Tetrahedron 64 (2008) 6824–6830

Contents lists available at ScienceDirect

Tetrahedron

journal homepage: www.elsevier.com/locate/tet

Conversion of 1,3-disubstituted arenes to chiral α,α-diaryl methylammonium chlorides using arene borylation

Timothy A. Boebel, John F. Hartwig *

Department of Chemistry, University of Illinois, 600 South Mathews Avenue, Urbana, IL 61801, United States

ARTICLE INFO

Article history:
Received 2 April 2008
Received in revised form 12 April 2008
Accepted 14 April 2008
Available online 18 April 2008

ABSTRACT

A two-step conversion of 1,3-disubstituted arenes to chiral α,α-diaryl methylammonium chlorides is described. In this procedure, arenes are converted to aryl boronic esters by iridium-catalyzed borylation, and the aryl boronic esters are converted to enantioenriched amines by subsequent rhodium-catalyzed addition to chiral *tert*-butanesulfinimes.

1. Introduction

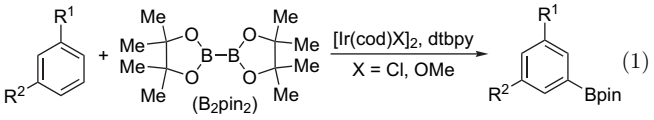
The methods for direct, intermolecular conversion of arenes to aryl methylamines are limited,[1–5] and the conversion to chiral, non-racemic amines is particularly uncommon.[6–9] In the context of our group's efforts to develop C–H bond functionalization processes using borane reagents,[10–12] we sought to develop the conversion of arenes to chiral, non-racemic amines using iridium-catalyzed arene borylation chemistry. To do so, we envisioned a reaction sequence involving the formation of aryl boronate esters from arenes by C–H activation, followed by addition of the resulting aryl boronate ester to imine electrophiles with control of stereochemistry.

The addition of organometallic reagents to chiral imine derivatives can lead to enantioenriched α,α-diarylated methylamines. One type of method to control the stereochemistry of this addition is based on chiral auxiliaries.[13] These strategies include the use of RAMP/SAMP hydrazones,[14] carbohydrate auxiliaries,[15] phenylglycinol-derived imines,[16] *ortho*-acylimines,[17] and *N*-sulfinimines.[18–21] In addition to magnesium nucleophiles, lithium[22–24] and zinc[25,26] species also add to *N*-sulfinimines developed by Ellman. The scope of the additions to the *N*-sulfinimines was recently extended to include reactions of aryl boronic acids in the presence of rhodium catalysts.[27] A single example of the addition of an aryl boronic ester to an *N*-sulfinimine was reported by Batey and coworkers.[28] Relative to other organometallic nucleophiles, aryl boron reagents possess greater chemical stability, ease of handling, and tolerance for auxiliary functionality.[29]

The traditional route to aryl boron reagents involves the addition of organolithium or Grignard reagents to boron electrophiles.[30] These intermediates are typically generated through either metal–halogen exchange[31] or directed *ortho*-metalation.[32] Aryl boron reagents are also readily accessed via the palladium-catalyzed coupling of aryl halides with bis(pinacolato)diboron (B_2pin_2) or pinacolborane (HBpin).[33]

These methods for generating aryl boron compounds are regioselective, but they rely on the presence of halides or *ortho*-directing groups on the arene starting materials, and they can be harsh. Metalation procedures create issues of functional group compatibility, and the borylation of aryl halides depends on the availability of haloarene substrates.

The direct C–H functionalization of arenes provides an alternative approach to the synthesis of aryl boron reagents. Catalysts based on rhodium[34,35] and iridium[36–42] have been developed using B_2pin_2 or HBpin as the boron source. To date, the most efficient catalyst system is generated from the combination of boron reagents, 4,4′-di-*tert*-butylbipyridine (dtbpy), and $[Ir(cod)X]_2$ (cod=1,5-cyclooctadiene, X=Cl, OMe) (Eq. 1).[43–45]

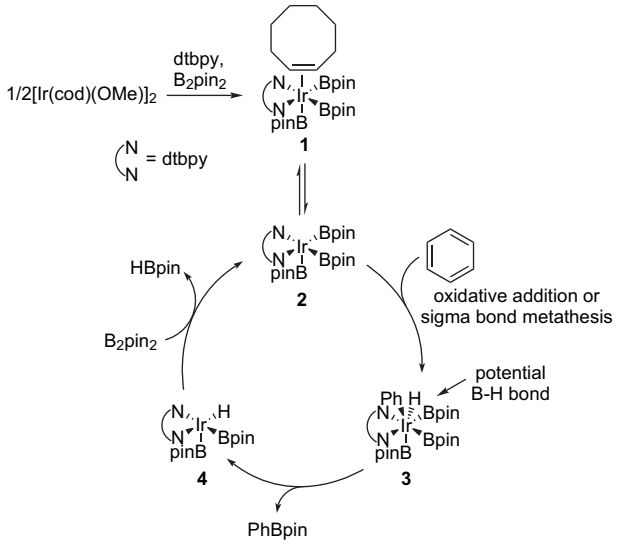


(1)

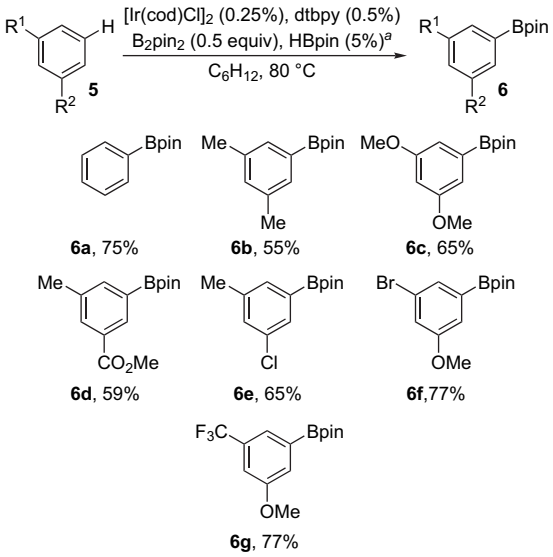
Iridium(III) complex **1**, generated by the reaction of $[Ir(cod)Cl]_2$, dtbpy, and boron reagents, has been identified as the catalyst resting state in the direct C–H borylation of arenes (Scheme 1).[43] Dissociation of the cyclooctene ligand from **1** provides the coordinatively unsaturated, and catalytically active iridium species **2**.[45] Arene C–H bond cleavage can then occur, either though oxidative addition[46] or sigma bond metathesis[47] to give complex **3**. Elimination of aryl boronic ester from **3** affords iridium fragment **4**, which can undergo reaction with B_2pin_2 to regenerate the active catalytic species (**2**).

* Corresponding author. Tel.: +1 217 244 7652; fax: +1 217 244 8024.
E-mail address: jhartwig@uiuc.edu (J.F. Hartwig).

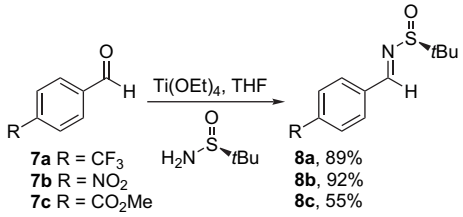
0040-4020/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2008.04.060



Scheme 1. Proposed mechanism of arene borylation.



Scheme 2. Synthesis of aryl boronic esters. [a]*n*-Dodecane (0.15 equiv) was used as an internal standard.



Scheme 3. Synthesis of chiral sulfinimines.

In contrast to other methods to prepare aryl boron reagents, the regioselectivity of catalytic arene C–H functionalization is governed largely by steric factors.[42,43] For example, the catalytic borylation of a 1,3-disubstituted arene results in almost exclusive formation of a 1,3,5-trisubstituted arene product (Eq. 1)—a substitution pattern that is difficult to achieve using traditional aromatic substitution chemistry.[48] Herein, we describe the synthesis of chiral, non-racemic substituted amines by the sequence of C–H borylation, followed by distereoselective rhodium-catalyzed additions to chiral, non-racemic *N*-sulfinimines. After acidic workup, enantiomerically enriched α,α-diaryl methylammonium chloride products are obtained in good to excellent yields.

2. Results and discussion

Aryl boronic esters were conveniently prepared without the need for a glove box using a variation of published procedures. Accordingly, a solution of arene (**5**), B_2pin_2 (0.5 equiv), and catalytic amounts of pinacolborane (HBpin, 5%), dtbpy (0.5%), and $[Ir(cod)Cl]_2$ (0.25%) in cyclohexane was heated to 80 °C to give borylated arenes (**6**) in moderate to good yields (Scheme 2). The added HBpin has been shown to improve the rate and yield of formation of the active triboryliridium catalyst.[45] As observed previously,[49] higher yields were obtained from reaction of more electron-deficient arenes. Products were isolated by concentration under high vacuum and were used without further purification.

Chiral sulfinimine electrophiles were prepared using a procedure previously described by Ellman and co-workers.[27] 4-Trifluoromethyl- and 4-nitro-substituted sulfinimines **8a** and **8b** (Scheme 3) were readily accessed by $Ti(OEt)_4$-mediated condensation of the corresponding aldehydes (**7a** and **7b**) with (*S*)-*tert*-butanesulfinamide. Carbomethoxy-substituted sulfinimine **8c** was prepared in moderate yield using $Ti(OMe)_4$, to make the reaction of the ester with the titanium alkoxide degenerate.

With both coupling partners in hand, we studied the rhodium-catalyzed 1,2-addition of the crude aryl boronic esters to the chiral sulfinimines. Following the procedure developed by Batey for the addition of boronic acids to sulfinimines,[28] a mixture of **8**, aryl boronic ester (**6**, 2 equiv), and rhodium catalyst (5%) was dissolved in dioxane, treated with triethylamine (2 equiv) and water, and allowed to stir at room temperature (Eq. 2). Isolation of the initial products of 1,2-addition (sulfinylated amine **9**) was difficult due to coelution of pinacol byproduct with sulfinyl amine (**9**) during silica gel chromatography. To circumvent this problem, the crude sulfinyl amine products (**9**) were treated with hydrogen chloride and methanol to generate α,α-diaryl methylammonium chlorides (**10**), which were readily isolated and purified.

The enantiopurity of the α,α-diaryl methylammonium chloride products (**10**) was determined by chiral HPLC analysis. Simple acetylation of the salts (**10**) with acetic anhydride provided amides, which were readily resolved by chiral HPLC methods.

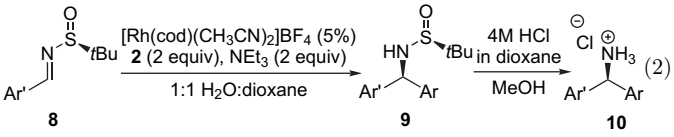
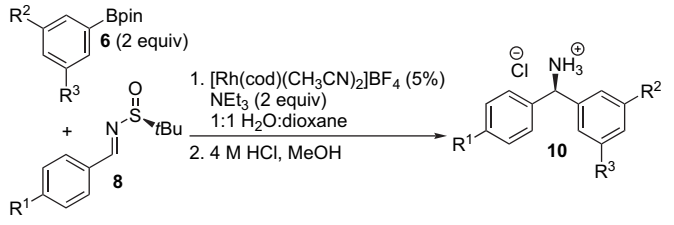


Table 1 summarizes the rhodium-catalyzed reactions between a number of chiral sulfinimes (**8**) and aryl boronic esters (**6**) formed by iridium-catalyzed C–H functionalization (Scheme 1). These reactions form α,α-diaryl methylammonium chlorides (**10**) that were isolated in yields that depended on the electronic properties of the aryl boronic esters. Those derived from electron-rich aryl boronic esters (R^2 and R^3=H, Me) formed in higher yields than those derived from electron-deficient aryl boronic esters (R^3=Cl, Br, CF_3). The trend in reactivities of the aryl boronic esters (**6**) roughly parallel the trends in nucleophilicities. Although three products (**10i**, **10o**, and **10q**) were formed with only modest levels of asymmetric induction, overall, the levels of enantiomeric excess of the final amines were generally good, with sulfinimine **8a** providing the best results.

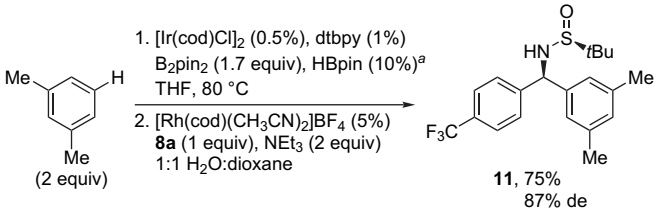
In addition to the two-step procedure outlined above, initial results indicate that a one-pot protocol can be developed. In a representative reaction, *meta*-xylene (2 equiv) underwent iridium-

Table 1
Preparation of chiral α,α-diaryl methylammonium chlorides



Entry	R^1	R^2	R^3	Product	Yield (%)	ee (%)
1	CF_3	H	H	**10a**	82	95
2	CF_3	Me	Me	**10b**	80	93
3	CF_3	Me	CO_2Me	**10c**	71	90
4	CF_3	Me	Cl	**10d**	39	87
5	CF_3	OMe	Br	**10e**	22	80
6	NO_2	H	H	**10f**	89	91
7	NO_2	Me	Me	**10g**	78	90
8	NO_2	OMe	OMe	**10h**	86	88
9	NO_2	Me	CO_2Me	**10i**	79	74
10	NO_2	Me	Cl	**10j**	70	88
11	NO_2	OMe	Br	**10k**	66	88
12	NO_2	OMe	CF_3	**10l**	19	92
13	CO_2Me	H	H	**10m**	87	85
14	CO_2Me	Me	Me	**10n**	82	87
15	CO_2Me	OMe	OMe	**10o**	83	79
16	CO_2Me	Me	Cl	**10p**	56	90
17	CO_2Me	OMe	Br	**10q**	61	66

catalyzed borylation to give aryl boronic ester **6c** (Scheme 4). After the removal of volatile materials under high vacuum, rhodium catalyst, **8a** (1 equiv), NEt_3, and solvent were added to the same reaction vessel to provide sulfinyl amine **11** in 75% yield and 87% de.[50] This yield of sulfinyl amine and de is similar to the yield of ammonium salt and ee of the hydrolyzed amine from the protocol in which the boronic ester is purified in between the two steps.



Scheme 4. One-pot conversion of sulfinyl amine **11**. [a]1,3,5-Trimethoxybenzene (6%) was used as an internal standard.

3. Summary

We have demonstrated that aryl pinacol boronates generated from C–H borylation are competent nucleophiles for rhodium-catalyzed additions to chiral sulfinimines to give enantioenriched α,α-diaryl methylammonium chlorides in moderate to good yields. Notably, the combination of iridium-catalyzed arene borylation, followed by rhodium-catalyzed additions to imines, allows for facile preparation of 3,5-disubstituted α,α-diaryl methylammonium chlorides, a reagent class that would be difficult to access through other means.

4. Experimental section

4.1. Materials and methods

All reactions, unless otherwise noted were performed in oven-dried 20 mL vials fitted with caps bearing TFE/silicone septa. Organic solutions were concentrated either under high vacuum or by rotary evaporation. Thin-layer chromatography was performed using glass plates pre-coated to a depth of 0.25 mm with 230–400 mesh silica gel impregnated with a fluorescent indicator (254 nm). Compounds were visualized using *para*-anisaldehyde stain. THF was purified by passage through two packed columns of neutral alumina under an argon atmosphere. $[Ir(cod)Cl]_2$[51] and $[Rh(cod)(CH_3CN)_2]BF_4$[52] were prepared as previously described. Triethylamine was distilled from calcium hydride at atmospheric pressure. All other reagents were obtained from commercial sources and used without further purification. ^1H, ^{13}C, and ^{19}F NMR spectra were recorded on a Varian 500, a Varian VXR 500, a Varian Inova 500, or a Varian Unity Inova 600 NMR spectrometer. ^1H chemical shifts are reported in parts per million (δ scale) downfield from tetramethylsilane and are referenced to the residual protium in the NMR solvent. ^{13}C NMR chemical shifts are reported in parts per million (δ scale) downfield from tetramethylsilane and are referenced to the ^{13}C resonance of the solvent. ^{19}F NMR chemical shifts are reported in parts per million (δ scale) and are referenced to external standard: C_6F_6 in $CDCl_3$ at $\delta=-163$ ppm. Data are presented as follows: chemical shift, multiplicity (s=singlet, d=doublet, t=triplet, q=quartet, m=multiplet and/or multiple resonances), integration, coupling constant in hertz (Hz). HPLC analyses were carried out on a Waters chromatography system (1525 binary pump, 717+ autosampler, 2487 dual wavelength detector).

4.2. General procedure for the preparation of aryl boronic esters (6a–6g)

An oven-dried 20 mL sealable reaction vessel was cooled under nitrogen, and then charged with B_2pin_2 (3.00 mmol), dtbpy (8.0 mg, 0.030 mmol), *n*-dodecane (100 μL, 0.440 mmol), anhydrous cyclohexane (3.6 mL), and arene (6.00 mmol). The solution was then degassed by freeze pump thaw using liquid nitrogen four times. To the resulting solution was added HBpin (43.5 μL, 0.300 mmol) and $[Ir(cod)Cl]_2$ (10.1 mg, 0.015 mmol). The reaction vessel was then sealed and heated at 80 °C. Reactions were monitored by GC. After no further consumption of arene was observed, the reactions were concentrated under high vacuum to remove volatile materials. The resulting crude aryl boronic esters were used in subsequent reactions without further purification.

4.3. (*S*)-2-Methyl-propane-2-sulfinic acid 1-(4-trifluoromethyl-phenyl)-meth-(*E*)-ylideneamide (8a)

An oven-dried 100 mL Schlenk flask was cooled under nitrogen and charged with (*S*)-*tert*-butanesulfinamide (1.86 g, 15.4 mmol), tetrahydrofuran (30 mL), and 4-trifluoromethylbenzaldehyde (2.00 mL, 14.6 mmol). Titanium(IV) ethoxide (6.75 mL, 32.2 mmol) was added, and the solution was allowed to stir at room temperature for 19 h. After that time, the reaction was transferred to a 500 mL Erlynmeyer flask and diluted with saturated aqueous sodium bicarbonate (100 mL). The resulting biphasic suspension was filtered though Celite, washed with ethyl acetate (125 mL), and transferred to a separatory funnel to remove the aqueous layer. The resulting organic solution was dried over magnesium sulfate, filtered, and concentrated by rotary evaporation. Further drying under high vacuum gave **8a** (3.61 g, 89%) as an off white solid. R_f=0.39 in 20% ethyl acetate in hexane; ^1H NMR ($CDCl_3$) δ 8.62 (s, 1H), 7.96 (d, 2H, J=8.2 Hz), 7.73 (d, 2H, J=8.2 Hz), 1.27 (s, 9H); ^{13}C NMR ($CDCl_3$) δ 161.4, 136.8, 133.7 (q, J=33.2 Hz), 129.5, 125.9 (q, J=3.5 Hz), 123.6 (q, J=272.9 Hz), 58.1, 22.6; ^{19}F NMR ($CDCl_3$) δ −64.3; HRMS (ESI) m/z: Calcd for $C_{12}H_{15}F_3NOS$ $(M+H)^+$ 278.0826, found 278.0823; Anal. Calcd for $C_{12}H_{14}F_3NOS$ C, 51.97%; H, 5.09%; N, 5.05%; found C, 51.82%; H, 5.16%; N, 4.96%.

4.4. (*S*)-2-Methyl-propane-2-sulfinic acid 1-(4-nitro-phenyl)-meth-(*E*)-ylideneamide (8b)

An oven-dried 100 mL Schlenk flask was cooled under nitrogen and charged with (*S*)-*tert*-butanesulfinamide (1.68 g, 13.9 mmol), tetrahydrofuran (27 mL), and 4-nitrobenzaldehyde (2.00 g, 13.2 mmol). Titanium(IV) ethoxide (6.10 mL, 29.1 mmol) was added, and the solution was allowed to stir at room temperature for 23 h. After that time, the reaction was transferred to a 500 mL Erlynmeyer flask and diluted with saturated aqueous sodium bicarbonate (100 mL). The resulting biphasic suspension was filtered though Celite, washed with ethyl acetate (125 mL), and transferred to a separatory funnel to remove the aqueous layer. The resulting organic solution was dried over magnesium sulfate, filtered, and concentrated by rotary evaporation. Further drying under high vacuum gave **8b** (3.09 g, 91%) as a yellow solid. R_f=0.18 in 20% ethyl acetate in hexane; ^{1}H NMR ($CDCl_3$) δ 8.65 (s, 1H), 8.31 (d, 2H, J=8.6 Hz), 8.01 (d, 2H, J=8.6 Hz), 1.27 (s, 9H); ^{13}C NMR ($CDCl_3$) δ 160.6, 149.8, 138.81, 123.0, 124.2, 58.4, 22.6; HRMS (ESI) m/z: Calcd for $C_{11}H_{15}N_2O_3S$ $(M+H)^+$ 255.0803, found 255.0797; Anal. Calcd for $C_{11}H_{14}N_2O_3S$ C, 51.95%; H, 5.55%; N, 11.02%; found C, 51.72%; H, 5.47%; N, 10.79%.

4.5. (*S*)-2-Methyl-propane-2-sulfinic acid 1-(4-methoxy-carbonyl-phenyl)-meth-(*E*)-ylideneamide (8c)

An oven-dried 25 mL Schlenk flask was cooled under nitrogen and charged with (*S*)-*tert*-butanesulfinamide (650 mg, 5.14 mmol), tetrahydrofuran (10 mL), and methyl 4-formylbenzoate (844 mg, 5.14 mmol). Titanium(IV) methoxide (2.00 g, 11.3 mmol) was added, and the solution was allowed to stir at room temperature for 18 h. To the crude reaction was added a mixture of sodium bicarbonate (5.00 g, 59.5 mmol) in methanol (50 mL). After stirring for 20 min, solids were removed by filtration though Celite, and the resulting organic solution was concentrated by rotary evaporation. Purified product was obtained by silica gel chromatography, eluting with 14% ethyl acetate in hexane, and then 25% ethyl acetate in hexane, to give **8c** (758 mg, 55%) as a white solid. R_f=0.20 in 20% ethyl acetate in hexane; ^{1}H NMR (500, $CDCl_3$) δ 8.61 (s, 1H), 8.11 (d, 2H, J=8.4 Hz), 7.89 (d, 2H, J=8.4 Hz), 3.93 (s, 3H), 1.26 (s, 9H); ^{13}C NMR ($CDCl_3$) δ 166.2, 161.8, 137.4, 133.2, 130.1, 129.1, 58.1, 52.4, 22.6; HRMS (ESI) m/z: Calcd for $C_{13}H_{18}NO_3S$ $(M+H)^+$ 268.1007, found 268.1002; Anal. Calcd for $C_{13}H_{17}NO_3S$ C, 58.40%; H, 6.41%; N, 5.24%; found C, 58.24%; H, 6.50%; N, 5.26%.

4.6. General procedure for the preparation of α,α-diaryl methylammonium chlorides (10a–10q)

Inside a nitrogen-filled glove box, a 20 mL vial was charged with $[Rh(cod)(CH_3CN)_2]BF_4$ (9.5 mg, 0.025 mmol), sulfinimine (0.500 mmol), aryl boronic ester (1.00 mmol), anhydrous dioxane (2.4 mL), and triethylamine (140 μL, 1.00 mmol). The solution was then removed from the glove box, whereupon water (2.4 mL) was added. After TLC showed no further consumption of sulfinimine (approximately 18 h), the crude mixture was partitioned between dichloromethane (20 mL) and 0.1 M aqueous sodium hydrogensulfate (20 mL). After removing the organic layer, the aqueous phase was extracted with dichloromethane (20 mL×2). The combined organic material was then dried over magnesium sulfate, filtered, and concentrated in a 20 mL vial. To the concentrated residue was added anhydrous methanol (4 mL) and then 4.0 M hydrogen chloride in dioxane (4 mL, 16 mmol). After stirring for 90 min, the reaction was concentrated to dryness by rotary evaporation, whereupon the residue was triturated with diethyl ether (5 mL) and allowed to stir over night (approximately 16 h). The solid product was then collected in a fritted funnel, rinsing with excess diethyl ether.

4.7. (*S*)-*C*-Phenyl-*C*-(4-trifluoromethyl-phenyl)-methyl-ammonium chloride (10a)

The general procedure was followed with sulfinimine **8a** (139 mg, 0.501 mmol) and aryl boronic ester **6a** (207 mg, 1.02 mmol) to give **10a** (118 mg, 82%) as a white solid. ^{1}H NMR (CD_3OD) δ 7.77 (d, 2H, J=8.5 Hz), δ 7.63 (d, 2H, J=8.5 Hz), δ 7.40–7.50 (m, 5H), δ 5.80 (s, 1H); ^{13}C NMR (CD_3OD) δ 142.86, 137.88, 131.99 (q, J=32.4 Hz), 130.50, 130.37, 129.19, 128.54, 127.17 (q, J=3.8 Hz), 125.33 (q, J=271.9 Hz), 58.81; ^{19}F NMR (CD_3OD) δ −64.6; HRMS (ESI) m/z: Calcd for $C_{14}H_{13}F_3N$ $(M-Cl)^+$ 252.1000, found 252.1006; HPLC analysis of acetylated **10a**: Diacel CHIRACEL OD-H, hexane/isopropanol 9:1, flow rate=0.5 mL/min, detection wavelength=230 nm.

4.8. (*R*)-*C*-(3,5-Dimethyl-phenyl)-*C*-(4-trifluoromethyl-phenyl)-methyl-ammonium chloride (10b)

The general procedure was followed with sulfinimine **8a** (138 mg, 0.497 mmol) and aryl boronic ester **6b** (232 mg, 0.998 mmol) to give **10b** (126 mg, 80%) as a white solid. ^{1}H NMR (CD_3OD) δ 7.76 (d, 2H, J=8.3 Hz), 7.62 (d, 2H, J=8.3 Hz), 7.07 (s, 1H), 7.04 (s, 2H), 5.68 (s, 1H), 2.32 (s, 6H); ^{13}C NMR (CD_3OD) δ 143.0, 140.5, 137.7, 131.9 (q, J=32.5 Hz), 131.7, 129.1, 127.1 (q, J=3.8 Hz), 126.1, 125.4 (q, J=271.8 Hz), 58.8, 21.3; ^{19}F NMR (CD_3OD) δ −64.6; HRMS (ESI) m/z: Calcd for $C_{16}H_{17}F_3N$ $(M-Cl)^+$ 280.1313, found 280.1314; HPLC analysis of acetylated **10b**: Diacel CHIRACEL OD-H, hexane/isopropanol 9:1, flow rate=0.5 mL/min, detection wavelength=230 nm.

4.9. (*R*)-*C*-(3-Methoxycarbonyl-5-methyl-phenyl)-*C*-(4-trifluoromethyl-phenyl)-methyl-ammonium chloride (10c)

The general procedure was followed with sulfinimine **8a** (138 mg, 0.497 mmol) and aryl boronic ester **6d** (264 mg, 1.00 mmol) to give **10c** (126 mg, 73%) as a beige solid. ^{1}H NMR (CD_3OD) δ 7.93 (s, 1H), 7.90 (s, 1H), 7.78 (d, 2H, J=8.0 Hz), 7.64 (d, 2H, J=8.0 Hz), 7.52 (s, 1H), 5.86 (s, 1H), 3.89 (s, 3H), 2.42 (s, 3H); ^{13}C NMR (CD_3OD) δ 167.8, 142.5, 141.4, 138.5, 133.9, 132.5, 133.9, 132.4 (q, J=32.6 Hz), 131.8, 129.2, 127.3 (q, J=3.8 Hz), 126.4, 125.3 (q, J=271.5 Hz), 58.4, 52.9, 21.3; ^{19}F NMR (CD_3OD) δ −64.8; HRMS (ESI) m/z: Calcd for $C_{17}H_{17}F_3NO_2$ $(M-Cl)^+$ 324.1211, found 324.1202; HPLC analysis of acetylated **10c**: Diacel CHIRACEL OD-H, hexane/isopropanol 9:1, flow rate=0.5 mL/min, detection wavelength=230 nm.

4.10. (*R*)-*C*-(3-Chloro-5-methyl-phenyl)-*C*-(4-trifluoromethyl-phenyl)-methyl-ammonium chloride (10d)

The general procedure was followed with sulfinimine **8a** (138 mg, 0.497 mmol) and aryl boronic ester **6e** (252 mg, 0.996 mmol) to give **10d** (66 mg, 39%) as an off white solid. ^{1}H NMR (CD_3OD) δ 7.78 (d, 2H, J=8.1 Hz), 7.64 (d, 2H, J=8.1 Hz), 7.28 (m, 2H), 7.22 (s, 1H), 5.77 (s, 1H), 2.36 (s, 3H); ^{13}C NMR (CD_3OD) δ 142.9, 142.3, 139.8, 136.0, 132.1 (q, J=32.3 Hz), 130.9, 129.2, 127.7, 127.3 (q, J=3.7 Hz), 125.7, 125.3 (q, J=271.8 Hz), 58.2, 21.2; ^{19}F NMR (CD_3OD) δ −64.8; HRMS (ESI) m/z: Calcd for $C_{15}H_{14}ClF_3N$ $(M-Cl)^+$ 300.0767, found 300.0768; HPLC analysis of acetylated **10d**: Diacel CHIRACEL OD-H, hexane/isopropanol 9:1, flow rate=0.5 mL/min, detection wavelength=230 nm.

4.11. (*R*)-*C*-(3-Bromo-5-methoxy-phenyl)-*C*-(4-trifluoro-methyl-phenyl)-methyl-ammonium chloride (10e)

The general procedure was followed with sulfinimine **8a** (137 mg, 0.494 mmol) and aryl boronic ester **6f** (312 mg, 0.998 mmol) to give **10e** (44 mg, 22%) as a white solid. ^{1}H NMR (CD_3OD) δ 7.79 (d, 2H, J=8.4 Hz), 7.62 (m, 2H), 7.17 (m, 2H), 7.01 (br s, 1H), 5.75 (s, 1H), 3.81 (s, 3H); ^{13}C NMR (CD_3OD) δ 162.6, 142.2,

141.0, 132.2 (q, J=32.5 Hz), 129.1, 127.3 (q, J=3.8 Hz), 125.3 (q, J=271.2 Hz), 124.7, 123.4, 118.8, 113.7, 58.1, 56.4; ^{19}F NMR (CD_3OD) δ −64.8; HRMS (ESI) m/z: Calcd for $C_{15}H_{14}BrF_3NO$ $(M-Cl)^+$ 360.0211, found 360.0210; HPLC analysis of acetylated **10e**: Diacel CHIRACEL OD-H, hexane/isopropanol 9:1, flow rate=1.0 mL/min, detection wavelength=230 nm.

4.12. (*S*)-*C*-(4-Nitro-phenyl)-*C*-phenyl-methyl-ammonium chloride (10f)

The general procedure was followed with sulfinimine **8b** (128 mg, 0.503 mmol) and aryl boronic ester **6a** (203 mg, 0.994 mmol) to give **10f** (119 mg, 89%) as a pale yellow solid. ^{1}H NMR (CD_3OD) δ 8.32 (m, 2H), 7.70 (m, 2H), 7.41–7.50 (m, 5H), 5.86 (s, 1H); ^{13}C NMR (CD_3OD) δ 149.3, 145.2, 137.4, 130.4, 130.4, 129.5, 128.4, 125.1, 58.5; HRMS (ESI) m/z: Calcd for $C_{13}H_{13}N_2O_2$ $(M-Cl)^+$ 229.0977, found 229.0968; HPLC analysis of acetylated **10f**: Diacel CHIRACEL OD-H, hexane/isopropanol 9:1, flow rate=1.0 mL/min, detection wavelength=230 nm.

4.13. (*R*)-*C*-(3,5-Dimethyl-phenyl)-*C*-(4-nitro-phenyl)-methyl-ammonium chloride (10g)

The general procedure was followed with sulfinimine **8b** (126 mg, 0.496 mmol) and aryl boronic ester **6b** (234 mg, 1.01 mmol) to give **10g** (114 mg, 78%) as a pale yellow solid. ^{1}H NMR (CD_3OD) δ 8.30 (m, 2H), 7.68 (m, 2H), 7.07 (s, 1H), 7.05 (s, 2H), 5.75 (s, 1H), 2.32 (s, 6H); ^{13}C NMR (CD_3OD) δ 149.4, 145.5, 140.6, 137.4, 131.9, 129.6, 126.16, 125.2, 58.6, 21.3; HRMS (ESI) m/z: Calcd for $C_{15}H_{17}N_2O_2$ $(M-Cl)^+$ 257.1290, found 257.1291; HPLC analysis of acetylated **10g**: Diacel CHIRACEL OD-H, hexane/isopropanol 9:1, flow rate=0.5 mL/min, detection wavelength=230 nm.

4.14. (*R*)-*C*-(3,5-Dimethoxy-phenyl)-*C*-(4-nitro-phenyl)-methyl-ammonium chloride (10h)

The general procedure was followed with sulfinimine **8b** (128 mg, 0.503 mmol) and aryl boronic ester **6c** (264 mg, 1.00 mmol) to give **10h** (140 mg, 86%) as a yellow solid. ^{1}H NMR (CD_3OD) δ 8.31 (m, 2H), 7.70 (m, 2H), 6.62 (d, 2H, J=2.2 Hz), 6.52 (t, 1H, J=2.2 Hz), 5.76 (s, 1H), 3.78 (s, 6H); ^{13}C NMR (CD_3OD) δ 163.2, 149.4, 145.2, 139.5, 129.7, 125.2, 106.6, 101.6, 58.6, 56.0; HRMS (ESI) m/z: Calcd for $C_{15}H_{17}N_2O_4$ $(M-Cl)^+$ 289.1188, found 289.1189; HPLC analysis of acetylated **10h**: Diacel CHIRACEL AD-H, hexane/isopropanol 9:1, flow rate=1.0 mL/min, detection wavelength=230 nm.

4.15. (*R*)-*C*-(3-Methoxycarbonyl-5-methyl-phenyl)-*C*-(4-nitro-phenyl)-methyl-ammonium chloride (10i)

The general procedure was followed with sulfinimine **8b** (128 mg, 0.502 mmol) and aryl boronic ester **6d** (276 mg, 0.999 mmol) to give **10i** (133 mg, 79%) as a yellow solid. ^{1}H NMR (CD_3OD) δ 8.32 (m, 2H), 7.93 (s, 1H), 7.90 (s, 1H), 7.70 (m, 2H), 7.54 (s, 1H), 5.92 (s, 1H), 3.89 (s, 3H), 2.42 (s, 3H); ^{13}C NMR (CD_3OD) δ 167.7, 149.6, 144.9, 141.5, 138.2, 133.9, 132.6, 131.9, 129.8, 126.5, 125.4, 58.2, 52.9, 21.3; HRMS (ESI) m/z: Calcd for $C_{16}H_{17}N_2O_4$ $(M-Cl)^+$ 301.1188, found 301.1184; HPLC analysis of acetylated **10i**: Diacel CHIRACEL AD-H, hexane/isopropanol 9:1, flow rate=1.0 mL/min, detection wavelength=230 nm.

4.16. (*R*)-*C*-(3-Chloro-5-methyl-phenyl)-*C*-(4-nitro-phenyl)-methyl-ammonium chloride (10j)

The general procedure was followed with sulfinimine **8b** (127 mg, 0.498 mmol) and aryl boronic ester **6e** (254 mg, 1.00 mmol) to give **10j** (110 mg, 70%) as an orange solid. ^{1}H NMR (CD_3OD) δ 8.32 (m, 2H), 7.69 (m, 2H), 7.29 (m, 2H), 7.23 (s, 1H), 5.84 (s, 1H), 2.36 (s, 3H); ^{13}C NMR (CD_3OD) δ 149.6, 144.8, 143.0, 139.4, 136.1, 131.1, 129.7, 127.8, 125.7, 125.3, 58.0, 21.2; HRMS (ESI) m/z: Calcd for $C_{14}H_{14}ClN_2O_2$ $(M-Cl)^+$ 277.044, found 277.0745; HPLC analysis of acetylated **10j**: Diacel CHIRACEL OD-H, hexane/isopropanol 9:1, flow rate=0.5 mL/min, detection wavelength=230 nm.

4.17. (*R*)-*C*-(3-Bromo-5-methoxy-phenyl)-*C*-(4-nitro-phenyl)-methyl-ammonium chloride (10k)

The general procedure was followed with sulfinimine **8b** (126 mg, 0.497 mmol) and aryl boronic ester **6f** (314 mg, 1.00 mmol) to give **10k** (122 mg, 66%) as a yellow solid. ^{1}H NMR (CD_3OD) δ 8.33 (m, 2H), 7.68 (m, 2H), 7.19 (m, 2H), 7.03 (m, 1H), 5.82 (s, 1H), 3.81 (s, 3H); ^{13}C NMR (CD_3OD) δ 162.6, 149.6, 144.6, 140.7, 129.7, 125.4, 124.8, 123.5, 119.0, 113.8, 58.1, 56.6; HRMS (ESI) m/z: Calcd for $C_{14}H_{14}BrN_2O_3$ $(M-Cl)^+$ 337.0188, found 337.0181; HPLC analysis of acetylated **10k**: Diacel CHIRACEL AD-H, hexane/isopropanol 9:1, flow rate=1.0 mL/min, detection wavelength=230 nm.

4.18. (*R*)-*C*-(3-Methoxy-5-trifluoromethyl-phenyl)-*C*-(4-nitro-phenyl)-methyl-ammonium chloride (10l)

The general procedure was followed with sulfinimine **8b** (128 mg, 0.501 mmol) and aryl boronic ester **6g** (303 mg, 1.00 mmol) to give **10l** (33 mg, 19%) as a yellow solid. ^{1}H NMR (CD_3OD) δ 8.33 (m, 2H), 7.12 (m, 2H), 7.36 (s, 1H), 7.34 (s, 1H), 7.26 (s, 1H), 5.96 (s, 1H), 3.88 (s, 3H); ^{13}C NMR (CD_3OD) δ 162.3, 149.6, 144.5, 140.4, 134.0 (q, J=32.8 Hz), 129.8, 125.4, 125.0 (q, J=271.9 Hz), 118.2, 117.1 (q, J=4.0 Hz), 112.7 (q, J=4.0 Hz), 58.1, 56.6; ^{19}F NMR (CD_3OD) δ −64.7; HRMS (ESI) m/z: Calcd for $C_{15}H_{14}F_3N_2O_3$ $(M-Cl)^+$ 327.0957, found 327.0950; HPLC analysis of acetylated **10l**: Diacel CHIRACEL OD-H, hexane/isopropanol 9:1, flow rate=0.5 mL/min, detection wavelength=230 nm.

4.19. (*S*)-*C*-(4-Methoxycarbonyl-phenyl)-*C*-phenyl-methyl-ammonium chloride (10m)

The general procedure was followed with sulfinimine **8c** (134 mg, 0.499 mmol) and aryl boronic ester **6a** (203 mg, 0.980 mmol) to give **10m** (120 mg, 87%) as a white solid. ^{1}H NMR (500, CD_3OD) δ 8.08 (m, 2H), 7.56 (m, 2H), 7.39–7.49 (m, 5H), 5.76 (s, 1H), 3.90 (s, 3H); ^{13}C NMR (126, CD_3OD) δ 167.7, 143.5, 138.0, 131.8, 131.3, 130.4, 130.3, 128.6, 128.5, 59.0, 52.8; HRMS (ESI) m/z: Calcd for $C_{15}H_{16}NO_2$ $(M-Cl)^+$ 242.1181, found 242.1172; HPLC analysis of acetylated **10m**: Diacel CHIRACEL OD-H, hexane/isopropanol 9:1, flow rate=0.5 mL/min, detection wavelength=230 nm.

4.20. (*R*)-*C*-(3,5-Dimethyl-phenyl)-*C*-(4-methoxycarbonyl-phenyl)-methyl-ammonium chloride (10n)

The general procedure was followed with sulfinimine **8c** (133 mg, 0.498 mmol) and aryl boronic ester **6b** (233 mg, 1.00 mmol) to give **10n** (126 mg, 82%) as a beige solid. ^{1}H NMR (CD_3OD) δ 8.07 (d, 2H, J=8.2 Hz), 7.53 (d, 2H, J=8.3 Hz), 7.06 (s, 1H), 7.03 (s, 2H), 5.65 (s, 1H), 3.90 (s, 3H), 2.31 (s, 6H); ^{13}C NMR (CD_3OD) δ 167.7, 143.7, 140.4, 137.9, 131.8, 131.7, 131.2, 128.5, 126.1, 59.0, 52.8, 21.3; HRMS (ESI) m/z: Calcd for $C_{17}H_{20}NO_2$ $(M-Cl)^+$ 270.1494, found 270.1496; HPLC analysis of acetylated **10n**: Diacel CHIRACEL OD-H, hexane/isopropanol 9:1, flow rate=0.5 mL/min, detection wavelength=230 nm.

4.21. (*R*)-*C*-(3,5-Dimethoxy-phenyl)-*C*-(4-methoxycarbonyl-phenyl)-methyl-ammonium chloride (10o)

The general procedure was followed with sulfinimine **8c** (133 mg, 0.497 mmol) and aryl boronic ester **6c** (264 mg,

1.00 mmol) to give **10o** (140 mg, 83%) as an off white solid. ^{1}H NMR (CD_3OD) δ 8.08 (d, 2H, J=8.4 Hz), 7.56 (d, 2H, J=8.4 Hz), 6.60 (d, 2H, J=2.0 Hz), 6.51 (t, 1H, J=2.0 Hz), 5.67 (s, 1H), 3.90 (s, 3H), 3.77 (s, 6H); ^{13}C NMR (CD_3OD) δ 167.7, 163.1, 143.3, 140.0, 131.9, 131.3, 128.5, 106.5, 101.4, 59.0, 56.0, 52.8; HRMS (ESI) m/z: Calcd for $C_{17}H_{20}NO_4$ $(M-Cl)^+$ 302.1392, found 302.1395; HPLC analysis of acetylated **6o**: Diacel CHIRACEL AD-H, hexane/isopropanol 9:1, flow rate=1.0 mL/min, detection wavelength=230 nm.

4.22. (*R*)-*C*-(3-Chloro-5-methyl-phenyl)-*C*-(4-methoxycarbonyl-phenyl)-methyl-ammonium chloride (10p)

The general procedure was followed with sulfinimine **8c** (133 mg, 0.498 mmol) and aryl boronic ester **6e** (253 mg, 1.00 mmol) to give **10p** (91 mg, 56%) as a red solid. ^{1}H NMR (CD_3OD) δ 8.09 (d, 2H, J=8.1 Hz), 7.55 (d, 2H, J=8.1 Hz), 7.27 (s, 2H), 7.21 (s, 1H), 5.74 (s, 1H), 3.90 (s, 3H), 2.35 (s, 3H); ^{13}C NMR (CD_3OD) δ 167.6, 142.9, 142.9, 139.9, 136.0, 132.0, 131.4, 130.8, 128.6, 127.7, 125.7, 58.4, 52.8, 21.2; HRMS (ESI) m/z: Calcd for $C_{16}H_{17}ClNO_2$ $(M-Cl)^+$ 290.0948, found 290.0958; HPLC analysis of acetylated **10p**: Diacel CHIRACEL OD-H, hexane/isopropanol 9:1, flow rate=0.5 mL/min, detection wavelength=230 nm.

4.23. (*R*)-*C*-(3-Bromo-5-methoxy-phenyl)-*C*-(4-methoxycarbonyl-phenyl)-methyl-ammonium chloride (10q)

The general procedure was followed with sulfinimine **8c** (133 mg, 0.498 mmol) and aryl boronic ester **6f** (315 mg, 1.01 mmol) to give **10q** (118 mg, 61%) as a beige solid. ^{1}H NMR (CD_3OD) δ 8.09 (d, 2H, J=8.3 Hz), 7.55 (d, 2H, J=8.2 Hz), 7.18 (s, 1H), 7.16 (s, 1H), 7.02 (s, 1H), 5.74 (s, 1H), 3.90 (s, 3H), 3.80 (s, 3H); ^{13}C NMR (CD_3OD) δ 167.6, 162.6, 142.8, 141.1, 132.1, 131.4, 128.6, 124.7, 123.5, 118.8, 113.7, 58.3, 56.4, 52.8; HRMS (ESI) m/z: Calcd for $C_{16}H_{17}BrNO_3$ $(M-Cl)^+$ 350.0392, found 350.0392; HPLC analysis of acetylated **10q**: Diacel CHIRACEL AD-H, hexane/isopropanol 9:1, flow rate=1.0 mL/min, detection wavelength=230 nm.

4.24. General procedure for the acetylation of α,α-diaryl methylammonium chloride products (10a–10q) for chiral HPLC analysis

A 1 dram vial was charged with α,α-diaryl methylammonium chloride (0.010 mmol), toluene (100 μL), acetic anhydride (1.4 μL, 0.015 mmol), and triethylamine (4.2 μL, 0.030 mmol) and allowed to stir. After 40 min, diethyl ether (500 μL) was added, and the crude mixture was filtered though a short plug of silica gel, rinsing with more diethyl ether (3×500 μL). The combined filtrates were concentrated by rotary evaporation and then under high vacuum to give solid amide products that were used without further purification.

4.25. One-pot conversion of *meta*-xylene to sulfinyl amine 11

Inside a nitrogen-filled glove box, 20 mL vial was charged with $[Ir(cod)Cl]_2$ (1.7 mg, 0.0026 mmol), dtbpy (1.5 mg, 0.0056 mmol), 1,3,5-trimethoxybenzene (9.6 mg, 0.057 mmol), B_2pin_2 (215 mg, 0.847 mmol), THF (1.0 mL), and *meta*-xylene (122 μL, 0.997 mmol). The resulting brown solution was heated at 80 °C for 12 h, after which time volatile materials were removed on high vacuum. To the crude aryl boronic ester was added **8a** (140 mg, 0.504 mmol), $[Rh(cod)(CH_3CN)_2]BF_4$ (9.6 mg, 0.025 mmol), dioxane (2.4 mL), and triethylamine (140 μL, 1.00 mmol). The solution was then removed from the glove box, whereupon water (2.4 mL) was added. After 22 h, TLC showed no further reaction, and the crude material was diluted with water (50 mL), and extracted with ethyl acetate (2×50 mL). The combined organic material was then dried over magnesium sulfate, filtered, and concentrated. Purified product was obtained by silica gel chromatography, eluting with 14% ethyl acetate in hexane, and then 25% ethyl acetate in hexane, to give **11** (144.3 mg, 75%) as a white solid. ^{1}H NMR of the isolated material indicated 87% de by integration of the benzylic protons. R_f=0.57 in 25% ethyl acetate in hexane; ^{1}H NMR (500, $CDCl_3$) δ 7.58 (d, 2H, J=8.3 Hz), 7.51 (d, 2H, J=8.3 Hz), 6.98 (s, 2H), 6.92 (s, 1H), 5.60 (d, 1H, J=3.0 Hz), 3.70 (d, 1H, J=2.9 Hz), 2.29 (s, 6H), 1.27 (s, 9H); ^{13}C NMR ($CDCl_3$) δ 146.6, 140.3, 138.2, 129.7 (q, J=32.1 Hz), 129.6, 127.5, 125.7 (q, J=3.7 Hz), 125.5, 123.9 (q, J=272.0 Hz), 61.8, 55.9, 22.5, 21.2; ^{19}F NMR ($CDCl_3$) δ −63.8; HRMS (ESI) m/z: Calcd for $C_{20}H_{25}F_3NOS$ $(M+H)^+$ 384.1609, found 384.1602.

Acknowledgements

We thank the NSF for funding, Advanced Asymmetrics for the gift of (*S*)-*tert*-butanesulfinamide and both Frontier Scientific and AllyChem for gifts of bis(pinacolato)diboron. We thank Dan Weix for many helpful discussions.

References and notes

1. *Friedel–Crafts Alkylation*; Sheldon, R. A., van Bekkum, H., Eds.; Wiley-VCH: New York, NY, 2001.
2. Zaugg, H. E.; Horrom, B. W. *J. Am. Chem. Soc.* **1958**, *80*, 4317.
3. Ross, S. D.; Finkelstein, M.; Petersen, R. C. *J. Org. Chem.* **1966**, *31*, 133.
4. Sataty, I.; Peled, N.; Ben-Ishai, D. *Isr. J. Chem.* **1976**, *13*, 145.
5. Ali, I. A. I.; El Ashry, E. S. H.; Schmidt, R. R. *Tetrahedron* **2004**, *60*, 4773.
6. Johannsen, M. *Chem. Commun.* **1999**, 2233.
7. Saaby, S.; Fang, X.; Gartherhood, N.; Jørgensen, K. A. *Angew. Chem., Int. Ed.* **2000**, *39*, 4114.
8. Jiang, B.; Huang, Z.-G. *Synthesis* **2005**, 2198.
9. Abid, M.; Teixeira, L.; Török, B. *Org. Lett.* **2008**, *10*, 933.
10. Murphy, J. M.; Tzschucke, C. C.; Hartwig, J. F. *Org. Lett.* **2007**, *9*, 757.
11. Tzschucke, C. C.; Murphy, J. M.; Hartwig, J. F. *Org. Lett.* **2007**, *9*, 761.
12. Murphy, J. M.; Liao, X.; Hartwig, J. F. *J. Am. Chem. Soc.* **2007**, *129*, 15434.
13. Gnas, Y.; Glorius, F. *Synthesis* **2006**, 1899.
14. Enders, D.; Schubert, H.; Nuebling, C. *Angew. Chem., Int. Ed. Engl.* **1986**, *98*, 1118.
15. Laschat, S.; Kunz, H. *J. Org. Chem.* **1991**, *56*, 5883.
16. Higashiyama, K.; Inoue, H.; Takahashi, H. *Tetrahedron Lett.* **1992**, *33*, 235.
17. Boezio, A. A.; Solberghe, G.; Lauzon, C.; Charette, A. B. *J. Org. Chem.* **2003**, *68*, 3241.
18. Zhou, P.; Chen, B.-C.; Davis, F. A. *Tetrahedron* **2004**, *60*, 8003.
19. Liu, G.; Cogan, D. A.; Ellman, J. A. *J. Am. Chem. Soc.* **1997**, *119*, 9913.
20. Davis, F. A.; Zhang, Y.; Andemichael, Y.; Fang, T.; Fanelli, D. L.; Zhang, H. *J. Org. Chem.* **1999**, *64*, 1403.
21. Ellman, J. A.; Owens, T. D.; Tang, T. P. *Acc. Chem. Res.* **2002**, *35*, 984.
22. Tang, T. P.; Ellman, J. A. *J. Org. Chem.* **1999**, *64*, 12.
23. Wang, Y.; He, Q.-F.; Wang, H.-W.; Zhou, X.; Huang, Z.-Y.; Qin, Y. *J. Org. Chem.* **2006**, *71*, 1588.
24. Truong, V. L.; Menard, M. S.; Dion, I. *Org. Lett.* **2007**, *9*, 683.
25. Chemla, F.; Ferreira, F. *J. Org. Chem.* **2004**, *69*, 8244.
26. Sun, X.-W.; Xu, M.-H.; Lin, G.-Q. *Org. Lett.* **2006**, *8*, 4979.
27. Weix, D. J.; Shi, Y.; Ellman, J. A. *J. Am. Chem. Soc.* **2005**, *127*, 1092.
28. Bolshan, Y.; Batey, R. A. *Org. Lett.* **2005**, *7*, 1481.
29. *Boronic Acids: Preparation and Applications in Organic Synthesis and Medicine*; Hall, D. G., Ed.; Wiley-VCH: Weinheim, 2005.
30. Brown, H. C.; Cole, T. E. *Organometallics* **1983**, *2*, 1316.
31. Wong, K.-T.; Chien, Y.-Y.; Liao, Y.-L.; Lin, C.-C.; Chou, M.-Y.; Leung, M.-K. *J. Org. Chem.* **2002**, *67*, 1041.
32. Sharp, M. J.; Cheng, W.; Snieckus, V. *Tetrahedron Lett.* **1987**, *28*, 5093.
33. Ishiyama, T.; Murata, M.; Miyaura, N. *J. Org. Chem.* **1995**, *60*, 7508.
34. Chen, H.; Schlecht, S.; Semple, T. C.; Hartwig, J. F. *Science* **2000**, *287*, 1995.
35. Shimada, S.; Batsanov, A. S.; Howard, J. A. K.; Marder, T. B. *Angew. Chem., Int. Ed.* **2001**, *40*, 2168.
36. Iverson, C. N.; Smith, M. R., III. *J. Am. Chem. Soc.* **1999**, *121*, 7696.
37. Cho, J.-Y.; Tse, M. K.; Holmes, D.; Maleczka, R. E. J.; Smith, M. R., III. *Science* **2002**, *295*, 305.
38. Takagi, J.; Sato, K.; Hartwig, J. F.; Ishiyama, T.; Miyaura, N. *Tetrahedron Lett.* **2002**, *43*, 5649.
39. Ishiyama, T.; Takagi, J.; Yonekawa, Y.; Hartwig, J. F.; Miyaura, N. *Adv. Synth. Catal.* **2003**, *345*, 1103.
40. Ishiyama, T.; Nobuta, Y.; Hartwig, J. F.; Miyaura, N. *Chem. Commun.* **2003**, 2924.
41. Mertins, K.; Zapf, A.; Beller, M. *J. Mol. Catal. A: Chem.* **2004**, *207*, 21.
42. Chotana, G. A.; Rak, M. A.; Smith, M. R., III. *J. Am. Chem. Soc.* **2005**, *127*, 10539.

43. Ishiyama, T.; Takagi, J.; Ishida, K.; Miyaura, N.; Anastasi, N. R.; Hartwig, J. F. *J. Am. Chem. Soc.* **2002**, *124*, 390.
44. Ishiyama, T.; Takagi, J.; Hartwig, J. F.; Miyaura, N. *Angew. Chem., Int. Ed.* **2002**, *41*, 3056.
45. Boller, T. M.; Murphy, J. M.; Hapke, M.; Ishiyama, T.; Miyaura, N.; Hartwig, J. F. *J. Am. Chem. Soc.* **2005**, *127*, 14263.
46. For calculations on an oxidative addition pathway, see: Tamura, H.; Yamazaki, H.; Sato, H.; Sakaki, S. *J. Am. Chem. Soc.* **2003**, *125*, 16114.
47. For evidence of sigma bond metathesis in related C–H borylations, see: (a) Webster, C. E.; Fan, Y.; Hall, M. B.; Kunz, D.; Hartwig, J. F. *J. Am. Chem. Soc.* **2003**, *125*, 858; (b) Hartwig, J. F.; Cook, K. S.; Hapke, M.; Incarvito, C. D.; Fan, Y.; Webster, C. E.; Hall, M. B. *J. Am. Chem. Soc.* **2005**, *127*, 2538.
48. Smith, M. B.; March, J. *March's Advanced Organic Chemistry: Reactions, Mechanisms, and Structure*, 5th ed.; John Wiley and Sons: New York, NY, 2001.
49. This trend is consistent with previous studies on iridium-catalyzed arene borylation. See Refs. 43 and 44.
50. Percent diastereomeric excess was determined by ^{1}H NMR.
51. Crabtree, R. H.; Quirk, J. M.; Felkin, H.; Fillebeen-Khan, T. *Synth. React. Inorg. Met.-Org. Chem.* **1982**, *12*, 407.
52. Oi, S.; Moro, M.; Fukuhara, H.; Kawanishi, T.; Inoue, Y. *Tetrahedron* **2003**, *59*, 4351.