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Design of Planar Chiral Phosphoric Acids with a [2.2]Paracyclophanyl Backbone as Organocatalysts for the Highly Enantioselective Aza-Friedel−Crafts Reaction

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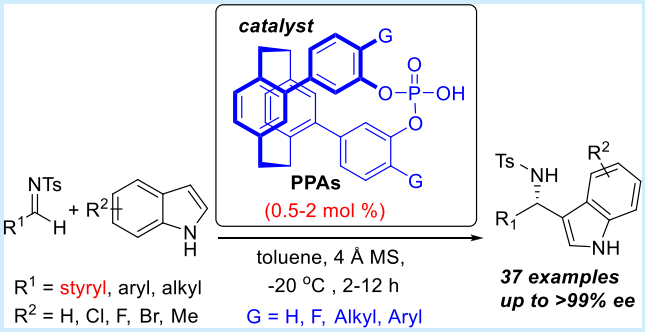
Supporting Information

ABSTRACT: A new type of robust planar chiral phosphoric acid bearing a [2.2]paracyclophane scaffold was synthesized and shown to be an optimal catalyst in asymmetric aza-Friedel−Crafts reactions for the first synthesis of enantioenriched styryl indolylmethanamine derivatives in good yields with excellent enantioselectivities (93−>99% ee) under 0.5−1 mol % catalyst loading.



Asymmetric phosphoric acid catalysis represents a substantial scientific contribution and has enabled numerous organic transformations in a highly enantioselective fashion since Akiyama, Terada, and co-workers reported BINOL-based chiral phosphoric acids in 2004.[1] The backbone of the chiral catalysts had a remarkable influence on their catalytic performance in many cases. Alongside new catalytic reactions, a variety of structurally diverse chiral phosphoric acids, mainly derived from centrally chiral TADDOL and axially chiral diols like H_8−BINOL, VAPOL, SPINOL, and others, have been developed (Figure 1, **1**−**4**).[2] Despite a growing focus toward efforts on new asymmetric reactions and new catalytic strategies, the development of chiral phosphoric acids bearing novel frameworks with excellent catalytic activities is still highly valuable and very challenging in a diverse range of asymmetric transformations.

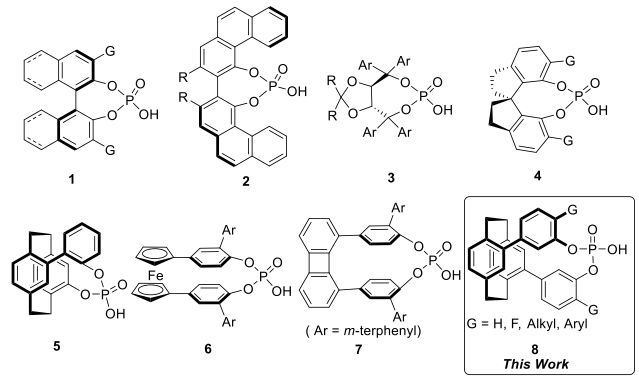


Figure 1. Chiral phosphoric acids.

Planar chirality plays an important role in asymmetric catalysis, especially disubstituted ferrocene or substituted [2.2]paracyclophanes [PCPs].[3] Recently, remarkable contributions have been achieved in the development of planar chiral phosphoric acids. Enders reported the first synthesis planar chiral phosphoric acid derived from [2.2]paracyclophane (Figure 1, **5**).[4] However, the new catalyst was evaluated in enantioselective aza-Friedel−Crafts reactions and Mannich-type reactions to give only ee values of up to 38%. Betzer and Marinetti disclosed the first series of planar chiral phosphoric acids with a paracyclophane backbone tethered by either a 1,1′-ferrocenediyl or a 1,8-biphenylenediyl unit (Figure 1, **6** and **7**) giving promising levels of enantioselectivity in organocatalytic asymmetric aza-Friedel−Crafts reaction and H-transfer reduction.[5] However, the synthetic approach to access these enantiomerically enriched catalysts **6** and **7** must utilize chiral HPLC preparative chromatography or diastereomers separation. In addition, acid **6** displayed only moderate thermal stability, giving partial decomposition at 60 °C. Despite these notable advances, developing new planar chiral phosphoric acids with excellent catalytic activities and readily accessible architectures is still highly valuable and desirable.

Our group reported the first synthesis and application of SPINOL-derived phosphoric acids (Figure 1, **4**), denoted as SPAs, which proved to be highly efficient in asymmetric catalysis and received increasing attention.[1l,2d,6] As a continuation of our work on the design and application of novel chiral catalysts,[2d,7] herein we describe a new type of robust planar chiral phosphoric acids bearing a [2.2]-

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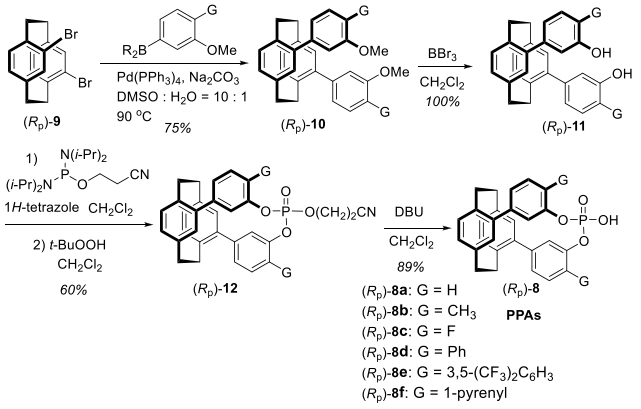
paracyclophane scaffold (Figure 1, **8**, denoted as PPAs), starting from commercially available starting materials (R_p)-4,12-dibromo[2.2]paracyclophane, and demonstrate that planar chiral PPAs can serve as highly efficient enantioselective strong Brønsted acid organocatalysts.

Six planar chiral phosphoric acids bearing a [2.2]-paracyclophane scaffold **8a–f** were prepared, and their syntheses are outlined in Scheme 1. The synthetic procedure

Scheme 1. Synthesis of Planar Chiral Phosphoric Acids[a]



[a]Yields are given for G = CH_3.

starts with the Suzuki coupling reaction between (R_p)-4,12-dibromo[2.2]paracyclophane (**9**) and the corresponding arylboron reagents, which feature a Me-protected hydroxyl function in their meta position and a G substituent in their para position. The desired compound (R_p)-**10b** (R = Me) was obtained in 75% yield and subsequently demethylated with BBr_3 in DCM to give the key [2.2]paracyclophane-based bisphenol (R_p)-**11b** (R = Me) in quantitative yield. The conversion of the bisphenol to the corresponding phosphoric acid was first tested with the typical $POCl_3$-based method.[2d] However, no desired product of cyclization was obtained when bisphenol (R_p)-**11b** was treated with $POCl_3$ in the presence of pyridine. The cyclization reaction of bisphenol (R_p)-**11b** with phosphorodiamidite $(i\text{-}Pr_2N)_2PO(CH_2)_2CN$ in the presence of 1*H*-tetrazole,[5a,8] followed by oxidation of the resulting phosphite with *tert*-butyl hydroperoxide, afforded the corresponding cyclic phosphate (R_p)-**12b** (R = Me) in 60% yield over two steps. Removal of the cyanoethyl substituent of phosphates (R_p)-**12** under basic conditions (DBU) afforded the desired planar chiral phosphoric acids **8a–f** in good yields. The X-ray crystal structure of (R_p)-**12b** is shown in Figure 2. The dihedral angle between the two phenyl planes of bisphenol in (R_p)-**12b** is 23.46°, and the distance between the two oxygen atoms of bisphenol is 2.504 Å, indicating that the corresponding phosphoric acid may have a unique chiral cavity, which could be beneficial for certain asymmetric transformations. The sample of (R_p)-**8b** was heated in toluene under reflux for 12 h and did not show any decomposition and epimerization, displaying good thermal stability.

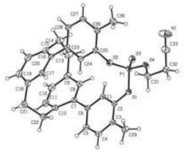
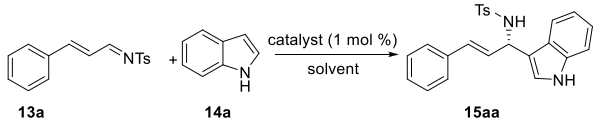


Figure 2. X-ray crystal structure of (R_p)-**12b**.

The catalytic enantioselective aza-Friedel–Crafts reaction of indoles with imines is the most versatile method to achieve the synthesis of enantiopure 3-indolylmethanamine derivatives, which are distributed in natural products having significant biological activities.[9] Therefore, extensive effort has been devoted to this research field, and some excellent chiral organocatalysts[10] and chiral metal salt catalysts[11] have been developed over the past decade. Despite these notable advances, to the best of our knowledge, cinnamaldehyde-derived *N*-tosylimines have not been used in these catalytic asymmeteric aza-Friedel–Crafts reactions. To evaluate the effectiveness of planar chiral PPAs as enantioselective Brønsted acid catalysts, we examined their performance in the first asymmetric aza-Friedel–Crafts reaction for the efficient synthesis of various enantioenriched styryl indolylmethanamine derivatives.

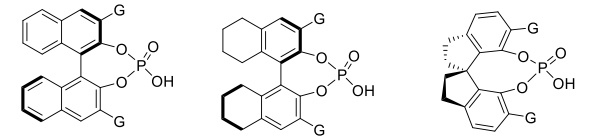
As shown in Table 1, we began with identification of the best catalyst using cinnamaldehyde-derived *N*-tosylimine **13a** as a model substrate and indole **14a** as a nucleophile in the presence of a catalytic planar chiral phosphoric acid. We observed that 1 mol % of (R_p)-**8a** catalyzed smoothly the reaction in toluene in the presence of 4 Å MS at −40 °C in 2 h

Table 1. Reaction Optimization[a]



entry	catalyst	solvent	temp (°C)	yield[b] (%)	ee[c] (%)
1	(R_p)-**8a**	toluene	−40	80	4
2	(R_p)-**8b**	toluene	−40	79	31
3	(R_p)-**8c**	toluene	−40	85	26
4	(R_p)-**8d**	toluene	−40	90	99
5	(R_p)-**8e**	toluene	−40	95	97
6	(R_p)-**8f**	toluene	−40	80	50
7[d]	(R_p)-**8d**	toluene	−40	91	98
8[e]	(R_p)-**8d**	toluene	−40	85	98
9	(R_p)-**8d**	m-xylene	−40	90	97
10	(R_p)-**8d**	CH_2Cl_2	−40	89	95
11	(R_p)-**8d**	THF	−40	nr	
12	(R_p)-**8d**	toluene	−20	92	99
13	(R_p)-**8d**	toluene	0	55	97
14	(*R*)-**1a**	toluene	−20	89	81
15	(*R*)-**1b**	toluene	−20	86	69
16	(*R*)-**1c**	toluene	−20	trace	
17	(*R*)-**1d**	toluene	−20	87	71
18	(*S*)-**4a**	toluene	−20	90	71
19	(*S*)-**4b**	toluene	−20	80	66

[a]Reaction conditions: **13a** (0.25 mmol), **14a** (0.25 mmol), catalyst (1 mol %), and 4 Å MS (75 mg) in 2.5 mL of solvent under N_2 for 2 h. [b]Isolated yields. [c]Determined by chiral HPLC analysis. [d]Without the use of 4 Å MS. [e]With catalyst (0.5 mol %).



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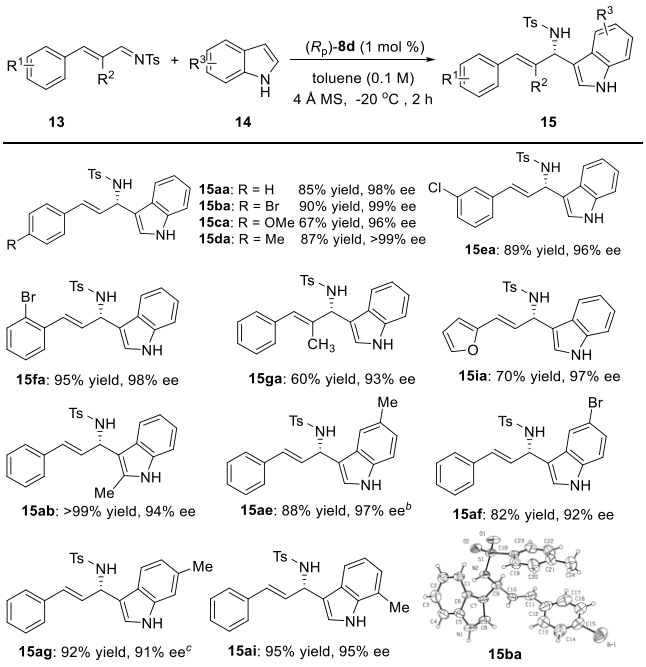
to give the desired product **15aa** in good yield but poor enantioselecitvity (entry 1). In terms of further catalyst screening, PPAs (R_p)-**8d** and (R_p)-**8e** were found to induce excellent enantioselectivity in this reaction (entries 2−6). The adduct **15aa** could be obtained in 90% yield and 99% enantiomeric excess (ee) in the case of using of 1 mol % of (R_p)-**8d** as a catalyst at −40 °C (entry 4). Removal of 4 Å MS or reducing the loading of catalyst (R_p)-**8d** to 0.5 mol % hardly compromised enantioselectivity (98% ee, entries 7 and 8). Furthermore, the reaction solvents and the temperature were screened, and the optimal results (**15aa** in 92% yield and 99% ee) could be delivered with 1 mol % of (R_p)-**8d** at −20 °C in toluene (entry 12). As a comparison, we examined the known privileged chiral phosphoric acid catalysts **1a−d** and **4a,b** in the model reaction to show a dramatic decrease of the reaction enantioselectivity (entries 14−19).

With the optimized reaction conditions in hand, we then evaluated the substrate scope of the asymmetric aza-Friedel−Crafts reaction between cinnamaldehyde-derived *N*-tosylimines and indoles. The results are summarized in Scheme 2.

Scheme 2. Substrate Scope for Reaction of Indoles with *N*-Tosylvinylaldimines[a]

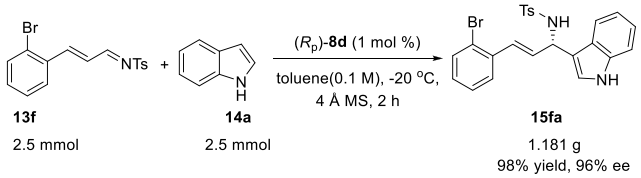


[a]Reaction conditions: **13** (0.25 mmol), **14** (0.25 mmol), (R_p)-**8d** (1 mol %), and 4 Å MS (75 mg) in 2.5 mL of toluene under N_2 at −20 °C for 2 h. [b]At −40 °C for 12 h. [c]One mol % of (R_p)-**8e** was used at −40 °C for 12 h.

We first investigated the substituent effects of cinnamaldehyde-derived *N*-tosylimines **13**. As a result, the substituent and its position of **13** had almost no effect on the enantioselectivity, and the corresponding products were obtained in good yield and with excellent enantioselectivity (**15aa−ga**, 60−95% yield, 93 to >99% ee). In addition, a substrate with a heteroaromatic structure was also compatible under the same conditions, and the corresponding products **15ia** was obtained with high enantioselectivity (97% ee). We next examined the scope of indoles **14**. In all cases, both electron-rich and electron-deficient indoles gave high yields and excellent enantioselectivities (**15ab**, **15ae−ag**, and **15ai**). Moreover, the absolute configuration (*S*) of the stereogenic center in product **15** was determined by X-ray crystallographic analysis of a single crystal of **15ba**.

To test the practicality of the current catalytic system, a gram-scale reaction was achieved under the optimized reaction conditions. As shown in Scheme 3, the reaction of **13f** with

Scheme 3. Gram-Scale Experiment



indole **14a** in the presence of 1 mol % of PPA (R_p)-**8d** was carried out on a 2.5 mmol scale of **13f**. The desired product **15fa** was obtained in 98% yield (1.181 g) with 96% ee.

Finally, we expanded the investigation of our new catalytic system to the asymmetric aza-Friedel−Crafts reaction between aromatic aldehyde-derived *N*-tosylimines and indoles. The reaction of *N*-tosyl phenyl aldimine with indole was initially examined, and a concise screening of PPAs and reaction conditions was carried out again. Gratifyingly, the reaction proceeded smoothly to give the desired product **17aa** in 99% yield with 96% ee using 2 mol % of (R_p)-**8e** as a catalyst in toluene in the presence of 4 Å MS at −20 °C in 2 h, as shown in Scheme 4. It is interesting to note that this result compares quite favorably with BINOL-phosphoric acid catalyst, which at 10 mol % loading was reported to catalyze the same reaction in toluene at −60 °C for 30 min to furnish **17aa** in 83% yield and 98% ee,[10c] while SPINOL−phosphoric acid catalyst was reported to catalyze the same reaction in toluene at −60 °C for 36 h with 10 mol % loading to afford **17aa** in 80% yield and 96% ee.[2d] Subsequently, diverse aromatic aldehyde-derived *N*-tosylimines **16** and indoles **14** were evaluated to define the reaction scope. We observed that the PPA (R_p)-**8e** catalyzed aza-Friedel−Crafts reaction of *N*-tosyl aryl aldimines with indole was found to be general with *N*-tosyl aryl aldimines bearing different either electron-donating groups or electron-withdrawing groups as substituents. In all cases, almost quantitative yields and excellent enantioselectivities could be achieved (**17aa−ka**, all 99% yields, 92−99% ee). We then examined several substituted indoles and found that 2-methylindole provided slightly lower enantioselectivity (**17db**, 87% ee) compared to those bearing 4,7-substituted indoles (**17dc−de** and **17ee−ek**, 91−99% ee), probably because of steric hindrance. In addition, we were pleased to find that *N*-tosylaldimine-derived 2-naphthaldehyde and heteroaryl 2-thiophenyl aldehyde could also be successfully employed to afford the corresponding products in good yields with excellent enantioselectivities (**17la**, 97% ee; **17ma**, 94% ee) under similar reaction conditions. In the case of an aliphatic aldehyde derived imine, high yield but only moderate enantioselectivity were obtained (**17na**, 95% yield, 77% ee).

In summary, we have developed a novel class of robust planar chiral phosphoric acids bearing a [2.2]paracyclophane scaffold which combines the features of easy accessibility, conformational rigidity, good thermal stability, and fascinating catalyst efficiency. Their advantageous catalytic performance

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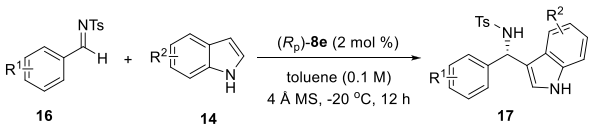
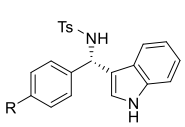
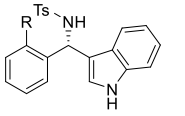
Scheme 4. Substrate Scope for Reaction of Indoles with *N*-Tosylarylaldimines[a]

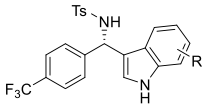




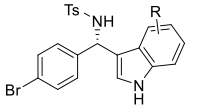
17aa: R = H 99% yield, 96% ee
17ba: R = CH_3 99% yield, 97% ee
17ca: R = OCH_3 99% yield, 96% ee
17da: R = CF_3 99% yield, 99% ee
17ea: R = Br 99% yield, 98% ee
17fa: R = Cl 99% yield, 94% ee
17ga: R = F 99% yield, 98% ee



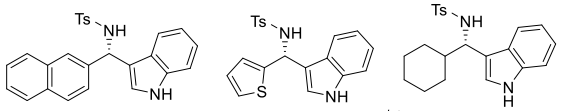
17ha: R = CH_3 99% yield, 94% ee
17ia: R = OCH_3 99% yield, 93% ee
17ja: R = Cl 99% yield, 92% ee
17ka: R = Br 99% yield, 92% ee



17db: R = 2-CH_3 83% yield, 87% ee[b]
17dc: R = 5-CH_3 70% yield, 98% ee[b]
17dd: R = 5-Br 91% yield, 97% ee
17de: R = 6-Br 99% yield, 99% ee



17ee: R = 6-Br 35% yield, 92% ee
17ef: R = 6-CH_3 80% yield, 96% ee
17eg: R = 6-F 70% yield, 99% ee
17eh: R = 6-Cl 40% yield, 95% ee
17ei: R = 4-Br 65% yield, 91% ee
17ek: R = 7-CH_3 99% yield, 98% ee



17la: 99% yield, 97% ee **17ma**: 60% yield, 94% ee[b] **17na**: 95% yield, 77% ee

[a]Reaction conditions: **16** (0.125 mmol), **14** (0.125 mmol), (R_p)-**8e** (2 mol %), and 4 Å MS (38 mg) in 1.25 mL of toluene under N_2 at −20 °C for 12 h. [b]At −40 °C

has been demonstrated to make them the optimal catalysts in asymmetric aza-Friedel−Crafts reactions with the first synthesis of enantioenriched styryl indolylmethanamine derivatives in good yields with excellent enantioselectivities (93−>99% ee) under 0.5−1 mol % catalyst loading. The new catalytic system was also successfully expanded to aromatic aldehyde-derived *N*-tosylimines, affording the corresponding aryl indolylmethanamines with excellent enantioselectivities (up to 99% ee). Further investigations for more effective planar chiral phosphoric acids bearing a [2.2]paracyclophane scaffold as well as expansion of their other challenging applications in asymmetric catalysis are underway in our laboratory.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.9b01127.

Experimental procedures, spectral data for all new compounds (PDF)

Accession Codes

CCDC 1904580−1904581 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) For pioneering works on chiral phosphoric acid catalysis, see: (a) Akiyama, T.; Itoh, J.; Yokota, K.; Fuchibe, K. *Angew. Chem., Int. Ed.* **2004**, *43*, 1566−1568. (b) Uraguchi, D.; Terada, M. *J. Am. Chem. Soc.* **2004**, *126*, 5356−5357 For reviews, see: . (c) Akiyama, T.; Itoh, J.; Fuchibe, K. *Adv. Synth. Catal.* **2006**, *348*, 999−1010. (d) Akiyama, T. *Chem. Rev.* **2007**, *107*, 5744−5758. (e) Terada, M. *Chem. Commun.* **2008**, 4097−4112. (f) Adair, G.; Mukherjee, S.; List, B. *Aldrichimica Acta* **2008**, *41*, 31−39. (g) You, S.-L.; Cai, Q.; Zeng, M. *Chem. Soc. Rev.* **2009**, *38*, 2190−2201. (h) Terada, M. *Synthesis* **2010**, *2010*, 1929−1982. (i) Rueping, M.; Kuenkel, A.; Atodiresei, I. *Chem. Soc. Rev.* **2011**, *40*, 4539−4549. (j) Yu, J.; Shi, F.; Gong, L.-Z. *Acc. Chem. Res.* **2011**, *44*, 1156−1171. (k) Parmar, D.; Sugiono, E.; Raja, S.; Rueping, M. *Chem. Rev.* **2014**, *114*, 9047−9153. (l) Rahman, A.; Lin, X. F. *Org. Biomol. Chem.* **2018**, *16*, 4753−4777.

(2) (a) Rowland, G. B.; Zhang, H.; Rowland, E. B.; Chennamadhavuni, S.; Wang, Y.; Antilla, J. C. *J. Am. Chem. Soc.* **2005**, *127*, 15696−15697. (b) Akiyama, T.; Saitoh, Y.; Morita, H.; Fuchibe, K. *Adv. Synth. Catal.* **2005**, *347*, 1523−1526. (c) Chen, X.-H.; Xu, X.-Y.; Liu, H.; Cun, L.-F.; Gong, L.-Z. *J. Am. Chem. Soc.* **2006**, *128*, 14802−14803. (d) Xu, F.; Huang, D.; Han, C.; Shen, W.; Lin, X. F.; Wang, Y. G. *J. Org. Chem.* **2010**, *75*, 8677−8680. (e) Corić, I.; Müller, S.; List, B. *J. Am. Chem. Soc.* **2010**, *132*, 17370−17373. (f) Chen, X.-H.; Zhang, W.-Q.; Gong, L.-Z. *J. Am. Chem. Soc.* **2008**, *130*, 5652−5653. (g) Wang, Y.-Z.; Liu, W.; Ren, W.-L.; Shi, Y.-A. *Org. Lett.* **2015**, *17*, 4976−4979.

(3) (a) Dai, L.-X., Hou, X.-L., Eds. *Chiral Ferrocenes in Asymmetric Catalysis*; Wiley-VCH: New York, 2010. (b) Dai, L.-X.; Tu, T.; You, S.-L.; Deng, W.-P.; Hou, X.-L. *Acc. Chem. Res.* **2003**, *36*, 659−667. (c) Wu, X.-W.; Sun, W.; Hou, X.-L. *Chin. J. Org. Chem.* **2003**, *23*, 906−913. (d) Gibson, S. E.; Knight, J. D. *Org. Biomol. Chem.* **2003**, *1*, 1256−1269. (e) Pye, P. J.; Rossen, K.; Reamer, R. A.; Tsou, N. N.; Volante, R. P.; Reider, P. J. *J. Am. Chem. Soc.* **1997**, *119*, 6207−6208.

(4) Enders, D.; Ludwig, M.; Raabe, G. *Chirality* **2012**, *24*, 215−222.

(5) (a) Stemper, J.; Isaac, K.; Duret, V.; Retailleau, P.; Voituriez, A.; Betzer, J.-F.; Marinetti, A. *Chem. Commun.* **2013**, *49*, 6084−6086. (b) Stemper, J.; Isaac, K.; Pastor, J.; Frison, G.; Retailleau, P.; Voituriez, A.; Betzer, J.-F.; Marinetti, A. *Adv. Synth. Catal.* **2013**, *355*, 3613−3624. (c) Isaac, K.; Stemper, J.; Servajean, V.; Retailleau, P.; Pastor, J.; Frison, G.; Kaupmees, K.; Leito, I.; Betzer, J.-F.; Marinetti, A. *J. Org. Chem.* **2014**, *79*, 9639−9646.

(6) For selected examples by this group, see: (a) Huang, D.; Li, X.; Xu, F.; Li, L.; Lin, X. F. *ACS Catal.* **2013**, *3*, 2244−2247. (b) Shen, X. M.; Wang, Y. G.; Wu, T. D.; Mao, Z. J.; Lin, X. F. *Chem. - Eur. J.* **2015**, *21*, 9039−9043. (c) Lou, H. Q.; Wang, Y. T.; Jin, E. Z.; Lin, X. F. *J. Org. Chem.* **2016**, *81*, 2019−2026. (d) Xie, E.; Rahman, A.; Lin, X. F. *Org. Chem. Front.* **2017**, *4*, 1407−1410. (e) Luo, J.; Zhang, T.; Wang, L.; Liao, G.; Yao, Q. J.; Wu, Y. J.; Zhan, B. B.; Lan, Y.; Lin, X. F.; Shi, B. F. *Angew. Chem., Int. Ed.* **2019**, DOI: 10.1002/anie.201902126. For recent examples by other groups, see: (f) Wang, F.-L.; Dong, X.-Y.; Lin, J.-S.; Zeng, Y.; Jiao, G.-Y.; Gu, Q.-S.; Guo, X.-Q.; Ma, C.-L.; Liu, X.-Y. *Chem.* **2017**, *3*, 979−990. (g) Qian, D.; Chen, M.; Bissember, A.-C.; Sun, J. *Angew. Chem., Int. Ed.* **2018**, *57*, 3763−3766. (h) Qi, L.-W.; Mao, J.-H.; Zhang, J.; Tan, B. *Nat. Chem.* **2018**, *10*,

DOI: 10.1021/acs.orglett.9b01127
Org. Lett. XXXX, XXX, XXX−XXX

58−64. (i) Li, J.-T.; Kong, M.; Qiao, B.-K.; Lee, R.; Zhao, X.-W.; Jiang, Z.-Y. *Nat. Commun.* **2018**, *9*, 2445−2453. (j) Zhang, J.; Yu, P.-Y.; Li, S.-Y.; Sun, H.; Xiang, S.-H.; Wang, J.; Houk, K. N.; Tan, B. *Science* **2018**, *361*, 8707−8715. (k) Lin, J.-S.; Li, T.-T.; Liu, J.-R.; Jiao, G.-Y.; Gu, Q.-S.; Cheng, J.-T.; Guo, Y.-L.; Hong, X.; Liu, X.-Y. *J. Am. Chem. Soc.* **2019**, *141*, 1074−1083.

(7) (a) Gu, H.-R.; Han, Z.; Xie, H. J.; Lin, X. F. *Org. Lett.* **2018**, *20*, 6544−6549. (b) Sun, W. Y.; Gu, H. R.; Lin, X. F. *J. Org. Chem.* **2018**, *83*, 4034−4043. (c) Shan, H. Y.; Zhou, Q. X.; Yu, J. L.; Zhang, S. Q.; Hong, X.; Lin, X. F. *J. Org. Chem.* **2018**, *83*, 11873−11885.

(8) Bannwarth, W.; Trzeciak, A. *Helv. Chim. Acta* **1987**, *70*, 175−186.

(9) For reviews on asymmetric aza-Friedel−Crafts reaction, see: (a) Bandini, M.; Melloni, A.; Umani-Ronchi, A. *Angew. Chem., Int. Ed.* **2004**, *43*, 550−556. (b) Poulsen, T. B.; Jorgensen, K. A. *Chem. Rev.* **2008**, *108*, 2903−2915. (c) Bandini, M.; Eichholzer, A. *Angew. Chem., Int. Ed.* **2009**, *48*, 9608−9644. (d) You, S.-L.; Cai, Q.; Zeng, M. *Chem. Soc. Rev.* **2009**, *38*, 2190−2201. (e) Reid, J. P.; Simón, L.; Goodman, J. M. *Acc. Chem. Res.* **2016**, *49*, 1029−1041. For recent examples, see: (f) Li, G.; Rowland, G. B.; Rowland, E. B.; Antilla, J. C. *Org. Lett.* **2007**, *9*, 4065−4068. (g) Husmann, R.; Sugiono, E.; Mersmann, S.; Raabe, G.; Rueping, M.; Bolm, C. *Org. Lett.* **2011**, *13*, 1044−1047. (h) Zhang, K.-F.; Nie, J.; Guo, R.; Zheng, Y.; Ma, J.-A. *Adv. Synth. Catal.* **2013**, *355*, 3497−3502. (i) Wang, S.-G.; You, S.-L. *Angew. Chem., Int. Ed.* **2014**, *53*, 2194−2197. (j) Kano, T.; Takechi, R.; Kobayashi, R.; Maruoka, K. *Org. Biomol. Chem.* **2014**, *12*, 724−727.

(10) (a) Wang, Y.-Q.; Song, J.; Hong, R.; Li, H.; Deng, L. J. *J. Am. Chem. Soc.* **2006**, *128*, 8156−8157. (b) Terada, M.; Sorimachi, K. *J. Am. Chem. Soc.* **2007**, *129*, 292−293. (c) Kang, Q.; Zhao, Z.-A.; You, S.-L. *J. Am. Chem. Soc.* **2007**, *129*, 1484−1485. (d) Terada, M.; Yokoyama, S.; Sorimachi, K.; Uraguchi, D. *Adv. Synth. Catal.* **2007**, *349*, 1863−1867. (e) Rowland, G. B.; Rowland, E. B.; Liang, Y.; Perman, J. A.; Antilla, J. C. *Org. Lett.* **2007**, *9*, 2609−2611. (f) Zhang, G.-W.; Wang, L.; Nie, J.; Ma, J.-A. *Adv. Synth. Catal.* **2008**, *350*, 1457−1463. (g) Qiu, H.; Li, M.; Jiang, L.-Q.; Lv, F.-P.; Zan, L.; Zhai, C.-W.; Doyle, M. P.; Hu, W.-H. *Nat. Chem.* **2012**, *4*, 733−738. (h) Li, X. J.; Chen, D.; Gu, H. R.; Lin, X. F. *Chem. Commun.* **2014**, *50*, 7538−7541. (i) Wang, L.; Rahman, A.; Lin, X. F. *Org. Biomol. Chem.* **2017**, *15*, 6033−6041. (j) Rahman, A.; Xie, E.; Lin, X. F. *Org. Biomol. Chem.* **2018**, *16*, 1367−1374. (k) Hatano, M.; Mochizuki, T.; Nishikawa, K.; Ishihara, K. *ACS Catal.* **2018**, *8*, 349−353.

(11) (a) Wang, B.-L.; Li, N.-K.; Zhang, J.-X.; Liu, G.-G.; Liu, T.; Shen, Q.; Wang, X.-W. *Org. Biomol. Chem.* **2011**, *9*, 2614−2617. (b) Takizawa, S.; Arteaga, F. A.; Yoshida, Y.; Kodera, J.; Nagata, Y.; Sasai, H. *DaltonTrans* **2013**, *42*, 11787−11790. (c) Kumari, P.; Bera, P.-K.; Khan, N.-U.-H.; Kureshy, R.-I.; Abdi, S.-H.-R.; Bajaj, H.-C. *Catal. Sci. Technol.* **2014**, *4*, 563−568. (d) Zou, K.; Ye, J.; Wu, X.-Y. *Tetrahedron* **2015**, *71*, 7869−7873. (e) Arai, T.; Kakino, J. *Angew. Chem., Int. Ed.* **2016**, *55*, 15263−15267. (f) Kim, M.-J.; Xue, L.; Liu, Y.; Paladhi, S.; Park, S.-J.; Yan, H.; Song, C.-E. *Adv. Synth. Catal.* **2017**, *359*, 811−823.

DOI: 10.1021/acs.orglett.9b01127
Org. Lett. XXXX, XXX, XXX−XXX