SCIENCE CHINA
Chemistry

•COMMUNICATIONS•

March 2019 Vol.62 No.3: 336–340
https://doi.org/10.1007/s11426-018-9418-7

Ligand controlled cobalt catalyzed regiodivergent 1,2-hydroboration of 1,3-dienes

Sihan Peng[1†], Ji Yang[2†], Guixia Liu[1*] & Zheng Huang[1,2*]

[1]*State Key Laboratory of Organometallic Chemistry, Center for Excellence in Molecular Synthesis, Shanghai Institute of Organic Chemistry, Shanghai 200032, China;*
[2]*School of Physical Science and Technology, Shanghai Tech University, Shanghai 201210, China*

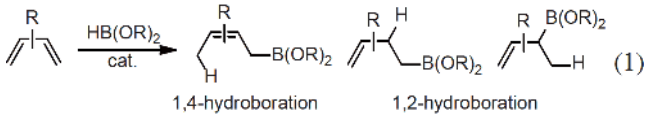
Received December 3, 2018; accepted December 27, 2018; published online January 22, 2019

Regiodivergent 1,2-hydroboration of 1,3-dienes with pinacolborane has been accomplished by well-defined cobalt complexes of different bidentate ligands. The iminopyridine-cobalt system is selective for Markovnikov 1,2-hydroboration to form allylboronates, while the FOXAP-cobalt (FOXAP=(*S*)-1-(diphenylphosphino)-2-[(*S*)-4-isopropyloxazolin-2-yl]ferrocene) catalyst effects the complementary anti-Markonikv 1,2-hydroboration to afford homoallyboronates with high regioselectivity.

cobalt, dienes, hydroboration, regiodivergent

Citation: Peng S, Yang J, Liu G, Huang Z. Ligand controlled cobalt catalyzed regiodivergent 1,2-hydroboration of 1,3-dienes. *Sci China Chem*, 2019, 62: 336–340, https://doi.org/10.1007/s11426-018-9418-7

Allylboronates and homoallylboronates are versatile synthetic intermediates, which participate in various transformations, such as oxidation to allylic or homoallylic alcohols, addition to aldehydes and imines, as well as cross-coupling reactions [1–6]. Thus, the development of selective approaches for their synthesis is highly desirable [7]. Monohydroboration of 1,3-dienes with hydroborane is one of the most straightforward and atom-economic routes to construct allylboronates and homoallylboronates. Although hydroboration of alkenes has been extensively studied in last decade [8], the highly selective hydroboration of 1,3-dienes remains underdeveloped [9]. Key challenges regarding catalytic hydroboration of 1,3-dienes arise from the difficulty in chemo- and regio-control, because the reaction could proceed through 1,2- or 1,4-hydroboration, and the boron atom could be incorporated into four possible positions in principle (Eq. (1)).



(1)

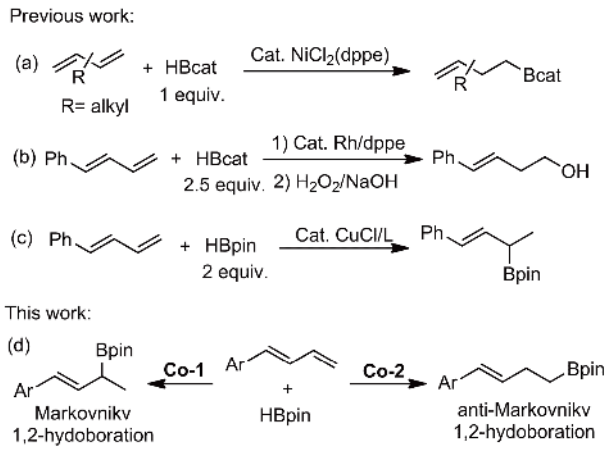
Elegant contributions have emerged in selective 1,4-hydroboration of 1,3-dienes for the synthesis of allylboranes under the influence of Pd [10a], Rh [10a], Fe [10b,10d], Ni [10c] catalysis. In contrast, examples of catalytic 1,2-hydroboration are relatively rare [11–14]. Zaidlewicz and coworkers [11] found that $NiCl_2$(dppe) effects anti-Markovnikov 1,2-hydroboration of alkyl-substituted 1,3-dienes with catecholborane (HBcat) for the synthesis of homoallylboronates, but this catalytic system is inactive for aryl-substituted 1,3-butadiene (Scheme 1(a)). While a moderate regioselectivity in favor of the anti-Markovnikov product was obtained in (dppe)Rh(I)-catalyzed 1,2-hydroboration of 1-phenyl-1,3-butadiene with HBcat (Scheme 1(b)) [12], the same substrate underwent Markovnikov 1,2-addition with 2 equiv. of pinacolborane (HBpin) using copper as the catalyst to give allyborane (Scheme 1(c)) [13]. Although excessive

†These authors contributed equally to this work.
*Corresponding authors (email: guixia@sioc.ac.cn; huangzh@sioc.ac.cn)

amounts of hydroborane were used and only one or two examples were given, these work demonstrated the possibility of controlling the regioselectivity of 1,2-hydroboration by the choice of an appropriate metal catalyst. In addition to hydroborane, diboron B_2pin_2 has also be used as the boron source in copper-catalyzed hydroboration of 1,3-dienes, wherein ROBpin is produced as the waste [13,15]. In this context, it is desired to develop practical and atom-economical catalytic systems for regiodivergent 1,2-hydroboration.

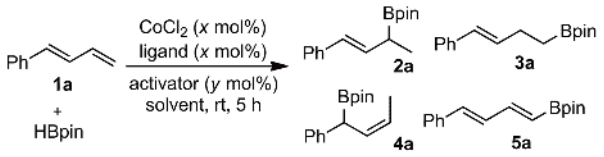
Our group [16] has been interested in developing catalysis based on well-defined non-precious metal complexes. In our previous work, we developed iminopyridine iron complexes for 1,4-hydroboration of 1-substituted 1,3-dienes with HBpin, affording secondary (*Z*)-allylboronates selectively [10d]. Herein, we disclose the regiodivergent 1,2-hydroboration of 1,3-dienes enabled by well-defined cobalt complexes with iminopyridine or FOXAP (FOXAP=(*S*)-1-(diphenylphosphino)-2-[(*S*)-4-isopropyloxazolin-2-yl]ferrocene) ligands, allowing for the convenient synthesis of allylboronates and homoallylboronates selectively (Scheme 1(d)).

Our initial investigations focused on the identification of suitable ligands for cobalt catalyzed hydrobotation of 1-phenyl-1,3-butadiene (**1a**) with HBpin. A series of bidentate N,N or N,P ligands were screened and the results are summarized in Table 1. With 5.0 mol% of $NaBEt_3H$ as the activator, the cobalt catalysts were generated *in situ* from cobalt chloride and the ligands. The reaction of **1a** with HBpin in tetrahydrofuran (THF) in the presence of dioxazoline ligand **L1** and cobalt chloride provided 1,2-Markovnikov hydroboration product allylboronate **2a** in a low yield (25%, entry 1) after 5 h at room temperature, along with small amounts of 1,2-anti-Markovnikov hydroboration product **3a**, 1,4-hydroboration product **4a** and a decent amount of the dehydrogenative borylation product **5a** (25%). The reaction with **L2** as the ligand gave a similar yield of **2a** (entry 2). The runs

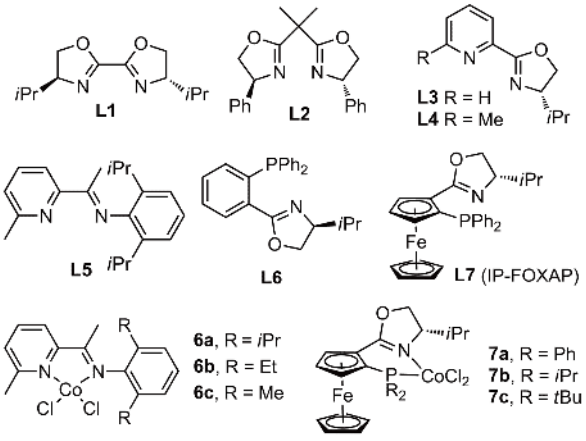


Scheme 1 Catalytic 1,2-hydroboration of 1,3-dienes with hydroborane.

Table 1 Evaluation of cobalt catalysts for diene hydroboration [a]



Entry	Co precusor (mol%)	Activator (mol%)	Solvent	Yield (%)			
				2a	**3a**	**4a**	**5a**
1	$CoCl_2$/**L1** (5)	$NaBEt_3H$ (10)	THF	25	2	8	25
2	$CoCl_2$/**L2** (5)	$NaBEt_3H$ (10)	THF	26	3	0	7
3	$CoCl_2$/**L3** (5)	$NaBEt_3H$ (10)	THF	46	5	0	7
4	$CoCl_2$/**L4** (5)	$NaBEt_3H$ (10)	THF	40	0	20	1
5	$CoCl_2$/**L5** (5)	$NaBEt_3H$ (10)	THF	53	5	1	15
6	$CoCl_2$/**L5** (5)	$NaBEt_3H$ (10)	Toluene	44	0	0	4
7	$CoCl_2$/**L5** (5)	$NaBEt_3H$ (10)	Et_2O	56	5	0	12
8	$CoCl_2$/**L5** (5)	CH_3MgCl (10)	Et_2O	56	2	0	12
9	$CoCl_2$/**L5** (5)	Mg(10)	Et_2O	76	0	0	6
10	$CoCl_2$/**L6** (5)	$NaBEt_3H$ (10)	THF	6	76	0	0
11	$CoCl_2$/**L7** (5)	$NaBEt_3H$ (10)	THF	4	79	0	0
12 [b]	**6a** (2)	Mg (5)	Et_2O	83	trace	0	0
13 [b]	**6b** (2)	Mg (5)	Et_2O	62	4	3	7
14 [b]	**6c** (2)	Mg (5)	Et_2O	54	7	5	10
15 [c]	**7a** (1)	$NaBEt_3H$ (2)	THF	trace	95	0	0
16 [c]	**7b** (1)	$NaBEt_3H$ (2)	THF	8	75	3	0
17 [c]	**7c** (1)	$NaBEt_3H$ (2)	THF	17	64	7	0



a) Reaction conditions: **1a** (0.2 mmol), HBpin (1.0 equiv.), $CoCl_2$ (5.0 mol%), ligand (5.0 mol%), activator (10 mol%) in solvent (1 mL). Yields were determined by gas chromatography (GC) analysis with mesitylene as an internal standard. b) **1a** (1.0 mmol), HBpin (1.0 equiv.), **7a** (2.0 mol%), Mg (5.0 mol%), in Et_2O (2 mL) at r.t. c) **1a** (0.5 mmol), HBpin (1.0 equiv.), **8a** (1.0 mol%), $NaBEt_3H$ (2.0 mol%), in THF (1 mL) at r.t.

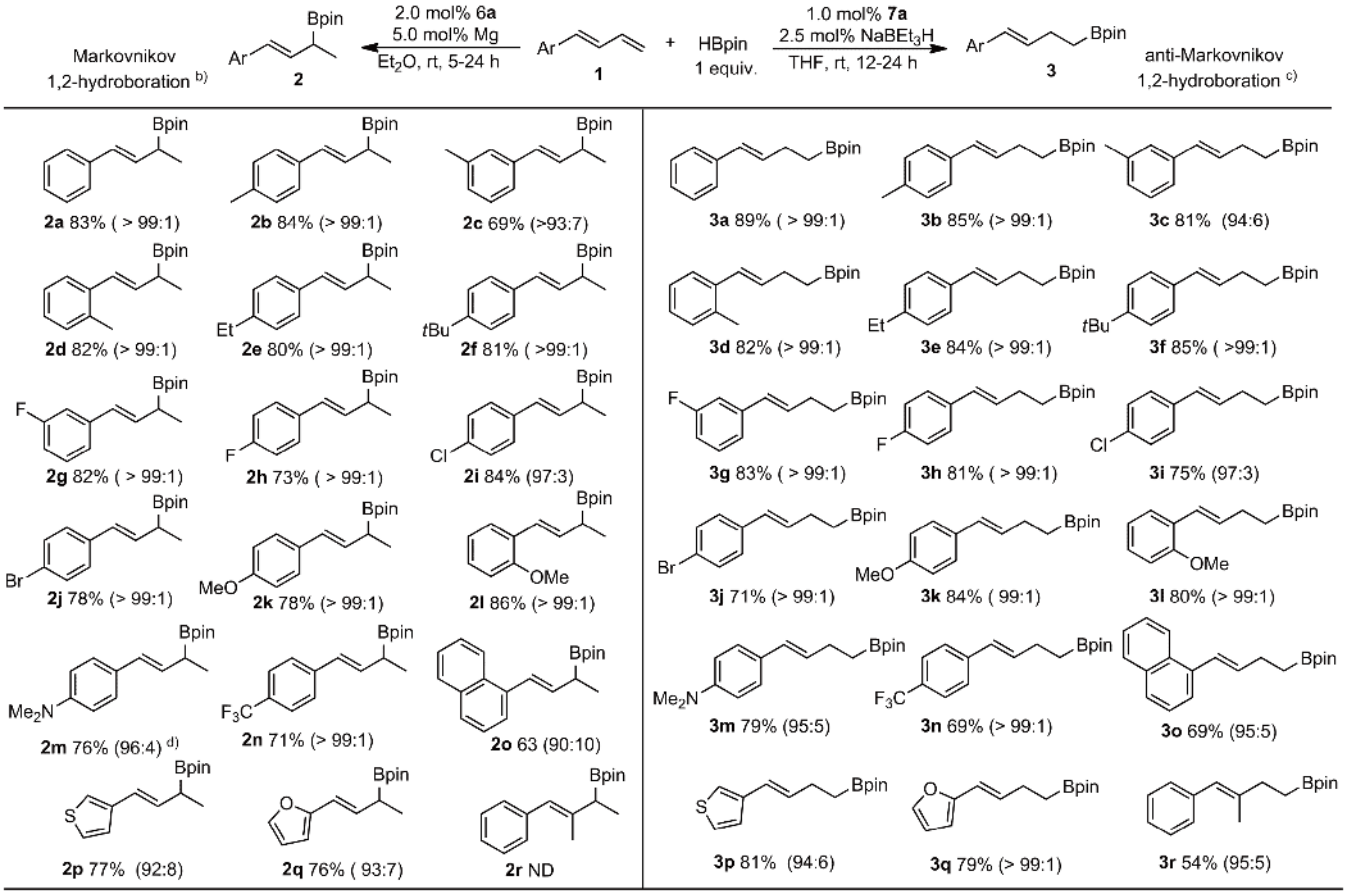
with pyridine-oxazoline ligands (**L3** and **L4**) gave moderate yields of **2a** as the major product (entries 3 and 4) [17]. Delightfully, the use of iminopyridine ligand **L5** increased the yield of **2a** to 53% with small amount of other side products (entry 5). The reaction conditions were further optimized under the $CoCl_2$/**L5** system. The runs in toluene and diethylether formed **2a** in 44% and 56% yield, respectively (entries 6 and 7). Additionally, the activator influenced

the reaction outcomes (entries 7–9). Among the activators screened, Mg gave the best yield (76%) of **2a** with very high regioselectity (>99:1, **2a**:**3a**) and no 1,4-hydroboration product **4a** was detected (entry 9). Remarkably, the regioselectivity could be switched when phosphine-oxazoline ligands **L6** and **L7** were employed, affording 1,2-anti-Markovnikov hydroboration product homoallylboronate **3a** as the major product with good yields and high regioselectivity (entries 10 and 11).

To further improve the reaction efficiency and selectivity, a series of well-defined cobalt dichloride complexes bearing imino-pyridine ligand or FOXAP ligand were synthesized and fully characterized. The catalytic properties of these complexes (**6a**–**6c**, **7a**–**7c**) were examined in the reaction of 1-phenyl-1,3-butadiene with HBpin. To our satisfaction, the well defined Co-complexes **6a** and **7a** led to enhanced efficiency in terms of yield and selectivity (Table 1, entries 12 and 15), compared with the corresponding $CoCl_2$/ligand system (entries 9 and 11). Co complexes **6a**–**6c** bearing the iminopyridine ligand favoured 1,2-hydroboration with Markovnikov selectivity (entries 12–14) and the most sterically hindered Co-complex **6a** exhibited highest activity, generating allylboronate **2a** in 83% yield with >99:1 regioselectivity (entry 12). The yield and regioselectivity for **2a** decreased as the size of iminopyridine ligand decreased. Swtiching of precatalyst **6a** to less hindered variants **6b** and **6c** resulted in detrimental effects on both yield and regioselectivity (entries 13 and 14). On the other hand, precatalysts **7a**–**7c** with FOXAP ligand favoured the anti-Markovnikov 1,2-hydroboration (entries 15–17), furnishing homoallyboronate **3a** as the major product. The substitution on the FOXAP ligand also plays pronounced influeneces on the reaction: while complex **7a** with phenyl group on phosphine atom offered 95% yield of **3a** with 99:1 regioselectivity (entry 15), the substitution of phenyl with *i*Pr or *t*Bu resulted in diminished yield and regioselectivity (entries 16 and 17).

With the optimized conditions in hand, the scope and limitation of the cobalt catalyzed regiodivergent 1,2-hydroboration were next evaluated as shown in Table 2. The imino-pyridine ligated cobalt complex **6a** is effective for Markovnikov 1,2-hydroboration of various aryl substituted 1,3-dienes to furnish allyboronates selectively. In most cases, these reactions proceeded to completion within 12 h at 25 °C using 2.0 mol% of **6a**, delivering allylboronates in good

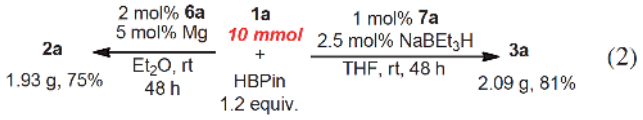
Table 2 Co-catalyzed regiodivergent 1,2-hydroboration of 1,3-dienes [a)]



a) Isolated yields were given. The ratio of regioselectivty in the bracket (**2a**:**3a** or **3a**:**2a**) was determined by GC analysis. b) **1** (1.0 mmol), HBpin (1.0 equiv), **6a** (2.0 mol %), Mg (5.0 mol %), in Et_2O (2 mL) at rt. c) **1** (0.5 mmol), HBpin (1.0 equiv), **7a** (1.0 mol %), $NaBEt_3H$ (2.0 mol %) in THF (1 mL) at rt. d) GC yield, mesitylene as internal standard.

yields with high regioselectivity. Substrates with both electron-donating or -withdrawing groups were readily hydroborated, and the position of the substituent on the aryl group did not influenece the reaction significantly. A variety of commonly encountered functional groups, such as the bromo, fluoro, trifluoromethyl, methoxy and amino group could be well tolerated. However, substrates bearing some reducible groups such as ester and nitro substituents were unreactive under reaction conditions. Naphthyl 1,3-diene could be applicable for 1,2-hydroboration to afford the corresponding allylboronate **2o** in 63% yield with 90:10 regioselectivity. In addition, the protocol also allows for the selective 1,2-hydroboration of heterocycle-containing substrates, as demonstrated by the isolation of **2p**, and **2q** in good yields with high regioselectivity. Unfortunately, this iminopyridine Co system was not effective for the hydroboration of 2-substituted 1,3-diene **1r**.

Noteworthily, with FOXAP-cobalt complex **7a** as the precatalyst, a variety of 1-aryl-1,3-dienes readily reacted with HBPin at ambient temperature with low catalyst loadings (1 mol%) to afford homoallylboronates in good yields (69%–89%) with high regioselectivity (>94:6). The electronic and steric properties of the aryl groups in 1,3-dienes have little influence on this Co-catalyzed anti-Markovnikov 1,2-hydroboration. Although unreactive under the iminopyridine Co system, 2-substituted 1,3-diene **1r** underwent selective 1,2-hydroboration smoothly under FOXAP-cobalt catalysis, delivering the desired homoallylboronate **3r** in 54% yield with 95:5 regioselectivity. To be note, the current method is not suitable for selective hydroboration of alkyl substituted 1,3-dienes, which produces a complex mixture consisting of several hydroboration and dehydrogenative borylation products.



(2)

Finally, we were pleased to find that the Co-catalyzed regiodivergent 1,2-hydroborations could be conducted on gram-scale (Eq. (2)). While the allylboronate **2a** could be isolated in 75% yield (1.93 g) from 10 mmol of **1a** with a relatively long reaction time (48 h), the large-scale preparation of homoallylboronate **3a** also required 48 h to gain a high isolated yield (2.09 g, 81%).

In summary, we have developed a regiodivergent 1,2-hydroboration of 1-aryl-1,3-dienes controlled by different cobalt catalysts, furnishing allyboronates and homoallylboronates with high efficiency and selectivity. While the iminopyridine ligated cobalt system is selective for Markovnikov 1,2-hydroboration, the IP-FOXAP-Co catalysis facilitates the complementary anti-Markonikov 1,2-hydroboration selectively. Both systems feature mild conditions, high level of regioselectivity, low catalyst loadings and the efficient access to synthetically useful products. Further studies on the asymmetric hydroboration of 1,3-dienes are currently underway in this laboratory.

Acknowledgements This work was supported by the National Key R&D Program of China (2016YFA0202900, 2015CB856600), the National Natural Science Foundation of China (21825109, 21432011, 21572255, 21732006), Chinese Academy of Sciences (XDB20000000, QYZDB-SSW-SLH016), and Science and Technology Commission Shanghai Municipality (17JC1401200).

Conflict of interest The authors declare that they have no conflict of interest.

Supporting information The supporting information is available online at http://chem.scichina.com and http://link.springer.com/journal/11426. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

1 (a) Kennedy JWJ, Hall DG. *Angew Chem Int Ed*, 2003, 42: 4732–4739; (b) Diner C, Szabó KJ. *J Am Chem Soc*, 2017, 139: 2–14
2 (a) Sugiura M, Hirano K, Kobayashi S. *J Am Chem Soc*, 2004, 126: 7182–7183; (b) Lou S, Moquist PN, Schaus SE. *J Am Chem Soc*, 2007, 129: 15398–15404; (c) Sasaki Y, Zhong C, Sawamura M, Ito H. *J Am Chem Soc*, 2010, 132: 1226–1227
3 (a) Rauniyar V, Zhai H, Hall DG. *J Am Chem Soc*, 2008, 130: 8481–8490; (b) Althaus M, Mahmood A, Suarez JR, Thomas SP, Aggarwal VK. *J Am Chem Soc*, 2010, 132: 4025–4028; (c) Hesse MJ, Essafi S, Watson CG, Harvey JN, Hirst D, Willis CL, Aggarwal VK. *Angew Chem*, 2014, 126: 6259–6263; (d) García-Ruiz C, Chen JLY, Sandford C, Feeney K, Lorenzo P, Berionni G, Mayr H, Aggarwal VK. *J Am Chem Soc*, 2017, 139: 15324–15327
4 Shao W, Kaldas SJ, Yudin AK. *Chem Sci*, 2017, 8: 4431–4436
5 (a) Chausset-Boissarie L, Ghozati K, LaBine E, Chen JLY, Aggarwal VK, Crudden CM. *Chem Eur J*, 2013, 19: 17698–17701; (b) Gerbino DC, Mandolesi SD, Schmalz HG, Podestá JC. *Eur J Org Chem*, 2009, 2009(23): 3964–3972; (c) Glasspoole BW, Ghozati K, Moir JW, Crudden CM. *Chem Commun*, 2012, 48: 1230–1232; (d) Sebelius S, Olsson VJ, Wallner OA, Szabó KJ. *J Am Chem Soc*, 2006, 128: 8150–8151; (e) Yamamoto Y, Takada S, Miyaura N. *Chem Lett*, 2006, 35: 704–705; (f) Yamamoto Y, Takada S, Miyaura N. *Chem Lett*, 2006, 35: 1368–1369; (g) Yamamoto Y, Takada S, Miyaura N, Iyama T, Tachikawa H. *Organometallics*, 2009, 28: 152–160; (h) Yang Y, Buchwald SL. *J Am Chem Soc*, 2013, 135: 10642–10645
6 Ryu I, Hirai A, Suzuki H, Sonoda N, Murai S. *J Org Chem*, 1990, 55: 1409–1410
7 (a) Burks HE, Kliman LT, Morken JP. *J Am Chem Soc*, 2009, 131: 9134–9135; (b) Farmer JL, Hunter HN, Organ MG. *J Am Chem Soc*, 2012, 134: 17470–17473; (c) Ishiyama T, Yamamoto M, Miyaura N. *Chem Commun*, 1996, 2073–2074; (d) Mao L, Bertermann R, Emmert K, Szabó KJ, Marder TB. *Org Lett*, 2017, 19: 6586–6589; (e) Mao L, Bertermann R, Rachor SG, Szabó KJ, Marder TB. *Org Lett*, 2017, 19: 6590–6593; (f) Olsson VJ, Sebelius S, Selander N, Szabó KJ. *J Am Chem Soc*, 2006, 128: 4588–4589; (g) Sebelius S, Olsson VJ, Szabó KJ. *J Am Chem Soc*, 2005, 127: 10478–10479; (h) Zhou Y, Wang H, Liu Y, Zhao Y, Zhang C, Qu J. *Org Chem Front*, 2017, 4: 1580–1585
8 For some reviews, see: (a) Burgess K, Ohlmeyer MJ. *Chem Rev*, 1991, 91: 1179–1191; (b) Beletskaya I, Pelter A. *Tetrahedron*, 1997, 53: 4957–5026; (c) Semba K, Fujihara T, Terao J, Tsuji Y. *Tetrahedron*, 2015, 71: 2183–2197; (d) Zuo Z, Wen H, Liu G, Huang Z. *Synlett*, 2018, 29: 1421–1429; (e) Chen J, Guo J, Lu Z. *Chin J Chem*, 2018, 36: 1075–1109
9 Brown HC, Bhat KS. *J Org Chem*, 1986, 51: 445–449

10 (a) Satoh M, Nomoto Y, Miyaura N, Suzuki A. *Tetrahedron Lett*, 1989, 30: 3789–3792; (b) Wu JY, Moreau B, Ritter T. *J Am Chem Soc*, 2009, 131: 12915–12917; (c) Ely RJ, Morken JP. *J Am Chem Soc*, 2010, 132: 2534–2535; (d) Cao Y, Zhang Y, Zhang L, Zhang D, Leng X, Huang Z. *Org Chem Front*, 2014, 1: 1101–1106
11 Zaidlewicz M, Meller J. *Tetrahedron Lett*, 1997, 38: 7279–7282
12 Matsumoto Y, Hayashi T. *Tetrahedron Lett*, 1991, 32: 3387–3390
13 Semba K, Shinomiya M, Fujihara T, Terao J, Tsuji Y. *Chem Eur J*, 2013, 19: 7125–7132
14 (a) Obligacion JV, Chirik PJ. *J Am Chem Soc*, 2013, 135: 19107–19110; (b) Ibrahim AD, Entsminger SW, Fout AR. *ACS Catal*, 2017, 7: 3730–3734
15 (a) Sasaki Y, Zhong C, Sawamura M, Ito H. *J Am Chem Soc*, 2010, 132: 1226–1227; (b) Liu Y, Fiorito D, Mazet C. *Chem Sci*, 2018, 9: 5284–5288
16 For some selected examples, see: (a) Peng D, Zhang Y, Du X, Zhang L, Leng X, Walter MD, Huang Z. *J Am Chem Soc*, 2013, 135: 19154–19166; (b) Zhang L, Peng D, Leng X, Huang Z. *Angew Chem Int Ed*, 2013, 52: 3676–3680; (c) Zhang L, Zuo Z, Leng X, Huang Z. *Angew Chem Int Ed*, 2014, 53: 2696–2700; (d) Zhang L, Zuo Z, Wan X, Huang Z. *J Am Chem Soc*, 2014, 136: 15501–15504; (e) Du X, Zhang Y, Peng D, Huang Z. *Angew Chem Int Ed*, 2016, 55: 6671–6675; (f) Du X, Huang Z. *ACS Catal,* 2017, 7: 1227–1243; (g) Wen H, Zhang L, Zhu S, Liu G, Huang Z. *ACS Catal,* 2017, 7: 6419–6425; (h) Wen H, Wan X, Huang Z. *Angew Chem Int Ed,* 2018, 57: 6319–6323; (i) Wen H, Wang K, Zhang Y, Liu G, Huang Z. *ACS Catal,* 2019, 9, doi: 10.1021/acscatal.8b04481
17 When chiral ligands **L2**, **L3**, **L4** were used, the ee values of the allylboronate product **2a** were checked by chiral HPLC, indicating low enantioselectity with 2% ee for **L2**, 3% ee for **L3** and 22% ee for **L4**