Tetrahedron: *Asymmetry* 19 (2008) 1778–1783

Contents lists available at ScienceDirect

Tetrahedron: *Asymmetry*

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

C_2-Symmetric tetrafluorobenzobarrelenes as highly efficient ligands for the iridium-catalyzed asymmetric annulation of 1,3-dienes with 2-formylphenylboron reagents

Takahiro Nishimura *, Yuichi Yasuhara, Makoto Nagaosa, Tamio Hayashi *

Department of Chemistry, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan

ARTICLE INFO

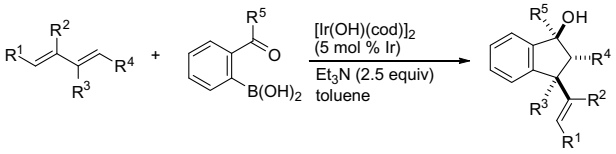
Article history:
Received 12 May 2008
Accepted 6 July 2008

ABSTRACT

New C_2-symmetric chiral diene ligands bearing a tetrafluorobenzobarrelene framework were prepared via a [4+2] cycloaddition of 1,4-bis((methoxymethoxy)methyl)benzene with tetrafluorobenzyne. The diene ligands realized the iridium-catalyzed enantioselective [3+2] annulation of 1,3-dienes with 2-formylphenylboron reagents giving 1-indanol derivatives in high yields and with high enantioselectivities.

1. Introduction

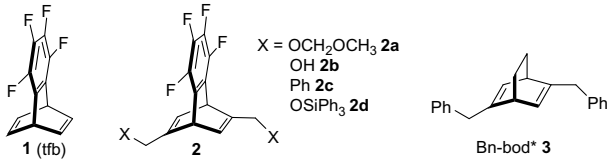
Recent findings of the distinctive features of chiral diene ligands for transition metal-catalyzed asymmetric reactions have expanded the possibility of ligand design for late transition metals.[1–5] The chiral dienes represented by those based on the bicyclo[2.2.2]octadiene framework[2,3] have frequently displayed higher activities and enantioselectivities than chiral phosphine ligands in catalytic asymmetric reactions. However, their successful use has been limited to rhodium-catalyzed reactions except for Carreira's kinetic resolution in an iridium-catalyzed allylic substitution.[2a] On the other hand, we have recently reported a [3+2] annulation, which is catalyzed by an iridium complex coordinated with a diene, $[IrCl(cod)]_2$ (cod = 1,5-cyclooctadiene), where the more electron-rich double bond of 1,3-diene participates in the reaction while the terminal carbon of the reactive double bond forms a bond with the carbonyl carbon of 2-formylphenylboronic acid giving indanol derivatives (Scheme 1).[6] Attempts to use chiral bicyclo[2.2.2]octadiene ligands in place of cod for asymmetric synthesis with the iridium-catalyzed annulation were disappointing, with the reactions only giving a low yield of the annulation product due to their low coordination ability to iridium (vide infra).



Scheme 1. Iridium-catalyzed [3+2] annulation.

* Corresponding authors.
E-mail addresses: tnishi@kuchem.kyoto-u.ac.jp (T. Nishimura), thayashi@kuchem-u.ac.jp (T. Hayashi).

0957-4166/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tetasy.2008.07.014

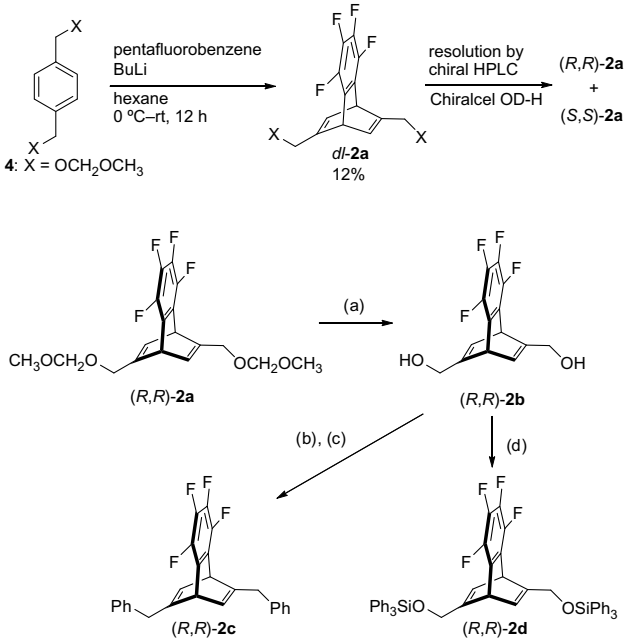


Scheme 2.

Tetrafluorobenzobicyclo[2.2.2]octatriene (tetrafluorobenzobarrelene; tfb) **1** (Scheme 2) and its derivatives are known to possess high coordination abilities toward rhodium(I) and iridium(I) due to their electron-deficient character.[7] They can be prepared in one step by the formal [4+2] cycloaddition of aromatic compounds with tetrafluorobenzyne generated from pentafluorophenyllithium or -magnesium.[8] Recently, the high performance of tfb **1** as a ligand has been disclosed by Masuda, where a cationic rhodium complex coordinated with **1** proved to be an efficient catalyst for polymerization of phenylacetylene.[9] Herein, we report the development of C_2-symmetric disubstituted tetrafluorobenzo[2.2.2]octatrienes **2** and their successful application to the iridium-catalyzed asymmetric annulation.

2. Results and discussion

The C_2-symmetric tfb dienes were prepared via a straightforward pathway (Scheme 3). The [4+2] cycloaddition of 1,4-bis((methoxymethoxy)methyl)benzene **4** with tetrafluorobenzyne generated according to a known procedure,[8b,c] gave the 2,5-disubstituted tfb *dl*-**2a**. Its resolution by the use of a chiral stationary phase column (Chiralcel OD-H) gave both enantiomers (*R*,*R*)-**2a** and (*S*,*S*)-**2a**, whose absolute configurations were assigned by

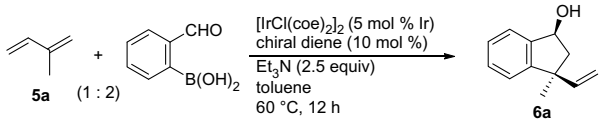


Scheme 3. Reagents and conditions: (a) concd HCl, MeOH, 60 °C (90% yield); (b) NBS, PPh_3, CH_2Cl_2, 0 °C; (c) PhMgBr, THF, rt (48% yield in two steps); (d) Ph_3SiCl, imidazole, DMF, rt (86% yield).

consideration of the stereochemical reaction pathway in the rhodium-catalyzed asymmetric 1,4-addition of phenylboronic acid to 2-cyclohexen-1-one. Thus, the diene, which gave (*R*)-3-phenylcyclohexanone (97% ee), was decided to be an (*R*,*R*)-isomer. Removal of the methoxymethyl protecting group in (*R*,*R*)-**2a** gave diol (*R*,*R*)-**2b** (X = OH), which led to (*R*,*R*)-**2c** (X = Ph) and (*R*,*R*)-**2d** (X = $OSiPh_3$).

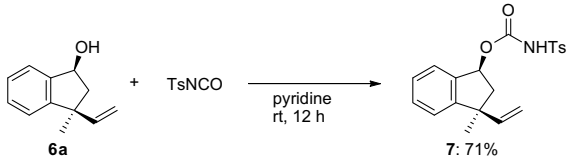
The results obtained for the reaction of isoprene (**5a**) with 2-formylphenylboronic acid (2 equiv) in the presence of iridium catalysts (5 mol % of Ir) coordinated with chiral tfb ligands **2** are summarized in Table 1, which also contain those obtained with one of the chiral bicyclo[2.2.2]octadiene ligands (Bn-bod* **3**)[3] for comparison. The Ir/Bn-bod* catalyst lost its catalytic activity within 0.5 h resulting in a very low yield (5%) of indanol **6a** even after a prolonged reaction time (entries 1 and 2). The loss of catalytic activity is attributed to the dissociation of the Bn-bod* ligand from iridium. Thus, the generation of free Bn-bod* ligand (78% based on [IrCl(Bn-bod*)]) was observed in the reaction of **5a** with 2-formylphenylboronic acid in the presence of $[IrCl(Bn\text{-}bod^*)]_2$ (5 mol % of Ir) at 80 °C for 0.5 h. The yield of **6a** was much higher (50%) with the chiral tfb ligand **2c**, because the Ir/**2c** complex retains its catalytic activity for a longer time (entries 5 and 6). The tetrafluorobenzo-framework is responsible for the high efficiency of tfb ligand **2c** in the present iridium-catalyzed reaction, which is demonstrated by the results obtained above with Bn-bod* **3** and tfb **2c**, with both of the dienes being substituted with benzyl groups on the olefinic double bonds. The use of triphenylsilyloxymethyl-substituted tfb ligand **2d** improved the yield of **6a** up to 61% (entry 7). The enantioselectivity of the (1*S*,3*S*)-**6a** isomer is high, ranging between 92% and 94% ee with the chiral tfb ligands **2a**–**d**. The absolute configuration of **6a** was determined to be (1*S*,3*S*) by X-ray analysis of the *N*-tosylcarbamate **7** derived from **6a**, whose Flack parameter is −0.04(5) with this configuration (Scheme 4, Fig. 1).[10]

Table 1
Iridium-catalyzed asymmetric [3+2] annulation of 2-formylphenylboronic acid with isoprene **5a**[a]



Entry	Ligand	Time (h)	Yield[b] (%)	ee[c] (%)
1	(*R*,*R*)-Bn-bod* **3**	0.5	5[d]	—
2	(*R*,*R*)-Bn-bod* **3**	12	5[d]	—
3	(*R*,*R*)-**2a**	12	38	94 (1*S*,3*S*)
4	(*R*,*R*)-**2b**	12	44	93 (1*S*,3*S*)
5	(*R*,*R*)-**2c**	0.5	9[d]	—
6	(*R*,*R*)-**2c**	12	50	92 (1*S*,3*S*)
7	(*R*,*R*)-**2d**	12	61	94 (1*S*,3*S*)

[a] Reaction conditions; isoprene **5a** (0.30 mmol), 2-formylphenylboronic acid (0.60 mmol), $[IrCl(coe)_2]_2$ (5 mol % of Ir), a diene ligand (10 mol %), Et_3N (0.75 mmol) in toluene (0.9 mL) at 60 °C for 12 h.
[b] Isolated yield.
[c] Determined by HPLC analysis with a chiral stationary phase column: Chiralcel OD-H.
[d] Determined by ^1H NMR.



Scheme 4.

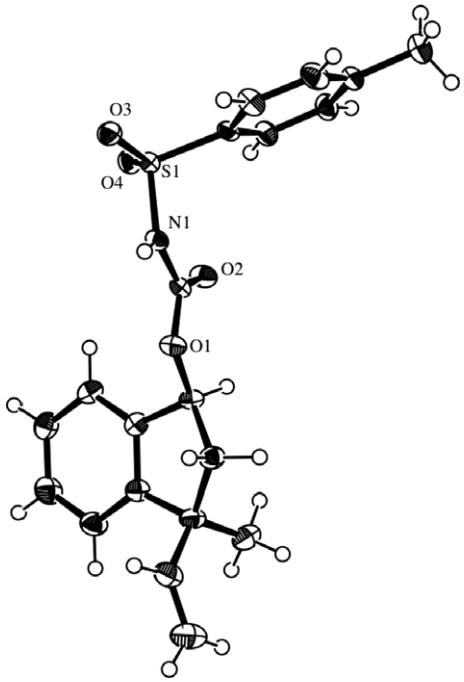
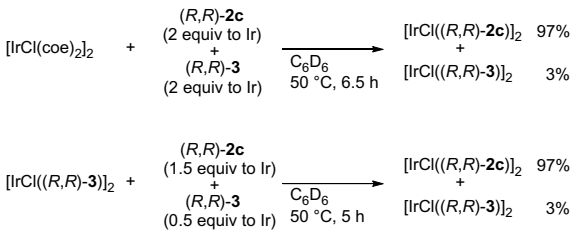


Figure 1. ORTEP illustration of **7** with thermal ellipsoids drawn at 50% probability level. Crystal data for **7**: $C_{20}H_{21}NO_4S$, *Mw* = 371.45, space group *C*2 (#5), *a* = 29.145(7) Å, *b* = 9.783(2) Å, *c* = 17.526(4) Å, *V* = 4232.2(17) Å^3, *Z* = 8, D_{calcd} = 1.166 g/cm^3, *T* = 123 K, *R* = 0.0394 ($I > 2.00\sigma(I)$), *Rw* = 0.1137 ($I > 2.00\sigma(I)$), GOF = 1.115, Flack parameter = −0.04(5).

An equilibrium experiment between diene ligands and their iridium complexes using tfb **2c** and Bn-bod **3** proved the much higher coordination ability of the tfb ligand over the bod ligand (Scheme 5). Thus, $[IrCl(coe)_2]_2$[11] (coe = cyclooctene), (*R*,*R*)-**2c**

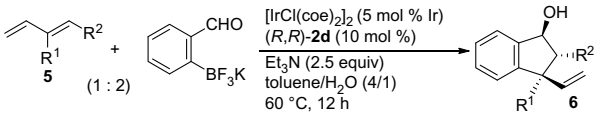


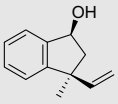
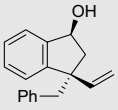
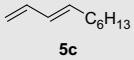
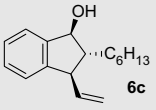
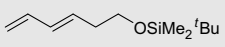
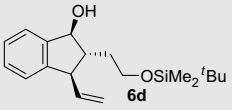
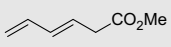
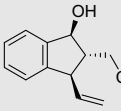
Scheme 5. Coordination experiments.

(2 equiv to Ir), and (*R*,*R*)-**3** (2 equiv to Ir) were dissolved in C_6D_6, and the solution was kept at 50 °C. After 6.5 h, the solution reached an equilibration state where the iridium complex consisted of 97% of $[IrCl((R,R)\text{-}\mathbf{2c})]_2$ and 3% of $[IrCl((R,R)\text{-}\mathbf{3})]_2$. The equilibrium of the same composition was also observed in the reaction (50 °C, 5 h) starting with $[IrCl((R,R)\text{-}\mathbf{3})]_2$, (*R*,*R*)-**2c** (1.5 equiv to Ir), and (*R*,*R*)-**3** (0.5 equiv to Ir). It follows that the tfb diene **2c** coordinates to the iridium chloro-bridge dimer much more strongly (>50 times) than the bod diene.

Table 2 summarizes the results obtained for the reaction of several 1,3-dienes with potassium trifluoro(2-formylphenyl)borate,[12] which was carried out in the presence of iridium/(*R*,*R*)-**2d** as a catalyst (5 mol % of Ir) in toluene/H_2O at 60 °C for 12 h. In the reaction of isoprene **5a**, the chemical yield of the [3+2] annulation product **6a** was increased from 61% to 82% by the use of the potassium borate in place of 2-formylphenylboronic acid (entry 1). The 1,3-dienes **5b**–**e** substituted with an alkyl group at the 1- or 2-position underwent the [3+2] annulation at the more electron-rich double bond to give the corresponding 1-indanols **6** in high yields (73–87%) (entries 2–5). The enantioselectivity was high (92–95% ee) for both 1- and 2-substituted dienes (entries 1–5).

Table 2
Iridium-catalyzed asymmetric [3+2] annulation of potassium trifluoro(2-formylphenyl)borate with 1,3-dienes[a]



Entry	Diene	Product	Yield[b] (%)	ee[c] (%)
1	 **5a**	 **6a**	82	95
2	 **5b**	 **6b**	73	94
3	 **5c**	 **6c**	83	93
4	 **5d**	 **6d**	83	92
5	 **5e**	 **6e**	87	92

[a] Reaction conditions; 1,3-dienes **5** (0.30 mmol), potassium trifluoro(2-formylphenyl)borate (0.60 mmol), $[IrCl(coe)_2]_2$ (5 mol % of Ir), (*R*,*R*)-**2d** (10 mol %), Et_3N (0.75 mmol) in toluene (0.9 mL) at 60 °C for 12 h.
[b] Isolated yield.
[c] Determined by HPLC analysis with a chiral stationary phase column: Chiralcel OD-H.

3. Conclusion

In conclusion, we have developed C_2-symmetric dienes having a tetrafluorobenzobarrelene (tfb) framework as a new type of chiral diene ligand. These chiral dienes realized the iridium-catalyzed enantioselective [3+2] annulation of 1,3-dienes with 2-formylphenylboron reagents.

4. Experimental

4.1. General

All anaerobic and moisture-sensitive manipulations were carried out with standard Schlenk techniques under predried nitrogen or glove box techniques under argon. NMR spectra were recorded on a JEOL JNM LA-500 spectrometer (500 MHz for ^1H, 125 MHz for ^{13}C). Chemical shifts are reported in δ ppm referenced to an internal $SiMe_4$ standard or the residual peaks of dichloromethane-d_2 ($CDHCl_2$, δ 5.30) and benzene-d_6 (δ 7.16) for ^1H NMR, and chloroform-d (δ 77.16), dichloromethane-d_2 (δ 53.52), and benzene-d_6 (δ 128.06) for ^{13}C NMR: the following abbreviations are used; s: singlet, d: doublet, t: triplet, q: quartet, m: multiplet, br: broad. Elemental analyses were performed at the Micro analytical center, Kyoto University. High-resolution mass spectra were obtained with a Bruker micrOTOF spectrometer. Optical rotations were measured on a JASCO DIP-370 polarimeter or JASCO P-2200 polarimeter. Preparative recycling gel permeation chromatography was performed with JAI LC-908 equipped with JAIGEL-1H and −2H using chloroform as an eluent.

4.2. Materials

Benzene and hexane were distilled over benzophenone ketyl. CH_2Cl_2 and DMF were distilled from CaH_2. Methanol was distilled over magnesium turnings. THF and toluene were purified by passing through a neutral alumina column under nitrogen atmosphere. Isoprene was purchased from Wako Chemicals and distilled prior to use. Triethylamine was purchased from Wako Chemicals and distilled over KOH prior to use. $[IrCl(coe)_2]_2$[11] potassium (2-formylphenyl)trifluoroborate,[13] 1,3-dienes **5b**,[14] **5c**,[15] **5d**,[16] and **5e**[17] were prepared according to the reported procedures. All other chemicals were purchased from commercial suppliers and used as received.

4.3. Preparation of 1,4-bis[(methoxymethoxy)methyl]benzene 4

To a solution of 1,4-benzenedimethanol (13.8 g, 100 mmol) and diisopropylethylamine (68 mL, 0.40 mol) in CH_2Cl_2 (100 mL) was added chloromethyl methyl ether (30 mL, 0.40 mol) at −20 °C, and the solution was allowed to warm up to room temperature and stirred for 24 h. The mixture was quenched with satd aq $NaHCO_3$ and extracted with Et_2O. The combined organic layer was washed with brine, dried over Na_2SO_4, and filtered. Evaporation of the solvent followed by a flash column chromatography on silica gel with hexane/ethyl acetate (7:1) gave compound **4** (21.5 g, 95% yield). ^1H NMR ($CDCl_3$) δ 3.41 (s, 6H), 4.59 (s, 4H), 4.70 (s, 4H), 7.35 (s, 4H); ^{13}C NMR ($CDCl_3$) δ 55.5, 69.0, 95.8, 128.1, 137.5. HRMS (ESI) calcd for $C_{12}H_{18}NaO_4$ $(M+Na)^+$ 249.1097, found 249.1097.

4.4. Preparation of 2,5-bis[(methoxymethoxy)methyl]-7,8-tetrafluorobenzobicyclo[2.2.2]octatriene 2a

To a solution of **4** (6.8 g, 30 mmol) and pentafluorobenzene (2.5 g, 15 mmol) in hexane (15 mL) was added *n*-BuLi (1.6 M in hexane, 10 mL, 16 mmol) at 0 °C. After completion of the addition, the solution was allowed to warm up to room temperature and stirred for 12 h. The resulting mixture was quenched with H_2O, filtered through a Celite pad, and extracted with Et_2O. The combined organic layer was washed with brine, dried over $MgSO_4$, and filtered. Evaporation of the solvent followed by flash column chromatography on silica gel with hexane/ethyl acetate (9:1) and gel permeation chromatography gave *dl*-**2a** (648 mg, 12% yield) as a colorless oil. Resolution was carried out by use of a chiral stationary phase column [Chiralcel OD-H (2.0 cm I.D. × 25 cm), hexane/2-propanol = 98:2, t_1 = 14 min for (*R*,*R*)-**2a**, t_2 = 18 min for (*S*,*S*)-**2a**] to give both enantiomers (*R*,*R*)-**2a** and (*S*,*S*)-**2a**. An injection of 40 mg of *dl*-**2a** in hexane (2 mL) without the recycling operation gave (*R*,*R*)-**2a** and (*S*,*S*)-**2a**, quantitatively. (*R*,*R*)-**2a**: ^{1}H NMR ($CDCl_3$) δ 3.36 (s, 6H), 4.17 (dd, J = 12.8, 1.5 Hz, 2H), 4.19 (dd, J = 12.8, 1.5 Hz, 2H), 4.52 (d, J = 6.5 Hz, 2H), 4.55 (d, J = 6.5 Hz, 2H), 5.14 (ddt, J = 5.9, 1.6, 0.9 Hz, 2H), 6.69 (dq, J = 5.9, 1.6 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 43.1, 55.5, 66.5, 95.5, 129.7–130.1 (m), 135.1, 136.2–138.7 (m), 140.7–143.0 (m), 151.1. Anal. Calcd for $C_{18}H_{18}F_4O_4$: C, 57.76; H, 4.85. Found: C, 57.60; H, 4.83. $[\alpha]_D^{20} = -8.2$ (*c* 0.97, $CHCl_3$). (*S*,*S*)-**2a**: $[\alpha]_D^{20} = +8.2$ (*c* 0.98, $CHCl_3$).

4.5. Preparation of (1*R*,4*R*)-2,5-bis(hydroxymethyl)-7,8-tetrafluorobenzobicyclo[2.2.2]octatriene (*R*,*R*)-2b

To a solution of (*R*,*R*)-**2a** (212 mg, 0.57 mmol) in methanol (4 mL) was added conc. HCl aq (4 drops). After heating at 60 °C for 4 h, the mixture was quenched with H_2O and extracted with Et_2O. The organic layer was washed with satd aq $NaHCO_3$, brine, dried over $MgSO_4$, and filtered. Evaporation of the solvent followed by a flash column chromatography on silica gel with hexane/ethyl acetate (1:1) gave (*R*,*R*)-**2b** (145 mg, 90% yield) as a white solid. ^{1}H NMR ($CDCl_3$) δ 1.50 (br s, 2H), 4.23–4.35 (br m, 4H), 5.13–5.17 (m, 2H), 6.65 (dq, J = 6.0, 1.8 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 42.8, 62.8, 129.8–130.2 (m), 133.3, 136.3–138.7 (m), 140.8–143.0 (m), 154.2. Anal. Calcd for $C_{14}H_{10}F_4O_2$: C, 58.75; H, 3.52. Found: C, 58.67; H, 3.60. $[\alpha]_D^{20} = -17.2$ (*c* 1.02, $CHCl_3$).

4.6. Preparation of (1*R*,4*R*)-2,5-dibenzyl-7,8-tetrafluorobenzobicyclo[2.2.2]octatriene (*R*,*R*)-2c

To a solution of (*R*,*R*)-**2b** (116 mg, 0.40 mmol) in CH_2Cl_2 (10 mL) were added successively PPh_3 (233 mg, 0.89 mmol) and NBS (158 mg, 0.89 mmol) at 0 °C. After stirring for 30 min, the mixture was quenched with H_2O and extracted with Et_2O. The combined organic layer was washed with brine, dried over $MgSO_4$, and filtered. Evaporation of the solvent followed by a flash column chromatography on silica gel with hexane/ethyl acetate (8:1) gave (1*R*,4*R*)-2,5-bis(bromomethyl)-7,8-tetrafluorobenzobicyclo[2.2.2]octatriene (*R*,*R*)-**2b′** (160 mg, 96% yield) as a white solid. ^{1}H NMR ($CDCl_3$) δ 4.13 (dd, J = 10.5, 1.0 Hz, 2H), 4.16 (dd, J = 10.5, 1.0 Hz, 2H), 5.13–5.17 (m, 2H), 6.71–6.76 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 31.8, 44.9, 128.7–129.1 (m), 136.0, 136.7–139.1 (m), 140.9–143.0 (m), 149.8. Anal. Calcd for $C_{14}H_8Br_2F_4$: C, 40.81; H, 1.96. Found: C, 41.08; H, 1.97. $[\alpha]_D^{20} = -31.1$ (*c* 0.99, $CHCl_3$). To a solution of (*R*,*R*)-**2b′** (143 mg, 0.35 mmol) in THF (6.0 mL) was added PhMgBr (2.0 M in THF, 0.38 mL, 0.77 mmol) at 0 °C, and the solution was allowed to warm up to room temperature and stirred for 12 h. The resulting mixture was quenched with H_2O and extracted with Et_2O. The combined organic layer was washed with brine, dried over $MgSO_4$, and filtered. Evaporation of the solvent followed by a flash column chromatography on silica gel with hexane gave (*R*,*R*)-**2c** (74 mg, 53% yield) as a white solid. ^{1}H NMR ($CDCl_3$) δ 3.52 (d, J = 16.4 Hz, 2H), 3.55 (d, J = 16.4 Hz, 2H), 4.80 (d, J = 5.9 Hz, 2H), 6.25–6.31 (m, 2H), 7.02 (d, J = 7.8 Hz, 4H), 7.16–7.31 (m, 6H); ^{13}C NMR ($CDCl_3$) δ 39.7, 45.3, 126.6, 128.6, 129.1, 130.4–130.7 (m), 132.8, 136.0–138.5 (m), 137.7, 140.3–142.6 (m), 153.6. Anal. Calcd for $C_{26}H_{18}F_4$: C, 76.84; H, 4.46. Found: C, 76.72; H, 4.36. $[\alpha]_D^{20} = +28.4$ (*c* 1.00, $CHCl_3$).

4.7. Preparation of (1*R*,4*R*)-2,5-bis[(triphenylsiloxy)methyl]-7,8-tetrafluorobenzobicyclo[2.2.2]octatriene (*R*,*R*)-2d

To a mixture of (*R*,*R*)-**2b** (146 mg, 0.51 mmol), Ph_3SiCl (601 mg, 2.0 mmol), and imidazole (347 mg, 5.1 mmol) was added DMF (2.0 mL) at 0 °C, and the solution was allowed to warm up to room temperature and stirred for 24 h. The mixture was quenched with H_2O and extracted with Et_2O. The combined organic layer was washed with brine, dried over $MgSO_4$, and filtered. Evaporation of the solvent followed by a flash column chromatography on silica gel with hexane/EtOAc (80:1) and gel permeation chromatography gave (*R*,*R*)-**2d** (350 mg, 86% yield) as a white solid. ^{1}H NMR ($CDCl_3$) δ 4.39 (dd, J = 13.7, 1.7 Hz, 2H), 4.44 (dd, J = 13.7, 1.7 Hz, 2H), 4.98 (d, J = 6.0 Hz, 2H), 6.41 (dq, J = 6.0, 1.7 Hz, 2H), 7.30–7.37 (m, 12H), 7.38–7.44 (m, 6H), 7.52–7.58 (m, 12H); ^{13}C NMR ($CDCl_3$) δ 42.4, 63.7, 128.0, 130.0–130.4 (m), 130.3, 132.8, 133.8, 135.5, 136.0–138.6 (m), 140.4–142.9 (m), 153.3. Anal. Calcd for $C_{50}H_{38}F_4O_2Si_2$: C, 74.79; H, 4.77. Found: C, 74.99; H, 4.78. $[\alpha]_D^{20} = +11.1$ (*c* 1.04, $CHCl_3$).

4.8. General procedure for preparation of iridium–chiral diene complexes

$[IrCl(coe)_2]_2$ (22.4 mg, 0.05 mmol Ir) and a chiral diene (0.050 mmol) were dissolved in benzene (2.0 mL), and the mixture was heated at 60 °C for 12 h. After being cooled to room temperature, the reaction mixture was concentrated under reduced pressure to give a quantitative yield of the iridium–chiral diene complex.

4.8.1. [IrCl((*R*,*R*)-Bn-bod*)]$_2$

^{1}H NMR (CD_2Cl_2) δ 0.17–0.30 (m, 4H), 0.38–0.51 (m, 4H), 2.65 (d, J = 13.8 Hz, 4H), 3.26 (d, J = 13.8 Hz, 4H), 3.37 (dd, J = 6.1, 1.2 Hz, 4H), 3.99–4.06 (m, 4H), 7.17–7.23 (m, 4H), 7.23–7.29 (m, 8H), 7.29–7.34 (m, 8H); ^{13}C NMR (CD_2Cl_2) δ 29.1, 36.1, 43.2, 47.0, 53.8, 126.4, 128.4, 129.0, 138.9. HRMS (ESI) calcd for $C_{44}H_{44}Cl_3Ir_2$ $(M+Cl)^-$ 1063.1745, found 1063.1796.

4.8.2. [IrCl((*R*,*R*)-2c)]$_2$

^{1}H NMR (CD_2Cl_2) δ 2.75 (d, J = 13.9 Hz, 4H), 3.34 (d, J = 5.7 Hz, 4H), 3.36 (d, J = 13.9 Hz, 4H), 5.34 (d, J = 5.7 Hz, 4H), 7.01–7.08 (m, 8H), 7.09–7.15 (m, 12H); ^{13}C NMR (CD_2Cl_2) δ 34.3, 41.9, 45.7, 52.9, 126.7, 128.3–128.7 (m), 128.5, 129.1, 136.2 137.2–138.6 (m), 139.0–140.6 (m). HRMS (ESI) calcd for $C_{52}H_{36}Cl_3F_8Ir_2$ $(M+Cl)^-$ 1303.0993, found 1303.0974.

4.8.3. [IrCl((*R*,*R*)-2d)]$_2$

^{1}H NMR (CD_2Cl_2) δ 2.49 (dd, J = 5.8, 0.9 Hz, 4H), 3.37 (d, J = 11.4 Hz, 4H), 4.18 (d, J = 11.4 Hz, 4H), 5.26 (d, J = 5.8 Hz, 4H), 7.27–7.34 (m, 24H), 7.36–7.47 (m, 36H); ^{13}C NMR (CD_2Cl_2) δ 35.4, 43.8, 51.2, 64.2, 128.0, 129.0–129.4 (m), 130.4, 133.6, 135.2, 137.8–139.4 (m), 139.7–141.6 (m). HRMS (ESI) calcd for $C_{100}H_{76}Cl_2F_8Ir_2NaO_4Si_4$ $(M+Na)^+$ 2083.3212, found 2083.3207.

4.9. Procedure for coordination experiments of chiral diene ligands Bn-tfb* (2c) and Bn-bod* (3)

In an NMR sample tube, $[IrCl(coe)_2]_2$ (4.5 mg, 0.010 mmol of Ir), (*R*,*R*)-Bn-tfb* (**2c**) (8.1 mg, 0.020 mmol), and (*R*,*R*)-Bn-bod* (**3**)

(5.7 mg, 0.020 mmol) were placed under N_2, and C_6D_6 (0.6 mL) was added at room temperature. Then, the mixture was heated at 50 °C for 6.5 h. After cooling to room temperature, ^{1}H NMR was measured to show the complete conversion of $[IrCl(coe)_2]_2$ with the formation of 97% of $[IrCl((R,R)\text{-}\mathbf{2c})]_2$ and 3% of $[IrCl((R,R)\text{-}\mathbf{3})]_2$. Another equilibrium experiment was carried out in C_6D_6 at 50 °C for 5 h starting with $[IrCl((R,R)\text{-}\mathbf{3})]_2$ (5.1 mg, 0.010 mmol of Ir), (*R*,*R*)-**2c** (6.1 mg, 0.015 mmol), and (*R*,*R*)-**3** (1.4 mg, 0.05 mmol).

4.10. Procedure for iridium-catalyzed asymmetric annulation of isoprene with 2-formylphenylboronic acid

$[IrCl(coe)_2]_2$ (6.7 mg, 0.015 mmol of Ir) and a chiral diene (0.030 mmol) were dissolved in benzene (2.0 mL), and the mixture was heated at 60 °C for 1 h. After being cooled to room temperature, the reaction mixture was concentrated under reduced pressure. To the residue were added successively 2-formylphenylboronic acid (90.0 mg, 0.60 mmol), toluene (0.90 mL), triethylamine (105 mL, 0.75 mmol), and isoprene (20.4 mg, 0.30 mmol), and the mixture was heated at 60 °C for 12 h. The mixture was quenched with H_2O and extracted with Et_2O. The combined organic layer was dried over $MgSO_4$, filtered, and concentrated on a rotary evaporator. The residue was purified by a flash column chromatography on silica gel with hexane/EtOAc (10:1) as an eluent to give (1*S*,3*S*)-3-methyl-3-vinyl-2,3-dihydro-1*H*-inden-1-ol **6a** [CAS: 944382-93-8 for the racemic compound **6a**]. The absolute configuration of **6a** was determined by X-ray crystallographic analysis of the corresponding *N*-tosylcarbamate of **6a** (vide infra). The ee was measured by HPLC (Chiralcel OD-H column, hexane/2-propanol = 98:2, 0.8 mL/min, 254 nm, t_1 = 16.6 min (major), t_2 = 21.7 min (minor)). $[\alpha]_D^{20} = +30.3$ (*c* 1.06, $CHCl_3$) for 95% ee. ^{1}H NMR ($CDCl_3$) δ 1.34 (s, 3H), 1.80 (br d, *J* = 8.2 Hz, 1H), 2.09 (dd, *J* = 13.3, 5.0 Hz, 1H), 2.36 (dd, *J* = 13.3, 6.6 Hz, 1H), 4.97 (dd, *J* = 17.3, 1.2 Hz, 1H), 5.03 (dd, *J* = 10.7, 1.2 Hz, 1H), 5.20–5.26 (m, 1H), 6.14 (dd, *J* = 17.3, 10.7 Hz, 1H), 7.13–7.17 (m, 1H), 7.26–7.34 (m, 2H), 7.40–7.45 (m, 1H); ^{13}C NMR ($CDCl_3$) δ 26.2, 48.7, 50.7, 74.8, 111.9, 123.8, 124.6, 127.5, 128.7, 144.2, 147.5, 149.1.

4.11. General procedure for iridium-catalyzed asymmetric annulation of 1,3-dienes with potassium 2-formylphenyltrifluoroborate

$[IrCl(coe)_2]_2$ (6.7 mg, 0.015 mmol Ir) and (*R*,*R*)-**2d** (24.1 mg, 0.030 mmol) were dissolved in benzene (2.0 mL), and the mixture was heated at 60 °C for 1 h. After being cooled to room temperature, the reaction mixture was concentrated under reduced pressure. To the residue were added successively potassium 2-formylphenyltrifluoroborate (127 mg, 0.60 mmol), toluene (0.90 mL), H_2O (0.23 mL), triethylamine (105 mL, 0.75 mmol), and a 1,3-diene (0.30 mmol), and the mixture was heated at 60 °C for 12 h. The mixture was quenched with H_2O and extracted with Et_2O. The combined organic layer was dried over $MgSO_4$, filtered, and concentrated on a rotary evaporator. The residue was purified by a flash column chromatography on silica gel with hexane/EtOAc as an eluent.

4.11.1. (1*S*,3*S*)-3-Benzyl-3-vinyl-2,3-dihydro-1*H*-inden-1-ol 6b

Pale yellow oil. The ee was measured by HPLC (Chiralcel OD-H column, hexane/2-propanol = 98:2, 0.4 mL/min, 254 nm, t_1 = 21.4 min (major), t_2 = 24.3 min (minor)). $[\alpha]_D^{20} = +56.9$ (*c* 0.84, $CHCl_3$) for 94% ee. ^{1}H NMR ($CDCl_3$) δ 1.73 (br s, 1H), 1.96 (dd, *J* = 13.3, 5.8 Hz, 1H), 2.57 (dd, *J* = 13.3, 7.0 Hz, 1H), 2.93 (d, *J* = 13.3 Hz, 1H), 2.94 (d, *J* = 13.3 Hz, 1H), 4.42–4.55 (m, 1H), 5.01 (dd, *J* = 17.4, 0.8 Hz, 1H), 5.11 (dd, *J* = 10.7, 0.8 Hz, 1H), 6.25 (dd, *J* = 17.4, 10.7 Hz, 1H), 6.78–6.85 (m, 2H), 7.09–7.17 (m, 3H), 7.19 (d, *J* = 7.4 Hz, 1H), 7.25–7.29 (m, 2H), 7.29–7.36 (m, 1H); ^{13}C NMR ($CDCl_3$) δ 46.6, 47.3, 53.6, 74.5, 112.9, 124.50, 124.52, 126.4, 127.8, 127.8, 128.5, 130.5, 137.8, 145.3, 146.4, 146.9. HRMS (ESI) calcd for $C_{18}H_{18}O_1Na_1$ $(M+Na)^+$ 273.1250, found 273.1244.

4.11.2. (1*S*,2*R*,3*R*)-2-Hexyl-3-vinyl-2,3-dihydro-1*H*-inden-1-ol 6c [CAS: 944382-94-9 for the racemic compound 6c]

White solid. The ee was measured by HPLC (Chiralcel OD-H column × 2, hexane/2-propanol = 98:2, 0.3 mL/min, 254 nm, t_1 = 42.9 min (minor), t_2 = 53.6 min (major)). $[\alpha]_D^{20} = +80.0$ (*c* 0.89, $CHCl_3$) for 93% ee. ^{1}H NMR ($CDCl_3$) δ 0.90 (t, *J* = 6.8 Hz, 3H), 1.25–1.43 (m, 6H), 1.45–1.61 (m, 2H), 1.61–1.79 (m, 2H), 1.87 (dd, *J* = 8.2, 1.8 Hz, 1H), 1.91–1.99 (m, 1H), 3.27 (dd, *J* = 8.9, 8.8 Hz, 1H), 4.84 (t, *J* = 7.8 Hz, 1H), 5.18 (dd, *J* = 9.7, 1.9 Hz, 1H), 5.21 (ddd, *J* = 17.1, 1.9, 0.9 Hz, 1H), 5.79 (ddd, *J* = 17.1, 9.7, 8.9 Hz, 1H), 7.09–7.16 (m, 1H), 7.23–7.31 (m, 2H), 7.36–7.43 (m, 1H); ^{13}C NMR ($CDCl_3$) δ 14.2, 22.8, 27.9, 29.9, 31.9, 32.4, 53.4, 57.6, 80.7, 116.6, 123.8, 124.5, 127.4, 128.3, 140.5, 143.8, 144.6.

4.11.3. (1*S*,2*R*,3*R*)-2-[2-(*tert*-Butyldimethylsiloxy)ethyl]-3-vinyl-2,3-dihydro-1*H*-inden-1-ol 6d

White solid. The ee was measured by HPLC (Chiralcel OD-H column × 2, hexane/2-propanol = 150:1, 0.3 mL/min, 224 nm, t_1 = 43.3 min (minor), t_2 = 45.6 min (major)). $[\alpha]_D^{20} = +39.9$ (*c* 0.97, $CHCl_3$) for 92% ee. ^{1}H NMR ($CDCl_3$) δ 0.13 (s, 3H), 0.14 (s, 3H), 0.95 (s, 9H), 1.69–1.79 (m, 1H), 1.90–2.01 (m, 2H), 3.20 (t, *J* = 9.3 Hz, 1H), 3.76 (ddd, *J* = 10.7, 10.6, 2.6 Hz, 1H), 3.99 (dt, *J* = 10.7, 4.0 Hz, 1H), 4.53 (d, *J* = 2.6 Hz, 1H), 4.87 (dd, *J* = 7.9, 2.6 Hz, 1H), 5.20 (dd, *J* = 16.7, 1.9 Hz, 1H), 5.21 (dd, *J* = 10.2, 1.9 Hz, 1H), 5.74 (ddd, *J* = 16.7, 10.2, 9.3 Hz, 1H), 7.09 (d, *J* = 7.3 Hz, 1H), 7.19–7.30 (m, 2H), 7.43 (d, *J* = 7.4 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ −5.3, −5.1, 18.5, 26.1, 34.6, 53.6, 57.9, 64.0, 79.7, 117.5, 123.7, 123.9, 127.4, 127.7, 139.5, 143.0, 144.4. HRMS (ESI) calcd for $C_{19}H_{30}O_2Si_1Na_1$ $(M+Na)^+$ 341.1907, found 341.1905.

4.11.4. Methyl 2-[(1*S*,2*R*,3*R*)-1-hydroxy-3-vinyl-2,3-dihydro-1*H*-inden-2-yl]acetate 6e

Colorless oil. The ee was measured by HPLC (Chiralcel OD-H column, hexane/2-propanol = 95:5, 0.4 mL/min, 254 nm, t_1 = 14.2 min (minor), t_2 = 15.9 min (major)). $[\alpha]_D^{20} = +94.4$ (*c* 1.05, $CHCl_3$) for 92% ee. ^{1}H NMR ($CDCl_3$) δ 2.30 (dddd, *J* = 10.1, 9.4, 7.7, 4.2 Hz, 1H), 2.63 (dd, *J* = 16.4, 10.1 Hz, 1H), 2.84 (dd, *J* = 16.4, 4.2 Hz, 1H), 3.26 (dd, *J* = 9.4, 9.1 Hz, 1H), 3.73 (s, 3H), 3.81 (d, *J* = 3.8 Hz, 1H), 4.99 (dd, *J* = 7.7, 3.8 Hz, 1H), 5.22 (ddd, *J* = 16.6, 1.7, 0.7 Hz, 1H), 5.23 (ddd, *J* = 10.3, 1.7, 0.5 Hz, 1H), 5.75 (ddd, *J* = 16.6, 10.3, 9.1 Hz, 1H), 7.10 (d, *J* =7.3 Hz, 1H), 7.22–7.32 (m, 2H), 7.43 (d, *J* = 7.1 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 36.2, 52.1, 53.0, 53.2, 79.8, 118.0, 123.9, 124.1, 127.7, 128.2, 138.8, 142.3, 143.9, 174.9. HRMS (ESI) calcd for $C_{14}H_{16}O_3Na_1$ $(M+Na)^+$ 255.0992, found 255.0993.

4.12. Transformation of 6a into (1*S*,3*S*)-3-methyl-3-vinyl-2,3-dihydro-1*H*-inden-1-yl tosylcarbamate 7

To a solution of **6a** (39.7 mg, 0.23 mmol) in pyridine (3 mL) was added *p*-toluenesulfonyl isocyanate (0.30 mL, 2.0 mmol), and the mixture was stirred at room temperature for 12 h. The mixture was quenched with H_2O and extracted with CH_2Cl_2. The combined organic layer was dried over $MgSO_4$ and filtered. Evaporation of the solvent followed by a flash column chromatography on silica gel with hexane/EtOAc (3:1) gave compound **7** (60.3 mg, 71% yield, >99% ee) as a white solid. Colorless crystals of **7** suitable for X-ray crystallographic analysis were obtained by recrystallization from 1,4-dioxane/hexane. The crystal structure has been deposited at the Cambridge Crystallographic Data Centre (deposition number: CCDC 680000). This analysis determined compound **6a** to be a (1*S*,3*S*)-enantiomer. The ee was measured by HPLC (Chiralcel

OD-H column, hexane/2-propanol/Et_2NH = 9:1:0.1, 0.4 mL/min, 254 nm, t_1 = 18.0 min (major), t_2 = 34.0 min (minor)). $[\alpha]_D^{20} = -17.2$ (c 0.55, $CHCl_3$) for >99% ee. ^1H NMR ($CDCl_3$) δ 1.33 (s, 3H), 2.12 (dd, J = 14.1, 4.0 Hz, 1H), 2.34 (dd, J = 14.1, 6.9 Hz, 1H), 2.44 (s, 3H), 4.97 (dd, J = 17.2, 0.9 Hz, 1H), 4.99 (dd, J = 10.6, 0.9 Hz, 1H), 5.98 (dd, J = 17.2, 10.6 Hz, 1H), 6.11 (dd, J = 6.9, 4.0 Hz, 1H), 7.14 (d, J = 7.6 Hz, 1H), 7.18–7.24 (m, 1H), 7.24–7.30 (m, 1H), 7.28 (d, J = 8.2 Hz, 2H), 7.30–7.36 (m, 1H), 7.46–7.56 (br s, 1H), 7.87 (d, J = 8.3 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 21.8, 26.2, 46.7, 48.9, 79.9, 111.7, 123.9, 125.8, 127.5, 128.6, 129.7, 129.9, 135.6, 138.7, 145.1, 145.9, 150.5, 150.6. HRMS (ESI) calcd for $C_{20}H_{21}N_1Na_1O_4S_1$ $(M+Na)^+$ 394.1083, found 394.1086.

Acknowledgments

This work was supported by a Grant-in-Aid for Scientific Research from the MEXT, Japan. Y.Y. thanks a research fellowship of the Japan Society for the Promotion of Science for Young Scientists.

References

1. For reviews, see: (a) Johnson, J. B.; Rovis, T. *Angew. Chem., Int. Ed.* **2008**, *47*, 840; (b) Defieber, C.; Grützmacher, H.; Carreira, E. M. *Angew. Chem., Int. Ed.* **2008**, *47*, 4482.
2. (a) Fischer, C.; Defieber, C.; Suzuki, T.; Carreira, E. M. *J. Am. Chem. Soc.* **2004**, *126*, 1628; (b) Defieber, C.; Paquin, J.-F.; Serna, S.; Carreira, E. M. *Org. Lett.* **2004**, *6*, 3873; (c) Paquin, J.-F.; Stephenson, C. R. J.; Defieber, C.; Carreira, E. M. *Org. Lett.* **2005**, *7*, 3821; (d) Paquin, J.-F.; Defieber, C.; Stephenson, C. R. J.; Carreira, E. M. *J. Am. Chem. Soc.* **2005**, *127*, 10850; (e) Miura, T.; Takahashi, Y.; Murakami, M. *Chem. Commun.* **2007**, 595; (f) Arikawa, K.; Akutagawa, S.; Mikami, K. *J. Am. Chem. Soc.* **2006**, *128*, 12648.
3. (a) Tokunaga, N.; Otomaru, Y.; Okamoto, K.; Ueyama, K.; Shintani, R.; Hayashi, T. *J. Am. Chem. Soc.* **2004**, *126*, 13584; (b) Otomaru, Y.; Okamoto, K.; Shintani, R.; Hayashi, T. *J. Org. Chem.* **2005**, *70*, 2503; (c) Shintani, R.; Okamoto, K.; Hayashi, T. *Chem. Lett.* **2005**, *34*, 1294; (d) Shintani, R.; Okamoto, K.; Otomaru, Y.; Ueyama, K.; Hayashi, T. *J. Am. Chem. Soc.* **2005**, *127*, 54; (e) Shintani, R.; Sannohe, Y.; Tsuji, T.; Hayashi, T. *Angew. Chem., Int. Ed.* **2007**, *46*, 7277.
4. For selected examples of chiral diene ligands for asymmetric reactions, see: (a) Hayashi, T.; Ueyama, K.; Tokunaga, N.; Yoshida, K. *J. Am. Chem. Soc.* **2003**, *125*, 11508; (b) Otomaru, Y.; Tokunaga, N.; Shintani, R.; Hayashi, T. *Org. Lett.* **2005**, *7*, 307; (c) Otomaru, Y.; Kina, A.; Shintani, R.; Hayashi, T. *Tetrahedron: Asymmetry* **2005**, *16*, 1673; (d) Kina, A.; Ueyama, K.; Hayashi, T. *Org. Lett.* **2005**, *7*, 5889; (e) Noël, T.; Vandyck, K.; Van der Eycken, J. *Tetrahedron* **2007**, *63*, 12961; (f) Wang, Z.-Q.; Feng, C.-G.; Xu, M.-H.; Lin, G.-Q. *J. Am. Chem. Soc.* **2007**, *129*, 5336; (g) Helbig, S.; Sauer, S.; Cramer, N.; Laschat, S.; Baro, A.; Frey, W. *Adv. Synth. Catal.* **2007**, *349*, 2331; (h) Läng, F.; Breher, F.; Stein, D.; Grützmacher, H. *Organometallics* **2005**, *24*, 2997.
5. For examples of the reactions using chiral dienes, see: (a) Takahashi, A.; Aso, M.; Tanaka, M.; Suemune, H. *Tetrahedron* **2000**, *56*, 1999; (b) Grundl, M. A.; Kennedy-Smith, J. J.; Trauner, D. *Organometallics* **2005**, *24*, 2831.
6. Nishimura, T.; Yasuhara, Y.; Hayashi, T. *J. Am. Chem. Soc.* **2007**, *129*, 7506.
7. For an review, see: (a) Esteruelas, M. A.; Oro, L. A. *Coord. Chem. Rev.* **1999**, *193–195*, 557; For selected early examples of the synthesis of iridium–tetrafluorobenzobarrelene complexes, see: (b) Uson, R.; Oro, L. A.; Carmona, D.; Esteruelas, M. A.; Foces-Foces, C.; Cano, F. H.; Garcia-Blanco, S. *J. Organomet. Chem.* **1983**, *254*, 249; (c) Uson, R.; Oro, L. A.; Carmona, D.; Esteruelas, M. A. *Inorganica. Chim. Acta* **1983**, *73*, 275; (d) Uson, R.; Oro, L. A.; Carmona, D.; Esteruelas, M. A. *J. Organomet. Chem.* **1984**, *263*, 109; (e) Uson, R.; Oro, L. A.; Carmona, D.; Esteruelas, M. A.; Foces-Foces, C.; Cano, F. H.; Garcia-Blanco, S.; Vazquez de Miguel, A. *J. Organomet. Chem.* **1984**, *273*, 111.
8. (a) Brewer, J. P. N.; Heaney, H. *Tetrahedron Lett.* **1965**, 4709; (b) Brewer, J. P. N.; Eckhard, I. F.; Heaney, H.; Marples, B. A. *J. Chem. Soc. (C)* **1968**, 664; (c) Callander, D. D.; Coe, P. L.; Tatlow, J. C.; Uff, A. J. *Tetrahedron* **1969**, *25*, 25.
9. (a) Saeed, I.; Shiotsuki, M.; Masuda, T. *Macromolecules* **2006**, *39*, 8567; (b) Saeed, I.; Shiotsuki, M.; Masuda, T. *Macromolecules* **2006**, *39*, 8977.
10. Flack, H. D. *Acta Crystallogr., Sect. A* **1983**, *39*, 876.
11. van der Ent, A.; Onderdelinden, A. L. *Inorg. Synth.* **1990**, *28*, 90.
12. For an example of the use of organoborates for rhodium-catalyzed asymmetric reactions, see: Pucheault, M.; Darses, S.; Genêt, J.-P. *Eur. J. Org. Chem.* **2002**, 3552.
13. Molander, G. A.; Figueroa, R. *J. Org. Chem.* **2006**, *71*, 6135.
14. Nájera, C.; Sansano, J. M. *Tetrahedron* **1994**, *50*, 5829.
15. Lebel, H.; Paquet, V. *Organometallics* **2004**, *23*, 1187.
16. Haynes, R. K.; Lam, K.-P.; Wu, K.-Y.; Williams, I. D.; Yeung, L.-L. *Tetrahedron* **1999**, *55*, 89.
17. Stevens, R. V.; Cherpek, R. E.; Harrison, B. L.; Lai, J.; Lapalme, R. *J. Am. Chem. Soc.* **1976**, *98*, 6317.