrawing CF₃ on the phenyl ring accelerated the reaction (entry 14), whereas the electron-donating substituents such as *tert*-butyl and methoxy groups were detrimental (entries 15 and 16). Additionally noteworthy is the indispensable role of LiOtBu (entry 17). More detailed results in optimization studies are involved in the SI.

The reaction of (*E*)-**1a** could also be performed on a 1.0 mmol scale without any difficulties, thus indicating good reliability and reproducibility of the reaction (Scheme 2). Moreover, the post functionalizations of Bpin moiety in **3a** were successfully conducted under the established conditions: oxidation (**4**), amination (**5**),⁹ vinylation (**6**),¹⁰ and homologation (**7**)¹¹ all proceeded smoothly to form the corresponding functionalized alkyl ethers with high stereochemical fidelity. Thus, the methoxyborated product **3a** is a valuable building block for the stereochemically defined, functionality-rich alkyl ethers.

With conditions of entry 10 in Table 1, we next examined the scope of styrene derivatives (Scheme 3). In addition to the model substrate (*E*)-**1a**, both electron-rich and -deficient (*E*)- β -methylstyrenes participated in the reaction to form the corresponding **3b** and **3c** with high *syn*-selectivity, although the yield of **3c** was relatively moderate because of poor stability under reaction conditions.⁵ More π -extended substrates such as





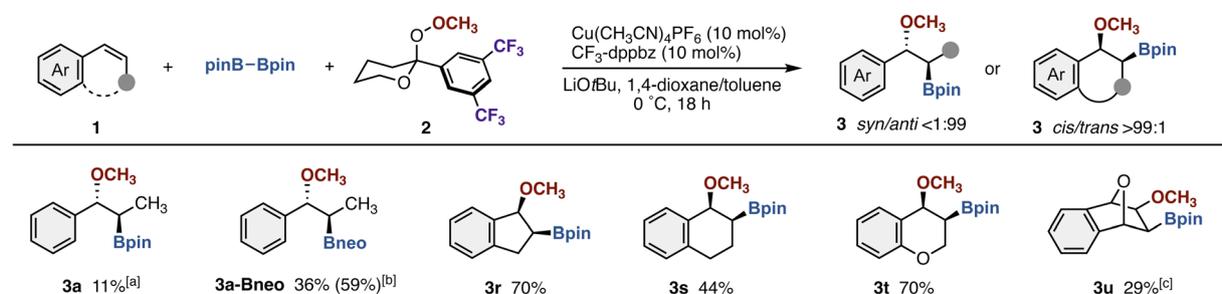
Scheme 3 Scope of styrene derivatives in copper-catalyzed methoxyboration. Conditions: **1** (0.10–0.20 mmol), pinB-Bpin (2.5 equiv.), **2** (1.5 equiv.), $\text{Cu}(\text{CH}_3\text{CN})_4\text{PF}_6$ (10 mol%), $\text{CF}_3\text{-dppbz}$ (10 mol%), LiOtBu (2.0 equiv.), 1,4-dioxane/toluene (1 : 1, v/v), 0 °C, 18 h, N_2 . Isolated yields are shown. ^[a]Isolated in a Bdan form after transesterification of crude material with H_2Bdan . See the SI for detailed conditions.

next catalytic cycle by the σ -bond metathesis with pinB-Bpin. The hemiacetal fragment and its ring-opening form arising from the released Li alkoxide **12** were actually recovered almost quantitatively (see the SI). The two-electron redox oxidative addition/reductive elimination pathway can reasonably explain the experimentally observed stereospecificity of the reaction.^{14,15}

Finally, we applied this protocol to the catalytic asymmetric synthesis by using an appropriate chiral ligand (Scheme 6). While still preliminary, the moderate enantioinduction (**3d**, 18%, 87 : 13 er) was observed in the presence of (*S,S*)-DTBM-BDPP. The reaction of terminal alkene **1k** instead of **1d** increased the yield but with lower enantioselectivity (**3k**, 37%,

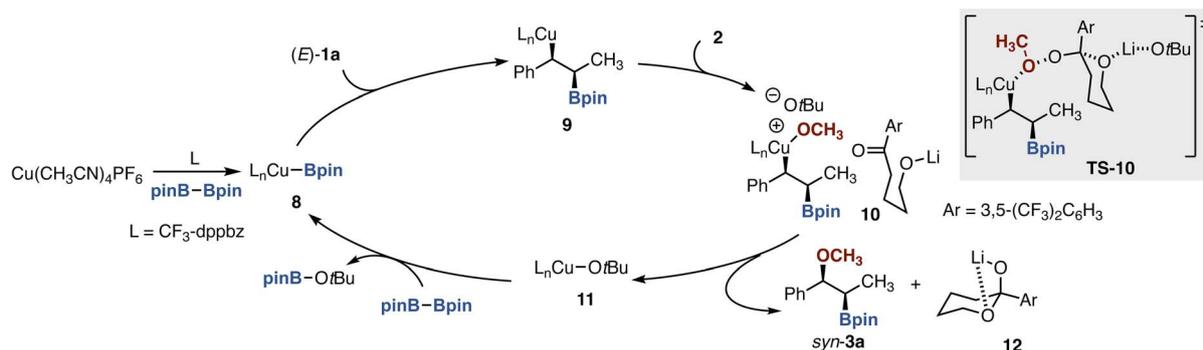
67 : 33 er). Further attempts to improve both the yield and enantioselectivity are currently underway.

Another current limitation is the narrow scope of alkenes and acetal-based peroxides (Scheme 7). Attempts to apply α -methylstyrene, β,β -dimethylstyrene, and simple aliphatic terminal alkene remained unsuccessful. We also tested alkyl peroxides other than methyl peroxide **2**, but formal protoboration exclusively occurred because of increasing steric hinderances. Additional optimizations of catalysts and design of peroxides are necessary for overcoming the aforementioned issues.

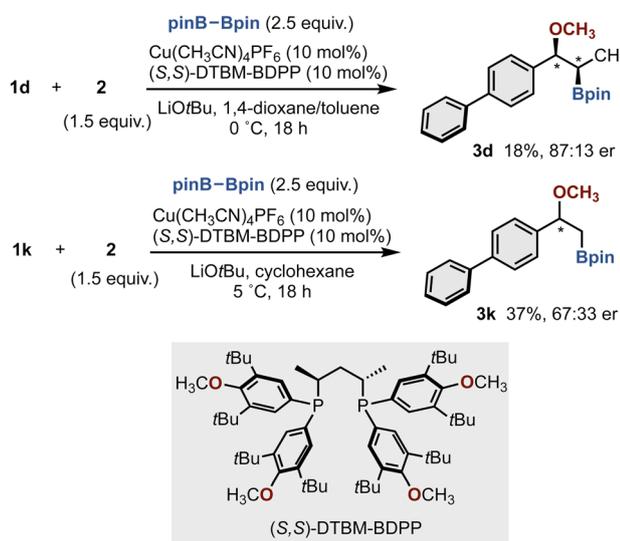


Scheme 4 Scope of (*Z*)-styrene derivatives in copper-catalyzed methoxyboration. Conditions: **1** (0.10–0.20 mmol), pinB-Bpin (2.5 equiv.), **2** (1.5 equiv.), $\text{Cu}(\text{CH}_3\text{CN})_4\text{PF}_6$ (10 mol%), $\text{CF}_3\text{-dppbz}$ (10 mol%), LiOtBu (2.0 equiv.), 1,4-dioxane/toluene (1 : 1, v/v), 0 °C, 18 h, N_2 . Isolated yields are shown. ^[a]¹H NMR yield. ^[b]With neoB-Bneo (4.0 equiv.), $\text{Cu}(\text{CH}_3\text{CN})_4\text{PF}_6$ (20 mol%), $\text{CF}_3\text{-dppbz}$ (20 mol%), and LiOtBu (4.0 equiv.). ^[c]In toluene.



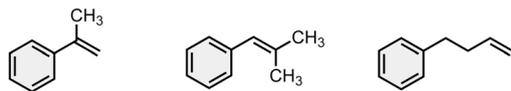


Scheme 5 Plausible reaction mechanism.



Scheme 6 Preliminary results of catalytic asymmetric methoxyboration with (S,S)-DTBM-BDPP ligand.

- unsuccessful alkenes (no methoxyboration products were observed.)



- unsuccessful peroxides (simple protoboration products were observed.)



Scheme 7 Unsuccessful alkenes and peroxides under current conditions.

Conclusions

We have developed an oxygen-umpolung-enabled, copper-catalyzed regioselective and stereospecific methoxyboration of styrenes, delivering *syn*- and *anti*-oxyborated products from (*E*)- and (*Z*)-styrenes, respectively. The key to success lies with a CF₃-

substituted acetal-based peroxide, which has unique two-electron redox character rather than the previously dominant one-electron redox nature associated with TEMPO. The newly developed copper catalysis combined with the designed acetal-based peroxide accesses the stereochemically defined organoboron compounds with oxygenated functionality from readily available and relatively simple hydrocarbon materials. Moreover, the obtained methoxyborated products can be valuable platforms for more complicated alkyl ethers *via* stereospecific post-functionalizations of boron moiety. Given the ubiquity of ether in bioactive molecules, natural products, and functional materials, the present findings will find wide applications in synthetic organic chemistry. Extension of oxygen umpolung concept beyond copper catalysis is ongoing in our laboratory.

Author contributions

K. H. conceived the idea. K. F. and S. N. performed all experiments. K. H. supervised the project and wrote the manuscript. All the authors discussed the results and commented on the manuscript.

Conflicts of interest

There are no conflicts to declare.

Data availability

All experimental procedures and spectroscopic data can be found in the supplementary information (SI). Supplementary information is available. See DOI: <https://doi.org/10.1039/d5sc07347b>.

Acknowledgements

This work was supported by JSPS KAKENHI Grants JP 23K23345 [Grant-in-Aid for Scientific Research (B), to K. H.], JP 25H02033 [Grant-in-Aid for Transformative Research Areas (A) (Publicly Offered Research), to K. H.], JP 25K22257 [Grant-in-Aid for Challenging Research (Exploratory), to K. H.], and JST FOREST Program Grant JPMJFR211X to K. H.



Notes and references

- 1 (a) A. Pelter, K. Smith and H. C. Brown, *Borane Reagents*, Academic Press, London, 1988; (b) N. Miyaura and A. Suzuki, *Chem. Rev.*, 1995, **95**, 2457; (c) M. Davison, A. K. Hughes, T. B. Marder and K. Wade, *Contemporary Boron Chemistry*, RSC, Cambridge, U.K., 2000; (d) *Boronic Acids*, ed. D. G. Hall, Wiley-VCH, Weinheim, Germany, 2nd edn, 2011; (e) S. Viso, R. Fernández de la Pradilla and M. Tortosa, *ACS Catal.*, 2022, **12**, 10603.
- 2 (a) F. Yang, M. Zhu, J. Zhang and H. Zhou, *Med. Chem. Commun.*, 2018, **9**, 201; (b) L. Ji and H. Zhou, *Tetrahedron Lett.*, 2021, **82**, 153411; (c) B. C. Das, N. K. Nandwana, S. Das, V. Nandwana, M. A. Shareef, Y. Das, M. Saito, L. M. Weiss, F. Almaguel, N. S. Hosmane and T. Evans, *Molecules*, 2022, **27**, 2615.
- 3 (a) Z. Sorádová and R. Šebesta, *ChemCatChem*, 2016, **8**, 2581; (b) Y.-S. Zhu, J.-X. Li, H.-T. Zhao and B. Su, *Chin. J. Chem.*, 2024, **42**, 3588; (c) K. Hirano and M. Miura, *J. Am. Chem. Soc.*, 2022, **144**, 648; (d) Y. Gao, M. F. Wagner, S. D. Mendoza and K. M. Engle, Carboboration and Carbosilylation, in *Comprehensive Organic Synthesis, III*, Elsevier, 2025, DOI: [10.1016/B978-0-323-96025-0.00101-0](https://doi.org/10.1016/B978-0-323-96025-0.00101-0); (e) *Science of Synthesis: Advances in Organoboron Chemistry towards Organic Synthesis*, ed. E. Fernández, Thieme, 2020, DOI: [10.1055/b-006-164898](https://doi.org/10.1055/b-006-164898).
- 4 T. Itoh, T. Matsueda, Y. Shimizu and M. Kanai, *Chem.–Eur. J.*, 2015, **21**, 15955.
- 5 X. Yuan, Y. Zhang, Y. Li, J. Yin, S. Wang, T. Xiong and Q. Zhang, *Angew. Chem., Int. Ed.*, 2023, **62**, e202313770.
- 6 For representative work on the C–O bond forming reaction based on the electrophilic etherification, see: (a) R. Willand-Charnley, B. W. Puffer and P. H. Dussault, *J. Am. Chem. Soc.*, 2014, **136**, 5821; (b) T. Javorskis, S. Sriubaitė, G. Bagdžiūnas and E. Orentas, *Chem.–Eur. J.*, 2015, **21**, 9157; (c) S. Katahara, T. Takahashi, K. Nomura, M. Uchiyama, T. Sato and N. Chida, *Chem.–Asian J.*, 2020, **15**, 1869; (d) B. Wu, J. Yang, M. Gao and L. Hu, *Org. Lett.*, 2020, **22**, 5561; (e) C. Zhong, Q. Yin, Y. Zhao and Q. Li and L. Hu, *Chem. Commun.*, 2020, **56**, 13189; (f) X. Liu, Y. Fu, Z. Chen, P. Liu and G. Dong, *Nat. Chem.*, 2023, **15**, 1391; (g) D.-M. Wang, L. Yang, D.-P. Chen, Y. Wu, Y. Tang and P. Wang, *Org. Lett.*, 2024, **26**, 3691.
- 7 (a) S. Nakamura, K. Fujiwara, Y. Kojima, K. Yasui and K. Hirano, *ACS Catal.*, 2025, **15**, 8353; (b) T. Inoue and K. Hirano, *Eur. J. Org. Chem.*, 2025, **2025**, e202500555, For related peroxides in C–O bond forming reactions with highly reactive organometallic reagents and enolates derivatives, see: (c) S. Kyasa, R. N. Meier, R. A. Pardini, T. K. Truttmann, K. T. Kuwata and P. H. Dussault, *J. Org. Chem.*, 2015, **80**, 12100; (d) T. J. Paris, C. Schwartz and R. Willand-Charnley, *J. Org. Chem.*, 2021, **86**, 2369; (e) T. J. Paris, C. Schwartz, E. Sundall and R. Willand-Charnley, *J. Org. Chem.*, 2021, **86**, 14797.
- 8 For selected recent applications of modified dppbz ligands in catalysis, see: (a) S. Ito, T. Itoh and M. Nakamura, *Angew. Chem., Int. Ed.*, 2011, **50**, 454; (b) T. Hatakeyama, T. Hashimoto, Y. Kondo, Y. Fujiwara, H. Seike, H. Takaya, Y. Tamada, T. Ono and M. Nakamura, *J. Am. Chem. Soc.*, 2010, **132**, 10674; (c) T. Fujihara, A. Sawada, T. Yamaguchi, Y. Tani, J. Terao and Y. Tsuji, *Angew. Chem., Int. Ed.*, 2017, **56**, 1539; (d) K. Kato, K. Hirano and M. Miura, *Angew. Chem., Int. Ed.*, 2016, **55**, 14400; (e) H. Iwamoto, K. Kubota and H. Ito, *Chem. Commun.*, 2016, **52**, 5916; (f) S. Nishino, M. Miura and K. Hirano, *Chem. Sci.*, 2021, **12**, 11525; (g) Y. Kojima, M. Miura and K. Hirano, *ACS Catal.*, 2021, **11**, 11663; (h) Y. Kojima, Y. Nishii and K. Hirano, *Angew. Chem., Int. Ed.*, 2024, **63**, e202403337.
- 9 X. Liu, Q. Zhu, D. Chen, L. Wang, L. Jin and C. Liu, *Angew. Chem., Int. Ed.*, 2020, **59**, 2745.
- 10 (a) R. P. Sonawane, V. Jheengut, C. Rabalakos, R. Larouche-Gauthier, H. K. Scott and V. K. Aggarwal, *Angew. Chem., Int. Ed.*, 2011, **50**, 3760; (b) A. Bonet, M. Odachowski, D. Leonori, S. Essafi and V. K. Aggarwal, *Nat. Chem.*, 2014, **6**, 584.
- 11 D. S. Matteson, *Chem. Rev.*, 1989, **89**, 1535.
- 12 (a) H. Noguchi, K. Hojo and M. Suginome, *J. Am. Chem. Soc.*, 2007, **129**, 758; (b) J. L. Wood, L. D. Marciasini, M. Vaultier and M. Pucheault, *Synlett*, 2014, **25**, 551.
- 13 D. S. Laitar, E. Y. Tsui and J. P. Sadighi, *Organometallics*, 2006, **25**, 2405.
- 14 For a related oxidative addition/reductive elimination pathway in the methylation of alkylcopper with CH₃I, see: Y. Dong, K. Shin, B. K. Mai, P. Liu and S. L. Buchwald, *J. Am. Chem. Soc.*, 2022, **144**, 16303.
- 15 The radical intermediacy cannot be completely excluded, but the reaction proceeded smoothly even in the presence of radical trapping reagent, 1,1-diphenylethene. See the SI for details.

