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Synthesis and Use of Water-Soluble Sulfonated Dibenzofuran-Based Phosphine Ligands

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Abstract: The syntheses of three triphenylphosphine analogues with one, two or three phenyl groups replaced by 2-dibenzofuranyl groups, respectively, and one enantiopure analogue of the atropisomeric diphosphine MeO-BIPHEP with all four phenyl groups replaced by 2-dibenzofuranyl are reported. Sulfonation of these compounds with sulfuric acid at rt proceeded with complete regioselectivity at the 8-position in the dibenzofuran moieties. These results proved the usefulness of dibenzofuran as a structural moiety in the synthesis of water-soluble phosphine ligands.
The dibenzofuran-based, water-soluble triphenylphosphine analogues were used as ligands in palladium-catalysed aqueous phase Heck and Suzuki reactions and in the rhodium-catalysed two-phase hydroformylation of propene.

Keywords: Phosphines, Solvents and solvent effects, Heck reaction, Suzuki reaction, Hydroformylation

INTRODUCTION

One of the most widely used strategies for obtaining water-soluble ligands is the direct sulfonation of successful known aromatic ligands. An example is the sulfonation of triphenylphosphine to give TPPTS, trisulfonated triphenylphosphine,[1] applied in the Ruhrchemie/Rhône-Poulenc oxo-process since 1984.[2] Most often direct sulfonation of phosphines requires harsh reaction conditions (high temperatures, oleum with high SO_3 content) giving rise to mixtures of several (regioisomeric) sulfonated compounds, and/or oxidised at phosphorus to a considerable extent. Separation of these mixtures is laborious and often not feasible.[3-9] In some cases the selectivity of the sulfonation is improved when an orthoboric acid medium is applied[10,11] or when the phosphine contains directing, activating substituents.[8,10,12,13] Indirect methods for introducing sulfonate groups have also been developed.[15-17]

The dibenzofuran skeleton has been studied extensively in heteroaromatic chemistry.[18-21] An important synthetic aspect of the dibenzofuran moiety is the directing effect of the furan oxygen on ring functionalisation. This oxygen atom mainly activates the *para* positions towards electrophilic substitution. Thus, Friedel-Crafts acylation and alkylation, halogenation and sulfonation give predominantly the *para*-substituted products. In contrast, treatment with nitric acid in a mixed acid system exclusively yields the *meta*-nitrated product.[20,22]

Here we report the synthesis of a new class of phosphines, based on a dibenzofuran moiety. The great advantage of this aromatic system is the high regioselectivity of sulfonation. The reaction conditions are relatively mild and purification is simple. Three of these compounds are used as water-soluble ligands in aqueous phase or two-phase Heck reactions, Suzuki reactions and hydroformylation reactions.

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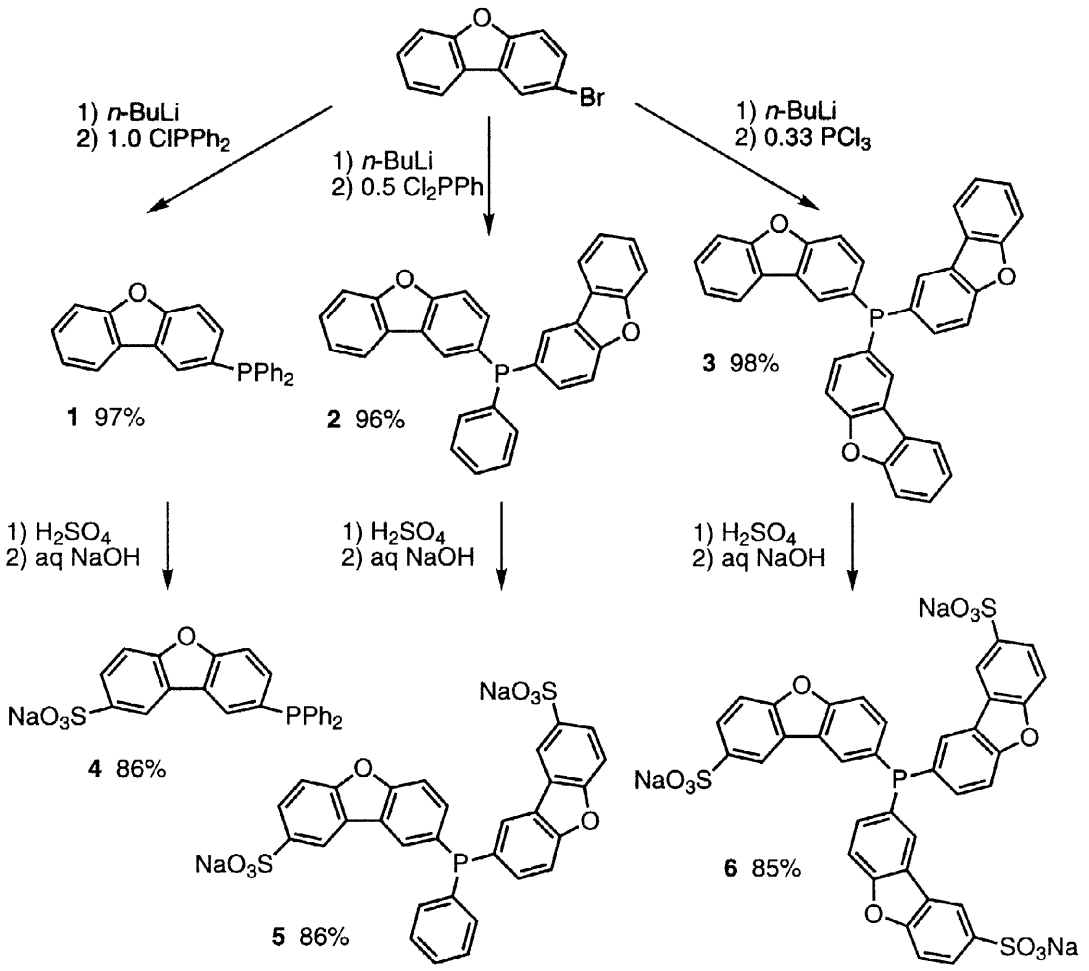
RESULTS AND DISCUSSION

Synthesis of Dibenzofuran-Based Triphenylphosphine Analogues

The synthesis of dibenzofuran-based triphenylphosphine analogues was accomplished in a three step procedure starting from dibenzofuran and using only inexpensive starting materials and reagents (Scheme 1). According to a literature procedure[23] dibenzofuran was monobrominated with bromine in acetic acid to give 2-bromodibenzofuran. Subsequently, the bromide was lithiated with *n*-BuLi in THF at -78 °C yielding a yellow slurry, which was reacted either with 1 equiv of $ClPPh_2$, 0.5 equiv of Cl_2PPh or 0.33 equiv of PCl_3. The compounds **1-3** were obtained in excellent yield (96-98%) as white solids.

Scheme 1

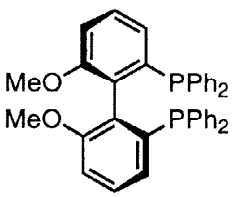


Sulfonation of **1-3** was accomplished by adding the solid phosphine to 95% sulfuric acid. The phosphine slowly dissolved yielding a red, viscous solution and after 1-20 h at rt the reaction was complete. After addition of water, neutralisation to pH 7.0-7.2, freeze-drying and extracting the residue with methanol, the ligands **4-6** were obtained as pure off-white solids in high yield (ca. 85%). No oxides were formed and no further purification was needed.

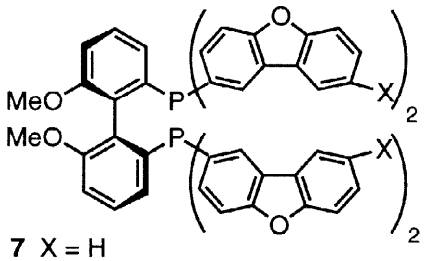
The solubilities of the sulfonated ligands **5** and **6** in water were determined to be very high (>1 kg/L for **6**, 800 g/L for **5**), comparable with the water-solubility of TPPTS (>1100 g/L).[2] The water-solubility of **4** (80 g/L) is the same as found for monosulfonated triphenylphosphine (80 g/L).[2] The ligands are also soluble in alcohols such as methanol or ethanol.

Synthesis of a Dibenzofuranyl-Analogue of the Diphosphine MeO-BIPHEP

The atropisomeric diphosphine MeO-BIPHEP was described by scientists at Hoffmann-La Roche in 1991.[24] The reported synthesis is straightforward and flexible and over 40 enantiopure derivatives, including a water-soluble analogue, have been prepared.[25,26] The ligand and its derivatives generally show high enantioselectivities in asymmetric hydrogenations, isomerisations, Heck reactions and allylic alkylations.[24-28] Based on the reported synthetic route we designed a synthesis for MeO-BIPHEP analogue 7 in which all four phenyl groups are replaced by 2-dibenzofuranyl moieties. Sulfonation would then lead to the water-soluble analogue 8.



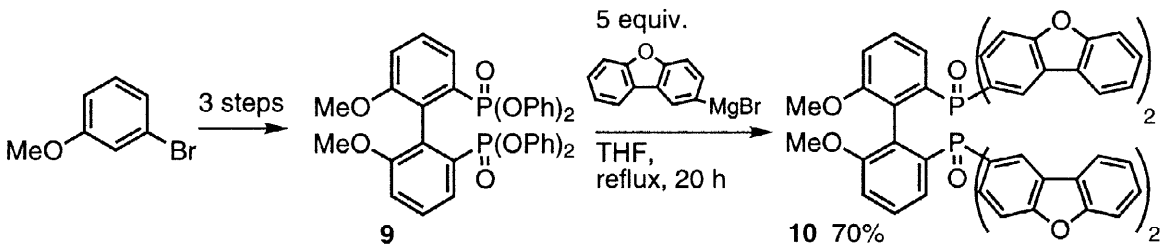
MeO-BIPHEP



7 X = H
8 X = SO_3K

Our synthesis of **8** started from racemic phosphonic ester **9**, prepared in three steps from *m*-bromoanisole as described in a patent of Hoffmann-La Roche.[26] The first step was the introduction of four dibenzofuranyl groups by reacting **9** with five equivalents of 2-bromomagnesiodibenzofuran in refluxing THF for 20 h (Scheme 2). The tetra-substituted diphosphine oxide **10** was isolated as a white solid in 70% yield. The elevated temperature and long reaction time were required in this reaction to achieve complete conversion. Reaction of 2-lithiodibenzofuran with **9** in THF at rt did not yield **10**, but only starting material and dibenzofuran. Raising the reaction temperatures did not improve the result. Thus, 2-lithiodibenzofuran is probably not stable in refluxing THF.

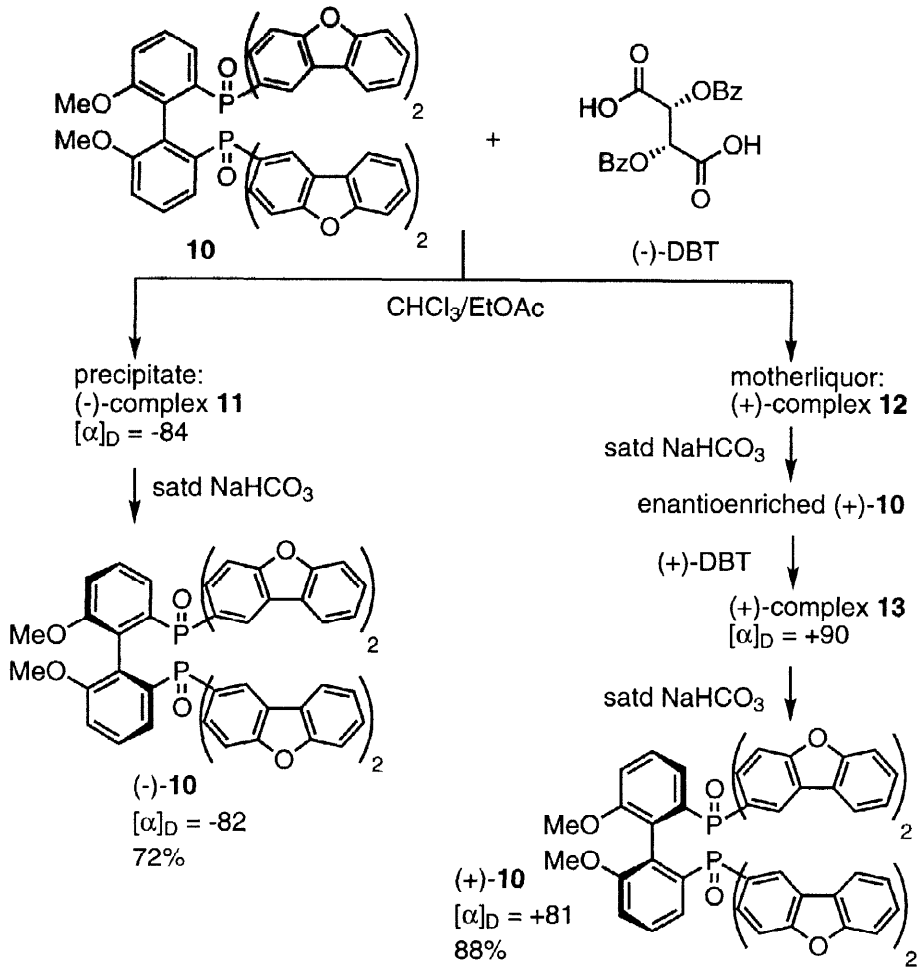
Scheme 2



The diphosphine oxide **10** was resolved (Scheme 3) by fractional crystallisation of the 1:1 complex of the racemate with enantiopure *O,O*-dibenzoyltartaric acid (DBT), similar as described for the synthesis of the well-known atropisomeric diphosphine BINAP.[29] Racemic **10** was dissolved in chloroform and a solution of (-)-DBT in EtOAc was added. After heating for ca. 1 min complex formation occurred and a white precipitate **11** was formed and isolated. The solids **12** from the mother liquor were treated with base, complexed with (+)-DBT and precipitated to furnish complex **13**.

The diastereopurities of the complexes were checked with ^{1}H NMR spectroscopy. The methoxy protons in the (-)/(-)complex **11** and the (+)/(+) complex **13** resonate at 3.12 ppm. In the (+)/(-) complex **12** they resonate at 3.52 ppm. A virtually complete diastereopurity was found for **11** and **13**, as was concluded from the absence of the signal at 3.52 ppm. Treatment of the complexes **11** and **13** with base provided the pure enantiomers (-)-**10** and (+)-**10** as white solids which showed optical rotations of virtually the same magnitude (Scheme 3).

Scheme 3



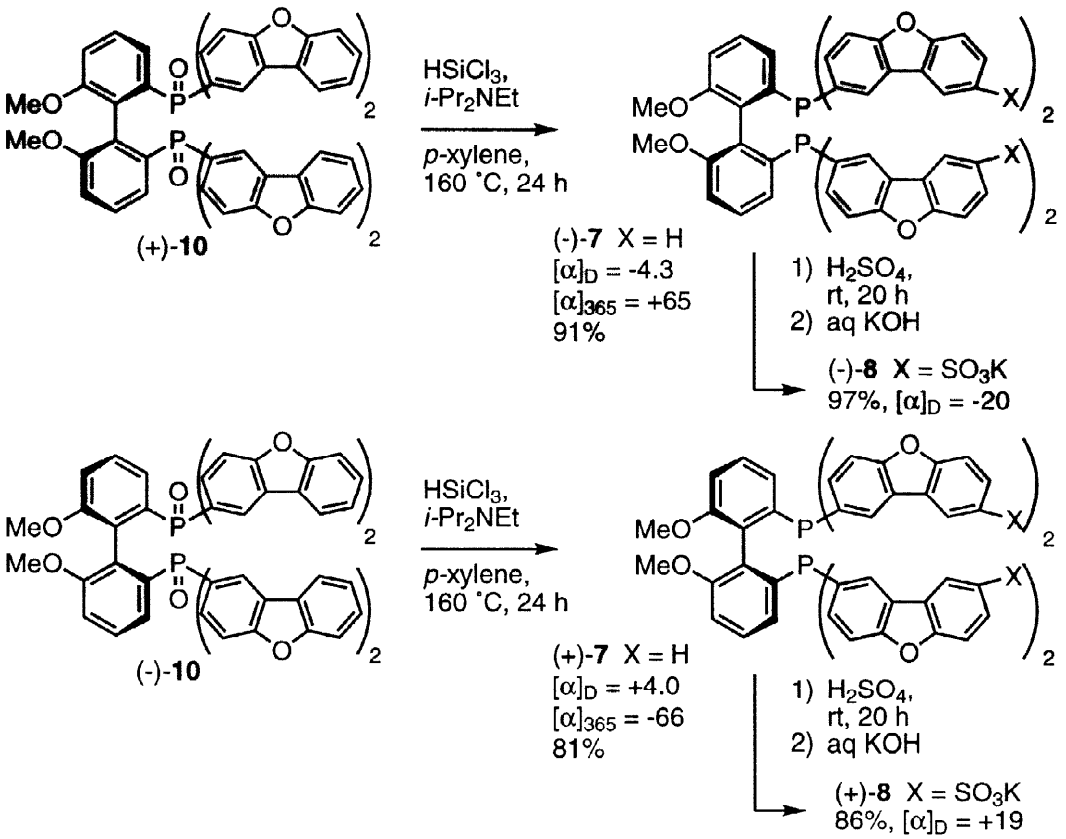
The diphosphine oxides (+)-**10** and (-)-**10** were reduced with trichlorosilane to give the diphosphines (-)-**7** and (+)-**7** (Scheme 4). Both reactions were performed in a sealed tube and were high yielding. The phosphines were purified by recrystallisation from a CH_2Cl_2/ethanol mixture. Surprisingly, on going from **10** to **7** an inversion of the sign of optical rotation in chloroform at the sodium D-line was observed. Thus, (-)-**10** yielded (+)-**7**, while (+)-**10** yielded (-)-**7**. However, at shorter wavelengths the optical rotations remained of the same sign.

Sulfonation of both (-)-**7** and (+)-**7** was performed in sulfuric acid at rt. After being stirred for 20 h and work-up, the tetrasulfonates (-)-**8** and (+)-**8** were obtained in excellent yield as off-white solids. The $[\alpha]^{20}_D$-values were -20 and +19, respectively. The results of the application of the diphosphines **7** and **8** as ligands in ruthenium-catalysed asymmetric hydrogenations will be reported elsewhere.

Heck and Suzuki Reactions in Aqueous Media

In the past few years several variations of the Heck reaction in water or mixtures of water and organic solvents were introduced. Beletskaya *et al.* were the first to publish in this field in 1988.[30,31] We have studied a number of Heck and Suzuki reactions in water, water/acetonitrile or water/methanol mixtures, using the ligands **4** and **6**. The results are summarised in Table 1. The reactions were performed with 5 mol% $Pd(OAc)_2$ and 15 mol% ligand, at temperatures ranging from 40-95 °C, with Et_3N or Na_2CO_3 as base and at substrate concentrations of ca. 0.1 M. The addition of a ligand was essential for the progress of the reaction as otherwise no product was obtained.

Scheme 4



The Heck and Suzuki reactions proceeded in moderate to good yields. The ligands **4** and **6** gave similar results for the cyclisation of *N*-(2-iodobenzoyl)-1,2,3,6-tetrahydropyridine (entry 2). In most cases the addition of acetonitrile or methanol as a cosolvent had a positive effect on the yield of the reaction, probably due to the enhanced solubility of the reactants. At first sight comparison of the results of ligand **6** with those of TPPTS (entries 1 and 4) is in favour of TPPTS. However, this is most likely a solvent effect, because the reported reactions with TPPTS were performed in 1:15 H_2O/MeCN mixtures while the reactions with **6** were carried out in 1:1 or 1:2 H_2O/MeCN mixtures. Using a higher acetonitrile content in the reactions with **6** was not possible. At ratios higher than 1:3 catalyst precipitation was observed.

Two-Phase Rhodium-Catalysed Hydroformylation of Propene

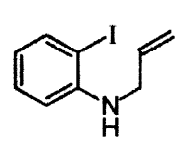
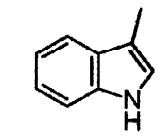
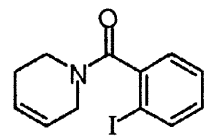
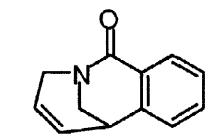
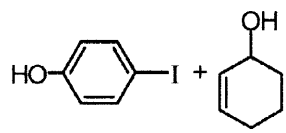
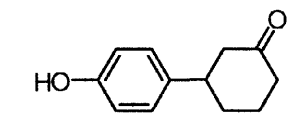
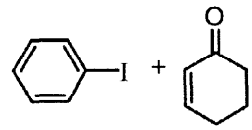
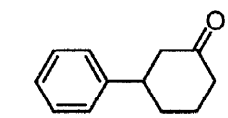
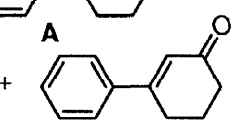
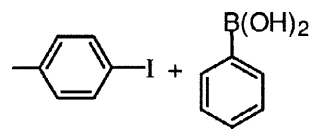
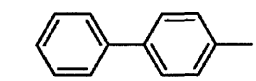
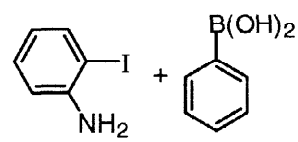
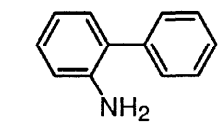
Two-phase catalysis in the hydroformylation of propene is commercially applied in the Ruhrchemie/Rhône-Poulenc oxo process. A $(TPPTS)_2RhH(CO)_2$ species catalyses the reaction of propene with synthesis gas to butanal (95%), 2-methylpropanal (4%) and propane (1%).[2]

The results of the rhodium-catalysed hydroformylation of propene using the ligands **4-6** are given in Table 2. The initial turnover frequencies for **4-6** are 30-93, while TPPTS gives a much faster reaction.[33] Assuming that the basicity of ligands **4-6** is higher compared to that of TPPTS, due to the electron releasing properties of the furan oxygens, these observations are in line with the general observation that a higher basicity of a phosphorus ligand results in lower rates.[34]

Furthermore, the observed linear/branched ratios with **4-6** (entries 1-3) are much lower than the linear/branched ratio found for TPPTS. The values for **4-6** are comparable to linear/branched ratios obtained in the hydroformylation of octene with triphenylphosphine in toluene (linear/branched = 2.8).[35] It is known that the bulkiness of the ligand is one of the factors determining selectivity and rate in the hydroformylation reaction.[36,37] TPPTS bears the sulfonate groups at the *meta*-positions of the phenyl rings, which are surrounded by a shell of

water molecules, resulting in a cone angle of ca. 30° larger than that of triphenylphosphine on the basis of X-ray information.[38] The sulfonate groups in the ligands **4-6** are located further away from the phosphorus centre. Therefore, the cone angles of these ligands are probably smaller than that of TPPTS, which might account for the lower selectivity observed.

Table 1: Heck and Suzuki reactions in the presence of ligands **4** and **6**.[a]

entry	substrate(s)	temp. (°C)	solvent (ratio)	ligand	product(s)	yield (%)
(1)		40	H_2O/MeCN (1:1)	**6**		97
		80	H_2O	**6**		60
		25	H_2O/MeCN (1:1)	TPPTS[b]		97
(2)		95	H_2O/MeCN (1:1)	**6**		50
		95	H_2O	**6**		50
		95	H_2O/MeCN (1:1)	**4**		52
		95	H_2O	**4**		50
(3)		80	H_2O	**6**		40
(4)		80	H_2O/MeCN (1:1)	**6**	 A +  B	71 (20:1)[c]
		50	H_2O/MeCN (1:1)	**6**		34 (5:1)[c]
		50	H_2O/MeOH (1:1)	**6**		44 (10:1)[c]
		27	H_2O/MeCN (1:1)	TPPTS[b]		98 (2:3)[c]
(5)		60	H_2O/MeCN (1:2)	**6**		90
(6)		50	H_2O/MeCN (1:1)	**6**		58

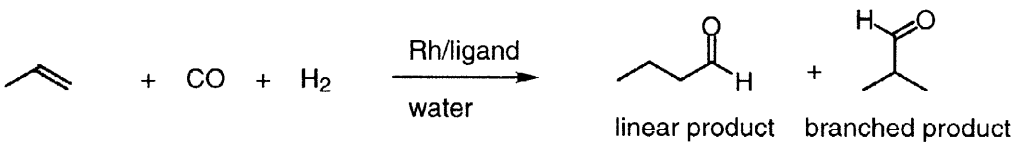
a) The reactions were performed with $Pd(OAc)_2$ (5 mol%) and ligand (15 mol%) with Et_3N or Na_2CO_3 as the base.
b) See ref. 32. c) Product ratio A:B.

CONCLUSIONS

The syntheses of the new phosphines **1-3** and both enantiomers of MeO-BIPHEP derivative **7** were accomplished. Sulfonations of these compounds with sulfuric acid occurred under mild conditions and with complete *para*-selectivity furnishing the sulfonates **4-6** and both enantiomers of tetrasulfonate **8** in high yield. These results prove the usefulness of dibenzofuran as a structural moiety for the synthesis of water-soluble phosphine ligands via aromatic sulfonation.

The phosphines **4-6** can be used as water-soluble ligands in the aqueous palladium-catalysed Heck and Suzuki reactions and in the rhodium-catalysed two-phase hydroformylation of propene. The ligands behave similarly to TPPTS with respect to water-solubility, but give somewhat lower yields in a number of Heck and Suzuki reactions. Furthermore, the selectivity and rate in the hydroformylation of propene is lower for the dibenzofuran-based ligands in comparion with TPPTS. Explanations for these differences are proposed. The results of application of the diphosphines **7** and **8** as ligands in ruthenium-catalysed asymmetric hydrogenations will be reported elsewhere.

Table 2: Rhodium-catalysed two-phase hydroformylation of propene.



entry	ligand	TOF[a]	linear/branched
(1)	**4**[b]	93	3.7
(2)	**5**[b]	71	3.4
(3)	**6**[b]	30	2.4
(4)	TPPTS[c]	500	16.0

a) TOF: (mole aldehydes)/(mole Rh × h), determined at 20% conversion; the selectivity for the formation of aldehydes was 100%. b) Reaction conditions: $T = 120$ °C, $p = 9$ bar propene and 10 bar CO/H_2 (1:1). [Rh] = 0.2 mM, ligand/Rh = 10/1, substrate/Rh = 9500/1. c) See ref. 33.

EXPERIMENTAL SECTION

General information. All reactions were carried out under an inert atmosphere of dry nitrogen and followed by TLC, except for the sulfonation reactions. Glassware was flame dried before use. Standard syringe techniques were applied to transfer dry solvents and reagents. Infrared (IR) spectra were obtained from $CHCl_3$ solutions or NaCl plates using a Perkin-Elmer 1310 spectrophotometer and wavelengths (ν) are reported in cm^{-1}. ^1H NMR and ^{13}C NMR (APT) spectra were determined in $CDCl_3$ (unless stated otherwise) using a Bruker ARX 400 (400 and 100.6 MHz, respectively) spectrometer. Chemical shifts (δ) are given in ppm downfield from tetramethylsilane. ^{31}P NMR spectra were recorded on a Bruker 300 AMX NMR (121.5 MHz) spectrometer. Chemical shifts (δ) are given in ppm downfield from 85% H_3PO_4. Optical rotations were measured on a Perkin-Elmer 241 polarimeter in a 1 dm cell (2 mL) in the indicated solvent at the indicated concentration, temperature and wavelength. Mass spectra and accurate mass measurements were carried out using a VG Micromass ZAB-2HF instrument. Elemental analyses were performed on a Vario EL. Melting points are uncorrected. Flash chromatography was performed as described in the literature by using Acros silica gel (0.035-0.07mm, ca. 6 nm pore diameter).[39]
THF was freshly distilled from sodium/benzophenone ketyl under a nitrogen atmosphere. CH_2Cl_2 was distilled from CaH_2 under nitrogen atmosphere and stored over 4 Å molecular sieves. MeCN and MeOH were distilled from 3 Å molecular sieves under nitrogen. Ethyl acetate and petroleum ether (PE, bp 60-80 °C) were distilled before use. Water, water/MeCN and water/MeOH mixtures were degassed before use by passing through a stream of nitrogen for at least 10 min. Benzene and *p*-xylene were distilled from CaH_2 and stored over 4 Å molecular sieves under nitrogen. *i*-Pr_2NEt, Et_3N and Et_2NH were distilled from KOH pellets and stored over KOH pellets under nitrogen. All other chemicals were used as obtained from Aldrich or Acros. For sulfonations 95% or 99.999% sulfuric acid was used.

2-Bromodibenzofuran. This compound was prepared from dibenzofuran according to a literature procedure[23] in 70% yield (lit.[23] 47%) after recrystallisation from PE 60/80 as white crystals: mp 108-109 °C (lit.[23] 107-108 °C); ^{1}H NMR: δ 8.06 (d, *J* = 2.0 Hz, H1), 7.90 (d, *J* = 7.6 Hz, H9), 7.56 (d, *J* = 8.1 Hz, H6), 7.54 (dd, *J* = 2.0, 8.7 Hz, H3), 7.47 (dt, *J* = 1.3, 8.1 Hz, H7), 7.43 (d, *J* = 8.7 Hz, H4), 7.34 (dt, *J* = 1.2, 7.6 Hz, H8).

(2-Dibenzofuranyl)-diphenylphosphine (1). To a stirred solution of 2-bromodibenzofuran (442 mg, 1.79 mmol) in THF (10 mL) *n*-BuLi (1.12 mL of a 1.6M solution in hexanes, 1.79 mmol) was added dropwise at -78 °C and stirring was continued for 1 h. To the resulting yellow slurry Ph_2PCl (322 μL, 1.79 mmol) was added. The mixture was allowed to warm to rt overnight. The resulting light yellow solution was concentrated *in vacuo*, taken up in degassed toluene and washed with water (2 × 5 mL). The organic fraction was concentrated *in vacuo* and a white solid was obtained. This solid was recrystallised from ethanol to give white crystals (611 mg, 97%): mp 94-96 °C; ^{31}P NMR δ -3.70; ^{1}H NMR δ 7.98 (dd, *J* = 7.7, 1.1 Hz, 1H, H9), 7.85 (dd, *J* = 7.7, 0.5 Hz, 1H, H1), 7.54-7.58 (m, 2H, H4 + H6), 7.43-7.48 (m, 2H, H7 + H8), 7.35-7.39 (m, 10H, Ph*H*), 7.30 (dt, *J* = 0.7 en 7.7 Hz, H3); ^{13}C NMR (50 Mhz) δ 156.6, 156.3, 137.4 (d, *J* = 10.4 Hz), 133.4 (d, *J* = 19.2 Hz, 4C-*ortho*), 132.8 (d, *J* = 20.0 Hz), 130.7 (d, *J* = 10.2 Hz), 128.6 (2C-*para*), 128.4 (d, *J* = 6.8 Hz, 4C-*meta*), 127.3, 126.5 (d, *J* = 24.0 Hz), 124.6 (d, *J* = 9.5 Hz), 123.5, 122.7, 120.6, 112.1, 111.7; IR (NaCl, cm^{-1}) 3070, 1588, 1466, 1444, 1434, 1198, 1124; HRMS (FAB+) calcd for $C_{24}H_{18}OP$ $[M+H]^+$ 353.1095, found 353.1118.

***Bis*-(2-dibenzofuranyl)-phenylphosphine (2).** To a stirred solution of 2-bromodibenzofuran (410 mg, 1.66 mmol) in THF (4 mL) *n*-BuLi (1.04 mL of a 1.6M solution in hexanes, 1.66 mmol) was added dropwise at -78 °C and stirring was continued for 1 h. To the resulting yellow slurry was added $PhPCl_2$ (113 μL, 0.83 mmol). The mixture was allowed to warm to rt overnight. The resulting light yellow solution was concentrated *in vacuo*, taken up in degassed toluene and washed with water (2 × 5 mL). The organic fraction was concentrated *in vacuo* and a white solid was obtained. This solid was recrystallised from ethanol to give white crystals (352 mg, 96%): mp 201-203 °C; ^{31}P NMR: δ -3.71; ^{1}H NMR: δ 7.96 (dd, *J* = 7.7, 1.0 Hz, H9), 7.85 (dd, *J* = 7.8, 0.5 Hz, 2H, H1), 7.52-7.57 (m, 4H, H4 + H6), 7.40-7.45 (m, 4H, H7 + H8), 7.35-7.38 (m, 5H, Ph*H*), 7.29 (dt, *J* = 7.8, 0.8 Hz, 2H, H3); ^{13}C NMR: δ 156.7, 156.3, 137.0 (bs), 133.4 (d, *J* = 19.0 Hz, 2C-*ortho*), 132.7 (d, *J* = 20.2 Hz), 130.7 (d, *J* = 10 Hz), 128.7 (C-*para*), 128.5 (d, *J* = 6.8 Hz, 2C-*meta*), 127.4, 126.4 (d, *J* = 23.5 Hz), 124.8 (d, *J* = 9.4 Hz), 123.6, 122.8, 120.8, 112.0 (d, *J* = 7.9 Hz), 111.6; IR (NaCl, cm^{-1}) 3051, 1589, 1465, 1444, 1198, 1122; HRMS (FAB+) calcd for $C_{30}H_{20}O_2P$ $[M+H]^+$ 443.1201, found 443.1201.

***Tris*-(2-dibenzofuranyl)-phosphine (3).** To a stirred solution of 2-bromodibenzofuran (1.28 g, 5.16 mmol) in THF (20 mL) *n*-BuLi (3.23 mL of a 1.6M solution in hexanes, 5.17 mmol) was added dropwise at -78 °C and stirring was continued for 1 h. To the resulting yellow slurry was added PCl_3 (150 μL, 1.72 mmol). The mixture was allowed to warm to rt overnight. The resulting almost colourless solution was concentrated *in vacuo*, taken up in degassed toluene and washed with water (2 × 5 mL). The organic fraction was concentrated *in vacuo* and a white solid was obtained. This solid was recrystallised from ethanol to give white crystals (899 mg, 98%): mp 191-195 °C; ^{31}P NMR: δ -3.07; ^{1}H NMR: δ 7.99 (dd, *J* = 7.6, 0.9 Hz, 3H, H9), 7.85 (dd, *J* = 7.7, 0.5 Hz, 3H, H1), 7.60 (d, *J* = 4.3 Hz, 3H, H6), 7.57 (d, *J* = 4.1 Hz, 3H, H4), 7.43-7.51 (m, 6H, H7 + H8), 7.30 (dt, *J* = 7.5, 0.5 Hz, 3H, H3); ^{13}C NMR: δ 156.6, 156.3, 132.6 (d, *J* = 20.5 Hz), 131.5 (d, *J* = 10.9 Hz), 127.4, 162.2 (d, *J* = 22.9 Hz), 124.8 (d, *J* = 9 Hz), 123.6, 122.8, 120.8, 112.0 (d, *J* = 6.8 Hz), 111.6; IR (NaCl, cm^{-1}) 3049, 1589, 1465, 1444, 1199, 1122; HRMS (FAB+) calcd for $C_{36}H_{22}O_3P$ $[M+H]^+$ 533.1306, found 533.1351.

2-(8-Sodium sulfonatodibenzofuranyl)-diphenylphosphine (4). (2-Dibenzofuranyl)-diphenylphosphine (442 mg, 1.26 mmol) was stirred with sulfuric acid (2 mL) at rt. The solid slowly dissolved to give a red solution. After being stirred for 1 h the mixture was cooled to 0 °C and degassed water (6 mL) was added slowly. The mixture decolourised and a white precipitate was formed. This solid was isolated by filtration and dissolved in water (2 mL). The colourless mixture was neutralised with 0.5M aqueous NaOH to pH 7 and concentrated by freeze-drying. The resulting white solid was extracted (3 × 2 mL) with methanol to give the product after evaporation of the solvent as an off-white solid (480 mg, 86 %): mp 235-241 °C; ^{31}P NMR (CD_3OD) δ -4.0; ^{1}H NMR (CD_3OD) δ 8.35 (d, *J* = 1.6 Hz,1H, H9), 7.99 (dd, *J* = 8.6, 1.8 Hz, 1H, H7), 7.95 (dd, *J* = 7.4, 1.4 Hz, 1H,

H1), 7.65 (d, J = 8.6 Hz, 1H, H6), 7.63 (d, J = 7.6 Hz, 1H, H4), 7.48 (dt, J = 7.4, 1.5 Hz, 1H, H3), 7.29-7.40 (m, 10H, Ph*H*); ^{13}C NMR (CD_3OD) δ 158.7, 158.5, 141.9, 138.8 (d, J = 9 Hz), 134.7 (d, J = 22 Hz), 134.6 (d, J = 20 Hz), 130.0, 129.7 (d, J = 7 Hz), 127.5 (d, J = 22 Hz), 127.0, 125.6 (d, J = 9 Hz), 124.6, 119.9, 113.1 (d, J = 8 Hz), 112.4. IR (KBr, cm^{-1}) 3500 (bs), 3020, 1590, 1470, 1205, 1106, 1021. HRMS (FAB+) was not successful for the sodium salt due to Na-matrix interference. Therefore 100 mg of the sodium salt was stirred for 1 h with acidic DOWEX 50 in water (3 mL). The DOWEX was filtered off and the solution freeze-dried to yield the sulfonic acid as an off-white solid (77 mg, 81%): ^{31}P NMR (CD_3OD) δ -2.2. This product was allowed to oxidise to the corresponding phosphine oxide: ^{31}P NMR (CD_3OD) δ 34.3; HRMS (FAB+) calcd for $C_{24}H_{18}O_5PS$ $[M+H]^+$ 449.0613, found 449.0637.

***Bis*-(2-(8-sodium sulfonatodibenzofuranyl)-phenylphosphine (5).** *Bis*-(2-dibenzofuranyl)-phenylphosphine (100 mg, 0.24 mmol) was stirred with sulfuric acid (1 mL) at rt. The solid slowly dissolved to give a red solution. After being stirred for 20 h the mixture was cooled to 0 °C and degassed water (8 mL) was added slowly. The mixture decolourised and a white precipitate was formed. This solid was isolated by filtration and dissolved in water (2 mL). The colourless mixture was neutralised with 0.5M aq NaOH to pH 7 and concentrated by freeze-drying. The resulting white solid was extracted (3 × 2 mL) with methanol to give the product after evaporation of the solvent as an off-white solid (127 mg, 86 %): mp >365 °C; ^{31}P NMR (CD_3OD) δ -2.3; ^{1}H NMR (CD_3OD) δ 8.38 (d, J = 1.8 Hz, 2H, H9), 8.04 (dd, J = 7.4, 1.1 Hz, 2H, H1), 7.99 (dd, J = 8.6, 1.8 Hz, 2H, H7), 7.66 (d, J = 8.6 Hz, 2H, H4), 7.65 (d, J = 8.6 Hz, 2H, H6), 7.52 (dt, J = 7.8, 1.7 Hz, 2H, H3), 7.42-7.37 (m, 5H, Ph*H*); ^{13}C NMR (CD_3OD) δ 158.7, 158.4, 141.9, 138.7 (d, J = 9 Hz), 134.6 (d, J = 21 Hz), 134.5 (d, J = 20 Hz), 130.1, 129.5 (d, J = 7 Hz), 127.5 (d, J = 23 Hz), 127.0, 125.7 (d, J = 9 Hz), 124.6, 120.0, 113.3 (d, J = 8 Hz), 112.4; IR (KBr, cm^{-1}) 3500 (bs), 3020, 1590, 1469, 1435, 1202, 1105, 1021. HRMS (FAB+) was not successful for the disodium salt due to Na-matrix interference. Therefore 30 mg of the disodium salt was stirred for 1 h with acidic DOWEX 50 in water (1 mL). The DOWEX was filtered off and the solution freeze-dried to yield the sulfonic acid as an off-white solid (27 mg, 95%): ^{31}P NMR (CD_3OD) δ -1.9. This product was allowed to oxidise to the corresponding phosphine oxide: ^{31}P NMR (CD_3OD) δ 34.7; HRMS (FAB+) calcd for $C_{30}H_{20}O_9PS_2$ $[M+H]^+$ 619.0286, found 619.0302.

***Tris*-(2-(8-sodium sulfonatodibenzofuranyl)-phosphine (6).** *Tris*-(2-dibenzofuranyl)-phosphine (899 mg, 1.69 mmol) was stirred with sulfuric acid (4 mL) at rt. The solid slowly dissolved to give a deep red solution. After being stirred for 20 h the mixture was cooled to 0 °C and degassed water (8 mL) was added slowly. The mixture decolourised and a white precipitate was formed. This solid was isolated by filtration and dissolved in water (2 mL). The colourless mixture was neutralised with 0.5M aq NaOH to pH 7 and concentrated by freeze-drying. The resulting white solid was extracted (3 × 3 mL) with methanol to give the product after evaporation of the solvent as an off-white solid (1.20 g, 85 %): mp >365 °C; ^{31}P NMR (CD_3OD) δ -2.62; ^{1}H NMR (CD_3OD): δ 8.38 (d, J = 1.5 Hz, 3H, H9), 8.11 (dd, J = 8.6, 1.3 Hz, 3H, H7), 7.99 (dd, J = 7.5, 1.5 Hz, 3H, H1), 7.70 (d, J = 8.6 Hz, 3H, H6), 7.62 (d, J = 7.6 Hz, 3H, H4), 7.57 (dt, J = 7.6, 1.5 Hz, 3H, H3). ^{13}C NMR (CD_3OD): δ 158.8, 158.5, 141.9, 134.6 (d, J = 21 Hz), 133.4 (d, J = 12 Hz), 127.5 (d, J = 23 Hz), 127.0, 125.8 (d, J = 9 Hz), 124.6, 120.0, 113.4 (d, J = 8 Hz), 112.4; IR (KBr, cm^{-1}) 3500 (bs), 3020, 1591, 1470, 1172, 1104, 1021. HRMS (FAB+) was not successful for the trisodium salt due to Na-matrix interference. Therefore 50 mg of tri-sodium salt was stirred for ca. 1h with some acidic DOWEX 50 in water (1 mL). The DOWEX was filtered off and the solution was freeze-dried to give 42 mg of the trisulfonic acid as an off-white solid. HRMS (FAB+) calcd for $C_{36}H_{22}O_{12}PS_3$ $[M+H]^+$ 773.0011, found 773.0079.

2,2'-Bis-(bis-(2-dibenzofuranyl)-phosphinoyl)-6,6'-dimethoxy-biphenyl (10). A solution of 2-bromodibenzofuran (2.0 g, 8.04 mmol) in THF (30 mL) was dropwise added in 30 min to activated magnesium (195 mg, 8.04 mmol). The mixture was warmed up with a heat gun to initiate the reaction. The obtained yellow/brown solution was heated at 50 °C for 1 h. The mixture was cooled to 0 °C and a solution of **9** (910 mg, 1.34 mmol) in THF (15 mL) was added dropwise in 15 min. The mixture was refluxed for 20 h. The resulting red solution was cooled to rt, quenched with sat. NH_4Cl and worked up with CH_2Cl_2 and water. After drying with $MgSO_4$ and evaporation a yellow solid was obtained. Flash chromatography (first EtOAc/PE 1:2, then EtOAc/PE 1:1, then

EtOAc) yielded 920 mg of product as a white solid (70%): mp 190-195 °C; ^{31}P NMR δ 31.3; ^{1}H NMR δ 3.32 (s, 6H, MeO), 6.83 (d, 2H, *J* = 8.3 Hz), 7.02 (dd, H3 and H3', *J* = 13.4, 7.4 Hz), 7.09 (t, 2H, *J* = 7.2 Hz), 7.20 (dt, 2H, *J* = 8.0, 3.5 Hz), 7.24-7.26 (m, 2H), 7.31-7.37 (m, 4H), 7.42-7.52 (m, 6H), 7.60 (d, 2H, *J* = 8.3 Hz), 7.63 (dd, 2H, *J* = 8.4, 2.0 Hz), 7.66-7.72 (m, 2H), 7.77-7.82 (m, 2H), 7.95 (d, 2H, *J* = 7.6 Hz), 8.15 (d, 2H, *J* = 11.2 Hz), 8.46 (d, 2H, *J* = 11.9 Hz); ^{13}C NMR δ 54.7, 110.5, 111.0, 111.2, 111.3, 111.4, 111.7, 112.8, 121.1 (d, *J* = 16 Hz), 122.9 (d, *J* = 41 Hz), 123.3 (d, *J* = 27 Hz), 123.8 (d, *J* = 15 Hz), 124.3 (d, *J* = 15 Hz), 125.5 (m, 5C), 127.5 (d, *J* = 34 Hz), 128.0 (d, *J* = 15 Hz), 128.9 (d, *J* = 108 Hz), 129.0 (d, *J* = 104 Hz), 130.5 (m), 131.0 (d, *J* = 12 Hz), 131.2 (d, *J* = 104 Hz), 131.3 (d, *J* = 12 Hz) 156.1, 156.5, 157.4 (d, *J* = 3 Hz), 157.6 (d, *J* = 14 Hz), 157.7 (d, *J* = 3 Hz); IR (NaCl, cm^{-1}) 2957, 1590, 1467, 1446, 1418, 1257, 1188; HRMS (FAB+) calcd for $C_{62}H_{41}O_8P_2$ $[M+H]^+$ 975.2276, found 975.2263.

Resolution of 2,2'-Bis-(bis-(2-dibenzofuranyl)-phosphinoyl)-6,6'-dimethoxy-biphenyl (10). To a stirred solution of racemic **10** (777 mg, 0.797 mmol) in EtOAc (6 mL) was added a solution of (-)-*O,O'*-dibenzoyl tartaric acid (425 mg, 1.13 mmol) in EtOAc (5 mL). The mixture was heated to reflux for 5 min. After approximately 1 min a white precipitate was formed. This 1:1 complex **11** of (-)-**10** and (-)-DBT was filtered off and dried in vacuo: $[\alpha]^{20}_D$= -84 (c = 1, EtOH) ^{31}P NMR: δ 35.6 ; ^{1}H NMR δ 3.12 (s, 6H, MeO), 5.96 (s, 2*H*-COBz), 6.60 (d, 2H, *J* = 8.3 Hz), 6.86 (dd, 2H, *J* = 13.7, 7.7 Hz), 7.04-7.13 (m, 6H), 7.21 (t, 2H, *J* = 7.6 Hz), 7.28 (dt, 2H, *J* = 7.2, 1.1 Hz), 7.35 (d, 2H, *J* = 8.2 Hz), 7.40-7.52 (m, 10H), 7.56 (d, 2H, *J* = 8.3 Hz), 7.63 (dt, 2H, *J* = 10.9, 1.4 Hz), 7.95 (d, 2H, *J* = 7.5 Hz), 8.00-8.03 (m, 6H), 8.50 (d, 2H, *J* = 11.4 Hz). The mother liquor was evaporated to obtain a light-yellow solid **12**: ^{31}P NMR: δ 35.4; ^{1}H NMR δ 3.52 (s, 6H, MeO).
The complex **11** was suspended in CH_2Cl_2 (10 mL) and stirred with satd $NaHCO_3$ (10 mL). After 1 h the white solid had dissolved completely. The organic layer was separated, washed with brine and water, and dried over $MgSO_4$. After evaporation (-)-**10** was obtained as a white solid (280 mg, 72%): mp 192-195 °C; $[\alpha]^{20}_D$= -81.6 (c = 1, $CHCl_3$); HRMS (FAB+) calcd for $C_{62}H_{41}O_8P_2$ $[M+H]^+$ 975.2276, found 975.2204; spectral data were identical to racemic **10**.
The light-yellow solid **12** was dissolved in CH_2Cl_2 (10 mL) and stirred with satd $NaHCO_3$ (10 mL). After 30 min the organic layer was separated, washed with brine and water, and dried over $MgSO_4$. After evaporation a light yellow solid was obtained. This solid was dissolved in EtOAc (4 mL). A solution of (+)-*O,O'*-dibenzoyl tartaric acid (560 mg, 1.48 mmol) in EtOAc (2 mL) was added and a white precipitate was formed after heating for several min. This 1:1 complex **13** of (+)-**10** and (+)-DBT was filtered off and dried in vacuo: $[\alpha]^{20}_D$= +90 (c = 1, EtOH); Spectral data were identical to the complex **11**.
The precipitate was suspended in CH_2Cl_2 (10 mL) and stirred with satd $NaHCO_3$ (10 mL). After 1 h, when the white solid was dissolved, the organic layer was separated, washed with brine and water, and dried over $MgSO_4$. After evaporation (+)-**10** was obtained as a white solid (340 mg, 88%): mp 192-196 °C; $[\alpha]^{20}_D$= +80.6 (c = 1, $CHCl_3$); HRMS (FAB+) calcd for $C_{62}H_{41}O_8P_2$ $[M+H]^+$ 975.2276, found 975.2240; spectral data were identical to racemic **10**.

(+)-2,2'-Bis-(bis-(2-dibenzofuranyl)-phosphanyl)-6,6'-dimethoxy-biphenyl ((+)-7). To a stirred solution of (-)-**10** (280 mg, 0.287 mmol) in *p*-xylene (10 mL) in a sealed tube was added diisopropylethyl amine (1.05 mL, 5.7 mmol) and trichlorosilane (0.58 mL, 5.7 mmol). The tube was closed and heated at 160 °C for 24 h. After cooling the reaction mixture was worked up with CH_2Cl_2 and 1N aq KOH, washed with water and brine and evaporated. The solids were dissolved in CH_2Cl_2 (5 mL) and EtOH (2 mL) was added. CH_2Cl_2 was slowly distilled off and (+)-**7** was obtained as a white crystalline solid (220 mg, 81%): mp 176-178 °C; $[\alpha]^{20}_D$= +4.0; $[\alpha]^{20}_{578}$= +4.2; $[\alpha]^{20}_{546}$= +2.7; $[\alpha]^{20}_{436}$= -22; $[\alpha]^{20}_{365}$= -66 (c = 0.5, $CHCl_3$); ^{31}P NMR δ -12.1; ^{1}H NMR δ 3.21 (s, 6H, MeO), 6.80 (d, 2H, *J* = 8.2 Hz), 6.83 (bd, 2H, *J* = 7.5 Hz), 7.16 (dt, 2H, *J* = 7.6, 0.9 Hz), 7.28-7.32 (m, 8H), 7.36 (dt, 2H, *J* = 7.6, 1.3 Hz), 7.42-7.46 (m, 6H), 7.52 (d, 2H, *J* = 8.3 Hz), 7.56 (d, 2H, *J* = 8.2 Hz), 7.63 (dd, 2H, *J* = 7.2, 0.5 Hz), 7.68-7.70 (m, 2H), 7.84 (dd, 2H, *J* = 7.6, 0.5 Hz), 7.87-7.89 (m, 2H); ^{13}C NMR δ 54.7, 110.6, 111.2, 111.4, 120.5, 120.6, 122.3, 122.6, 123.5, 123.7, 124, 1 (m), 125.3 (m), 126.2, 126.5, 126.8, 127.0, 128.7, 131.8, 131.9, 132.0, 132.1, 132.3, 132.5 (d), 133.0 (m), 139.1 (m), 155.9, 156.0, 156.1, 156.3, 157.3 (m); IR (NaCl, cm^{-1}) 3010 (w), 1576, 1465, 1199; HRMS (FAB+) calcd for $C_{62}H_{41}O_6P_2$ $[M+H]^+$ 943.2378, found 943.2357.

(-)-2,2'-Bis-(bis-(2-dibenzofuranyl)-phosphanyl)-6,6'-dimethoxy-biphenyl ((-)-7). Compound (+)-**10** (340 mg, 0.349 mmol) was treated as described for the synthesis of (+)-**7**. The product (-)-**7** was obtained as a white crystalline solid (300 mg, 91%): mp 176-178 °C; $[\alpha]^{20}_{D}$= -4.3; $[\alpha]^{20}_{578}$= -4.1; $[\alpha]^{20}_{546}$= -1.7; $[\alpha]^{20}_{465}$= +22; $[\alpha]^{20}_{365}$= +65 (c = 0.5, $CHCl_3$); HRMS (FAB+) calcd for $C_{62}H_{41}O_8P_2$ $[M+H]^+$ 943.2378, found 943.2390. spectral data were identical to (+)-**7**.

(-)-2,2'-Bis-(bis-(2-dibenzofuranyl-8-potassium sulfonato)-phosphanyl)-6,6'-dimethoxy-biphenyl ((-)-8). Compound (-)-**7** (70 mg, 0.074 mmol) was dissolved in sulfuric acid (1 mL), yielding a brown viscous solution. The mixture was stirred at rt for 20 h. The mixture was cooled to 0 °C and water (3 mL) was added. A white sticky precipitate was formed. 30% aq KOH was added until the pH of the mixture was between 7.0 and 7.3. The milky mixture was evaporated and the obtained white solid was extracted three times with MeOH (2 mL) and filtered. The combined fractions were evaporated and the off-white solid was extracted two times with EtOH (2 mL). After evaporation of the combined fractions the pure product (-)-**8** was obtained as a off-white solid (101 mg, 97%): mp >365 °C; $[\alpha]^{20}_{D}$= -20, $[\alpha]^{20}_{365}$= -90 (c = 0.3, MeOH/H_2O 1:1); ^{31}P NMR (CD_3OD) δ -6.7; ^{1}H NMR (CD_3OD) δ 3.42 (s, 6H, MeO), 6.81 (d, 2H, *J* = 8.1 Hz), 6.97 (d, 2H, *J* = 8.5 Hz), 7.17 (m, 4H), 7.32-7.37 (m, 4H), 7.50 (m, 4H), 7.60 (d, 2H, *J* = 8.7 Hz), 7.64 (d, 2H, *J* = 8.5 Hz), 7.84 (dd, 2H, *J* = 8.6, 1.6 Hz), 7.98 (dd, 2H, *J* = 8.6, 1.7 Hz), 8.03 (m, 2H), 8.18 (d, 2H, *J* = 1.7 Hz), 8.46 (d, 2H, *J* = 1.6 Hz); ^{13}C NMR (CD_3OD) δ 56.2, 112.5, 112.7, 113.0, 113.1, 119.8, 124.5, 124, 7 (m), 125.2 (m), 126.2 (m), 126.7, 126.9, 127.7 (m), 127.9, 130.7, 133.1 (m), 134.6 (m), 139.8, 140.6, 140.9, 157.6, 158.1, 158.5, 158.6, 158.7 (m); IR (KBr, cm^{-1}) 3441 (br.) 3020, 1662, 1590, 1469, 1437, 1197, 1102, 1020;

(+)-2,2'-Bis-(bis-(2-dibenzofuranyl-8-potassium sulfonato)-phosphanyl)-6,6'-dimethoxy-biphenyl ((+)8). Compound (+)-**7** (50 mg, 0.074 mmol) was treated as described for (-)-2,2'-bis-(bis-(2-dibenzofuranyl)-phosphanyl)-6,6'-dimethoxy-biphenyl. The product (+)-**8** was obtained as a off-white solid (64 mg, 86%): mp >365 °C; $[\alpha]^{20}_{D}$= +19, $[\alpha]^{20}_{365}$= +78 (c = 0.3, MeOH/H_2O 1:1); spectral data were identical to (-)-**8**.

2-Iodo-*N*-allylaniline. This compound was prepared according to a literature procedure[40] and obtained as a pale yellow oil (870 mg, 88%, lit.[40] 89%): ^{1}H NMR δ 7.66 (dd, *J* = 1.4, 7.8 Hz, 1H, Ar*H*), 7.19 (dt, *J* = 1.4, 7.7 Hz, 1H, Ar*H*), 6.56 (dd, *J* = 1.2, 8.2 Hz, 1H, Ar*H*), 6.44 (dt, *J* = 7.6, 1.3 Hz, 1H, Ar*H*), 5.9-6.0 (m, 1H, C*H*=C), 5.18-5.31 (m, 2H, C=CH_2), 4.32 (bs, 1H, N*H*), 4.81-4.85 (m, 2H, N-CH_2).

***N*-(2-Iodobenzoyl)-1,2,3,6-tetrahydropyridine.** See also lit.[41] 2-Iodobenzoyl chloride (1.24 g, 4.64 mmol) was dissolved in CH_2Cl_2 (30 mL). To this stirred solution a solution of 1,2,3,6-tetrahydropyridine (464 mg, 5.57 mmol) and triethylamine (1.0 g, 9.9 mmol) in CH_2Cl_2 (10 mL) was added dropwise. After stirring for 1 h at rt, a pale yellow turbid solution was obtained. The mixture was worked up with 1N HCl, satd $NaHCO_3$, dried and concentrated *in vacuo*. The product was obtained as a pale yellow oil after flash chromatography (EtOAc/PE 1:2) (1.13 g, 80%): ^{1}H NMR (two rotamers, ca. 1:1) δ 7.84-7.81 (m, 2H, H1 and H1'), 7.41-7.36 (m, 2H, H3 and H3'), 7.21-7.19 (m, 2H, H4 and H4'), 7.10-7.04 (m, 2H, H2 and H2'), 5.88-5.53 (m, 4H, H6 + H7 and H6'+ H7'), 4.36-4.10 (m, 1H, H5), 3.89-3.85 (m, 1H, H5'), 3.77-3.59 (m, 1H, H9'), 3.33-3.28 (m, 1H, H9), 2.20-2.05 (m, 2H, H8 and H8'). These spectral data compared well with literature data.[41]

General procedures for the Heck reactions. **A**: $Pd(OAc)_2$ (5 mol%) and ligand (15 mol%) were mixed in water/acetonitrile 1:1 (2-4 mL) and stirred for at least 15 min. To the yellow solution was added substrate(s) (ca. 0.22 mmol) and two equivalents of Et_3N and the mixture was heated to the given temperature for the given time. After work up with CH_2Cl_2 and water, drying and evaporation of the solvents, the products were purified by flash chromatography. **B**: $Pd(OAc)_2$ (5 mol%) and ligand (15 mol%) were mixed in water (2-4 mL) and stirred for at least 15 min. To the yellow solution was added substrate(s) (0.22 mmol) and 2 equivalents of Na_2CO_3 and the mixture was heated to the given temperature for the given time. After work up with CH_2Cl_2 and water, drying and evaporation of the solvents, the products were purified by flash chromatography.

3-Methylindole. I) 2-Iodo-*N*-allylaniline (79 mg, 304 μmol) was reacted as described in procedure **A** with ligand **6** at 40 °C for 19 h (flash chromatography with EtOAc/PE 1:2), yielding the product as a white solid (39 mg, 97%): ^{1}H NMR δ = 7.84 (bs, 1H, *NH*), 7.61 (d, *J* = 7.8 Hz, 1H, Ar*H*), 7.36 (d, *J* = 8.0 Hz, 1H, Ar*H*), 7.21 (dt, *J* = 7.6, 1.1 Hz, 1H, Ar*H*), 7.15 (dt, *J* = 7.4, 1.0 Hz, 1H, Ar*H*), 6.97 (d, *J* = 1.0 Hz, 1H, NH-*CH*=C), 2.37 (d, *J* = 1.0 Hz, 3H, -*CH*$_3$); ^{13}C NMR δ 136.2, 128.2, 121.8, 121.4, 119.0, 118.7, 111.6, 110.8, 9.6 (similar to literature data[42]). II) 2-Iodo-*N*-allylaniline (57 mg, 220 μmol) was reacted as described in procedure **B** with ligand **6** at 80 °C for 18 h (flash chromatography with EtOAc/PE 1:2), yielding the product as a white solid (17 mg, 60%): Spectral data as for I.

Cyclisation of *N*-(2-iodobenzoyl)-1,2,3,6-tetrahydropyridine. I) *N*-(2-Iodobenzoyl)-1,2,3,6-tetrahydropyridine (70 mg, 0.22 mmol) was reacted as described in procedure **A** with ligand **6** at 95 °C for 24 h (flash chromatography with EtOAc/PE 1:2), yielding the product as a colourless oil (21 mg, 50%): ^{1}H NMR δ 7.95 (d, *J* = 7.4 Hz, 1H, ArH), 7.39 (t, *J* = 7.4 Hz, 1H, ArH), 7.33 (t, *J* = 7.4 Hz, 1H, ArH), 7.20 (d, *J* = 7.3 Hz, 1H, ArH), 6.00-5.95 (m, 1H, C=C*H*), 5.64 (dd, *J* = 9.7, 4.0 Hz, 1H, C*H*=C), 4.34 (dd, *J* = 17.6, 3.9 Hz, 1H, NC*H*HC=), 3.85 (dd, *J* = 17.6, 1.9 Hz, 1H, NCH*H*C=), 3.78 (d, *J* = 12.7 Hz, 1H, NC*H*H), 3.53 (dd, *J* = 12.7, 2.6 Hz, 1H, NCH*H*), 3.12 (d, *J* = 5.4 Hz, 1H, CH$_2$C*H*C=); ^{13}C NMR (50 MHz) δ 176.2, 146.5, 131.8, 129.9, 129.5, 128.9, 127.5, 126.9, 125.0, 51.7, 51.4, 35.8 (similar to literature data[41]). II) *N*-(2-Iodobenzoyl)-1,2,3,6-tetrahydropyridine (70 mg, 0.22 mmol) was reacted as described in procedure **A** with ligand **4** at 95 °C for 24 h (flash chromatography with EtOAc/PE 1:2), yielding the product as a colourless oil (22 mg, 52%): ^{1}H NMR as for I. III) *N*-(2-Iodobenzoyl)-1,2,3,6-tetrahydropyridine (70 mg, 0.22 mmol) was reacted as described in procedure **B** with ligand **6** at 95 °C for 21 h (flash chromatography with EtOAc/PE 1:2), yielding the product as a colourless oil (21 mg, 50%): ^{1}H NMR as for I. IV) *N*-(2-Iodobenzoyl)-1,2,3,6-tetrahydropyridine (70 mg, 0.22 mmol) was reacted as described in procedure **B** with ligand **4** at 95 °C for 20 h (flash chromatography with EtOAc/PE 1:2), yielding the product as a colourless oil (21 mg, 50%): ^{1}H NMR as for I.

3-(4-Hydroxyphenyl)-cyclohexanone. 4-Iodophenol (51 mg, 0.23 mmol) and 2-cyclohexene-1-ol (34 mg, 0.35 mmol) were reacted as described in procedure **B** with ligand **6** at 80 °C for 18 h (flash chromatography with EtOAc/PE 1:1), yielding the product as a pale yellow oil (18 mg, 40%): ^{1}H NMR δ 7.08 (d, *J* = 8.8 Hz, 2H, Ar*H*), 6.79 (d, *J* = 8.8 Hz, 2H, Ar*H*), 5.27 (s, 1H, O*H*), 3.00-2.91 (m, 1H, Ar*CH*), 2.62-2.32 (m, 4H, C*H*$_2$ (CO)C*H*$_2$), 2.17-2.02 (m, 2H), 1.87-1.60 (m, 2H); ^{13}C NMR δ 154.2, 136.4, 127.5, 115.3, 49.1, 43.8, 41.1, 32.8, 25.3 (carbonyl-C was not observed); IR ($CHCl_3$, cm^{-1}): 3331, 3014, 2942, 1706, 1613, 1515. These spectral data compared well with literature data.[43]

3-Phenylcyclohexanone and 3-phenyl-2-cyclohexene-1-one. Iodobenzene (84 mg, 0.41 mmol) and 2-cyclohexenone (59 mg, 0.62 mmol) were reacted as described in procedure **A** (with a water/MeCN 1:2 mixture as the solvent) with ligand **6** at 80 °C for 94 h (flash chromatography with EtOAc/PE 1:3), yielding a mixture of products as a pale yellow oil (50 mg, 71%): 3-phenyl-2-cyclohexenone: ^{1}H NMR δ 7.57-7.50 (m, 2H, Ph-*ortho*), 7.45-7.39 (m, 3H, Ph-*meta* + *para*), 6.41 (s, 1H, =CH), 2.81-2.75 (m, 2H, C*H*$_2$C=O), 2.51-2.45 (m, 2H), 2.20-2.10 (m, 2H). 3-Phenylcyclohexanone: ^{1}H NMR δ 7.38-7.30 (m, 2H, Ph-*ortho*), 7.28-7.20 (m, 3H, Ph-*meta* + *para*), 3.06-2.97 (m, 1H, PhC*H*), 2.63-2.33 (m, 4H, C*H*$_2$ (CO)C*H*$_2$), 2.18-2.05 (m, 2H), 1.92-1.72 (m, 2H). These spectral data compared well with literature data.[44]

4-Methylbiphenyl via a Suzuki reaction. $Pd(OAc)_2$ (4.7 mg, 21 μmol) and ligand **6** (50 mg, 60 μmol) were dissolved in a H_2O/MeCN 1:2 or a H_2O/MeOH 1:3 mixture (2 mL) and the yellow solution was stirred for 15 min. Phenyl boronic acid (102 mg, 0.81 mmol), 4-iodotoluene (190 mg, 0.85 mmol) and Na_2CO_3 (480 mg, 4.5 mmol) were added and the mixture was heated at 60 °C. After 24 h the reaction was worked up with water and CH_2Cl_2. After drying, evaporation of the solvents and flash chromatography (EtOAc/PE 1:1) the product was obtained as a pale yellow oil (115 mg, 90 %): ^{1}H NMR δ 7.62 (dd, *J* = 1.4, 8.5 Hz, 2H, Ph-*ortho*), 7.54 (d, *J* = 8.1 Hz, 2H, Ar*H*), 7.46 (t, *J* = 7.9 Hz, 2H, Ph-*meta*), 7.36 (dt, *J* = 7.4, 1.4 Hz, 1H, Ph-*para*), 7.29 (d, *J* = 8.1 Hz, 2H, Ar*H*), 2.44 (s, 3H, Me). ^{13}C NMR δ 141.5, 138.5, 136.9, 129.4, 128.3, 126.9, 21.0. These spectral data compared well with literature data.[45]

2-Phenylaniline via a Suzuki reaction. $Pd(OAc)_2$ (6.8 mg, 29 μmol) and ligand **6** (56 mg, 67 μmol) were dissolved in a H_2O/MeCN 1:1 (2 mL) and the yellow solution was stirred for 15 min. Phenyl boronic acid (76 mg, 0.62 mmol), 2-iodoaniline (126 mg, 0.58 mmol) and Et_3N (0.2 mL, 1.4 mmol) were added and the mixture was heated at 50 °C. After 18 h the reaction was worked up with water and CH_2Cl_2. After drying, evaporation of the solvents and flash chromatography (EtOAc/PE 1:2) the product was obtained as a pale yellow oil (56 mg, 58 %): ^{1}H NMR δ 7.51-7.35 (m, 5H Ar*H*), 7.21-7.15 (m, 2H, H3 + H5), 6.86 (dt, J = 1.1, 7.5 Hz, 1H, H4), 6.79 (dd, J = 0.9, 7.9 Hz, 1H, H6), 3.77 (bs, 2H, NH_2); ^{13}C NMR δ 143.4, 139.4, 130.4, 129, 128.7, 128.4, 127.5, 127.1, 118.5, 115.5. These spectral data compared well with literature data.[46]

Hydroformylation of propene. $Rh(CO)_2$acac (1 mg, 4×10^{-6} mmol) and ligand (4×10^{-5} mmol) were mixed in a 100 mL Schlenk vessel under argon in degassed water (30 mL). The mixture was transferred into a 100 mL stainless steel autoclave, previously flushed with argon and synthesis gas (3×). The autoclave was pressurised with synthesis gas and heated for 16 h at 120 °C. The autoclave was cooled to 60 °C and depressurised. Then the mixture was pressurised with 9 bar of propene and 10 bar of synthesis gas. The reaction was initiated by heating the mixture at 120 °C. After 5 h the reaction was terminated by cooling the autoclave in ice after which it was depressurised. The organic contents was analysed by ^{1}H NMR spectroscopy: ^{1}H NMR (300 MHz): δ 9.26 (t, J = 15.9 Hz, 1H, butanal), 9.22 (d, J = 10.5 Hz, 1H, 2-methylpropanal).

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REFERENCES

1 Manassen, J. In *Catalysis Progress in Research*; Basolo, F.; Burwell, R. L., Eds.; Plenum Press: London, 1973; p. 183.
2 Kuntz, E. G. *CHEMTECH* **1987**, *17*, 570; Kuntz, E. G. French Patent 2314910, 20.06, **1975** and US Patent Re 31812, 29.05, **1982** to Rhône-Poulenc.
3 Sabot, J. L. Eur. Patent 0,104,967, **1982** to Rhône-Poulenc.
4 Herrmann, W. A.; Kulpe, J. A.; Kellner, J.; Riepl, H.; Bahrmann, H.; Konkol, W. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 391.
5 Lecomte, L.; Triolet, J.; Sinou, D.; Bakos, J.; Heil, B. *J. Chrom.* **1987**, *408*, 416.
6 Lecomte, L.; Sinou, D. *J. Chrom.* **1990**, *514*, 91.
7 Lensink, C.; de Vries, J. G. *Tetrahedron: Asymm.* **1992**, *3*, 235.
8 Fell, B.; Papadogianakis, G. *J. Prakt. Chem.* **1994**, *336*, 591.
9 Wan, K-t.; Davis, M. E. *J. Chem. Soc., Chem. Commun.* **1993**, 1262.
10 Herrmann, W. A.; Albanese, G. P.; Manetsberger, R. B.; Lappe, P.; Bahrmann, H. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 811.
11 Herrmann, W. A.; Manetsberger, R.; Albanese, G.; Bahrmann, H.; Lappe, P.; Bergrath, K. Eur. Patent 0,632,047,A1, **1995** to Hoechst AG (*Chem. Abstr.* **1995**, *122*, 133420).
12 Bartik, T.; Bartik, B.; Hanson, B. E.; Guo, I.; Toth, I. *Organometallics* **1993**, *12*, 164.
13 Bartik, T.; Bartik, B.; Hanson, B. E. *J. Mol. Catal.* **1994**, *88*, 43.
14 Bartik, T.; Ding, H.; Bartik, B.; Hanson, B. E. *J. Mol. Catal. A* **1995**, *98*, 117.
15 Herd, O.; Hessler, A.; Langhans, K. P.; Stelzer, O. *J. Organomet. Chem.* **1994**, *475*, 99.
16 Gulyas, H.; Arva, P.; Bakos, J. *J. Chem. Soc., Chem. Commun.* **1997**, 2385.
17 Fell, B.; Papadogianakis, G. *J. Mol. Catal.* **1991**, *66*, 143.
18 Sargent, M. V.; Dean, F. M. Furans and their Benzo Derivatives: (*ii*) Reactivity. In *Comprehensive Heterocyclic Chemistry*; Katritzky, A. R.; Rees, C. W., Eds.; Pergamon: Oxford, 1984; Vol. 4, p. 643.

19 Elderfield, R. C. *Heterocyclic Compounds*; Wiley: New York; 1961, Vol. 2, p. 123.
20 Keumi, T.; Tomioka, N.; Hamanaka, K.; Kakihara, H.; Fukushima, M.; Morita, T.; Kitajima, H. *J. Org. Chem.* **1991**, *56*, 4671.
21 Hand, E. S.; Johnson, S. C.; Baker, D. C. *J. Org. Chem.* **1997**, *62*, 1348.
22 Keumi, T.; Nakamura, M.; Kitamura, M.; Tomioka, N.; Kitajima, H. *J. Chem. Soc., Perkin Trans. 2* **1985**, 909.
23 Buu-Hoi, N. P.; Roger, R. *Rec. Trav. Chim. Pays-Bas* **1948**, *67*, 175; improved procedure: Hand, E. S.; Johnson, S. C.; Baker, D. C. *J. Org. Chem.* **1997**, *62*, 1348.
24 Schmidt, R.; Foricher, J.; Cereghetti, M.; Schonholzer, P. *Helv. Chim. Acta* **1991**, *74*, 370.
25 Schmidt, R.; Broger, E. A.; Cereghetti, M.; Crameri, Y., Foricher, J.; Lalonde, M.; Muller, R. K.; Scalone, M.; Schoettel, G.; Zutter, U. *Pure & Appl. Chem.* **1996**, *68*, 131.
26 Foricher, J.; Heiser, B.; Schmid, R. US patent 5,302,738, **1994** to Hoffmann-La Roche (*Chem. Abstr.* **1992**, *118*, 147774).
27 Feiken, N.; Pregosin, P. S.; Trabesinger, G. *Organometallics* **1997**, *16*, 5756.
28 Trabesinger, G.; Albinati, A.; Feiken, N.; Kunz, R. W.; Pregosin, P. S.; Tschoerner, M. *J. Am. Chem. Soc.* **1997**, *119*, 6315.
29 Takaya, H.; Akutagawa, S.; Noyori, R. *Organic Synthesis* **1989**, *67*, 20.
30 Bumagin, N.A.; Andryukhova, N. P.; Beletskaya, I. P. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1988**, *6*, 1248.
31 Bumagin, N. A.; More, P. G.; Beletskaya, I. P. *J. Organomet. Chem.* **1989**, *371*, 397.
32 Genet, J. P.; Blart, E.; Savignac, M. *Synlett* **1992**, 715.
33 Schreuder Goedheijt, M.; Kamer, P. C. J.; Van Leeuwen, P. W. N. M. *J. Mol. Catal. A: Chem.* **1998**, *134*, 243.
34 Van der Veen, L. A.; Boele, M. D. K.; Bregman, F. R.; Kamer, P. C. J.; Van Leeuwen, P. W. N. M.; Goubitz, K.; Fraanje, J.; Schenk, H.; Bo, C. *J. Am. Chem. Soc.* **1998**, *120*, 11616.
35 Buhling, A.; Kamer, P. C. J.; Van Leeuwen, P. W. N. M. *J. Mol. Catal. A* **1995**, *98*, 69.
36 Van Leeuwen, P. W. N. M.; Kamer, P. C. J. *Organic Synthesis via Organometallics*; Helmchen, G.; Dibo, J.; Flubacher, D.; Wiese, B., Eds.: Vieweg; 1996, p. 229.
37 Oswald, A. A.; Hendriksen, D. E.; Kastrup, R. V.; Irikura, K.; Mozeleski, E. J.; Young, D. A. *Phosphorus and Sulfur* **1987**, *30*, 237.
38 Darensbourg, D. J.; Bischoff, C. J. *Inorg. Chem.* **1993**, *32*, 47. See also: Stelzer, O. Variation of Ligands: Monophosphines. In *Aqueous-Phase Organometallic Catalysis - Concept and Applications*; Cornils, B.; Herrmann, W. A., Eds.; Wiley-VCH: Weinheim, 1998; Chapter 3.2.1, especially p. 75.
39 Still, W. C.; Kahn, M.; Mitra, A. *J. Org. Chem.* **1978**, *43*, 2923.
40 Odle, R.; Blevins, B.; Ratcliff, M.; Hegedus, L. S. *J. Org. Chem.* **1980**, *45*, 2709.
41 Grigg, R.; Santhakumar, V.; Sridharan, V.; Stevenson, P.; Teasdale, A.; Thornton-Pett, M.; Worakun, T. *Tetrahedron* **1991**, *47*, 9703.
42 Tsuji, Y.; Kotachi, S.; Huh, K.-T.; Watanabe, Y. *J. Org. Chem.* **1990**, *55*, 580.
43 Angle, S. R.; Louie, M. S. *J. Org. Chem.* **1991**, *56*, 2853.
44 Cho, C. S.; Motofusa, S.; Ohe, K.; Uemura, S. *J. Org. Chem.* **1995**, *60*, 883.
45 Casalnuovo, A. L.; Calabrese, J. C. *J. Am. Chem. Soc.* **1990**, *112*, 4324.
46 Herndon, J. W.; McMullen, L. A.; *J. Organomet. Chem.* **1989**, *368*, 83.