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Synthesis of BINOL derived phosphorodithioic acids as new chiral Brønsted acids and an improved synthesis of 3,3′-disubstituted H_8-BINOL derivatives

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ABSTRACT

Original phosphorodithioic acid diesters were prepared according to an improved synthesis of 3,3′-disubstituted H_8-BINOL derivatives. In preliminary experiments, these new Brønsted acids were tested as organocatalysts in three reactions. They promoted the Nazarov cyclisation with mixed selectivities, the Mannich reaction with good enantioselectivity and they catalyzed efficiently the alkylation of *N*-acyliminium with enol silyl ether.

1. Introduction

The recent emergence of organocatalysis has received a lot of attention because it opens new perspectives for the mild catalysis of important reactions with lower environmental impact. Noteworthy is the design and development of new chiral Brønsted acids. Since the seminal work of Terada and Akiyama in 2004,[1] many applications of these acids have been reported.[2] In our recent interest to discover new organic Brønsted acids for the catalysis of the Nazarov reaction,[3] we were interested in the development of new derivatives of chiral H_8-BINOL phosphoric acid diester as enantioselective organocatalysts.

Preliminary results have shown that BINOL phosphoric acid diesters **1** display low activity as organocatalysts for the Nazarov cyclisation,[4] most likely due to an inadequate acidity. Recognizing that sulfur atom would better accommodate a negative charge owing to its *d* orbitals leading to a more stabilized phosphorodithioate anion than its oxygen analog,[5] we reasoned that, phosphorodithioic acids **2** would be more acidic candidates to be tested (Fig. 1). In addition, this catalyst class may be considered as a structurally simpler and synthetically cheaper alternative to Yamamoto's *N*-triflylphosphoramide catalysts.[2d]

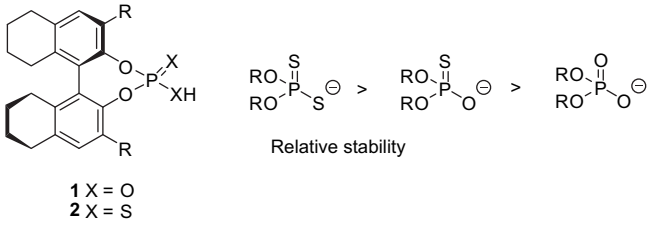

Figure 1. Order of stability of the conjugated bases.

2. Results and discussion

In order to prepare the catalyst candidates, we re-evaluated the general introduction of substituents in the 3,3′ position of H_8-BINOL backbones. The usual synthetic approaches involve regioselective *ortho* metalation of suitably protected H_8-BINOL followed by Suzuki–Miyaura coupling to set up bulky aromatic stereodifferentiating groups.[6] This strategy requires a lengthy protecting–deprotecting sequence and the use of expensive ligand/palladium

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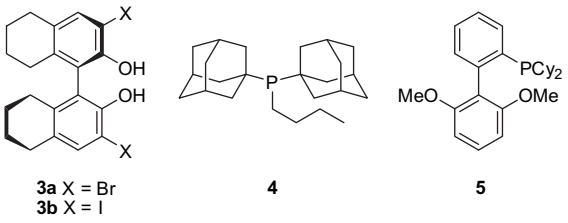
catalytic systems for the cross–coupling reaction. Therefore, a more efficient approach to these structures is highly desired, notably when bulk quantities are required.

While it is well know that Suzuki–Miyaura coupling accommodates protection-free phenols,[7] it is only recently that a successful application involving dibromo H_8-BINOL **3a** has been reported.[8] One key feature of the methodology is the use of the bulky and electron-rich *n*-butyl-*di*-1-adamantylphosphine **4** to generate biaryl products with high yields (Fig. 2). However, the glove-box required for the manipulation of such air-sensitive phosphine and therefore rigorously oxygen-free reaction conditions associated with the expensive cost of the latter render this method less attractive when larger reaction scale is required.

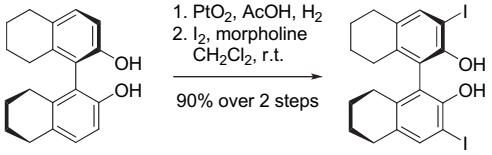


3a X = Br
3b X = I

4 **5**

Figure 2. Substrates and ligands used in Suzuki–Miyaura reactions.

Therefore we envisioned ligandless conditions for the Suzuki–Miyaura cross coupling. We directed our efforts toward conditions involving an inexpensive and reusable catalyst, such as heterogeneous palladium on charcoal.[9] Several attempts to use dibromo derivative **3a** as substrate for the coupling reaction were unexpectedly not successful, even under forced conditions (Pd/C 5 mol %, K_2CO_3, dioxane/water, 120 °C, 10 h) only very low conversion was observed. In order to facilitate the oxidative insertion of the palladium in the carbon–halogen bond, we sought to use diiodo analog **3b**, which is readily prepared in two steps from (*R*)-BINOL **6** and isolated in 92% yield (Scheme 1).



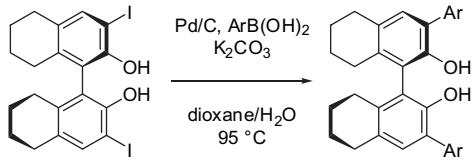
6 **3b**

Scheme 1. Synthesis of the 3,3′-diiodo H_8-BINOL **3b**.

Initial attempts at using room temperature aqueous conditions[10] failed to afford the desired product **7**, even when dioxane was used as co-solvent (Table 1, entries 1–2). However, upon warming the reaction at 95 °C, the bis-arylated products **7** were isolated in 72–97% yield (Table 1, entries 3–12). By comparison with the previous coupling of simple iodophenols at room temperature in water,[10] this result is likely the consequence of an increased solubility of the reactants.

Optimized conditions afforded high yields under aerobic conditions regardless of whether electron rich or electron poor aryl boronic acids were used (Table 1, comparison of entries 6 and 11 with entries 5 and 12). Even very low loading of catalyst (1 mol %) deliver excellent yield (Table 1, entry 4). Sterically hindered 2-*iso*-propylbenzene boronic acid gave **2j** with good yield (72%). Surprisingly the coupling reaction with styrene boronic acid produced **7k** in a low 32% yield (Table 1, entries 14), even though complete conversion was observed by TLC monitoring. No side-product arising from an unwanted Heck reaction was identified. The more congested mesityl boronic acid failed to give any conversion, even after prolonged reaction time or increased warming.

Table 1
Ligandless Suzuki coupling using 3,3′-diiodo-H_8-BINOL **3b**[a]



3b **7a-m**

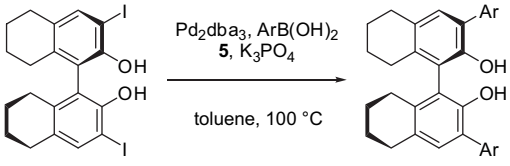
Entry	Ar	Product	Yield[b] (%)
1	Ph	**7a**	0[c,d]
2	Ph	**7a**	0[d]
3	Ph	**7a**	87
4	Ph	**7a**	92[e]
5	4-MeO-C_6H_4	**7b**	88
6	3,5-CF_3-C_6H_3	**7c**	70
7	1-naphtyl	**7d**	98
8	4-Cl-C_6H_4	**7e**	93
9	9-phenanthryl	**7f**	94
10	4-*t*Bu-C_6H_4	**7g**	97
11	4-F-C_6H_4	**7h**	81
12	2,5-MeO-C_6H_3	**7i**	94
13	2-*i*Pr-C_6H_4	**7j**	72
14	4-vinyl-C_6H_4	**7k**	32

[a] Reaction conditions $ArB(OH)_2$ (4 equiv), Pd/C (5 mol %), K_2CO_3 (5 equiv), dioxane, water, 7–8 h, 95 °C.
[b] Isolated yield.
[c] Run only in water.
[d] Run at room temperature.
[e] Run with 1 mol % Pd/C.

In order to solve the problem associated with the use of highly hindered boronic acids we developed a second set of reaction conditions involving air-stable *S*-Phos **5**, which can be easily recovered once the reaction is complete.[11]

Under carefully optimized conditions, higher yields than those previously reported by Beller[8] were achieved with various aryl boronic acids (Table 2) using small amount of catalyst and ligand. Satisfyingly, mesityl boronic acid delivered a 64% yield (Table 2, entries 5). Also noteworthy was the yield of **7k** (Ar=4-vinyl-C_6H_4, Table 2, entry 4), which was substantially improved to 78%. Test experiments showed that the dibromo derivative **3a** was also a good substrate, although higher ligand loading (20 mol %) was necessary to achieve high yields (data not shown).

Table 2
Synthesis of 3,3′-H_8-BINOL derivatives using ligand **5**[a]



3b **7a-m**

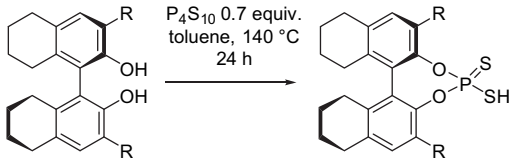
Entry	Ar	Product	Yield[b] (%)
1	Ph	**7a**	97
2	1-naphtyl	**7d**	88
3	9-phenanthryl	**7f**	88
4	4-vinyl-C_6H_4	**7k**	78
5	2,4,6-Me-C_6H_2	**7l**	64

[a] Reaction conditions $ArB(OH)_2$ (4 equiv), $Pd_2(dba)_3$ (2 mol %), **5** (4 mol %), K_3PO_4 (5 equiv), toluene, 3–18 h, 100 °C.
[b] Isolated yield.

Having revisited the synthesis of H_8-BINOL derivatives, we next prepared a series of phosphorodithioic acid diesters by the treatment of the biphenols with P_4S_{10} at 140 °C in toluene.[12] High yields

were obtained with less hindered derivatives (Table 3, entries 1–4), whereas increased steric hindrance of the substrate gave lower amounts of the corresponding dithioic acids.

Table 3
Preparation of phosphorodithioic acid diesters



1a, 7a-f **2a-f** 46-82 %

Entry	R	Product	Yield[a] (%)
1	H	**2a**	79
2	Br	**2b**	70
3	Ph	**2c**	82
4	3,5-CF_3-C_6H_3	**2d**	71
5	9-phenanthryl	**2e**	54
6	1-Naphthyl	**2f**	46

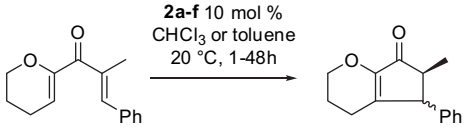
[a] Isolated yield.

Due to the high temperature used for their preparation (140 °C), one may question the configurational stability of the BINOL phosphorodithioic acid diesters. The absence of racemization during the process was ascertained by reducing **2c** with lithium aluminum hydride to yield **7a** in ee higher than 99% (measured by chiral HPLC).

As expected, phosphorodithioic acids diesters displayed an improved activity for the Nazarov cyclization of a model substrate **8** compared to the phosphoric acid counterparts.

To illustrate this point, **2d** afforded **9** with a 83% yield in 1.5 h at room temperature in $CHCl_3$ while reactions using corresponding phosphoric acids (Table 4) typically require 60 °C in toluene (60–70% yield).[2n]

Table 4
Nazarov cyclisations



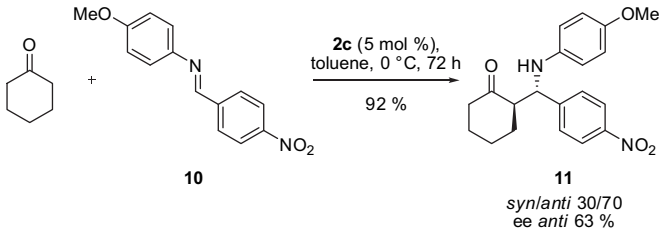
8 **9**

Entry	Catalyst	Solvent	Yield[a] (%)	*syn*/*anti*[b]	ee (%) (*syn*, *anti*)[c]
1	**2a**	$CHCl_3$	74	3:1	4, 4
2	**2b**	$CHCl_3$	85	3:1	5, 10
3	**2c**	$CHCl_3$	93	9:1	2, 10
4	**2c**	Toluene	60	<5:1	4, 20
5	**2d**	$CHCl_3$	83	9:1	10, 18
6	**2e**	$CHCl_3$	87	9:1	2, 5
7	**2f**	$CHCl_3$	70	6:1	9, 1

[a] Isolated yield.
[b] Determined by ^{1}H NMR.
[c] Determined by HPLC: Daicel OJ-H column 4.6 mm×250 mm, 1 mL/min, 90% *n*-heptane 10% propan-2-ol, 20 °C.

While the enantioselectivity was much lower than those reported using BINOL *N*-triflyl phosphoramides,[2n] higher diastereoselectivity was obtained (*syn*/*anti* 9:1 compared to 6:1). In an attempt to achieve interesting selectivity, phosphorodithioic acid diesters were tested for the Mannich reaction[13] between cyclohexanone and an electron poor aldimine **10** (Scheme 2).

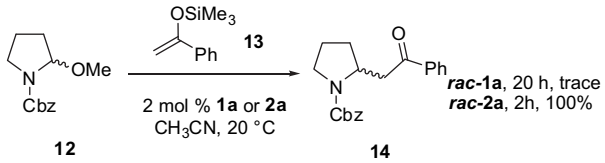
Gratifyingly, amongst the various catalysts tested **2a**–**f**, **2c** afforded the Mannich adduct **11** in 92% yield with a 63% ee for the major *anti* product.



10 **11**
syn/*anti* 30/70
ee *anti* 63 %

Scheme 2. Mannich reaction.

Despite those puzzling results in terms of selectivity for the Nazarov and the Mannich reactions, we examined another reaction in which these new catalysts might offer interesting complementary or additional reactivity to the known phosphoric acid diesters. In particular we tested the alkylation of hemiaminal **12** with silyl enol ether **13** derived from acetophenone. This reaction is known to be easily triggered by a strong Brønsted acid (2 mol %), such as triflimide (Tf_2NH).[14] Several attempts to define suitable conditions to carry out the reaction using BINOL phosphoric acid ***rac*-1a** as catalyst were unsuccessful. As expected, the stronger phosphorodithioic acid ***rac*-2a** gave a quantitative yield of the substituted pyrrolidine **14** after only 2 h (Scheme 3).



12 **14**

Scheme 3. *N*-Acyliminium alkylation reaction.

3. Conclusion

In conclusion we have reported a convenient method to access 3,3′-disubstituted H_8-BINOL derivatives with an inexpensive Pd source and under aerobic conditions. We have also improved the previously reported yields when mesityl boronic acid is used in the cross coupling step. The phosphorodithioic acid diesters synthesized using this method were efficiently tested for three reactions, and thus constitute a new class of organocatalysts. While these catalysts displayed good diastereoselectivity but no useful enantioselectivity for the Nazarov cyclization, interesting reactivity was found for the alkylation of *N*-acyliminium ion precursor with enol silyl ether **13** and for a Mannich reaction involving cyclohexanone.[15] We are currently exploring the scope and limitations of this reaction with various substrates catalyzed by a series of chiral phosphorodithioic acids. The full study will be reported in due course.

4. Experimentals

4.1. General remarks

Commercially available compounds were used without further purification. Solvents (THF, CH_2Cl_2, MeCN, Et_2O, DMF, toluene) were dried and purified from Pure-Solv™ 400 Solvent Purification System. Melting points were determined on an Electrothermal digital apparatus IA9100 series and are uncorrected. ^{1}H NMR, ^{13}C NMR, and ^{19}F, and ^{31}P NMR spectra were recorded on a Bruker Avance DPX 500 or Bruker Avance DPX 400 spectrometers. Chemical shifts are reported in parts per million (δ) relative to TMS or to solvent as the internal standard. Thin layer chromatography was performed on silica gel 60 F-254 plates (0.1 mm, Merck). Detection was

accomplished by irradiation with a UV lamp or staining with $KMnO_4$. Chromatographic separations were achieved on silica gel columns (Kieselgel 60, 40–63 μm, Merck). Analytical high performance liquid chromatographies (HPLC) were carried out with a Waters instrument [detector M996 (200–400 nm) and pump 600]. The conditions are precised for each compound. Mass spectra and high resolution mass spectra (HRMS) were obtained on a Waters-Micromass Q-Tof micro instrument. IR spectra were recorded on a Perkin–Elmer 16 PC FTIR spectrometer. Optical rotations were measured, at room temperature, on a Perkin–Elmer 241 LC polarimeter in a 10 cm cell. $[\alpha]_D$ values are given in units of 10^{-1} deg $cm^2\ g^{-1}$.

4.2. (*R*)-3,3′-Diiodo-octahydrobinaphtol 3b

To a solution of (*R*)-5,5′,6,6′,7,7′,8,8′-octahydro-1,1′-binaphthyl-2,2′-diol[16] (2 g, 6.8 mmol) in CH_2Cl_2 (60 mL) were added successively at room temperature, morpholine (3.6 mL, 41 mmol, 6 equiv) and I_2 (3.45 g, 13.6 mmol, 2 equiv). The mixture was stirred at this temperature for 5 h and turned progressively red. Then CH_2Cl_2 (50 mL) and HCl (1 N, 50 mL) were added. The aqueous layer was extracted with CH_2Cl_2 and the combined organic layers were washed successively with a saturated sodium thiosulfate solution (3×50 mL) and brine, then dried over $MgSO_4$ and concentrated to afford **3b** as a colorless solid (3.36 g, 91%), which can be used without any purification. Mp: 214 °C. $[\alpha]_D$ −24 (*c* 1.0, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$) δ 7.51 (s, 2H), 4.97 (s, 2H), 2.78–2.70 (m, 4H), 2.31–2.22 (m, 2H), 2.15–2.05 (m, 2H), 1.76–1.65 (m, 8H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 149.8, 139.3, 137.8, 132.5, 120.7, 81.1, 28.9, 27.0, 22.8, 22.7; IR (neat) 3446, 2923, 2857, 1458, 1396, 1307, 1151, 1013, 873 cm^{-1}. HRMS (ESI) calcd for $C_{20}H_{19}I_2O_2$ 544.9475, found 544.9473.

4.3. General procedure for the ligandless Suzuki–Miyaura cross coupling

4.3.1. (R)-3,3′-Bis(4-tBu-phenyl)-5,5′,6,6′,7,7′,8,8′-octahydro-1,1′-binaphthyl-2,2′-diol ***7g****.* To a solution of (*R*)-3,3′-diiodo-5,5′,6,6′,7,7′,8,8′-octahydro-1,1′-binaphthyl-2,2′-diol **3b** (50 mg, 0.092 mmol) in dioxane/water (1/1, 2 mL) was added successively at room temperature, potassium carbonate (49 mg, 0.36 mmol, 4 equiv), palladium on charcoal 10% (4.5 mg, 0.0046 mmol, 0.05 equiv) and 4-*tert*-butylphenylboronic acid (66 mg, 0.36 mmol, 4 equiv). The mixture was stirred at 95 °C for 6 h, then EtOAc (10 mL) and HCl (2 N, 10 mL) were added. The aqueous layer was extracted with EtOAc and the organic layers were combined, washed with brine (10 mL), dried over $MgSO_4$ and concentrated. The crude product was purified by flash chromatography (cyclohexane/EtOAc, 95:5) to afford **7g** as a colorless solid (50 mg, 97%). Mp: 147 °C ($CHCl_3$). $[\alpha]_D$: −52.3 (*c* 1.0, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.60–7.55 (m, 4H), 7.50–7.46 (m, 4H), 7.19 (s, 2H), 4.97 (s, 2H), 2.85–2.80 (m, 4H), 2.49–2.39 (m, 2H), 2.33–2.18 (m, 2H), 1.84–1.70 (m, 8H), 1.39 (s, 18H). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 149.9 (C), 148.2 (C), 136.3 (C), 135.0 (C), 131.6 (CH), 130.1 (C), 128.8 (CH), 125.9 (C), 125.4 (CH), 120.2 (C), 34.6 (C), 31.4 (CH_3), 29.3 (CH_2), 27.2 (CH_2), 23.2 (CH_2), 23.1 (CH_2). IR (neat, cm^{-1}): 3515, 2926, 1515, 1457, 1393, 1261, 1136, 1021, 834, 803. HRMS calcd for $(M+H)^+$ $C_{40}H_{47}O_2$: 559.3576 found: 559.3600.

4.4. (*R*)-3,3′-1-Naphtyl-5,5′,6,6′,7,7′,8,8′-octahydro-1,1′-binaphthyl-2,2′-diol 7d

Prepared according to the general procedure from **3b** as a colorless solid (86% yield). Mp: 149 °C ($CHCl_3$). $[\alpha]_D$: −31 (*c* 1.0, $CHCl_3$). ^1H NMR (500 MHz, DMSO, 110 °C) δ (ppm) 7.92 (d, *J*=7.5 Hz, 2H), 7.88 (d, *J*=8 Hz, 2H), 7.86–7.73 (m, 2H), 7.55 (t, *J*=8 Hz, 2H), 7.50–7.45 (m, 4H), 7.44–7.36 (m, 2H), 6.93 (s, 2H), 6.59 (s, 2H), 2.82–2.74 (m, 4H), 2.59–2.42 (m, 2H), 2.42–2.29 (m, 2H), 1.84–1.73 (m, 8H). ^{13}C NMR (100.6 MHz, DMSO, 110 °C) δ 150.4 (C), 138.2 (C), 137.2 (C), 134.4 (2C, C), 133.2 (CH), 131.9 (C), 129.1 (CH), 128.7 (C), 128.4 (CH), 128.0 (CH), 126.3 (CH), 126.2 (3C, CH), 124.3 (C), 29.7 (CH_2), 27.7 (CH_2), 23.8 (CH_2), 23.6 (CH_2). IR (neat, cm^{-1}): 3524, 2923, 2851, 1609, 1448, 1233, 801, 776. HRMS calcd for $(M+H)^+$ $C_{40}H_{35}O_2$: 547.2637 found: 547.2628.

4.5. (*R*)-3,3′-Bis(2,5-dimethoxyphenyl)-5,5′,6,6′,7,7′,8,8′-octahydro-1,1′-binaphthyl-2,2′-diol 7i

Prepared according to the general procedure from **3b** as a colorless solid (94% yield). Mp: 117 °C ($CHCl_3$). $[\alpha]_D$: −0.5 (*c* 1.0, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.10 (s, 2H), 7.02 (d, *J*=28 Hz, 2H), 6.97–6.94 (m, 2H), 6.91–6.88 (m, 2H), 5.97 (s, 2H), 3.84 (s, 6H), 3.80 (s, 6H), 2.88–2.83 (m, 4H), 2.59–2.49 (m, 2H), 2.36–2.27 (m, 2H), 1.86–1.73 (m, 8H). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 154.4 (C), 150.1 (C), 148.7 (C), 136.9 (C), 131.3 (CH), 129.6 (C), 129.0 (C), 124.1 (C), 123.6 (C), 117.4 (CH), 113.8 (CH), 112.9 (CH), 56.9 (CH_3), 55.8 (CH_3), 29.4 (CH_2), 27.2 (CH_2), 23.3 (CH_2), 23.2 (CH_2). IR (neat, cm^{-1}): 3302, 2923, 2853, 1609, 1584, 1497, 1455, 1272, 1217, 1048, 1012, 868, 733. HRMS calcd for $(M+H)^+$ $C_{36}H_{39}O_6$: 567.2747 found: 567.2725.

4.6. (*R*)-3,3′-Bis(2-*iso*propylphenyl)-5,5′,6,6′,7,7′,8,8′-octahydro-1,1′-binaphthyl-2,2′-diol 7j

Prepared according to the general procedure from **3b** as colorless foam (72% yield). Mp: 90 °C ($CHCl_3$). $[\alpha]_D$: +0.5 (*c* 1.0, $CHCl_3$). ^1H NMR (400 MHz, DMF, 110 °C) δ (ppm) 7.45–7.43 (m, 2H), 7.39–7.36 (m, 2H), 7.26–7.20 (m, 4H), 6.89 (s, 2H, $H_{4,4'}$), 3.15–3.09 (m, 2H, 2×CH), 2.83–2.80 (m, 4H), 2.57–2.50 (m, 2H), 2.35–2.29 (m, 2H), 1.83–1.75 (m, 8H), 1.28–1.17 (m, 12H, 4×CH_3). ^{13}C NMR (100.6 MHz, DMF, 110 °C) δ 149.6 (C), 148.1 (C), 138.1 (C), 136.4 (C), 130.9 (CH), 130.7 (CH), 128.7 (C), 127.7 (CH), 127.1 (C), 125.4 (CH), 125.3 (CH), 123.0 (C), 30.2 (CH_2), 29.2 (CH), 27.1 (CH_3), 26.9 (CH_2), 23.4 (CH_2), 23.2 (CH_3). IR (neat, cm^{-1}): 3528, 2926, 2863, 1610, 1437, 1232, 1135, 757. HRMS calcd for $(M+H)^+$ $C_{36}H_{43}O_2$: 531.3263 found: 531.3244.

4.7. General procedure for the Suzuki–Miyaura coupling with phosphine 5

A round bottom flask was charged with (*R*)-3,3′-diiodo-5,5′,6,6′,7,7′,8,8′-octahydro-1,1′-binaphthyl-2,2′-diol **3b** (580 mg, 1.06 mmol), $Pd_2(dba)_3$ (19 mg, 0.021 mmol, 0.02 equiv), K_3PO_4 (1.12 g, 5.3 mmol, 5 equiv), 2,4,6-trimethylphenylboronic acid (697 mg, 4.25 mmol, 4 equiv), the phosphine **5** (18 mg, 0.043 mmol, 0.04 equiv) in 10 mL of toluene under an argon atmosphere. The mixture was degassed with argon during 2 min, and then stirred at 100 °C for 18 h. Then EtOAc (30 mL) and HCl (2 N, 30 mL) were added. The aqueous layer was extracted with EtOAc and the organic layers were combined, washed with brine (30 mL), dried over $MgSO_4$ and concentrated. The crude product was purified by flash chromatography (cyclohexane/EtOAc, 98:2) to afford **7l** as a colorless solid (360 mg, 64%).

4.8. General procedure for the synthesis of phosphorodithioic acids

4.8.1. (R)-5,6,7,8,5′,6′,7′,8′-Octahydro-[1,1′]binaphthalenyl-2,2′-phosphorodithioic acid ***2a****.* P_4S_{10} (60.5 mg, 0.27 mmol, 0.6 equiv) was added to a solution of H_8-BINOL **7a** (130 mg, 0.44 mmol, 1 equiv) in dry toluene (5 mL). The mixture was stirred under argon for 20 h at 140 °C. The reaction mixture was evaporated and the residue purified by flash chromatography (CH_2Cl_2/MeOH from 100:0 to 90:10)

to afford **2a** (140 mg, 79%) as a colorless solid. Mp: 100 °C (decomposition). $[\alpha]_D$: −209.5 (*c* 1.0, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.20–7.13 (d, 2H, *J*=8.3 Hz), 7.11–7.08 (dd, 2H, *J*=8.2 Hz and 2 Hz), 2.95–2.75 (m, 4H), 2.72–2.65 (dq, 2H, *J*=16.3 Hz and 4.2 Hz), 2.29 (dt, 2H, *J*=16.3 Hz and 5.6 Hz), 1.86–1.75 (m, 6H), 1.62–1.52 (m, 2H). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 146.6 (C), 139.2 (C), 136.7 (C), 130.3 (CH), 127.3 (C), 119.3 (CH), 29.6 (CH_2), 28.3 (CH_2), 22.8 (CH_2), 22.7 (CH_2). ^{31}P NMR (162.0 MHz, $CDCl_3$) δ (ppm) 95.3. IR (neat, cm^{-1}): 2927, 1464, 1212, 1051, 940, 854, 715, 681. HRMS calcd for $(M-H)^-$ $C_{20}H_{20}O_2PS_2$: 387.0642 found: 387.0656.

4.9. (*R*)-3,3′-Dibromo-5,6,7,8,5′,6′,7′,8′-octahydro-[1,1′]-binaphthalenyl-2,2′-phosphorodithioic acid 2b

Prepared according to the general procedure from **3a** as colorless foam (70% yield). Mp: 130 °C (decomposition). $[\alpha]_D$: −209.1 (*c* 1.0, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.44 (s, 2H), 2.88–2.78 (m, 4H), 2.62–2.50 (m, 2H), 2.21–2.13 (m, 2H), 1.84–1.72 (m, 6H), 1.62–1.52 (m, 2H). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 143.6 (C), 138.3 (C), 138.0 (C), 134.2 (CH), 128.7 (C), 112.8 (C), 29.4 (CH_2), 28.1 (CH_2), 22.7 (CH_2), 22.5 (CH_2). ^{31}P NMR (162.0 MHz, $CDCl_3$) δ (ppm) 92.7. IR (neat, cm^{-1}): 2931, 1417, 1220, 1012, 949, 869, 699. HRMS calcd for $(M-H)^-$ $C_{20}H_{18}Br_2O_2PS_2$: 542.8853 found: 542.8826.

4.10. (*R*)-3,3′-Diphenyl-5,6,7,8,5′,6′,7′,8′-octahydro-[1,1′]binaphthalenyl-2,2′-phosphorodithioic acid 2c

Prepared according to the general procedure from **7a** as colorless foam (82% yield). Mp: 170 °C (decomposition). $[\alpha]_D$: −226.5 (*c* 1.0, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.61–7.56 (m, 4H), 7.44–7.38 (m, 4H), 7.37–7.32 (m, 2H), 2.98–2.91 (m, 4H), 2.78–2.68 (m, 2H), 2.45–2.38 (m, 2H), 1.91–1.80 (m, 6H), 1.74–1.69(m, 2H). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 143.3 (C), 138.1 (C), 137.7 (C), 136.5 (C), 132.6 (C), 131.5 (CH), 130.2 (CH), 129.9 (C), 128.6 (CH), 127.7 (CH), 29.7 (CH_2), 28.2 (CH_2), 23.0 (CH_2), 22.9 (CH_2). ^{31}P NMR (162.0 MHz, $CDCl_3$) δ (ppm) 91.3. IR (neat, cm^{-1}): 2925, 1601, 1444, 1409, 1207, 944, 862, 767, 696. HRMS calcd for $(M-H)^-$ $C_{32}H_{28}O_2PS_2$: 539.1268 found: 539.1259.

4.11. (*R*)-3,3′-Bis-(3,5-bis-trifluoromethyl-phenyl)-5,6,7,8,5′,6′,7′,8′-octahydro-[1,1′]binaphthalenyl-2,2′-phosphorodithioic acid 2d

Prepared according to the general procedure from **7c** as a colorless foam (71% yield). Mp: 140 °C (decomposition). $[\alpha]_D$: −166.8 (*c* 1.0, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.03 (s, 4H), 7.88 (s, 2H), 7.29 (s, 2H), 2.98–2.92 (m, 4H), 2.80–2.68 (m, 2H), 2.51–2.40 (m, 2H), 1.97–1.84 (m, 6H), 1.80–1.68 (m, 2H). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 143.2 (C), 140.2 (C), 139.6 (C), 137.5 (C), 132.1 (C), 131.7 (C), 131.3 (CH), 130.4 (CH), 129.8 (C), 128.5 (C), 125.1 (C), 122.4 (C), 121.5 (CH), 29.6 (CH_2), 28.3 (CH_2), 22.8 (CH_2), 22.6 (CH_2). ^{31}P NMR (162.0 MHz, $CDCl_3$) δ (ppm) 91.1. ^{19}F NMR (235.3 MHz, $CDCl_3$) δ (ppm) −62.7. IR (neat, cm^{-1}): 2937, 1620, 1460, 1388, 1275, 1179, 1108, 957, 892, 705, 681. HRMS calcd for $(M-H)^-$ $C_{32}H_{24}F_2O_2PS_2$: 811.0764 found: 811.0750.

4.12. (*R*)-3,3′-Bis-(phenanthryl)-5,6,7,8,5′,6′,7′,8′-octahydro-[1,1′]binaphthalenyl-2,2′-phosphorodithioic acid 2e

Prepared according to the general procedure from **7f** as a colorless foam (54% yield). Mp: 232 °C (decomposition). $[\alpha]_D$: −73.5 (*c* 0.5, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.78–8.68 (m, 4H), 8.18–8.10 (m, 1H), 7.92–7.82 (m, 4H), 7.70–7.48 (m, 9H), 7.38–7.28 (m, 2H), 3.06–2.86 (m, 6H), 2.70–2.58 (m, 2H), 2.05–1.82 (m, 8H). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 144.1–143.9 (m, C), 138.2 (C), 137.8 (m, C), 136.4 (C), 135.3 (m, C), 134.1–134.0 (m, C), 133.3–133.2 (m, CH), 132.7–132.2 (m, CH), 131.2–131.4 (m, C), 131.0–130.8 (m, C), 130.4–130.2 (m, CH), 130.1–129.7 (m, C), 128.9–128.7 (m, 2*CH), 127.9–127.5 (m, C), 126.0–126.7 (m, 3*CH), 122.7–122.8 (m, CH), 122.5–122.6 (m, CH), 29.5–29.4 (m, CH_2), 28.1 (m, CH_2), 22.8–22.6 (m, 2*CH_2). ^{31}P NMR (162.0 MHz, $CDCl_3$) δ (ppm) 91.8–91.2 (m, P). IR (neat, cm^{-1}): 2924, 1448, 1418, 1214, 936, 862, 747, 725. HRMS calcd for $(M-H)^-$ $C_{48}H_{37}O_2PS_2$: 739.1894 found: 739.1901.

4.13. (*R*)-3,3′-Bis-(1-naphtyl)-5,6,7,8,5′,6′,7′,8′-octahydro-[1,1′]binaphthalenyl-2,2′-phosphorodithioic acid 2f

Prepared according to the general procedure from **7d** as a colorless foam (46% yield). Mp: 225 °C (decomposition). $[\alpha]_D$: −174.5 (*c* 1.0, $CHCl_3$). ^1H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.95–7.70 (m, 4H), 7.55–7.35 (m, 10H), 7.18 (s, 1H), 7.12 (s, 1H), 2.94–2.7 (m, 6H), 2.59–2.38 (m, 2H), 1.95–1.65 (m, 8H). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ (ppm) 144.2–144.1 (m, C), 138.5–138.2 (m, C), 136.8–136.7 (m, C), 135.9–135.7 (m, C), 134.5–134.4 (m, C), 133.7–133.5 (m, CH), 133.2–133.1 (m, CH), 132.4–132.1 (m, C), 131.5–131.2 (m, C), 129.9–129.7 (m, CH), 129.3–129.2 (m, C), 128.9–128.5 (m, 2*CH), 127.9–127.8 (m, C), 127.2–127.0 (m, CH), 126.5–126.2 (m, CH), 126.1–125.9 (m, CH), 125.6–125.4 (m, CH), 29.8 (m, CH_2), 28.5 (m, CH_2), 23.1 (m, CH_2), 23.0 (m, CH_2). ^{31}P NMR (162.0 MHz, $CDCl_3$) δ (ppm) 90.9–91.4 (m, P). IR (neat, cm^{-1}): 2929, 1507, 1395, 1214, 1088, 942, 886, 800, 767, 705. HRMS calcd for $(M-H)^-$. $C_{40}H_{32}O_2PS_2$: 639.1581 found: 639.1600.

4.14. 2-((4-Methoxyphenylamino) (4-nitrophenyl)methyl)-cyclohexanone 11

To a cold solution (0 °C) of **13** (51 mg, 0.2 mmol, 1 equiv) and catalyst **2c** (5.4 mg, 0.01 mmol, 5 mol%) in 2.5 mL of toluene was added cyclohexanone (196 mg, 2 mmol, 10 equiv). The reaction was stirred at 0 °C during 3 days. The crude mixture (*anti*/*syn* 70/30 by NMR) was concentrated and purified by flash chromatography (cyclohexane/EtOAc, 80:20) to afford **14** as a colorless solid (65 mg, 92%). Enantiomeric excess was determined using Daicel AD-H chiral HPLC (1 mL min^{-1}, *n*-heptane 75%, 12.5% MeOH, 12.5% EtOH, 20 °C) to be 63% for the major *anti* diastereoisomer. Analytical data was found to be identical as reported previously.[14]

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Supplementary data

Supplementary data associated with this article (NMR spectra of new compounds) can be found in the online version, at doi:10.1016/j.tet.2009.10.068.

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