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Novel benzoferrocenyl chiral ligands: Synthesis and evaluation of their suitability for asymmetric catalysis

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Abstract

Four benzoferrocenyl phosphorus chiral ligands were conveniently prepared in good overall yields. These ligands were found to be stable in solid form and in solution. Two of the four ligands were resolved by chiral HPLC. Unlike a reported bis(phosphino-η^5-indenyl)iron(II) complex, in which the indenyl ligands undergo ring flipping through an η^1-intermediate, these two ligands were found to be configurationally stable in solution and in solid state. The suitability of these ligands for enantioselective catalysis was assessed in studies on allylic alkylation reactions. When the two less sterically hindered ligands were used, excellent chemical yields were obtained, but the other two more sterically hindered ones gave lower yields. When the two enantiopure ligands were used, enantioselectivity of up to 51% *ee* was observed. These findings suggest that benzoferrocene derivatives may be used as chiral ligands for asymmetric catalysis.

Keywords: Benzoferrocene; Phosphorus ligands; Catalysis; Planar chiral

1. Introduction

Catalytic asymmetric reactions are most constructive for the synthesis of enantiopure compounds because with this method sub-stoichiometric amounts of enantiopure catalyst can produce large amounts of enantiomerically pure or enriched product [1]. In transition metal catalyzed asymmetric reactions, to achieve high enantioselectivity, the design and synthesis of chiral ligands are crucial. Consequently, numerous ligands incorporating central, axial or planar chiralities were developed; and in many cases, incorporating two or more types of chiralities in one ligand was found to be beneficial. Planar chiral ligands based on ferrocene derivatives have found wide application because of their well-defined rigid conformation and ability to bring chirality close to reaction centers [2]. Most of these ligands contain electron donating heteroatoms (D) such as phosphorus, sulfur, nitrogen or oxygen that can coordinate with transition metals either from the cyclopentadienyl (Cp) ring directly or from a carbon atom that is attached to the Cp ring (Fig. 1, **1** and **2**). Using **1** and **2** as subunits, by combining the two in various ways, attaching chiral groups to "D", or further functionalization of the Cps, numerous chiral ligands have been designed and synthesized. In addition to ligands based on **1** and **2**, although with much fewer examples, chiral ligands based on structures **3** and **4**, where "D" is a nitrogen or phosphorus atom, have been synthesized; Fu and co-workers used such ligands for copper catalyzed conjugate addition of diethylzinc to enones [3] and for carbene insertion into O–H bonds [4]. Ferrocene derivatives based on **4** have also been used for organocatalyses such as kinetic resolution of secondary alcohols [5].

We recently initiated a project that is aimed toward the design and synthesis of planar chiral benzoferrocene ligands and their applications in asymmetric catalytic reactions. This new type of ligand contains the common structure unit **5** (Fig. 1), in which "D" is attached to C-4 of the benzoferrocene. Unit **5** by itself is a monodentate ligand, but through functionalization of positions such as C-3 and C-5 and/or attaching groups to "D", a new family of multidentate ligand can be designed and synthesized. This

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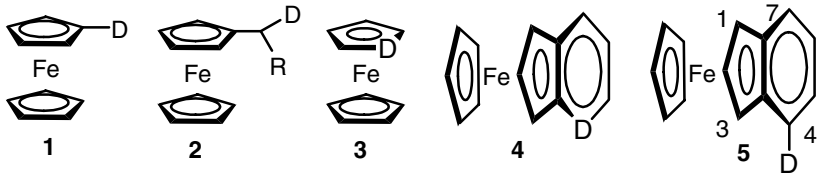


Fig. 1. Basic structural units of ferrocenyl ligands.

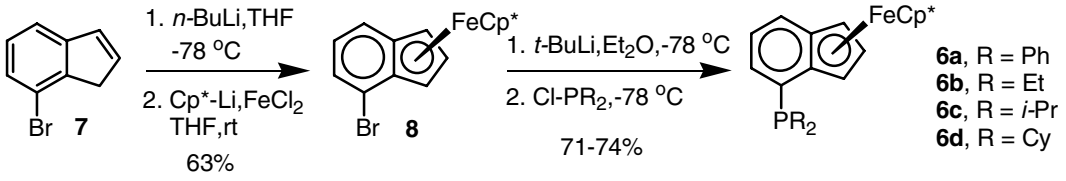
type of ligand is expected to have the following favorable structural features: the position of "D" shown in **5** is fixed due to the rigid conformation of benzoferrocene, heteroatom "D" shown in **5** is in a biased environment created by the ferrocenyl unit and the electron density on "D" can be tuned by attaching different functionalities at C-7. Moreover, the size of the Cp in **5** can be adjusted to achieve suitable steric hindrance and when multidentate ligands are used, a bulky Cp group can shield one face of the catalyst with a well-defined rigid conformation. In this paper, we describe the synthesis and characterization of the simplest ligands of this family **6a–d** (Scheme 1) and their application in allylic alkylation reactions. Our goal is to demonstrate that these new ligands can be easily prepared, are chemically and configurationally stable, and are compatible with transition metal catalyzed asymmetric reaction conditions.

2. Results

The ligands **6a–d** were prepared from the easily obtainable indene derivative **7** [6] in two steps (Scheme 1). To avoid possible debromination, **7** in THF was carefully treated with *n*-BuLi at −78 °C and warmed to room temperature slowly. Concurrently, lithium pentamethyl-cyclopentadienylide (Li–Cp*), a white suspension in THF, was prepared by treating H–Cp* with *n*-BuLi at room temperature. The suspension of Li–Cp* was transferred to a suspension of anhydrous $FeCl_2$ in THF *via* a cannula. After stirring this reaction mixture at room temperature for 1 h, the solution of lithiated **7** was added dropwise *via* a cannula, and the resulting deep purple solution was stirred at room temperature. After 2 h, TLC indicated complete consumption of indene **7**. However, after aqueous workup (10% K_2CO_3) and recrystallization (cold hexane), only 63% yield of pure product **8** could be obtained; a significant quantity of product remained in the mother liquor. In addition to product **8**, the mother liquor also contained some starting material **7** and H–Cp*, which resulted from oxidative decomposition of **8** during workup. Because **8**, **7** and H–Cp* are all non-polar and have very similar R_f values, isolation of more pure **8** from the mother liquor by recrystallization and flash column chromatography was not successful. The pure product **8** is a deep purple crystalline solid and it is highly soluble in solvents such as hexane, ether, CH_2Cl_2, $CHCl_3$, THF, EtOAc, benzene and toluene. Once in its pure form, solid **8** can be stored at room temperature for long periods even exposed to air. In solution in solvents such as hexane and diethyl ether at room temperature, no decomposition of **8** was observed within two weeks even exposed to air.

Converting **8** to **6a–d** was achieved by treating **8** with *t*-BuLi (*n*-BuLi gave the same results) followed by addition of *P*-chlorodiphenylphosphine (**6a**) or *P*-chlorodialkylphosphines (**6b–d**) and in all cases, good yields were obtained. These compounds were easily purified by flash column chromatography. In pure form, they are purple solids and are stable exposed to air. However, in solution in $CDCl_3$ exposed to the atmosphere, slow oxidation of the pendant phosphorus atom to phosphorus oxide was observed in ^{31}P NMR spectra.

The ^1H and ^{13}C NMR spectra of compound **8** are easily resolved. The three hydrogens on the benzene ring resonate at δ 7.28, 7.19 and 6.78, and those on C-1, C-2 and C-3 of the 5-membered ring resonate at δ 4.51, 4.38 and 3.84. In the ^{13}C NMR spectrum, the two quaternary carbons that are part of the 5-membered ring of the indenyl moiety resonate at δ 90.1 and 89.8. In contrast to the simple NMR spectra of **8**, those of compounds **6a–d** are relatively more complicated. In addition to the couplings between the hydrogen and carbon atoms and phosphorus atom in both ^1H and ^{13}C spectra, the two identical substituents on the phosphorus atoms show different hydrogen and carbon signals because of the chiral environment created by the ferrocenyl moiety of the molecules. For example, in the ^1H NMR spectrum of **6b**, the two methyl groups of the ethyl groups that are attached to the phosphorus atom resonate



Scheme 1. Synthesis of monodentate phosphorus ligands **6a–d**.

at δ 1.28 and 0.84 as two doublets of triplets due to coupling to the phosphorus atom and the methylene groups; in the ^{13}C NMR spectrum, the corresponding two carbons of the methyl groups show two doublets at δ 10.7 ($J = 66.8$ Hz) and 9.5 ($J = 30.4$ Hz). To further confirm the structure of this class of compound, **6a** was chosen for X-ray crystallography analysis. The ORTEP-3 drawing [7] of **6a** in Fig. 2 shows that one phenyl group on the phosphorus atom points to the *exo* face of the indenyl ring and the other one adopts a position that is opposite to the 5-membered ring of the indenyl moiety. This conformation of the two phenyl groups presumably reduces the steric hindrance between them and the ferrocenyl moiety of the compound. As a result of such an orientation of the two phenyl groups, the lone pair on the phosphorus atom is pointed to the *endo* face of the indenyl plane, which is significant for controlling enantioselectivity of catalytic reactions. Fig. 2 also shows that the iron atom is coordinated to the indene in an η^5 fashion, and the distances between the iron and the five carbon atoms of the 5-membered ring are not identical as the ring is tilted upwards slightly. The carbon and hydrogen atoms of the indenyl moiety are nearly planar and the plane almost parallel to that of Cp^* (angle between planes is 4.42°). This rigid conformation of the benzoferrocene is ideal for using this class of compound as a chiral ligand for asymmetric catalysis.

Ligands **6a** and **6b** were readily resolved by chiral HPLC using a semi-preparative CHIRALPAK AD-H column eluting with the solvent mixture of 0.25% 2-propanol in hexane at a flow rate of 7 mL/min. The two enantiomers of **6a** were eluted at 9.7 min (**6a**$_1$) and 12.3 min (**6a**$_2$) and those of **6b** at 8.3 min (**6b**$_1$) and 9.1 min (**6b**$_2$). Under similar conditions, the enantiomers of **6c** and **6d** were not well-separated. To test the configurational stability of this class of compound, solutions of enantiopure **6a** and **6b** in hexane, ether and THF were stirred under nitrogen atmosphere at room temperature and at reflux temperature for 12 h. In all cases, no racemization was observed as verified by chiral HPLC analysis. In order to assign the absolute configuration of the enantiomers, attempts were made to grow crystals of the single enantiomers or their complexes of palladium(II) for X-ray crystallography study but failed at this time.

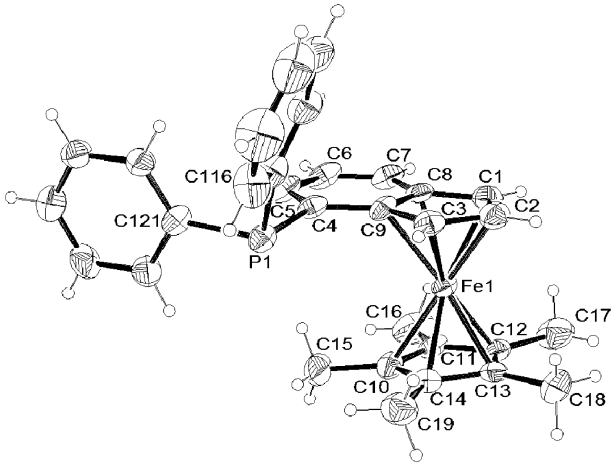
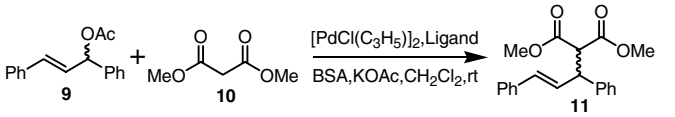


Fig. 2. ORTEP-3 drawing [7] of **6a** with selected atom numbering. Thermo ellipsoids are drawn at the 30% probability level. Hydrogen atoms are represented by spheres of arbitrary radii. Selected bond distances and angles: Fe1–C1, 2.046(9) Å; Fe1–C2, 2.024(9) Å; Fe1–C3, 2.050(9) Å; Fe1–C8, 2.094(7) Å; Fe1–C9, 2.094(8) Å; Fe1–C10, 2.063(8) Å; Fe1–C11, 2.044(8) Å, Fe1–C12, 2.036(9) Å; Fe1–C13, 2.028(8) Å; Fe1–C14, 2.045(8) Å, P1–C4, 1.849(9) Å; P1–C111, 1.824(9) Å; P1–C121, 1.826(9) Å; C4–P1–C111, 103.6(4)°; C4–P1–C121, 101.3(4)°; C111–P1–C121, 101.9(4) °.

Enantiopure **6a**–**b** and racemic **6c**–**d** were then used for palladium catalyzed allylic alkylation reactions between allyl acetate **9** and dimethylmalonate (**10**) (Eq. (1)). The catalysts were generated in situ by stirring $[Pd(C_3H_5)Cl]_2$ and a ligand in CH_2Cl_2 at room temperature for 1 h. Enantiopure **6a** was first used to find out the optimum ratio of ligand to palladium (L/Pd) for the reaction. At an L/Pd ratio of 1.25/1.0, under previously established allylic alkylation reaction conditions (see Section 5) [8], complete conversion was realized within 24 h at room temperature as indicated by GC–MS. Aqueous workup and flash column chromatography afforded pure **11** in 91% yield (entry 1, Table 1). The *ee* of the product, determined by chiral HPLC (see Section 5 for details), was 26%; and when **6a**$_1$ was used, the configuration of the major enantiomer of the product was *S*. If the L/Pd ratio was increased to 2.5/1.0, a 100% conversion was reached within 3 h with an isolated yield of 87%. The *ee* of the product was improved to 39% (entry 2). Further increases in the L/Pd ratio to 3.0/1.0 and 4.0/1.0 slowed down the reaction and both the yield and the *ee* were reduced (entries 3 and 4). As a result, when other ligands (**6b**–**d**) were used for the reaction, the L/Pd ratio was set to 2.5/1.0. As shown in Table 1, the reaction was highly efficient with **6b** as ligand, within 30 min, 100% conversion was realized and an excellent yield (93%) was obtained, but the *ee* remained moderate (51%, entry 5). When ligands **6c** and **6d** were used, the reactions were found to be very slow (entries 6 and 7) probably due to the bulky ligands preventing the substrates **9** and/or **10** from approaching the palladium catalytic center.



(1)

3. Discussion

Benzoferrocene derivatives containing donor atoms such as phosphorus, nitrogen, sulfur and oxygen are potential useful chiral ligands for catalytic asymmetric reactions. However, to our knowledge, there is no report on the synthesis of this type of ligand even in racemic form, not to mention their application in transition metal catalyzed reactions. The lack of such publications may be attributed

Table 1
Application of ligands **6a–d** in allylic alkylation reactions

Entry	Ligand	Ligand/Pd	Time (h)	Conversion[a] %	Yield[b] %	*ee*[c] % (config.[d])
1	**6a**$_1$	1.25/1.0	24	100	91	26 (*S*)
2	**6a**$_1$	2.5/1.0	3	100	87	39 (*S*)
3	**6a**$_2$	3.0/1.0	44	80	75	27 (*R*)
4	**6a**$_1$	4.0/1.0	44	50	47	26 (*S*)
5	**6b**$_2$	2.5/1.0	0.5	100	93	51 (*R*)
6	**6c**	2.5/1.0	43	56	23	–
7	**6d**	2.5/1.0	48	20	16	–

[a] Determined by GC.
[b] Isolated yield.
[c] Determined by analytical chiral HPLC.
[d] Assigned from the optical rotation by comparison with literature data [9].

to the perceived chemical and configurational instability of this type of compound and perhaps their demonstrated incompatibility with transition metal catalyzed reactions.

Indeed, it is reasonable to believe that benzoferrocene derivatives are less stable than ferrocene because energy is required to partially break the aromaticity of the benzene ring in the starting indene during its formation. Although Fu and co-workers reported the preparation of a number of ferrocene derivatives that are fused to a pyridine ring (pyroferrocene), this does not imply that the benzoferrocene derivatives will be equally stable because pyridine is electron deficient and allows for electron back donation from the iron center to its π^* orbital. Even in those cases, oxidation of Fe(II) to Fe(III) followed by decomposition was observed during the isolation of the product in the reactions for preparing pyroferrocene and its derivatives [10]. In order to use benzoferrocene derivatives as chiral ligands, one or more electron donating atoms such as phosphorus and oxygen atoms must be attached to the benzene ring; this will increase the electron density on the indene ring and the iron center, making the iron center possibly more susceptible to oxidation. During our preparation and characterization of the phosphorus ligands **6a–d**, although these compounds are indeed less stable than ferrocene, they were easily handled and were stable at room temperature for at least one year in capped vials; these observations negate any concern over their chemical stability and their use as chiral ligands for asymmetric catalysis.

In terms of configurational stability, our concerns on using benzoferrocene derivatives as chiral ligands arose from several reports by the Curnow's research group [11]. Here, the authors documented facile *meso* to *rac* isomerization of bis(1-(diphenylphosphino)-η^5-indenyl)iron(II) in THF through ring-flipping of the indenyl ligands *via* a phosphorus atom coordinated or less likely an sp^2 carbon atom coordinated η^1-intermediate. If such a process also pertained with our ligands **6a–d**, this project of developing a new type of benzoferrocene ligand for enantioselective catalysis would have to be reconsidered. Fortunately, our results showed that enantiopure **6a** and **6b** were configurationally stable both in solid and in solution states even at elevated temperature for an extended period of time. The third concern on using benzoferrocene ligands in catalysis is their stability in the presence of other transition metals. The iron(II) center of the less strongly coordinated benzoferrocenyl compounds (compared with ferrocene) may participate in redox reactions with transition metals such as palladium required for the catalysis. If such redox communication between Fe(II) and Pd(II) occurred and the resulting cationic benzoferrocenium complexes were not stable, the benzoferrocene ligands would not be able to control the stereochemistry of the catalytic reactions. In order to address this concern, the enantiopure **6a–b** and the racemic **6c–d** were used in palladium catalyzed allylic alkylation reaction between allyl acetate **9** and dimethylmalonate (**10**). Gratifyingly, when enantiopure **6a** and **6b** were used as ligands, excellent chemical yields were obtained although the enantioselectivities were moderate and these indicated that this new type of chiral ligand was compatible with palladium catalyzed reaction conditions. We did anticipate moderate enantioselectivity because in the enantio-determination step of allylic alkylation reactions the chiral ligand and the incoming nucleophile are on different sides of the intermediate π-allyl complex. In addition, the monodentate nature of ligands **6a** and **6b** may result in different catalyst conformations, which further contribute to the moderate enantioselectivity. Compared with known monodentate ligands, **6a** and **6b** gave lower *ee*s for allylic alkylation. For example, Nelson's group used monodentate phosphine ligands based on chiral η^6-Cr[arene] templates to catalyze allylic alkylation, up to 90% *ee* was obtained [12]; Hamada's group used 9-PBN, up to 98% *ee* was obtained [13]; Tsarev's group used the *P*-chiral monodentate diamidophophites giving up to 97% *ee* [14] and Burgess' group used C^3-symmetric triarylphosphines giving up to 82% *ee* [15]. According to these reports, monodentate ligands generally gave much lower *ee*s than bidentate ligands in allylic alkylation reactions. It is reasonable to expect that derivatization of **6a** and **6b** to bidentate ligands should increase the enantioselectivity of the alkylation reaction. The slower rates of reaction when **6c** and **6d** were used as ligands may be attributed to the difficulty for the substrates **9** and/or **10** in approaching the catalytic palladium center due to the bulkiness of these ligands.

4. Conclusions

In conclusion, we have shown that new benzoferrocenyl phosphorus chiral ligands **6a**–**d**, the simplest of a new family of ligand, can be prepared conveniently in good yields. These ligands are chemically and configurationally stable and are compatible with palladium catalyzed allylic alkylation reactions. Asymmetric syntheses of this new type of ligand, derivatizing them to produce multidentate ligands and using them to solve challenging problems in asymmetric catalysis are ongoing.

5. Experimental

5.1. General procedures

All reactions were performed under a nitrogen atmosphere using standard Schlenk techniques. Reagents and solvents available from commercial sources were used as received unless otherwise noted. THF and Et_2O were distilled from Na/benzophenone ketyl. CH_2Cl_2 was distilled over CaH_2. Thin layer chromatography (TLC) was performed using Sigma–Aldrich TLC plates, silica gel 60F-254 over glass support, 0.25 μm thickness. Flash column chromatography was performed using Selecto Scientific silica gel, particle size 32–63. ^1H, ^{13}C and ^{31}P NMR were measured on a Varian ^{UNITY}INOVA spectrometer at 400 Hz; chemical shifts (δ) were reported to residue $CHCl_3$ ($\delta = 7.27$ ppm for ^1H and 77.23 ppm for ^{13}C) and H_3PO_4 ($\delta = 0$ ppm). GC–MS were measured on GCMS-QP5050A, Shimadzu; column, DB-5MS, 0.25 μm thickness, 0.25 mm diameter, 25 m length; MS, positive EI. Melting points were determined using a MEL-TEMP® melting point apparatus and are uncorrected. HPLC was performed on a JASCO LC-2000Plus System, Pump PU-2080Plus, Detector UV-2075Plus.

5.2. 4-Bromoindenyl-pentamethylcyclopentadienyliron (*8*)

7-Bromo-1(*H*)-indene [6] (**7**, 5.0 g, 25.7 mmol) in THF (150 mL) was cooled to −78 °C, *n*-BuLi (2.0 M in pentane, 12.8 mL, 25.7 mmol) was added *via* syringe along the wall of flask in a dropwise manner. After addition, the solution was warmed to rt slowly. Pentamethylcyclopentadiene (Cp*–H, 3.7 mL, 25.7 mmol) in THF (100 mL) in another round-bottomed flask was treated with *n*-BuLi (2.0 M in pentane, 12.8 mL, 25.7 mmol) at rt giving a white suspension. This white suspension was added to a suspension of anhydrous $FeCl_2$ (3.3 g, 25.7 mmol) in THF (100 mL) with vigorous stirring *via* a cannula. After stirring at rt for 1 h, the solution of lithiated **7** was added dropwise *via* a cannula, and the resulting deep purple solution was stirred at rt. After 2 h, TLC (SiO_2, hexane) indicated quantitative conversion. THF was removed under reduced pressure on a rotary evaporator, the deep purple residue was partitioned between 10% K_2CO_3 (100 mL) and hexane (200 mL) and the organic layer was further washed with 10% K_2CO_3 (25 mL) and water (25 mL). After drying over anhydrous Na_2SO_4, the deep purple solution was concentrated to about 15 mL. Cooling the solution to −20 °C gave the pure product **8** as deep purple crystals (6.2 g, 63%). The mother liquor contained more product but was contaminated with Cp*–H and **7**, which resulted from oxidation of product **8**, further purification by recrystallization could not afford pure **8**; purification by flash column chromatography (SiO_2, hexane) also failed because Cp*–H, **7** and **8** had very similar R_f values, all were highly nonpolar and had very short retention time on the column: $R_f = 0.70$ (hexane); mp 126–8 °C; ^1H NMR ($CDCl_3$, 400 MHz) δ 7.28 (d, 1H, $J = 8.4$ Hz, H-5 or 7), 7.19 (d, 1H, $J = 6.8$ Hz, H-5 or 7), 6.78 (dd, 1H, $J = 8.4$, 6.8 Hz, H-6), 4.51 (dt, 1H, $J = 2.8$, 0.8 Hz, H-1 or 3), 4.38 (dd, 1H, $J = 2.4$, 1.2 Hz, H-1 or 3), 3.84 (t, 1H, $J = 2.4$ Hz, H-2), 1.66 (s, 15H, Cp*–CH_3); ^{13}C NMR ($CDCl_3$, 400 MHz) δ 127.1 (C-5, 6 or 7), 124.3 (C-5, 6 or 7), 123.1 (C-4), 122.5 (C-5, 6 or 7), 90.1 (C-3′ or 7′), 89.8 (C-3′ or 7′), 78.5 (C-2), 76.6 (Cp*–C), 67.2 (C-2 or 3), 66.7 (C-2 or 3), 10.2 (Cp*–CH_3); EI-MS calcd for $C_{19}H_{21}BrFe$ (*m*/*z*) [M^+] 384; found 384; FAB-HRMS (NBA) calcd for $C_{19}H_{21}BrFe$ (*m*/*z*) [M^+] 384.0176; found 384.0180.

5.3. 4-(Diphenylphosphino)indenyl-pentamethylcyclopentadienyliron (*6a*)

The deep purple solution of **8** (1.0 g, 2.6 mmol) in Et_2O (25 mL) in a round-bottomed flask was cooled to −78 °C. To this solution was added *t*-BuLi (1.7 M in pentane, 3.3 mL, 5.7 mmol) or *n*-BuLi (2.0 M in pentane, 2.8 mL, 5.7 mmol) slowly *via* syringe and the mixture was stirred at the same temperature for 30 min giving a deep red solution. *P*-Chlorodiphenylphosphine (1.1 mL, 5.7 mmol) was next added dropwise *via* syringe and the color of the solution returned to deep purple immediately. After stirring at −78 °C for 1 h, the reaction was quenched with water, and the mixture partitioned between 10% K_2CO_3 (25 mL) and ether (50 mL) and the isolated organic layer further washed with 10% K_2CO_3 (25 mL) and water (25 mL). After drying over anhydrous Na_2SO_4, the deep purple solution was concentrated to dryness. Flash column chromatography (SiO_2, pretreated with 5% Et_3N in hexane; hexane) gave product **6a** as deep purple crystals (0.92 g, 72%): $R_f = 0.25$ (hexane); mp 159–61 °C; ^1H NMR ($CDCl_3$, 400 MHz) δ 7.40–7.37 (m, 5 H, Ph), 7.31 (dt, 1H, $J = 8.8$, 0.8 Hz, H-7), 7.27–7.22 (m, 5H, Ph), 6.85 (ddd, 1H, $J = 8.4$, 6.8, 1.2 Hz, H-6), 6.42 (ddd, 1H, $J_{HH,HP,HH} = 6.4$, 5.2, 0.8 Hz, H-5), 4.35–4.33 (m, 1H, H-1 or 3), 4.30 (dt, 1H, $J = 2.8$, 1.2 Hz, H-1 or 3), 3.72 (*t*, 1H, $J = 2.8$ Hz, H-2), 1.71 (s, 15H, Cp*–CH_3); ^{13}C NMR ($CDCl_3$, 400 MHz) δ 136.6 (d, $J_{CP} = 30.4$ Hz, C × 2, Ph), 135.0 (Ph), 134.8 (Ph), 134.3 (Ph), 134.1 (Ph), 129.1 (C-5, 6 or 7), 128.7 (Ph), 128.6 (d, $J_{CP} = 54.4$ Hz, C-4), 128.6 (Ph), 127.3 (C-5, 6 or 7), 122.1 (C-5, 6 or 7), 91.0 (d, $J_{CP} = 97.2$ Hz, C-3′), 87.9 (C-7′), 78.2 (C-2), 76.5 (Cp*–C), 66.3 (d, $J_{CP} = 42.8$ Hz, C-3), 66.1 (C-1), 10.5 (Cp*–CH_3); ^{31}P

NMR ($CDCl_3$, 400 MHz) δ −11.25; EI-MS calcd for $C_{31}H_{31}FeP$ (m/z) [M^+] 490, found 490; Anal. Calc. for $C_{31}H_{31}FeP$: C, 75.92; H, 6.37. Found: C, 76.03; H, 6.24%. The two enantiomers of **6a** were resolved with semi-preparative chiral HPLC using a CHIRALPAK AD-H column eluting with the solvent mixture of 0.25% 2-propanol in hexane at a flow rate of 7 mL/min. The two enantiomers were eluted at 9.7 min (**6a**$_1$) and 12.3 min (**6a**$_2$, $[\alpha]_D^{25}$ −1895.5, *c* 0.045, hexane), respectively. In enantiopure form, the two enantiomers are deep purple sticky solids.

5.4. 4-(Diethylphosphino)indenyl-pentamethylcyclopentadienyliron (6b)

Following the procedure for the preparation of **6a**, compound **6b** was synthesized in 71% yield as a deep purple sticky solid: $R_f = 0.25$ (hexane); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.27 (d, 1H, $J = 7.2$ Hz, H-7), 6.99–6.93 (m, 2H, H-5 and 6), 4.65 (brs, 1H, H-1 or 3), 4.31 (brs, 1H, H-1 or 3), 3.81 (t, 1H, $J = 2.4$ Hz, H-2), 1.97–1.88 (m, 1H, PCH_2), 1.83–1.73 (m, 1H, PCH_2), 1.65 (s, 15H, Cp^*–CH_3), 1.63–1.55 (m, 2H, PCH_2), 1.28 (dt, 3H, $J_{HP,HH} = 16.4$, 7.6 Hz, CH_3), 0.84 (dt, 3H, $J_{HP,HH} = 12.0$, 7.6 Hz, CH_3); ^{13}C NMR ($CDCl_3$, 400 MHz) δ 137.9 (d, $J_{CP} = 72.8$ Hz, C-4), 127.7 (C-5, 6 or 7), 123.5 (C-5, 6 or 7), 121.9 (C-5, 6 or 7), 91.8 (d, $J_{CP} = 90.8$ Hz, C-3′), 88.1 (C-7′), 78.1 (C-2), 76.1 (Cp^*–C), 66.1 (C-1), 65.2 (d, $J_{CP} = 42.8$ Hz, C-3), 20.2 (d, $J_{CP} = 54.8$ Hz, PCH_2), 15.5 (d, $J_{CP} = 42.8$ Hz, PCH_2), 10.7 (d, $J_{CP} = 66.8$ Hz, CH_3), 10.4 (Cp^*–CH_3), 9.5 (d, $J_{CP} = 30.4$ Hz, CH_3); ^{31}P NMR ($CDCl_3$, 400 MHz) δ − 24.53; EI-MS calcd for $C_{23}H_{31}FeP$ (m/z) [M^+] 394, found 394; FAB-HRMS (NBA) calcd for $C_{23}H_{31}PFe$ (m/z) [M^+] 394.1513; found 394.1510. The two enantiomers were resolved using chiral HPLC under the same conditions used for resolution of **6a**, and were eluted at 8.3 min (**6b**$_1$, $[\alpha]_D^{25}$ +2061.1, *c* 0.035, hexane) and 9.1 min (**6b**$_2$), respectively. In enantiopure form, the two enantiomers are deep purple sticky solids.

5.5. 4-(Diisopropylphosphino)indenyl-pentamethylcyclopentadienyliron (6c)

Following the procedure for the preparation of **6a**, compound **6c** was synthesized in 78% yield as a deep purple solid: $R_f = 0.19$ (hexane); mp 68–74 °C; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.30 (d, 1H, $J = 8.4$ Hz, H-7), 6.98 (brs, 1H, H-5), 6.94 (t, 1H, $J = 7.6$ Hz, H-6), 4.77 (brs, 1H, H-1 or 3), 4.30 (brs, 1H, H-1 or 3), 3.79 (brs, 1H, H-2), 2.41–2.28 (m, 1H, PCH), 1.92–1.79 (m, 1H, PCH), 1.66 (s, 15H, Cp^*–CH_3), 1.31–1.21 (m, 6H, CH_3), 0.88–0.84 (m, 6H, CH_3); ^{13}C NMR ($CDCl_3$, 400 MHz) δ 134.2 (d, $J_{CP} = 91.2$ Hz, C-4), 127.7 (C-5, 6 or 7), 126.0 (C-5, 6 or 7), 121.6 (C-5, 6 or 7), 94.3 (d, $J_{CP} = 97.2$ Hz, C-3′), 88.3 (C-7′), 78.3 (C-2), 75.6 (Cp^*–C), 65.8 (d, $J_{CP} = 48.4$ Hz, C-3), 65.5 (C-1), 25.3 (d, $J_{CP} = 60.8$ Hz, PCH), 21.4 (d, $J_{CP} = 66.8$ Hz, PCH), 20.4 (d, $J_{CP} = 42.4$ Hz, CH_3), 20.1 (d, $J_{CP} = 42.8$ Hz, CH_3), 19.7 (d, $J_{CP} = 73.2$ Hz, CH_3), 18.2 (CH_3), 10.5 (Cp^*–CH_3); ^{31}P NMR ($CDCl_3$, 400 MHz) δ −1.61; EI-MS calcd for $C_{25}H_{35}FeP$ (m/z) [M^+] 422, found 422; FAB-HRMS (NBA) calcd for $C_{25}H_{35}FeP$ (m/z) [M^+] 422.1826; found 422.1829.

5.6. 4-(Dicyclohexylphosphino)indenyl-pentamethylcyclopentadienyliron (6d)

Following the procedure for the preparation of **6a**, compound **6d** was synthesized in 74% yield as a deep purple solid: $R_f = 0.30$ (hexane); mp 83–6 °C; ^{1}H NMR (C_6D_6, 400 MHz) δ 7.20 (d, 1H, $J = 8.4$ Hz, H-7), 7.02 (dd, 1H, $J = 6.4$, 3.2 Hz, H-5), 6.88 (dd, 1H, $J = 8.8$, 6.8 Hz, H-6), 4.95 (brs, 1H, H-1 or 3), 4.15–4.1.3 (m, 1H, H-1 or 3), 3.71 (t, 1H, $J = 2.4$ Hz, H-2), 2.27–2.18 (m, 2H, PCH × 2), 0.59–1.99 (m, 35H, two cyclohexyls (Cy) and Cp^*–CH_3); ^{13}C NMR (C_6D_6, 400 MHz) δ 134.8 (d, $J_{CP} = 90.8$ Hz, C-4), 125.59 (C-5, 6 or 7), 125.56 (C-5, 6 or 7), 121.5 (C-5, 6 or 7), 94.6 (d, $J_{CP} = 103.2$ Hz, C-3′), 88.5 (d, $J_{CP} = 30.4$ Hz, C-7′), 78.0 (C-2), 75.8 (Cp^*–C), 66.0 (d, $J_{CP} = 48.4$ Hz, C-3), 65.7 (C-1), 35.5 (d, $J_{CP} = 66.8$ Hz, Cy), 31.2 (d, $J_{CP} = 48.4$ Hz, Cy), 30.3 (d, $J_{CP} = 54.8$ Hz, Cy), 29.5 (d, $J_{CP} = 60.8$ Hz, Cy), 28.9 (d, $J_{CP} = 12.4$ Hz, Cy), 28.1 (d, $J_{CP} = 42.4$ Hz, Cy), 27.8 (d, $J_{CP} = 18.4$ Hz, Cy), 27.1 (d, $J_{CP} = 42.4$ Hz, Cy), 26.8 (Cy), 26.3 (Cy), 22.9 (Cy), 14.2 (Cy), 10.5 (Cp^*–CH_3); ^{31}P NMR (C_6D_6, 400 MHz) δ −10.30; EI-MS calcd for $C_{31}H_{43}FeP$ (m/z) [M^+] 502, found 502; FAB-HRMS (NBA) calcd for $C_{31}H_{43}FeP$ (m/z) [M^+] 502.2452; found 502.2449.

5.7. General procedure for palladium catalyzed allylic alkylation reactions

The pre-catalyst $[Pd(C_3H_5)Cl]_2$ (0.02 mmol) and a ligand with a specific ligand to palladium ratio were combined in a two-necked round-bottomed flask and flushed with nitrogen. Freshly distilled CH_2Cl_2 (2 mL) was then added *via* a syringe and the mixture was stirred at rt for 1 h. Allyl acetate **9** (1 mmol) in CH_2Cl_2 (2 mL) was then added *via* a cannula, and dimethylmalonate (**10**, 3.0 mmol) and BSA (3.0 mmol) were added *via* syringes, and finally KOAc (0.5 mmol) was added under positive nitrogen pressure. The reaction mixture was stirred at rt and monitored by GC–MS. Aqueous workup (Et_2O/4% HCl) and flash column chromatography (SiO_2, hexane/ether 8:1) gave pure product **11** with isolated yields ranging from 16% to 91%. Enantiomeric excess was determined by analytical chiral HPLC using CHIRALPAK AD-H column eluting with 2-propanol at a flow rate of 0.6 mL/min by integration of the two peaks with retention times of 13 and 21 min. Configuration of the major enantiomer of the product **11** was assigned from the optical rotation by comparison with literature data [9].

Table 2
Summary of crystallographic data for **6a**.

	6a
Formula	$C_{31}H_{31}FeP$
Formula weight (g mol^{-1})	490.38
Crystal system	Monoclinic
Space group	*P* 21/*c*
a (Å)	11.646(1)
b (Å)	16.568(6)
c (Å)	13.493(2)
α (°)	90
β (°)	92.61(1)
γ (°)	90
V (Å^3)	2600.8(10)
Z	4
d_{calc} (g cm^{-3})	1.252
μ (mm^{-1})	0.658
θ (°)	1.75–22.48
λ (Å)	0.71073
T (K)	293(2)
GOF	1.01
R_1[a], wR_2 ($I > 2\sigma(I)$)[b]	0.073, 0.202[c]

[a] $R_1 = \sum \| F_o | - | F_c \| / \sum | F_o |$.
[b] $wR_2 = [\sum [w(F_o^2 - F_c^2)^2] / \sum [w(F_o^2)^2]]^{1/2}$.
[c] $w = 1/[^2(F_o^2) + (0.1653P)^2]$ where $P = (F_o^2 + 2(F_c)^2)/3$.

5.8. X-ray crystallography

A suitable crystal of compound **6a** (obtained by crystallization from hexane at −20 °C) was rolled in epoxy resin and mounted on a glass fiber. An Enraf–Nonius CAD-4 X-Ray diffractometer was the instrument used for the determination. The windows program WINGX was used as the interface for the solution and refinement of the model [16]. The data were first reduced and corrected for absorption using *psi*-scans [17], and then solved using the program SIR97 [18]. The model was refined using the program SHELXL97 [19]. All non-hydrogens atoms were refined with anisotropic thermal parameters and the hydrogen atoms were refined at calculated positions with thermal parameters constrained to the carbon atom on which they were attached. Crystal data and final structural refinement parameters are listed in Table 2.

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Appendix A. Supplementary material

CCDC 624026 contains the supplementary crystallographic data for **6a**. These data can be obtained free of charge via http://www.ccdc.cam.ac.uk/conts/retrieving.html, or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: (+44) 1223-336-033; or e-mail: deposit@ccdc.cam.ac.uk. Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jorganchem.2007.01.004.

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