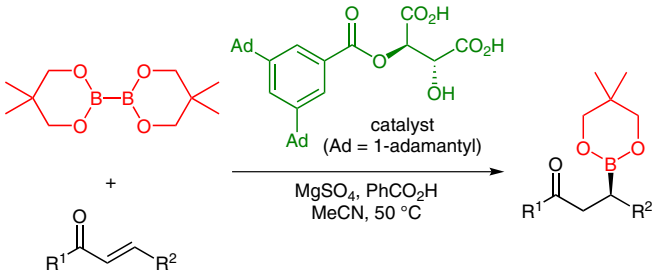
Synthesis M. Sugiura et al. Special Topic

Conjugate Addition of Diboron Catalyzed by *O*-Monoacyltartaric Acids

Masaharu Sugiura*
Wakoto Ishikawa
Yukinobu Kuboyama
Makoto Nakajima

Graduate School of Pharmaceutical Sciences, Kumamoto University, 5-1 Oe-honmachi, Chuo-ku, Kumamoto 862-0973, Japan
msugiura@kumamoto-u.ac.jp



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Abstract *O*-3,5-Di(adamantan-1-yl)benzoyltartaric acid catalyzes the conjugate addition of bis(neopentyl glycolato)diboron to α,β-unsaturated ketones with good enantioselectivity. The addition of magnesium sulfate as a dehydrating agent and benzoic acid as a co-catalyst was found to be effective.

Key words organocatalysts, conjugate addition, diboron

The enantioselective conjugate addition of diboron reagents to α,β-unsaturated carbonyl compounds is a useful method for the construction of a chiral carbon center attached to a boryl group.[1] The boryl group can be converted to a hydroxyl group without loss of optical purity,[2] or used for carbon–carbon bond formation.[3] While several asymmetric transition metal (copper,[4] rhodium,[5] nickel, and palladium[6]) catalysts have been developed, only a few organocatalysts [chiral N-heterocyclic carbenes (NHC),[7] chiral phosphines,[8] and a prolinol derivative with achiral NHC[9]] have been described.

We have reported earlier that *O*-monoacyltartaric acids effectively catalyze the conjugate addition of boronic acids to α,β-unsaturated ketones (enones).[10] We therefore envisaged that other types of boron compounds could be activated by those chiral hydroxy acids as well and report here the results on the activation of diboron compounds.

Using catalyst **1a** from our previous work, which was effective for the conjugate addition of styrylboronic acid to enones,[10] the reaction of chalcone (**2a**) with various diborons **3** in toluene at room temperature was initially investigated (Table 1). The crude borated product was directly oxidized with sodium perborate[2] in order to evaluate the reaction regardless of the boryl group. To our delight, bis(neopentyl glycolato)diboron (**3a**) reacted at room temperature to provide good enantioselectivity, although the yield was moderate (Table 1, entry 1). The presence of the catalyst was indispensable because diboron **3a** did not react at all in its absence (entry 2). Unexpectedly, the addition of methanol, which was effective for the reaction of styrylboronic acid,[10] completely suppressed the reaction (entry 3). We thus speculated that water might inhibit the reaction as well. Indeed, addition of magnesium sulfate as a dehydrating agent effectively improved the chemical yield (entry 4). Although Na_2SO_4, $CaSO_4$, CaH_2, and molecular sieves were also tested, $MgSO_4$ afforded the best performance. Heating at 50 °C with $MgSO_4$ largely increased the yield with a slight loss of enantioselectivity (entry 5).

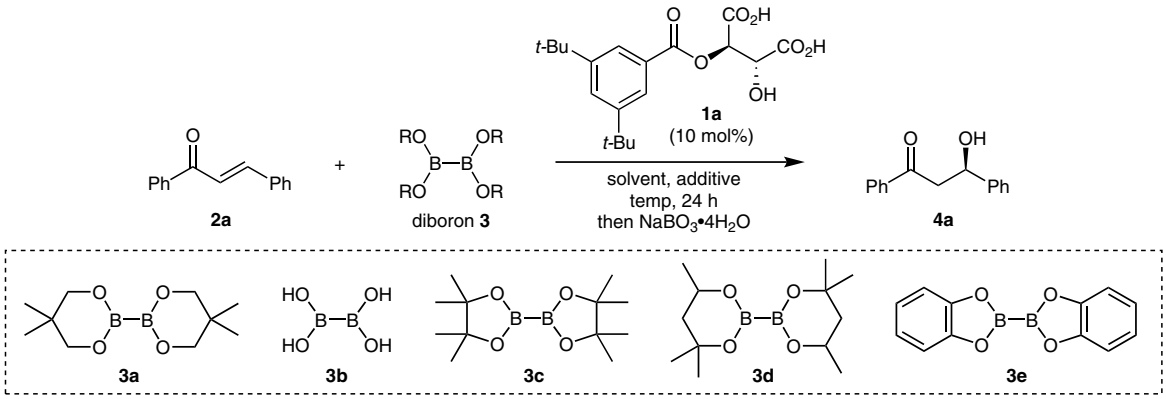
Under the conditions of entry 5, other diborons, tetrahydoxydiboron (**3b**), bis(pinacolato)diboron (**3c**), bis(hexylene glycolato)diboron (**3d**), and bis(catecholato)diboron (**3e**) were examined (entries 6–9). However, none was superior to neopentyl glycolate **3a**. Diboron **3b** showed low solubility under the reaction conditions. The low reactivity of diborons **3c** and **3d** bearing congested tertiary alcohols suggests that ligand exchange between the catalyst and a diol ligand attached to the boron atom is essential for the current catalysis.[11] The catechol ligand on **3e** might be too labile under the reaction conditions.

With diboron **3a**, the reaction parameters were further optimized. Changing the solvent from toluene to dichloromethane, ethyl acetate, or diethyl ether decreased both the yield and selectivity. Acetonitrile also lowered the yield, but improved the selectivity (entry 10). In combination with acetonitrile as solvent, benzoic acid was added as a promoter of the ligand exchange process, which increased the yield (entry 11). Furthermore, use of a new catalyst, *O*-3,5-di(adamantan-1-yl)benzoyltartaric acid (**1b**) with $MgSO_4$ and benzoic acid in acetonitrile largely improved the yield and selectivity (entry 12).

Under the optimized conditions (Table 1, entry 12), the reactions of other enones were investigated (Table 2). Although the reaction was found to be quite sensitive to the enone structure, good enantioselectivities were obtained in most cases. Higher reactivity was observed with an electron-rich aromatic substituent at the carbonyl β-position (entry 3).[12]

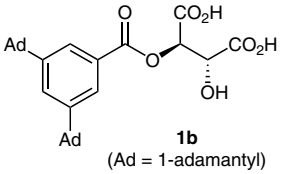
Without the oxidative workup, the β-boryl ketone **5a** could be isolated by chromatography on silica gel (Scheme 1). The enantiomeric excess of **5a** indicated that oxidation of the (neopentyl glycolato)B–C bond proceeded without loss of optical purity. The enantioselective synthesis of neopentyl glycolates of β-boryl ketones has not been reported before.

Table 1 Screening of Diborons **3** and Optimization of the Reaction Conditions[a]



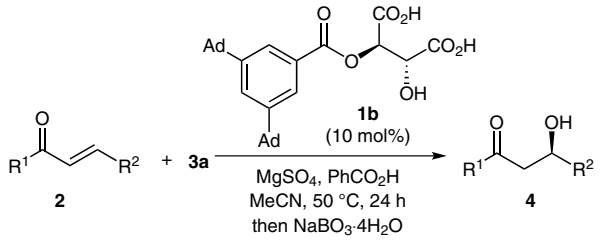
Entry	3	Additive	Temp (°C)	Yield (%)[b]	ee (%)[c]
1	**3a**	–	r.t.	31	55
2[d]	**3a**	–	r.t.	0	–
3	**3a**	MeOH[e]	r.t.	0	–
4	**3a**	$MgSO_4$[f]	r.t.	44	55
5	**3a**	$MgSO_4$[f]	50	72	50
6	**3b**	$MgSO_4$[f]	50	0	–
7	**3c**	$MgSO_4$[f]	50	7	36
8	**3d**	$MgSO_4$[f]	50	29	29
9	**3e**	$MgSO_4$[f]	50	0	–
10[g]	**3a**	$MgSO_4$[f]	50	40	57
11[g]	**3a**	$MgSO_4$[f] $PhCO_2H$[h]	50	53	58
12[g,i]	**3a**	$MgSO_4$[f] $PhCO_2H$[h]	50	68	78

[a] Unless otherwise noted, the reaction was carried out using chalcone **2a** (0.3 mmol), diboron **3** (0.36 mmol), and catalyst **1a** (10 mol%) in toluene (1 mL) for 24 h.
[b] Isolated yields of **4a**.
[c] Determined by HPLC analysis.
[d] Without catalyst.
[e] Amount of additive: 0.72 mmol.
[f] Amount of additive: 90 mg.
[g] In MeCN instead of toluene.
[h] Amount of additive: 0.36 mmol.
[i] With catalyst **1b** instead of **1a**.



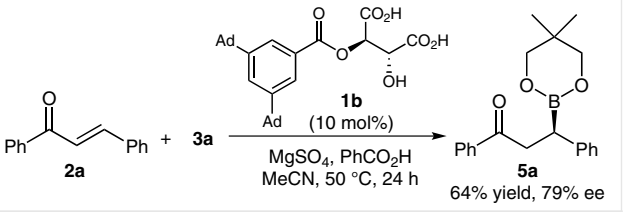
1b
(Ad = 1-adamantyl)

Table 2 Reaction of Various Enones **2** with Diboron **3a** Catalyzed by Catalyst **1b**[a]



Entry	R^1	R^2	4	Yield (%)[b]	ee (%)[c]
1	Ph	Ph	**4a**	68	78
2	Ph	4-BrC_6H_4	**4b**	33	70
3	Ph	4-$MeOC_6H_4$	**4c**	78	76
4	Ph	1-naphthyl	**4d**	42	49
5	Ph	*i*-Pr	**4e**	8	71
6	4-BrC_6H_4	Ph	**4f**	36	75
7	4-$MeOC_6H_4$	Ph	**4g**	28	79

[a] The reaction was carried out with enone **2** (0.3 mmol), diboron **3a** (0.36 mmol), catalyst **1b** (10 mol%), $MgSO_4$ (90 mg), and benzoic acid (0.36 mmol) in MeCN (1 mL) at 50 °C for 24 h.
[b] Isolated yields of ketone **4**.
[c] Determined by HPLC analysis.



Scheme 1 Reaction without oxidative workup

For the organocatalytic methods that use N-heterocyclic carbenes[8,10] or phosphines,[9] activation of the diboron species by these nucleophilic catalysts (to generate tetravalent boron intermediates) has been suggested. Meanwhile, the current catalyst system likely proceeds through a ligand exchange mechanism (generation of chiral trivalent boron species).[11] To discern this possibility, a stoichiometric reaction of diboron **3a** with catalyst **1a** in CD_3CN at 50 °C in the presence of $MgSO_4$ was performed and monitored by ^1H and ^{11}B NMR spectroscopy.[13] However, no significant change was observed.[14,15] This step might be energetically unfavorable. Further study is necessary to clarify the precise mechanism.

In summary, we have demonstrated that *O*-monoacyltartaric acids catalyze the conjugate addition of diborons to α,β-unsaturated ketones with good enantioselectivity. Further improvements and applications are now under investigation.

Catalyst **1a** was prepared according to our previous report.[10a] Bis(neopentyl glycolate)diboron (**3a**), tetrahydroxydiboron (**3b**), bis(pinacolate)diboron (**3c**), bis(hexylene glycolate)diboron (**3d**), and bis(catecholate)diboron (**3e**) were purchased from Boron Molecular or Tokyo Chemical Industry and used without purification. Toluene (>99%) was purchased from Nacalai Tesque, Inc. and stored over 4 Å MS pellets. Anhydrous MeCN was purchased from Wako Pure Chemical Industries and used without purification.

Melting points were measured with Yanaco MP-J3 and are uncorrected. ^1H and $^{13}C\{^1H\}$ NMR spectra were recorded in $CDCl_3$ or DMSO-d_6 on a JEOL JNM-ECX 400 spectrometer. TMS (δ = 0) and $CDCl_3$ (δ = 77.0) served as internal standards for ^1H and ^{13}C NMR, respectively. $^{11}B\{^1H\}$ NMR spectra were recorded in $CDCl_3$ or CD_3CN on a Bruker Avance 600 spectrometer. $BF_3{\cdot}OEt_2$ (δ = 0 ppm) in a glass capillary was used as an external standard for ^{11}B NMR. IR spectra were recorded on PerkinElmer Frontier spectrometer. Mass spectra were recorded on a JEOL JMS-700MStation mass spectrometer. Optical rotations were measured on a JASCO P-1010 polarimeter. High-performance liquid chromatography (HPLC) was performed on JASCO PU-2080Plus and UV-2075Plus instruments. TLC analysis was carried out using Merck silica gel plates. Visualization was accomplished with UV light, phosphomolybdic acid and/or anisaldehyde. Column chromatography was performed using Kanto Chemical Silica Gel 60N (spherical, neutral, 63–210 μm). The reactions under anhydrous conditions were carried out using oven- and heating gun-dried glassware under argon atmosphere.

Dibenzyl (*R*,*R*)-*O*-3,5-Di(adamantan-1-yl)benzoyltartrate

To a solution of dibenzyl (*R*,*R*)-tartrate (356.8 mg, 1.08 mmol) and 3,5-di(adamantan-1-yl)benzoic acid[13] (281.2 mg, 0.72 mmol) in anhydrous CH_2Cl_2 (7.2 mL) were added 1-ethyl-3-(3′-dimethylaminopropyl)carbodiimide hydrochloride (EDC·HCl; 151.8 mg, 0.792 mmol) and DMAP (8.8 mg, 0.072 mmol) at 0 °C. The mixture was stirred at r.t. for 17.5 h and evaporated. The residue was purified by silica gel column chromatography [SiO_2 16 g, hexane–CH_2Cl_2 (1:1), then CH_2Cl_2 only] to give the title compound as a viscous oil; yield: 213.7 mg (42%); $[\alpha]_D^{19}$ +20.0 (*c* 1.360, $CHCl_3$).

IR (ATR): 2903, 2849, 1728, 1599, 1455, 1194, 1123 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.77 (d, *J* = 1.9 Hz, 2 H, ArH), 7.61 (t, *J* = 1.9 Hz, 1 H, ArH), 7.37–7.29 (m, 5 H, C_6H_5), 7.22–7.17 (m, 2 H, C_6H_5), 7.14–7.08 (m, 3 H, C_6H_5), 5.69 (d, *J* = 2.3 Hz, 1 H, $ArCO_2CH$), 5.27 (s, 2 H, $PhCH_2$), 5.25 (d, *J* = 11.9 Hz, 1 H, $PhCH_2$), 5.13 (d, *J* = 11.9 Hz, 1 H, $PhCH_2$), 4.92 (dd, *J* = 7.8, 2.3 Hz, 1 H, HOC*H*), 3.31 (d, *J* = 7.8 Hz, 1 H, OH), 2.17–2.08 (m, 6 H, Ad), 1.98–1.86 (m, 12 H, Ad), 1.85–1.72 (m, 12 H, Ad).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 170.7, 166.5, 165.8, 151.2, 135.0, 134.3, 128.49, 128.32, 128.26, 128.03, 127.96, 127.1, 124.0, 73.3, 70.7, 68.1, 67.5, 43.1, 36.6, 36.4, 28.8.

MS (FAB+, $CHCl_3$ + NBA + NaI): *m*/*z* (%) = 725 (28, $[M + Na]^+$), 373 (100, $[Ad_2C_6H_3CO]^+$), 135 (71, $[Ad]^+$), 91 (93, $[Bn]^+$).

HRMS (FAB+, $CHCl_3$ + NBA + NaI): *m*/*z* $[M + Na]^+$ calcd for $C_{45}H_{50}O_7Na$: 725.3454; found: 725.3457.

(*R*,*R*)-*O*-3,5-Di(adamantan-1-yl)*benzoyltartaric* Acid (1b)

To a solution of dibenzyl (*R*,*R*)-*O*-3,5-di(adamantan-1-yl)benzoyltartrate (105.0 mg, 0.15 mmol) in EtOAc (4.5 mL) under argon atmosphere was added 10% Pd/C (10.5 mg). The argon was replaced by H_2 gas using a balloon and the reaction mixture was stirred at r.t. for 4 h.

The mixture was filtered through a Celite pad. The filtrate was concentrated under vacuum to give **1b** as a colorless solid; yield: 78.6 mg (quant); mp 186–189 °C; $[\alpha]_D^{19}$ –3.4 (*c* 1.28, EtOH).

IR (ATR): 2901, 2847, 1728, 1701, 1600, 1210, 1118, 765 cm^{-1}.

^1H NMR (400 MHz, DMSO-d_6): δ = 7.79 (s, 2 H), 7.66 (s, 1 H), 5.41 (s, 1 H), 4.64 (s, 1 H), 2.13–2.02 (m, 6 H), 1.95–1.83 (m, 12 H), 1.82–1.68 (m, 12 H).

^{13}C NMR (100 MHz, DMSO-d_6): δ = 172.1, 168.4, 165.7, 151.2, 128.6, 126.8, 123.3, 74.0, 70.1, 42.5, 36.07, 36.02, 28.3.

MS (FAB+, DMSO + NBA + NaI): *m*/*z* (%) = 567 (9, $[M + 2 Na]^+$), 545 (7, $[M + Na]^+$), 435 (20, $[M + H - 2 CO_2]^+$), 373 (39, $[Ad_2C_6H_3CO]^+$), 135 (100, $[Ad]^+$).

HRMS (FAB+, DMSO + NBA + NaI): *m*/*z* $[M + Na]^+$ calcd for $C_{31}H_{38}O_7Na$: 545.2515; found: 545.2516.

Conjugate Addition of Diboron 3a to Enone 2 Followed by Oxidation; General Procedure

A 20-mL, screw-top test tube charged with $MgSO_4$ (90 mg) was dried under vacuum using heating gun. After cooling to r.t. under argon atmosphere, an enone **2** (0.3 mmol), catalyst **1b** (15.7 mg, 10 mol%), and MeCN (1 mL) were successively added to the test tube. After stirring at r.t. for 30 min, bis(neopentyl glycolate)diboron (**3a**; 81.3 mg, 0.36 mmol) and benzoic acid (44.0 mg, 0.36 mmol) were added to the mixture. The mixture was heated at 50 °C for 24 h, cooled to r.t., and filtered through a Celite pad and washed with EtOAc (30 mL). The organic layer was concentrated under vacuum. The residue was diluted with THF–H_2O (3:1, 3 mL) and treated with $NaBO_3{\cdot}4H_2O$ (332 mg, 3.6 mmol). After stirring at r.t. for 2 h, the mixture was extracted with EtOAc (3 × 20 mL). The combined organic layers were washed with brine (20 mL), dried (Na_2SO_4), filtered, and concentrated under vacuum. The residue was purified by column chromatography on silica gel (hexane–EtOAc) to give the product **4** (Table 2). The enantiomeric excess of **4** was determined by HPLC analysis using a chiral stationary phase column.[13]

(*R*)-3-Hydroxy-1,3-diphenylpropan-1-one (4a)

According to the general procedure, the reaction of chalcone (**2a**; 62.5 mg, 0.3 mmol) and diboron **3a** (81.3 mg, 0.36 mmol) at 50 °C for 24 h gave the adduct **4a**; yield: 46.0 mg (68%); 78% ee (*R*). The spectral data were consistent with the literature.[16] The absolute configuration was determined to be *R* in comparison with HPLC data;[16] $[\alpha]_D^{18}$ +60.3 (*c* 0.765, $CHCl_3$) for 78% ee (*R*) {Lit.[16] $[\alpha]_D^{20}$ +60.8 (*c* 1.0, $CHCl_3$) for 88% ee (*R*)}.

HPLC: Chiralcel OD-H, hexane–*i*-PrOH (85:15), flow rate = 0.7 mL/min, UV detection at 254

nm) t_R = 13.2 min (*S*), 14.7 min (*R*).

The products **4a**–**g** are known. For further details, see the Supporting Information.

(*R*)-3-(5,5-Dimethyl-1,3,2-*dioxaborinan*-2-yl)-1,3-diphenylpropan-1-one (5a)

A 20-mL, screw-top test tube charged with $MgSO_4$ (90 mg) was dried under vacuum using heating gun. After cooling to r.t. under argon atmosphere, chalcone **2a** (63.0 mg, 0.3 mmol), catalyst **1b** (15.9 mg, 10 mol%), and MeCN (1 mL) were successively added to the test tube. After stirring at r.t. for 30 min, bis(neopentyl glycolate)diboron (**3a**; 81.5 mg, 0.36 mmol) and benzoic acid (43.5 mg, 0.36 mmol) were added to the mixture. The mixture was heated at 50 °C for 24 h, cooled to r.t., and filtered through a Celite pad and washed with EtOAc (30 mL). The filtrate was washed with sat. aq $NaHCO_3$ (2 × 10 mL) and brine (10 mL). The organic layer was dried (Na_2SO_4), filtered, and concentrated under vacuum. The residue was purified by column chromatography on silica gel (SiO_2 2.2 g, hexanes–EtOAc, 20:1 to 5:1) to give **5a** as a viscous oil; yield: 61.4 mg (64%); 79% ee (*R*); $[\alpha]_D^{19}$ –32.3 (*c* 1.565, $CHCl_3$).

HPLC: Chiralcel AD-H, hexane–*i*-PrOH (24:1), flow rate = 1.0 mL/min, UV detection at 240 nm, t_R = 10.4 min (*S*), 14.0 min (*R*).

IR (ATR): 1681, 1599, 1580, 1476, 1253, 750 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.98 (d, *J* = 7.3 Hz, 2 H, C_6H_5CO), 7.54 (t, *J* = 7.3 Hz, 1 H, C_6H_5CO), 7.44 (t, *J* = 7.3 Hz, 2 H, C_6H_5CO), 7.33–7.26 (m, 4 H, C_6H_5), 7.19–7.12 (m, 1 H, C_6H_5), 3.62 (d, *J* = 10.8 Hz, 2 H, 2 × OCHH), 3.59 (dd, *J* = 18.3, 11.0 Hz, 1 H, PhCOC*H*H), 3.55 (d, *J* = 10.8 Hz, 2 H, 2 × OCHH), 3.34 (dd, *J* = 18.3, 5.0 Hz, 1 H, PhCOCH*H*), 2.70 (dd, *J* = 11.0, 5.0 Hz, 1 H, CHB), 0.89 (s, 6 H, 2 × CH_3).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 200.4, 143.1, 136.8, 132.8, 128.42, 128.40, 128.10, 128.00, 125.3, 72.0, 42.6, 31.8, 30.5 (br), 21.8.

$^{11}B\{^1H\}$ NMR (192.5 MHz, $CDCl_3$): δ = 29.1.

HRMS (FAB+, $CHCl_3$ + NBA + NaI): *m*/*z* $[M]^+$ calcd for $C_{20}H_{23}BO_3Na$: 345.1642; found: 345.1643.

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Supporting Information

Supporting information for this article is available online at http://dx.doi.org/10.1055/s-0034-1378835.

References

(1) In addition to the conjugate addition, there are several enantioselective reactions for the construction of chiral carbon centers attached to boryl groups: borane or diboron additions to alkenes, allylic substitution, and diboron addition to imines. For a review on hydroboration, see: (a) Carroll, A.-M.; O'Sullivan, T. P.; Guiry, P. J. *Adv. Synth. Catal.* **2005**, *347*, 609. For a leading reference on diboration of alkenes, see: (b) Pelz, N. F.; Woodward, A. R.; Burks, H. E.; Sieber, J. D.; Morken, J. P. *J. Am. Chem. Soc.* **2004**, *126*, 16328. (c) Bonet, A.; Sole, C.; Gulyás, H.; Fernández, E. *Org. Biomol. Chem.* **2012**, *10*, 6621. For a leading reference on proto-boration, see: (d) Lee, Y.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2009**, *131*, 3160. For a leading reference on allylic substitution, see: (e) Ito, H.; Ito, S.; Sasaki, Y.; Matsuura, K.; Sawamura, M. *J. Am. Chem. Soc.* **2007**, *129*, 14856. For leading references on diboron addition to imines, see: (f) Beenen, M.; An, C.; Ellman, J. A. *J. Am. Chem. Soc.* **2008**, *130*, 6910. (g) Solé, C.; Gulyás, H.; Fernández, E. *Chem. Commun.* **2012**, *48*, 3769. (h) Zhang, S.-S.; Zhao, Y.-S.; Tian, P.; Lin, G.-Q. *Synlett* **2013**, *24*, 437. (i) Hong, K.; Morken, J. P. *J. Am. Chem. Soc.* **2013**, *135*, 9252.

(2) (a) Chinnusamy, T.; Feeney, K.; Watson, C. G.; Leonori, D.; Aggarwal, V. K. In *Comprehensive Organic Synthesis*, 2nd ed., Vol. 7; Knochel, P.; Molander, G. A., Eds.; Elsevier: Oxford, **2014**, 692–718. (b) Brown, H. C.; Snyder, C.; Rao, B. C. S.; Zweifel, G. *Tetrahedron* **1986**, *42*, 5505. (c) Kabalka, G. W.; Shoup, T. M.; Goudgaon, N. M. *Tetrahedron Lett.* **1989**, *30*, 1483.

(3) (a) Sandrock, D. L.; Jean-Gérard, L.; Chen, C.-y.; Dreher, S. D.; Molander, G. A. *J. Am. Chem. Soc.* **2010**, *132*, 17108. (b) Molander, G. A.; Wisniewski, S. R.; Hosseini-Sarvari, M. *Adv. Synth. Cat.* **2013**, *355*, 3037. (c) Zhang, C.; Yun, J. *Org. Lett.* **2013**, *15*, 3416.

(4) For leading references on enantioselective copper catalysis, see: (a) Lee, J.-E.; Yun, J. *Angew. Chem. Int. Ed.* **2008**, *47*, 145. (b) Lillo, V.; Prieto, A.; Bonet, A.; Díaz-Requejo, M. M.; Ramírez, J.; Pérez, P. J.; Fernández, E. *Organometallics* **2009**, *28*, 659. (c) O'Brien, J. M.; Lee, K.-s.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2010**, *132*, 10630. (d) Chen, I.-H.; Yin, L.; Itano, W.; Kanai, M.; Shibasaki, M. *J. Am. Chem. Soc.* **2009**, *131*, 11664. (e) Chen, I.-H.; Kanai, M.; Shibasaki, M. *Org. Lett.* **2010**, *12*, 4098. (f) Mantilli, L.; Mazet, C. *ChemCatChem* **2010**, *2*, 501. (g) Kobayashi, S.; Xu, P.; Endo, T.; Ueno, M.; Kitanosono, T. *Angew. Chem. Int. Ed.* **2012**, *51*, 12763. (h) Zhao, L.; Ma, Y.; Duan, W.; He, F.; Chen, J.; Song, C. *Org. Lett.* **2012**, *14*, 5780. (i) See also: Ito, H.; Yamanaka, H.; Tateiwa, J.; Hosomi, A. *Tetrahedron Lett.* **2000**, *41*, 6821.

(5) For enantioselective rhodium catalysis, see: (a) Shiomi, T.; Adachi, T.; Toribatake, K.; Zhou, L.; Nishiyama, H. *Chem. Commun.* **2009**, 5987. (b) Toribatake, K.; Zhou, L.; Tsuruta, A.; Nishiyama, H. *Tetrahedron* **2013**, *69*, 3551. (c) See also: Kabalka, G. W.; Das, N. C.; Das, S. *Tetrahedron Lett.* **2002**, *43*, 2323.

(6) For enantioselective nickel and palladium catalysis, see: (a) Lillo, V.; Geier, M. J.; Westcott, S. A.; Fernández, E. *Org. Biomol. Chem.* **2009**, *7*, 4674. (b) See also: Hirano, K.; Yorimitsu, H.; Oshima, K. *Org. Lett.* **2007**, *9*, 5031.

(7) (a) Wu, H.; Radomkit, S.; O'Brien, J. M.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2012**, *134*, 8277. (b) Radomkit, S.; Hoveyda, A. H. *Angew. Chem. Int. Ed.* **2014**, *53*, 3387. (c) See also: Lee, K.-s.; Zhugralin, A. R.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2009**, *131*, 7253.

(8) (a) Bonet, A.; Gulyas, H.; Fernández, E. *Angew. Chem. Int. Ed.* **2010**, *49*, 5130. (b) See also: Pubill-Ulldemolins, C.; Bonet, A.; Bo, C.; Gulyas, H.; Fernández, E. *Chem. Eur. J.* **2012**, *18*, 1121. (c) See also: Pubill-Ulldemolins, C.; Bonet, A.; Bo, C.; Gulyas, H.; Fernández, E. *Org. Biomol. Chem.* **2012**, *10*, 9677.

(9) Ibrahem, I.; Breistein, P.; Córdova, A. *Chem. Eur. J.* **2012**, *18*, 5175.

(10) (a) Sugiura, M.; Tokudomi, M.; Nakajima, M. *Chem. Commun.* **2010**, *46*, 7799. (b) Grimblat, N.; Sugiura, M.; Pellegrinet, S. *J. Org. Chem.* **2014**, *79*, 6754. (c) Sugiura, M.; Kinoshita, R.; Nakajima, M. *Org. Lett.* **2014**, *16*, 5172.

(11) For related catalytic mechanisms, see: (a) Wu, T. R.; Chong, J. M. *J. Am. Chem. Soc.* **2007**, *129*, 4908. (b) Wu, T. R.; Chong, J. M. *J. Am. Chem. Soc.* **2005**, *127*, 3244. (c) Turner, H. M.; Patel, J.; Niljianskul, N.; Chong, J. M. *Org. Lett.* **2011**, *13*, 5796. (d) Lou, S.; Moquist, P. N.; Schaus, S. E. *J. Am. Chem. Soc.* **2007**, *129*, 15398. (e) Bishop, J. A.; Lou, S.; Schaus, S. E. *Angew. Chem. Int. Ed.* **2009**, *48*, 4337. (f) Barnett, D. S.; Moquist, P. N.; Schaus, S. E. *Angew. Chem. Int. Ed.* **2009**, *48*, 8672. (g) Moquist, P. N.; Kodama, T.; Schaus, S. E. *Angew. Chem. Int. Ed.* **2010**, *49*, 7096. (h) Kodama, T.; Moquist, P. N.; Schaus, S. E. *Org. Lett.* **2011**, *13*, 6316. (i) Luan, Y.; Barbato, K. S.; Moquist, P. N.; Kodama, T.; Schaus, S. E. *J. Am. Chem. Soc.* **2015**, *137*, 3233. (j) Lundy, B. J.; Jansone-Popova, S.; May, J. A. *Org. Lett.* **2011**, *13*, 4958. (k) Le, P. Q.; Nguyen, T. S.; May, J. A. *Org. Lett.* **2012**, *14*, 6104. (l) Nguyen, T. S.; Yang, M. S.; May, J. A. *Tetrahedron Lett.* **2015**, *56*, 3337. (m) See also ref. 10.

(12) Recently, May et al. revealed a similar reactivity of enones in the BINOL-catalyzed conjugate addition of styrylboronates by systematic kinetic study, see ref. 11l.

(13) See the Supporting Information.

(14) In the previous study (ref. 10b), smooth complexation between catalyst **1a** and styrylboronic acid was observed.

(15) Participation of $MgSO_4$ in the enantio-determining step is unlikely, because the identical selectivity was observed even without $MgSO_4$ (Table 1, entries 1 and 4).

(16) Cheon, C. H.; Yamamoto, H. *Org. Lett.* **2010**, *12*, 2476.