Synthesis of Phosphane Oxide Bridged Bis- and Triscatechol Derivatives

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Abstract: Linear biscatechols and triangular triscatechols possessing spacers containing phosphane oxide were synthesized. For this, the central phosphorus was introduced by the reaction of active organometallic intermediates with either dichlorophenylphosphane or phosphorus trichloride/phosphoryl chloride. In the final steps, the methyl ethers at the veratrol units were cleaved by boron tribromide to afford the free phosphane oxide catechol derivatives, which in metal-directed self-assembly processes would lead to helical or tetrahedral supramolecular aggregates.

Key words: phosphane oxide, amides, catechol, ligands, Suzuki coupling

The metal-directed self-assembly process of linear or triangular catechol ligands can lead to helicate-type dinuclear complexes[1] or to supramolecular tetrahedra.[2] The internal cavity of the resulting aggregates allows them to act as 'molecular containers' with certain reactive functionalities.[3] As a fascinating kind of 'reactors', molecular containers can stabilize reactive intermediates,[4] promote chemical reactions,[5] and enhance selectivities of intra- or intermolecular reactions[6] through accommodation of guest molecules. Therefore, the design of functionalized ligands which can assemble to functional molecular containers is currently one of the most challenging topics in supramolecular chemistry.

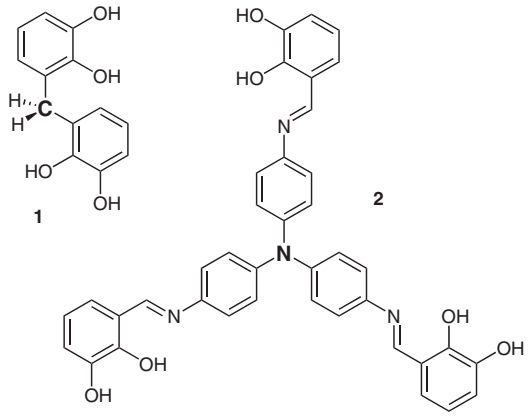

Figure 1 Structures of bis- and triscatechol ligands **1** and **2** with central carbon or nitrogen atoms

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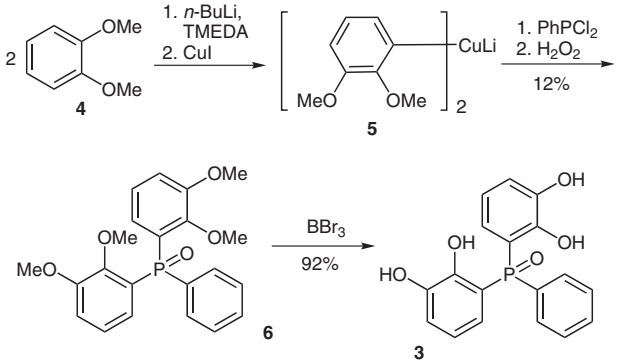
In our previous work, a series of bis- and triscatechol ligands **1** and **2** (Figure 1) with central carbon or nitrogen atoms have been synthesized. Systematic investigations of the binding behavior of these ligands with various metal ions as well as the structural analysis of the resulting complexes indicated that the structures of the supramolecular aggregates mainly depend on the geometry of the ligands.[7] To further understand the influence of slight alterations of the central atoms on the structure of the aggregates and to elucidate the general assembly mechanisms, we now introduce phosphane oxide as the central unit instead of carbon or nitrogen, and prepared a series of linear and triangular bis- and triscatechol ligands. This work is expected to open up a new approach for the design of helicate-type complexes and molecular containers with functionalities introduced in the 'wall' of the containers.[8]

Linear Dicatechols

In earlier studies, we showed that linear biscatechol **1** (Figure 1), with a methylene unit providing the central carbon atom, can assemble with titanium(IV) ions in the presence of sodium or lithium cations to form triple-stranded meso-helicates.[7a]

In the present work, we substituted the methylene unit of **1** by a phosphoryl group, to obtain the linear biscatechol **3** (Scheme 1). Ligand **3** was prepared from veratrole (**4**), which was *ortho*-metalated with butyllithium (Scheme 1). Transmetalation to form the copper(I) species **5** was followed by coupling with dichlorophenylphosphane; subsequent oxidation with 30% hydrogen peroxide afforded phosphane oxide **6**. Deprotection with boron tribromide led to the free ligand **3**.

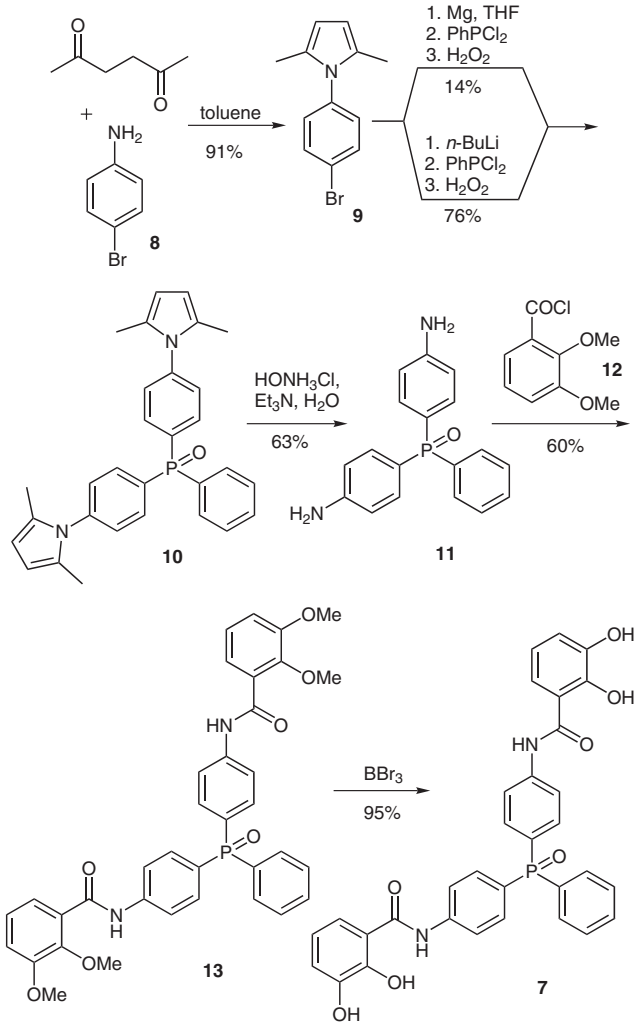


Scheme 1 Preparation of linear biscatechol **3** with a phosphoryl group as the central unit

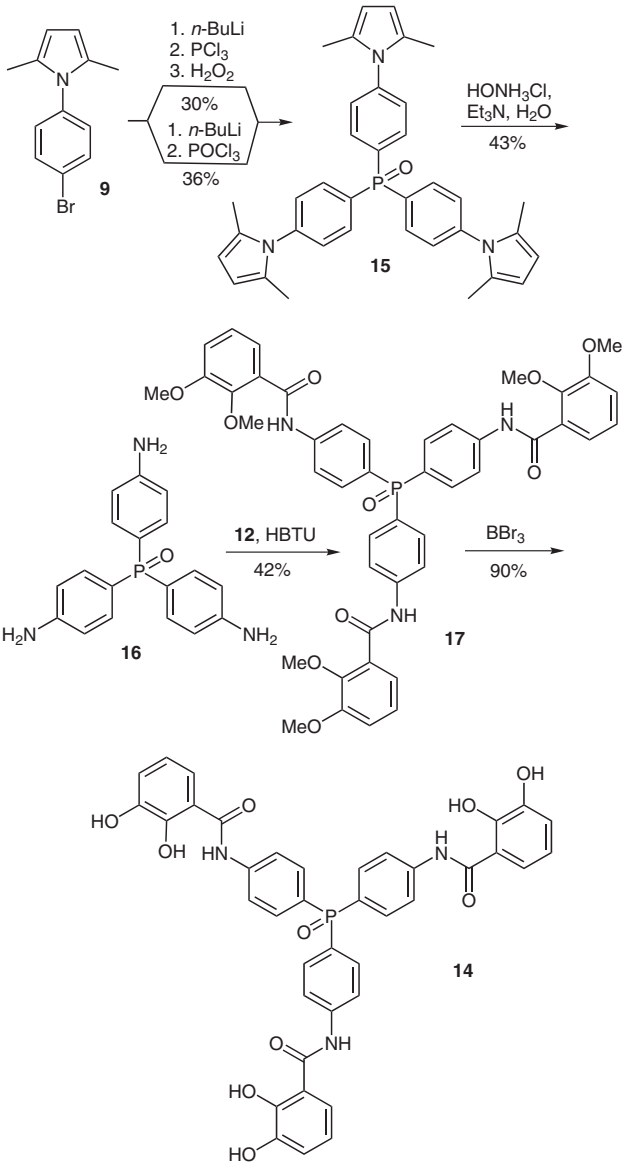
To separate the two catechol units by a longer spacer, we prepared compound **7** from 4-bromoaniline (**8**) by a six-step reaction sequence (Scheme 2). The amine group of 4-bromoaniline (**8**) was first protected by the addition of hexane-2,5-dione.[9] The organometallic species formed by the reaction of protected aniline **9** with magnesium or butyllithium subsequently reacted with dichlorophenylphosphane, and oxidation by 30% hydrogen peroxide followed. For this reaction step, we found that butyllithium in dry diethyl ether gives more of the active organometallic intermediate of **9** than magnesium in tetrahydrofuran can, to give phosphane oxide **10** in 76% yield instead of 14%. After cleavage of the protected pyrrole groups of **10** with hydroxylamine hydrochloride, the diamino derivative **11** was acylated by addition of 2,3-dimethoxybenzoyl chloride (**12**). Finally, removal of the methoxy groups of derivative **13** by boron tribromide gave ligand **7** in 95% yield (Scheme 2).

Triangular Triscatechols

Triangular catechol amides similar to imine **2** were prepared by us[10] and by Raymond.[11] In the study presented here, analogue **14**, in which the central triangular unit is substituted by a phosphoryl group, was prepared (Scheme 3). Triscatechol **14** was prepared by procedures similar to those employed in the synthesis of ligand **7**. In the first step, either phosphorus trichloride (followed by oxidation with hydrogen peroxide) or phosphoryl chloride could be coupled with three equivalents of the organolithium reagent obtained from protected aniline **9**. The reaction afforded phosphane oxide **15**, which was deprotected with hydroxylamine hydrochloride to yield triaminophenyl phosphane oxide **16**, for which we had developed a reliable synthetic procedure.[12] This building block could be also of interest as a ligand for catalysis or for materials science. Three equivalents of 2,3-dimethoxybenzoyl chloride (**12**) were coupled with phosphane oxide **16** in the presence of *O*-benzotriazol-1-yl-*N*,*N*,*N*′,*N*′-tetramethyluronium hexafluorophosphate (HBTU) to yield **17**, whose deprotection gave ligand **14**.

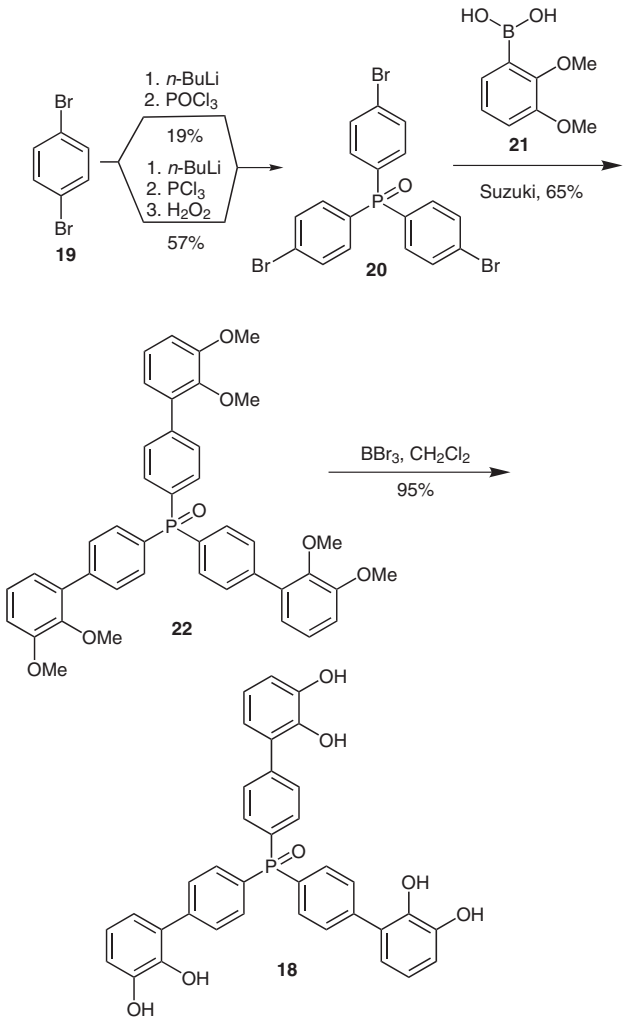


Scheme 2 Preparation of linear biscatechol **7** with a phosphoryl group in the center and with long spacers between the catechol units



Scheme 3 Synthesis of triscatechol amide **14** via phosphane oxide **16** as a key intermediate

Scheme 4 illustrates the synthetic route to an alternative triscatechol **18**, in which a purely carbon skeleton connects the ligand units to the phosphoryl center. 1,4-Dibromobenzene **19** was metalated with butyllithium and then reacted with phosphoryl chloride or phosphorus trichloride/hydrogen peroxide. The thus obtained tris(4-bromophenyl)phosphane oxide (**20**) was coupled with (2,3-dimethoxyphenyl)boronic acid (**21**) in a Suzuki cross-coupling reaction[13] to afford hexamethoxy derivative **22**. Removal of the methoxy protecting groups of precursor **22** by boron tribromide smoothly gave triscatechol ligand **18**.



Scheme 4 Preparation of triscatechol **18**

We have presented reliable reaction sequences leading to a new type of bis- and triscatechol ligands with a phosphoryl-functionalized center. Our synthetic approach allows us to generate ligands with different symmetries and with different connecting units in the spacers. The compounds should be appropriate building blocks for the metal-directed self-assembly of supramolecular aggregates. The coordination chemistry of the new ligands is currently being studied in our laboratories.

^{1}H, ^{31}P, and ^{13}C NMR spectra were recorded on a Varian Inova 400 spectrometer. FT-IR spectra were recorded on a Bruker IFS spectrometer (KBr or neat). Mass spectra (EI, 70 eV; FAB) were measured on a Finnigan MAT 95 or 212 mass spectrometer. Elemental analyses were obtained with a Heraeus CHNO-Rapid analyzer. Melting points were determined on a Büchi B-540 apparatus and are uncorrected. For organometallic reactions, the reaction flasks were flame-dried and the reactions were performed under an atmosphere of dry N_2.

Bis(2,3-dimethoxyphenyl)(phenyl)phosphane Oxide (6)

A 1.6 M soln of *n*-BuLi in hexane (5.6 mL, 8.96 mmol) was added to 1,2-dimethoxybenzene (**4**; 1.2 g, 8.7 mmol) and TMEDA (1.2 mL, 7.95 mmol) in dry Et_2O (20 mL). After being stirred for 3 h at r.t., the mixture was added dropwise to a rapidly stirring slurry of CuI (835.0 mg, 4.4 mmol) in anhyd THF (25 mL) at –78 °C. The resulting mixture was stirred at –78 °C for 15 min. $PhPCl_2$ (780.0 mg, 4.4 mmol) and a few drops of HMPA were added. The mixture was allowed to warm to r.t. and was washed with sat. aq NH_4Cl. After the aqueous phase had been extracted with Et_2O (3 × 30 mL), the combined organic layer was concentrated (to 30 mL), and 30% H_2O_2 (3.0 mL) was added. After the mixture had refluxed for 4 h, the solvent was removed and the residue was dissolved in EtOAc (30 mL). A 10% soln of NaOH (10 mL) was added and the mixture was stirred for an additional 20 min. The organic layer was washed with sat. aq NaCl (15 mL). The aqueous layer was extracted with EtOAc (2 × 20 mL). The combined organic phase was dried ($MgSO_4$), the solvent was removed, and the crude product was purified by column chromatography (silica gel, EtOAc, R_f = 0.38); this gave **6** as an off-white solid.

Yield: 207 mg (12%); mp 137–138 °C.

IR (KBr): 3060, 2988, 2938, 2839, 2348, 2076, 1973, 1909, 1734, 1674, 1577, 1465, 1270, 1195, 1079, 1041, 990, 865, 790, 747, 699, 663, 589, 514, 480 cm^{-1}.

^{31}P NMR (162 MHz, $CDCl_3$): δ = 25.2 (s).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.90 (m, 2 H), 7.45 (m, 3 H), 7.18 (m, 2 H), 7.10 (m, 4 H), 3.85 (s, 6 H), 3.46 (s, 6 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 152.4, 150.4, 131.9, 131.1, 128.3, 127.9, 127.3, 124.6, 123.7, 116.1, 60.2, 55.8.

MS (EI, 70 eV): *m*/*z* = 367.0, 398.0 [M + H]$^+$.

Anal. Calcd for $C_{22}H_{23}O_5P$: C, 66.33; H, 5.82. Found: C, 66.31; H, 6.28.

Bis(2,3-dihydroxyphenyl)(phenyl)phosphane Oxide (3)

Phosphane oxide **6** (207 mg, 0.52 mmol) was dissolved in CH_2Cl_2 (20 mL). BBr_3 (0.2 mL, 439.4 mg, 2.2 mmol) was added at 0 °C. After overnight stirring at r.t., the mixture was quenched with MeOH (4 mL) and concentrated under vacuum, and the residue was dissolved in EtOAc. After being washed with H_2O, the organic phase was dried ($MgSO_4$), and the solvent was removed under vacuum. This gave **3** as a beige solid.

Yield: 162 mg (92%); mp 70 °C.

IR (KBr): 3850.8, 3745.3, 3676.9, 3442.9, 3185.1, 2964.4, 2518.7, 2361.5, 2338.6, 1913.1, 1590.4, 1381.7, 1340.9, 1256.6, 1087.8, 906.6, 822.3, 733.9, 658.6, 577.9, 532.2, 468.6 cm^{-1}.

^{31}P NMR (162 MHz, $CDCl_3$): δ = 49.9 (s).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 10.68 (s, 2 H), 7.64 (m, 3 H), 7.52 (m, 2 H), 7.10 (d, *J* = 8.0 Hz, 2 H), 6.82 (m, 2 H), 6.60 (m, 2 H), 5.80 (s, 2 H).

^{13}C NMR (100 MHz, CD_3OD): δ = 163.3, 149.5, 145.7, 132.8, 131.1, 128.0, 123.0, 119.1, 114.8, 113.7.

MS (EI, 70 eV): *m*/*z* = 342.0 [M + H]$^+$.

Anal. Calcd for $C_{18}H_{15}O_5P·1.5EtOAc$: C, 60.76; H, 5.74. Found: C, 60.49; H, 6.09.

1-(4-Bromophenyl)-2,5-dimethyl-1*H*-pyrrole (9)

4-Bromoaniline (**8**; 10.0 g, 58.5 mmol), hexane-2,5-dione (7.5 mL, 64.4 mmol), and TsOH (100.0 mg, 53.3 mmol) were dissolved in toluene (100.0 mL), and the mixture was refluxed in a Dean–Stark apparatus for 6 h. After the dark mixture had cooled down, it was washed with sat. aq $NaHCO_3$ (2 × 100 mL), H_2O (5 × 100 mL), and brine (100 mL), and decolorized with active carbon. After the soln had been dried ($MgSO_4$), the solvent was removed under vacuum; this gave **9** as a brown solid.

Yield: 13.2 g (90%).

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.59 (d, *J* = 8.7 Hz, 2 H), 7.10 (d, *J* = 8.7 Hz, 2 H), 5.90 (s, 2 H), 2.02 (s, 6 H).

1,1′-[(Phenylphosphoryl)di-4,1-phenylene]bis(2,5-dimethyl-1*H*-pyrrole) (10)

Method A: A three-necked flask under N_2 was charged with Mg (80.0 mg, 6.7 mmol), dry THF (2 mL), and several drops of a soln of pyrrole **9** (640 mg, 2.57 mmol) in dry THF (3 mL). Then I_2 was added to initiate the reaction under reflux temperature. When the resulting mixture turned colorless, the THF soln of **9** was added continuously. After addition, the suspension turned a grape color and was allowed to reflux for 2 h, after which it was cooled to 0 °C. At this temperature, $PhPCl_2$ (228.0 mg, 1.3 mmol) dissolved in dry THF (3 mL) was added over 30 min. The mixture changed color from brown to pale yellow, and was stirred at r.t. overnight. H_2O was added dropwise to quench the excess Grignard reagent. After the aqueous phase had been extracted with EtOAc (3 × 20 mL), the combined organic layer was concentrated by rotary evaporation. The residue was dissolved in acetone (12 mL) to which of 30% H_2O_2 (1.0 mL) had been added. The mixture was refluxed for 5 h, and the solvent was removed. Then 10% NaOH (6.0 mL) was added to the EtOAc soln of the residue. The organic layer was washed with sat. aq NaCl (15 mL), and the aqueous layer was extracted with EtOAc (2 × 20 mL). The combined organic phase was dried ($MgSO_4$) and the solvent was removed under vacuum. The crude product was purified by column chromatography (silica gel, EtOAc–hexane, 2.5:1, R_f = 0.43); this gave **10** as an off-white solid.

Yield: 87.0 mg (14.4%).

Method B: A 1.6 M soln of *n*-BuLi in hexane (2.1 mL, 3.36 mmol) was added to a soln of pyrrole **9** (790.0 mg, 3.18 mmol) in dry Et_2O (10 mL) under N_2 at 0 °C. After the mixture had stirred for 2 h, a soln of $PhPCl_2$ (287.5 mg, 1.6 mmol) in dry Et_2O (6 mL) was added slowly. The resulting mixture was stirred overnight at r.t., and sat. aq NH_4Cl (10 mL) was added to terminate the reaction. After the aqueous layer had been extracted with Et_2O (3 × 15 mL), the combined organic layer was concentrated (to 30 mL). A 30% soln of H_2O_2 (1 mL) was added, and the mixture was refluxed for 4 h. Then 10% NaOH (10.0 mL) was added, and the organic layer was washed with sat. aq NaCl (15 mL). The aqueous layer was extracted with EtOAc (2 × 20 mL). The combined organic phase was dried ($MgSO_4$) and the solvent was removed. The crude product was purified by column chromatography (silica gel, EtOAc, R_f = 0.53); this gave **10** as an off-white solid.

Yield: 570.0 mg (76%); mp 83 °C.

IR (KBr): 3865, 3744, 3431, 3054, 2917, 2543, 2364, 2343, 1922, 1733, 1651, 1594, 1503, 1318, 991, 842, 703, 617 cm^{-1}.

^{31}P NMR (162 MHz, $CDCl_3$): δ = 28.5 (s).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.80 (m, 6 H), 7.62 (m, 1 H), 7.56 (m, 2 H), 7.36 (m, 4 H), 5.93 (s, 4 H), 2.06 (s, 12 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 142.5, 132.9, 132.3, 132.2, 132.0, 130.9, 128.8, 128.6, 128.3, 106.7, 13.2.

MS (EI, 70 eV): *m*/*z* = 464.2 $[M + H]^+$.

Anal. Calcd for $C_{30}H_{29}N_2OP·H_2O$: C, 74.67; H, 6.48; N, 5.81. Found: C, 74.79; H, 6.33; N, 5.37.

Bis(4-aminophenyl)(phenyl)phosphane Oxide (11)

A mixture of compound **10** (570.0 mg, 1.23 mmol), $NH_2OH·HCl$ (2.6 g, 37.4 mmol), Et_3N (1.4 mL), EtOH (9.0 mL), and H_2O (3.6 mL) was refluxed for 24 h. Then second portions of $NH_2OH·HCl$ (2.6 g, 37.4 mmol) and Et_3N (1.0 mL) were added, and the mixture was refluxed for 30 h until TLC monitoring showed complete consumption of **10**. The reaction mixture was allowed to cool to r.t., its pH was adjusted to 12.0 with aq NaOH, and it was stirred for 1 h. The solvent was removed by rotary evaporation and the residue was purified by column chromatography (silica gel, EtOAc–MeOH, 10:1, R_f = 0.48); this gave **11** as a beige solid.

Yield: 240 mg (63%).

^{1}P NMR (162 MHz, $CDCl_3$): δ = 30.1 (s).

1H NMR (400 MHz, $CDCl_3$): δ = 7.65 (m, 2 H), 7.48 (m, 1 H), 7.40 (m, 6 H), 6.68 (m, 4 H), 3.96 (br s, 4 H).

MS (EI, 70 eV): *m*/*z* = 308.0 $[M + H]^+$.

***N*,*N*′-[(Phenylphosphoryl)di-4,1-phenylene]bis(2,3-dimethoxybenzamide) (13)**

Benzoyl chloride **12** (184.0 mg, 0.92 mmol), 4-Å molecular sieves, and HBTU (200.0 mg, 0.53 mmol) were added at 0 °C to py (15 mL). Then phosphane oxide **11** (130.0 mg, 0.42 mmol) dissolved in MeCN (15 mL) was added dropwise. The mixture was stirred overnight in an ice bath, and then at r.t. for 24 h. The solvent was removed under reduced pressure, the residue was dissolved in CH_2Cl_2, and the soln was washed with aq NH_4Cl (20 mL), aq $NaHCO_3$ (20 mL), H_2O (2 × 20 mL), and brine (20 mL). The organic layer was dried ($MgSO_4$) and the solvent was removed. The residue was purified by column chromatography (silica gel, CH_2Cl_2–MeOH, 10:1, R_f = 0.51); this gave **13** as an off-white solid.

Yield: 161 mg (60%); mp 105–107 °C.

IR (KBr): 3764.6, 3306.3, 2937.4, 2835.2, 2347.4, 2295.7, 2193.6, 1395.2, 1259.1, 1174.1, 1111.4, 1054.9, 987.8, 922.3, 828.5, 529.5 cm^{-1}.

^{31}P NMR (162 MHz, $CDCl_3$): δ = 28.5 (s).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 10.22 (s, 2 H), 7.79 (m, 6 H), 7.68 (m, 6 H), 7.55 (m, 1 H), 7.47 (m, 2 H), 7.22 (t, *J* = 15.9 Hz, 2 H), 7.12 (m, 2 H), 4.00 (s, 6 H), 3.94 (s, 6 H).

^{13}C NMR (75 MHz, CD_3OD): δ = 163.4, 152.6, 147.3, 141.7, 133.4, 132.1, 131.9, 128.5, 128.1, 126.6, 126.4, 124.8, 122.9, 119.7, 116.1, 61.7, 56.2.

ESI-MS: *m*/*z* = 637.4 $[M]^+$.

Anal. Calcd for $C_{36}H_{33}N_2O_7P·3H_2O$: C, 62.60; H, 5.69; N, 4.06. Found: C, 62.20; H, 5.22; N, 4.00.

***N*,*N*′-[(Phenylphosphoryl)di-4,1-phenylene]bis(2,3-dihydroxybenzamide) (7)**

Biscatechol **7** was prepared as a beige solid from protected precursor **13** by the method employed for the synthesis of biscatechol **3**.

Yield: 95%; mp 160 °C (dec.).

IR (KBr): 3726, 3342, 3043, 2872, 2473, 2347, 2335, 2241, 1716, 1649, 1384, 1333, 1255, 955, 831, 583, 530 cm^{-1}.

^{31}P NMR (162 MHz, CD_3OD): δ = 31.9 (s).

^{1}H NMR (400 MHz, CD_3OD): δ = 7.83 (m, 4 H), 7.56 (br, 8 H), 7.48 (m, 1 H), 7.34 (m, 2 H), 6.89 (m, 2 H), 6.71 (m, 2 H), 4.78 (s, 6 H).

^{13}C NMR (75 MHz, CD_3OD): δ = 168.2, 148.1, 146.0, 142.1, 132.6, 131.7, 130.7, 128.5, 126.9, 125.4, 120.5, 118.7, 116.5; two signals of carbon atoms were not observed.

ESI-MS: *m*/*z* = 579.4 $[M]^+$.

Anal. Calcd for $C_{32}H_{25}N_2O_7P·3.5H_2O$: C, 59.72; H, 5.01; N, 4.35. Found: C, 59.73; H, 5.16; N, 4.08.

1,1′,1″-(Phosphoryltri-4,1-phenylene)tris(2,5-dimethyl-1*H*-pyrrole) (15)

A 1.6 M soln of *n*-BuLi in hexane (2.1 mL, 3.36 mmol) was added to a soln of pyrrole **9** (790.0 mg, 3.18 mmol) in dry Et_2O (10 mL) under N_2 at 0 °C. After the mixture had stirred for 2 h, a soln of $POCl_3$ (136.8 mg, 0.9 mmol) in dry Et_2O (5 mL) was added dropwise, and the mixture was stirred overnight at r.t. Then sat. aq NH_4Cl (15 mL) and EtOAc (20 mL) were added, and the organic layer was washed with aq NH_4Cl (15 mL), H_2O (15 mL), and brine (15 mL). Finally, the aqueous layer was extracted with EtOAc (2 × 20 mL). The combined organic phase was dried ($MgSO_4$) and the solvent was removed. The crude product was purified by column chromatography (silica gel, CH_2Cl_2–MeOH, 15:1, R_f = 0.69); this gave pure **15** as an off-white solid.

Yield: 220 mg (36%); mp 205 °C (dec.).

IR (KBr): 3741.7, 3537.5, 3439.3, 3089.0, 2923.3, 2365.4, 2342.6, 2312.2, 2294.3, 1931.4, 1734.8, 1595.7, 1502.9, 1446.7, 1318.0, 1181.2, 1114.6, 994.1, 843.0, 621.4, 578.2, 492.2 cm^{-1}.

^{31}P NMR (122 MHz, $CDCl_3$): δ = 28.0 (s).

^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.83 (m, 6 H), 7.40 (m, 6 H), 5.94 (s, 6 H), 2.07 (s, 18 H).

^{13}C NMR (75 MHz, $CDCl_3$): δ = 142.8, 132.9, 131.7, 130.3, 128.6, 106.8, 13.2.

MS (EI, 70 eV): *m*/*z* = 557.4 $[M + H]^+$.

Anal. Calcd for $C_{36}H_{36}N_3OP·H_2O$: C, 74.64; H, 6.68; N, 7.25. Found: C, 75.11; H, 6.65; N, 7.30.

4,4′,4″-Phosphoryltrianiline (16)

A mixture of phosphine oxide **15** (284.0 mg, 0.51 mmol), $NH_2OH·HCl$ (1.6 g, 23.0 mmol), Et_3N (0.9 mL), EtOH (21.0 mL), and H_2O (4.1 mL) was refluxed for 30 h. Second portions of $NH_2OH·HCl$ (1.6 g, 23.0 mmol), Et_3N (0.9 mL), and H_2O (2.0 mL) were added, and the mixture was refluxed for 24 h until TLC monitoring revealed complete consumption of **15**. After removal of the solvents, the residue was poured into 30% $NH_3·H_2O$ (15 mL) and was stirred for 1 h. The pure product was collected by filtration and dried under high vacuum; this gave **16** as a brown solid.

Yield: 106 mg (43%); mp 175 °C (dec.).

IR (KBr): 3436.6, 3343.2, 3225.1, 3025.1, 2589.0, 2488.8, 2427.1, 2362.6, 2329.4, 1903.7, 1502.5, 1412.7, 1282.9, 824.1, 722.1, 670.1, 531.5, 479.1 cm^{-1}.

^{31}P NMR (162 MHz, CD_3OD): δ = 35.7 (s).

^{1}H NMR (400 MHz, CD_3OD): δ = 7.21 (m, 6 H), 6.70 (m, 6 H), 4.79 (s, 6 H).

^{13}C NMR (100 MHz, CD_3OD): δ = 151.7, 133.1, 118.7, 113.5.

MS (EI, 70 eV): *m*/*z* = 323.2 $[M + H]^+$.

Anal. Calcd for $C_{18}H_{18}N_3OP·1.5H_2O$: C, 61.71; H, 6.04; N, 11.99. Found: C, 61.46; H, 6.20; N, 12.24.

***N*,*N*′,*N*″-(Phosphoryltri-4,1-phenylene)tris(2,3-dimethoxybenzamide) (17)**

Benzoyl chloride **12** (185.0 mg, 0.93 mmol), 4-Å molecular sieves, and HBTU (150.0 mg, 0.39 mmol) were added at 0 °C to py (15 mL). A soln of triamine **16** (75.0 mg, 0.23 mmol) in DMF (15 mL) was added dropwise. The mixture was stirred in an ice bath overnight, and then at r.t. for 24 h. The solvent was removed under reduced pressure, the residue was dissolved in CH_2Cl_2, and the soln was washed successively with aq NH_4Cl (15 mL), aq $NaHCO_3$ (15 mL), H_2O (15 mL), and brine (15 mL). The organic layer was dried ($MgSO_4$) and the solvent was removed. The remaining residue was purified by column chromatography (silica gel, EtOAc–MeOH, 8:1, R_f = 0.51); this gave protected precursor **17** as an off-white solid.

Yield: 79 mg (42%); mp 239 °C (dec.).

IR (KBr): 3311.7, 2943.7, 2832.5, 2361.6, 2338.9, 1587.2, 1470.2, 1395.3, 1319.6, 1170.9, 1114.6, 1055.1, 989.8, 928.7, 825.1, 746.3, 689.4, 577.9, 535.5 cm^{-1}.

^{31}P NMR (162 MHz, $CDCl_3$): δ = 28.1 (s).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 10.23 (s, 3 H), 7.78 (m, 9 H), 7.70 (m, 6 H), 7.20 (t, *J* = 15.9 Hz, 3 H), 7.12 (m, 3 H), 4.01 (s, 9 H), 3.93 (s, 9 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 163.0, 152.4, 147.0, 141.5, 133.1, 128.0, 126.9, 124.7, 122.8, 119.4, 115.9, 61.7, 56.1.

ESI-MS: *m*/*z* = 816.3 $[M + H]^+$.

Anal. Calcd for $C_{45}H_{42}N_3O_{10}P·H_2O$: C, 64.82; H, 5.32; N, 5.04. Found: C, 64.42; H, 5.32; N, 5.28.

***N*,*N*′,*N*″-(Phosphoryltri-4,1-phenylene)tris(2,3-dihydroxybenzamide) (14)**

Triscatechol **14** was prepared as a beige solid from protected precursor **17** by the method employed for the synthesis of biscatechol **3**.

Yield: 90%; mp 175 °C (dec.).

IR (KBr): 3851.6, 3743.9, 3614.5, 3384.3, 2846.1, 2715.2, 1918.3, 1837.5, 1790.6, 1738.2, 1652.7, 1586.5, 1450.7, 1392.4, 1329.2, 1253.2, 1118.3, 956.3, 830.8, 741.9, 681.2, 586.3, 533.7 cm^{-1}.

^{31}P NMR (162 MHz, CD_3OD): δ = 31.7 (s).

^{1}H NMR (400 MHz, CD_3OD): δ = 7.92 (m, 6 H), 7.64 (m, 6 H), 7.42 (m, 3 H), 6.97 (m, 3 H), 6.78 (m, 3 H), 5.46 (s, 3 H).

^{13}C NMR (100 MHz, CD_3OD): δ = 168.0, 148.0, 145.9, 142.0, 132.6, 129.2, 126.8, 125.7, 120.5, 118.7, 116.4.

ESI-MS: *m*/*z* = 730.3 $[M]^+$.

Anal. Calcd for $C_{39}H_{30}N_3O_{10}P·3.5H_2O$: C, 58.94; H, 4.69; N, 5.29. Found: C, 58.48; H, 4.88; N, 5.26.

Tris(4-bromophenyl)phosphane Oxide (20)[14]

A 1.51 M soln of *n*-BuLi in hexane (3.3 mL, 5.0 mmol) was added slowly to a soln of 1,4-dibromobenzene (**19**; 1.18 g, 5.0 mmol) in THF (5.0 mL) at –78 °C. A white suspension formed, to which PCl_3 (0.14 mL, 0.23 g, 1.65 mmol) in THF (3.0 mL) was added dropwise over 1 h. The suspension was allowed to warm to r.t. overnight, and was stirred for another 30 min after the addition of 6% H_2O_2 (5.0 mL). The aqueous phase was extracted with CH_2Cl_2 (2 × 10 mL). The organic phase was dried ($MgSO_4$) and the solvent was removed. The residue was purified by column chromatography (silica gel, EtOAc, R_f = 0.63); this gave pure **20** as a white solid; yield: 493.6 mg (57%). However, under the same conditions, reaction of the active organolithium intermediate with $POCl_3$ afforded the pure product **20** in only 19% yield.

^{31}P NMR (121 MHz, $CDCl_3$): δ = 27.4 (s).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.65 (m, 6 H), 7.52 (m, 6 H).

Tris(2′,3′-dimethoxybiphenyl-4-yl)phosphine Oxide (22)

Phosphane oxide **20** (149 mg, 0.29 mmol) and $Pd(PPh_3)_4$ (48 mg, 0.042 mmol) were dissolved in toluene (10 mL) under N_2. A mixture of 2 M aq Na_2CO_3 (1.5 mL) and (2,3-dimethoxyphenyl)boronic

acid (**21**; 170.0 mg, 0.94 mmol) were added in several portions. The mixture was refluxed for 2 d, and, after cooling to r.t., was washed with aq Na_2CO_3 (4 × 20 mL). The organic phase was dried ($MgSO_4$) and the solvent was removed under vacuum. The residue was purified by column chromatograph (silica gel, EtOAc, R_f = 0.3); this gave the protected ligand precursor **22** as a white solid.

Yield: 113 g (65%); mp 80–82 °C.

IR (KBr): 3720, 3434, 2935, 2832, 2348, 2292, 1732, 1670, 1585, 1387, 1313, 1188, 1122, 791, 645, 590, 546 cm^{-1}.

^{31}P NMR (162 MHz, $CDCl_3$): δ = 29.4 (s).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.82 (m, 6 H), 7.70 (m, 6 H), 7.12 (t, *J* = 10.9 Hz, 3 H), 6.96 (t, *J* = 13.5 Hz, 6 H), 3.91 (s, 9 H), 3.62 (s, 9 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 152.9, 146.4, 141.8, 134.5, 131.8, 131.4, 129.6, 124.1, 122.2, 112.1, 60.7, 55.9.

MS (EI, 70 eV): *m*/*z* = 686.3 $[M + H]^+$.

Anal. Calcd for $C_{42}H_{39}O_7P \cdot H_2O$: C, 71.58; H, 5.86. Found: C, 71.58; H, 6.36.

4′,4″,4‴-Phosphoryltribiphenyl-2,3-diol (18)

Triscatechol **18** was prepared as a beige solid from the protected precursor **22** by the method employed for the synthesis of biscatechol **3**.

Yield: 95%; mp 158 °C.

IR (KBr): 3478.2, 3189.4, 3046.4, 2926.2, 2849.9, 2683.9, 2365.3, 2341.7, 2233.8, 1832.0, 1701.8, 1592.2, 1463.8, 1357.8, 1210.4, 1070.4, 891.8, 827.9, 632.2, 541.5 cm^{-1}.

^{31}P NMR (162 MHz, CD_3OD): δ = 33.4 (s).

^{1}H NMR (400 MHz, CD_3OD): δ = 7.67 (m, 6 H), 7.60 (m, 6 H), 6.72 (m, 6 H), 6.64 (m, 3 H).

^{13}C NMR (100 MHz, CD_3OD): δ = 145.3, 143.3, 142.6, 130.2, 131.3, 129.3, 128.4, 127.1, 120.8, 114.5.

ESI-MS: *m*/*z* = 601.4 $[M]^+$.

Anal. Calcd for $C_{36}H_{27}O_7P \cdot 2H_2O$: C, 67.71; H, 4.89. Found: C, 67.62; H, 5.14.

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