Synthesis C. L. Peck et al. Special Topic

Copper(II)-Catalyzed β-Borylation of Acetylenic Esters in Water

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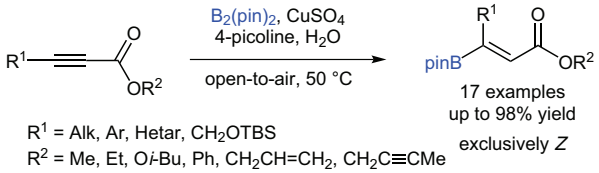

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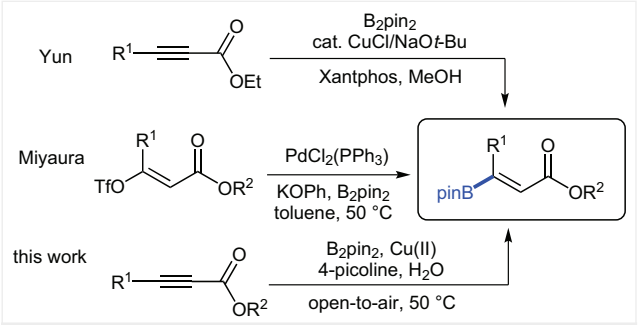
Abstract A method for the β-borylation of alkynoates has been developed. In the presence of bis(pinacolato)diboron and catalytic amounts of both copper(II) and 4-picoline, substituted alkynoates undergo borylation in a regio-, stereo-, and chemoselective fashion. The reaction is performed under mild conditions using water as solvent and open to the atmosphere to exclusively afford (*Z*)-β-boryl-α,β-unsaturated esters.

Key words boron, copper, stereoselectivity, hydroboration, alkynes

Vinylboronic acids and their derivatives are vital synthetic intermediates for the Suzuki–Miyaura cross-coupling reaction and they are synthetic handles for transformations into other functional groups.[1] Although borylation of alkynes serves as an efficient method to access vinylboronates, a limited number of methods for the borylation of alkynoates have been reported (Scheme 1).[2] In 2003, Miyaura and co-workers reported a palladium-catalyzed cross-coupling of vinyl triflates to afford β-boryl-α,β-unsaturated carbonyl compounds.[3] Subsequently, Yun and co-workers[4] disclosed copper(I)-catalyzed borylation conditions employing bis(pinacolato)diboron (B_2pin_2) as the boron source.[5] Some of these methods, however, have shortcomings ranging from limited substrate scope to poor *E*- and *Z*-stereoselectivity. Furthermore, the reactions must be conducted under inert atmospheric conditions because of the air- and moisture-sensitivity of the catalytic system.

In recent years, synthetic protocols that utilize boronic acid derivatives and employ environmentally friendly conditions have been reported, eliminating the necessity for organic solvents.[6] In contrast, complementary processes that generate boronic acid derivatives using copper as a catalyst in an aqueous environment are emerging.[7] Our laboratory previously reported a Cu(II)-catalyzed borylation protocol of α,β-unsaturated esters and ketones using water as the solvent in open-air.[8] Because of our interest in this area, we aimed to develop a catalytic system that could be used to conduct borylation reactions in aqueous media. Herein, we disclose an efficient and simple β-borylation method for alkynoates that afford β-boryl-α,β-unsaturated esters in good to excellent yield using an aqueous Cu(II)-catalyst system. In addition to broad substrate scope, the protocol yields exclusively *Z*-products in a chemoselective fashion.

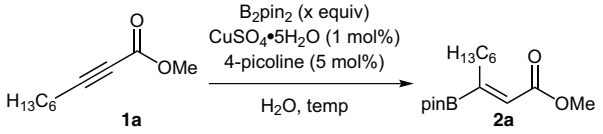


Scheme 1 Strategies toward β-boryl-α,β-unsaturated esters

We initiated our investigations by employing conditions used for borylations of α,β-unsaturated compounds (Table 1).[8] Methyl non-2-ynoate (**1a**) served as the model substrate because of its borderline aqueous solubility. Fortunately, standard conditions afforded vinyl boronate **2a** in 59% yield (entry 1). Nuclear Overhauser effect (NOE) studies indicated exclusive formation of the *Z*-product. Increase in reaction time did not significantly affect the reaction yield (entry 2). However, changing the number of equivalents of B_2pin_2 to 1.5 and increasing the temperature resulted in improved reaction yields (entries 3–6). The screening

study revealed that B_2pin_2 (1.5 equiv), $CuSO_4$ (1 mol%), and 4-picoline (5 mol%) in water at 50 °C were the optimal conditions.

Table 1 Screening of Reaction Conditions



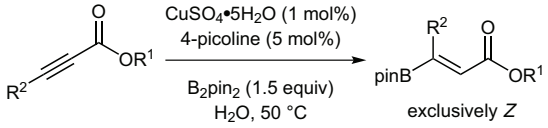
Entry	Time (h)	B_2pin_2 (equiv)	Temp. (°C)	Yield (%)[a]
1	4	1.3	r.t.	59
2	6.5	1.3	r.t.	61
3	6.5	1.5	r.t.	67
4	4.5	1.5	40	70
5	3	1.5	50	76
6	6.5	1.5	60	67

[a] Isolated yield.

With the optimization conditions in hand, we explored the scope and limitations of the reaction by using a wide range of acetylenic esters (Table 2). Aliphatic alkyl groups ranging from methyl (**1b**), propyl (**1c**), hexyl (**1a**), and heptyl (**1d**) groups were efficient substrates, affording the corresponding (*Z*)-β-boryl-α,β-unsaturated esters **2a–d** in good to excellent yields (entries 1–4).

Surprisingly, the use of a dodecyl-bearing substituent resulted in no reaction (Table 2, entry 5). Attempts to improve the reaction were unsuccessful (biphasic conditions, increased temp, etc). However, substrates with a cyclopropyl or larger cyclohexyl group with either ethyl or isobutyl ester moieties were borylated in excellent yield (entries 6–8). Furthermore, cyclohexenyne **1i** was borylated regioselectively on the β-position to generate α,β,γ,δ-unsaturated diene **2i** in 98% yield. Aryl substitutions were also tolerated. For example, substrates bearing phenyl (**1j**), electron-donating methoxy (**1k**), or electron-withdrawing fluorine (**1l**) groups yielded the corresponding borylated products in excellent yields (entries 10–12). Finally, *tert*-butyldimethylsilyl-protected alcohol **1m** gave product **2m** in 84% yield, confirming the good functional group compatibility of the reaction conditions.

Table 2 Cu(II)-Catalyzed Monoboration of Alkynoates



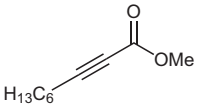
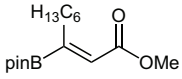
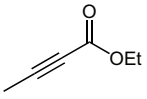
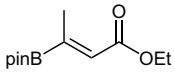
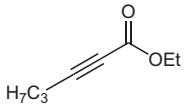
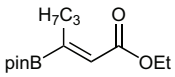
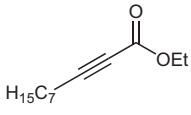
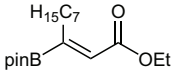
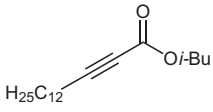
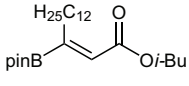
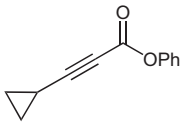
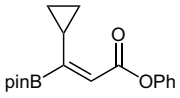
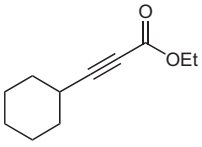
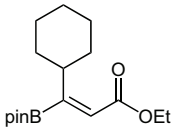
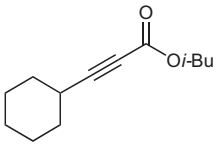
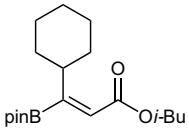
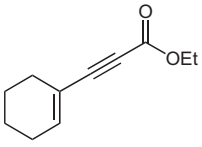
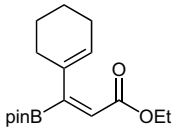
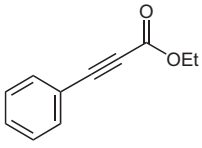
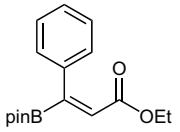
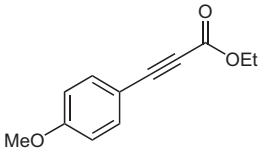
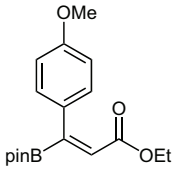
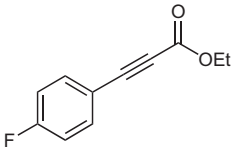
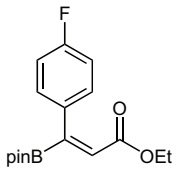
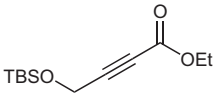
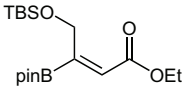
Entry	1	Substrate	Product	2	Time (h)	Isolated yield (%)
1	**1a**			**2a**	3	76
2[a,b]	**1b**			**2b**	2	96
3	**1c**			**2c**	4	84
4	**1d**			**2d**	2	85
5	**1e**			**2e**	–	nr

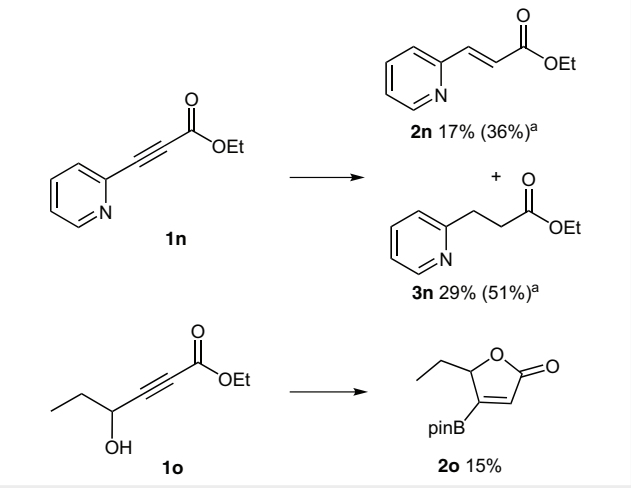
Table 2 (continued)

Entry	1	Substrate	Product	2	Time (h)	Isolated yield (%)
6	**1f**			**2f**	4	85
7	**1g**			**2g**	3	76
8	**1h**			**2h**	6	70
9	**1i**			**2i**	22	98
10[a,c]	**1j**			**2j**	4	95
11	**1k**			**2k**	20	91
12[a]	**1l**			**2l**	24	90
13	**1m**			**2m**	3	84

[a] The reaction was performed at r.t.
[b] B_2pin_2 (1.1 equiv) was used.
[c] B_2pin_2 (1.3 equiv) was used.

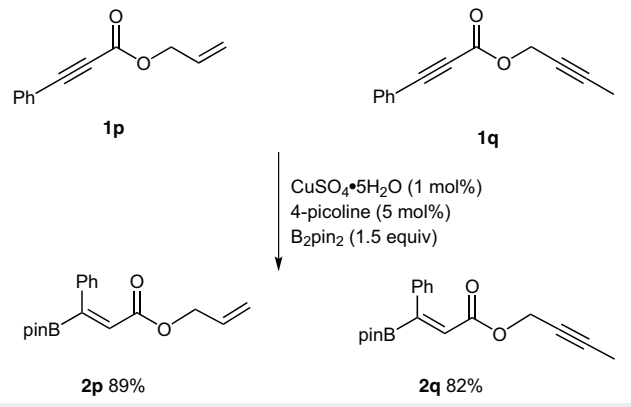
To assess the limitations of the reaction, 2-pyridyl substituted substrate **1n** was subjected to the same conditions (Scheme 2). In this case, the resulting products underwent protodeboration: mono- and diboration followed by spontaneous protodeboration generated semihydrogenated **2n** and fully reduced **3n**. Surprisingly, the double bond geometry of **2n** was found to be *E*, possibly a result of isomerization leading to the more stable *trans* isomer. Whereas

TBS-protected **1m** was readily borylated, the corresponding propargylic alcohol **1o** underwent β-borylation. However, only the cyclized butenolide **2o** was isolated in low yield.



Scheme 2 Reaction conditions: B_2pin_2 (1.5 equiv), $CuSO_4$ (1 mol%), 4-picoline (5 mol%), H_2O, 50 °C. [a] NMR yield.

The selective borylation on the β-position of enyne **1i** prompted us to further explore the selectivity of the reaction (Scheme 3). Given that copper(I)-catalyzed borylations of nonactivated alkenes and alkynes have been reported,[9] it was unclear whether a copper(II) catalyst system was sufficiently selective in the presence of competing functional groups. Thus, 3-phenylpropiolate substrates containing allyl (**1p**) or propargyl (**1q**) groups were synthesized. When these substrates were subjected to the borylation conditions, products **2p** and **2q** were isolated in excellent yields; exquisite reactivity at the more activated alkyne was observed, demonstrating the chemoselectivity of the reaction.



Scheme 3 Chemoselectivity of the reaction

In summary, we have developed a simple, mild, and efficient copper(II)-catalyzed borylation method for acetylenic esters. The reaction is performed in air and utilizes water as the reaction medium to afford (*Z*)-β-borylated products exclusively. Furthermore, acetylenic esters were transformed chemoselectivity into the desired products in the presence of competing functional groups. Further investigations on the substrate scope and applications of the method are underway.

^{1}H and ^{13}C NMR spectra were recorded with a Bruker Avance II 500 MHz, Agilent MR 400 MHz, or Agilent DD2 400 MHz spectrometer in $CDCl_3$ with TMS as an internal reference. ^{11}B NMR spectra were recorded with a Varian Inova 400 MHz spectrometer in $CDCl_3$ with boron trifluoride diethyl etherate as an external standard. High-resolution mass spectra (HRMS) were obtained with an Agilent LC-ESI-TOF. Bis(pinacolato)diboron was donated by AllylChem and used as received. Copper sulfate pentahydrate, 4-picoline, and other commercially available reagents were used as received.

General Procedure

In a 1 dram vial, methyl non-2-ynoate (88 mg, 1.0 equiv), 4-picoline (2.55 µL, 0.05 equiv), half the amount of bis(pinacolato)diboron (198 mg total, 1.5 equiv), and $CuSO_4$ stock solution (1.3 mg/mL, 1 mL, 0.01 equiv) were mixed and stirred vigorously at 50 °C. The remaining half of bis(pinacolato)diboron was added over a period of 10 min. After 3 h, hexanes (1 mL) was added to quench the reaction. The aqueous layer was extracted three times with hexanes. The organic layer was washed five times with H_2O, dried over Na_2SO_4, filtered, and concentrated in vacuo. Column chromatography was used to purify the product.

Methyl (*Z*)-3-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolan-2-yl)non-2-enoate (2a)

Yield: 115 mg (76%); colorless oil; bp 299.2 °C; R_f = 0.56 (hexanes–EtOAc, 90:10).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.87 (t, *J* = 6.7 Hz, 3 H, CH_3), 1.27 (s, 12 H, CH_3-Bpin), 1.27–1.37 (m, 6 H, $CH_2CH_2CH_2$), 1.37–1.46 (m, 2 H, CH_2), 2.66 (t, *J* = 7.3 Hz, 2 H, CH_2CCH), 3.70 (s, 3 H, OCH_3), 6.39 [s, 1 H, CC*H*(C=O)].

^{13}C NMR (101 MHz, $CDCl_3$): δ = 14.2 (CH_3), 22.4 (CH_2), 24.8 (CH_3-Bpin), 29.5 (CH_2), 29.7 (CH_2), 30.2 (CH_2), 31.9 (CH_2), 51.2 (OCH_3), 84.2 (C-Bpin), 129.3 [*C*H(C=O)], 166.6 (C=O).

^{11}B NMR (128 MHz, $CDCl_3$): δ = 30.1.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{16}H_{29}BO_4$: 297.2275; found: 297.2248.

Ethyl (*Z*)-3-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolan-2-yl)but-2-enoate (2b)

Yield: 120 mg (96%); colorless oil; R_f = 0.45 (hexanes–EtOAc, 90:10).

^{1}H and ^{13}C NMR data are consistent with the reported data.[4]

^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.27 (s, 12 H, CH_3-Bpin), 1.28 (t, *J* = 7.1 Hz, 3 H, OCH_2CH_3), 2.17 [d, *J* = 1.8 Hz, 3 H, CH_3CH(CO)], 4.17 (d, *J* = 7.1 Hz, 2 H, OCH_2), 6.44 [q, *J* = 1.8 Hz, 1 H, CH(CO)].

Ethyl (*Z*)-3-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolan-2-yl)hex-2-enoate (2c)

Yield: 116 mg (84%); pale-yellow oil; bp 281 °C; R_f = 0.65 (hexanes–EtOAc, 90:10).

^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.93 (t, *J* = 7.4 Hz, 3 H, CH_3), 1.26 (s, 12 H, CH_3-Bpin), 1.27 (t, *J* = 7.1 Hz, 3 H, CH_3), 1.41–1.50 (m, 2 H, $CH_3CH_2CH_2$), 2.64 (t, *J* = 7.6 Hz, 2 H, CH_2CH_2C), 4.16 (q, *J* = 7.1 Hz, 2 H, OCH_2), 6.41 [s, 1 H, C*H*(C=O)].

^{13}C NMR (126 MHz, $CDCl_3$): δ = 14.2 (CH_3), 14.3 (CH_3), 22.9 (CH_2), 24.7 (CH_3-Bpin), 31.9 (CH_2), 59.8 (OCH_2), 84.0 (C-Bpin), 130.0 [*C*H(C=O)], 166.1 (C=O).

^{11}B NMR (128 MHz, $CDCl_3$): δ = 29.9.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{14}H_{25}BO_4$: 269.18; found: 269.08.

Ethyl (*Z*)-3-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolan-2-yl)dec-2-enoate (2d)

Yield: 144 mg (85%); pale-yellow liquid; bp 232.7 °C; R_f = 0.72 (hexanes–EtOAc, 90:10).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.87 (t, *J* = 6.9 Hz, 3 H, CH_3), 1.21–1.36 (m, 23 H, CH_2CH_2 CH_2CH_2, CH_3, CH_3-Bpin), 1.37–1.46 (m, 2 H, CH_2), 2.65 (t, *J* = 7.5 Hz, 2 H, CH_2CCH), 4.16 (q, *J* = 7.2 Hz, 2 H, OCH_2), 6.39 [s, 1 H, C*H*(C=O)].

^{13}C NMR (101 MHz, $CDCl_3$): δ = 14.3 (CH_3), 14.4 (CH_3), 22.8 (CH_2), 24.9 (CH_3-Bpin), 29.4 (CH_2), 29.9 (CH_2), 29.8 (CH_2), 30.2 (CH_2), 32.0 (CH_2), 59.9 (OCH_2), 84.1 (C-Bpin), 129.9 [*C*H(C=O)], 166.2 (C=O).

^{11}B NMR (128 MHz, $CDCl_3$): δ = 30.2.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{18}H_{33}BO_4$: 325.2546; found: 325.2560.

Phenyl (*Z*)-3-Cyclopropyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (2f)

Yield: 139 mg (85%); white solid; mp 105.1–108.6 °C; R_f = 0.57 (hexanes–EtOAc, 90:10).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.88–0.93 (m, 2 H, CH_2), 1.01–1.06 (m, 2 H, CH_2), 1.27 (s, 12 H, CH_3-Bpin), 3.05–3.15 (m, 1 H, CH_2CHC), 6.56 [s, 1 H, C*H*(C=O)], 7.10–7.14 (m, 2 H, ArH), 719–7.24 (m, 1 H, ArH), 7.35–7.41 (m, 2 H, ArH).

^{13}C NMR (400 MHz, $CDCl_3$): δ = 9.2 [$(CH_2)_2CHC$], 14.3 [$(CH_2)_2CHC$], 24.8 (CH_3-Bpin), 84.2 (C-Bpin), 121.9 (CH-Ar), 125.7 (CH-Ar), 126.7 (CH-Ar), 129.4 [*C*H(C=O)], 150.9 (CH-Ar), 165.0 (C=O).

^{11}B NMR (128 MHz, $CDCl_3$): δ = 29.1.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{18}H_{23}BO_4$: 315.1762; found: 315.1765.

Ethyl (*Z*)-3-Cyclohexyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (2g)

Yield: 120 mg (76%); pale-yellow oil; R_f = 0.50 (hexanes–EtOAc, 90:10). ^{1}H and ^{13}C NMR data are consistent with the reported data.[4]

^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.27 (s, 12 H, CH_3-Bpin), 1.28 (t, *J* = 7.1 Hz, 3 H, OCH_2CH_3), 1.58–1.44 (m, 6 H, $CH_2CH_2CH_2$), 1.77–1.62 (m, 4 H, CH_2CH_2), 3.44–3.34 [m, 1 H, *C*HCCH(CO)], 4.16 (q, *J* = 7.1 Hz, 2 H, OCH_2), 6.23 [s, 1 H, CH(CO)].

Isobutyl (*Z*)-3-Cyclohexyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (2h)

Yield: 121 mg (70%); colorless oil; bp 338 °C; R_f = 0.64 (hexanes–EtOAc, 90:10).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.95 [d, *J* = 6.7 Hz, 6 H, $CH(CH_3)_3$], 1.28 (s, 12 H, CH_3-Bpin), 1.43–1.61 (m, 6 H, $CH_2CH_2CH_2$), 1.63–1.76 (m, 4 H, CH_2CH_2), 1.89–2.00 (m, 1 H, OCH_2CH), 3.34–3.44 [m, 1 H, *C*HCCH(C=O)], 3.89 (d, *J* = 6.6 Hz, 2 H), 6.24 [s, 1 H, C*H*(C=O)].

^{13}C NMR (101 MHz, $CDCl_3$): δ = 19.3 [$(CH_3)_3$], 24.9 (C-Bpin), 26.1 (CH_2), 26.4 (CH_2), 27.9 (OCH_2CH), 31.5 (CH_2), 40.2 ($CHCCH_2$), 70.3 (OCH_2), 83.9 (CH_3-Bpin), 127.8 [*C*H(C=O)], 166.5 (C=O).

^{11}B NMR (128 MHz, $CDCl_3$): δ = 30.3.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{19}H_{33}BO_4$: 337.2561; found: 337.2545.

Ethyl (*Z*)-3-(Cyclohex-1-en-1-yl)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (2i)

Yield: 155 mg (98%); yellow oil; bp >220 °C (dec); R_f = 0.53 (hexanes–EtOAc, 90:10).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.25 (t, *J* = 7.1 Hz, 3 H, CH_3), 1.26 (s, 12 H, CH_3-Bpin), 1.56–1.63 (m, 2 H, CH_2), 1.64–1.71 (m, 2 H, CH_2), 2.02–2.15 (m, 4 H, CH_2CH_2), 4.14 (q, *J* = 7.1 Hz, 2 H, OCH_2), 5.42–5.46 (m, 1 H, CH_2CHC), 6.31 [s, 1 H, C*H*(C=O)].

^{13}C NMR (101 MHz, $CDCl_3$): δ = 14.4 (CH_3), 22.1 (CH_2), 22.8 (CH_2), 24.8 (CH_3-Bpin), 25.5 (CH_2), 28.1 (CH_2), 60.2 (OCH_2), 84.2 (C-Bpin), 123.7 [*C*H(C=O)], 130.1 (CH_2CHC), 137.6 (*C*HCCC), 167.1 (C=O).

^{11}B NMR (128 MHz, $CDCl_3$): δ = 30.0.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{17}H_{27}BO_4$: 307.2070; found: 307.2075.

Ethyl (*Z*)-3-Phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (2j)

Yield: 148 mg (95%); yellow oil; R_f = 0.31 (hexanes–EtOAc, 90:10).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.06 (t, *J* = 7.1, 3 H, CH_3), 1.27 (s, 12 H, CH_3-Bpin), 4.02 (q, *J* = 7.1 Hz, 2 H, CH_2), 6.64 [s, 1 H, C*H*(C=O)], 7.18–7.23 (m, 2 H, ArH), 7.23–7.32 (m, 3 H, ArH).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 14.0 (CH_3), 24.9 (CH_3-Bpin), 60.3 (CH_2), 84.6 (C-Bpin), 127.4 (CH-Ar), 127.8 (CH-Ar), 128.1 (CH-Ar), 132.4 [*C*H(C=O)], 138.8 (CH-Ar), 166.5 (C=O).

^{11}B NMR (128 MHz, $CDCl_3$): δ = 29.7.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{17}H_{23}BO_4$: 303.17; found: 303.06.

Ethyl (*Z*)-3-(4-Methoxyphenyl)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (2k)

Yield: 156 mg (91%); yellow liquid; bp 308 °C; R_f = 0.34 (hexanes–EtOAc, 90:10).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.14 (t, *J* = 7.1 Hz, 3 H, CH_3), 1.29 (s, 12 H, CH_3-Bpin), 3.80 (s, 3 H, CH_3O), 4.07 (q, *J* = 7.1 Hz, 2 H, OCH_2), 6.58 [s, 1 H, C*H*(C=O)], 6.83–6.87 (m, 2 H, ArH), 7.19–7.23 (m, 2 H, ArH).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 14.2 (OCH_2CH_3), 24.9 (CH_3-Bpin), 55.3 (CH_3O), 60.3 (OCH_2), 84.6 (C-Bpin), 113.3 (CH-Ar), 129.8 [*C*H(C=O)], 130.8 (CH-Ar), 131.2 (CH-Ar), 159.3 (CH_3OC), 166.7 (C=O).

^{11}B NMR (128 MHz, $CDCl_3$): δ = 30.5.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{18}H_{25}BO_5$: 333.1868; found: 333.1875.

Ethyl (*Z*)-3-(4-Fluorophenyl)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (2l)

Yield: 150 mg (90%); pale-yellow solid; mp 57.2–61.4 °C; R_f = 0.43 (hexanes–EtOAc, 90:10).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.12 (t, *J* = 7.1 Hz, 3 H, CH_3), 1.28 (s, 12 H, CH_3-Bpin), 4.06 (q, *J* = 7.1 Hz, 2 H, OCH_2), 6.65 [s, 1 H, C*H*(C=O)], 6.97–7.03 (m, 2 H, ArH), 7.17–7.23 (m, 2 H, ArH).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 14.1 (CH_3), 24.9 (CH_3-Bpin), 60.4 (OCH_2), 84.7 (C-Bpin), 114.6 (CH-Ar, ^2J = 21.5 Hz), 114.9 (CH-Ar, ^2J = 21.5 Hz), 129.9 (CH-Ar, ^3J = 8.1 Hz), 130.0 (CH-Ar, ^3J = 8.1 Hz), 132.5 [*C*H(C=O)], 134.5 (CH-Ar, ^4J = 3.4 Hz), 134.5 (CH-Ar, ^4J = 3.4 Hz), 161.2 (F-CH-Ar, ^1J = 247 Hz), 163.6 (F-CH-Ar, ^1J = 247 Hz), 166.3 (C=O).

^{11}B NMR (128 MHz, $CDCl_3$): δ = 29.6.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{17}H_{22}BFO_4$: 321.1695; found: 321.167.

Ethyl (*Z*)-4-[(*tert*-Butyldimethylsilyl)oxy]-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)but-2-enoate (2m)

Yield: 162 mg (84%); pale-yellow liquid; bp 290.8 °C; R_f = 0.53 (hexanes–EtOAc, 90:10).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.07 [s, 6 H, Si(*CH*$_3$)$_2$C(CH$_3$)$_3$], 0.90 [s, 9 H, Si(CH$_3$)$_2$C(*CH*$_3$)$_3$], 1.26 (t, *J* = 7.1 Hz, 3 H, OCH$_2$*CH*$_3$), 1.28 (s, 12 H, CH$_3$-Bpin), 4.16 (q, *J* = 7.1 Hz, 2 H, OCH_2), 4.82 (d, *J* = 2.0 Hz, 2 H, O*CH*$_2$C), 6.19 [t, *J* = 2.0 Hz, 1 H, C*H*(C=O)].

^{13}C NMR (101 MHz, $CDCl_3$): δ = –5.1 [Si(*CH*$_3$)$_2$ C(CH$_3$)$_3$], 14.4 (OCH$_2$*CH*$_3$), 18.6 [Si(CH$_3$)$_2$*C*(CH$_3$)$_3$], 24.9 (CH$_3$-Bpin), 26.2 [Si(CH$_3$)$_2$ *C*(*CH*$_3$)$_3$], 60.2 (O*CH*$_2$C), 62.2 (OCH_2), 84.2 (C-Bpin), 126.8 [*CH*(C=O)], 165.9 (C=O).

^{11}B NMR (128 MHz, $CDCl_3$): δ = 30.3.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{18}H_{35}BO_5Si$: 371.2420; found: 371.2384.

Ethyl (*E*)-3-(pyridin-2-yl)acrylate (2n)

Yield: 16 mg (17%); colorless liquid; R_f = 0.66 (hexanes–EtOAc, 1:1). ^{1}H and ^{13}C NMR data are consistent with the reported data.[10]

^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.33 (t, *J* = 7.1 Hz, 3 H, OCH$_2$*CH*$_3$), 4.27 (q, *J* = 7.1 Hz, 2 H, OCH_2), 6.91 [d, *J* = 15.7 Hz, 1 H, CH(CO)], 7.28–7.23 (m, 1 H, ArH), 7.42 (d, *J* = 7.7 Hz, 1 H, ArH), 7.68 [d, *J* = 15.7 Hz, 1 H, *CH*CH(CO)], 7.69 (td, *J* = 7.7 Hz, 1 H, ArH), 8.64 (d, *J* = 4.5 Hz, 1 H).

Ethyl 3-(Pyridin-2-yl)propanoate (3n)

Yield: 27 mg (29%); colorless liquid; R_f = 0.17 (hexanes–EtOAc, 1:1). ^{1}H and ^{13}C NMR data are consistent with the reported data.[11]

^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.22 (t, *J* = 7.1 Hz, 3 H, OCH$_2$*CH*$_3$), 2.80 (t, *J* = 7.5 Hz, 2 H, CH_2), 3.12 (t, *J* = 7.5 Hz, 2 H, CH_2), 4.12 (q, *J* = 7.1 Hz, 2 H, OCH_2), 7.14–7.10 (m, 1 H, ArH), 7.20 (d, *J* = 7.7 Hz, 1 H, ArH), 7.60 (td, *J* = 7.7, 1.9 Hz, 1 H, ArH), 8.52 (d, *J* = 4.9 Hz, 1 H, ArH).

5-Ethyl-4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)furan-2(5*H*)-one (2o)

Yield: 19 mg (15%); white solid; mp 64.9–68.1 °C; R_f = 0.19 (hexanes–EtOAc, 70:30).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.94 (t, *J* = 7.4 Hz, 3 H, CH_3), 1.30 (s, 6 H, CH_3-Bpin), 1.31 (s, 6 H, CH_3-Bpin), 1.63 (m, 1 H, CH_3CH_2), 2.07 (dqd, *J* = 14.7, 7.4, 3.7 Hz, 1 H, CH_3CH_2), 5.11 (ddd, *J* = 7.5, 3.7, 2.1 Hz, 1 H, OCH), 6.49 [d, *J* = 2.1 Hz, 1 H, CHC(C=O)].

^{13}C NMR (101 MHz, $CDCl_3$): δ = 9.2 (CH_3), 24.7 (CH_3-Bpin), 25.0 (CH_3-Bpin), 26.2 (CH_2), 85.0 (C-Bpin), 87.2 (OCH), 131.9 [*CH*(C=O)], 151.4 (C=O).

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{12}H_{19}BO_4$: 239.1449; found: 239.1458.

Allyl (*Z*)-3-Phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (2p)

Yield: 146 mg (89%); colorless liquid; bp >277 °C (dec); R_f = 0.52 (hexanes–EtOAc, 90:10).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.28 (s, 12 H, CH_3-Bpin), 4.49 (dt, *J* = 5.6, 1.4 Hz, 2 H, OCH_2), 5.10–5.18 (m, 2 H, CHC*H*$_2$), 5.74 (ddt, *J* = 17.2, 10.4, 5.7 Hz, 1 H, OCH$_2$*CH*CH$_2$), 6.68 [s, 1 H, CH(C=O)], 7.20–7.24 (m, 2 H, ArH), 7.27–734 (m, 3 H, ArH).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 24.7 (CH_3-Bpin), 64.9 (OCH_2), 84.5 (C-Bpin), 118.1 (CH*C*H$_2$), 127.3 (CH-Ar), 127.7 (CH-Ar), 127.9 (CH-Ar), 131.6 [*C*H(C=O)], 131.8 (*C*HCH$_2$), 138.5 (CH-Ar), 165.8 (C=O).

^{11}B NMR (128 MHz, $CDCl_3$): δ = 29.8.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{18}H_{23}BO_4$: 315.1762; found: 315.1758.

But-2-yn-1-yl (*Z*)-3-Phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (2q)

Yield: 139 mg (82%); white solid; mp 86.1–92.5 °C; R_f = 0.55 (hexanes–EtOAc, 90:10).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.28 (s, 12 H, CH_3-Bpin), 1.82 (t, *J* = 2.4 Hz, 3 H, CH_3), 4.57 (q, *J* = 2.4 Hz, 2 H, OCH_2), 6.68 [s, 1 H, C*H*(C=O)], 7.21–7.26 (m, 2 H, ArH), 7.27–7.34 (m, 3 H, ArH).

^{13}C NMR (101 MHz, $CDCl_3$): δ = 3.8 (CH_3), 24.9 (CH_3-Bpin), 52.7 (OCH_2), 73.1 (*C*CCH$_3$), 83.2 (*C*CCH$_3$), 84.7 (C-Bpin), 127.6 (CH-Ar), 127.8 (CH-Ar), 128.2 (CH-Ar), 131.1 [*C*H(C=O)], 138.3 (CH-Ar), 165.4 (C=O).

^{11}B NMR (128 MHz, $CDCl_3$): δ = 30.1.

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{19}H_{23}BO_4$: 327.1762; found: 327.175.

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Supporting Information

Supporting information for this article is available online at http://dx.doi.org/10.1055/s-0034-1380524.

References

(1) (a) Hall, D. *Boronic Acids: Preparation, Applications in Organic Synthesis, Medicine and Materials*; Wiley-VCH: Weinheim, **2011**, 2nd ed.. (b) Takaya, J.; Iwasawa, N. *ACS Catal.* **2012**, *2*, 1993. (c) Beletskaya, I.; Moberg, C. *Chem. Rev.* **2006**, *106*, 2320. (d) Burks, H. E.; Morken, J. P. *Chem. Commun.* **2007**, 4717. (e) Brown, J. M.; Nguyen, B. N. *Stereoselective Synthesis 1: Stereoselective Reactions of Carbon—Carbon Double Bonds In Science of Synthesis*; Vol. 1; de Vries, J. G., Ed.; Thieme: Stuttgart, **2011**, 295.

(2) (a) Thomas, R. L.; Souza, F. E. S.; Marder, T. B. *J. Chem. Soc., Dalton Trans.* **2001**, 1650. (b) Anderson, K. M.; Lesley, M. J. G.; Norman, N. C.; Orpen, A. G.; Starbuck, J. *New J. Chem.* **1999**, *23*, 1053. (c) Ishiyama, T.; Matsuda, N.; Murata, M.; Ozawa, F.; Suzuki, A.; Miyaura, N. *Organometallics* **1996**, *15*, 713.

(3) Ishiyama, T.; Takagi, J.; Kamon, A.; Miyaura, N. *J. Organomet. Chem.* **2003**, *687*, 284.
(4) Lee, J.-E.; Kwon, J.; Yun, J. *Chem. Commun.* **2008**, 733.
(5) (a) Semba, K.; Fujihara, T.; Terao, J.; Tsuji, Y. *Chem. Eur. J.* **2012**, *18*, 4179. (b) Tai, C.-C.; Yu, M.-S.; Chen, Y.-L.; Chuang, W.-H.; Lin, T.-H.; Yap, G. P. A.; Ong, T.-G. *Chem. Commun.* **2014**, *50*, 4344.
(6) (a) Lipshutz, B. H.; Moser, R.; Voigtritter, K. R. *Isr. J. Chem.* **2010**, *50*, 691. (b) Isley, N. A.; Gallou, F.; Lipshutz, B. H. *J. Am. Chem. Soc.* **2013**, *135*, 17707.
(7) For examples of borylation of α,β-unsaturated carbonyl compounds, see: (a) Chea, H.; Sim, H. S.; Yun, J. *Bull. Korean Chem. Soc.* **2010**, *31*, 551. (b) Kobayashi, S.; Xu, P.; Endo, T.; Ueno, M.; Kitanosono, T. *Angew. Chem. Int. Ed.* **2012**, *51*, 12763. (c) Kitanosono, T.; Kobayashi, S. *Asian J. Org. Chem.* **2013**, *2*, 961. (d) Kitanosono, T.; Xu, P.; Kobayashi, S. *Chem. Commun.* **2013**, *49*, 8184. (e) Stavber, G.; Časar, Z. *Appl. Organomet. Chem.* **2013**, *27*, 159. (f) For a review of copper-catalyzed borylation in water, see: Stavber, G.; Časar, Z. *ChemCatChem* **2014**, *6*, 2162.
(8) Thorpe, S. B.; Calderone, J. A.; Santos, W. L. *Org. Lett.* **2012**, *14*, 1918.
(9) For reviews, see ref. 1b and:Oestreich, M.; Hartmann, E.; Mewald, M. *Chem. Rev.* **2013**, *113*, 402.
(10) Cho, S. H.; Hwang, S. J.; Chang, S. *J. Am. Chem. Soc.* **2008**, *130*, 9254.
(11) Barbe, G.; Pelletier, G.; Charette, A. B. *Org. Lett.* **2009**, *11*, 3398.