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# Synthesis of *N*-aryl $\beta$ -amino acid derivatives via Cu(II)-catalyzed asymmetric 1,4-reduction in air†

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In the presence of the inexpensive and stable stoichiometric reductant polymethylhydrosiloxane (PMHS) as well as certain amounts of appropriate alcohol and base additives, the non-precious metal copper-catalyzed asymmetric 1,4-hydrosilylation of  $\beta$ -aryl or  $\beta$ -alkyl-substituted *N*-aryl  $\beta$ -enamino esters was well realized to afford a diverse range of *N*-aryl  $\beta$ -amino acid esters in high yields and excellent enantioselectivities (26 examples, 90–98% ee). This approach tolerated the handling of both catalyst and reactants in air without special precautions. The chiral products obtained have been successfully converted to the corresponding enantiomerically enriched  $\beta$ -lactam and unprotected  $\beta$ -amino acid ester, which highlighted the synthetic utility of the developed catalytic procedure.

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## Introduction

Enantiomerically pure *N*-aryl  $\beta$ -amino acids and their derivatives are very attractive targets for asymmetric synthesis in view of their usefulness as key structural backbones of many drug intermediates and natural products.<sup>1</sup> For instance, they are important synthons in the synthesis of  $\beta$ -lactam, which have proven to be of interest as antibiotics,<sup>2</sup> human leucocyte elastase inhibitors or  $\beta$ -lactamase inhibitors.<sup>3</sup> One of the most facile methods toward enantiomerically enriched *N*-aryl  $\beta$ -amino acids and their derivatives is the catalytic enantioselective reduction of *N*-aryl  $\beta$ -dehydroamino acid derivatives.<sup>4</sup> Ru,<sup>4,5</sup> Rh,<sup>4,6</sup> and Ir<sup>4e,7</sup>-catalyzed asymmetric hydrogenation of *N*-acyl protected  $\beta$ -dehydroamino acid esters have been intensively pursued and good to excellent enantioselectivities have been realized. With respect to the studies on the reduction of *N*-aryl  $\beta$ -dehydroamino acid derivatives, Zhang *et al.* presented the first Rh-catalyzed asymmetric hydrogenation of *N*-aryl  $\beta$ -enamino esters with good to high ee's in 2005.<sup>8</sup> The enantioselective hydrogenation of exocyclic *N*-arylenamines mediated by Ir catalyst system was described by Zhou and co-workers in 2009.<sup>9</sup> In 2014, Zhou *et al.* reported the non-noble metal nickel-catalyzed asymmetric transfer hydrogenation for the preparation of  $\beta$ -amino acid derivatives in good to excellent enantioselectivities while only 30% ee and 10% yield were obtained for

the substrate ethyl  $\beta$ -phenyl  $\beta$ -(phenylamino)acrylate.<sup>10</sup> In addition, organocatalytic asymmetric hydrosilylation of *N*-aryl  $\beta$ -enamino esters using HSiCl<sub>3</sub> as the reducing reagent has also emerged as an efficient alternative to transition metal-catalyzed hydrogenation for the synthesis of chiral  $\beta$ -amino acids derivatives.<sup>11</sup>

Employing stoichiometric amounts of silane as reductant, copper hydride-catalyzed stereoselective conjugate reduction of  $\beta,\beta$ -disubstituted Michael acceptors represents a practical, efficient, and cost-effective method that generate enantio-enriched carbonyl compounds possessing a tertiary stereocenter at the  $\beta$ -position.<sup>12</sup> The first copper mediated asymmetric 1,4-hydrosilylation of various  $\beta$ -amino-substituted  $\alpha,\beta$ -unsaturated esters to  $\beta$ -azaheterocyclic acid derivatives of excellent enantiopurities was disclosed by Buchwald *et al.* in 2004.<sup>13</sup> Zheng and co-workers then successfully applied this catalyst system in the preparation of  $\gamma$ -amino butyric acid derivatives.<sup>14</sup> By utilizing a Cu(II)/dipyridylphosphine (P-Phos)<sup>15</sup>/PMHS (polymethylhydrosiloxane) system, we described the highly enantioselective conjugate reduction of a variety of  $\beta$ -alkyl-substituted  $\beta$ -(acylamino)acrylates with up to 99% ee in 2011.<sup>16</sup> Later on, we attempted to extend this catalyst system to the asymmetric 1,4-hydrosilylation of  $\beta$ -methyl  $\beta$ -(arylamino) acrylates, which rendered low-to-moderate yields and enantioselectivities (7 examples, 33–72% yield, 23–91% ee) in the presence of certain amounts of MeONa and *t*BuOH as additives.<sup>17</sup> To the best of our knowledge, a highly stereoselective 1,4-reduction of  $\beta$ -substituted *N*-aryl  $\beta$ -enamino esters mediated by non-noble metal catalysts has not been realized at present. Herein, we report our systematical studies on the CuH-catalyzed asymmetric conjugate reduction in ambient atmosphere for constructing a broad assortment of chiral  $\beta$ -aryl or  $\beta$ -alkyl-substituted  $\beta$ -(arylamino) acid derivatives. Further, the

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synthetic utility of the methodology was demonstrated by efficient conversion of representative enantiomerically enriched *N*-aryl  $\beta$ -amino acid esters to the corresponding unprotected  $\beta$ -amino acid ester and  $\beta$ -lactam.

## Results and discussion

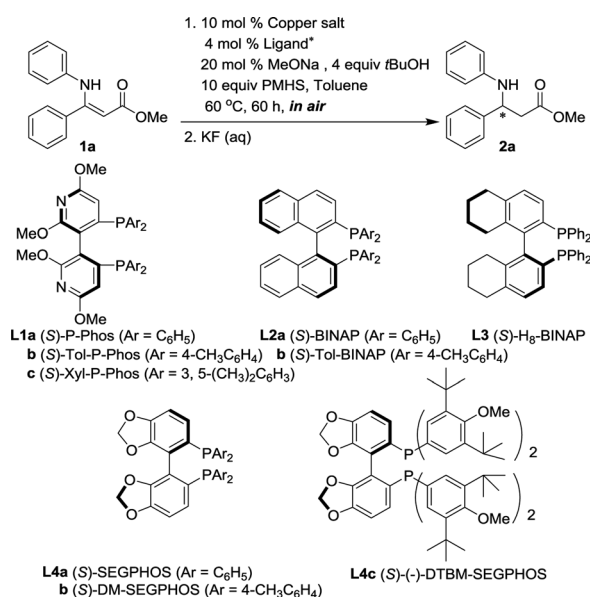
As almost no (*E*)-geometric isomers were obtained during the synthesis of substrates,<sup>18,19</sup> we commenced our studies by examining the effects of various copper precursors on the conjugate reduction of the model substrate (*Z*)-methyl 3-phenyl-3-(phenylamino)acrylate **1a** (Table 1). PMHS, which is a by-product of the organosilicon industry and has been well-known for its low-cost, non-toxicity and air stability, was selected as the hydride donor. As shown in entry 1, when **1a** was

submitted to a given set of conditions [10 mol% of CuF<sub>2</sub>, 4 mol% of **L1a** as the chiral ligand, 10 equiv. of PMHS as the reductant, 20 mol% of MeONa and 4 equiv. of *t*BuOH as the additives], the reaction proceeded in toluene at 60 °C under ambient atmosphere to 53% conversion after 60 h to furnish (–)-methyl 3-phenyl-3-(phenylamino)propionate (**2a**) in 91% ee. Similar to previous findings,<sup>20</sup> the extent of conversions varied considerably as function of the counterions of copper. Although promising enantioselectivities were achieved as well by applying Cu(OAc)<sub>2</sub>·H<sub>2</sub>O or Cu(OAc)<sub>2</sub>, lower activities exhibited (entries 3 and 4 vs. entry 1). Almost no reaction was observed by using CuCl<sub>2</sub> or Cu(CH<sub>3</sub>COCH<sub>2</sub>COCF<sub>3</sub>)<sub>2</sub> as the copper precursor (entries 2 and 6). With respect to CuTC, 45% conversion and 90% ee were reached (entry 5). In consideration of both activity and enantioselectivity, CuF<sub>2</sub> appeared to be the preponderant choice.

Subsequently, the abilities of chiral ligands were investigated for the hydrosilylation of **1a** (Table 1, entries 7–14). Among the chiral diphosphines screened, (*S*)-Tol-P-Phos (**L1b**) gave comparative ee with that of (*S*)-P-Phos under otherwise identical conditions (entry 7 vs. entry 1). Besides, a higher ee (95%) was achieved by employing (*S*)-SEGPHOS (**L4a**) as the chiral ligand while the reaction conversion was only 25% after 60 h (entry 12).

Further studies demonstrated that the reaction outcomes also largely relied on the selection of both base and alcohol additives (Table 2), which was consistent with previous findings.<sup>12c,13,16,21</sup> When MeONa was replaced with more bulky EtONa or *t*BuONa, the enantioselectivity remained almost unchanged using (*S*)-P-Phos as the chiral ligand whilst a lower reaction activity was rendered (Table 2, entries 1 and 2 vs. Table 1, entry 1). To our delight, the replacement of *t*BuOH with less sterically encumbered alcoholic additive MeOH led to dramatic enhancements in reaction activity [53% conv. to 98% conv. for (*S*)-P-Phos **L1a**, 25% conv. to >99% conv. for (*S*)-SEGPHOS **L4a**,

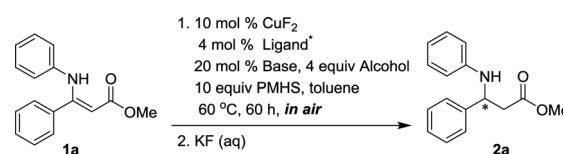
**Table 1** Effects of copper salts and ligands on the asymmetric 1,4-reduction of (*Z*)-methyl 3-phenyl-3-(phenylamino)acrylate **1a**<sup>a</sup>



Entry	Copper salt	Ligand	Conv. <sup>b</sup> (%)	ee <sup>c</sup> (%)
1	CuF <sub>2</sub>	<b>L1a</b>	53	91 (–)
2	CuCl <sub>2</sub>	<b>L1a</b>	<5	n.d. <sup>d</sup>
3	Cu(OAc) <sub>2</sub>	<b>L1a</b>	31	90 (–)
4	Cu(OAc) <sub>2</sub> ·H <sub>2</sub> O	<b>L1a</b>	10	90 (–)
5	CuTC	<b>L1a</b>	45	90 (–)
6	Cu(CH <sub>3</sub> COCH <sub>2</sub> COCF <sub>3</sub> ) <sub>2</sub>	<b>L1a</b>	<5	n.d. <sup>d</sup>
7	CuF <sub>2</sub>	<b>L1b</b>	27	90 (–)
8	CuF <sub>2</sub>	<b>L1c</b>	<5	85 (–)
9	CuF <sub>2</sub>	<b>L2a</b>	<5	n.d. <sup>d</sup>
10	CuF <sub>2</sub>	<b>L2b</b>	16	84 (–)
11	CuF <sub>2</sub>	<b>L3</b>	<5	n.d. <sup>d</sup>
12	CuF <sub>2</sub>	<b>L4a</b>	25	95 (–)
13	CuF <sub>2</sub>	<b>L4b</b>	<5	84 (–)
14	CuF <sub>2</sub>	<b>L4c</b>	<5	n.d. <sup>d</sup>

<sup>a</sup> Reaction conditions: 0.30 mmol substrate, substrate concentration = 0.30 M in toluene. <sup>b</sup> The conversions were determined by NMR and GC analysis. <sup>c</sup> The ee values were determined by chiral HPLC analysis (see the ESI). <sup>d</sup> n.d. = not determined.

**Table 2** Effects of additives on the asymmetric 1,4-reduction of (*Z*)-methyl 3-phenyl-3-(phenylamino)acrylate **1a**<sup>a</sup>



Entry	Ligand	Alcohol	Base	Conv. <sup>b</sup> (%)	ee <sup>c</sup> (%)
1	<b>L1a</b>	<i>t</i> BuOH	EtONa	44	90 (–)
2	<b>L1a</b>	<i>t</i> BuOH	<i>t</i> BuONa	44	90 (–)
3	<b>L1a</b>	MeOH	MeONa	98	89 (–)
4	<b>L1a</b>	MeOH	EtONa	98	90 (–)
5	<b>L1a</b>	MeOH	<i>t</i> BuONa	>99%	89 (–)
6	<b>L4a</b>	MeOH	MeONa	>99%	95 (–)
7	<b>L4a</b>	MeOH	<i>t</i> BuONa	>99% <sup>d</sup>	96 (–)

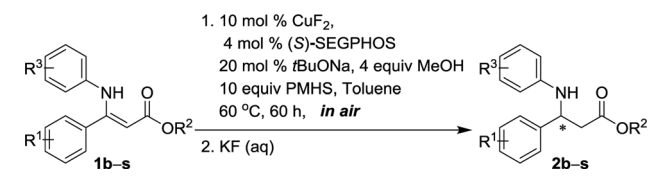
<sup>a</sup> Reaction conditions: 0.30 mmol substrate, substrate concentration = 0.30 M in toluene. <sup>b</sup> The conversions were determined by NMR and GC analysis. <sup>c</sup> The ee values were determined by chiral HPLC analysis. <sup>d</sup> The isolated yield was 92%.



Table 2, entries 3 and 6 vs. Table 1, entries 1 and 12]. Moreover, utilizing (*S*)-SEGPHOS as the ligand, in the presence of MeOH and *t*BuONa as the additives, the desirable product **2a** was obtained quantitatively (>99% conversion, 92% isolated yield) with 96% ee (entry 7).

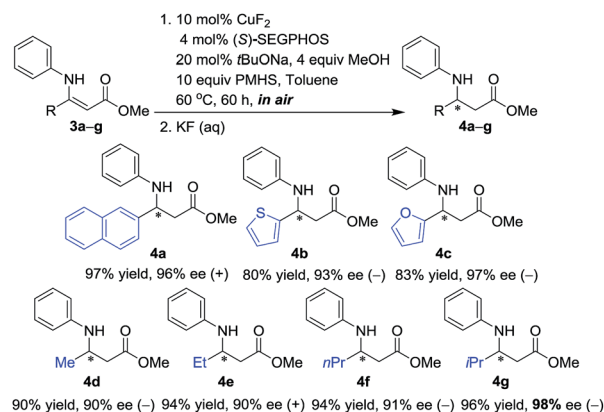
With the aforementioned preferred conditions in hand, we set out to establish the general utility of this copper-catalyzed protocol for the asymmetric conjugate reduction of a vast array of *N*-aryl  $\beta$ -aryl  $\beta$ -enamino esters **1b–s** in air. As the results summarized in Table 3 indicated, consistently high enantioselectivities were obtained in all cases (91–98% ee). Replacing the methyl ester of **1a** with ethyl ester (**1b**) slightly diminished the enantiopurity of the product (entry 1 vs. Table 2, entry 7). The introduction of a *para*-MeO substituent to the *N*-arene ring of **1a** resulted in distinct decreases in reaction activities (entries 4 and 6 vs. Table 2, entry 7). Similarly, the presence of an electron-donating group on the  $\beta$ -aryl group had a pronounced influence on the reactivities (entries 7, 8, 13 and 14 vs. Table 2, entry 7). For instance, when the *ortho*-position of  $\beta$ -phenyl on **1a** was substituted by a methoxy group (**1h**), the isolated yield of chiral product dropped from 92% (Table 2, entry 7) to 22% (entry 7). Nonetheless, the existence of an electron-withdrawing group on the  $\beta$ -aryl group favored the conjugate reductions in terms of both activities and enantioselectivities (entries 3, 9–12 and 15–18).

Table 3 Copper-catalyzed asymmetric hydrosilylation of various *N*-aryl  $\beta$ -aryl  $\beta$ -enamino esters<sup>a</sup>



Entry	Substrate	R <sup>1</sup>	R <sup>2</sup>	R <sup>3</sup>	Yield <sup>b</sup> (%)	ee <sup>c</sup> (%)
1	<b>1b</b>	H	Et	H	90	93 (+)
2	<b>1c</b>	4-MeO	Et	H	65	92 (+)
3	<b>1d</b>	4-Br	Et	H	94	94 (+)
4	<b>1e</b>	H	Me	4-MeO	30	94 (+)
5	<b>1f</b>	4-Me	Me	4-MeO	90	93 (+)
6	<b>1g</b>	4-Cl	Me	4-MeO	30	95 (–)
7	<b>1h</b>	2-MeO	Me	H	22	92 (–)
8	<b>1i</b>	3-MeO	Me	H	62	95 (–)
9	<b>1j</b>	3-F	Me	H	95	94 (+)
10	<b>1k</b>	3-Cl	Me	H	94	94 (–)
11	<b>1l</b>	3-Br	Me	H	93	98 (+)
12	<b>1m</b>	3-CF <sub>3</sub>	Me	H	95	96 (+)
13	<b>1n</b>	4-Me	Me	H	88	91 (+)
14	<b>1o</b>	4-MeO	Me	H	65	94 (–)
15	<b>1p</b>	4-F	Me	H	96	94 (+)
16	<b>1q</b>	4-Cl	Me	H	95	94 (–)
17	<b>1r</b>	4-Br	Me	H	94	95 (–)
18	<b>1s</b>	4-CF <sub>3</sub>	Me	H	96	94 (+)

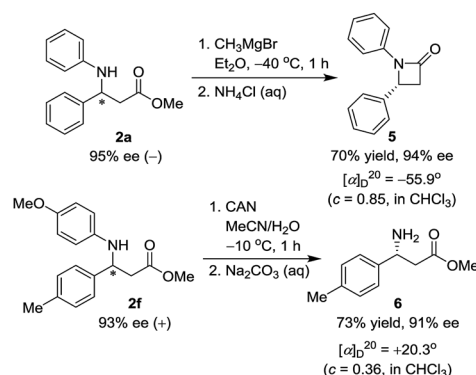
<sup>a</sup> Reaction conditions: 0.30 mmol substrate, substrate concentration = 0.30 M in toluene. <sup>b</sup> Isolated yield. <sup>c</sup> The ee values were determined by chiral HPLC analysis.



Scheme 1 Copper-catalyzed asymmetric hydrosilylation of  $\beta$ -heteroaryl or  $\beta$ -alkyl-substituted *N*-phenyl  $\beta$ -enamino esters.

Encouraged by the successful 1,4-hydrosilylation of *N*-aryl  $\beta$ -aryl  $\beta$ -enamino esters, we then applied the present catalyst system in the enantioselective conjugate reduction of a wide scope of  $\beta$ -alkyl,  $\beta$ -naphthyl or  $\beta$ -heteroaryl substituted *N*-phenyl  $\beta$ -enamino esters (**3a–g**). Gratifyingly, as illustrated in Scheme 1, the present protocol worked effectively for the productive access to a variety of desirable products (**4a–g**) of excellent enantiopurities (90–98% ee) under a given set of conditions. The sterically hindered  $\beta$ -alkyl substituent on the substrates was conducive to higher ee values (**4g** vs. **4d–f**).

With the availability of an effective catalytic method for the asymmetric preparation of structurally diverse  $\beta$ -substituted  $\beta$ -(arylamino) acid esters, a range of other enantiomerically enriched molecules become accessible. For instance, as Scheme 2 outlined, treatment of (–)-methyl 3-phenyl-3-(phenylamino)propionate (**2a**, 95% ee) with methylmagnesium bromide in ether at  $-40$  °C furnished chiral  $\beta$ -lactam (*R*)-1,4-diphenylazetidin-2-one (**5**) in 70% yield with 94% ee after 1 h.<sup>22</sup> The  $\beta$ -lactam derivatives possess the basic skeleton of monobactam antibiotics,<sup>2</sup>  $\beta$ -lactamase inhibitors,<sup>3</sup> and cholesterol absorption inhibitors.<sup>23</sup> Moreover, *N*-(*para*-methoxyphenyl) group of **2f** (93% ee) was readily deprotected by using ceric ammonium nitrate (CAN) at  $-10$  °C for only 1 h to provide  $\beta$ -



Scheme 2 Conversion of *N*-aryl  $\beta$ -amino esters **2a** and **2f** to chiral  $\beta$ -lactam **5** and unprotected  $\beta$ -amino ester **6**.



amino ester (*R*)-methyl 3-amino-3-(*p*-tolyl)propanoate **6** in 73% yield and 91% ee,<sup>24</sup> which constitutes crucial structural elements of  $\beta$ -peptides and many other biologically active compounds.<sup>25</sup>

## Conclusions

In conclusion, in the presence of certain amounts of appropriate additives *t*BuONa and MeOH, the combination of catalytic amounts of CuF<sub>2</sub> and chiral ligand SEGPHOS as well as the stoichiometric hydride donor PMHS generated *in situ* an efficient catalyst system for the asymmetric conjugate reduction of a broad spectrum of  $\beta$ -aryl,  $\beta$ -heteroaryl, or  $\beta$ -alkyl-substituted *N*-aryl  $\beta$ -enamino esters with good activity and uniformly high ee values (26 examples, 90–98% ee). The present catalyst system features high air-stability, excellent stereocontrols, cost efficiency, and mild conditions and therefore offers a good opportunity for the practical preparation of *N*-aryl  $\beta$ -amino acid derivatives. The efficient transformation of enantiomerically enriched *N*-aryl  $\beta$ -amino esters to  $\beta$ -lactam and unprotected  $\beta$ -amino ester further evinced the good utility of this methodology.

## Experimental

### General procedure of asymmetric hydrosilylation in air [Table 2, entry 7, (*Z*)-methyl 3-phenyl-3-(phenylamino)acrylate, **1a**]

CuF<sub>2</sub> (3.0 mg, 3.0  $\times 10^{-2}$  mmol), (*S*)-SEGPHOS (**L4a**, 7.3 mg, 1.2  $\times 10^{-2}$  mmol) and sodium *tert*-butoxide (5.8 mg, 6.0  $\times 10^{-2}$  mmol) were weighed under air and placed in a 25 mL round-bottomed flask equipped with a magnetic stirring bar. Toluene (0.5 mL) was added and the mixture was stirred at room temperature for 30 min. Then PMHS (200  $\mu$ L, 3.0 mmol) was added, and the solution was allowed to stir for further 10 min. Finally, a solution of (*Z*)-methyl 3-phenyl-3-(phenylamino)acrylate **1a** (76 mg, 0.3 mmol) and MeOH (49  $\mu$ L, 1.2 mmol) in toluene (0.5 mL) was added under vigorous stirring and the flask was stoppered. The reaction was carried out at 60 °C and monitored by TLC. Upon completion, the reaction mixture was treated with saturated KF solution (2 mL) and 2.0 mL diethyl ether. The mixture was stirred vigorously for 1 h. The aqueous layer was extracted with diethyl ether (3  $\times$  3 mL). The combined organic layer was washed with water, dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>, filtered through a plug of silica gel and concentrated *in vacuo* to provide the crude product. The conversion was determined by NMR and GC (column, HP-5; 25 m  $\times$  0.25 mm, carrier gas, N<sub>2</sub>). The enantiomeric excess of the product (–)-methyl 3-phenyl-3-(phenylamino)propanoate **2a** was determined by chiral HPLC (column, Daicel Chiralcel OD-H, 25 cm  $\times$  4.6 mm) analysis. The pure product was isolated by column chromatography (ethyl acetate : petroleum ether = 1 : 10).

### Procedure for the synthesis of $\beta$ -lactam (*R*)-1,4-diphenylazetididin-2-one (**5**)<sup>22</sup>

To a solution of compound (–)-**2a** (95% ee, 50 mg, 0.20 mmol) in anhydrous Et<sub>2</sub>O (5 mL) was added dropwise a solution of 1 M

CH<sub>3</sub>MgBr in Et<sub>2</sub>O (0.4 mL, 0.40 mmol) at –40 °C under nitrogen atmosphere. After stirring at –40 °C for 1 h, the reaction was quenched by adding an excess amount of saturated aqueous NH<sub>4</sub>Cl solution, followed by extracting with Et<sub>2</sub>O (2  $\times$  10 mL). The organic phase was washed with brine and then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>, filtered, and concentrated under vacuum. The residue was purified by column chromatography on silica gel (ethyl acetate : petroleum ether = 1 : 15) to afford the chiral  $\beta$ -lactam **5** (31 mg, 70% yield, 94% ee) as a white solid. The ee value was determined by chiral HPLC analysis with a 25 cm  $\times$  4.6 mm Daicel Chiralcel OD-H column (eluent, 2-propanol/hexane 4 : 96; flow rate: 1.0 mL min<sup>–1</sup>; detection: 254 nm light).

### Procedure for the synthesis of (*R*)-methyl 3-amino-3-(*p*-tolyl)propanoate (**6**)<sup>24a</sup>

A solution of ceric ammonium nitrate (280 mg, 0.51 mmol) in water (5 mL) was added dropwise to a solution of compound (+)-**2f** (93% ee, 50 mg, 0.17 mmol) in acetonitrile (5 mL) at –10 °C over 10 min. After the mixture was stirred for 1 h, water (5 mL) was added and MeCN was evaporated under vacuum. The residue was washed with Et<sub>2</sub>O (2  $\times$  10 mL) and then added 10% aqueous Na<sub>2</sub>CO<sub>3</sub> solution until pH = 6. The mixture was further washed with Et<sub>2</sub>O (2  $\times$  10 mL). After the pH of the aqueous solution was tuned to be 8 by further adding 10% aqueous Na<sub>2</sub>CO<sub>3</sub> solution, the mixture was extracted with EtOAc (3  $\times$  10 mL). The combined organic layers were dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>, filtered, and concentrated under vacuum. The residue was purified by column chromatography on silica gel (ethyl acetate : petroleum ether = 1 : 1) to give **6** (24 mg, 73% yield, 91% ee) as a brown oil. The ee value was determined by chiral HPLC analysis with a 25 cm  $\times$  4.6 mm Daicel Chiralcel OD-H column (eluent, 2-propanol/hexane 1 : 99; flow rate: 1.0 mL min<sup>–1</sup>; detection: 215 nm light).

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

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## Notes and references

- (a) M. F. Pozza, K. Zimmermann, S. Bischoff and K. Lingenhohl, *Prog. Neuro-Psychopharmacol. Biol. Psychiatry*, 2000, **24**, 647–670; (b) L. Zhi, C. M. Tegley, K. B. Marschke and T. K. Jones, *Bioorg. Med. Chem. Lett.*, 1999, 1009–1012.



- 2 (a) S. Hata, T. Iwasawa, M. Iguchi, K. Yamada and K. Tomioka, *Synthesis*, 2004, 1471–1475; (b) C. C. Silveira, A. S. Vieira, A. L. Braga and D. Russowsky, *Tetrahedron*, 2005, **61**, 9312–9318; (c) X.-R. Li, C.-F. Lu, Z.-X. Chen, Y. Li and G.-C. Yang, *Tetrahedron: Asymmetry*, 2012, **23**, 1380–1384.
- 3 (a) R. Joyeau, A. Felk, S. Guillaume, M. Wakselman, I. Vergely, C. Doucet, N. Roggetto and M. Reboud-Ravaux, *J. Pharm. Pharmacol.*, 1996, **48**, 1218–1230; (b) M. Bordeau, F. Frébault, M. Gobet and J.-P. Picard, *Eur. J. Org. Chem.*, 2006, 4147–4154.
- 4 For some representative reviews, see: (a) M. Liu and M. P. Sibi, *Tetrahedron*, 2002, **58**, 7991–8035; (b) J.-A. Ma, *Angew. Chem., Int. Ed.*, 2003, **42**, 4290–4299; (c) C. Bruneau, J.-L. Renaud and T. Jerphagnon, *Coord. Chem. Rev.*, 2008, **252**, 532–544; (d) B. Weiner, W. Szymański, D. B. Janssen, A. J. Minnaard and B. L. Feringa, *Chem. Soc. Rev.*, 2010, **39**, 1656–1691; (e) J.-H. Xie, S.-F. Zhu and Q.-L. Zhou, *Chem. Rev.*, 2011, **111**, 1713–1760; (f) Y.-H. Ma, Y.-J. Zhang and W.-B. Zhang, *Chin. J. Org. Chem.*, 2007, **27**, 289–297; (g) P. S. Bhadury, S. Yang and B.-A. Song, *Curr. Org. Synth.*, 2012, **9**, 695–726 and references cited therein.
- 5 Examples include: (a) W. D. Lubell, M. Kitamura and R. Noyori, *Tetrahedron: Asymmetry*, 1991, **2**, 543–554; (b) Y.-G. Zhou, W. Tang, W.-B. Wang, W. Li and X. Zhang, *J. Am. Chem. Soc.*, 2002, **124**, 4952–4953; (c) J. Wu, X. Chen, R. Guo, C.-H. Yeung and A. S. C. Chan, *J. Org. Chem.*, 2003, **68**, 2490–2493; (d) L. Qiu, J. Wu, S. Chan, T. T.-L. Au-Yeung, J.-X. Ji, R. Guo, C.-C. Pai, Z. Zhou, X. Li, Q.-H. Fan and A. S. C. Chan, *Proc. Natl. Acad. Sci. U. S. A.*, 2004, **101**, 5815–5820; (e) L. Qiu, F. Y. Kwong, J. Wu, W. H. Lam, S. Chan, W.-Y. Yu, Y.-M. Li, R. Guo, Z. Zhou and A. S. C. Chan, *J. Am. Chem. Soc.*, 2006, **128**, 5955–5965.
- 6 Examples include: (a) G. Zhu, Z. Chen and X. Zhang, *J. Org. Chem.*, 1999, **64**, 6907–6910; (b) M. Yasutake, I. D. Gridnev, N. Higashi and T. Imamoto, *Org. Lett.*, 2001, **3**, 1701–1704; (c) D. Peña, A. J. Minnaard, J. G. de Vries and B. L. Feringa, *J. Am. Chem. Soc.*, 2002, **124**, 14552–14553; (d) W. Tang, W. Wang, Y. Chi and X. Zhang, *Angew. Chem., Int. Ed.*, 2003, **42**, 3509–3511; (e) J. You, H.-J. Drexler, S. Zhang, C. Fischer and D. Heller, *Angew. Chem., Int. Ed.*, 2003, **42**, 913–916; (f) M. T. Reetz and X. Li, *Angew. Chem., Int. Ed.*, 2005, **44**, 2959–2962; (g) W. Tang, A. G. Capacci, A. White, S. Ma, S. Rodriguez, B. Qu, J. Savoie, N. D. Patel, X. Wei, N. Haddad, N. Grinberg, N. K. Yee, D. Krishnamurthy and C. H. Senanayake, *Org. Lett.*, 2010, **12**, 1104–1107; (h) X. Zhang, K. Huang, G. Hou, B. Cao and X. Zhang, *Angew. Chem., Int. Ed.*, 2010, **49**, 6421–6424.
- 7 S. Enthaler, G. Erre, K. Junge, K. Schröder, D. Addis, D. Michalik, M. Hapke, D. Redkin and M. Beller, *Eur. J. Org. Chem.*, 2008, 3352–3355.
- 8 Q. Dai, W. Yang and X. Zhang, *Org. Lett.*, 2005, **7**, 5343–5345.
- 9 X.-B. Wang, D.-W. Wang, S.-M. Lu, C.-B. Yu and Y.-G. Zhou, *Tetrahedron: Asymmetry*, 2009, **20**, 1040–1045.
- 10 P. Yang, H. Xu and J. Zhou, *Angew. Chem., Int. Ed.*, 2014, **53**, 12210–12213.
- 11 Examples for enantioselective organocatalytic reduction of *N*-aryl  $\beta$ -enamino esters include: (a) A. V. Malkov, S. Stončius, K. Vranková, M. Arndt and P. Kočovský, *Chem.–Eur. J.*, 2008, **14**, 8082–8085; (b) H. J. Zheng, W. B. Chen, Z. J. Wu, J. G. Deng, W. Q. Lin, W. C. Yuan and X. M. Zhang, *Chem.–Eur. J.*, 2008, **14**, 9864–9867; (c) A. V. Malkov, K. Vranková, S. Stončius and P. Kočovský, *J. Org. Chem.*, 2009, **74**, 5839–5849; (d) Y. Jiang, X. Chen, Y. Zheng, Z. Xue, C. Shu, W. Yuan and X. Zhang, *Angew. Chem., Int. Ed.*, 2011, **50**, 7304–7307; (e) S. Jones and X. Li, *Tetrahedron*, 2012, **68**, 5522–5532; (f) P. Zhang, C. Wang, L. Zhou and J. Sun, *Chin. J. Chem.*, 2012, **30**, 2636–2640; (g) X. Chen, X.-Y. Hu, C. Shu, Y.-H. Zhang, Y.-S. Zheng, Y. Jiang, W.-C. Yuan, B. Liu and X.-M. Zhang, *Org. Biomol. Chem.*, 2013, **11**, 3089–3093; (h) Y. Jiang, X. Chen, X.-Y. Hu, C. Shu, Y.-H. Zhang, Y.-S. Zheng, C.-X. Lian, W.-C. Yuang and X.-M. Zhang, *Adv. Synth. Catal.*, 2013, **355**, 1931–1936; (i) J. Ye, C. Wang, L. Chen, X. Wu, L. Zhou and J. Sun, *Adv. Synth. Catal.*, 2016, **358**, 1042–1047; (j) D. Brenna, R. Porta, E. Massolo, L. Raimondi and M. Benaglia, *ChemCatChem*, 2017, **9**, 941–945; (k) X. Dai, G. Weng, S. Yu, H. Chen, J. Zhang, S. Cheng, X. Xu, W. Yuan, Z. Wang and X. Zhang, *Org. Chem. Front.*, 2018, **5**, 2787–2793.
- 12 For representative reviews, see: (a) O. Riant, N. Mostefai and J. Courmarcel, *Synthesis*, 2004, 2943–2958; (b) S. Rendler and M. Oestreich, *Angew. Chem., Int. Ed.*, 2007, **46**, 498–504; (c) C. Deutsch, N. Krause and B. H. Lipshutz, *Chem. Rev.*, 2008, **108**, 2916–2927; (d) B. H. Lipshutz, *Synlett*, 2009, 509–524 and references cited therein; (e) J. Chen and Z. Lu, *Org. Chem. Front.*, 2018, **5**, 260–272.
- 13 M. P. Rainka, Y. Aye and S. L. Buchwald, *Proc. Natl. Acad. Sci. U. S. A.*, 2004, **101**, 5821–5823.
- 14 J. Deng, X.-P. Hu, J.-D. Huang, S.-B. Yu, D.-Y. Wang, Z.-C. Duan and Z. Zheng, *J. Org. Chem.*, 2008, **73**, 6022–6024.
- 15 (a) J. Wu and A. S. C. Chan, *Acc. Chem. Res.*, 2006, **39**, 711–720; (b) C.-C. Pai, C.-W. Lin, C.-C. Lin, C.-C. Chen, A. S. C. Chan and W. T. Wong, *J. Am. Chem. Soc.*, 2000, **122**, 11513–11514.
- 16 Y. Wu, S.-B. Qi, F.-F. Wu, X.-C. Zhang, M. Li, J. Wu and A. S. C. Chan, *Org. Lett.*, 2011, **13**, 1754–1757.
- 17 Y. Sui, Q. Fang, M. Li, Y. Hu, H. Xia, S. Li and J. Wu, *Chin. J. Chem.*, 2012, **30**, 2611–2614.
- 18 L. Zhang and J. Herndon, *Organometallics*, 2004, **23**, 1231–1235.
- 19 A. Gossauer, F. Nydegger, T. Kiss, R. Slezziak and S.-E. Helen, *J. Am. Chem. Soc.*, 2004, **126**, 1772–1780.
- 20 (a) S. Sirol, J. Courmarcel, N. Mostefai and O. Riant, *Org. Lett.*, 2001, **3**, 4111–4113; (b) J. Wu, J. X. Ji and A. S. C. Chan, *Proc. Natl. Acad. Sci. U. S. A.*, 2005, **102**, 3570–3575; (c) F. Yu, J.-N. Zhou, X.-C. Zhang, Y.-Z. Sui, F.-F. Wu, L.-J. Xie, A. S. C. Chan and J. Wu, *Chem.–Eur. J.*, 2011, **17**, 14234–14240.
- 21 (a) J. Yun and S. L. Buchwald, *J. Am. Chem. Soc.*, 1999, **121**, 5640–5644; (b) D. S. Hays and G. C. Fu, *Tetrahedron*, 1999, **55**, 8815–8832; (c) G. Hughes, M. Kimura and S. L. Buchwald, *J. Am. Chem. Soc.*, 2003, **125**, 11253–11258;



- (d) B. H. Lipshutz, J. M. Servesko and B. R. Taft, *J. Am. Chem. Soc.*, 2004, **126**, 8352–8353.
- 22 (a) V. Michaut, F. Metz, J.-M. Paris and J.-C. Plaquevent, *J. Fluorine Chem.*, 2007, **128**, 889–895; (b) S. Tang, J. He, Y. Sun, L. He and X. She, *J. Org. Chem.*, 2010, **75**, 1961–1966.
- 23 C. P. Cannon, *N. Engl. J. Med.*, 2015, **372**, 2387–2397.
- 24 (a) D. R. Kronenthal, C. Y. Han and M. K. Taylor, *J. Org. Chem.*, 1982, **47**, 2765–2768; (b) M. Rodríguez-Mata, E. García-Urdiales, V. Gotor-Fernández and V. Gotor, *Adv. Synth. Catal.*, 2010, **352**, 395–406.
- 25 (a) B. Geueke, T. Heck, M. Limbach, V. Nesatyy, D. Seebach and H.-P. Kohler, *FEBS J.*, 2006, **273**, 5261–5272; (b) Y. Zhang, L. Li, W. Yuan and X. Zhang, *Chem. Res. Chin. Univ.*, 2015, **31**, 381–387; (c) A. Onoda, H. Harada, T. Uematsu, S. Kuwabata, R. Yamanaka, S. Sakurai and T. Hayashi, *RSC Adv.*, 2017, **7**, 1089–1092.

