

Cite this: *Chem. Sci.*, 2022, 13, 8834

All publication charges for this article have been paid for by the Royal Society of Chemistry

Received 4th May 2022

Accepted 4th July 2022

DOI: 10.1039/d2sc02497g

rsc.li/chemical-science

Access to chiral β -sulfonyl carbonyl compounds via photoinduced organocatalytic asymmetric radical sulfonylation with sulfur dioxide†Fu-Sheng He,^{‡a} Chun Zhang,^{‡a} Minghui Jiang,^a Lujun Lou,^a Jie Wu^{†*abc} and Shengqing Ye^{†*a}

An organocatalytic enantioselective radical reaction of potassium alkyltrifluoroborates, DABCO·(SO₂)₂ and α,β -unsaturated carbonyl compounds under photoinduced conditions is developed, which provides an efficient pathway for the synthesis of chiral β -sulfonyl carbonyl compounds in good yields with excellent enantioselectivity (up to 96% ee). Aside from α,β -unsaturated carbonyl compounds with auxiliary groups, common chalcone substrates are also well compatible with this organocatalytic system. This method proceeds through an organocatalytic enantioselective radical sulfonylation under photoinduced conditions, and represents a rare example of asymmetric transformation involving sulfur dioxide insertion.

Introduction

The catalytic asymmetric conjugate addition of α,β -unsaturated carbonyl compounds is one of the most powerful synthesis strategies for the synthesis of chiral β -substituted carbonyl compounds.¹ Compared with the well-developed classic Michael addition, the photoinduced radical addition process provides more promising opportunities since the high activity of radical species can overcome the inherent deficiencies of the traditional pathway in terms of substrate activity and steric hindrance. Since the pioneering work of Bach in photoinduced catalytic enantioselective radical addition,² research in this field has developed rapidly. Various carbon-centered radicals or N-centered radicals are compatible in this transformation, leading to diverse chiral β -substituted carbonyl compounds.^{3,4}

Chiral sulfur-containing molecules are ubiquitous in market drugs and bioactive molecules.⁵ Great attention has been devoted to the catalytic asymmetric synthesis of enantioenriched sulfones and considerable progress has been made in recent years.⁶ However, construction of chiral sulfones through a catalytic enantioselective radical process remains challenging.

There are few reports on catalytic asymmetric sulfonyl radical conjugate addition to α,β -unsaturated carbonyl compounds, which would afford biologically interesting enantioenriched β -sulfonyl carbonyl compounds (Scheme 1a). In 2017, Meggers and co-workers described a photoinduced, chiral Rh catalyzed enantioselective reaction of allyl sulfones with α,β -unsaturated *N*-acylpyrazoles, affording a sulfonyl radical asymmetric addition product.⁷ In 2019, Wu and co-workers reported one example to access a chiral β -sulfonyl carbonyl compound using sulfinic acid as a sulfonyl radical source.⁸ Recently, Gong and co-workers demonstrated a photoinduced asymmetric sulfonyl radical addition to α,β -unsaturated carbonyl compounds under chiral nickel catalysis.⁹ The sulfonyl radical was generated *in situ* from the reaction of the C(sp³)-H precursor and

^aSchool of Pharmaceutical and Materials Engineering & Institute for Advanced Studies, Taizhou University, 1139 Shifu Avenue, Taizhou 318000, China. E-mail: shengqing.ye@tzu.edu.cn; jie_wu@fudan.edu.cn

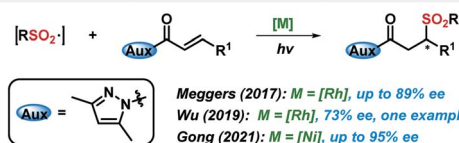
^bState Key Laboratory of Organometallic Chemistry, Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences, 345 Lingling Road, Shanghai 200032, China

^cSchool of Chemistry and Chemical Engineering, Henan Normal University, Xinxiang 453007, China

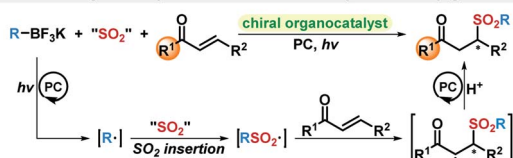
† Electronic supplementary information (ESI) available: Experimental details and spectral data and copies of ¹H and ¹³C NMR spectra. CCDC 2165683. For ESI and crystallographic data in CIF or other electronic format see <https://doi.org/10.1039/d2sc02497g>

‡ These authors contributed equally to this work.

a) Transition-metal catalyzed enantioselective sulfonyl radical conjugate additions



b) This work: organocatalytic enantioselective sulfonyl radical conjugate additions



- ♦ Organocatalytic enantioselective sulfonyl radical conjugate addition process
- ♦ Common chalcones and α,β -unsaturated *N*-acylpyrazoles are compatible
- ♦ Photoinduced asymmetric sulfur dioxide insertion
- ♦ 36 examples, up to 87% yield, up to 96% ee

Scheme 1 Catalytic asymmetric sulfonyl radical conjugate addition to α,β -unsaturated carbonyl compounds.



DABCO·(SO₂)₂ in this transformation. Despite significant advances, the aforementioned metal-catalyzed radical additions still suffer from substrate limitations, where the coordination of an auxiliary group to the metal center is essential for substrate activation and stereochemical control. The development of a novel catalytic system for the asymmetric synthesis of chiral β-sulfonyl carbonyl compounds with excellent enantioselectivity and broader substrate scope is still highly desirable.

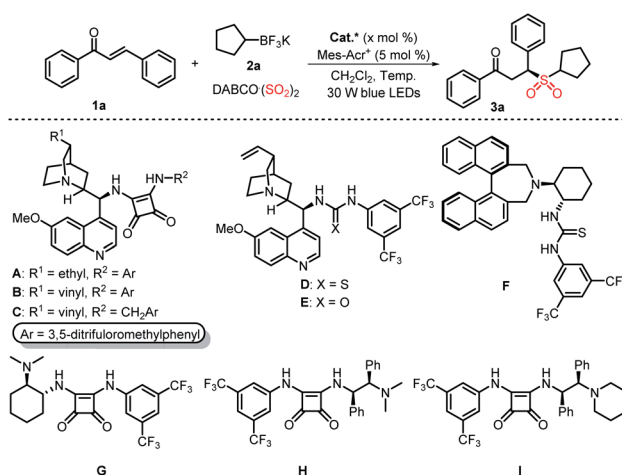
On the other hand, construction of a sulfonyl nucleus through the radical-based sulfur dioxide insertion strategy has been developed rapidly.^{10,11} Based on our continuous interest in radical-based sulfur dioxide insertion and recent success in squaramide catalyzed asymmetric addition of sulfonyl radicals to VQMs (vinylidene *ortho*-quinone methides),¹² we develop an

organocatalytic enantioselective radical reaction of α,β-unsaturated carbonyl compounds, potassium alkyltrifluoroborates, and DABCO·(SO₂)₂ under visible light irradiation, affording chiral β-sulfonyl carbonyl compounds in good yields with excellent enantioselectivity (up to 96% ee). This method proceeds through a photoinduced organocatalytic enantioselective sulfonyl radical conjugate addition process, and represents a rare example of asymmetric transformation involving sulfur dioxide insertion (Scheme 1b).

Results and discussion

We commenced this study by using commercially available chalcone **1a** and potassium cyclopentyltrifluoroborate **2a** as

Table 1 Initial studies for the reaction of chalcone **1a**, potassium cyclopentyltrifluoroborate **2a** and DABCO·(SO₂)₂^a



Entry	PC (mol%)	Cat* (mol%)	T (°C)	Solvent	Yield ^b (%)	ee ^c (%)
1	Mes-Acr ⁺ ClO ₄ ⁻	A (5)	-5	CH ₂ Cl ₂	80	-68
2	Mes-Acr ⁺ ClO ₄ ⁻	B (5)	-5	CH ₂ Cl ₂	78	-73
3	Mes-Acr ⁺ ClO ₄ ⁻	C (5)	-5	CH ₂ Cl ₂	78	-60
4	Mes-Acr ⁺ ClO ₄ ⁻	D (5)	-5	CH ₂ Cl ₂	78	-60
5	Mes-Acr ⁺ ClO ₄ ⁻	E (5)	-5	CH ₂ Cl ₂	88	-68
6	Mes-Acr ⁺ ClO ₄ ⁻	F (5)	-5	CH ₂ Cl ₂	84	-46
7	Mes-Acr ⁺ ClO ₄ ⁻	G (5)	-5	CH ₂ Cl ₂	72	60
8	Mes-Acr ⁺ ClO ₄ ⁻	H (5)	-5	CH ₂ Cl ₂	84	80
9	Mes-Acr ⁺ ClO ₄ ⁻	I (5)	-5	CH ₂ Cl ₂	78	80
10	<i>fac</i> -Ir(ppy) ₃	H (5)	-5	CH ₂ Cl ₂	n.r.	—
11	[Ir(dFCF ₃ ppy) ₂ bpy]PF ₆	H (5)	-5	CH ₂ Cl ₂	n.r.	—
12	Ru(bpy) ₃ Cl ₂	H (5)	-5	CH ₂ Cl ₂	n.r.	—
13	Mes-Acr ⁺ ClO ₄ ⁻	H (5)	-20	CH ₂ Cl ₂	54	89
14	Mes-Acr ⁺ ClO ₄ ⁻	H (5)	-20	CHCl ₃	70	87
15	Mes-Acr ⁺ ClO ₄ ⁻	H (5)	-20	EtOAc	30	93
16	Mes-Acr ⁺ ClO ₄ ⁻	H (5)	-20	ⁱ PrOH	20	86
17	Mes-Acr ⁺ ClO ₄ ⁻	H (5)	-20	MTBE	32	73
18	Mes-Acr ⁺ ClO ₄ ⁻	H (5)	-20	MeCN	56	93
19	Mes-Acr ⁺ ClO ₄ ⁻	H (1)	-20	MeCN	64 (60)	95
20	Mes-Acr ⁺ ClO ₄ ⁻	—	-20	MeCN	Trace	—
21 ^d	Mes-Acr ⁺ ClO ₄ ⁻	H (1)	-20	MeCN	n.r.	—
22 ^e	Mes-Acr ⁺ ClO ₄ ⁻	H (1)	-20	MeCN	n.r.	—

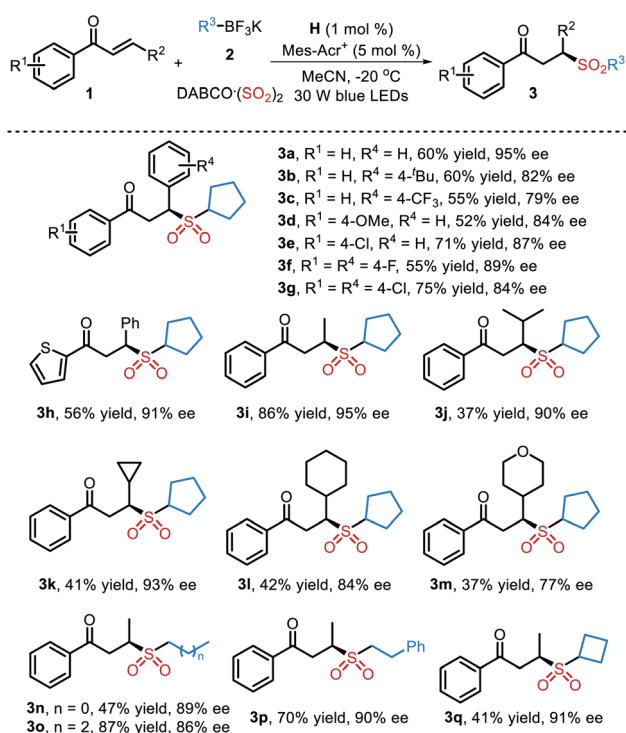
^a Reaction conditions: chalcone **1a** (0.1 mmol), potassium cyclopentyltrifluoroborate **2a** (0.2 mmol), DABCO·(SO₂)₂ (0.1 mmol), Mes-Acr⁺ClO₄⁻ (5 mol%), solvent (2.0 mL), 30 W blue LED, 72 h. ^b Determined by ¹H NMR analysis (isolated yield in parentheses). ^c Determined by HPLC analysis on a chiral stationary phase. ^d In the dark. ^e In the absence of Mes-Acr⁺.



model substrates with $\text{DABCO} \cdot (\text{SO}_2)_2$ as the sulfur dioxide surrogate to explore suitable reaction conditions (Table 1). Pleasingly, the reaction proceeded smoothly with **A** as the organocatalyst, and $\text{Mes-Acr}^+\text{ClO}_4^-$ as the photocatalyst in CH_2Cl_2 at -5°C , providing the desired product **3a** in 80% NMR yield with -68% ee (Table 1, entry 1). Encouraged by this result, we then examined the reaction with other bifunctional organocatalysts **B-I** (Table 1, entries 2–9). It was found that **H** was the optimal organocatalyst in terms of yield and enantioselectivity (Table 1, entry 8). No reaction occurred when other Ir or Ru photocatalysts were used in this reaction (Table 1, entries 10–12). Lowering the reaction temperature to -20°C resulted in an improvement of enantioselectivity, albeit with a slightly decreased yield (Table 1, entry 13). Furthermore, the screening of solvents including CHCl_3 , EtOAc , $^i\text{PrOH}$, MTBE , and MeCN showed that MeCN was the ideal solvent for this transformation (Table 1, entries 14–18). Remarkably, when the loading of catalyst **H** was decreased to 1 mol%, an improved yield and ee value of **3a** was obtained (Table 1, entry 19). Control experiments without an organocatalyst, light irradiation, or a photocatalyst suggested that these components were all essential to achieve a product with excellent enantioselectivity (Table 1, entries 20 and 21).

Under optimal reaction conditions, the substrate scope of this organocatalytic asymmetric three-component reaction with respect to α,β -unsaturated ketones **1** and potassium alkyltrifluoroborates **2** was investigated (Table 2). In general, the

Table 2 Scope exploration for the reaction of α,β -unsaturated ketones **1**, potassium alkyltrifluoroborates **2** and $\text{DABCO} \cdot (\text{SO}_2)_2^a$

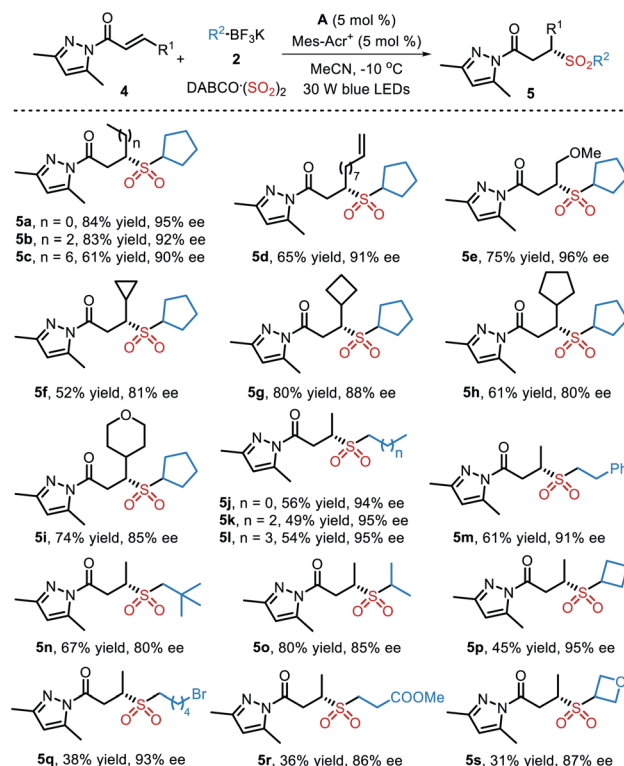


^a Isolated yield based on α,β -unsaturated ketone **1**.

reaction proceeded smoothly with a wide range of substrates to give the desired products in moderate to good yields with universally high enantioselectivities. For example, α,β -unsaturated ketones bearing both electron-donating or -withdrawing substituents on the phenyl group participated in the reaction well to furnish the corresponding products **3b–3g**. Changing the aryl group of R^2 to an alkyl group had little effect on the enantioselectivities (**3i–3m**). Moreover, the reaction was also compatible with primary potassium alkyltrifluoroborates, leading to the chiral sulfones **3n–3p** in 47–87% yields with 86–90% ee. The absolute configuration of **3d** was determined to be *S* by single-crystal X-ray diffraction analysis.¹³ No product was obtained when phenyltrifluoroborate was utilized in this reaction under the standard reaction conditions.

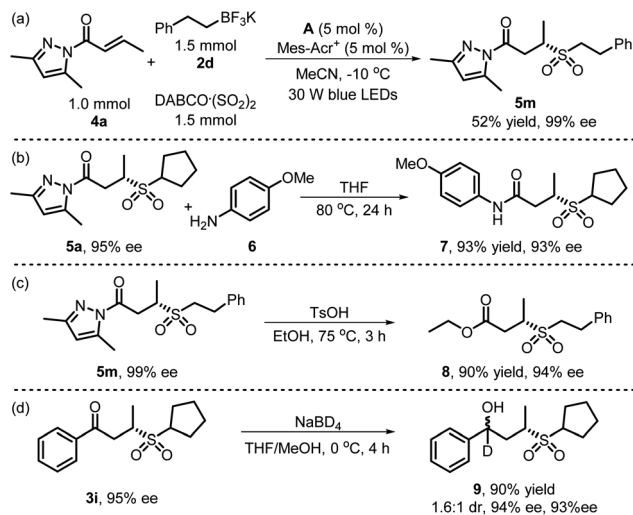
Subsequently, the generality of this transformation utilizing α,β -unsaturated *N*-acylpyrazoles as radical acceptors was also explored. As summarized in Table 3, a variety of structurally diverse chiral sulfones were afforded under slightly modified reaction conditions (see the ESI for details). It was found that α,β -unsaturated *N*-acylpyrazoles with different substituents (R^1) were all suitable for this reaction, providing the chiral products **5a–5i** in moderate to good yields with high ee values. The absolute configuration of **5a** was assigned as *S* by comparison with Gong's work.⁹ Additionally, both primary and secondary potassium alkyltrifluoroborates worked well and delivered the target products **5j–5q** in 31–80% yields with 80–95% ee.

Table 3 Scope exploration for the reaction of α,β -unsaturated *N*-acylpyrazoles **4**, potassium alkyltrifluoroborates **2** and $\text{DABCO} \cdot (\text{SO}_2)_2^a$



^a Isolated yield based on α,β -unsaturated *N*-acylpyrazole **4**.

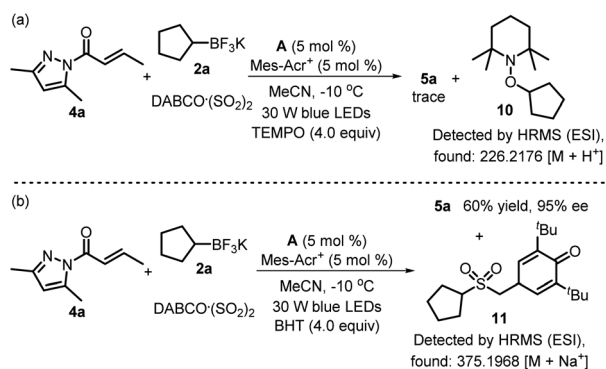




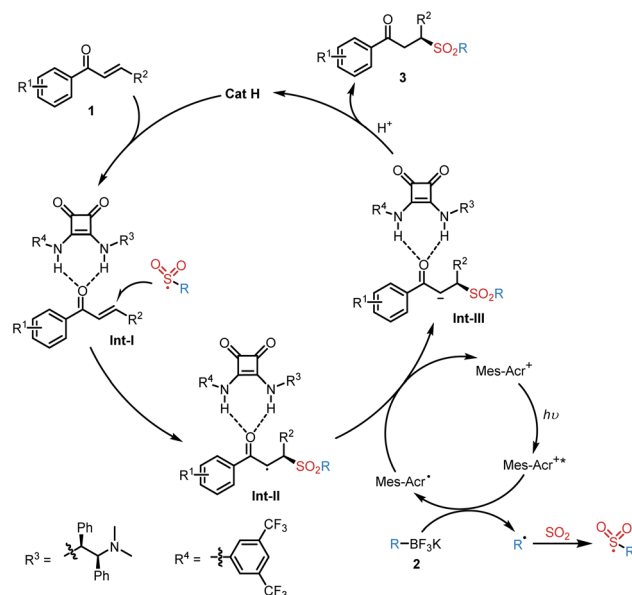
Scheme 2 (a) Large-scale synthesis. (b)–(d) Synthetic transformations.

To further evaluate the practicality of this method, a 1 mmol scale reaction of α,β -unsaturated *N*-acylpyrazole **4a**, potassium phenethyltrifluoroborate **2d** and **DABCO·(SO₂)₂** was carried out under standard conditions, affording the desired product **5m** in 52% yield and with 99% ee (Scheme 2a). In addition, the pyrazole moiety of chiral sulfone product **5a** could be substituted by 4-methoxyaniline **6** and delivered the amide derivative **7** in 91% yield with 93% ee (Scheme 2b). Furthermore, esterification product **8** could be generated in 90% yield with 94% ee from the reaction of chiral sulfone product **5m** with ethanol (Scheme 2c). Next, a γ -hydroxy sulfone product could be constructed by the hydrogenation of the carbonyl group of chiral sulfone product **3i**, and γ -hydroxy sulfone product **9** could be obtained in 90% yield with 1.6 : 1 dr (94% ee, 93% ee) (Scheme 2d).

Next, two control experiments were performed to elucidate the reaction mechanism. As shown in Scheme 3a, the reaction of α,β -unsaturated *N*-acylpyrazole **4a**, potassium cyclopentyltrifluoroborate **2a** and **DABCO·(SO₂)₂** was completely suppressed in the presence of 4.0 equiv. of radical scavenger **TEMPO** (2,2,6,6-tetramethylpiperidine-1-oxyl) under standard conditions, and radical trapping adduct **10** was detected by



Scheme 3 (a) Radical trapping with TEMPO. (b) Radical trapping with BHT.



Scheme 4 Proposed mechanism.

HRMS (high-resolution mass spectrometry). Moreover, the addition of 4.0 equiv. of another radical scavenger **BHT** (butylated hydroxytoluene) led to a decreased yield of product **5a** with retention of enantioselectivity, and confirmed the existence of a sulfonyl radical upon the detection of compound **11** (Scheme 3b). Taken together, these results suggested that the organocatalytic asymmetric reaction involved a radical process.

Based on the above experiment results and previous reports on the organocatalytic asymmetric radical transformations,¹⁴ a plausible reaction pathway for this photoinduced enantioselective radical sulfonylation with sulfur dioxide is shown in Scheme 4. Initially, potassium alkyltrifluoroborate **2** could be oxidized by a photocatalyst under visible light irradiation to afford the alkyl radical, which would react with sulfur dioxide to generate the alkylsulfonyl radical. The asymmetric addition of a sulfonyl radical to substrate **1** was achieved by the hydrogen-bond interaction in the presence of chiral squaramide catalyst **H**, giving rise to the chiral radical intermediate **Int II** in the *S* configuration. Subsequently, **Int II** would undergo single electron transfer (SET) reduction to produce the anion intermediate **Int-III**. The desired product **3** was obtained by the protonation of **Int-III** and regeneration of the organocatalyst **H**.

Conclusions

In conclusion, we have developed a photoinduced enantioselective organocatalytic radical conjugate addition to access enantioenriched β -sulfonyl carbonyl compounds through a three-component reaction of potassium alkyltrifluoroborates, **DABCO·(SO₂)₂** and α,β -unsaturated carbonyl compounds. Chiral β -sulfonyl carbonyl compounds were achieved with excellent enantioselectivity and good yields. This process features mild reaction conditions and broad substrate scope. Not only α,β -unsaturated carbonyl compounds with auxiliary



groups, but also common chalcone substrates were workable in this reaction. This method represents a rare example of asymmetric transformation involving sulfur dioxide insertion as well.

Data availability

The data supporting this study are available within the article and the ESI.† The X-ray crystallographic coordinates for the structure of **3d** have been deposited at the Cambridge Crystallographic Data Center (CCDC: 2165683).

Author contributions

F.-S. H. and C. Z. contributed equally to this work. S. Y. conceived the study. F.-S. H. and C. Z. conducted the experiments and analysed the data. M. J. and L. L. conducted the preparation of the starting materials. S. Y. and J. W. directed the project. S. Y. and F.-S. H. prepared the manuscript. C. Z. prepared the ESI.† All authors discussed the results and commented on the manuscript.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

Financial support from the National Natural Science Foundation of China (No. 21901178), the Natural Science Foundation of Zhejiang Province (LY21B020002), the Leading Innovative and Entrepreneur Team Introduction Program of Zhejiang (No. 2019R01005), and the Open Research Fund of School of Chemistry and Chemical Engineering, Henan Normal University (2020ZD04) is gratefully acknowledged.

Notes and references

- (a) A. Córdova, *Catalytic Asymmetric Conjugate Reactions*, Wiley-VCH, Weinheim, 2010; (b) J. L. Vicario, E. Reyes, L. Carrillo and U. Uria, *Organocatalytic Asymmetric Nucleophilic Addition to Electron-Deficient Alkenes*, *Comprehensive Organic Synthesis (Second Edition)*, 4.03 *Organocatalytic Asymmetric Nucleophilic Addition to Electron-Deficient Alkenes*, WileyVCH, Weinheim, 2014, pp. 119–188; (c) M. Mauduit, O. Basle, H. Clavier, C. Crévisy and A. Denicourt-Nowicki, *Metal-Catalyzed Asymmetric Nucleophilic Addition to Electron-Deficient Alkenes*, *Comprehensive Organic Synthesis (Second Edition)*, 4.04 *Organocatalytic Asymmetric Nucleophilic Addition to Electron-Deficient Alkenes*, Wiley-VCH, Weinheim, 2014, pp. 189–341; (d) C. Hui, F. Pu and J. Xu, *Chem.-Eur. J.*, 2017, **23**, 4023–4036; (e) K. Zheng, X. Liu and X. Ming, *Chem. Rev.*, 2018, **118**, 7586–7656.
- A. Bauer, F. Westkämper, S. Grimme and T. Bach, *Nature*, 2005, **436**, 1139–1140.
- For selected examples, see: (a) L. Ruiz Espelt, I. S. McPherson, E. M. Wiensch and T. P. Yoon, *J. Am. Chem. Soc.*, 2015, **137**, 2452–2455; (b) J. J. Murphy, D. Bastida, S. Paria, M. Fagnoni and P. Melchiorre, *Nature*, 2016, **532**, 218–222; (c) C. Wang, K. Harms and E. Meggers, *Angew. Chem., Int. Ed.*, 2016, **55**, 13495–13498; (d) H. Huo, K. Harms and E. Meggers, *J. Am. Chem. Soc.*, 2016, **138**, 6936–6939; (e) M. Silvi, C. Verrier, Y. P. Rey, L. Buzzetti and P. Melchiorre, *Nat. Chem.*, 2017, **9**, 868–873; (f) Z. Zhou, Y. Li, B. Han, L. Gong and E. Meggers, *Chem. Sci.*, 2017, **8**, 5757–5763; (g) S.-X. Lin, G.-J. Sun and Q. Kang, *Chem. Commun.*, 2017, **53**, 7665–7668; (h) P. Bonilla, Y. P. Rey, C. M. Holden and P. Melchiorre, *Angew. Chem., Int. Ed.*, 2018, **57**, 12819–12823; (i) X. Shen, Y. Li, Z. Wen, S. Cao, X. Hou and L. Gong, *Chem. Sci.*, 2018, **9**, 4562–4568; (j) Z.-Y. Cao, T. Ghosh and P. Melchiorre, *Nat. Commun.*, 2018, **9**, 3274; (k) J. Ma, J. Lin, L. Zhao, K. Harms, M. Marsch, X. Xie and E. Meggers, *Angew. Chem., Int. Ed.*, 2018, **57**, 11193–11197; (l) Y. Yin, Y. Dai, H. Jia, J. Li, L. Bu, B. Qiao, X. Zhao and Z. Jiang, *J. Am. Chem. Soc.*, 2018, **140**, 6083–6087; (m) K. Zhang, L.-Q. Lu, Y. Jia, Y. Wang, F.-D. Lu, F. Pan and W.-J. Xiao, *Angew. Chem., Int. Ed.*, 2019, **58**, 13375–13379; (n) E. L. Saux, D. Ma, P. Bonilla, C. M. Holden, D. Lustosa and P. Melchiorre, *Angew. Chem., Int. Ed.*, 2021, **60**, 5357–5362.
- For selected reviews, see: (a) K. Nakajima, Y. Miyake and Y. Nishibayashi, *Acc. Chem. Res.*, 2016, **49**, 1946–1956; (b) T. P. Yoon, *Acc. Chem. Res.*, 2016, **49**, 2307–2315; (c) M. Silvi and P. Melchiorre, *Nature*, 2018, **554**, 41–49; (d) B.-C. Hong, *Org. Biomol. Chem.*, 2020, **18**, 4298–4353; (e) A. L. Gant Kanegusuku and J. L. Roizen, *Angew. Chem., Int. Ed.*, 2021, **60**, 21116–21149; (f) T. Xiong and Q. Zhang, *Chem. Soc. Rev.*, 2021, **50**, 8857–8873; (g) M. J. Genzink, J. B. Kidd, W. B. Swords and T. P. Yoon, *Chem. Rev.*, 2022, **122**, 1654–1716; (h) S. Ye and J. Wu, *Acta Chim. Sin.*, 2019, **77**, 814–831.
- (a) N. A. McGrath, M. Brichacek and J. T. Njardarson, *J. Chem. Educ.*, 2010, **87**, 1348–1349; (b) M. Feng, B. Tang, S. H. Liang and X. Jiang, *Curr. Top. Med. Chem.*, 2016, **16**, 1200–1216; (c) K. A. Scott and J. T. Njardarson, *Top. Curr. Chem.*, 2018, **376**, 5.
- For selected examples, see: (a) X.-S. Wu, Y. Chen, M.-B. Li, M.-G. Zhou and S.-K. Tian, *J. Am. Chem. Soc.*, 2012, **134**, 14694–14697; (b) Z. Jin, J. Xu, S. Yang, B.-A. Song and Y. R. Chi, *Angew. Chem., Int. Ed.*, 2013, **52**, 12354–12358; (c) J. Choi, P. Martín-Gago and G. C. Fu, *J. Am. Chem. Soc.*, 2014, **136**, 12161–12165; (d) K. M.-H. Lim and T. Hayashi, *J. Am. Chem. Soc.*, 2015, **137**, 3201–3204; (e) S. Jia, Z. Chen, N. Zhang, Y. Tan, Y. Liu, J. Deng and H. Yan, *J. Am. Chem. Soc.*, 2018, **140**, 7056–7060; (f) J. Long, L. Shi, X. Li, H. Lv and X. Zhang, *Angew. Chem., Int. Ed.*, 2018, **57**, 13248–13251; (g) Q. Yan, G. Xiao, Y. Wang, G. Zi, Z. Zhang and G. Hou, *J. Am. Chem. Soc.*, 2019, **141**, 1749–1756; (h) A. Cai and A. W. Kleij, *Angew. Chem., Int. Ed.*, 2019, **58**, 14944–14949; (i) Q. Zhang, D. Dong and W. Zi, *J. Am. Chem. Soc.*, 2020, **142**, 15860–15869.
- X. Huang, S. Luo, O. Burghaus, R. D. Webster, K. Harms and E. Meggers, *Chem. Sci.*, 2017, **8**, 7126–7131.



- 8 Y. Kuang, K. Wang, X. Shi, X. Huang, E. Meggers and J. Wu, *Angew. Chem., Int. Ed.*, 2019, **58**, 16859–16863.
- 9 S. Cao, W. Hong, Z. Ye and L. Gong, *Nat. Commun.*, 2021, **12**, 2377.
- 10 For selected reviews, see: (a) P. Vogel, M. Turks, L. Bouchez, D. Marković, A. Varela-Álvarez and J. Á. Sordo, *Acc. Chem. Res.*, 2007, **40**, 931–942; (b) G. Liu, C. Fan and J. Wu, *Org. Biomol. Chem.*, 2015, **13**, 1592–1599; (c) E. J. Emmett and M. C. Willis, *Asian J. Org. Chem.*, 2015, **4**, 602–611; (d) G. Qiu, K. Zhou, L. Gao and J. Wu, *Org. Chem. Front.*, 2018, **5**, 691–705; (e) D. Zheng and J. Wu, *Sulfur Dioxide Insertion Reactions for Organic Synthesis*, Nature Springer, Berlin, 2017; (f) G. Qiu, K. Zhou and J. Wu, *Chem. Commun.*, 2018, **54**, 12561–12569; (g) K. Suta and M. Turks, *Chem. Heterocycl. Compd.*, 2018, **54**, 584–586; (h) S. Ye, G. Qiu and J. Wu, *Chem. Commun.*, 2019, **55**, 1013–1019; (i) S. Ye, M. Yang and J. Wu, *Chem. Commun.*, 2020, **56**, 4145–4155; (j) S. P. Blum, K. Hofman, G. Manolikakes and S. R. Waldvogel, *Chem. Commun.*, 2021, **57**, 8236–8249.
- 11 For selected examples, see: (a) D. Zheng, Y. An, Z. Li and J. Wu, *Angew. Chem., Int. Ed.*, 2014, **53**, 2451–2454; (b) D. Zheng, J. Yu and J. Wu, *Angew. Chem., Int. Ed.*, 2016, **55**, 11925–11929; (c) F. Liu, J.-Y. Wang, P. Zhou, G. Li, W.-J. Hao, S.-J. Tu and B. Jiang, *Angew. Chem., Int. Ed.*, 2017, **56**, 15570–15574; (d) H. Wang, S. Sun and J. Cheng, *Org. Lett.*, 2017, **19**, 5844–5847; (e) Y. Wang, L. Deng, J. Zhou, X. Wang, H. Mei, J. Han and Y. Pan, *Adv. Synth. Catal.*, 2018, **360**, 1060–1065; (f) Y. Meng, M. Wang and X. Jiang, *Angew. Chem., Int. Ed.*, 2020, **59**, 1346–1353; (g) K. Chen, W. Chen, B. Han, W. Chen, M. Liu and H. Wu, *Org. Lett.*, 2020, **22**, 1841–1845; (h) Y. Liu, Q.-L. Wang, Z. Chen, H. Li, B.-Q. Xiong, P.-L. Zhang and K.-W. Tang, *Chem. Commun.*, 2020, **56**, 3011–3014; (i) Y. Liu, D. Yu, Y. Guo, J.-C. Xiao, Q.-Y. Chen and C. Liu, *Org. Lett.*, 2020, **22**, 2281–2286; (j) Z. Chen, N.-W. Liu, M. Bolte, H. Ren and G. Manolikakes, *Green Chem.*, 2018, **20**, 3059–3070; (k) N. Von Wolff, J. Char, X. Frogneux and T. Cantat, *Angew. Chem., Int. Ed.*, 2017, **56**, 5616–5619; (l) K. Zhou, J. Chen and J. Wu, *Chin. Chem. Lett.*, 2020, **31**, 2996–2998; (m) F.-S. He, M. Yang, S. Ye and J. Wu, *Chin. Chem. Lett.*, 2021, **32**, 461–464; (n) Y. Liu, L. Wang, L.-H. Zeng, Y. Zhao, T. Zhu and J. Wu, *Chin. Chem. Lett.*, 2022, **33**, 2383–2386; (o) Y. Liu, X. Zhang, J. Lv, C. Zhang, X. Chang, S. Ye and J. Wu, *Org. Chem. Front.*, 2022, **9**, 450–455.
- 12 C. Zhang, Z. Tang, Y. Qiu, J. Tang, S. Ye, Z. Li and J. Wu, *Chem Catal.*, 2022, **2**, 164–177.
- 13 CCDC 2165683 contains the supplementary crystallographic data for this paper.†
- 14 (a) S. Mondal, F. Dumur, D. Gignes, M. P. Sibi, M. P. Bertrand and M. Nechab, *Chem. Rev.*, 2022, **122**, 5842–5976; (b) D. Liang, J.-R. Chen, L.-P. Tan, Z.-W. He and W.-J. Xiao, *J. Am. Chem. Soc.*, 2022, **144**, 6040–6049; (c) Y. Yin, Y. Dai, H. Jia, J. Li, L. Bu, B. Qiao, X. Zhao and Z. Jiang, *J. Am. Chem. Soc.*, 2018, **140**, 6083–6087; (d) Y. Zhu, L. Zhang and S. Luo, *J. Am. Chem. Soc.*, 2014, **136**, 14642–14645; (e) L. J. Rono, H. G. Yayla, D. Y. Wang, M. F. Armstrong and R. R. Knowles, *J. Am. Chem. Soc.*, 2013, **135**, 17735–17738; (f) M.-C. Fu, R. Shang, B. Zhao, B. Wang and Y. Fu, *Science*, 2019, **363**, 1429–1434.

