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Imidate–Phosphanes as Highly Versatile N,P Ligands and Their Application in Palladium-Catalyzed Asymmetric Allylic Alkylation Reactions

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Keywords: Asymmetric catalysis / N,P ligands / Palladium / Allylic alkylation / Imidate ligands

Chiral imidate–phosphanes were developed as a new type of N,P ligands. These ligands are easily accessible through a one-step procedure starting from a commercially available chiral aminophosphane and an imidate precursor. Excellent performance of the catalyst system was observed with various carbon nucleophiles in the Pd^0-catalyzed asymmetric allylic alkylation (up to 99 % yield and >99 % *ee*). Moreover, good to excellent enantioselectivities could also be obtained in the allylic alkylation of more difficult linear unhindered substrates and cyclic substrates, demonstrating that this new catalyst system has a broad substrate scope.

Introduction

The dramatic growth of enantioselective catalysis calls for a permanent search for new and improved chiral ligands. A key factor in the design of new ligands is their stability and the ease with which they can be accessed. To be economically viable, ligands should be synthesized in no more than one to three steps starting from commercially available starting materials. Moreover, the use of the ligand can be further precluded if it is extremely air and moisture sensitive. Ligands meeting these requirements are highly attractive to both organic and inorganic chemists.

We became interested in addressing this need and therefore have developed chiral imidates containing an exocyclic nitrogen atom as a new class of nitrogen-based ligands.[1] Remarkably, the use of such chiral imidates with an exocyclic nitrogen atom as ligands in transition-metal catalysis has been precluded, presumably due to their assumed instability. Very recently, C_2-symmetrical imidate ligands like **1** and **2** were developed by our group as stable alternatives for imine ligands (Figure 1).[1] They are very efficiently synthesized in a single step by a condensation reaction starting from a chiral (di)amine and an imidate hydrochloride. They are easily purified by flash chromatography and are shelf stable for several months at room temperature. These ligands show promising results in asymmetric aziridination reactions and diethylzinc additions.[1]

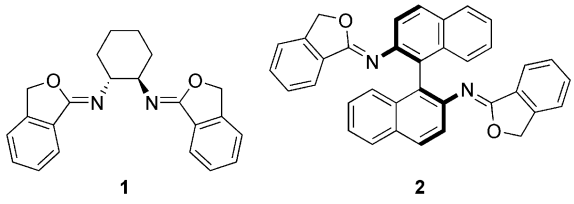

Figure 1. C_2-symmetrical imidate ligands.

Palladium-catalyzed asymmetric allylic alkylation is one of the most versatile methods for the formation of carbon–carbon bonds.[2] A wide variety of chiral ligands has been developed for this type of reaction. Among these, the most successful ligands are mixed nitrogen–phosphorus ligands.[3] Their efficiency has been attributed to the electronic differentiation of the two allylic termini due to the distinctly different *trans* influences of the phosphorus and nitrogen atoms. However, most catalytic systems developed so far suffer from some tedious drawbacks. First, the synthesis of the ligands is mostly laborious. Second, some ligands are air or moisture sensitive, which hampers their widespread use. Third, most catalytic systems display a very narrow substrate scope. Typically, if high enantioselectivities are obtained for linear hindered substrates (e.g., **S1**), low enantioselectivities are observed for linear unhindered (e.g., **S2**) and cyclic substrates (e.g., **S3**), or vice versa (Figure 2).[4–6] Ligands showing high enantioselectivities for both hindered and unhindered substrates are still very scarce.[7] Hence, the development of enantioselective catalysts displaying high enantioselectivities for both substrate classes remains a major challenge. In this paper, we wish to report on a novel family of mixed imidate–phosphane ligands as a new type of hybrid N,P ligands that can tackle most of these drawbacks. These ligands are easily synthesized in one step and show excellent selectivity and reactiv-

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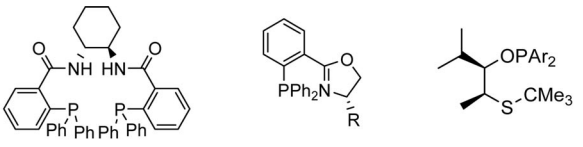
ity in Pd^0-catalyzed asymmetric allylic alkylations. We also demonstrate that these ligands have a remarkably broad substrate scope.



	Trost's Ligand[3]	PHOX Ligand[4]	Evans' Ligand[5]
S1	9% yield 52% *ee*	100% yield 99% *ee*	28% yield 96% *ee*
S2	98% yield 92% *ee*	96% yield 71% *ee*	94% yield 91% *ee*
S3	86% yield 96% *ee*	– 0% *ee*	–

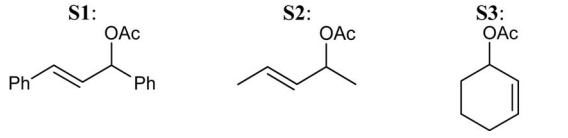
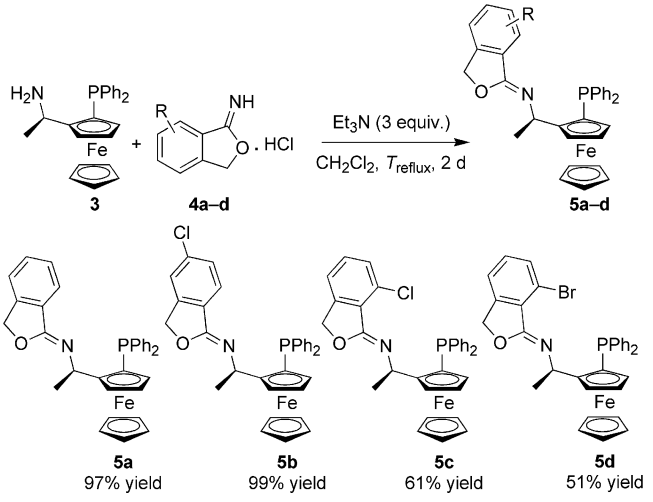


Figure 2. Overview of the best results obtained for some of the most popular ligands in the asymmetric allylic alkylations of **S1**–**S3**.

Results and Discussion

Ferrocenylaminophosphane **3** was chosen as an interesting catalyst precursor. This commercially available[8] aminophosphane is known to be air stable[9] and represents a convenient source of chirality for ligand construction.[10,11] Condensation of **4a** or **4b**[12] with ferrocenylaminophosphane **3** resulted in the formation of the corresponding hybrid imidate–phosphane ligands **5a** or **5b** in excellent yield (Scheme 1). The lower yields obtained for **5c** and **5d** were due to a higher steric hindrance in corresponding imidates **4c** and **4d**, caused by the *ortho* substituent.



Scheme 1. Synthesis of imidate–phosphane ligands **5a**–**d**.

These ligands were tested in palladium(0)-catalyzed asymmetric allylic alkylations. First, the allylic substitution of 1,3-diphenyl-2-propenyl acetate (**S1**) with dimethyl malonate, which is regarded as a standard test substrate for evaluating enantioselective catalysts, was investigated (Table 1).

Table 1. Pd^0-catalyzed asymmetric allylic alkylation of **S1** with dimethyl malonate with the use of bisimidate ligands **1** and **2** and imidate–phosphane ligands **5a**–**d**.[a]

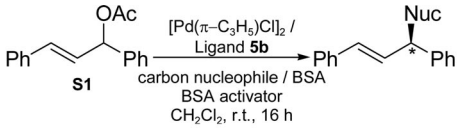
Entry	Ligand	BSA activator	Yield [%][b]	*ee* [%][c,d]
1	**1**	LiOAc	n.c.[e]	–
2	**2**	LiOAc	53	95 (*R*)
3	**5a**	LiOAc	82	94 (*S*)
4	**5b**	LiOAc	85	96 (*S*)
5	**5c**	LiOAc	84	96 (*S*)
6	**5d**	LiOAc	85	96 (*S*)
7	**5b**	NaOAc	93	99 (*S*)
8	**5b**	KOAc	99	99 (*S*)
9	**5b**	CsOAc	99	99 (*S*)

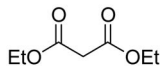
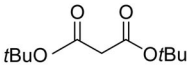
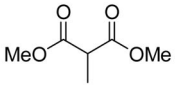
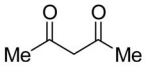
[a] Reaction conditions: **S1** (0.22 mmol), dimethyl malonate (0.66 mmol), BSA (0.66 mmol), BSA activator (10.6 μmol), $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ (5.5 μmol), ligand (21.8 μmol), CH_2Cl_2 (2 mL), room temp., 16 h. [b] Isolated yield. [c] Determined by HPLC analysis with a chiral stationary phase column (Chiralcel AD-H). [d] Absolute configuration was assigned by the sign of the optical rotation. [e] N.c.: no conversion was observed.

Bisimidate ligand **1** gave no conversion, whereas ligand **2** gave a moderate yield but an excellent enantioselectivity (Table 1, Entries 1 and 2). To our delight, high yields and excellent enantioselectivities were obtained with all imidate–phosphane ligands (Table 1, Entries 3–6). The best result was obtained with ligand **5b** (Table 1, Entry 4). We observed also a pronounced *N*,*O*-bis(trimethylsilyl)acetamide (BSA)-activator effect (Table 1, Entries 7–9). The enantioselectivity could be further improved when NaOAc was used (Table 1, Entry 7). With KOAc and CsOAc as a BSA activator, almost perfect selectivities and nearly quantitative yields were obtained (Table 1, Entries 8 and 9).

To further study the potential of these readily available ligands, other nucleophiles were tested (Table 2). When the reaction was performed with more sterically demanding malonates, excellent yields and selectivities were obtained for the corresponding adducts (Table 2, Entries 1 and 2). Use of dimethyl methylmalonate as a nucleophile and LiOAc as a BSA activator afforded the corresponding adduct in excellent yield and good enantioselectivity (Table 2, Entry 3). By variation of the BSA activator (Table 2, Entries 4–6), the enantioselectivity could be further improved to >99%*ee* by using NaOAc (Table 2, Entry 4). Also, acetylacetone was an effective nucleophile in the palladium-catalyzed allylic alkylation reaction: the adduct was formed in 96% yield and with 94%*ee* (Table 2, Entry 7).

Table 2. Asymmetric allylic alkylation reactions with various carbon nucleophiles with the use of **5b** as an imidate–phosphane ligand.[a]

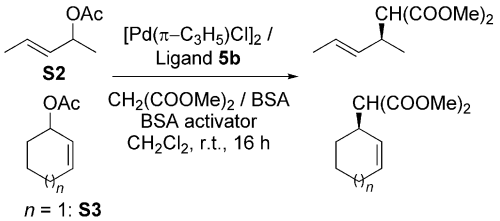


Entry	Carbon Nucleophile (NucH)	BSA activator	Yield [%][b]	*ee* [%][c,d]
1		LiOAc	98	99 (*S*)
2		LiOAc	81	99 (*S*)
3		LiOAc	100	79 (*R*)
4		NaOAc	75	>99 (*R*)
5		KOAc	100	94 (*R*)
6		CsOAc	100	82 (*R*)
7		KOAc	96	94 (*S*)

[a] Reaction conditions: **S1** (0.22 mmol), carbon nucleophile (0.66 mmol), BSA (0.66 mmol), BSA activator (10.6 μmol), $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ (5.5 μmol), ligand **5b** (21.8 μmol), CH_2Cl_2 (2 mL), room temp., 16 h. [b] Isolated yield. [c] Determined by HPLC analysis with a chiral stationary phase column or by ^{1}H NMR spectroscopy with the use of (+)-Eu(hfc)$_3$, see the Supporting Information. [d] Absolute configuration was assigned by the sign of the optical rotation.

Encouraged by the excellent performance of new imidate–phosphane ligand **5b**, we studied its potential in the allylic alkylation of unhindered linear substrate **S2** and cyclic substrates **S3**–**S5**. Although highly selective catalysts have been developed for these substrates, they generally exhibit low enantiocontrol in more hindered substrates, such as substrate **S1**.[9] On the other hand, most catalysts displaying superior enantioselectivities for more hindered substrates like **S1** behave very poorly for substrates like **S2** and cyclic substrates **S3**–**S5**.[2] Remarkably, also for unhindered substrate **S2** good enantioselectivities were observed with our catalyst system **5b** (Table 3, Entries 1–5). The best result was obtained when NaOAc was used as a BSA activator (Table 3, Entry 4). For six-membered cyclic substrate **S3**, good enantioselectivities were obtained with all BSA activators (Table 3, Entries 6–9). The best results were obtained with KOAc: a good yield was combined with a good enantioselectivity (Table 3, Entry 7). We observed a higher selectivity and a higher quantitative yield for five-membered cyclic substrate **S4** than for **S3** (Table 3, Entries 10–13). The best result was obtained in the presence of KOAc (Table 3, Entry 11). For seven-membered cyclic substrate **S5** an excellent enantioselectivity (90%*ee*) and yield (100%) were obtained in the presence of NaOAc as a BSA activator (Table 3, Entry 16).

Table 3. Pd^0-catalyzed asymmetric allylic alkylation of **S2**–**S5** with dimethyl malonate with the use of **5b** as an imidate–phosphane ligand.[a]



Entry	Substrate	BSA activator	Yield [%][b]	*ee* [%][c,d]
1	**S2**	LiOAc	79	78 (*S*)
2[e]	**S2**	LiOAc	23	80 (*S*)
3	**S2**	KOAc	86	59 (*S*)
4	**S2**	NaOAc	91	83 (*S*)
5	**S2**	CsOAc	80	65 (*S*)
6	**S3**	LiOAc	49	74 (*R*)
7	**S3**	KOAc	76	74 (*R*)
8	**S3**	NaOAc	31	73 (*R*)
9	**S3**	CsOAc	61	73 (*R*)
10[f]	**S4**	LiOAc	100	75 (*R*)
11[f]	**S4**	KOAc	100	86 (*R*)
12[f]	**S4**	NaOAc	100	78 (*R*)
13[f]	**S4**	CsOAc	100	80 (*R*)
14[f]	**S5**	LiOAc	100	87 (*R*)
15[f]	**S5**	KOAc	100	58 (*R*)
16[f]	**S5**	NaOAc	100	90 (*R*)
17[f]	**S5**	CsOAc	100	85 (*R*)

[a] Reaction conditions: **S2**–**S5** (0.22 mmol), dimethyl malonate (0.66 mmol), BSA (0.66 mmol), BSA activator (10.6 μmol), $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ (5.5 μmol), ligand **5b** (21.8 μmol), CH_2Cl_2 (2 mL), room temp., 16 h. [b] Isolated yield. [c] Determined by ^{1}H NMR spectroscopy by using (+)-Eu(hfc)$_3$. [d] Absolute configuration was assigned by the sign of the optical rotation. [e] The reaction was performed at 0 °C. [f] Complete conversion was obtained within 2 h.

In order to determine whether these excellent results and the broad substrate scope were due to the combination of both the chiral ferrocenyl backbone and the imidate nitrogen donor or solely to the presence of the chiral ferrocenyl backbone, we investigated some other nitrogen donors (Figure 3). When imine–phosphane ligand **6** was used, we observed a good, but significantly lower enantioselectivity for substrate **S1**, whereas with substrates **S2** and **S3** a much lower enantioselectivity was obtained. In addition, when we investigated amidine–phosphane ligand **7**, which can be considered as the nitrogen analogue of an imidate ligand, both yield and enantioselectivity were much lower than that of imidate–phosphane ligand **5b**. These results show clearly that the presence of the imidate nitrogen donor is required to obtain both high enantioselectivities and a broad substrate scope.

In the literature, several N,P bidentate ligands with a ferrocenyl backbone have been synthesized. In Figure 4, an overview is shown of the best results obtained with these ligands. With oxazoline–phosphane ligand **8**, very high enantioselectivity was obtained for substrate **S1**. However, a very low enantioselectivity was observed for nonhindered

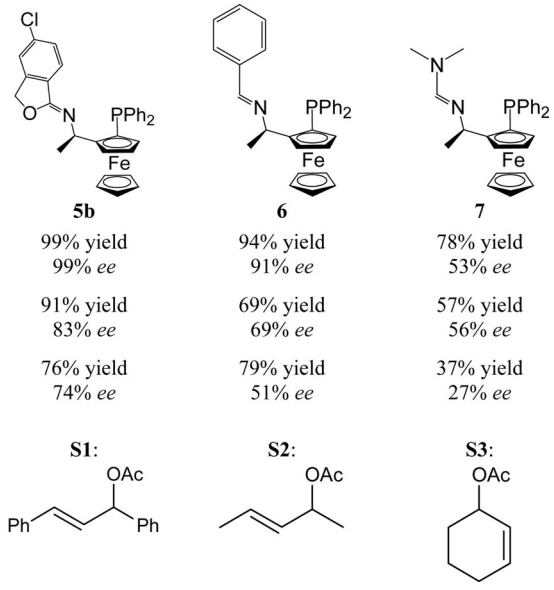


Figure 3. Comparison of imidate–phosphane ligand **5b** with imine–phosphane ligand **6** and amidine–phosphane ligand **7** in the asymmetric allylic alkylation of **S1**–**S3**.

substrate **S2**. With imine derivatives **9** and **10**, a broader substrate scope was observed. However, nonhindered substrate **S2** was not investigated.

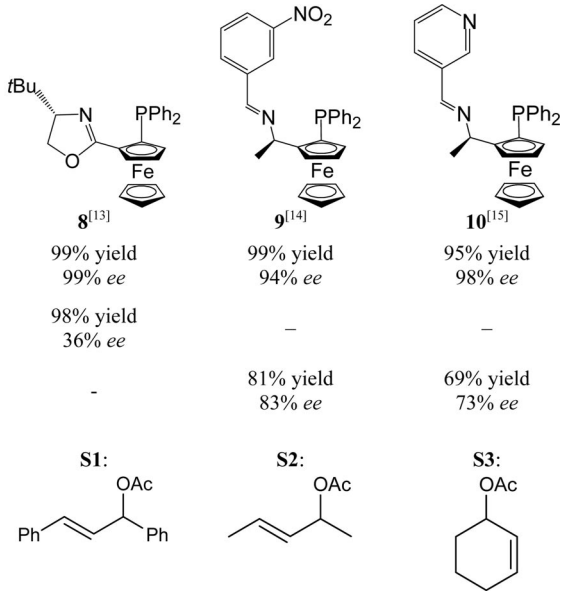


Figure 4. Overview of the best results obtained for some N,P ligands with a chiral ferrocenyl backbone in asymmetric allylic alkylations of **S1**–**S3**.

Conclusions

In conclusion, we have successfully developed for the first time imidate–phosphane ligands as a new type of N,P ligands, easily accessible in one step through condensation of a chiral aminophosphane and an imidate precursor. These imidate–phosphane ligands were demonstrated to be highly valuable in palladium(0)-catalyzed asymmetric allylic alkylation reactions. Excellent performance of this catalyst system was observed in the asymmetric allylic alkylation of 1,3-diphenyl-2-propenyl acetate (**S1**) with various nucleophiles (up to 99% yield and >99% *ee*). In addition, the allylic alkylation of linear unhindered (**S2**) as well as cyclic substrates (**S3**–**S5**), which are known to be more difficult, resulted in good to excellent conversions and enantioselectivities. Rarely are enantioselective catalysts successful in both substrate classes. Therefore, this imidate–phosphane ligand family can compete with a few other ligands that also provide high selectivities for both hindered and unhindered substrates.[3–5] Moreover, we have also demonstrated that the presence of the imidate as a nitrogen donor is required to obtain these excellent results. Further studies towards the application of these imidate–phosphane ligands in asymmetric transition-metal-catalyzed reactions are in progress and will be reported in due course.

Experimental Section

General Experimental Methods: All reactions were carried out under an argon atmosphere in dry solvents under anhydrous conditions, unless otherwise stated. All reagents were purchased and used without purification, unless otherwise noted. Imidates **4a**–**c** were synthesized by our earlier described method.[1] Analytical TLC was performed by using Macherey–Nagel SIL G-25 UV_{254} plates. Flash chromatography was carried out with Rocc silica gel (0.040–0.063 mm). ^1H NMR and ^{13}C NMR spectra were recorded with a Bruker Avance 300 or a Bruker DRX 500 spectrometer as indicated, with chemical shifts reported in ppm relative to TMS, by using the residual solvent signal as a standard and relative to 85% aqueous phosphoric acid for ^{31}P–^{13}C NMR spectra were recorded using the attached proton test. IR spectra were recorded with a Perkin–Elmer SPECTRUM-1000 FTIR spectrometer with a Pike Miracle Horizontal Attenuated Total Reflectance (HATR) module. Mass spectra (EI) were recorded with a Hewlett–Packard 5988A mass spectrometer. LC–MS analysis was performed with an Agilent 1100 series HPLC with quaternary pump, DAD and single quadrupole MS detector type VL with an API-ES source, by using a Phenomenex Luna C18(2) column (250 × 4.6 mm, particle size 5 μm). Analytical chiral HPLC separations were performed with an Agilent 1100 series HPLC system with DAD detection. Exact molecular masses were measured with a Kratos MS50TC mass spectrometer. Melting points were measured with a Kofler melting point apparatus.

General Procedure for the Preparation of Hybrid Imidate–Phosphane Ligands 5a–d: A suspension of (S_p)-1-[(1*R*)-(1-aminoethyl)]-2-(diphenylphosphanyl)ferrocene (**3**; 100.0 mg, 0.24 mmol) and corresponding imidate **4** (0.31 mmol) in dry CH_2Cl_2 (2.5 mL) was cooled in an ice bath. Et_3N (102.0 μL, 0.73 mmol) was added, and the resulting suspension was heated at reflux for 48 h. Evaporation in vacuo and purification by flash chromatography over silica gel (hexane/EtOAc, 8:2) resulted in corresponding ligand **5** as a brownish oil.

(S_p)-1-[(1*R*)-(1-(3*H*-Isobenzofuran-1-ylideneamino)-ethyl)]-2-(diphenylphosphanyl)ferrocene (5a): Yield: 123.0 mg (97%). ^1H NMR (300 MHz, $CDCl_3$): δ = 1.62 (d, J = 6.6 Hz, 3 H, CH_3), 3.63 (m, 1 H, Cp), 4.08 (s, 5 H, Cp), 4.7 (m, 1 H, Cp), 4.65 (m, 1 H, Cp), 4.83 (d, J = 14.2 Hz, 1 H, CH_2O), 5.10 (d, J = 14.2 Hz, 1 H, CH_2O),

5.36–5.43 (m, 1 H, CHMe), 6.59–6.64 (m, 1 H, Ph), 6.72–6.77 (m, 2 H, Ph), 6.97–7.02 (m, 2 H, Ph), 7.06–7.16 (m, 2 H, Ph), 7.27–7.33 (m, 5 H, Ph), 7.45–7.51 (m, 2 H, Ph) ppm. ^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 20.7 (CH_3), 49.6 (d, $J_{C,P}$ = 8.8 Hz, CH), 68.7 (d, $J_{C,P}$ = 4.0 Hz, CH), 68.8 (CH), 69.5 (5 CH), 71.3 (d, $J_{C,P}$ = 4.5 Hz, CH), 71.8 (CH_2), 75.3 (d, $J_{C,P}$ = 6.6 Hz, 1 C), 98.3 (d, $J_{C,P}$ = 23.9 Hz, 1 C), 120.5 (CH), 123.6 (CH), 126.8 (CH), 127.0 (d, $J_{C,P}$ = 6.3 Hz, CH), 127.4 (CH), 127.9 (d, $J_{C,P}$ = 7.7 Hz, CH), 128.8 (CH), 129.8 (C), 130.4 (CH), 132.0 (d, $J_{C,P}$ = 18.6 Hz, CH), 135.2 (d, $J_{C,P}$ = 20.9 Hz, CH), 137.6 (d, $J_{C,P}$ = 8.6 Hz, 1 C), 139.2 (d, $J_{C,P}$ = 9.4 Hz, 1 C), 142.8 (C), 158.0 (C) ppm. ^{31}P NMR (121.4 MHz, $CDCl_3$): δ = –22.5 ppm. IR (HATR): $\tilde{\nu}$ = 3050, 2972, 2931, 2873, 1681, 1469, 1451, 1433, 1363, 1290, 1243, 1167, 1106, 1081, 1044, 1017, 1000, 819, 747, 728, 697 cm^{-1}. MS (EI): *m*/*z* (%) = 529 (8) $[M]^+$, 396 (19), 275 (8), 212 (9), 183 (17), 165 (15), 133 (11), 121 (100), 77 (17), 56 (30). MS (ESI): *m*/*z* = 530 $[M + H]^+$. $[\alpha]_D^{20}$ = –338.8 (*c* = 0.64, $CHCl_3$). HRMS (EI): calcd. for $C_{32}H_{28}NOPFe$ 529.1258; found 529.1257.

(S_p)-1-[(1*R*)-(1-(5-Chloro-3*H*-isobenzofuran-1-ylideneamino)-ethyl)]-2-(diphenylphosphanyl)ferrocene (5b): Yield: 134.0 mg (99%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.63 (d, *J* = 6.6 Hz, 3 H, CH_3), 3.66 (m, 1 H, Cp), 4.11 (s, 5 H, Cp), 4.30 (s, 1 H, Cp), 4.67 (m, 1 H, Cp), 4.83 (d, *J* = 14.4 Hz, 1 H, CH_2O), 5.09 (d, *J* = 14.4 Hz, 1 H, CH_2O), 5.37–5.44 (m, 1 H, CHMe), 6.70–6.75 (m, 1 H, Ph), 6.80–6.84 (m, 2 H, Ph), 6.99–7.04 (m, 2 H, Ph), 7.09–7.28 (m, 3 H, Ph), 7.34–7.35 (m, 3 H, Ph), 7.47–7.53 (m, 2 H, Ph) ppm. ^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 20.5 (CH_3), 49.8 (d, $J_{C,P}$ = 8.8 Hz, CH), 68.7 (d, $J_{C,P}$ = 4.0 Hz, CH), 68.9 (CH), 69.5 (5 CH), 71.1 (CH_2), 71.4 (d, $J_{C,P}$ = 4.4 Hz, CH), 75.3 (d, $J_{C,P}$ = 6.6 Hz, 1 C), 98.2 (d, $J_{C,P}$ = 23.7 Hz, 1 C), 120.9 (CH), 124.7 (CH), 126.9 (CH), 127.1 (d, $J_{C,P}$ = 6.2 Hz, CH), 127.9 (d, $J_{C,P}$ = 7.7 Hz, CH), 128.03 (CH), 128.7 (C), 128.8 (CH), 132.0 (d, $J_{C,P}$ = 18.6 Hz, CH), 135.2 (d, $J_{C,P}$ = 20.9 Hz, CH), 136.5 (C), 137.5 (d, $J_{C,P}$ = 8.7 Hz, 1 C), 139.3 (d, $J_{C,P}$ = 9.8 Hz, 1 C), 144.4 (C), 156.5 (C) ppm. ^{31}P NMR (121.4 MHz, $CDCl_3$): δ = –22.6 ppm. IR (HATR): $\tilde{\nu}$ = 3067, 2969, 2931, 2871, 2358, 2341, 1689, 1613, 1473, 1456, 1432, 1354, 1304, 1265, 1242, 1222, 1192, 1167, 1106, 1080, 1042, 1018, 879, 822, 742, 697, 668 cm^{-1}. MS (EI) *m*/*z* (%) = 563 (5) $[M]^+$, 396 (100), 331 (20), 288 (20), 252 (15), 226 (6), 183 (18), 167 (39), 138 (68), 102 (27), 75 (24), 56 (45). MS (ESI): *m*/*z* = 564 $[M + H]^+$. $[\alpha]_D^{20}$ = –338.1 (*c* = 0.64, $CHCl_3$). HRMS (EI): calcd. for $C_{32}H_{27}NOP^{35}ClFe$ 563.0868; found 563.0888.

(S_p)-1-[(1*R*)-(1-(7-Chloro-3*H*-isobenzofuran-1-ylideneamino)-ethyl)]-2-(diphenylphosphanyl)ferrocene (5c): Yield: 82.5 mg (61%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.64 (d, *J* = 6.6 Hz, 3 H, CH_3), 3.62 (m, 1 H, Cp), 4.08 (s, 5 H, Cp), 4.27 (m, 1 H, Cp), 4.65 (m, 1 H, Cp), 4.72 (d, *J* = 14.3 Hz, 1 H, CH_2O), 5.01 (d, *J* = 14.3 Hz, 1 H, CH_2O), 5.33–5.41 (m, 1 H, CHMe), 6.54–6.59 (m, 1 H, Ph), 6.75–6.80 (m, 2 H, Ph), 6.93–7.02 (m, 3 H, Ph), 7.14–7.21 (m, 2 H, Ph), 7.30–7.35 (m, 3 H, Ph), 7.45–7.52 (m, 2 H, Ph) ppm. ^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 21.1 (CH_3), 50.0 (d, $J_{C,P}$ = 8.8 Hz, CH), 68.8 (d, $J_{C,P}$ = 3.9 Hz, CH), 68.9 (CH), 69.5 (5 CH), 70.4 (CH_2), 71.0 (d, $J_{C,P}$ = 4.3 Hz, CH), 75.1 (d, $J_{C,P}$ = 6.1 Hz, 1 C), 99.0 (d, $J_{C,P}$ = 24.2 Hz, 1 C), 118.9 (CH), 126.6 (CH), 126.7 (C), 127.0 (d, $J_{C,P}$ = 6.1 Hz, CH), 127.9 (d, $J_{C,P}$ = 7.7 Hz, CH), 128.8 (CH), 129.5 (CH), 130.8 (CH), 131.2 (C), 131.9 (d, $J_{C,P}$ = 18.3 Hz, CH), 135.3 (d, $J_{C,P}$ = 21.0 Hz, CH), 137.7 (d, $J_{C,P}$ = 8.8 Hz, 1 C), 139.2 (d, $J_{C,P}$ = 9.9 Hz, 1 C), 145.6 (C), 154.5 (C) ppm. ^{31}P NMR (121.4 MHz, $CDCl_3$): δ = –22.0 ppm. IR (HATR): $\tilde{\nu}$ = 3054, 2972, 2931, 1678, 1606, 1585, 1478, 1462, 1433, 1361, 1306, 1265, 1244, 1220, 1167, 1106, 1078, 1040, 1026, 1000, 915, 818, 774, 738, 698, 668 cm^{-1}. MS (EI): *m*/*z* (%) = 563 (7) $[M]^+$, 396 (100), 331 (21), 288 (21), 252 (17), 226 (6), 183 (20), 167 (32), 138 (60), 102 (31), 75 (24), 56 (52). MS (ESI): *m*/*z* = 564 $[M + H]^+$. $[\alpha]_D^{20}$ = –367.6 (*c* = 0.70, $CHCl_3$). HRMS (EI): calcd. for $C_{32}H_{27}NOP^{35}ClFe$ 563.0868; found 563.0857.

(S_p)-1-[(1*R*)-(1-(7-Bromo-3*H*-isobenzofuran-1-ylideneamino)-ethyl)]-2-(diphenylphosphanyl)ferrocene (5d): Yield: 74.5 mg (51%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.64 (d, *J* = 6.6 Hz, 3 H, CH_3), 3.61 (m, 1 H, Cp), 4.09 (s, 5 H, Cp), 4.27 (m, 1 H, Cp), 4.65–4.70 (m, 2 H, 1 H from CH_2O + 1 H from Cp), 4.99 (d, *J* = 14.3 Hz, 1 H, CH_2O), 5.31–5.39 (m, 1 H, CHMe), 6.53–6.58 (m, 1 H, Ph), 6.75–6.81 (m, 2 H, Ph), 6.97–7.02 (m, 3 H, Ph), 7.08–7.13 (m, 1 H, Ph), 7.31–7.51 (m, 6 H, Ph) ppm. ^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 21.3 (CH_3), 49.8 (d, $J_{C,P}$ = 8.7 Hz, CH), 68.8 (d, $J_{C,P}$ = 4.0 Hz, CH), 68.9 (CH), 69.5 (5 CH), 70.1 (CH_2), 71.0 (d, $J_{C,P}$ = 4.4 Hz, CH), 75.0 (d, $J_{C,P}$ = 6.1 Hz, 1 C), 99.1 (d, $J_{C,P}$ = 23.9 Hz, 1 C), 119.2 (C), 119.6 (CH), 126.5 (CH), 127.1 (d, $J_{C,P}$ = 6.2 Hz, CH), 127.9 (d, $J_{C,P}$ = 7.7 Hz, CH), 128.2 (C), 128.9 (CH), 130.9 (CH), 131.9 (d, $J_{C,P}$ = 18.3 Hz, CH), 132.9 (CH), 135.3 (d, $J_{C,P}$ = 21.0 Hz, CH), 137.8 (d, $J_{C,P}$ = 8.9 Hz, 1 C), 139.2 (d, $J_{C,P}$ = 10.0 Hz, 1 C), 145.7 (C), 154.4 (C) ppm. ^{31}P NMR (121.4 MHz, $CDCl_3$): δ = –22.0 ppm. IR (HATR): $\tilde{\nu}$ = 3052, 2971, 2930, 1680, 1580, 1478, 1458, 1433, 1361, 1321, 1303, 1266, 1244, 1217, 1106, 1079, 1039, 1000, 892, 819, 774, 741, 696, 668 cm^{-1}. MS (EI): *m*/*z* (%) = 607 (5) $[M]^+$, 396 (100), 331 (22), 319 (10), 288 (22), 252 (18), 211 (20), 182 (34), 165 (27), 121 (57), 102 (27), 56 (55). MS (ESI): *m*/*z* = 607.9 $[M + H]^+$. $[\alpha]_D^{20}$ = –322.2 (*c* = 0.99, $CHCl_3$). HRMS (EI): calcd. for $C_{32}H_{27}NOP^{79}BrFe$ 607.0363; found 607.0382.

Synthesis of Imine–Phosphane Ligand 6: A suspension of (S_p)-1-[(1*R*)-(1-aminoethyl)]-2-(diphenylphosphanyl)ferrocene (**3**; 100.0 mg, 0.24 mmol), $MgSO_4$ (200 mg), and benzaldehyde (24.6 μL, 0.24 mmol) in CH_2Cl_2 (2 mL) was stirred for 24 h. Evaporation in vacuo and purification by flash chromatography over basic alumina (Et_2O) resulted in the corresponding ligand **6** as a yellow oil. Yield: 108.3 mg (90%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.69 (d, *J* = 6.7 Hz, 3 H, CH_3), 3.77 (m, 1 H, Cp), 4.09 (s, 5 H, Cp), 4.35 (m, 1 H, Cp), 4.70 (m, 1 H, Cp), 4.83 (m, 1 H, CHMe), 6.76–6.81 (m, 1 H, Ph), 6.85–6.90 (m, 2 H, Ph), 6.97–7.02 (m, 2 H, Ph), 7.11–7.24 (m, 5 H, Ph), 7.36–7.38 (m, 3 H, Ph), 7.50–7.56 (m, 2 H, Ph), 8.03 (s, 1 H, CNH) ppm. ^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 21.9 (CH_3), 64.3 (d, $J_{C,P}$ = 6.8 Hz, CH), 69.3 (CH), 69.3 (d, $J_{C,P}$ = 4.1 Hz, CH), 69.6 (5 CH), 71.6 (d, $J_{C,P}$ = 4.6 Hz, CH), 75.5 (d, $J_{C,P}$ = 7.7 Hz, 1 C), 96.6 (d, $J_{C,P}$ = 23.3 Hz, 1 C), 127.3 (CH), 127.6 (CH), 127.7 (2 CH), 127.7 (CH), 128.0 (CH), 128.0 (2 CH), 128.1 (CH), 129.0 (CH), 129.8 (CH), 132.3 (CH), 132.6 (CH), 135.1 (CH), 135.4 (CH), 135.9 (C), 137.5 (d, $J_{C,P}$ = 8.5 Hz, 1 C), 138.6 (d, $J_{C,P}$ = 8.5 Hz, 1 C), 160.1 (CH) ppm. ^{31}P NMR (121.4 MHz, $CDCl_3$): δ = –23.8 ppm. IR (HATR): $\tilde{\nu}$ = 3052, 2966, 2932, 2848, 1638, 1477, 1449, 1433, 1373, 1364, 1299, 1262, 1240, 1218, 1167, 1106, 1080, 1069, 1039, 1026, 1000, 967, 908, 818, 739, 691 cm^{-1}. MS (ESI): *m*/*z* = 502.1 $[M + H]^+$. $[\alpha]_D^{20}$ = –440.0 (*c* = 0.93, $CHCl_3$). HRMS (EI): calcd. for $C_{31}H_{28}NPFe$ 501.1309; found 501.1319.

Synthesis of Amidine–Phosphane Ligand 7:[16] A mixture of (S_p)-1-[(1*R*)-(1-aminoethyl)]-2-(diphenylphosphanyl)ferrocene (**3**; 100.0 mg, 0.24 mmol) and *N*,*N*-dimethylformamide dimethylacetal (2 mL, 15.0 mmol) was stirred at room temperature for 4 h. The volatiles were removed in vacuo, resulting in **7** as a brownish oil. Yield: 112.4 mg (100%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.53 (d, *J* = 6.6 Hz, 3 H, CH_3), 2.20 [s, 6 H, $N(CH_3)_2$] 3.69 (m, 1 H, Cp), 3.96 (s, 5 H, Cp), 4.24 (m, 1 H, Cp), 4.54 (m, 1 H, CHMe), 4.59 (m, 1 H, Cp), 7.06–7.15 (m, 6 H, Ph + 1 H from CNH), 7.32–7.34 (m, 3 H, Ph), 7.47–7.52 (m, 2 H, Ph) ppm. ^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 22.8 (CH_3), 37.5 (2 CH_3), 59.4 (d, $J_{C,P}$ = 6.2 Hz, CH), 68.9 (CH), 69.2 (d, $J_{C,P}$ = 4.5 Hz, CH), 69.4 (5 CH), 71.3 (d, $J_{C,P}$

= 4.8 Hz, CH), 74.4 (d, $J_{C,P}$ = 7.0 Hz, 1 C), 99.3 (d, $J_{C,P}$ = 23.0 Hz, 1 C), 127.2 (CH), 127.5 (CH), 127.6 (CH), 127.9 (CH), 128.0 (CH), 128.9 (CH), 132.5 (CH), 132.7 (CH), 135.3 (CH), 135.6 (CH), 137.9 (d, $J_{C,P}$ = 7.9 Hz, 1 C), 140.1 (d, $J_{C,P}$ = 8.9 Hz, 1 C), 154.2 (CH), 154.3 (CH) ppm. ^{31}P NMR (121.4 MHz, $CDCl_3$): δ = –23.1 ppm. IR (HATR): $\tilde{\nu}$ = 3053, 2966, 2926, 1639, 1585, 1478, 1433, 1366, 1256, 1240, 1166, 1106, 1067, 1039, 1000, 910, 817, 740, 730, 695 cm^{-1}. MS (ESI): *m*/*z* = 469.1 [M + H]$^+$. $[\alpha]_D^{20}$ = –427.0 (*c* = 0.77, $CHCl_3$). HRMS (EI): calcd. for $C_{27}H_{29}N_2PFe$ 468.1418; found 468.1422.

General Procedure for the Palladium-Catalyzed Asymmetric Allylic Alkylation Reaction: Imidate–phosphane ligand **5b** (12.3 mg, 21.8 μmol) and $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ (2.0 mg, 5.5 μmol) were dissolved in degassed CH_2Cl_2 (1 mL), and the mixture was stirred for 1 h at room temperature. Next, a solution of *rac*-1,3-diphenyl-3-acetoxy-prop-1-ene (**S1**; 55.0 mg, 0.22 mmol) in CH_2Cl_2 (0.5 mL) was added, and the mixture was stirred for another 30 min at room temperature. Finally, a solution of dimethyl malonate (75 μL, 0.66 mmol), BSA (160 μL, 0.66 mmol), and KOAc (1.4 mg, 10.6 μmol) in CH_2Cl_2 (0.5 mL) was added, and the reaction mixture was stirred for 16 h at room temperature. The reaction mixture was passed through a short pad of silica gel and eluted with CH_2Cl_2. Evaporation in vacuo and purification by flash chromatography over silica gel (hexane/EtOAc, 90:10) resulted in the (*S*) adduct (69.8 mg, 99%, 99%*ee*).

All adducts were fully characterized by comparison of their spectroscopic data with those reported in the literature. The absolute configurations were assigned by correlation of their optical rotation with literature values.[17–20]

Supporting Information (see footnote on the first page of this article): General experimental methods, synthesis of imidate **4d**, conditions for enantiomeric excess determination, and ^{1}H NMR and APT spectra of all compounds.

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