# Synthesis of Di- or Tetrafunctionalized Phosphorus Macrocycles

Joëlle Mitjaville, Anne-Marie Caminade, Jean-Pierre Majoral*
Laboratoire de Chimie de Coordination du CNRS, 205 route de Narbonne, F-31077 Toulouse Cedex, France
Fax + 33(61)553003
*Received 25 January 1995*
Dedicated to Professor Manfred Regitz on the occasion of his 60th birthday

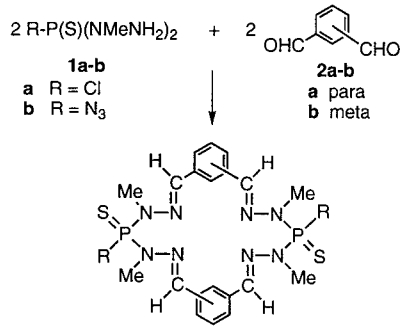
The reaction of functionalized phosphodihydrazides $RP(X)[NMeNH_2]_2$ (R = Cl, $N_3$) **(1)** with organic **(2)** or phosphorus **(4)** dialdehydes leads to the synthesis of di- or tetrafunctionalized phosphorus macrocycles **3a–d, 5a–h** in good yield. PCl containing macrocycles are quantitatively converted to $PN_3$ containing macrocyclic with sodium azide. All compounds are useful precursors of cryptands and multimacrocyclic species.

Extensive work has been devoted in the last few years to the synthesis and study of properties of complex organic molecular architectures such as cryptands and multimacrocyclic compounds.[1] Several pathways have been designed for the synthesis of these organic compounds, many of them starting with difunctionalized macrocycles.[2] Analogous reactions applied to the synthesis of phosphorus containing multimacrocyclic compounds are almost unknown, probably because difunctionalized macrocycles, with functions on phosphorus, are very rare.[3] However, we recently demonstrated that this strategy may be successfully applied to the synthesis of a wide range of original phosphorus species such as cryptands[4,5] and multimacrocycles.[6] We focus this report on the synthesis of twelve di- and tetrafunctionalized phosphorus macrocycles, potential precursors of multimacrocyclic species. We have already described some of these functionalized macrocycles,[4–6] but no experimental procedure and only partial spectroscopic data were given. We report here three different strategies to prepare rare PCl[7] and previously unknown $PN_3$ containing macrocycles.

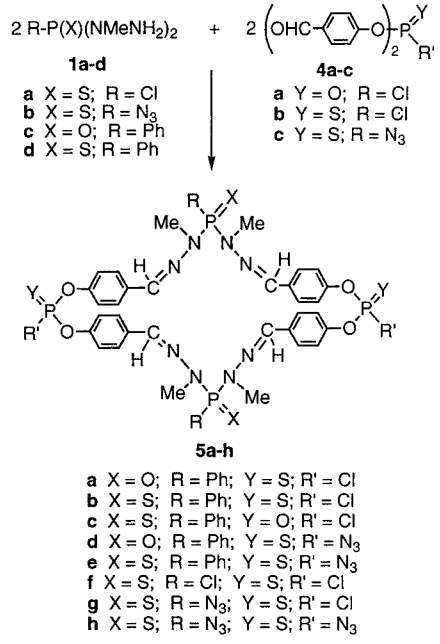
The first method is an extension of our cyclocondensation reaction of phosphodihydrazides $RP(S)(NMeNH_2)_2$ **(1)** (where R is mainly Ph) with dialdehydes[8] which leads in most cases to "[2 + 2] cycloadducts".[9] The functionality may be introduced either on the phosphodihydrazide or on the dialdehyde leading to difunctionalized macrocycles **3a–d, 5a–e** but also on both reagents leading to tetrafunctionalized macrocycles **5f–h**. Functionalized phosphodihydrazides **1a, b** are prepared by reaction of 4 equivalents of methylhydrazine on $S=PCl_3$ to yield **1a** (R = Cl). Further reaction with sodium azide in the presence of dibenzo-18-crown-6 affords **1b** ($R = N_3$).

Reaction of **1a, b** with benzene-1,3- (or 1,4-)dicarbaldehyde at room temperature resulted in the formation of the expected functionalized macrocycles **3a–d** (Scheme 1). The condensation is proved by a distinct shielding of $^{31}P$ NMR signals ($\Delta\delta$ = 19 ppm for **1a**, 15 ppm for **1b**) and by the disappearance of aldehyde and $NH_2$ functions, as shown by $^1H$ and $^{13}C$ NMR and infrared spectroscopy. Mass spectrometry indicates in all cases the formation of macrocycles arising from [2 + 2] cyclocondensation reactions.

Functionalized phosphodialdehydes Y = P(R′) $(OC_6H_4CHO)_2$ **(4)** are prepared by reaction of 2 equivalents of 4-hydroxybenzaldehyde with phosphorus oxychloride or thiophosphoryl chloride in the presence of triethylamine. Dialdehydes **4a** (R′ = Cl, Y = O) and **4b** (R′ = Cl, Y = S) are thus obtained in good yield (70–85%). Compound **4b** reacts readily with sodium azide to give dialdehyde **4c** ($R' = N_3$, Y = S). Difunctionalized tetraphosphorus macrocycles **5a–e** are isolated in moderate to good yields (35–90%) by reacting these functionalized dialdehydes with phosphodihydrazides **1c, d** at low temperature and in the presence of molecular sieves in the cases where R′ = Cl (Scheme 2).



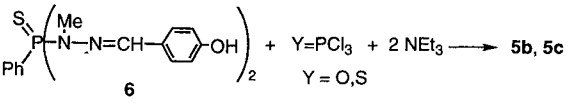

**Scheme 1**




**Scheme 2**

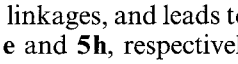
As already indicated for macrocycles **3a–d**, a shielding effect is observed in the $^{31}P$ NMR spectra for the phosphodihydrazide part ($\Delta\delta \approx 7$ ppm for **1c, d**) whereas the signal of the phosphodialdehyde part remains almost unchanged. [2 + 2] Cyclocondensations are proved in these cases also by mass spectrometry.

Tetrafunctionalized macrocycles **5f–h**, which bear either four PCl or four $PN_3$ functions, or two PCl and two $PN_3$ functions, are obtained in the same way by combining functionalized phosphodihydrazides **1a, b** with functionalized dialdehydes **4b, c** (Scheme 2). A second way to synthesize functionalized macrocycles consists of the reaction of the phosphodihydrazone **6**[10] with phosphorus oxychloride or thiophosphoryl chloride, in the presence of triethylamine (Scheme 3). Macrocycles **5b, c** are thus obtained, but in lower yield than with the first method.



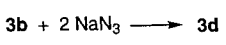

**Scheme 3**

Lastly, PCl functions of macrocycles may be converted into $PN_3$ functions with sodium azide. This reaction proceeds smoothly starting from macrocycle **3b**, which contains N-P-N linkages, and also with macrocycles **5h, g** which have O-P-O linkages, and leads to di- or tetraazido macrocycles **3d, 5e** and **5h**, respectively (Scheme 4).










**Scheme 4**

We have already demonstrated the synthetic utility of these functionalized phosphorus macrocycles[4–6] to prepare original cryptands and multimacrocyclic systems, and we are currently studying other aspects of their reactivity.

All procedures were carried out with standard high vacuum or dry argon atmosphere techniques. Solvents were distilled prior to use. $^1H$, $^{13}C$ and $^{31}P$ NMR spectra were recorded on a Bruker AC 200 spectrometer. $^{31}P$ NMR chemical shifts are reported in ppm relative to 85% $H_3PO_4$. Infrared spectra were recorded on a Perkin-Elmer 983 G or FT 1725 × spectrometer. Mass spectra were obtained by electronic impact or chemical ionization on a Nermag R10-10H or by fast atom bombardment on a Finnigan-MAT TSQ 700 spectrometer. Mps were measured on an "Electrothermal digital melting point". Elemental analyses were obtained in our laboratory or in the Service Central d'Analyses CNRS. Compounds **1a, b**, **3a–d**, **4a, b** and **5a–h** gave C, H, N analysis ±0.33%, except **4a**, C – 0.42; **5a**, C – 0.57; **5c**, C + 0.55; **5h**, C – 0.78%.

The syntheses of phosphodihydrazides **1c, d**[11] and phosphodihydrazone **6**[10] have been published.

**Bis(1-methylhydrazino)thiophosphonyl Chloride (1a):**
To a solution of thiophosphoryl chloride (2.03 mL, 20 mmol) in $CHCl_3$ (150 mL) at −10 °C was added dropwise methylhydrazine (4.25 mL, 80 mmol) in $CHCl_3$ (15 mL). After stirring for 3 h at −10 °C, the temperature was allowed to rise overnight to r.t. The solution was filtered and the solvent evaporated. The resulting powder was recrystallized at −20 °C from $Et_2O$ to give white crystals; yield: 50% (1.88 g), mp 53–55 °C.

$^{31}P\{^1H\}$NMR ($CDCl_3$): $\delta = 93.7$ (s).

$^1H$ NMR ($CDCl_3$): $\delta = 2.85$ (d, $^3J_{HP} = 14.3$ Hz, 6H, $PNCH_3$), 3.7 (s, 4H, $NH_2$).

$^{13}C\{^1H\}$NMR ($CDCl_3$): $\delta = 38.1$ (d, $^2J_{CP} = 9.5$ Hz, $PNCH_3$).

MS: $m/z = 188$ ($M^+$).

**Bis(1-methylhydrazino)thiophosphoryl Azide (1b):**
To a solution of **1a** (3.77 g, 20 mmol) in THF (100 mL) was added sodium azide (1.95 g, 30 mmol) and dibenzo-18-crown-6 (0.72 g, 2 mmol). The resulting mixture was stirred for 4 d at r.t., then filtered and the solvent was evaporated to give a white powder which was washed with toluene (2 × 10 mL); yield: 60% (2.34 g).

$^{31}P\{^1H\}$NMR ($C_6D_6$): $\delta = 82.4$ (s).

$^1H$ NMR ($C_6D_6$): $\delta = 2.60$ (d, $^3J_{HP} = 12.2$ Hz, 6H, $PNCH_3$), 3.24 (br s, 4H, $NH_2$).

$^{13}C\{^1H\}$NMR ($C_6D_6$): $\delta = 38.6$ (d, $^2J_{CP} = 9.5$ Hz, $PNCH_3$).

IR (THF): $\nu = 2150\ cm^{-1}$ ($N_3$).

MS: $m/z = 195$ ($M^+$).

**Macrocycles 3a, b:**
To a solution of chloride **1a** (0.471 g, 2.5 mmol) in $CHCl_3$ (20 mL) was added the dialdehyde **2a** or **2b** (0.335 g, 2.5 mmol), at r.t., in the presence of molecular sieves (4 Å). The resulting solution was stirred for 1 h, then filtered. The solvent was evaporated and the resulting yellow powder was washed with $Et_2O$ (2 × 10 mL).

*5,16-Dichloro-4,6,15,17-tetramethyl-3,4,6,7,14,15,17,18-octaaza-5,16-diphosphatricyclo[18.2.2.2$^{9,12}$]hexacosa-2,7,9,11,13,18,20,22, 23,25-decene 5,16-Disulfide* **(3a)**:

Yield: 90%; 0.64 g.

$^{31}P\{^1H\}$NMR ($CDCl_3$): $\delta = 74.5$ (s).

$^1H$ NMR ($CDCl_3$): $\delta = 3.37$ (d, $^3J_{HP} = 11$ Hz, 12H, $PNCH_3$), 7.52 (s, 8H, $C_6H_4$), 7.78 (s, 4H, HC=N).

$^{13}C\{^1H\}$NMR ($CDCl_3$): $\delta = 31.5$ (d, $^2J_{CP} = 7.5$ Hz, $PNCH_3$), 126.4 (s, $C_6H_4$), 134.9 (s, *i*-$C_6H_4$), 137.2 (br s, HC=N).

MS: $m/z = 573$ ($M^+ + 1$).

*5,17-Dichloro-4,6,16,18-tetramethyl-3,4,6,7,15,16,18,19-octaaza-5,17-diphosphatricyclo[19.3.1.1$^{9,13}$]hexacosa-1(25),2,7,9,11,13 (26),14,19,21,23,-decene 5,17-Disulfide* **(3b)**:

Yield: 88%; 0.63 g.

$^{31}P\{^1H\}$NMR ($CDCl_3$): $\delta = 74.5$ (s).

$^1H$ NMR ($CDCl_3$): $\delta = 3.29$ (d, $^3J_{HP} = 9$ Hz, 12H, $PNCH_3$), 7.2–7.8 (m, 12H, $C_6H_4$, HC=N).

$^{13}C\{^1H\}$NMR ($CDCl_3$): $\delta = 31.8$ (d, $^2J_{CP} = 10$ Hz, $PNCH_3$), 124.3–136.0 (m, $C_6H_4$), 138.4 (d, $^3J_{CP} = 17$ Hz, HC=N).

MS: $m/z = 573$ ($M^+ + 1$).

**Macrocycles 3c, d (from Phosphodihydrazide 1b):**
To a solution of phosphodihydrazide **1b** (0.298 g, 1.53 mmol) in THF (20 mL) was added the dialdehyde **2a** or **2b** (0.205 g, 1.53 mmol), at r.t. After stirring for 2 h, the solvent was evaporated giving a yellow powder that was washed with $Et_2O$ (10 mL).

*5,16-Diazido-4,6,15,17-tetramethyl-3,4,6,7,14,15,17,18-octaaza-5,16-diphosphatricyclo[18.2.2.2$^{9,12}$]hexacosa-2,7,9,11,13,18,20, 22,23,25-decene 5,16-Disulfide* **(3c)**:

Yield: 88%; 0.40 g.

$^{31}P\{^1H\}$NMR ($CDCl_3$): $\delta = 67.0$ (s).

$^1H$ NMR ($CDCl_3$): $\delta = 3.35$ (d, $^3J_{HP} = 10$ Hz, 12H, $PNCH_3$), 7.57 (s, 8H, $C_6H_4$), 7.75 (s, 4H, HC=N).

$^{13}C\{^1H\}$NMR ($CDCl_3$): $\delta = 31.6$ (d, $^2J_{CP} = 9$ Hz, $PNCH_3$), 126.7 (s, $C_6H_4$), 135.0 (s, *i*-$C_6H_4$), 137.5 (d, $^3J_{CP} = 10$ Hz, HC=N).

IR (KBr): $\nu = 2150\ cm^{-1}$ ($N_3$).

MS: $m/z = 587$ ($M^+ + 1$).

*5,17-Diazido-4,6,16,18-tetramethyl-3,4,6,7,15,16,18,19-octaaza-5,17-diphosphatricyclo[19.3.1.1$^{9,13}$]hexacosa-1(25),2,7,9,11,13(26),14,19,21,23,-decene 5,17-Disulfide* **(3d)**:

Yield: 85%; 0.38 g, mp 196–197°C.

$^{31}P\{^1H\}$NMR ($CDCl_3$): $\delta = 66.9$ (s).

$^1H$ NMR ($CDCl_3$): $\delta = 3.23$ (d, $^3J_{HP} = 9.5$ Hz, 12H, $PNCH_3$), 7.1–7.9 (m, 12H, $C_6H_4$, HC=N).

$^{13}C\{^1H\}$NMR ($CDCl_3$): $\delta = 31.6$ (d, $^2J_{CP} = 10$ Hz, $PNCH_3$), 127.4–135.1 (m, $C_6H_4$), 138.7 (d, $^3J_{CP} = 12$ Hz, HC=N).

IR (KBr): $\nu = 2151\ cm^{-1}$ ($N_3$).

MS: $m/z = 587$ ($M^+ + 1$).

**Macrocycle 3d (from Macrocycle 3b):**

To a solution of macrocycle **3b** (2.00 g, 3.5 mmol) in THF (150 mL) was added sodium azide (0.682 g, 10.5 mmol) and dibenzo-18-crown-6 (0.252 g, 0.7 mmol). This mixture was refluxed for 72 h, then filtered, and the solvent was evaporated. The resulting yellow powder was washed several times with $Et_2O$ (5 × 30 mL); yield: 70% (1.08 g).

**Dialdehydes 4a, b:**

To a solution of 4-hydroxybenzaldehyde (2.44 g, 20 mmol) in THF (20 mL) at r.t. was added $Et_3N$ (2.8 mL, 20 mmol). After stirring for 30 min, this mixture was added dropwise to phosphoryl trichloride (0.93 mL, 10 mmol) or thiophosphoryl trichloride (1.01 mL, 10 mmol) in THF (20 mL) maintained at −80°C. The resulting mixture was stirred for 2 h, warmed to r.t., filtered and the solvent evaporated, giving a white powder which was washed with $CHCl_3$/pentane (1:1).

*Bis(4-formylphenyl) Chlorophosphonate* **(4a)**:

Yield: 70%; 2.27 g.

$^{31}P\{^1H\}$NMR ($CDCl_3$): $\delta = -7.7$ (s).

$^1H$ NMR ($CDCl_3$): $\delta = 7.33$ (d, $^3J_{HH} = 3.0$ Hz, 4H, $C_6H_4$), 7.78 (d, $^3J_{HH} = 3.0$ Hz, 4H, $C_6H_4$), 10.0 (s, 2H, CHO).

$^{13}C\{^1H\}$NMR ($CDCl_3$): $\delta = 121.5$ (d, $^3J_{CP} = 5.5$ Hz, *o*-$C_6H_4$), 131.1 (s, *m*-$C_6H_4$), 133.9 (s, *p*-$C_6H_4$), 154.0 (d, $^2J_{CP} = 8.7$ Hz, $C_iOP$).

IR (KBr): $\nu = 1703\ cm^{-1}$ (C=O).

*Bis(4-formylphenyl) Chlorothiophosphonate* **(4b)**:

Yield: 85%; 2.89 g.

$^{31}P\{^1H\}$NMR ($CDCl_3$): $\delta = 58.2$ (s).

$^1H$ NMR ($CDCl_3$): $\delta = 7.2$ (d, $^3J_{HH} = 3.1$ Hz, 4H, $C_6H_4$), 7.6 (d, $^3J_{HH} = 3.1$ Hz, 4H, $C_6H_4$), 10.2 (s, 2H, CHO).

$^{13}C\{^1H\}$NMR ($CDCl_3$): $\delta = 121.7$ (d, $^3J_{CP} = 5.8$ Hz, *o*-$C_6H_4$), 131.4 (s, *m*-$C_6H_4$), 134.1 (s, *p*-$C_6H_4$), 153.9 (d, $^2J_{CP} = 8.7$ Hz, $C_iOP$).

IR (KBr): $\nu = 1700\ cm^{-1}$ (C=O).

**Bis(4-formylphenyl) Azidothiophosphonate (4c):**

After filtration of a crude solution of **4b** prepared as described above, sodium azide (0.65 g, 10 mmol) was added at r.t. and the mixture was stirred for 24 h, then filtered and the solvent evaporated to give a yellow oil used as it was.

Yield from thiophosphoryl chloride: 60%; 2.08 g.

$^{31}P\{^1H\}$NMR ($CDCl_3$): $\delta = 57.7$ (s).

$^1H$ NMR ($CDCl_3$): $\delta = 7.38$ (d, $^3J_{HH} = 6.5$ Hz, 4H, $C_6H_4$), 7.90 (d, $^3J_{HH} = 6.5$ Hz, 4H, $C_6H_4$), 9.90 (s, 2H, CHO).

$^{13}C\{^1H\}$NMR ($CDCl_3$): $\delta = 121.7$ (d, $^3J_{CP} = 5.7$ Hz, *o*-$C_6H_4$), 131.5 (s, *m*-$C_6H_4$), 134.1 (s, *p*-$C_6H_4$), 153.9 (d, $^2J_{CP} = 8.7$ Hz, $C_iOP$), 190.4 (s, CHO).

IR (THF): $\nu = 2160$ ($N_3$), 1700 $cm^{-1}$ (CO).

**Difunctionalized Macrocycles 5a, b (from Dialdehyde 4b):**

To a solution of dialdehyde **4b** (2.04 g, 6 mmol) prepared in situ in THF (15 mL) at −80°C (bath temperature), was added a solution of phosphodihydrazide **1c** (1.28 g, 6 mmol) or **1d** (1.38 g, 6 mmol) in THF (10 mL) in the presence of molecular sieves (4 Å). The resulting mixture was stirred for 4 h while the temperature was allowed to rise slowly to r.t. After filtration, the solution was evaporated to dryness, and the resulting pale-yellow powder was washed with $Et_2O$ (3 × 10 mL).

*3,21-Dichloro-11,13,29,31-tetramethyl-12,30-diphenyl-2,4,20,22-tetraoxa-10,11,13,14,28,29,31,32-octaaza-3,12,21,30-tetraphosphapentacyclo[32.2.2.2$^{5,8}$.2$^{16,19}$.2$^{23,26}$]tetratetraconta-5,7,9,14,16,18,23,25,27,32,34,36,37,39,41,43-hexadecene 12,30-Dioxide 3,21-Disulfide* **(5a)**:

Yield: 80%; 2.49 g.

$^{31}P\{^1H\}$NMR ($CDCl_3$): $\delta = 24.7$ [s, NP(O)N], 57.9 [s, OP(S)O].

$^1H$ NMR ($CDCl_3$): $\delta = 3.2$ (d, $^3J_{HP} = 9$ Hz, 12H, $PNCH_3$), 6.7–8.3 (m, 30H, $C_6H_4$, $C_6H_5$ and CH=N).

$^{13}C\{^1H\}$NMR ($CDCl_3$): $\delta = 31.2$ (d, $^2J_{CP} = 8$ Hz, $PNCH_3$), 116.1–134.0 (m, $C_6H_5$), $C_6H_4$), 136.3 (d, $^3J_{CP} = 13$ Hz, HC=N), 149.4 (br s, COP).

MS: $m/z = 1037$ ($M^+ + 1$).

*3,21-Dichloro-11,13,29,31-tetramethyl-12,30-diphenyl-2,4,20,22-tetraoxa-10,11,13,14,28,29,31,32-octaaza-3,12,21,30-tetraphosphapentacyclo[32.2.2.2$^{5,8}$.2$^{16,19}$.2$^{23,26}$]tetratetraconta-5,7,9,14,16,18,23,25,27,32,34,36,37,39,41,43-hexadecene 3,12,21,30-Tetrasulfide* **(5b)**:

Yield: 81%; 2.59 g.

$^{31}P\{^1H\}$NMR ($CDCl_3$): $\delta = 79.1$ [s, NP(S)N], 58.0 [s, OP(S)O].

$^1H$ NMR ($CDCl_3$): $\delta = 3.2$ (d, $^3J_{HP} = 9.0$ Hz, 12H, $PNCH_3$), 6.7–7.8 (m, 30H, $C_6H_4$, $C_6H_5$ and CH=N).

$^{13}C\{^1H\}$NMR ($CDCl_3$): $\delta = 30.6$ (d, $^2J_{CP} = 5$ Hz, $PNCH_3$), 116.0–133.5 (m, $C_6H_4$ and $C_6H_5$), 135.5 (d, $^3J_{CP} = 14$ Hz, HC=N), 149.2 (br s, COP).

MS: $m/z = 1069$ ($M^+ + 1$).

**Difunctionalized Macrocycles 5b, c:**

To a solution of phosphodihydrazone **6** (0.877 g, 2 mmol) in THF (50 mL) at 0°C was added $Et_3N$ (0.56 mL, 4 mmol). This mixture was stirred for 30 min, then cooled to −80°C and thiophosphoryl trichloride (0.203 mL, 2 mmol) or phosphoryl trichloride (0.186 mL, 2 mmol) in THF (20 mL) was added. The mixture was slowly warmed to r.t. over 3 h, then filtered and the solvent was evaporated. The resulting pale yellow powder was washed with $Et_2O$ (2 × 20 mL). **5b**: yield: 60% (0.64 g). **5c**: yield: 30% (0.31 g).

**3,21-Dichloro-11,13,29,31-tetramethyl-12,30-diphenyl-2,4,20,22-tetraoxa-10,11,13,14,28,29,31,32-octaaza-3,12,21,30-tetraphosphapentacyclo[32.2.2.2$^{5,8}$.2$^{16,19}$.2$^{23,26}$]tetratetraconta-5,7,9,14,16,18,23,25,27,32,34,36,37,39,41,43-hexadecene 3,21-Dioxide 12,30-Disulfide (5c):**

To a solution of dialdehyde **4a** (1.95 g, 6 mmol) prepared in situ in THF (15 mL) at −100°C (bath temperature), was added a solution of phosphodihydrazide **1c** (1.28 g, 6 mmol) in THF (10 mL) in the presence of molecular sieves (4 Å). The resulting mixture was stirred for 4 h while the temperature was allowed to rise slowly to r.t. After filtration, the solution was evaporated to dryness, and the resulting pale yellow powder was washed with $Et_2O$ (3 × 10 mL), yield: 35% (1.09 g).

$^{31}P\{^1H\}$NMR ($CDCl_3$): $\delta = 78.9$ [s, NP(S)N], −5.8 [s, OP(O)O].

$^1H$ NMR ($CDCl_3$): $\delta = 3.2$ (d, $^3J_{HP} = 8.0$ Hz, 12H, $PNCH_3$), 7.4–8.1 (m, 30H, $C_6H_4$, $C_6H_5$ and CH=N).

$^{13}C\{^1H\}$NMR ($CDCl_3$): $\delta = 31.1$ (d, $^2J_{CP} = 5$ Hz, $PNCH_3$), 114.0–132.9 (m, $C_6H_4$ and $C_6H_5$), 135.2 (d, $^3J_{CP} = 14$ Hz, HC=N), 148.7 (br s, COP).

MS: $m/z = 1037$ ($M^+ + 1$).

**Difunctionalized Macrocycles 5d, e (from Dialdehyde 4c):**

To a solution of oxo- or thiophosphodihydrazide **1c** (4.280 g, 20 mmol) or **1d** (4.605 g, 20 mmol) in THF (30 mL) was added the phosphorus dialdehyde **4c** (6.94 g, 20 mmol) prepared in situ (and filtered) in THF (80 mL) at r.t. in the presence of molecular sieves (4 Å). After stirring for 48 h (compound **5d**) or 3 h (compound **5e**)

at r.t., filtration, and evaporation of the solvent, the resulting powder was washed with MeOH (2 × 20 mL).

*3,21-Diazido-11,13,29,31-tetramethyl-12,30-diphenyl-2,4,20,22-tetraoxa-10,11,13,14,28,29,31,32-octaaza-3,12,21,30-tetraphosphapentacyclo[32.2.2.$^{5,8}$.2$^{16,19}$.2$^{23,26}$]tetratetraconta-5,7,9,14,16,18,23,25,27,32,34,36,37,39,41,43-hexadecene 12,30-Dioxide 3,21-Disulfide* **(5d)**:

Yellow powder; yield: 86%; 9.03 g, mp 152°C.

$^{31}P\{^1H\}$NMR ($CDCl_3$): $\delta$ = 24.8 [s, NP(O)N], 58.7 [s, OP(S)O].

$^1H$ NMR ($CDCl_3$): $\delta$ = 3.2 (d, $^3J_{HP}$ = 9.0 Hz, 12 H, $PNCH_3$), 6.7–8.2 (m, 30 H, $C_6H_4$, $C_6H_5$ and CH=N).

$^{13}C\{^1H\}$NMR ($CDCl_3$): $\delta$ = 31.0 (d, $^2J_{CP}$ = 9 Hz, $PNCH_3$), 122.2–134.1 (m, $C_6H_4$ and $C_6H_5$), 135.7 (d, $^3J_{CP}$ = 12 Hz, HC=N), 149.2 (d, $^2J_{CP}$ = 8 Hz, COP).

IR (KBr): $\nu$ = 2162 cm$^{-1}$ ($N_3$).

MS: $m/z$ = 1051 ($M^+ + 1$).

*3,21-Diazido-11,13,29,31-tetramethyl-12,30-diphenyl-2,4,20,22-tetraoxa-10,11,13,14,28,29,31,32-octaaza-3,12,21,30-tetraphosphapentacyclo[32.2.2.2$^{5,8}$.2$^{16,19}$.2$^{23,26}$]tetratetraconta-5,7,9,14,16,18,23,25,27,32,34,36,37,39,41,43-hexadecene 3,12,21,30-Tetrasulfide* **(5e)**:

White powder; yield: 90%; 9.74 g, mp 194–195°C.

$^{31}P\{^1H\}$NMR ($CDCl_3$): $\delta$ = 79.2 [s, NP(S)N], 58.7 [s, OP(S)O].

$^1H$ NMR ($CDCl_3$): $\delta$ = 3.2 (d, $^3J_{HP}$ = 9 Hz, 12 H, $PNCH_3$), 6.7–8.2 (m, 30 H, $C_6H_4$, $C_6H_5$ and CH=N).

$^{13}C\{^1H\}$NMR ($CDCl_3$): $\delta$ = 31.2 (d, $^2J_{CP}$ = 9 Hz, $PNCH_3$), 121.2–133.6 (m, $C_6H_5$ and $C_6H_4$), 135.9 (d, $^3J_{CP}$ = 13 Hz, HC=N), 149.7 (br s, COP).

IR (KBr): $\nu$ = 2161 cm$^{-1}$ ($N_3$).

MS: $m/z$ = 1083 ($M^+ + 1$).

**Macrocycles 5e, h (from Macrocycles 5b, g):**

To a solution of macrocycle **5b** (1.07 g, 1 mmol) or **5g** (0.999 g, 1 mmol) in THF (20 mL) was added sodium azide (0.13 g, 2 mmol) at r.t. After stirring overnight, the mixture was filtered, and the solvent was evaporated. The resulting powder was washed several times with $Et_2O$ (5 × 20 mL). **5e**: yield: 95% (1.03 g). **5h**: yield: 97% (0.98 g).

**Tetrafunctionalized Macrocycles 5f, g:**

To a solution of dialdehyde **4b** (0.340 g, 1 mmol) prepared in situ (and filtered) in THF (15 mL) at −70°C was added in the presence of molecular sieves (4Å) phosphodihydrazide **1a** (0.188 g, 1 mmol) or **1b** (0.195 g, 1 mmol) in THF (10 mL). The resulting mixture was stirred overnight (for **5f**) or one week (for **5g**) at r.t. After filtration, the solution was evaporated to dryness, and the resulting yellow powder was washed with MeCN (2 × 10 mL).

*3,12,21,30-Tetrachloro-11,13,29,31-tetramethyl-2,4,20,22-tetraoxa-10,11,13,14,28,29,31,32-octaaza-3,12,21,30-tetraphosphapentacyclo[32.2.2.2$^{5,8}$.2$^{16,19}$.2$^{23,26}$]tetratetraconta-5,7,9,14,16,18,23,25,27,32,34,36,37,39,41,43-hexadecene 3,12,21,30-Tetrasulfide* **(5f)**:

Yield: 60% (0.30 g).

$^{31}P\{^1H\}$NMR (THF-$d_8$): $\delta$ = 74.3 [s, NP(S)N], 57.4 [s, OP(S)O].

$^1H$ NMR (THF-$d_8$): $\delta$ = 3.4 (d, $^3J_{HP}$ = 11.0 Hz, 12 H, $PNCH_3$), 7.3 (d, $^3J_{HH}$ = 8.0 Hz, 8 H, $C_6H_4$), 7.7 (s, 4 H, CH=N), 7.8 (d, $^3J_{HH}$ = 8.0 Hz, 8 H, $C_6H_4$).

$^{13}C\{^1H\}$NMR (THF-$d_8$): $\delta$ = 31.8 (d, $^2J_{CP}$ = 10 Hz, $PNCH_3$), 121.6 (d, $^3J_{CP}$ = 5 Hz, Cd), 128.5 (d, $^2J_{CP}$ = 1.5 Hz, Cc), 134.5 (s, CC=N), 138.6 (d, $^3J_{CP}$ = 15 Hz, HC=N), 150.9 (d, $^2J_{CP}$ = 10 Hz, COP).

MS: $m/z$ = 985 ($M^+ + 1$).

*12,30-Diazido-3,21-dichloro-11,13,29,31-tetramethyl-2,4,20,22-tetraoxa-10,11,13,14,28,29,31,32-octaaza-3,12,21,30-tetraphosphapentacyclo[32.2.2.2$^{5,8}$.2$^{16,19}$.2$^{23,26}$[tetratetraconta-5,7,9,14,16,18,23,25,27,32,34,36,37,39,41,43-hexadecene 3,12,21,30-Tetrasulfide* **(5g)**:

Yield: 90% (0.45 g); mp 172–173°C.

$^{31}P\{^1H\}$NMR (THF): $\delta$ = 66.9 [s, NP(S)N], [s, OP(S)O].

$^1H$ NMR ($CDCl_3$): $\delta$ = 3.2 (d, $^3J_{HP}$ = 9.6 Hz, 12 H, $PNCH_3$), 6.8–7.8 (m, 20 H, $C_6H_4$ and CH=N).

$^{13}C\{^1H\}$NMR ($CDCl_3$): $\delta$ = 32.5 (d, $^2J_{CP}$ = 9 Hz, $PNCH_3$), 116.1–133.7 (m, $C_6H_4$), 137.8 (d, $^3J_{CP}$ = 14 Hz, HC=N), 150.1 (br s, COP).

IR (KBr): $\nu$ = 2150 cm$^{-1}$ ($N_3$).

MS: $m/z$ = 999 ($M^+ + 1$).

**3,12,21,30-Tetraazido-11,13,29,31-tetramethyl-2,4,20,22-tetraoxa-10,11,13,14,28,29,31,32-octaaza-3,12,21,30-tetraphosphapentacyclo[32.2.2.2$^{5,8}$.2$^{16,19}$.2$^{23,26}$]tetratetraconta-5,7,9,14,16,18,23,25,27,32,34,36,37,39,41,43-hexadecene 3,12,21,30-Tetrasulfide (5h) (from Dialdehyde 4c):**

To a solution of phospodihydrazide **1b** (0.195 g, 1 mmol) in THF (20 mL) was added dialdehyde **4c** (0.347 g, 1 mmol) prepared in situ (and filtered) in THF (20 mL) in the presence of molecular sieves (4 Å), at r.t. After stirring for 24 h at r.t., the solution was filtered and the solvent evaporated. The resulting yellow powder was washed with THF/pentane (1:3); yield: 80% (0.81 g).

$^{31}P\{^1H\}$NMR ($CDCl_3$): $\delta$ = 67.2 [s, NP(S)N], 59.2 [s, OP(S)O].

$^1H$ NMR ($CDCl_3$): $\delta$ = 3.2 (d, $^3J_{HP}$ = 9.6 Hz, 12 H, P−N−$CH_3$), 6.8–7.8 (m, 20 H, $C_6H_4$ and CH=N).

$^{13}C\{^1H\}$NMR ($CDCl_3$): $\delta$ = 32.3 (d, $^2J_{CP}$ = 8.7 Hz, $PNCH_3$), 122.1–134.0 (m, $C_6H_4$), 136.1 (d, $^3J_{CP}$ = 12.7 Hz, HC=N), 149.6 (d, $^2J_{CP}$ = 8.9 Hz, C−O−P).

IR (KBr): $\nu$ = 2150 and 2162 cm$^{-1}$ ($N_3$).

MS: $m/z$ = 1013 ($M^+ + 1$).


(1) See for instance: Izatt, R.M.; Pawlak, K.; Bradshaw, J.S.; Bruening, R.L. *Chem. Rev.* **1991**, *91*, 1721, and references cited.

(2) See for instance: Mertes, K.B.; Lehn, J.M. In *Comprehensive Coordination Chemistry*; Wilkinson, G., Ed.; Pergamon: Oxford, 1987, Vol. 2, chap. 21.3.

(3) Caminade, A.-M.; Majoral, J.-P. *Chem. Rev.* **1994**, 1183.

(4) Mitjaville, J.; Caminade, A.-M.; Majoral, J.-P. *J. Chem. Soc., Chem. Commun.* **1994**, 2161.

(5) Mitjaville, J.; Caminade, A.-M.; Mathieu, R.; Majoral, J.-P. *J. Am. Chem. Soc.* **1994**, *116*, 5007.

(6) Mitjaville, J.; Caminade, A.-M.; Daran, J.-C.; Donnadieu, B.; Majoral, J.-P. *J. Am. Chem. Soc.* **1995**, *117*, 1712.

(7) Razumova, N.A.; Evtikhov, Z.H.; Petrov, A.A. *Zh. Obsch. Khim.* **1968**, *38*, 1117; *J. Gen. Chem. SSSR* **1968**, 1072.
Bradshaw, J.S.; Huszthy, P.; Izatt, R.M. *J. Heterocycl. Chem.* **1986**, *23*, 1673.

(8) Majoral, J.-P.; Badri, M.; Caminade, A.-M.; Delmas, M.; Gaset, A. *Inorg. Chem.* **1988**, *27*, 3873.
Badri, M.; Majoral, J.-P.; Caminade, A.-M.; Delmas, M.; Gaset, A.; Gorgues, A.; Jaud, J. *J. Am. Chem. Soc.* **1990**, *112*, 5618.
Badri, M.; Majoral, J.-P.; Gonce, F.; Caminade, A.-M.; Sallé, M.; Gorgues, A. *Tetrahedron Lett.* **1990**, *31*, 6343.
Gonce, F.; Caminade, A.-M.; Majoral, J.-P. *Tetrahedron Lett.* **1991**, *32*, 203.
Majoral, J.-P.; Badri, M.; Caminade, A.-M.; Delmas, M.; Gaset, A. *Inorg. Chem.* **1991**, *30*, 344.
Majoral, J.-P.; Badri, M.; Caminade, A.-M. *Heteroatom Chem.* **1991**, *2*, 45.
Colombo, D.; Caminade, A.-M.; Majoral, J.-P. *Inorg. Chem.* **1991**, *30*, 3365.
Majoral, J.-P.; Caminade, A.-M. In *The Chemistry of Inorganic Ring Systems*; Steudel, R., Ed.; Elsevier Science: Berlin; 1992, Vol. 14, chap. 12.
Gonce, F.; Caminade, A.-M.; Jaud, J.; Vignaux, P.; Majoral, J.-P. *Bull. Soc. Chim. Fr.* **1992**, *129*, 237.
Gonce, F.; Caminade, A.-M.; Boutonnet, F.; Majoral, J.-P. *J. Org. Chem.* **1992**, *57*, 970.

Colombo-Khater, D.; Caminade, A.-M.; Delavaux-Nicot, B.; Majoral, J.-P. *Organometallics* **1993**, *12*, 2861.
Oussaid, B.; Garrigues, B.; Jaud, J.; Caminade, A.-M.; Majoral, J.-P. *J. Org. Chem.* **1993**, *58*, 4500.
(9) The term cyclocondensation indicates the condensation between two functionalized species leading to a macrocycle; a [2 + 2] cycloadduct is, *here*, a compound arising from the cyclocondensation of 2 equiv of each reagent.
(10) Colombo-Khater, D.; Hé, Z.; Caminade, A.-M.; Dahan, F.; Kraemer, R.; Majoral, J.-P. *Synthesis* **1993**, 1145.
(11) Majoral, J.-P.; Kraemer, R.; Navech, J.; Mathis, F. *Tetrahedron* **1976**, *32*, 2633.