

EDGE ARTICLE

View Article Online
View Journal | View IssueCite this: *Chem. Sci.*, 2021, 12, 7498

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

Received 24th February 2021

Accepted 22nd April 2021

DOI: 10.1039/d1sc01096d

rsc.li/chemical-science

Catalytic asymmetric addition of thiols to silyl glyoxylates for synthesis of multi-hetero-atom substituted carbon stereocenters†

Mingming Guan,^{ID} Shiyu Wang, Yao Luo, Weidi Cao,* Xiaohua Liu^{ID} and Xiaoming Feng^{ID}*

A chiral Lewis acid-catalyzed enantioselective addition of thiols to silyl glyoxylates was developed. The reaction proceeds well with a broad range of thiols and acylsilanes, affording the target tertiary chiral α -silyl- α -sulfhydryl alcohols with multi-hetero-atom carbon stereocenters in excellent yields (up to 99%) and enantioselectivities (up to 98% ee). A series of control experiments were conducted to elucidate the reaction mechanism.

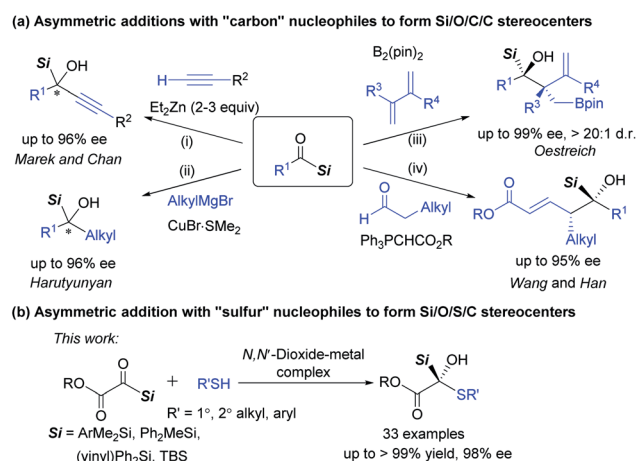
Introduction

Heteroatoms are prevalent in numerous organic compounds. As a significant subset of heteroatom-containing compounds, organosilanes are important skeletons of many known drugs and provide an opportunity to control pharmacokinetic properties.¹ They have been also widely applied in modern organic synthesis due to their unique properties. Particularly, optically active α -hydroxysilanes, containing a carbon stereocenter linked with a silicon atom and an oxygen atom simultaneously, are highly useful reagents in stereoselective C–C bond formation and rearrangement reactions for delivering various chiral molecules.² As a result, catalytic asymmetric preparation of chiral α -hydroxysilanes attracts much attention.

Enantioselective access to α -silyl alcohols could be obtained from nucleophilic addition of organosilanes to carbonyl compounds,³ or from reduction⁴ and addition reactions^{5–9} of acylsilanes, which represent a class of unusual and fascinating carbonyl compounds.¹⁰ The addition of highly reactive (pro) nucleophilic organometallic reagents to acylsilanes has emerged for the construction of α -hydroxysilanes bearing two saturated or unsaturated hydrocarbonyl groups. For example, Marek's⁵ and Chan's⁶ group reported zinc-catalyzed enantioselective alkynylations of acylsilanes to give alkyl substituted α -silyl alcohols (Scheme 1a, path i). Harutyunyan⁷ later extended the nucleophiles to a series of alkyl Grignard reagents in the presence of a copper ferrocenyl diphosphine complex catalyst

(path ii), and the competing Meerwein–Ponndorf–Verley reduction could be largely suppressed by using an equivalent mixture of CeCl_3 and $\text{BF}_3 \cdot \text{Et}_2\text{O}$. Recently, Oestreich developed the stereoselective addition of chiral allylic copper intermediates (*in situ* generated from boron nucleophile and 1,3-dienes) to acylsilanes (path iii).⁸ Alternatively, Wang, Han and co-workers realized an organocatalytic (vinylogous) aldol reaction with carbonyl compounds as nucleophiles (path iv).⁹ The advance in synthesis of chiral α -silyl alcohols by using “carbon” nucleophiles intrigued us to investigate enantioselective construction of multi-hetero-atom-bearing carbon stereogenic centers by using hetero-atom nucleophiles.¹¹

The asymmetric construction of a carbon–sulfur (C–S) bond plays a prominent role for the synthesis of valuable chiral organosulfur compounds.¹² Significant progress has been



Scheme 1 Enantioselective nucleophilic addition reactions of acylsilanes for the construction of chiral tertiary α -silyl alcohols.

Key Laboratory of Green Chemistry & Technology, Ministry of Education, College of Chemistry, Sichuan University, Chengdu 610064, P. R. China. E-mail: wdcao@scu.edu.cn; xmfeng@scu.edu.cn; Web: http://www.scu.edu.cn/chem_asl/

† Electronic supplementary information (ESI) available: ^1H , $^{13}\text{C}\{^1\text{H}\}$ and $^{19}\text{F}\{^1\text{H}\}$ NMR, and HPLC spectra. X-ray crystallographic data for **3w** (CIF). CCDC 2056433 and 2064772. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/d1sc01096d

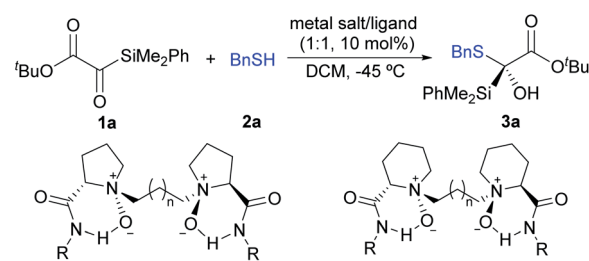
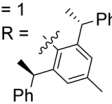
achieved through the addition of “sulfur” nucleophiles to carbon–carbon or carbon–nitrogen double bonds, as well as thiolysis of epoxides or aziridines, and so on. However, the enantioselective addition of thiols to carbonyl compounds is hard to realize, although the corresponding thiohemiacetal and thiohemiketal products are common skeletons in many pharmaceuticals,¹³ which are generally considered as unstable structures and prone to racemization.

As a continuation of our interest in asymmetric sulfur-chemistry,¹⁴ we envisaged that chiral *N,N'*-dioxide–metal complex catalysts¹⁵ would be potentially useful in asymmetric addition of thiols to silyl glyoxylates,¹⁶ although the reaction was found to be highly reactive in some solvents including water without catalysts.^{11a} Herein we report an efficient enantioselective addition of silyl glyoxylates with various thiols as nucleophiles for the formation of chiral tertiary α -silyl alcohols containing a thiohemiketal skeleton (Scheme 1b). The adducts with multi-hetero-atom carbon stereocenters were afforded in excellent yields, and the competing Brook rearrangement² products were suppressed.¹¹

Results and discussion

Our study commenced with silyl glyoxylate **1a** and benzyl mercaptan **2a** as the model substrates to optimize the reaction conditions (Table 1). Considering the strong background reaction response,¹¹ the initial attempts focused on exploring various chiral *N,N'*-dioxide ligands with Er(OTf)₃ (10 mol%) in DCM at a low temperature (−45 °C). To our delight, the Er(OTf)₃/L₃-PrPr₂ complex could promote this reaction to afford the desired product **3a** in 85% yield with 49% ee (entry 1). It was found that the chiral backbones, the amide substituents, and the linker of the ligands displayed obvious effects on the enantioselectivity of the reaction (entries 1–6, see Table S1 in the ESI† for details). The amide substituents with the *tert*-butyl group exhibited poor enantioselectivity compared to that with the aryl group (entry 3 vs. 1). The investigation of the linker of the ligands revealed that L₅-PrPr₂ provided higher enantioselectivity (87% ee) than L₄-PrPr₂ (81% ee) and L₃-PrPr₂ (49% ee) (entry 6 vs. entries 4 and 1). Comparatively, when other representative chiral ligands, such as bis(oxazoline) (BOX), pyridine-2,6-bis(oxazoline) (Pybox), BINAP or chiral phosphoric acid (CPA), were used instead of the *N,N'*-dioxide ligand, moderate yields with low ee values were achieved (see Table S9 in the ESI† for details). In view of the high reactivity, lowering the reaction temperature to −60 °C led to an increased ee value slightly to 89% (entry 11). Other reaction parameters including solvent (entries 7–10), additives and the concentration were also explored; unfortunately, no better results were obtained (see the ESI† for details). Notably, when protonic additives were used, the racemic version of the reaction process was increased through hydrogen bonding catalysis,^{11a} leading to reduced enantiomeric excess. We next chose L₅-PrPr₂ as a chiral ligand to screen the metal salts. La(OTf)₃ could provide 88% yield with moderate enantioselectivity (51% ee, entry 12). Nevertheless, Y(OTf)₃ led to a slight improvement of enantioselectivity with quantitative yield (99% yield, 91% ee, entry 13). In addition,

Table 1 Optimization of the reaction conditions^a

|  | | | | | |
|--|-----------------------------------|----------------------|--------------------|------------------------|---------------------|
| <p>L₃-PrPr₂: R = 2,6-<i>i</i>-Pr₂C₆H₃, n = 1 L₃-PiPr₂: R = 2,6-<i>i</i>-Pr₂C₆H₃, n = 1 L₄-PrPr₂: R = 2,6-<i>i</i>-Pr₂C₆H₃, n = 2 L₄-PiPr₂: R = 2,6-<i>i</i>-Pr₂C₆H₃, n = 2 L₅-PrPr₂: R = 2,6-<i>i</i>-Pr₂C₆H₃, n = 3 L₃-Pr<i>t</i>Bu: R = <i>t</i>Bu, n = 1 L₃-Pr-(S)-(EPh)₂Me: R = , n = 1</p> | | | | | |
| Entry | Ligand | Metal salt | Solvent | Yield ^b (%) | ee ^c (%) |
| 1 | L ₃ -PrPr ₂ | Er(OTf) ₃ | DCM | 85 | 49 |
| 2 | L ₃ -PiPr ₂ | Er(OTf) ₃ | DCM | 88 | 55 |
| 3 | L ₃ -Pr <i>t</i> Bu | Er(OTf) ₃ | DCM | 74 | 12 |
| 4 | L ₄ -PrPr ₂ | Er(OTf) ₃ | DCM | 86 | 81 |
| 5 | L ₄ -PiPr ₂ | Er(OTf) ₃ | DCM | 99 | 77 |
| 6 | L ₅ -PrPr ₂ | Er(OTf) ₃ | DCM | 87 | 87 |
| 7 | L ₅ -PrPr ₂ | Er(OTf) ₃ | CH ₃ CN | 86 | 0 |
| 8 | L ₅ -PrPr ₂ | Er(OTf) ₃ | THF | 85 | 10 |
| 9 | L ₅ -PrPr ₂ | Er(OTf) ₃ | Et ₂ O | NR | — |
| 10 | L ₅ -PrPr ₂ | Er(OTf) ₃ | Toluene | NR | — |
| 11 ^d | L ₅ -PrPr ₂ | Er(OTf) ₃ | DCM | 95 | 89 |
| 12 ^d | L ₅ -PrPr ₂ | La(OTf) ₃ | DCM | 88 | 51 |
| 13 ^d | L ₅ -PrPr ₂ | Y(OTf) ₃ | DCM | 99 | 91 |
| 14 ^{d,e} | L ₅ -PrPr ₂ | Y(OTf) ₃ | DCM | 96 | 90 |

^a Unless otherwise noted, all reactions were performed with a metal salt/ligand (1 : 1, 10 mol%), **1a** (0.10 mmol), **2a** (0.10 mmol) in DCM (1.0 mL) at −45 °C. ^b Yield of isolated product. ^c Determined by HPLC analysis on a chiral stationary phase. ^d Run at −60 °C. ^e The reaction was performed with 2 mol% of Y(OTf)₃/L₅-PrPr₂ for 12 hours.

excellent yield (96%) and enantioselectivity (90% ee) could still be achieved when the catalyst loading was reduced to 2 mol% (entry 14).

With the optimized reaction conditions in hand (Table 1, entry 13), the silyl glyoxylate scope was next investigated (Table 2). Good substrate compatibility was observed with this Lewis acid catalysis system, and PhMe₂Si, Ph₂MeSi and Ph₂(vinyl)Si substituted silyl glyoxylate (entries 1–3) could be transformed into the corresponding products smoothly with excellent yields and enantioselectivities (**3a–3c**, 97–99% yields, 91–96% ee). The substituents of the phenyl group have little influence on the activity and enantioselectivity (entries 4–6). The aromatic silyl glyoxylate bearing methyl or fluoro groups at the *para*-position provided the desired α -silyl- α -sulfhydryl alcohols with decreased yields and enantioselectivities (**3d**, 88% yield with 85% ee; **3e**, 76% yield with 80% ee). Delightedly, the silyl glyoxylate with the 4-chloro group attached to the phenyl ring could be converted into **3f** with 84% yield and 91% ee (entry 6). The alkyl silyl group (TBS) substituted silyl glyoxylate was also tolerated in this



Table 2 Substrate scope of silyl glyoxylates^a

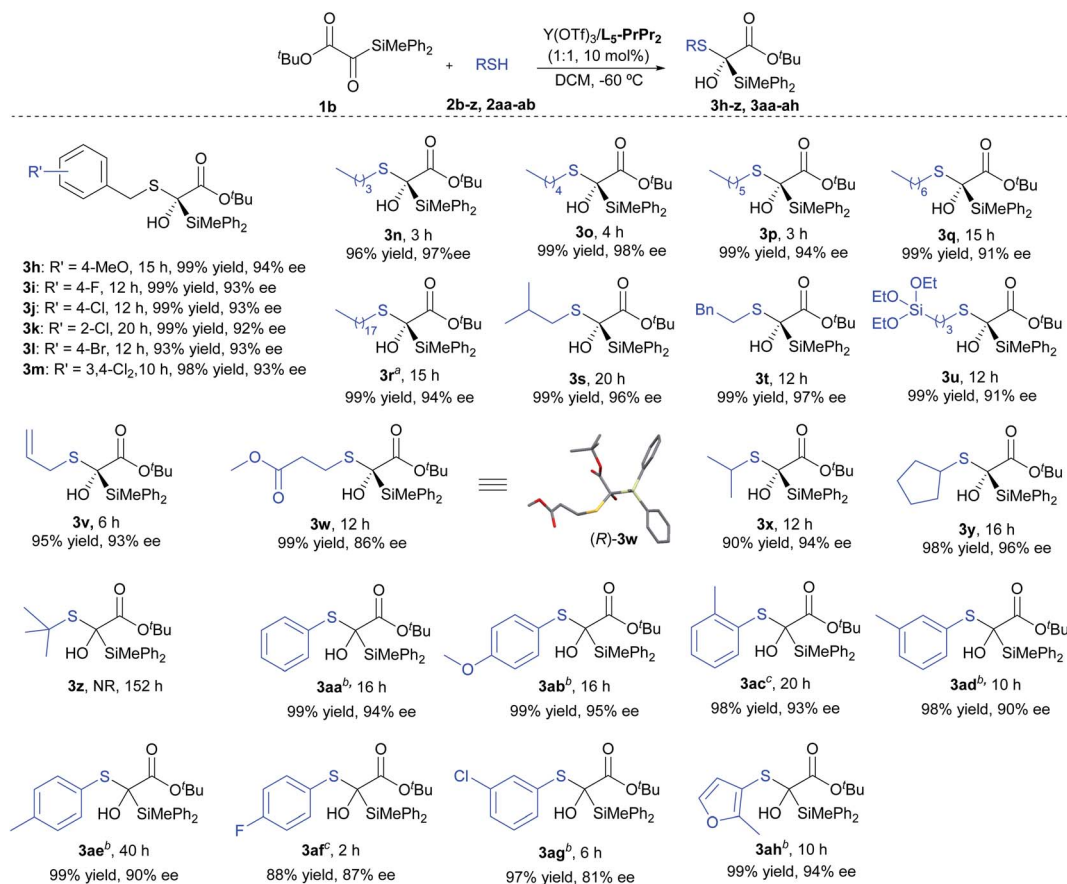
| Entry | Si | Yield ^b (%) | ee ^c (%) |
|------------------|---------------------------------------|------------------------|---------------------|
| 1 | PhMe ₂ Si | 99 (3a) | 91 |
| 2 | Ph ₂ MeSi | 99 (3b) | 95 |
| 3 | Ph ₂ (vinyl)Si | 97 (3c) | 96 |
| 4 | (<i>p</i> -Tolyl)-Me ₂ Si | 88 (3d) | 85 |
| 5 | (4-Fluorophenyl)-Me ₂ Si | 76 (3e) | 80 |
| 6 | (4-Chlorophenyl)-Me ₂ Si | 84 (3f) | 91 |
| 7 ^{d,e} | ^t BuMe ₂ Si | 87 (3g) | 80 |

^a Unless otherwise noted, all reactions were performed with Y(OTf)₃/L₅-PrPr₂ (1 : 1, 10 mol%), **1** (0.10 mmol), **2a** (0.10 mmol) in DCM (1.0 mL) at –60 °C. ^b Yield of the isolated product. ^c Determined by HPLC analysis on a chiral stationary phase. ^d L₃-Pr-(S)-EPh₂Me was used instead of L₅-PrPr₂. ^e Run at –45 °C.

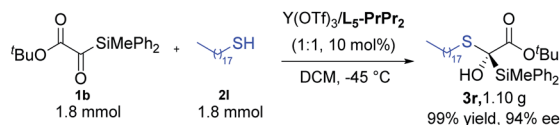
reaction and produced the product **3g** in 87% yield with 80% ee by switching the ligand L₅-PrPr₂ to L₃-Pr-(S)-EPh₂Me (entry 7). However, when less sterically hindered groups, such as the TMS

and TES group, were introduced into the silyl glyoxylate, poor results were obtained (see Table S10 in the ESI† for details).

Subsequently, we turned our attention to the scope of mercaptans **2** (Scheme 2). Regardless of the electronic effect or steric hindrance of the substituents on the phenyl ring of benzyl thiols, this asymmetric reaction proceeded smoothly to afford **3h–3m** with efficient yields (93–99%) and ee values (92–94%). For the primary alkyl thiols, the increase of the alkyl chain length did not affect the activity and enantioselectivity of the reaction; the corresponding products (**3n–3r**) were obtained in 96–99% yields with 91–98% ee. Interestingly, functionalized mercaptan reagents, containing silyl, alkenyl or ester groups at the terminal chain of thiols, could be also tolerated, readily yielding the desired products (**3u–3w**) with good results (95–99% yield, 86–93% ee). The absolute configuration of the product **3w** was determined to be (*R*) by X-ray crystallography analysis.¹⁷ It was found that the nucleophilic addition with branched alkyl thiols, such as 2-propanethiol and cyclopentanethiol, proceeded successfully to give **3x** and **3y** in 90% yield with 94% ee and 98% yield with 96% ee, respectively. However, no product was observed when the sterically hindered *t*-butyl mercaptan was used. Apart from the above alkyl mercaptans, aryl mercaptans could also react with silyl glyoxylate **1b** to produce the desired products with high yields and



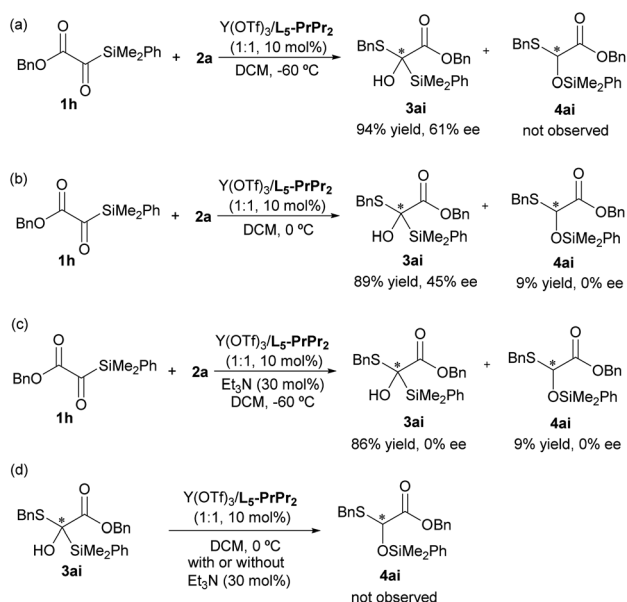
Scheme 2 Substrate scope of mercaptans. Unless otherwise noted, all reactions were performed with Y(OTf)₃/L₅-PrPr₂ (1 : 1, 10 mol%), **1b** (0.10 mmol), and **2** (0.10 mmol) in DCM (1.0 mL) at –60 °C. ^aThe reaction was performed at –45 °C. ^bEu(OTf)₃/L₃-PrPr₂ was used instead of Y(OTf)₃/L₅-PrPr₂. ^cEr(OTf)₃/L₃-PrPr₂ was used instead of Y(OTf)₃/L₅-PrPr₂.

Scheme 3 Gram-scale reaction of **3r**.

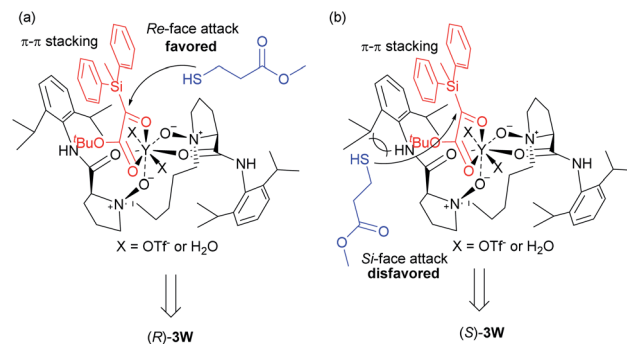
moderate to high enantioselectivities (**3aa–3ah**, 88–99% yields, 81–95% ee).

To evaluate the synthetic value of the catalytic system, a gram-scale synthesis of three-heteroatomic substituted chiral α -silyl- α -sulfhydryl alcohol was carried out. **1b** (1.8 mmol) reacted with **2l** (1.8 mmol) under the standard reaction conditions, providing the corresponding product **3r** in 99% yield with 94% ee (Scheme 3).

To explore the fact that Brook rearrangement products are rarely observed during the reaction, we conducted a series of control experiments. Firstly, the reaction between **1a** and **2a** was performed in the presence of the L_5 -PrPr₂/Y(OTf)₃ complex at a higher temperature (0 °C); the product of Brook rearrangement was still not detected (see the ESI† for details). When the benzyl 2-(dimethyl(phenyl)silyl)-2-oxoacetate **1h** reacted with **2a** at –60 °C, only addition product **3ai** was observed in 94% yield with 61% ee (Scheme 4a). However, increasing the reaction temperature to 0 °C, a mixture of **3ai** and Brook rearrangement product **4ai** was obtained with a ratio of 10 : 1 (Scheme 4b), suggesting that the Brook rearrangement could be significantly suppressed under low temperature conditions.^{11b} Moreover, the result that 45% ee of **3ai** and racemate of **4ai** were observed suggests that oxygen anion **Int-A** generated from **1h** and **2a** facilitated Brook rearrangement to afford the carbon anion **Int-B**, which rapidly underwent racemization before proton transfer due to the existence of the α -ester group (Scheme 4b, see the ESI† for details). Subsequently, the influence of the base was



Scheme 4 Control experiments.



Scheme 5 The proposed working mode.

explored. For the *tert*-butyl 2-silyl-2-oxoacetate **1a**, only racemic addition product **3a** was obtained when Et₃N (30 mol%) was added (see the ESI† for details). In contrast, when benzyl 2-silyl-2-oxoacetate **1h** reacted with **2a** under the same conditions, a mixture of addition product and Brook rearrangement product was observed with a ratio of 10 : 1 (Scheme 4c). These experiments suggest that the ester group of substrates and base (Et₃N) have an important influence on the Brook rearrangement reaction. In addition, the conversion experiment of addition product **3ai** into Brook rearrangement product **4ai** was also performed with or without addition of Et₃N. It was found that no **4ai** was observed (Scheme 4d), which indicates that the formations of the addition product and Brook rearrangement product were competing processes from the oxygen anion **Int-A** (see the ESI† for details).

To further gain insight into the mechanism, the relationship between the ee values of the product **3a** and ligand L_5 -PrPr₂ was explored. A self-evident linear effect was observed, which indicates that the monomeric catalyst of L_5 -PrPr₂ and Y(OTf)₃ may be the main catalytically active species (see the ESI† for details). Based on the absolute configuration of **3w** and X-ray single-crystal structure of the N,N' -dioxide/Y^{III} complex,¹⁸ a proposed transition-state model was described in Scheme 5. The four oxygen atoms of ligand N,N' -dioxide, two oxygen atoms of silyl glyoxylate **1b** and two molecules of the OTf[–] anion or a trace amount of H₂O in solvent coordinate to Y^{III} in an eight-coordinated manner. In combination with the above experimental results and our previous report,¹⁹ we conjectured that a π – π interaction between the aryl silyl group of the substrate and the aryl group of the ligand exists and is beneficial to the reactivities and enantioselectivities. The *Si*-face of the carbonyl group is blocked by the 2,6-diisopropylphenyl group of the ligand (Scheme 5b), and thus the “sulfur” nucleophile **2q** preferably attacks from the *Re*-face to generate the (*R*)-configured product **3w** (Scheme 5a).

Conclusions

In summary, we have developed the first catalytic asymmetric addition of various thiol nucleophiles to silyl glyoxylates. The corresponding tertiary chiral α -silyl- α -sulfhydryl alcohols containing multi-hetero-atom carbon stereocenters were obtained



with high yields and good to excellent enantioselectivities (76–99% yields, 80–98% ee). A series of control experiments were conducted to elucidate the reaction mechanism. The application of this methodology to the modification of protein and pharmaceutical structures needs further research.

Author contributions

M. G. performed experiments and prepared the ESI[†] and paper. S. W. repeated some experiments. Y. L. helped with crystal growth. W. C. and X. L. helped with modifying the paper and ESI[†]. X. F. conceived and directed the project.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We appreciate the National Natural Science Foundation of China (21801174 and 21890723) for financial support. We thank Dr Yuqiao Zhou for the assistance in X-ray analysis.

Notes and references

- (a) K. Miura and A. Hosomi, in *Main Group Metals in Organic Synthesis*, ed. H. Yamamoto and K. Oshima, Wiley-VCH, Weinheim, 2005, p. 409; See also; (b) G. K. Min, D. Hernandez and T. Skrydstrup, *Acc. Chem. Res.*, 2013, **46**, 457; (c) A. K. Franz and S. O. Wilson, *J. Med. Chem.*, 2013, **56**, 388.
- (a) A. G. Brook, *Acc. Chem. Res.*, 1974, **7**, 77; (b) W. H. Moser, *Tetrahedron*, 2001, **57**, 2065; (c) G. Eppe, D. Didier and I. Marek, *Chem. Rev.*, 2015, **115**, 9175; (d) N. Lee, C.-H. Tan and D. Leow, *Asian J. Org. Chem.*, 2019, **8**, 25; (e) L. Gao, W. Yang, Y. Wu and Z. Song, in *Organic Reactions*, ed. P. A. Evans, *et al.*, Wiley-VCH, Weinheim, 2020, p. 5.
- V. Cirriez, C. Rasson, T. Hermant, J. Petriguet, J. D. Alvarez, K. Robeyn and O. Riant, *Angew. Chem., Int. Ed.*, 2013, **52**, 1785.
- (a) L. Panella, B. L. Feringa, J. G. de Vries and A. J. Minnaard, *Org. Lett.*, 2005, **7**, 4177; (b) N. Arai, K. Suzuki, S. Sugizaki, H. Sorimachi and T. Ohkuma, *Angew. Chem., Int. Ed.*, 2008, **47**, 1770; (c) J. Matsuo, Y. Hattori and H. Ishibashi, *Org. Lett.*, 2010, **12**, 2294.
- (a) R. Unger, F. Weissner, N. Chinkov, A. Stanger, T. Cohen and I. Marek, *Org. Lett.*, 2009, **11**, 1853; (b) P. Smirnov, J. Mathew, A. Nijs, E. Katan, M. Karni, C. Bolm, Y. Apeloig and I. Marek, *Angew. Chem., Int. Ed.*, 2013, **52**, 13717; (c) P. Smirnov, E. Katan, J. Mathew, A. Kostenko, M. Karni, A. Nijs, C. Bolm, Y. Apeloig and I. Marek, *J. Org. Chem.*, 2014, **79**, 12122.
- F.-Q. Li, S. Zhong, G. Lu and A. S. C. Chan, *Adv. Synth. Catal.*, 2009, **351**, 1955.
- J. Rong, R. Oost, A. Desmarchelier, A. J. Minnaard and S. R. Harutyunyan, *Angew. Chem., Int. Ed.*, 2015, **54**, 3038.
- J.-J. Feng and M. Oestreich, *Angew. Chem., Int. Ed.*, 2019, **58**, 8211.
- (a) M.-Y. Han, X. Xie, D. Zhou, P. Li and L. Wang, *Org. Lett.*, 2017, **19**, 2282; (b) M.-Y. Han, W.-Y. Luan, P.-L. Mai, P. Li and L. Wang, *J. Org. Chem.*, 2018, **83**, 1518.
- For reviews on acylsilane chemistry, see: (a) H.-J. Zhang, D. L. Priebbenow and C. Bolm, *Chem. Soc. Rev.*, 2013, **42**, 8540; (b) G. R. Boyce, S. N. Greszler, J. S. Johnson, X. Linghu, J. T. Malinowski, D. A. Nicewicz, A. D. Satterfield, D. C. Schmitt and K. M. Steward, *J. Org. Chem.*, 2012, **77**, 4503; (c) D. L. Priebbenow, *Adv. Synth. Catal.*, 2020, **362**, 1927; (d) X. Wang, F. Liu, Y. Li, Z. Yan, Q. Qiang and Q.-Q. Rong, *ChemCatChem*, 2020, **12**, 5022.
- The only example for the formation of racemic tertiary α -silyl alcohol with a three-heteroatomic substituted chiral carbon center, see: (a) M.-Y. Han, J. Lin, W. Li, W.-Y. Luan, P.-L. Mai and Y. Zhang, *Green Chem.*, 2018, **20**, 1228; (b) M.-Y. Han, F.-Y. Yang, D. Zhou and Z. Xu, *Org. Biomol. Chem.*, 2017, **15**, 1418.
- For the reviews on carbon–sulfur bond-forming reactions, see: (a) T. Kondo and T.-A. Mitsudo, *Chem. Rev.*, 2000, **100**, 3205; (b) P. Bichler and J. A. Love, *Top. Organomet. Chem.*, 2010, **31**, 39; (c) I. P. Beletskaya and V. P. Ananikov, *Chem. Rev.*, 2011, **111**, 1596; (d) P. Chauhan, S. Mahajan and D. Enders, *Chem. Rev.*, 2014, **114**, 8807; (e) H. Chen, W. Jiang and Q. Zeng, *Chem. Rev.*, 2020, **20**, 1269.
- Selected examples: (a) K. Brocklehurst and J. P. G. Malthouse, *Biochem. J.*, 1978, **175**, 761; (b) A. N. Matralis, M. G. Katselou, A. Nikitakis and A. P. Kourounakis, *J. Med. Chem.*, 2011, **54**, 5583; (c) A. N. Matralis and A. P. Kourounakis, *J. Med. Chem.*, 2014, **57**, 2568.
- (a) Y. H. Hui, J. Jiang, W. T. Wang, W. L. Chen, Y. F. Cai, L. L. Lin, X. H. Liu and X. M. Feng, *Angew. Chem., Int. Ed.*, 2010, **49**, 4290; (b) G. Wang, Y. Tang, Y. Zhang, X. H. Liu, L. L. Lin and X. M. Feng, *Chem.–Eur. J.*, 2017, **23**, 554; (c) Y. Zhang, F. C. Zhang, L. Chen, J. Xu, X. H. Liu and X. M. Feng, *ACS Catal.*, 2019, **9**, 4834; (d) F. C. Zhang, Y. Zhang, Q. Tan, L. L. Lin, X. H. Liu and X. M. Feng, *Org. Lett.*, 2019, **21**, 5928; (e) T. F. Kang, L. Z. Hou, S. Ruan, W. D. Cao, X. H. Liu and X. M. Feng, *Nat. Commun.*, 2020, **11**, 3869; (f) F. Z. Chang, B. Shen, S. J. Wang, L. L. Lin and X. M. Feng, *Chem. Commun.*, 2020, **56**, 13429.
- For selected reviews on *N,N'*-dioxide ligands, see: (a) X. H. Liu, L. L. Lin and X. M. Feng, *Acc. Chem. Res.*, 2011, **44**, 574; (b) X. H. Liu, L. L. Lin and X. M. Feng, *Org. Chem. Front.*, 2014, **1**, 298; (c) X. H. Liu, H. F. Zheng, Y. Xia, L. L. Lin and X. M. Feng, *Acc. Chem. Res.*, 2017, **50**, 2621; (d) X. H. Liu, S. X. Dong, L. L. Lin and X. M. Feng, *Chin. J. Chem.*, 2018, **36**, 791; (e) Z. Wang, X. H. Liu and X. M. Feng, *Aldrichimica Acta*, 2020, **53**, 3; For recently selected examples: (f) D. Zhang, Z. S. Su, Q. W. He, Z. K. Wu, Y. Q. Zhou, C. J. Pan, X. H. Liu and X. M. Feng, *J. Am. Chem. Soc.*, 2020, **142**, 15975; (g) X. B. Lin, Z. Tan, W. K. Yang, W. Yang, X. H. Liu and X. M. Feng, *CCS Chem.*, 2020, **2**, 1423; (h) J. Xu, Z. W. Zhong, M. Y. Jiang, Y. Q. Zhou, X. H. Liu and X. M. Feng, *CCS Chem.*, 2020, **2**,



- 1894; (i) F. Tan, M. Pu, J. He, J. Z. Li, J. Yang, S. X. Dong, X. H. Liu, Y.-D. Wu and X. M. Feng, *J. Am. Chem. Soc.*, 2021, **143**, 2394.
- 16 Selected examples: (a) Y. Matsuya, K. Wada, D. Minato and K. Sugimoto, *Angew. Chem., Int. Ed.*, 2016, **55**, 10079; (b) M. Bouzrati-Zerelli, J. Kirschner, C. P. Fik, M. Maier, C. Dietlin, F. Morlet-Savary, J. P. Fouassier, J.-M. Becht, J. E. Klee and J. Lalevée, *Macromolecules*, 2017, **50**, 6911; (c) F.-G. Zhang and I. Marek, *J. Am. Chem. Soc.*, 2017, **139**, 8364; (d) C. Zhu, M.-Y. Han, X.-X. Liang, B. Guan, P. Li and L. Wang, *Org. Lett.*, 2021, **23**, 54.
- 17 The absolute configuration of **3w** was determined to be *R* by X-ray crystal analysis and the others were also determined by comparing the circular dichroism spectra with those of **3w**. CCDC 2056433 (**3w**) contain the supplementary crystallographic data for this paper.†
- 18 CCDC 2064772.†
- 19 S. J. Zou, W. W. Li, K. Fu, W. D. Cao, L. L. Lin and X. M. Feng, *Adv. Synth. Catal.*, 2019, **361**, 2295.

