DOI: 10.1002/ejoc.200901080

Use of the Diels–Alder Cycloaddition of Tetracyclone and Internal Aryl Acetylenes for the Synthesis of Functionalized Atropisomeric Biaryls

Marko Hapke,*[a] Andrey Gutnov,[a] Nico Weding,[a] Anke Spannenberg,[a] Christine Fischer,[a] Christian Benkhäuser-Schunk,[b] and Barbara Heller[a]

Dedicated to the memory of Prof. Dr. Peter Köll

Keywords: Atropisomerism / Biaryls / Diels–Alder reaction / Cycloaddition / Alkynes

The Diels–Alder cycloaddition reaction of tetracyclone and functionalized, internal aryl acetylenes gave access to a number of bulky atropisomeric biaryls in good to excellent yield. The synthesis is convenient and yields the pure biaryls without tedious work-up and purification procedures. Exemplarily the atropisomers have been resolved via the diastereomers in an easy and efficient manner to yield the enantiomers.

Introduction

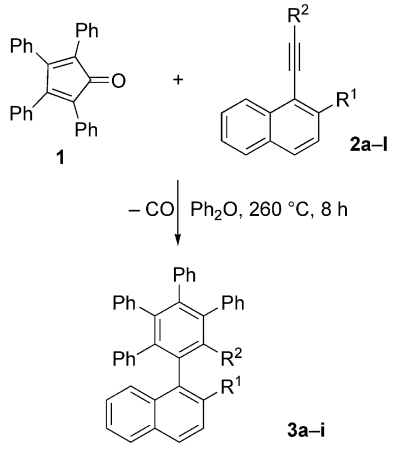
The Diels–Alder cycloaddition of tetraphenylcyclopentadienone (tetracyclone, **1**) or its aryl-substituted derivatives with acetylenes has been developed in recent years into a powerful tool for the preparation of a number of interesting molecular architectures, like e.g. hexaarylbenzenes,[1] dendrimers,[2] molecular propellers,[3] polycyclic aromatic compounds,[4] or discotic liquid crystals.[5] The [4+2] cycloaddition reaction with heterocyclic alkynes or nitriles also proved to be a suitable approach for the synthesis of ligand systems in the preparation of coordination compounds with transition metal ions, which exhibit interesting properties.[6] The reaction of **1** with acetylenes in general proceeds at high temperatures with the extrusion of carbon monoxide from the primary cycloaddition intermediate, yielding the aromatic products.[7] The circular array of six aromatic rings around the central benzene ring in hexaarylbenzenes leads to a propeller-shaped structure, and the property can give rise to chiral conformations if unequally substituted aryls are used, resulting from the introduction of axial chirality into the molecule and therefore the formation of atropisomers.[8] Substituted polyphenylated arenes have recently also found interest for the preparation of very bulky phosphane ligands, that can be used in a number of palladium-catalyzed reactions, namely the transformation of unactivated aryl chlorides in cross-coupling reactions.[9] The Diels–Alder approach for the reaction of functionalized acetylenes and dienes has also been utilized to prepare less substituted phosphoryl group-containing biaryls, that can act as ligands in other palladium-catalyzed cross-coupling reactions.[10] Herein we present an approach to apply the Diels–Alder cycloaddition strategy to the synthesis of functionalized, sterically hindered atropisomeric hexaarylbenzenes, potential ligands for general as well as for asymmetric catalytic purposes.

Results and Discussion

Earlier we reported that a number of activated internal 1-naphthylacetylenes can be successfully utilized in cobalt(I)-catalyzed enantioselective [2+2+2] cross-cyclotrimerization reactions with other acetylenes to give axially chiral biphenyls with good yields and enantioselectivities.[11] In this work we have applied the same substrate acetylenes **2a**–**l** as dienophiles for the [4+2] cycloaddition with tetracyclone (Scheme 1).

The conditions chosen are quite general for such type of cycloaddition reactions (diphenyl ether, 260 °C, 8 h). The reaction proceeds smoothly in most cases to give the compounds **3a**–**i** after a very simple work-up procedure with excellent yields (Table 1). The products are high-melting, crystalline substances which are easy to purify chromatographically or with a simple crystallization. At first view, interestingly, (phosphoryl)acetylenes with bulky aliphatic groups (R^2 = *tert*-butyl, adamantyl, entry 10 and 11) have not furnished any cycloaddition products under standard conditions.

[a] Leibniz-Institut für Katalyse e. V. an der Universität Rostock (LIKAT),
Albert-Einstein-Str. 29a, 18059 Rostock, Germany
Fax: +49-381-128151213
E-mail: marko.hapke@catalysis.de
[b] Universität Bonn, Kekulé-Institut für Organische Chemie und Biochemie,
Gerhard-Domagk-Str. 1, 53121 Bonn, Germany
Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/ejoc.200901080.



Scheme 1. Diels–Alder cycloaddition of tetracyclone (**1**) with different acetylenes **2a**–**l**, yielding the biaryls **3a**–**i**.

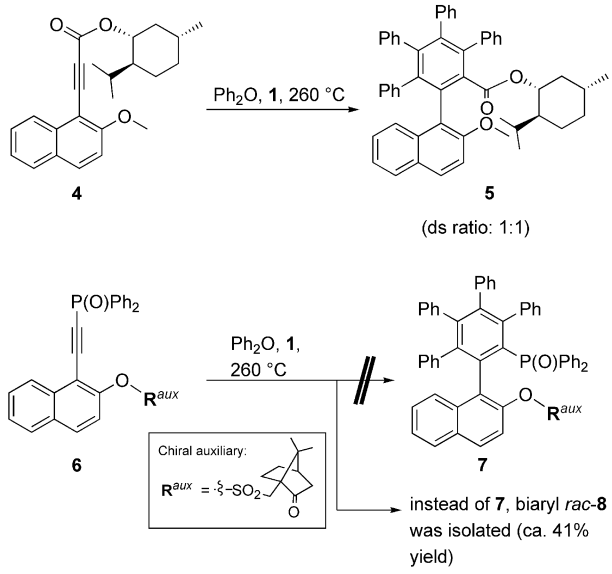
Table 1. Synthesis of the functionalized biaryls.

Entry	Acetylenes **2**	% Yield of **3**[a]
1	**2a**: R^1 = H, R^2 = $P(O)Ph_2$	**3a**, 92
2	**2b**: R^1 = OCH_3, R^2 = $P(O)Ph_2$	**3b**, 83
3	**2c**: R^1 = OCH_3, R^2 = $P(O)[(3,5\text{-}CF_3)_2Ph]_2$	**3c**, 93
4	**2d**: R^1 = OCH_3, R^2 = $P(O)[(4\text{-}OCH_3)Ph]_2$	**3d**, 81
5	**2e**: R^1 = CH_3, R^2 = $P(O)Ph_2$	**3e**, 80
6	**2f**: R^1 = OCH_3, R^2 = PPh_2	**3f**, 24
7	**2g**: R^1 = OCH_3, R^2 = $COOCH_3$	**3g**, 93
8	**2h**: R^1 = OCH_3, R^2 = COOPh	**3h**, 60
9	**2i**: R^1 = OCH_3, R^2 = COPh	**3i**, 87
10	**2k**: R^1 = OCH_3, R^2 = $P(O)Ad_2$	**3k**, –
11	**2l**: R^1 = OCH_3, R^2 = $P(O)[t\text{Bu}]_2$	**3l**, –

[a] Isolated yield.

Electron-withdrawing phosphoryl and carbonyl groups in the acetylenes **2** are in general a prerequisite for a successful reaction. This is exemplified by entry 6 (Table 1), where in acetylene **2f** the $POPh_2$ group was replaced with the more electron-rich PPh_2 moiety, which resulted in a significantly lower yield of the product **3f**. The use of electron-deficient (entry 3, **2c**) or electron-rich (entry 4, **2d**) substituted phenyl groups at the phosphorus atom did not show significant differences in the reaction outcome. Several experiments with HPLC using a chiral stationary phase have revealed that the compounds **3a**–**i** form racemates. Investigations towards the interconversion temperature for single enantiomers in the range up to 60 °C showed no interconversion, which is in agreement with observations made for hexaarylbenzene systems with substituents in the *ortho*-position, where interconversions have only been observed at high temperatures.[8] However, the herein reported biaryls possess large substituents in the *ortho*-positions of the biaryl bond, which is a requirement for a high stability against interconversion and therefore the configurational stability barrier can be expected to be much higher than 60 °C.[8b]

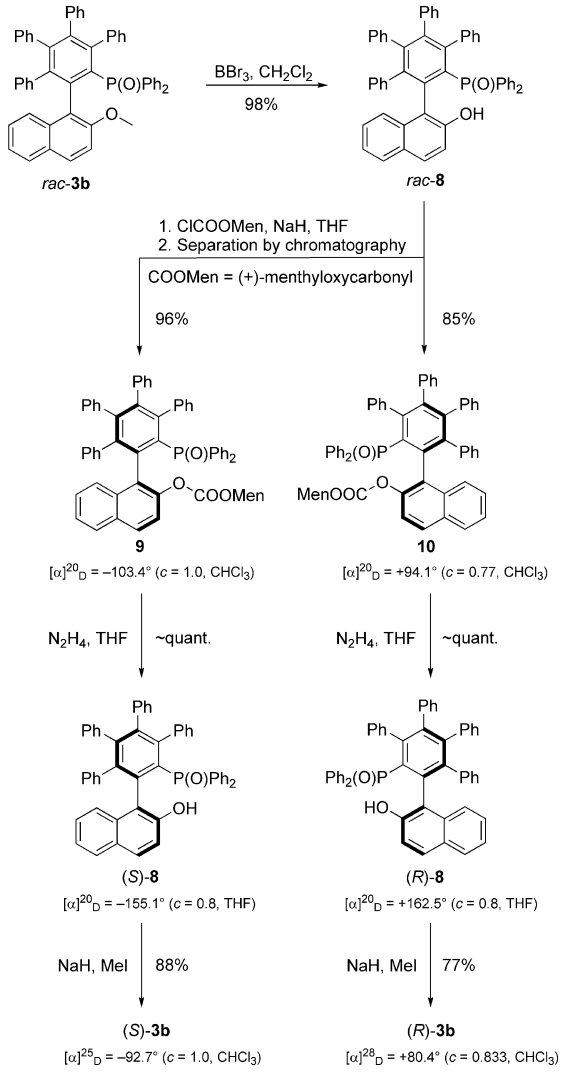
We investigated the influence of chiral groups attached to the naphthylacetylenes like in **4** (menthyl group) and **6** (camphoryl group), where these groups are either directly attached to the alkyne moiety or bound to the hydroxy group of the naphthyl fragment (Scheme 2). In the case of **4**, we basically obtained a 1:1 ratio of the resulting diastereomers **5**. The introduction of chirality in the substrates obviously has no influence on the preferred formation of one of the diastereomers. When turning to the chiral derivative **6**, unfortunately the expected diastereomers **7** could not be isolated and the ratio determined. Instead, the biaryl *rac*-**8**, bearing a free hydroxy group at the naphthyl ring, was isolated in ca. 41% yield, presumably due to the elimination of the camphoryl group during the reaction.



Scheme 2. Attempted introduction of stereogenic information in the Diels–Alder cycloaddition reaction with chiral acetylene **4** and **6**.

In order to resolve the formed biaryls preparatively, we have investigated and exemplified the appropriate procedure using the biaryl product *rac*-**3b** (Scheme 3).

In the first step the methoxy group was demethylated using BBr_3 to quantitatively yield the phenolic derivative *rac*-**8**. However, all of our attempts have failed in preparing corresponding diastereomeric camphorsulfonates as compound *rac*-**8** did not react with (1*S*)-(+)-10-camphorsulfonyl chloride (1.2 equiv.), neither in the presence of an excess of pyridine at elevated temperatures (100 °C) nor in THF with sodium hydride (1.2 equiv.) as a base. Fortunately, we did succeed in the preparation of corresponding diastereomeric menthyl carbonates from (+)-menthyl chloroformate and compound *rac*-**8** in the presence of NaH in refluxing THF. Both the deprotection as well as the protection as the (+)-menthyl carbonates proceeded with very high to nearly quantitative yields. After extensive screening of solvents, the individual diastereomers **9** and **10** have been smoothly separated by chromatography on silica gel with Et_2O/*n*-hexane mixture (5:1) as the eluent. The menthyloxycarbonyl group in the compounds **9** and **10** was easily and quantitatively removed by refluxing with hydrazine hydrate in THF to give the optically pure (–)-(*S*)- and (+)-(*R*)-enantiomers of the corresponding hydroxyphosphane oxide



Scheme 3. Preparation of the single enantiomeric atropisomers of **3b** via diastereomeric resolution as the menthyl carbonates.

8. The oxides can be transformed into the methylated compounds (*S*/*R*)-**3b** by methylation with methyl iodide/NaH in very good yields.

For the determination of the absolute configuration a single crystal of the diastereomer **10** has been grown from a benzene/*n*-heptane mixture and a X-ray crystal structure analysis has revealed the (*R*) configuration of the biphenyl part of the molecule with respect to the (+)-menthyloxycarbonyl group. The molecular structure is depicted in Figure 1. The central phenyl ring is almost planar (mean deviation from the best plane is 0.032 Å). Four phenyl rings and the substituted naphthyl ring are twisted into a propeller conformation around the central phenyl ring.

We also investigated the deoxygenation of phosphane oxide **3b** yielding phosphane **3f** (Scheme 4). From the preparation of biaryls by cobalt-catalyzed cycloaddition reactions we knew, that the use of AlH_3 was advantageous for obtaining the phosphanes without loss of chirality and in high yields in the case of enantiomerically pure biaryl phosphanes.[11b] The use of this method for the reduction of *rac*-

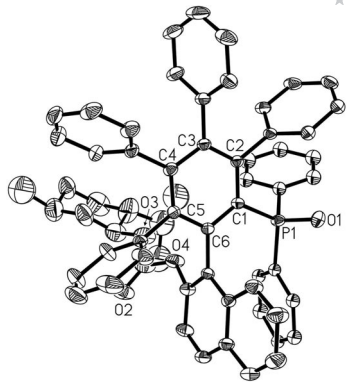
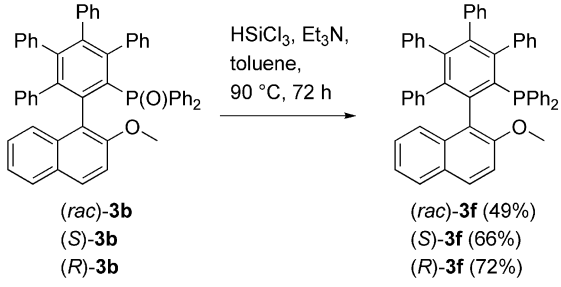


Figure 1. ORTEP drawing of the molecular structure of diastereomer **10**. The thermal ellipsoids correspond to 30% probability. Hydrogen atoms have been omitted for clarity.[12]

3b with a solution of AlH_3 in THF showed some difficulties, because the reaction gave several unidentified side products.[13] We then turned our attention on the use of trichlorosilane for the reduction of phosphane oxides, which has also been used for the reduction of chiral phosphane oxides without the loss of chirality (Scheme 4).[14] The reaction of $HSiCl_3$ in toluene/triethylamine finally yielded the free phosphane *rac*-**3f** with 49% yield after chromatography. We attempted the separation of *rac*-**3f** with HPLC using preparative chiral stationary phases like the chiral Whelk and Daicel phases, but observed problems in resolving the enantiomers. The deoxygenation of the chiral phosphanes **3** according to the above mentioned protocol worked smoothly and yielded the enantiomeric free phosphanes in 66% yield for (*S*)-**3f** and 72% yield for (*R*)-**3f**.



Scheme 4. Deoxygenation of phosphane oxide **3b**.

Conclusions

In conclusion, a simple and convenient way for the synthesis of highly sterically hindered atropisomeric functionalized biphenyls based on a Diels–Alder cycloaddition has been developed. The functional groups investigated comprise esters, ketone or highly interesting phosphane oxides, which are versatile precursors for the preparation of phosphane ligands used in catalytic applications. The separation procedure for the racemic atropisomers has been developed and successfully applied to furnish the pure enantiomeric phosphanes. The reduction of the phosphane oxides has been exemplarily investigated and $HSiCl_3/Et_3N$/toluene found as the suitable reduction system.

Experimental Section

General: The NMR spectra were recorded on a Bruker ARX 300 spectrometer at 298 K. Chemical shifts are reported in ppm relative to the ^1H and ^{13}C residue of the deuterated solvent. Mass spectra were obtained with a Varian AMD-402 instrument at an ionizing voltage of 70 eV. Relative intensities in percentages are given in parentheses. Melting points were measured with a Büchi 540 melting point determination apparatus. Optical rotations were determined on a Gyromat-HP polarimeter. In all cases the enantiomeric excesses were analyzed by HPLC with a Liquid Chromatograph 1090 equipped with DAD (Hewlett–Packard) and Chiralyser (IBZ Messtechnik GmbH, Hannover). The alkyne starting materials **2a**–**e** and **2i**–**l** have been prepared after published procedures from 1-ethynyl-2-methoxynaphthalene.[11b] The phosphane **2f** was prepared following the literature procedure.[15] The synthesis and characterization of compounds **2g**, **2h**, **4**, **6** and the product **5** as well as the details for the reaction of **4** and **6** with **1** are given in the Supporting Information.

General Procedure for the Cycloaddition Reaction of Tetracyclone (1) with Internal Alkynes 2a–l Yielding the Functionalized Biaryls 3: Acetylenes **2a**–**i** (1 mmol), tetracyclone (384 mg, 1 mmol), and diphenyl ether (2 g) were mixed in a Schlenk tube under argon, and the flask was placed in a silicon oil bath at 260 °C for 8 h. After cooling, the mixture was poured into *n*-hexane (30 mL), and precipitated products **3a**–**i** were filtered off and washed with *n*-hexane. They can be additionally purified by chromatography or recrystallization from ethyl acetate/*n*-hexane for extra purity.

1-[2-(Diphenylphosphoryl)-3,4,5,6-tetraphenylphenyl]naphthalene (3a): Reaction of tetracyclone (**1**) and the alkyne **2a** according to the General Procedure gave the desired compound **3a**; yield 652 mg, 92%; m.p. 286–287 °C. ^1H NMR (300 MHz, $CDCl_3$): δ = 7.96 (d, J = 8.7 Hz, 1 H, Ar-H), 7.91 (d, J = 7.2 Hz, 1 H, Ar-H), 7.67 (d, J = 7.8 Hz, 1 H, Ar-H), 7.54–7.29 (m, 11 H, Ar-H), 7.23–7.09 (m, 6 H, Ar-H), 7.02–6.89 (m, 6 H, Ar-H), 6.83–6.56 (m, 11 H, Ar-H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 147.6, 147.5, 145.4, 144.1, 144.0, 143.6, 143.5, 142.8, 142.7, 140.3, 140.0, 139.3, 138.9, 137.6, 137.5, 136.6, 135.0, 134.3, 134.0, 133.8, 133.2, 133.0, 132.2, 132.0, 131.9, 131.4, 131.3, 131.2, 130.6, 130.4, 130.3, 130.2, 130.1, 130.0, 129.0, 128.6, 128.5, 127.8, 127.7, 127.6, 127.1, 127.0, 126.7, 126.6, 126.3, 126.1, 126.0, 125.8, 125.6, 125.3, 125.0, 124.5 ppm. ^{31}P NMR (125 MHz, $CDCl_3$): δ = 23.7 ppm. MS (70 eV): m/z (%) = 708 (100) [M^+], 631 (18), 506 (27), 354 (11), 315 (15). $C_{52}H_{37}OP$ (708.82): calcd. C 88.11, H 5.26; found C 88.05, H 5.22.

1-[2-(Diphenylphosphoryl)-3,4,5,6-tetraphenylphenyl]-2-methoxynaphthalene (3b): After reaction of tetracyclone (**1**) and the alkyne **2b** according to the General Procedure the desired compound **3b** was obtained; yield 613 mg, 83%; m.p. 285–286 °C. ^1H NMR (300 MHz, $CDCl_3$): δ = 8.03 (d, J = 8.4 Hz, 1 H, Ar-H), 7.84 (d, J = 7.6 Hz, 1 H, Ar-H), 7.70 (d, J = 7.7 Hz, 2 H, Ar-H), 7.63–7.51 (m, 3 H, Ar-H), 7.40 (d, J = 9.7 Hz, 1 H, Ar-H), 7.36–7.05 (m, 12 H, Ar-H), 7.01–6.95 (m, 10 H, Ar-H), 6.82 (d, J = 7.3, 1.3 Hz, 1 H, Ar-H), 6.76–6.65 (m, 2 H, Ar-H), 6.61–6.49 (m, 3 H, Ar-H), 3.99 (s, 3 H, OCH_3) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 171.6, 153.5, 147.4, 147.3, 145.6, 143.4, 143.3, 143.0, 142.9, 140.5, 140.3, 139.9, 139.7, 139.6, 138.7, 138.6, 137.3, 136.3, 136.2, 136.1, 135.0, 134.4, 134.3, 133.3, 133.2, 131.8, 131.5, 131.2, 131.0, 130.9, 130.6, 130.5, 130.0, 129.9, 129.7, 128.4, 127.6, 127.5, 127.0, 126.9, 126.8, 126.7, 126.6, 126.4, 126.0, 125.8, 125.7, 125.6, 123.4, 122.4, 117.1, 111.1, 60.9, 54.9 ppm. ^{31}P NMR (125 MHz, $CDCl_3$): δ = 24.1 ppm. MS (70 eV): m/z (%) = 738 (100) [M^+], 536 (55), 353 (25), 201 (56). $C_{53}H_{39}O_2P$ (738.85): calcd. C 86.16, H 5.32; found C 86.11, H 5.44.

1-(2-{Bis[3,5-bis(trifluoromethyl)phenyl]phosphoryl}-3,4,5,6-tetraphenylphenyl)-2-methoxynaphthalene (3c): Reacting tetracyclone (**1**, 0.5 mmol) and the alkyne **2c** (0.5 mmol) in accordance to the General Procedure furnished the desired compound **3c**; yield 470 mg, 93%; m.p. 306–307 °C. ^1H NMR (300 MHz, $CDCl_3$): δ = 7.70 (d, J = 11.0 Hz, 2 H, Ar-H), 7.61–7.49 (m, 4 H, Ar-H), 7.44 (s, 1 H, Ar-H), 7.38–7.27 (m, 2 H, Ar-H), 7.20–7.06 (m, 3 H, Ar-H), 6.83 (q, J = 8.4 Hz, 3 H, Ar-H), 6.75–6.54 (m, 12 H, Ar-H), 6.48–6.27 (m, 4 H, Ar-H), 6.19 (dd, J = 7.4, 1.0 Hz, 1 H, Ar-H), 3.63 (s, 3 H, OCH_3) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 154.1, 146.7, 146.6, 146.2, 146.1, 143.3, 143.2, 143.1, 142.9, 140.0, 139.8, 139.4, 139.2, 138.7, 138.4, 138.0, 137.8, 137.7, 133.2, 133.0, 132.5, 131.3, 130.9, 130.8, 130.5, 130.2, 129.9, 129.4, 128.9, 127.3, 126.7, 126.0, 125.9, 125.8, 125.7, 125.6, 125.2, 125.1, 124.4, 123.3, 123.0, 121.4, 120.8, 110.7, 54.9 ppm. ^{31}P NMR (125 MHz, $CDCl_3$): δ = 16.6 ppm. MS (70 eV): m/z (%) = 1009 (100) [M^+], 488 (15). $C_{57}H_{35}F_{12}O_2P$ (1010.84): calcd. C 67.73, H 3.49; found C 67.59, H 3.52.

1-{2-[Bis(4-methoxyphenyl)phosphoryl]-3,4,5,6-tetraphenylphenyl}-2-methoxynaphthalene (3d): Reaction of tetracyclone (**1**) and the alkyne **2d** according to the General Procedure gave the desired compound **3d**; yield 647 mg, 81%; m.p. 278–279 °C. ^1H NMR (300 MHz, $CDCl_3$): δ = 7.61 (d, J = 8.2 Hz, 1 H, Ar-H), 7.42 (d, J = 7.6 Hz, 1 H, Ar-H), 7.35–7.26 (m, 2 H, Ar-H), 7.21–7.11 (m, 3 H, Ar-H), 7.06 (d, J = 9.0 Hz, 1 H, Ar-H), 6.89–6.54 (m, 16 H, Ar-H), 6.48–6.37 (m, 5 H, Ar-H), 6.33 (d, J = 9.1 Hz, 1 H, Ar-H), 6.22–6.03 (m, 4 H, Ar-H), 3.68 (s, 3 H, OCH_3), 3.61 (s, 3 H, ArOCH_3), 3.51 (s, 3 H, ArOCH_3) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 160.9, 160.3, 153.1, 147.0, 145.0, 143.0, 142.5, 140.2, 139.6, 138.8, 134.8, 133.9, 132.6, 132.0, 131.4, 130.9, 129.7, 128.2, 127.2, 126.3, 125.4, 123.0, 122.4, 113.0, 112.2, 111.0, 60.4, 55.2, 55.1, 54.7 ppm. ^{31}P NMR (125 MHz, $CDCl_3$): δ = 25.7 ppm. MS (70 eV): m/z (%) = 799 (92) [M^+], 784 (37), 768 (29), 536 (100), 383 (29), 261 (68). $C_{55}H_{43}O_4P\cdot(C_4H_8O_2$, EtOAc) (887.01): calcd. C 79.89, H 5.80; found C 79.94, H 5.95.

1-[2-(Diphenylphosphoryl)-3,4,5,6-tetraphenylphenyl]-2-methylnaphthalene (3e): The reaction of tetracyclone (**1**, 0.5 mmol) and the alkyne **2e** (0.5 mmol) under the conditions described in the General Procedure gave the desired compound **3e**; yield 289 mg, 80%; m.p. 271–274 °C. ^1H NMR (300 MHz, $CDCl_3$): δ = 7.80 (d, J = 8.4 Hz, 1 H, Ar-H), 7.54–7.41 (m, 2 H, Ar-H), 7.35–7.18 (m, 4 H, Ar-H), 7.10–6.90 (m, 9 H, Ar-H), 6.89–6.46 (m, 17 H, Ar-H), 6.41–6.31 (m, 3 H, Ar-H), 2.53 (s, 3 H, CH_3) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 147.4, 147.2, 145.8, 145.7, 143.5, 143.2, 142.0, 141.9, 141.8, 139.9, 139.7, 138.8, 138.1, 138.0, 135.6, 135.5, 135.3, 135.2, 134.5, 134.0, 133.6, 133.5, 133.1, 132.9, 132.3, 131.2, 131.1, 130.8, 130.5, 130.1, 130.0, 129.9, 129.7, 129.6, 129.0, 128.8, 128.7, 128.4, 127.9, 127.5, 127.4, 127.3, 127.2, 126.6, 126.4, 126.3, 126.2, 126.1, 125.9, 125.7, 125.5, 125.4, 125.3, 125.2, 124.2, 31.7, 22.7, 22.2 ppm. ^{31}P NMR (125 MHz, $CDCl_3$): δ = 24.1 ppm. MS (70 eV): m/z (%) = 722 (32) [M^+], 631 (100), 520 (45), 443 (16), 361 (12). $C_{53}H_{39}OP$ (722.85): calcd. C 88.06, H 5.44; found C 88.11, H 5.65.

1-[2-(Diphenylphosphanyl)-3,4,5,6-tetraphenylphenyl]-2-methoxynaphthalene (3f): According to the General Procedure tetracyclone (**1**) and the alkyne **2f** were reacted to give compound **3f**; yield 173 mg, 24%; m.p. 220–221 °C (dec.). ^1H NMR (300 MHz, $CDCl_3$): δ = 7.81 (d, J = 8.4 Hz, 1 H, Ar-H), 7.61–7.46 (m, 3 H, Ar-H), 7.38–6.25 (m, 32 H, Ar-H), 3.66 (s, 3 H, OCH_3) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 154.3, 154.2, 147.3, 143.6, 143.2, 143.1, 142.8, 142.2, 142.0, 140.6, 140.5, 140.4, 139.6, 137.5, 137.4, 137.3, 134.4, 134.2, 134.1, 132.7, 132.4, 132.3, 132.1, 131.4, 131.3, 131.0, 129.6, 129.5, 129.0, 128.0, 127.8, 127.4, 127.3, 127.0, 126.9, 126.6, 126.5, 126.4, 126.3, 126.2, 126.1, 125.9, 125.8, 125.7, 125.3, 125.2, 125.1, 124.9, 124.5, 124.4, 122.8, 111.4, 54.8 ppm. ^{31}P NMR

(125 MHz, $CDCl_3$): δ = –2.3 ppm. MS (70 eV): *m*/*z* (%) = 722 (28) [M^+], 691 (100), 361 (10). HRMS (EI) for $C_{53}H_{38}PO$ [M^+] calcd. 721.2655; found 721.2661.

2-Methoxy-1-[(2-methoxycarbonyl)-3,4,5,6-tetraphenylphenyl]naphthalene (3 g): After reaction of tetracyclone (**1**) and the alkyne **2g** according to the General Procedure the desired compound **3g** was obtained; yield 556 mg, 93%; m.p. 243–244 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.06 (d, *J* = 8.5 Hz, 1 H, Ar-H), 7.52–7.33 (m, 5 H, Ar-H), 7.26 (d, *J* = 7.7 Hz, 1 H, Ar-H), 7.13–6.62 (m, 17 H, Ar-H), 6.52–6.45 (m, 2 H, Ar-H), 3.36 (s, 3 H, OCH_3), 2.71 (s, 3 H, $COOCH_3$) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 169.2, 154.1, 142.3, 142.1, 140.4, 140.0, 139.7, 139.6, 138.2, 135.7, 133.7, 133.1, 131.5, 131.3, 131.2, 130.4, 130.2, 130.0, 129.6, 129.5, 129.3, 128.3, 127.5, 127.2, 126.7, 126.6, 126.5, 126.0, 125.9, 125.8, 125.6, 125.5, 123.1, 122.0, 112.6, 56.3, 51.1 ppm. MS (70 eV): *m*/*z* (%) = 597 (100) [M^+], 421 (15), 282 (27). $C_{43}H_{32}O_3$ (596.71): calcd. C 86.55, H 5.41; found C 86.43, H 5.38.

2-Methoxy-1-[(2-phenoxycarbonyl)-3,4,5,6-tetraphenylphenyl]naphthalene (3h): Reacting tetracyclone (**1**, 0.5 mmol) and the alkyne **2h** (0.5 mmol) in accordance to the General Procedure furnished the desired compound **3h**; yield 196 mg, 60%; m.p. 174–175 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.19 (d, *J* = 8.5 Hz, 1 H, Ar-H), 7.57 (d, *J* = 8.1 Hz, 1 H, Ar-H), 7.52–7.45 (m, 3 H, Ar-H), 7.38 (d, *J* = 7.9 Hz, 1 H, Ar-H), 7.26 (d, *J* = 7.7 Hz, 1 H, Ar-H), 7.19 (s, 1 H, Ar-H), 7.12–7.04 (m, 3 H, Ar-H), 6.99–6.43 (m, 18 H, Ar-H), 5.98 (d, *J* = 1.5 Hz, 1 H, Ar-H), 5.95 (d, *J* = 1.0 Hz, 1 H, Ar-H), 3.32 (s, 3 H, OCH_3) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 167.1, 154.4, 150.2, 142.7, 142.3, 140.6, 140.0, 139.9, 139.4, 138.2, 135.0, 133.8, 133.1, 131.5, 131.4, 131.3, 130.8, 130.4, 130.2, 129.8, 129.5, 128.9, 128.4, 127.7, 127.5, 127.4, 126.9, 126.8, 126.7, 126.3, 126.2, 125.9, 125.7, 125.6, 125.3, 123.2, 121.7, 121.0, 118.9, 112.9, 56.3 ppm. MS (70 eV): *m*/*z* (%) = 658 (5) [M^+], 565 (100), 282 (10). $C_{48}H_{34}O_3$ (658.78): calcd. C 87.51, H 5.20; found C 87.51, H 5.17.

2-Methoxy-1-[2-(phenylcarbonyl)-3,4,5,6-tetraphenylphenyl]naphthalene (3i): Reaction of tetracyclone (**1**) and the alkyne **2i** according to the General Procedure gave the desired compound **3i**; yield 559 mg, 87%; m.p. 269–270 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.69 (d, *J* = 8.5 Hz, 1 H, Ar-H), 7.58–7.41 (m, 4 H, Ar-H), 7.32–6.45 (m, 26 H, Ar-H), 3.52 (br. s, 3 H, OCH_3) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 197.6, 142.4, 141.9, 140.8, 140.6, 140.2, 139.8, 139.6, 139.1, 138.6, 137.8, 133.1, 131.8, 131.6, 131.4, 131.0, 129.8, 129.6, 129.2, 129.0, 127.3, 127.1, 127.0, 126.8, 126.7, 126.6, 126.2, 126.1, 126.0, 125.9, 125.6, 125.4, 123.0, 121.3, 111.2, 55.0 ppm. MS (70 eV): *m*/*z* (%) = 642 (100) [M^+], 282 (19), 105 (94). $C_{48}H_{34}O_2$ (642.78): calcd. C 89.41, H 5.63; found C 89.49, H 5.58.

***rac*-1-[2-(Diphenylphosphoryl)-3,4,5,6-tetraphenylphenyl]naphthalene-2-ol (*rac*-8) by Demethylation of 3b:** *rac*-Phosphane oxide **3b** (0.739 g, 1 mmol) was dissolved in dry CH_2Cl_2 (40 mL), and BBr_3 (20 mL, 2 mmol, 1 M solution on *n*-hexane) was added dropwise to the cooled solution (0 °C). After the addition is completed, the mixture was warmed up to room temp. and stirred for 8 h. The resulted solution was poured into water, the organic layer was washed with sat. $NaHCO_3$ solution, then separated and dried with Na_2SO_4. The solvent was evaporated to give the title compound *rac*-**8** as a colorless solid (710 mg, 98%), m.p. >350 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.89 (br. s, 1 H, O*H*), 7.26–6.19 (m, 36 H, Ar-H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 153.9, 145.8, 145.7, 145.5, 144.0, 143.9, 143.0, 142.9, 140.7, 140.6, 139.7, 139.3, 138.7, 138.5, 138.4, 135.2, 133.8, 132.9, 132.5, 132.2, 131.8, 131.2, 131.1, 130.8, 130.4, 130.1, 129.9, 129.6, 129.1, 128.9, 128.6, 127.6, 127.5, 127.1, 126.9, 126.8, 126.7, 126.6, 126.3, 126.2, 126.1, 126.0, 125.9, 125.6, 125.4, 125.3, 124.6, 122.6, 121.7 ppm. ^{31}P NMR (125 MHz, $CDCl_3$): δ = 30.3 ppm. MS (70 eV): *m*/*z* (%) = 724 (29) [M^+], 522 (100), 362 (18), 201 (9). $C_{52}H_{37}O_2P$ (724.82): calcd. C 86.17, H 5.15; found C 85.94, H 5.11.

Resolution of *rac*-1-[2-(Diphenylphosphoryl)-3,4,5,6-tetraphenylphenyl]naphthalene-2-ol (*rac*-8): Racemate **8** (724 mg, 1 mmol) was added to the suspension of NaH (40 mg, 1.2 mmol, 60% suspension in paraffin oil) in THF (10 mL). The mixture was stirred for 30 min, and (+)-menthyl chloroformate (212 μL, 1 mmol) was added. The reaction was heated under reflux for 10 h, then cooled and filtered through a thin pad of silica. The solvent was removed, and the residue containing the two diastereomers was plugged to silica. Repeated chromatographic separation with an Et_2O/*n*-hexane mixture (5:1) as the eluent furnished first the diastereoisomer **9** (435 mg, 96% yield), and then the diastereomer **10** as the second fraction (384 mg, 85% yield).

Diastereomer 9: M.p. 307–308 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.76 (d, *J* = 8.3 Hz, 1 H, Ar-H), 7.55–7.44 (m, 2 H, Ar-H), 7.43–7.35 (m, 1 H, Ar-H), 7.34–7.11 (m, 7 H, Ar-H), 7.05–6.46 (m, 24 H, Ar-H), 6.37–6.30 (m, 1 H, Ar-H), 4.92 (dd, *J* = 10.8, 4.4 Hz, menthyl-H), 2.58 (d, *J* = 11.7 Hz, 1 H, menthyl-H), 2.28–2.16 [m, 1 H, $CH(CH_3)_2$], 1.92–1.62 (m, 4 H, menthyl-H), 1.48–1.19 (m, 3 H, menthyl-H), 1.12 [dd, *J* = 6.8, 2.0 Hz, 6 H, $CH(CH_3)_2$], 1.05 (*J* = 7.0 Hz, 3 H, CH_3) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 152.5, 147.2, 147.0, 145.1, 143.6, 143.5, 142.4, 142.2, 139.9, 139.7, 138.5, 138.1, 138.0, 137.1, 137.0, 135.8, 135.6, 134.6, 134.4, 134.2, 133.7, 133.2, 133.0, 131.4, 130.9, 130.7, 130.6, 130.5, 130.1, 129.7, 129.5, 129.3, 127.9, 127.2, 127.0, 126.9, 126.6, 126.5, 126.4, 126.3, 125.9, 125.8, 125.7, 125.6, 125.5, 125.4, 125.3, 125.2, 125.1, 124.9, 119.3, 78.8, 47.7, 41.1, 34.2, 31.4, 27.3, 24.3, 22.3, 20.7, 17.4 ppm (due to the large number of signals with similar shifts and splitting of signals due to C–P coupling all observed peaks are given). ^{31}P NMR (125 MHz, $CDCl_3$): δ = 26.74 ppm. MS (70 eV): *m*/*z* (%) = 907 (23) [M^+], 724 (33), 522 (100), 200 (13). $[\alpha]_D^{20}$ = –103.4 (*c* = 1.0, $CHCl_3$). $C_{63}H_{55}O_4P$ (907.08): calcd. C 83.42, H 6.11; found C 83.81, H 6.34.

Diastereomer 10: M.p. 282–283 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.78 (d, *J* = 8.2 Hz, 1 H, Ar-H), 7.54–7.36 (m, 5 H, Ar-H), 7.34–7.26 (m, 1 H, Ar-H), 7.22 (d, *J* = 8.9 Hz, 1 H, Ar-H), 7.15–7.02 (m, 3 H, Ar-H), 7.0–6.61 (m, 20 H, Ar-H), 6.59–6.32 (m, 5 H, Ar-H), 4.77 (td, *J* = 10.7, 4.5 Hz, 1 H, menthyl-H), 2.40–2.15 [m, 2 H, menthyl-H, $CH(CH_3)_2$], 1.92–1.57 (m, 4 H, menthyl-H), 1.39–1.16 (m, 4 H, menthyl-H), 1.13 (d, *J* = 7.1 Hz, 3 H, CH_3), 1.05 [d, *J* = 6.7 Hz, 6 H, $CH(CH_3)_2$] ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 152.3, 147.1, 147.0, 146.4, 145.2, 145.1, 143.7, 143.6, 142.4, 142.2, 139.9, 139.7, 138.7, 137.9, 137.8, 137.0, 136.9, 136.3, 135.5, 134.9, 134.4, 134.1, 134.0, 133.7, 133.0, 132.9, 131.2, 131.1, 130.9, 130.8, 130.7, 130.6, 130.4, 130.3, 130.1, 129.9, 129.8, 129.6, 129.5, 129.4, 127.6, 127.2, 127.1, 127.0, 126.7, 126.6, 126.5, 126.3, 126.2, 126.0, 125.8, 125.7, 125.5, 125.3, 125.2, 125.0, 119.1, 79.2, 77.3, 47.3, 40.9, 35.4, 34.2, 31.5, 26.8, 26.5, 23.8, 22.2, 20.9, 16.9 ppm (due to the large number of signals with similar shifts and splitting of signals due to C–P coupling all observed peaks are reported). ^{31}P NMR (125 MHz, $CDCl_3$): δ = 26.72 ppm. MS (70 eV): *m*/*z* (%) = 907 (0.5) [M^+], 522 (2), 215 (33). $[\alpha]_D^{20}$ = +94.1 (*c* = 0.77, $CHCl_3$).

Hydrolysis of Diastereomers 9 and 10 in the Preparation of the Enantiomers (*S*)-8 and (*R*)-8: General procedure for the hydrolysis: a solution of diastereomer **9** (400 mg, 0.44 mmol) in THF (5 mL) was treated with hydrazine hydrate (200 μL, 6.42 mmol) and stirred under reflux for 4 h. To the cooled mixture CH_2Cl_2 (20 mL) was added and the mixture washed with water. The organic layer was separated and the aqueous phase was again extracted with CH_2Cl_2. The combined organic phases were washed with water and brine and dried with Na_2SO_4. The solvent was removed to give the prod-

uct (*S*)-**8**, $[\alpha]_D^{20}$ = –155.1 (*c* = 0.8, THF), as a white solid in near quantitative yield.

The product (*R*)-**8**, $[\alpha]_D^{20}$ = +162.5 (*c* = 0.8, THF), was obtained from diastereomer **10** following the hydrolysis procedure for (*S*)-**8**. Both enantiomers showed optical purity >99% *ee* (HPLC).

Preparation of Enantiomeric (*S*)-3b and (*R*)-3b by Methylation of the Enantiomers (*S*)-8 and (*R*)-8: The hydroxyphosphane oxide (*R*)-**6** (150 mg, 0.207 mmol) was dissolved in 5 mL of THF and NaH (16.6 mg, 0.414 mmol) added. After stirring at room temp. for 1 h methyl iodide (32 μL, 74 mg, 0.518 mmol) was added and the reaction mixture stirred at room temp. for another 12 h. The reaction was quenched with sat. NH_4Cl solution and extracted with diethyl ether. The combined organic phases were washed with water and brine and dried with Na_2SO_4. The residue obtained after evaporation can be purified by column chromatography on silica gel with diethyl ether/*n*-hexane (5:1 v/v) as the eluent to quantitatively yield the enantiomerically pure (*S*)-**3b** (135 mg, 88% yield) with $[\alpha]_D^{25}$ = –92.7 (*c* = 1.0, $CHCl_3$). The corresponding enantiomer (*R*)-**3b** was obtained in a comparable manner in 77% yield with $[\alpha]_D^{28}$ = +80.4 (*c* = 0.833, $CHCl_3$). The other characterization data are in agreement with the data reported for **3**.

Preparation of Phosphanes 3f by the Deoxygenation of Phosphane Oxides 3b: In a 50 mL Schlenk flask compound *rac*-**3b** (148 mg, 0.2 mmol) was dissolved in 15 mL of dry toluene under argon and then dry Et_3N (0.28 mL, 2 mmol) and $HSiCl_3$ (0.1 mL, 1 mmol) added. The mixture was heated to 90 °C and stirred for 72 h. After cooling the reaction mixture was diluted with diethyl ether and washed with sat. $NaHCO_3$ solution. The organic phase is dried with Na_2SO_4, the solvent evaporated and the residue purified by flash chromatography with silica gel using *n*-hexane/ethyl acetate (1:1, v/v) as the eluent, yielding *rac*-**3f** as a white solid (70 mg, 49%). The NMR spectroscopic data are corresponding to the data reported for *rac*-**3f**. Following this procedure (*S*)-**3b** (135 mg, 0.183 mmol) was reduced to (*S*)-**3f** (87 mg, 66%), $[\alpha]_D^{27}$ = –2.04 (*c* = 0.539, $CHCl_3$) and (*R*)-**3b** (101 mg, 0.137 mmol) was reduced to (*R*)-**3f** (71 mg, 72%), $[\alpha]_D^{28}$ = +6.21 (*c* = 0.986, $CHCl_3$).

Supporting Information (see also the footnote on the first page of this article): Synthetic procedure for the synthesis of starting materials (**2g**, **2h**, **4** and **6**) and the product **5**, details for the reaction of **4** and **6** with **1** as well as ^1H and ^{13}C NMR spectra of the biaryl compounds **3**, **8**, **9**, **10** and crystallographic data for diastereomer **10**.

Acknowledgments

We thank Fabian Fischer and the Analytical Department for excellent technical assistance and Prof. Uwe Rosenthal for helpful discussions und support.

[1] Examples: a) C. J. Walsh, B. K. Mandal, *J. Org. Chem.* **1999**, *64*, 6102–6105; b) P. J. Steel, N. C. Webb, *Eur. J. Inorg. Chem.* **2002**, 2257–2260; c) L. Cracium, D. M. Ho, M. Jones Jr., R. A. Pascal Jr., *Tetrahedron Lett.* **2004**, *45*, 4985–4987; d) R. G. Potter, T. S. Hughes, *Org. Lett.* **2007**, *9*, 1187–1190.

[2] Recent reviews on the synthesis of dendrimers by cycloaddition reactions: a) B. Voit, *New J. Chem.* **2007**, *31*, 1139–1151; b) G. Franc, A. K. Kakkar, *Chem. Eur. J.* **2009**, *15*, 5630–5639.

[3] a) R. Rathore, C. L. Burns, S. A. Abdelwahed, *Org. Lett.* **2004**, *6*, 1689–1692; b) H. Komber, K. Stumpe, B. Voit, *Tetrahedron Lett.* **2007**, *48*, 2655–2659.

[4] Examples: a) V. S. Iyer, M. Wehmeier, J. D. Brand, M. A. Keegstra, K. Müllen, *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 1604–1607; b) M. Müller, V. S. Iyer, C. Kübel, V. Enkelmann, K. Müllen, *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 1607–1610; c) C. J. Walsh, B. K. Mandal, *J. Org. Chem.* **1999**, *64*, 6102–6105; d) F. Dötz, J. D. Brand, S. Ito, L. Gherghel, K. Müllen, *J. Am. Chem. Soc.* **2000**, *122*, 7707–7717; e) S. M. Draper, D. J. Gregg, R. Madathil, *J. Am. Chem. Soc.* **2002**, *124*, 3486–3487; f) A. H. M. Elwahy, *Tetrahedron Lett.* **2002**, *43*, 711–714; g) S. Ito, A. Nomura, N. Morita, C. Kabuto, H. Kobayashi, S. Maejima, K. Fujimoro, M. Yasunami, *J. Org. Chem.* **2002**, *67*, 7295–7302; h) J. Wu, A. Fechtenkötter, J. Gauss, M. D. Watson, M. Kastler, C. Fechtenkötter, M. Wagner, K. Müllen, *J. Am. Chem. Soc.* **2004**, *126*, 11311–11321; i) K. E. Maly, E. Gagnon, T. Maris, J. D. Wuest, *J. Am. Chem. Soc.* **2007**, *129*, 4306–4322.

[5] S. Ito, M. Wehmeier, J. D. Brand, C. Kübel, R. Epsch, J. P. Rabe, K. Müllen, *Chem. Eur. J.* **2000**, *6*, 4327–4342.

[6] Recent examples: a) C. M. A. Ollagnier, S. D. Perera, C. M. Fitchett, S. M. Draper, *Dalton Trans.* **2008**, 283–290; b) P. Du, J. Schneider, W. W. Brennessel, R. Eisenberg, *Inorg. Chem.* **2008**, *47*, 69–77; c) M. C. Haberecht, J. M. Schnorr, E. V. Andreitchenko, C. G. Clark Jr., M. Wagner, K. Müllen, *Angew. Chem. Int. Ed.* **2008**, *47*, 1662–1667.

[7] C. F. H. Allen, *Chem. Rev.* **1962**, *62*, 653–664.

[8] a) D. Gust, *J. Am. Chem. Soc.* **1977**, *99*, 6980–6982; b) E. L. Eliel, S. H. Wilen, L. N. Mander, *Stereochemistry of Organic Compounds*, Wiley, New York, **1994**.

[9] T. Iwasawa, T. Komano, A. Tajima, M. Tokunaga, Y. Obora, T. Fujihara, Y. Tsuji, *Organometallics* **2006**, *25*, 4665–4669.

[10] Examples: a) B. O. Ashburn, R. G. Carter, *Angew. Chem. Int. Ed.* **2006**, *45*, 6737–6741; b) S. Doherty, C. H. Smyth, R. W. Harrington, W. Clegg, *Organometallics* **2009**, *28*, 5273–5276, and references cited therein.

[11] a) A. Gutnov, B. Heller, C. Fischer, H.-J. Drexler, A. Spannenberg, C. Sundermann, B. Sundermann, *Angew. Chem. Int. Ed.* **2004**, *43*, 3795–3797; b) B. Heller, A. Gutnov, C. Fischer, H.-J. Drexler, A. Spannenberg, D. Redkin, C. Sundermann, B. Sundermann, *Chem. Eur. J.* **2007**, *13*, 1117–1128; c) B. Heller, M. Hapke, *Chem. Soc. Rev.* **2007**, *36*, 1085–1094.

[12] CCDC-733394 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

[13] Control experiments with $Ph_3P{=}O$ and the AlH_3/THF reagent showed, that the phosphane oxide was quantitatively reduced to PPh_3 with only insignificant amounts of side products, as detected by ^{31}P NMR spectroscopy. We also investigated the use of commercially available $AlH_3{\cdot}NEtMe_2$ in the reduction, which was unsuccessful [a solution of $AlH_3{\cdot}NEtMe_2$ in toluene (0.5 M), is available from Sigma–Aldrich or ABCR GmbH]. Examples for using $AlH_3{\cdot}NEtMe_2$ in reductions: a) M. S. Morales-Ríos, O. R. Suárez-Castillo, J. J. Trujillo-Serrato, P. Joseph-Nathan, *J. Org. Chem.* **2001**, *66*, 1186–1192; b) T. Kawasaki, M. Shinada, M. Ohzono, A. Ogawa, R. Terashima, M. Sakamoto, *J. Org. Chem.* **2008**, *73*, 5959–5964. The use of these aluminium-based reagents therefore seemed to be problematic in some cases with highly substituted biaryl phosphane oxides.

[14] a) Y. Uozumi, A. Tanahashi, S.-Y. Lee, T. Hayashi, *J. Org. Chem.* **1993**, *58*, 1945–1948; b) Y. Uozumi, N. Suzuki, A. Ogiwara, T. Hayashi, *Tetrahedron* **1994**, *50*, 4293–4302; c) J.-M. Valk, T. D. W. Claridge, J. M. Brown, D. Hibbs, M. B. Hursthouse, *Tetrahedron: Asymmetry* **1995**, *6*, 2597–2610; d) Y. Uozumi, M. Kawatsura, T. Hayashi, *Org. Synth.* **2002**, *78*, 1–13; e) A. Börner (Ed.), *Phosphorus Ligands in Asymmetric Catalysis*, Wiley-VCH, Weinheim, **2008**.

[15] A. Kondoh, H. Yorimitsu, K. Oshima, *J. Am. Chem. Soc.* **2007**, *129*, 6996–6997.

Received: September 22, 2009
Published Online: December 2, 2009

