

Cite this: *Chem. Sci.*, 2023, 14, 4413

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

Received 19th December 2022

Accepted 20th March 2023

DOI: 10.1039/d2sc06950d

rsc.li/chemical-science

Chiral organophosphorus compounds play a significant role in bioactive molecules, agrochemistry, and functional materials.¹ In addition, they are also broadly applied in transition metal catalysis and organocatalysis as chiral ligands and chiral catalysts.² Compared with conventional methods using a stoichiometric amount of chiral starting materials or chiral reagents,³ asymmetric catalytic approaches have attracted increasing attention in the construction of chiral phosphines. Among them, catalytic asymmetric hydrophosphination is one of the most direct and atom-economical ways for preparation of optically active phosphines.

Pd-Catalyzed asymmetric hydrophosphination of α,β -unsaturated compounds (including α,β -unsaturated aldehydes, ketones, esters, pyrrole amides, sulfonic esters, and sulfonamides) with secondary phosphines has emerged as a versatile method for the construction of chiral phosphine compounds (Scheme 1a).⁴ Other transition metal complexes such as chiral Ni,⁵ Pt,⁶ Cu⁷ and Mn⁸ catalysts and organocatalysts⁹ were also applied in the asymmetric hydrophosphination of electron-deficient alkenes, recently. However, examples where heteroarenes were employed in alkene activation have not appeared due to the relatively poor reactivity of alkenylheteroarenes. In 2021, Terada reported hydrophosphinylation of β -unsubstituted alkenylheteroarene *N*-oxides with SPO (secondary phosphine oxide) catalyzed by their chiral bis(guanidino)iminophosphorane organosuperbase (Scheme 1b).¹⁰ The subsequent reduction of the phosphine oxide product could give quinoline phosphine. Inspired by Yin's recent elegant work on the Cu/TANIAPhos-catalyzed enantioselective

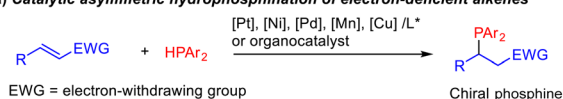
Enantioselective copper-catalyzed hydrophosphination of alkenyl isoquinolines†‡

Qingjing Yang,^a Jian Zhou^{ab} and Jun (Joelle) Wang^{id}*^b

An enantioselective hydrophosphination of alkenyl isoquinolines is developed by using a copper-chiral diphosphine ligand catalyst. It provides a direct and atom-efficient approach to prepare a variety of chiral phosphines with an isoquinoline unit in good yields and high enantioselectivities. In addition, these chiral phosphine products are useful bidentate P,N-ligands which showed potential application in asymmetric catalysis.

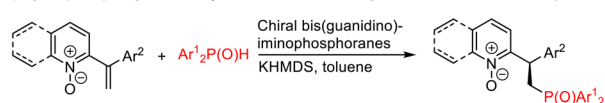
hydrophosphination of α,β -unsaturated amides in which the olefin moiety is sluggishly activated by the adjacent carboxamide group (Scheme 1c),^{7a} we envisioned that the long-time unsolved asymmetric hydrophosphination of intrinsic low electrophilic alkenyl-heteroarenes might be realized with a suitable Cu/chiral phosphine catalyst because of its relative stability in the presence of excess HPPH₂. Furthermore, the chiral tertiary phosphine products bearing a *N*-heteroaromatic ring themselves are potentially useful chiral bidentate P,N-ligands in asymmetric catalysis.

a) Catalytic asymmetric hydrophosphination of electron-deficient alkenes

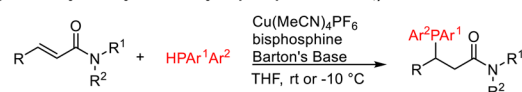


- A. Pt, acrylonitrile and acrylate esters
B. Ni, methacrylonitrile
C. Pd, enones, enals, enamide, nitroalkenes, carboxylic and sulfonic esters
D. Mn, acrylonitrile and alkenyl phosphine oxide
E. Cu, enones, alkenyl phosphine sulfide and alkenyl amide

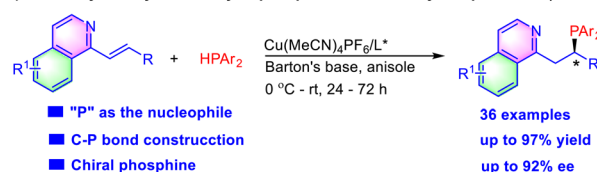
b) Hydrophosphinylation of β -unsubstituted alkenylheteroarenes *N*-oxides (Terada)



c) Cu-catalyzed asymmetric hydrophosphination of α,β -unsaturated amides (Yin)



d) Cu-catalyzed asymmetric hydrophosphination of alkenyl isoquinolines (This work)



^aDepartment of Chemistry, Southern University of Science and Technology (SUSTech), Shenzhen, 518055, China

^bDepartment of Chemistry, Hong Kong Baptist University, Kowloon, Hong Kong, China. E-mail: junwang@hkbu.edu.hk

† Dedicated to Professor Guo-Qiang Lin on the occasion of his 80th birthday.

‡ Electronic supplementary information (ESI) available. CCDC 2201645. For ESI and crystallographic data in CIF or other electronic format see DOI: <https://doi.org/10.1039/d2sc06950d>

Scheme 1 Examples of asymmetric hydrophosphination of electron-deficient alkenes and asymmetric hydrophosphination to alkenyl azarenes.



Based on these design considerations and our prior experience in the construction of chiral organophosphorus compounds,¹¹ we began our study by examining the hydrophosphination of alkenyl isoquinoline **1a** with diphenyl phosphine **2a** in the presence of a copper complex and Barton's base in toluene at room temperature (Table 1). (*R*)-Binap (**L1**) gave the bench-stable secondary phosphine oxide **3a** in 85% yield by the *in situ* oxidation of the labile secondary phosphine product with hydrogen peroxide, avoiding their isolation and purification while maintaining their structural diversity. However, the enantioselectivity of **3a** was very poor (entry 1). Other biphosphine ligands-(*R*)-Segphos (**L2**), (*R*)-difluorophos (**L3**), (*R*, *R*)-BDPP (**L4**), (*R*, *R*)-Ph-BPE (**L5**) and (*R*, *R*)-Me-Duphos (**L6**) resulted in low yields and enantio-control (entries 2–6). Catalyzed by (*R*, *R*)-QuinoxP* (**L7**), 68% ee was obtained with 77% yield (entry

7). To our delight, the reaction with (*R*, *R*)-BenzP* (**L8**) provided the hydrophosphination product **3a** in 88% yield with 83% ee (entry 8). Therefore, (*R*, *R*)-BenzP* (**L8**) was chosen for further optimization. Other Cu precursors, such as Cu(MeCN)₄BF₄, Cu(OAc)₂, Cu(ClO₄)₂·6H₂O, and Cu(OTf)₂, were employed, indicating that Cu(MeCN)₄PF₆ was the best choice (entry 8 *vs.* entries 9–12). Next, we examined the effect of a solvent on the reaction. It was showed that the reactions in THF, 1,4-dioxane, DME, and anisole provided product **3a** with similar high yields, but the reaction in anisole gave the highest ee (entries 13–16). Other bases, including DABCO, K₂CO₃, and KOAc, were then tested, and led to a slight decrease of the reaction yields (entries 17–19). On increasing the molar ratio of Barton's base/**1a** from 1 : 1 to 1.5/1, the ee of product **3a** was enhanced to 87% (entry 20). Finally, product **3a** was obtained in 94% yield with 90% ee by lowering the temperature to 0 °C (entry 21).

With the optimal conditions, the substrate scope of substituted alkenyl isoquinolines was then investigated (Table 2). As for β-alkyl substituted alkenyl isoquinolines, both linear alkyl (**3b** and **3c**), benzyl (**3d**) and cyclopropanyl (**3e**) reacted efficiently with diphenyl phosphine **2a** to afford the corresponding products in 80–96% yields with 80–86% ee. The absolute configuration of product **3e** was confirmed as (*R*) by X-ray crystal structure analysis.¹² Interestingly, there was only 1,4-addition when the conjugate divinyl isoquinoline **1f** was investigated, and the hydrophosphination product **3f** was obtained in 70% yield with 86% ee. Subsequently, substrates with aryl groups were also evaluated. The 1-styrylisoquinoline **1g** reacted smoothly under the reaction conditions, providing the product **3g** in 87% yield and 92% ee. A wide range of alkenyl isoquinolines with an electron-donating group (**3h** and **3i**) or an electron-withdrawing group (**3j**, **3k**, **3l**, **3m**, and **3n**) at the *para*-position of the phenyl ring were tolerated. In general, the reactions afforded products in moderate to excellent yields with moderate to high enantioselectivity. A good outcome was also achieved upon introducing a methyl group at the *meta*-position of the aryl group of the substrate (**3p**). The reaction of **1q** containing a 2-naphthyl substituent proceeded to afford **3q** with a decreased yield and enantioselectivity (70% yield and 77% ee). Substrates with a heteroaryl, such as 2-furanyl (**3r**), 3-furanyl (**3s**), 3-thienyl (**3t**), and 3-pyridinyl (**3u**), were well-tolerated under this catalytic condition. The 2-pyridinyl (**3v**) or 4-pyridinyl (**3w**) substituted substrate also worked well to deliver products in excellent yields, but led to an obvious decrease in enantioselectivities. The reaction between α-phenyl-substituted **1x** and Ph₂PH was attempted, affording the product **3x** in 93% yield and 53% ee. It was found that quinoline **1y** also could be hydrophosphinated with this catalyst at 60 °C to provide the product **3y** in 73% yield with 54% ee. Furthermore, alkenyl pyridines were also compatible with the reaction conditions to deliver the corresponding products in good yields and enantioselectivities (**3z** and **3aa**).

The substitute groups on isoquinolines were also evaluated (Table 2). Substrates with electron-donating groups (Me and OMe) or with electron-withdrawing groups (F and Br) at the 4- (**3ab** and **3ac**), 5- (**3ad**), and 6-positions (**3ae**, **3af**, **3ag** and **3ah**) of the isoquinoline ring were well-tolerated affording products in

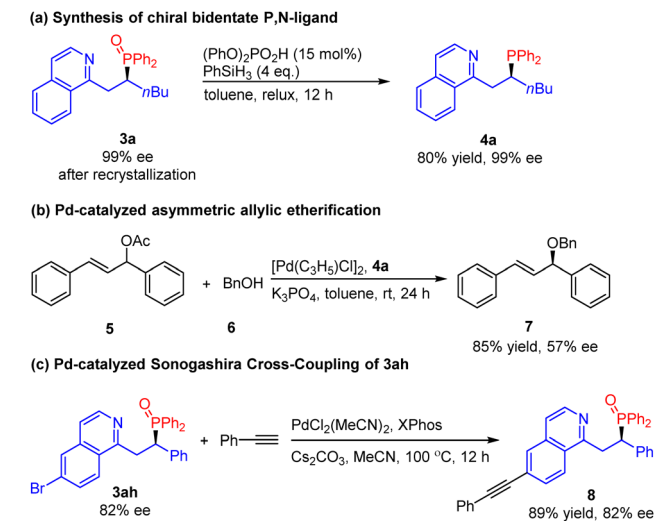
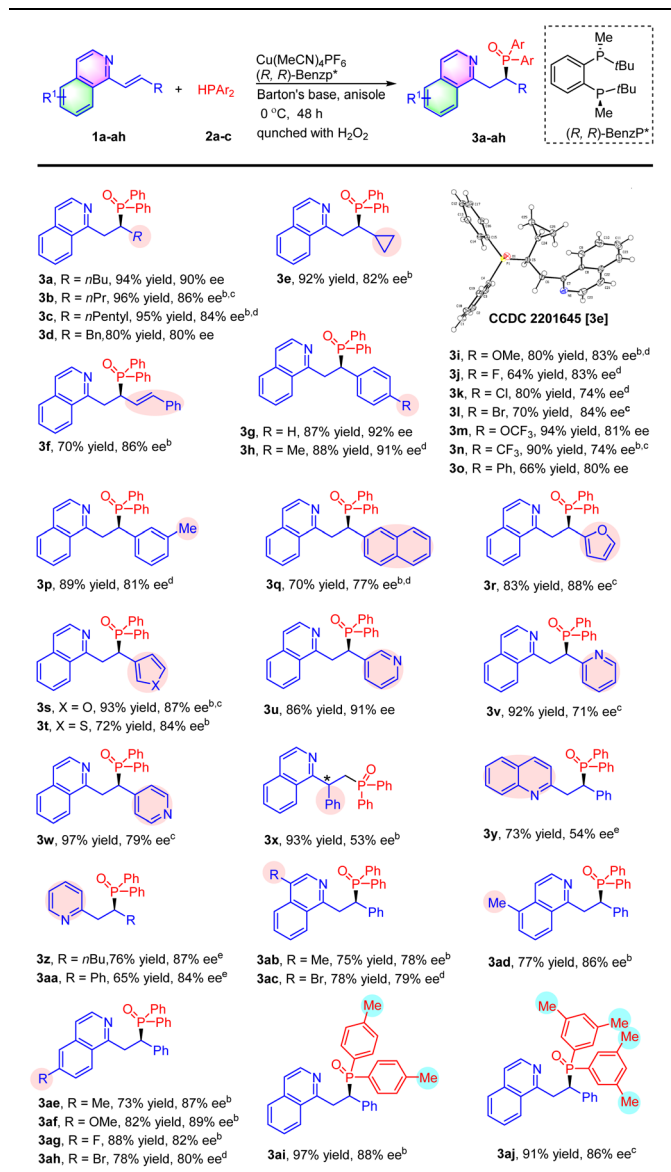
Table 1 Optimization of reaction conditions^a

Entry	[Cu]	Ligand	Solvent	Yield ^b (%)	ee ^c (%)
1	Cu(MeCN) ₄ PF ₆	L1	Toluene	85	3
2	Cu(MeCN) ₄ PF ₆	L2	Toluene	51	32
3	Cu(MeCN) ₄ PF ₆	L3	Toluene	52	20
4	Cu(MeCN) ₄ PF ₆	L4	Toluene	44	40
5	Cu(MeCN) ₄ PF ₆	L5	Toluene	30	–35
6	Cu(MeCN) ₄ PF ₆	L6	Toluene	11	7
7	Cu(MeCN) ₄ PF ₆	L7	Toluene	77	68
8	Cu(MeCN) ₄ PF ₆	L8	Toluene	88	83
9	Cu(MeCN) ₄ BF ₄	L8	Toluene	36	83
10	Cu(OAc) ₂	L8	Toluene	48	86
11	Cu(ClO ₄) ₂ ·6H ₂ O	L8	Toluene	74	66
12	Cu(OTf) ₂	L8	Toluene	41	73
13	Cu(MeCN) ₄ PF ₆	L8	THF	86	84
14	Cu(MeCN) ₄ PF ₆	L8	1,4-Dioxane	91	83
15	Cu(MeCN) ₄ PF ₆	L8	DME	93	82
16	Cu(MeCN) ₄ PF ₆	L8	Anisole	92	85
17 ^d	Cu(MeCN) ₄ PF ₆	L8	Anisole	20	73
18 ^e	Cu(MeCN) ₄ PF ₆	L8	Anisole	35	70
19 ^f	Cu(MeCN) ₄ PF ₆	L8	Anisole	24	68
20 ^g	Cu(MeCN) ₄ PF ₆	L8	Anisole	90	87
21 ^h	Cu(MeCN) ₄ PF ₆	L8	Anisole	91	86
22 ^{g,i}	Cu(MeCN) ₄ PF ₆	L8	Anisole	94	90

^a Reaction conditions: [Cu] (10 mol%), ligand (11 mol%), **1a** (0.2 mmol), **2a** (0.3 mmol), Barton's base (1.0 eq.), solvent (1.0 mL). ^b Isolated yields.

^c The ee values were determined by chiral HPLC. ^d DABCO. ^e K₂CO₃. ^f KOAc. ^g 1.5 eq. Barton's base. ^h 2.0 eq. Barton's base. ⁱ 0 °C.



Table 2 Substrate scope^a

Scheme 2 Synthesis applications.

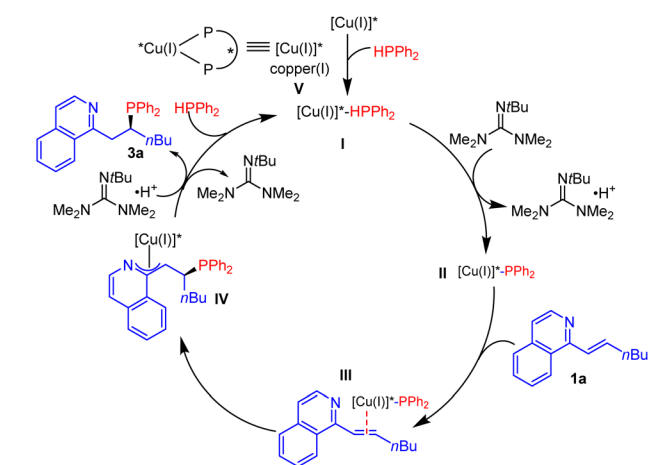
resolution or required tedious multistep synthesis.¹⁴ Herein, the reduction of phosphine oxide product **3a** with phenylsilane in the presence of diphenyl phosphate provided phosphine **4a** in 80% yield without loss of enantiomeric purity (Scheme 2). Subsequently, we examined our P,N-ligand **4a** in the Pd-catalyzed asymmetric allylic etherification of benzyl alcohol, obtaining the desired product **7** in good yield (85%) and moderate ee (57%). In addition, the product **3ah** could also be transformed by Pd-catalyzed Sonogashira cross-coupling. The corresponding alkynylation product **8** was obtained in excellent yield without a decline in enantiopurity.

A possible mechanism for the reaction was proposed based on the literature (Scheme 3).^{7a,b,15} Chiral copper complex **V** is formed by $Cu(MeCN)_4PF_6$ and $(R,R)\text{-Benzp}^*$. Coordination between $HPPH_2$ and chiral copper complex **V** generates complex **I**, which undergoes deprotonation in the presence of Barton's base to produce the nucleophilic copper(I)-diphenylphosphide species **II**. Then, the alkene tethered with isoquinoline coordinates to complex **II** and affords the Cu-phosphido-alkene

^a Reaction conditions: $Cu(MeCN)_4PF_6$ (10 mol%), ligand (11 mol%), **1** (0.2 mmol), **2** (0.3 mmol), Barton's base (0.3 mmol), anisole (1.0 mL). Isolated yields. The ee values were determined by chiral HPLC.
^b Room temperature. ^c 24 h. ^d 72 h. ^e 60 °C.

73–93% yields with 78–89% ee. Finally, we turned our attention towards the scope of diarylphosphines **2**. Hydrophosphination with $(p\text{-Me-C}_6\text{H}_4)_2\text{PH}$ and $(3,5\text{-Me-C}_6\text{H}_3)_2\text{PH}$ led to the corresponding products **3ai** and **3aj** with excellent yields and good enantioselectivities. However, other phosphines, such as $(o\text{-Me-C}_6\text{H}_4)_2\text{PH}$, $(p\text{-MeO-C}_6\text{H}_4)_2\text{PH}$, $(p\text{-F-C}_6\text{H}_4)_2\text{PH}$ and $Cy_2\text{PH}$, were not suitable for the reaction and only trace expected products were detected.

Chiral bidentate P,N-ligands are one of the most important family of ligands widely used in asymmetric catalysis.¹³ Therefore, there is an increasing demand for the efficient synthesis of chiral bidentate P,N-ligands. However, most of the protocols for the synthesis of chiral P,N-ligands focused on the chiral



Scheme 3 Proposed catalytic cycle.



complex **III**. Next, asymmetric addition of the diarylphosphido group on copper to the alkenyl-substituted isoquinoline provides an aza- π -allylcopper intermediate **IV**, which is protonated to release the phosphination product **3a** and regenerates copper complex **V** for the next catalytic cycle.

In summary, we have established an operationally simple and highly enantioselective Cu(I)-catalyzed hydrophosphination reaction of alkenyl-substituted isoquinolines. This method afforded a direct and atom efficient access to chiral phosphines with an isoquinoline unit in high yields and enantioselectivities in most cases. Furthermore, the product was showcased as a new chiral P,N-type ligand in palladium-catalyzed asymmetric allylic etherification. Further work on the structure modification and application of these chiral phosphine products in other asymmetric reactions is underway in our laboratory.

Data availability

The datasets supporting this article have been uploaded as part of the ESI.†

Author contributions

Dr Q. Yang performed the experiments and prepared the supplementary information. J. Zhou collected some data. Prof. J. Wang conceived and directed the project. Q. Yang and J. Wang wrote the paper.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We gratefully thank the Research Grants Council of Hong Kong (GRF 12301821) and National Natural Science Foundation of China (NSFC 21971102) for financial support. Dr Xiaoyong Chang from SUSTech is gratefully acknowledged for X-ray crystallographic analysis.

Notes and references

- (a) G. P. Horsman and D. L. Zechel, *Chem. Rev.*, 2017, **117**, 5704; (b) A. Mucha, P. Kafarski and L. Berlicki, *J. Med. Chem.*, 2011, **54**, 5955; (c) J. P. Kahler and S. H. L. Verhelst, *RSC Chem. Biol.*, 2021, **2**, 1285; (d) C. E. Stieger, L. Franz, F. Körlin and C. P. R. Hackenberger, *Angew. Chem., Int. Ed.*, 2021, **60**, 15359.
- For selected reviews on phosphines in asymmetric catalysis, see: (a) T. Wang, X. Han, F. Zhong, W. Yao and Y. Lu, *Acc. Chem. Res.*, 2016, **49**, 1369; (b) H.-U. Blaser, B. Pugin, F. Spindler, E. Meja and A. Togni, *Josiphos Ligands: From Discovery to Technical Applications*, in *Privileged Chiral Ligands and Catalysts*, ed., Q.-L. Zhou, Wiley, 2011, pp. 93–136; (c) P. W. N. M. van Leeuwen, P. C. J. Kamer, J. N. H. Reek and P. Dierkes, *Chem. Rev.*, 2000, **100**, 2741; (d) H. Guo, Y. C. Fan, Z. Sun, Y. Wu and O. Kwon, *Chem. Rev.*, 2018, **118**, 10049; (e) Y. Wei and M. Shi, *Acc. Chem. Res.*, 2010, **43**, 1005; (f) C. S. Demmer, N. Krosggaard-Larsen and L. Bunch, *Chem. Rev.*, 2011, **111**, 7981.
- (a) W. Chen, F. Spindler, B. Pugin and U. Nettekoven, *Angew. Chem., Int. Ed.*, 2013, **52**, 8652; (b) J. P. Djukic, *Cyclopalladated Compounds as Resolving Agents for Racemic Mixtures of Ligands*, in *Palladacycles: Synthesis, Characterization and Applications*, ed. J. Dupont and M. Pfeffer, Wiley, Weinheim, 2008, pp. 123–153.
- (a) J.-J. Feng, X.-F. Chen, M. Shi and W.-L. Duan, *J. Am. Chem. Soc.*, 2010, **132**, 5562; (b) D. Du and W.-L. Duan, *Chem. Commun.*, 2011, **47**, 11101; (c) Y.-R. Chen and W.-L. Duan, *Org. Lett.*, 2011, **13**, 5824; (d) J.-J. Feng, M. Huang, Z.-Q. Lin and W.-L. Duan, *Adv. Synth. Catal.*, 2012, **354**, 3122; (e) J. Lu, J. Ye and W.-L. Duan, *Org. Lett.*, 2013, **15**, 5016; (f) D. Du, Z.-Q. Lin, J.-Z. Lu, C. Li and W.-L. Duan, *Asian J. Org. Chem.*, 2013, **2**, 392; (g) J. Lu, J. Ye and W.-L. Duan, *Chem. Commun.*, 2014, **50**, 698; (h) J. Huang, M.-X. Zhao and W.-L. Duan, *Tetrahedron Lett.*, 2014, **55**, 629; (i) Y.-C. Song, G.-F. Dai, F. Xiao and W.-L. Duan, *Tetrahedron Lett.*, 2016, **57**, 2990; (j) Y. Huang, S. A. Pullarkat, Y. Li and P.-H. Leung, *Chem. Commun.*, 2010, **46**, 6950; (k) Y. Huang, R. J. Chew, Y. Li, S. A. Pullarkat and P.-H. Leung, *Org. Lett.*, 2011, **13**, 5862; (l) Y. Huang, S. A. Pullarkat, S. Teong, R. J. Chew, Y. Li and P.-H. Leung, *Organometallics*, 2012, **31**, 4871; (m) R. J. Chew, Y. Huang, Y. Li, S. A. Pullarkat and P.-H. Leung, *Adv. Synth. Catal.*, 2013, **355**, 1403; (n) R. J. Chew, Y. Lu, Y.-X. Jia, B.-B. Li, E. H. Y. Wong, R. Goh, Y. Li, Y. Huang, S. A. Pullarkat and P.-H. Leung, *Chem.–Eur. J.*, 2014, **20**, 14514; (o) R. J. Chew, K. Sepp, B.-B. Li, Y. Li, P.-C. Zhu, N. S. Tan and P.-H. Leung, *Adv. Synth. Catal.*, 2015, **357**, 3297; (p) X.-Y. Yang, W. S. Tay, Y. Li, S. A. Pullarkat and P.-H. Leung, *Organometallics*, 2015, **34**, 5196; (q) X.-Y. Yang, Y.-X. Jia, W. S. Tay, Y. Li, S. A. Pullarkat and P.-H. Leung, *Dalton Trans.*, 2016, **45**, 13449; (r) R. H. X. Teo, H. J. Chen, Y. Li, S. A. Pullarkat and P.-H. Leung, *Adv. Synth. Catal.*, 2020, **362**, 2373; (s) B. Ding, Z. Zhang, Y. Xu, Y. Liu, M. Sugiya, T. Imamoto and W. Zhang, *Org. Lett.*, 2013, **15**, 5476; (t) Y. Xu, Z. Yang, B. Ding, D. Liu, Y. Liu, M. Sugiya, T. Imamoto and W. Zhang, *Tetrahedron*, 2015, **71**, 6832; (u) K. Gan, A. Sadeer, C. Xu, Y. Li and S. A. Pullarkat, *Organometallics*, 2014, **33**, 5074; (v) X.-Q. Hao, Y.-W. Zhao, J.-J. Yang, J.-L. Niu, J.-F. Gong and M.-P. Song, *Organometallics*, 2014, **33**, 1801; (w) X.-Q. Hao, J.-J. Huang, T. Wang, J. Lv, J.-F. Gong and M.-P. Song, *J. Org. Chem.*, 2014, **79**, 9512.
- (a) A. D. Sadow, I. Haller, L. Fadini and A. Togni, *J. Am. Chem. Soc.*, 2004, **126**, 14704; (b) A. D. Sadow and A. Togni, *J. Am. Chem. Soc.*, 2005, **127**, 17012; (c) L. Huang, E. Q. Lim and M. J. Koh, *Chem Catal.*, 2022, **2**, 508.
- I. Kovacic, D. K. Wicht, N. S. Grewal and D. S. Glueck, *Organometallics*, 2000, **19**, 950.
- (a) Y.-B. Li, H. Tian and L. Yin, *J. Am. Chem. Soc.*, 2020, **142**, 20098; (b) W.-J. Yue, J.-Z. Xiao, S. Zhang and L. Yin, *Angew. Chem., Int. Ed.*, 2020, **59**, 7057; (c) Y.-R. Chen, J.-J. Feng and W.-L. Duan, *Tetrahedron Lett.*, 2014, **55**, 595.



- 8 (a) J. M. Pérez, R. Postolache, M. C. Reis, E. G. Sinnema, D. Vargová, F. de Vries, E. Otten, L. Ge and S. R. Harutyunyan, *J. Am. Chem. Soc.*, 2021, **143**, 20071; (b) L. Ge and S. R. Harutyunyan, *Chem. Sci.*, 2022, **13**, 1307.
- 9 (a) G. Bartoli, M. Bosco, A. Carlone, M. Locatelli, A. Mazzanti, L. Sambri and P. Melchiorre, *Chem. Commun.*, 2007, 722; (b) A. Carlone, G. Bartoli, M. Bosco, L. Sambri and P. Melchiorre, *Angew. Chem., Int. Ed.*, 2007, **46**, 4504; (c) I. Ibrahim, R. Rios, J. Vesely, P. Hammar, L. Eriksson, F. Himo and A. Córdova, *Angew. Chem., Int. Ed.*, 2007, **46**, 4507; (d) I. Ibrahim, P. Hammar, J. Vesely, R. Rios, L. Eriksson and A. Córdova, *Adv. Synth. Catal.*, 2008, **350**, 1875; (e) R. Mait, J.-L. Yan, X. Yang, B. Mondal, J. Xu, H. Chai, Z. Jin and Y. R. Chi, *Angew. Chem., Int. Ed.*, 2021, **60**, 26616.
- 10 S. Das, Q. Hu, A. Kondoh and M. Terada, *Angew. Chem., Int. Ed.*, 2021, **60**, 1417.
- 11 (a) Z. Lu, H. Zhang, Z. Yang, N. Ding, L. Meng and J. Wang, *ACS Catal.*, 2019, **9**, 1457; (b) L. Zhang, S.-H. Xiang, J. Wang, J. Xiao, J.-Q. Wang and B. Tan, *Nat. Commun.*, 2019, **10**, 566; (c) Z. Yang, X. Gu, L.-B. Han and J. Wang, *Chem. Sci.*, 2020, **11**, 7451; (d) Z. Yang and J. Wang, *Angew. Chem., Int. Ed.*, 2021, **60**, 27288; (e) Z. Yang, Q. Du, Y. Jiang and J. Wang, *CCS Chem.*, 2022, **4**, 1901; (f) Y. Zhang, Y. Jiang, M. Li, Z. Huang and J. Wang, *Chem. Catal.*, 2022, **2**, 3163–3173; (g) B. Cai, Y. Cui, J. Zhou, Y.-B. Wang, L. Yang, B. Tan and J. Wang, *Angew. Chem., Int. Ed.*, 2022, **61**, DOI: [10.1002/anie.202215820](https://doi.org/10.1002/anie.202215820).
- 12 CCDC 2201645 [for **3e**] contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via https://www.ccdc.cam.ac.uk/data_request/cif.
- 13 (a) G. Helmchen and A. Pfaltz, *Acc. Chem. Res.*, 2000, **33**, 336; (b) M. P. Carroll and P. J. Guiry, *Chem. Soc. Rev.*, 2014, **43**, 819; (c) B. V. Rokade and P. J. Guiry, *ACS Catal.*, 2018, **8**, 624; (d) W. A. Munzeiwa, B. Omondi and V. O. Nyamori, *Beilstein J. Org. Chem.*, 2020, **16**, 362.
- 14 For selected examples, see: (a) T. Hayashi, T. Mise, M. Fukushima, M. Kagotani, N. Nagashima, Y. Hamada, A. Matsumoto, S. Kawakami, M. Konishi, K. Yamamoto and M. Kumada, *Bull. Chem. Soc. Jpn.*, 1980, **53**, 1138; (b) N. W. Alcock, J. M. Brown and D. I. Hulmes, *Tetrahedron: Asymmetry*, 1993, **4**, 743; (c) A. Lightfoot, P. Schnider and A. Pfaltz, *Angew. Chem., Int. Ed.*, 1998, **37**, 2897; (d) T. Bunlaksananusorn, K. Polborn and P. Knochel, *Angew. Chem., Int. Ed.*, 2003, **42**, 3941; (e) S. Kaiser, S. P. Smidt and A. Pfaltz, *Angew. Chem., Int. Ed.*, 2006, **45**, 5194; (f) Q.-B. Liu and Y.-G. Zhou, *Tetrahedron Lett.*, 2007, **48**, 2101; (g) Z. Han, Z. Wang, X. Zhang and K. Ding, *Angew. Chem., Int. Ed.*, 2009, **48**, 5345.
- 15 Y.-L. Zeng, B. Chen, Y.-T. Wang, C.-Y. He, Z.-Y. Mu, J.-Y. Du, L. He, W.-D. Chu and Q.-Z. Liu, *Chem. Commun.*, 2020, **56**, 1693.

