Phosphorylated Hydrazines and Aldehydes as Precursors of Phosphorus-Containing Multimacrocycles

Joëlle Mitjaville, Anne-Marie Caminade, Jean-Claude Daran, Bruno Donnadieu, and Jean-Pierre Majoral*

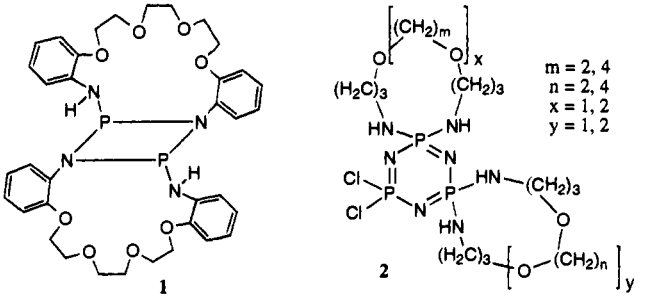
Contribution from Laboratoire de Chimie de Coordination du CNRS, 205 route de Narbonne, 31077 Toulouse Cedex, France

Received October 3, 1994[⊗]

Abstract: Treatment of phosphodihydrazides $PhP(Y)(N(CH_3)NH_2)_2$ (**4a**, Y = S; **4b**, Y = O) with either the 3,3′-[(3-oxapentane-1,5-diyl)dioxy]bis(2-hydroxybenzaldehyde) (**6**) or 3,3′-[(3,6-dioxaoctane-1,8-diyl)dioxy]bis(2-hydroxybenzaldehyde) (**7**) gave rise to macrocycles **8a,b**, **9a,b**, **10a**, and **11a** resulting from cyclocondensation between 1 equiv of each partner. Similar reactions in the presence of $Ba(CF_3SO_3)_2$ as a template salt led either to 1/1 complexes (1 macrocycle/1 $Ba(CF_3SO_3)_2$) **12** and **13** or to a sandwich complex, **14**. **14** crystallized in the monoclinic space group $P2_1/c$ with a = 14.507 (3) Å, b = 15.776 (4) Å, c = 14.513 (4) Å, β = 109.44 (2)°, Z = 2, and V = 3132 (1) Å^3. Bimacrocycles **15a,b** can be obtained by reacting the dialdehyde **7** with phosphotrihydrazide $(Y)P[N(CH_3)NH_2]_3$ (**5a**, Y = S; **5b**, Y = O). Reaction of the monofunctionalized phosphorus macrocycle **18** with the sodium salt of a phosphodihydrazone, $PhP(S)[N(Me)N{=}CHC_6H_4ONa]_2$ (**19**), afforded another type of bimacrocyclic species, **20**, containing five phosphorus atoms. A Staudinger reaction between the phosphine **22** bearing a crown ether unit and the diazido tetraphosphorus-containing macrocycle **21** led to a trimacrocycle, **24**, possessing one central phosphorus macrocycle and two crown ethers. Similarly the reaction between phosphine **22** (4 equiv) with the tetraazido tetraphosphorus-containing macrocycle **25** gave the pentamacrocyclic species **27**.

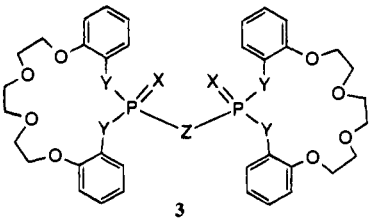
Introduction

Intensive studies in the field of oxygen-, nitrogen-, sulfur-containing macrocycles, cryptands, spherands, multimacrocycles, etc., appeared in the middle of the 1970's, several years after the discovery of the complex-forming properties of crown ethers by Pedersen in 1967.[1] Similarly the synthesis of phosphorus-containing macrocycles is now well documented, and several hundred of these derivatives exhibiting powerful complexation properties are well characterized.[2] In contrast a few phosphorus cryptands[3,4] and only one phosphorus-like spherand[4] are known. Moreover, bimacrocyclic phosphorus compounds are rare: only species **1**[5] (cis and trans), **2**,[6] and **3**[7] are reported. Furthermore, to the best of our knowledge, no phosphorus-containing multimacrocyclic derivative has been described in the literature to date. Therefore, there is a need to find routes to these elaborated systems which might present useful properties (complexation of several metals, bimetallic activation of small molecules, etc.).



1

2



3

X = O, S
Y = O, NH
-Z- = -NH(C_6H_4)[O-(CH_2)$_2$]$_3$O-(C_6H_4)HN- ;

Three strategies are described here which allow the quick and facile synthesis of new bimacrocyclic compounds as well as that of the first tri- and pentamacrocyclic phosphorus derivatives from easily available functionalized acyclic or macrocyclic species. A preliminary study of the complexation properties of one of these systems has been carried out.

[⊗] Abstract published in *Advance ACS Abstracts,* February 1, 1995.

(1) Pedersen, C. J. *J. Am. Chem. Soc.* **1967**, *89*, 7017.
(2) Caminade, A.-M.; Majoral, J.-P. *Chem. Rev.* **1994**, *94*, 1183.
(3) (a) Parks, J. E.; Wagner, B. E.; Holm, R. H. *J. Am. Chem. Soc.* **1970**, *92*, 3500. (b) Churchill, M. R.; Reis, A. H. *J. Chem. Soc., Chem. Commun.* **1970**, 879. (c) Höhn, A.; Geue, R. J.; Sargeson, A. M.; Willis, A. C. *J. Chem. Soc., Chem. Commun.* **1989**, 1644. (d) Bolm, C.; Sharpless, K. B. *Tetrahedron Lett.* **1988**, *29*, 5101. (e) Pascal, R. A., Jr.; West, A. P., Jr.; Van Engen, D. *J. Am. Chem. Soc.* **1990**, *112*, 6406. (f) L'Esperance, R. P.; West, A. P., Jr.; Van Engen, D.; Pascal, R. A., Jr. *J. Am. Chem. Soc.* **1991**, *113*, 2672. (g) West, A. P.; Smyth, N.; Kraml, C. M.; Ho, D. M.; Pascal, R. A. *J. Org. Chem.* **1993**, *58*, 3502. (h) Friedrichsen, B. P.; Powell, D. R.; Whitlock, H. W. *J. Am. Chem. Soc.* **1990**, *112*, 8931. (i) Friedrichsen, B. P.; Whitlock, H. W. *J. Am. Chem. Soc.* **1989**, *111*, 9132. (j) Alder, R. W.; Ganter, C.; Harris, C. J.; Orpen, A. G. *Phosphorus, Sulfur Silicon Relat. Elem.* **1993**, *77*, 234. (k) Wild, S. B. *Pure Appl. Chem.* **1990**, *62*, 1139. (l) Van Oijen, A. H.; De Bont, H. B. A.; Van Boom, J. H.; Liskamp, R. M. J. *Tetrahedron Lett.* **1991**, *32*, 7723. (m) Nifant'ev, E. E.; Zavalishina, A. I.; Smirnova, E. I.; Filimonov, V. F. *Zh. Obshch. Khim.* **1985**, *55*, 2806. (n) Pietrusiewciz, K. M.; Kuznikowski, M. *Phosphorus, Sulfur Silicon Relat. Elem.* **1993**, *77*, 57.
(4) Mitjaville, J.; Caminade, A.-M.; Majoral, J.-P.; Mathieu, R. *J. Am. Chem. Soc.* **1994**, *116*, 5007.
(5) Dutasta, J.-P.; Declercq, J.-P.; Esteban-Calderon, C.; Tinant, B. *J. Am. Chem. Soc.* **1989**, *111*, 7136.
(6) Labarre, J.-F.; Sournies, F. *Adv. Supramol. Chem.* **1993**, *4*, 555.
(7) Koodrja, T. N.; Stepanek, A. S.; Yurchenko, R. I.; Tchaikovskaja, A. A.; Lavrova, S. E. *Phosphorus, Sulfur Silicon Relat. Elem.* **1990**, *51*, 348. Chaikovskaya, A. A.; Kudrya, T. N.; Yurchenko, R. I.; Voitsekhovskaya, O. M.; Pinchuk, A. M. *Zh. Obshch. Khim.* **1988**, *58*, 1925.

0002-7863/95/1517-1712$09.00/0

Results and Discussion

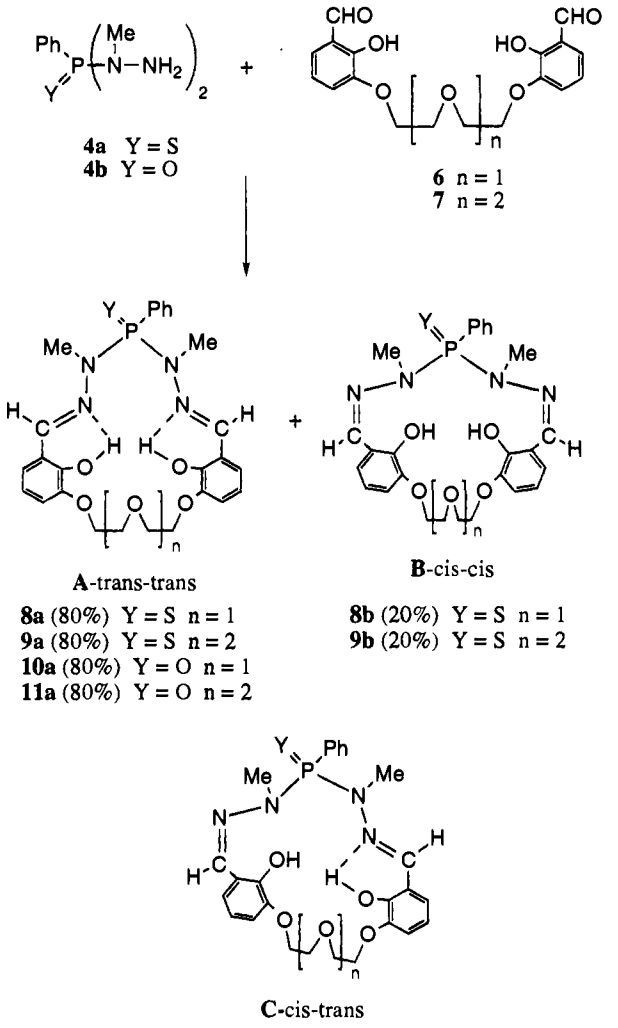
We have already demonstrated[8] that the reaction of difunctionalized phosphorus ligands such as phosphodihydrazides RP(Y)[N(CH$_3$)NH$_2$]$_2$ **4** (R = alkyl, aryl, aryloxy, dimethylamino, etc., Y = O, S) with various dialdehydes led to a great variety of macrocycles arising from [1 + 1], [2 + 2], [3 + 3], or even [4 + 4] cyclocondensations.[9] Therefore a possible starting point for the elaboration of bimacrocycles was the use of trifunctional phosphorus ligands such as (Y)P[N(CH$_3$)NH$_2$]$_3$ **5** (Y = S, O) and dialdehydes following the same procedure. In order to avoid the formation of oligomers, we dealt with the relatively rigid aldehydes **6** and **7**, well known to easily give macrocycles when reacted, for example, with *o*-phenylenediamine.[10] First we checked the reaction of **6** and **7** (1 equiv) with phosphodihydrazides **4a** (R = Ph, Y = S) and **4b** (R = Ph, Y = O) (1 equiv).

Macrocycles. Cyclocondensation of **4a** with **6** led to a mixture of two compounds, **8a,b** in a 4/1 ratio, while addition of **4a** to **7** afforded two derivatives, **9a,b**, also in a 4/1 ratio (Scheme 1). Compounds **8a,b** and **9a,b** were isolated and fully characterized. The structures of these species were mainly deduced from ^{1}H and ^{13}C NMR. Mass spectrometry (fast atom bombardment) clearly showed the formation of [1 + 1] cyclocondensation products exclusively. No traces of macrocycles resulting from [2 + 2] or [3 + 3] cyclocondensation reactions were detected. Therefore, it appeared that **8a,b** (or **9a,b**) were two different isomers. Three different types of isomers—A, B, C—could be envisaged for **8a,b** or **9a,b**. ^{1}H NMR data allowed the exclusion of form C which possesses nonequivalent methyl groups; indeed only one doublet (8.5 < $^3J_{PH}$ < 9.3 Hz) was detected for the N-CH$_3$ groups of **8a,b** and **9a ,b**. Since the position of hydroxyl groups in form A favors the formation of hydrogen bonds with imino nitrogen atoms, as it has already been demonstrated by X-ray crystallographic studies on related systems possessing similar PN(CH$_3$)N=CHC$_6$H$_4$-*o*-OH framework,[11] it was reasonable to postulate that the major diasteroisomers (**8a, 9a**) existed in form A (trans configuration for each imine function of the macrocycle). Consequently cis−cis configuration (form B) could be suggested for the minor isomers **8b** and **9b**.

The same reactions performed with **6** or **7** and phosphodihydrazide **4b** (Y = O) gave rise to a mixture of two compounds, from which the major compound **10a** or **11a** (form A for each of them) were isolated.

These results are in marked contrast with those already reported.[10] Indeed from the literature, it is known that macrocyclization of dialdehyde **6** or **7** with, for example, *o*-phenylenediamine only gave traces of monomeric cyclic products. Mostly polymeric material was isolated even under high-dilution conditions, and the use of suitable template salts (Ni(OAc)$_2$, Ba(CF$_3$SO$_3$)$_2$) was necessary to help the macrocyclization, with

Scheme 1



8a (80%) Y = S n = 1
9a (80%) Y = S n = 2
10a (80%) Y = O n = 1
11a (80%) Y = O n = 2

8b (20%) Y = S n = 1
9b (20%) Y = S n = 2

the formation of the corresponding complexes. Moreover, the type of cyclocondensation strongly depends on the nature of the dialdehyde: [1 + 1] cyclocondensation reactions were observed with **7** (n = 2),[10a] while [2 + 2] cyclocondensations occur with **6** (n = 1).[10b]

Our reactions involving **6** and **7** and phosphodihydrazides **4a,b** led selectively to the [1 + 1] cycloadducts **8a,b**, **9a,b**, **10a**, and **11a** and allowed us to obtain directly the corresponding free macrocycles. Therefore the lengthening of the dialdehyde chain dramatically changed the course of the reaction since the same reactions performed with **4a** or **4b** and 1,2-, 1,3-, or 1,4-dialdehydes exclusively led to [2 + 2] cyclocondensation macrocycles.[8]

Compound **6** or **7** (1 equiv) and phosphodihydrazide **4a** or **4b** (1 equiv) in a THF/MeOH (1/1) solution were also added to a refluxing THF/MeOH (1/1) solution of Ba(CF$_3$SO$_3$)$_2$ (1 equiv). In all cases, the reaction was stereospecific and led to compounds arising from the reaction of only 1 equiv of each reagent ([1 + 1] cyclocondensation) even when dialdehyde **6** (n = 1) was used. Indeed, two types of compounds were isolated, the 1/1 complexes **12** and **13** coming from the reaction of **4a** or **4b** with **7** or the sandwich complex **14** resulting from the addition of **4a** with **6** (Scheme 2). Mass spectrometry (electro spray) allowed us to detect the corresponding parent peaks at 871 [**9** + BaCF$_3$SO$_3$]$^+$ for **12** and 855 [**11** + BaCF$_3$SO$_3$]$^+$ for **13**. Complexes **12** and **13** can be directly prepared by reacting macrocycle **9** or **11** with a stoichiometric amount of Ba(CF$_3$SO$_3$)$_2$.

(8) Majoral, J.-P.; Badri, M.; Caminade, A.-M.; Delmas, M.; Gaset, A. *Inorg. Chem.* **1988**, *27*, 3878. Badri, M.; Majoral, J.-P.; Caminade, A.-M.; Delmas, M.; Gaset, A.; Gorgues, A.; Jaud, J. *J. Am. Chem. Soc.* **1990**, *112*, 5618.

(9) The term cyclocondensation indicates the condensation between two functionalized species leading to a macrocycle. For example, a [2 + 2] cyclocondensation product is *here* a compound arising from the cyclocondensation of 2 equiv of each partner.

(10) (a) van Staveren, C. J.; van Eerden, J.; van Veggel, F. C. J. M.; Harkema, S.; Reinhoudt, D. N. *J. Am. Chem. Soc.* **1988**, *110*, 4994 and references included therein. (b) van Veggel, F. C. J. M.; Bos, M.; Harkema, S.; Verboom, W.; Reinhoudt, D. N. *Angew. Chem., Int. Ed. Engl.* **1989**, *28*, 746.

(11) Colombo-Khater, D.; He, Z.; Caminade, A.-M.; Dahan, F.; Kramer, R.; Majoral, J.-P. *Synthesis* **1993**, 1145. Colombo-Khater, D.; Caminade, A.-M.; Raynaud, B.; Jaud, J.; Majoral, J.-P. *Bull. Soc. Chim. Fr.* **1994**, *131*, 733.

Scheme 2

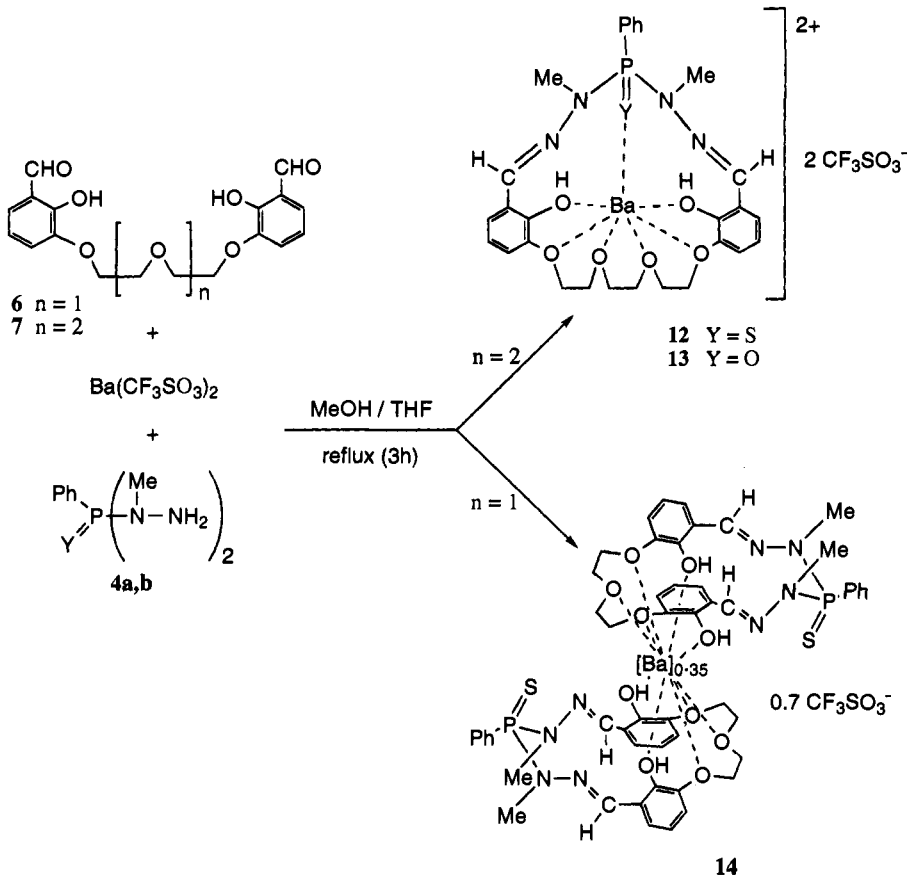


Table 1. Crystallographic Data

compound	$[C_{26}N_4O_5H_{29}PS]_2Ba_{0.35}(SO_3CF_3)_{0.7}, CH_2Cl_2$
fw	1336
crystal system	monoclinic
space group	$P2_1/c$
a, Å	14.507 (3)
b, Å	15.776 (4)
c, Å	14.513 (4)
β, deg	109.44 (2)
V, Å^3	3132 (1)
Z	2
ϱ(calcd), g cm^{-3}	1.33
μ (Mokα), cm^{-1}	3.11
diffractometer	Enraf Nonius CAD4F
monochromator	graphite
radiation	Mo Kα (l = 0.71069)
scan type	$\omega/2\theta$
scan range θ, deg	0.8 + 0.345 tgθ
2θ range, deg	$1 < 2\theta < 26$
reflctn collected	6696
reflctn merged (R_m)	6140 (0.057)
reflctn used ($I > 3\sigma(I)$)	2488
R	0.0691
R_w	0.0745
abs corr	Difabs
transmission coeff range	0.87–1.11
weighting scheme	Unity
s parameters	449

Suitable yellow crystals for X-ray crystallography studies were obtained for **14** in a CH_2Cl_2/Et_2O (1/1) solution (Table 1). The CAMERON[12] drawing of this complex shows the atomic numbering scheme we used, Figure 1. Selected bond lengths and angle values are listed in Table 2. Several remarkable features can be pointed out; 0.7 Ba atom and four macrocycles are present in the unit cell. Statistically a 2/1 sandwich complex (2 macrocycles/1 metal) is present among four free macrocycles. The two macrocycles of the complex are folded around the barium, thereby allowing coordination by all 10 oxygen atoms (d_{Ba-O} = 2.84–3.06 Å). Of interest is the particular position of the thiophosphoryl groups directed toward the metal. Interatomic distances between nonlinked atoms allow to have an idea of the cavity size of the macrocycle (Table 2). O(1)···O(5), O(3)···O(1), and O(3)···O(5) distances, 3.28, 4.12, and 4.12 Å, respectively, are shorter than the sum of the ionic radius of barium (2.70 Å) and twice the covalent radius of oxygen (2 × 0.73 Å). Therefore, the cavity size of the macrocycle appears too small for the formation of a 1/1 complex. We can also point out that hydrogen bonds between hydroxyl groups and imino nitrogen atoms take place with the formation of six-membered rings. Such an observation corroborates our assumption concerning the existence of similar hydrogen bonds in **8a** and **9a** (see above). The CAMERON[12] drawing of a free macrocycle of the unit cell is shown in Figure 2.

Bimacrocycles. The [2 + 3] cyclocondensation reaction involving phosphotrihydrazide **5a** (Y = S) or **5b** (Y = O) and the dialdehyde **7** was investigated (Scheme 3). Indeed, **5a** (2 equiv) was reacted with **7** (3 equiv) in a 1/1 methanol/THF solution. After stirring for 2 h at room temperature, two compounds were formed in a 4/1 ratio as indicated by the ^{31}P NMR spectra of the resulting mixture (δ = 71.2 and 71.5). The difference of solubility of these two species permitted the isolation of the major one, **15a**, in 65% yield. The ^1H NMR spectra of **15a** showed two doublets for the methyl groups in a 2/1 ratio (δ = 3.33, $^3J_{HP}$ = 9.2 Hz; δ = 3.35, $^3J_{HP}$ = 9.2 Hz).

(12) Watkin, D. J.; Carruthers, J. R.; Betteridge, P. W. *CRYSTALS User Guide;* Chemical Crystallography Laboratory, University of Oxford: Oxford, England, 1985.

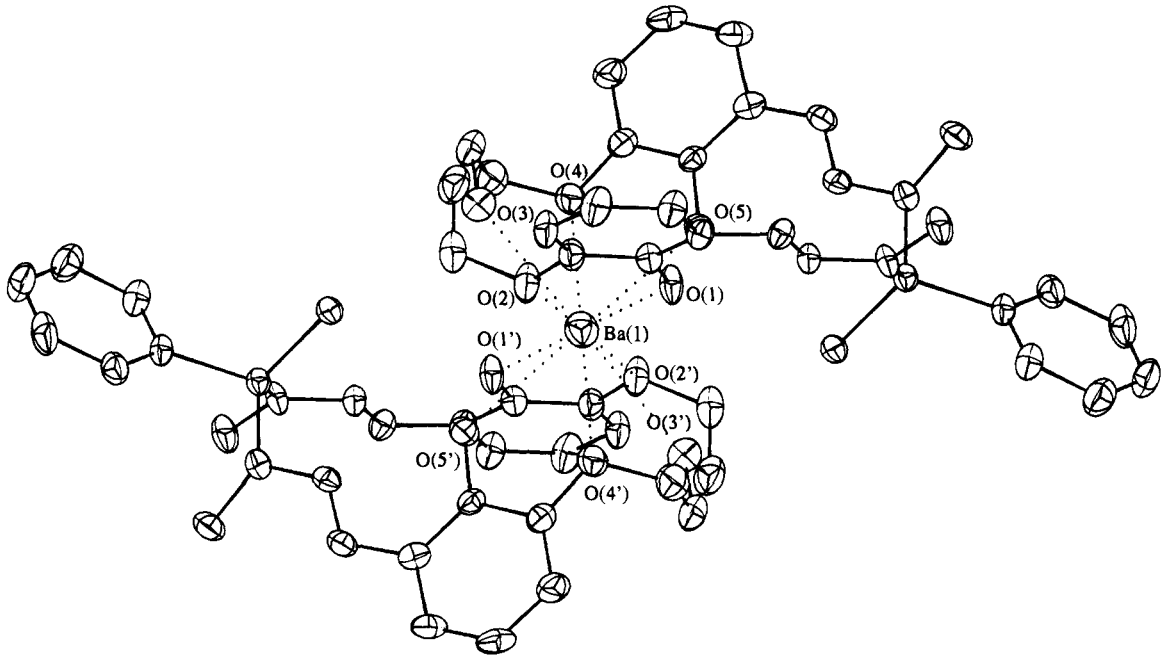


Figure 1. CAMERON drawing of the sandwich complex **14**. Ellipsoids represent 20% probability.

Table 2. Selected Interatomic Distances (Å) and Angles (deg) for Compound **14**

Ba(1)–O(1)	2.8(3)	P(1)–S(1)	1.936(3)
Ba(1)–O(2)	3.0(4)	P(1)–N(2)	1.696(8)
Ba(1)–O(3)	2.9(4)	P(1)–N(3)	1.693(7)
Ba(1)–O(4)	3.1(4)	P(1)–C(20)	1.795(9)
Ba(1)–O(5)	2.9(3)	N(1)–C(5)	1.27(1)
		N(4)–C(6)	1.28(1)
S(1)–P(1)–N(3)	111.7(3)	N(2)–P(1)–C(20)	105.3(4)
N(2)–P(1)–N(3)	109.8(4)	N(3)–P(1)–C(20)	104.3(4)
S(1)–P(1)–C(20)	113.8(3)		

Two singlets in a 2/1 ratio were also detected at 9.90 and 10.33 ppm for the hydroxyl groups. ^{13}C NMR corroborated the existence of two different sets of methyl groups. Fast atom bombardment mass spectrometry showed a signal at *m/z* 1460 $[M + 1]^+$ which corresponds to a compound arising from a [2 + 3] cyclocondensation reaction. All these spectroscopic data were in agreement with a bimacrocyclic structure. Attempts to isolate the minor compound of the reaction have failed until now.

A similar reaction performed with the dialdehyde **7** and the phosphotrihydrazide **5b** gave rise to the phosphorus-containing bimacrocycle **15b** in 80% yield (Scheme 3). **15a** was also obtained but in a lower yield (35%) when **5a** was treated with **7** (1 equiv of each) in the same experimental conditions as above. Such a reaction also led to another species which was isolated and characterized as the trifunctionalized macrocycle **16** possessing two hydroxyl groups and one hydrazino group (Scheme 4). The ^1H NMR spectrum of **16** showed two doublets for the methyl groups at 2.98 ($N(CH_3)NH_2$) and 3.30 ($N(CH_3)$-N=C) ppm and one singlet for the free NH_2 group. Other spectroscopic data including mass spectrometry (*m/z*, 553 $[M + 1]^+$) corroborated such an assignment.

Potentially another approach to the preparation of bimacrocycles consisted in the bridging of two functionalized macrocycles. To explore the feasibility of this process, we tried first to prepare new P-halogenated macrocycles. As illustrated in Scheme 5 the P-halogenated dialdehyde **17** reacted with **4a** at −100 °C leading to the cyclocondensation product **18** in 90% yield. The formation of **18** was detected by ^{31}P NMR (δ = 78.5 (N-P(S)-N) and 57.3 (O-P(S)(Cl)-O)), while the ^{13}C NMR spectrum was fully consistent with the presence of imino carbon atom. Moreover fast atom bombardment mass spectrometry showed the molecular ion peak *m/z* corresponding to a [1 + 1] cyclocondensation. A facile and quantitative condensation occurred when **18** was treated with the disodium salt **19**. The ^{31}P NMR spectrum of the resulting bimacrocycle **20** (Scheme 5) exhibited three resonances at δ = 79.3 (N-P(S)-N), 78.7 (N-P(S)-N), and 52.5 (O-P(S)-O) in a 2/1/2 ratio. Mass spectrometry (*m/z* = 1435 $[M + 1]^+$) as well as the other spectral data corroborated such a structure.

Multimacrocycles. No phosphorus-containing multimacrocyclic compound has ever been described at present. Convinced that the source of the problems was due to experimental difficulties, with, for example, the formation of numerous oligomeric products, we concentrated our efforts to find a clean and easy way to form these elaborated systems.

A strategy for the formation of multimacrocycles was based upon the use of a reaction involving bis-azido or tetraazido phosphorus-containing macrocycles and a phosphine already linked to a crown ether. Indeed the reaction of compound **21** with the crown ether phosphine **22** led, after stirring for 72 h at room temperature, to the trimacrocyclic species **24** (Scheme 6). ^{31}P NMR spectra of **24** showed, besides a singlet at 79.1 ppm due to the N-P(Ph)(S)-N- part of the central macrocycle, two doublets at 48.9 (NH-P(S)-O) and 10.7 (N-$P(Ph)_2$=N-) ppm with $^2J_{PP}$ = 29 Hz. The structure of **24** was mainly corroborated by mass spectrometry (*m/z* = 1964 $[M + 1]^+$). The reaction leading to **24** was monitored by ^{31}P NMR which allows to detect an interesting prototropic phenomenon. Indeed, the first compound formed in this reaction was the derivative **23** (^{31}P NMR: δ 79.1 (s), 46.5 (d, $^2J_{PP}$ = 41.5 Hz, =N-P(S)-O), 22.5 (d, $^2J_{PP}$ = 41.5 Hz, N=P-NH)) resulting from a Staudinger type reaction between **21** and **22**. The transient trimacrocyclic compound **23** was slowly converted at room temperature into **24**. The shielding effect observed for the two acyclic phosphorus atoms of **24** could be related to the modification of the environment around these atoms.

To explore the potentiality of this reaction which only leads to nitrogen as a byproduct, we performed the same experiment starting from the tetraazido phosphorus-containing macrocycle

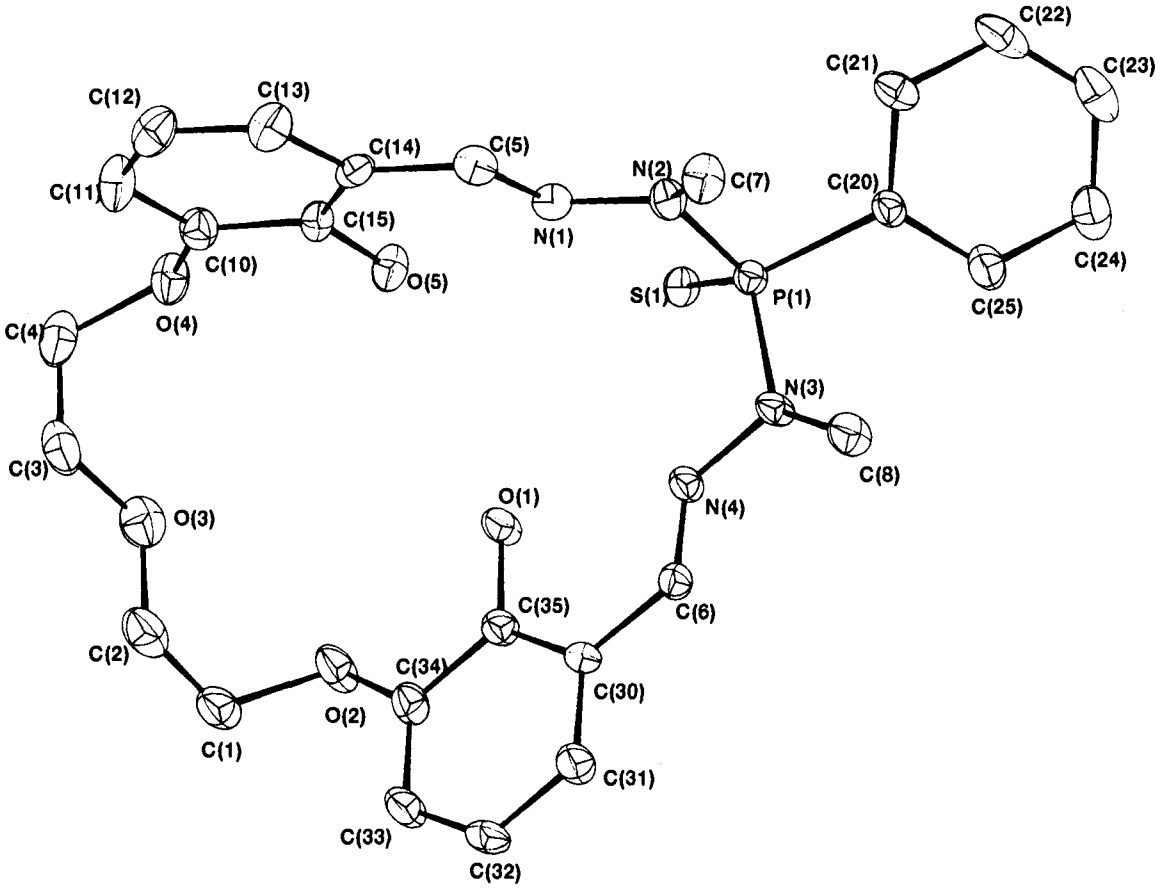
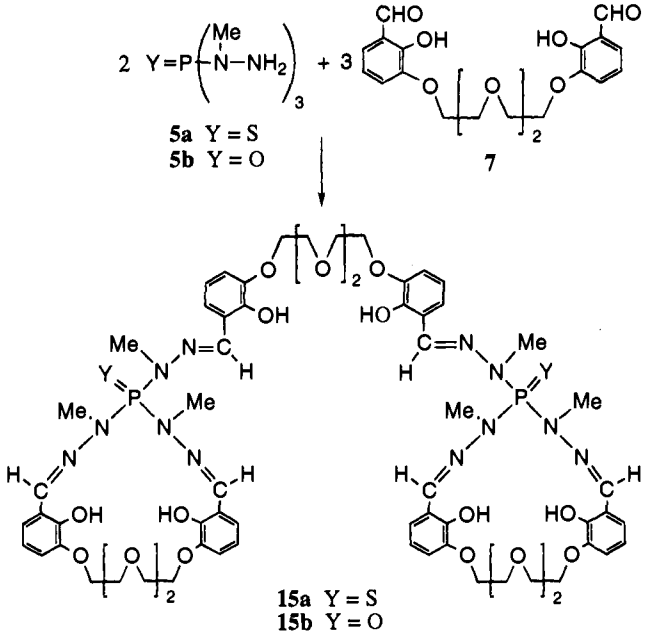
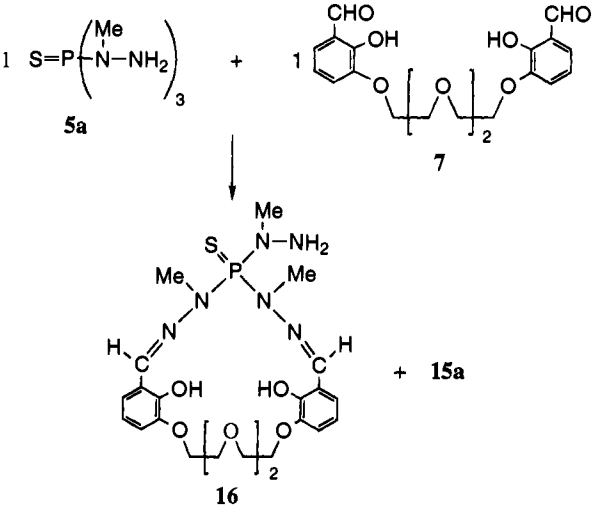


Figure 2. CAMERON drawing of a free macrocycle in **14**. Ellipsoids represent 20% probability.

Scheme 3



Scheme 4

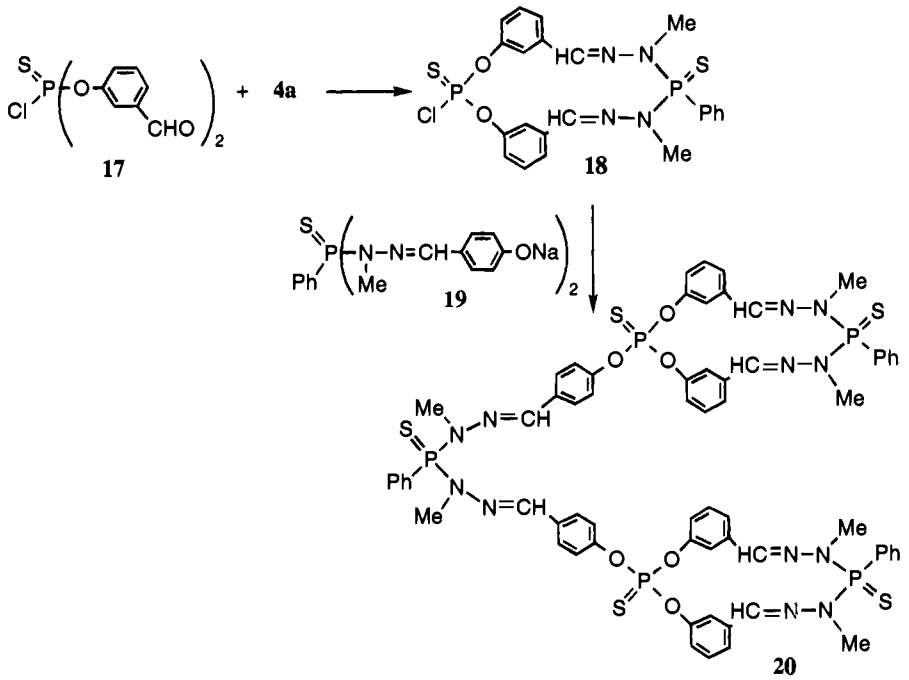


25 (1 equiv) and the phosphine **22** (4 equiv) (Scheme 7). The reaction needed 5 days of stirring at room temperature to go to completion. ^{31}P NMR spectra of the resulting pentamacrocyclic species **27** showed, as expected, four doublets. All the ^{31}P chemical shifts and the phosphorus–phosphorus coupling constants were close to those detected for **24** suggesting that this polymacrocycle exhibits P-NH-P fragments and not P=N-P linkages. Therefore a similar prototropy to the one found during the transformation of **23** → **24** occurred here, but we were not able to detect the intermediate **26** during the formation of **27** (Scheme 7). Nevertheless these reactions appeared very useful for the preparation of tri- and pentamacrocyclic species possessing two or four crown ethers directly grafted to a phosphorus-containing macrocyclic core.

Conclusion

Several strategies for the preparation of new phosphorus bimacrocyclic derivatives were proposed and considerably broaden the synthetic usefulness of linear trifunctionalized phosphorus species such as phosphotrihydrazides $(Y)P[N(CH_3)NH_2]_3$ or azidophosphodihydrazides $N_3P(Y)[N(CH_3)NH_2]_2$ (Y = S, O). Similarly difunctionalized or tetrafunctionalized

Scheme 5



macrocycles possessing two or four azido groups appeared to be reagents of choice for the formation of the first tri- and pentamacrocyclic phosphorus systems obtained in near quantitative yield, the only byproduct formed in these reactions being nitrogen. Some of these multimacrocycles came from a new type of [2 + 3] cyclocondensation reaction in phosphorus macrocyclic chemistry.

Template reactions made with barium triflate gave information in two directions: the complexation can be directed toward either the formation of a 1/1 complex (1 macrocycle/1 metal) or the preparation of a sandwich complex, depending on the ring size of the resulting macrocycle. Some of these complexes can be directly obtained from the free macrocycles.

All these experiments pointed out the diversity of reactions introduced by the starting phosphorus reagents in comparison with literature results. We believe that other useful transformations can also be developed using these routes and these acyclic and macrocyclic reagents.

Experimental Section

General. All manipulations were carried out with standard high-vacuum or dry argon atmosphere techniques. ^{1}H, ^{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. Mass spectra were obtained by fast atom bombardment or electro spray.

Synthesis of Compounds 8a,b and 9a,b. To a solution of dialdehyde **6** (0.60 g, 1.74 mmol) or **7** (0.68 g, 1.74 mmol) in 10 mL of THF was added powdered phosphodihydrazide **4a** (0.40 g, 1.74 mmol) at room temperature. After stirring for 18h, the solvent was evaporated and the resulting powder was washed several times with a chloroform/pentane (2/1) solution (**8a,b** mixture) or acetonitrile (**9a,b** mixture). The residue was pure **8a** or **9a**. The washing solutions were evaporated to dryness, and the resulting powder was extracted with a chloroform/pentane (1/1) solution. Evaporation of the solution gave **8b** or **9b**.

8a: pale yellow powder (42% yield). ^{31}P [^{1}H] NMR ($CDCl_3$): δ 78.8 (s). ^{1}H NMR ($CDCl_3$): δ 3.2 (d, $^{3}J_{HP}$ = 8.5 Hz, 6H, P-N-CH_3), 3.7 (br s, 4H, O-CH_2), 4.0 (br s, 4H, O-CH_2), 6.7–8.0 (m, 13H, C_6H_5, C_6H_3, and HC=N), 10.0 (br s, 2H, OH). ^{13}C NMR ($CDCl_3$): δ 30.4 (dq, $^{2}J_{CP}$ = 8.5 Hz, $^{1}J_{CH}$ = 139 Hz, P-N-CH_3), 68.6 (t, $^{1}J_{CH}$ = 141.0 Hz, O-CH_2), 69.2 (t, $^{1}J_{CH}$ = 141.0 Hz, O-CH_2), 115.6–133.4 (m, C_6H_5 and C_6H_3), 141.6 (dd, $^{3}J_{CP}$ = 12.0 Hz, $^{1}J_{CH}$ = 160.0 Hz, HC=N), 146.4 (m, C-OH or *C*-O-CH_2), 147.0 (m, C-OH or *C*-O-CH_2). IR (KBr): 1645 ($\nu_{C=N}$), 946 (ν_{P-N}), 657 ($\nu_{P=S}$) cm^{-1}. MS: *m/z* 541 [M + 1]$^+$. Anal. Calcd for $C_{26}H_{29}N_4O_5PS$: C, 57.77; H, 5.37; N, 10.37. Found: C, 57.27; H, 5.20; N, 10.68.

8b: yellow oil (3% yield). ^{31}P [^{1}H] NMR ($CDCl_3$): δ 77.3 (s). ^{1}H NMR ($CDCl_3$): δ 3.4 (d, $^{3}J_{HP}$ = 8.9 Hz, 6H, P-N-CH_3), 3.6 (br s, 4H, O-CH_2), 4.0 (br s, 4H, O-CH_2), 6.7–8.0 (m, 13H, C_6H_5, C_6H_3, and HC=N), 10.0 (br s, 2H, OH). ^{13}C [^{1}H] NMR ($CDCl_3$): δ 30.3 (d, $^{2}J_{CP}$ = 9.9 Hz, P-N-CH_3), 69.0 (s, O-CH_2), 70.4 (s, O-CH_2), 117.4–134.4 (m, C_6H_5 and C_6H_3), 140.7 (d, $^{3}J_{CP}$ = 12.0 Hz, HC=N), 145.9 (s, C-OH or *C*-O-CH_2), 147.8 (s, C-OH or *C*-O-CH_2). MS: *m/z* 541 [M + 1]$^+$.

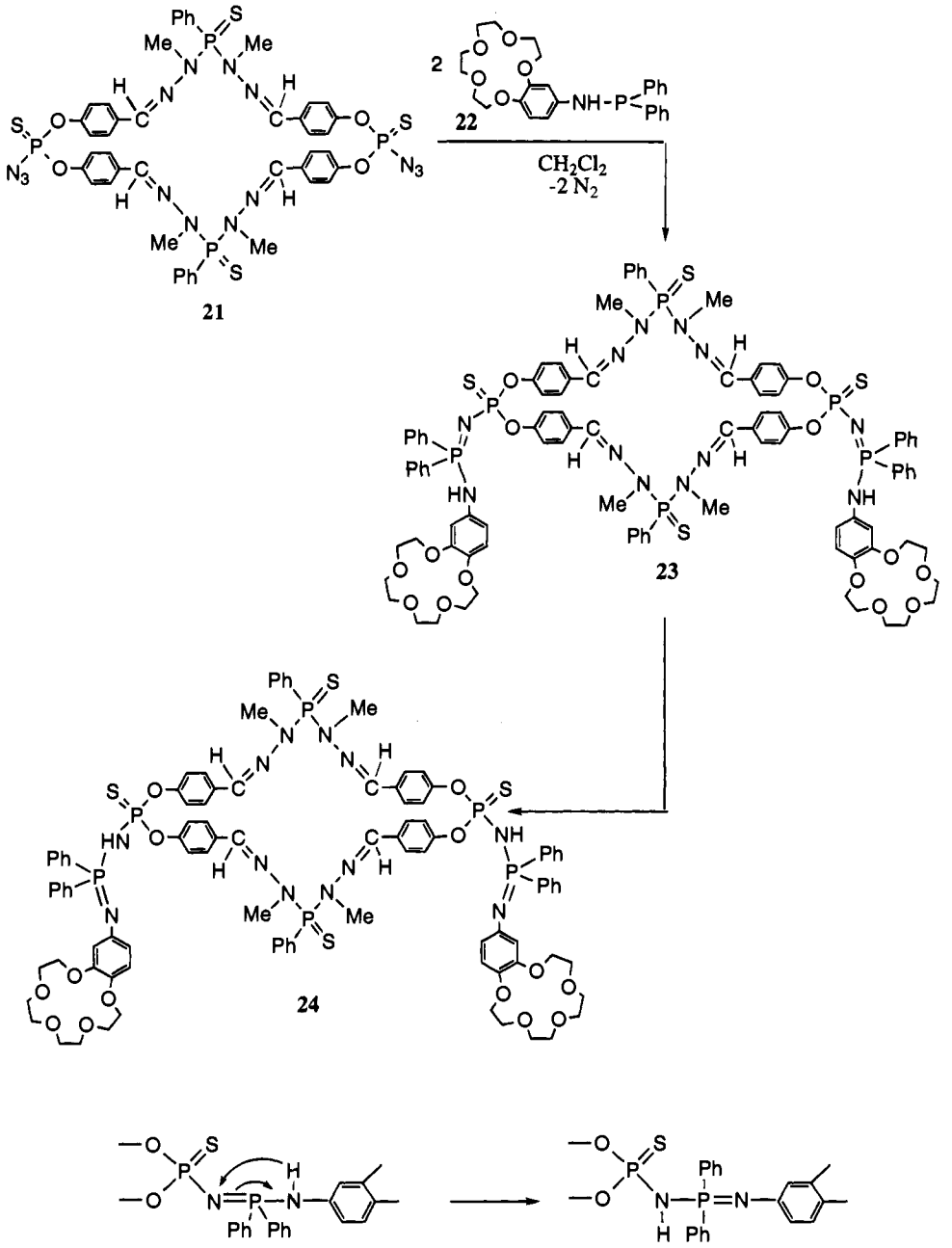
9a: pale yellow powder (46% yield). ^{31}P [^{1}H] NMR ($CDCl_3$): δ 78.8 (s). ^{1}H NMR ($CDCl_3$): δ 3.2 (d, $^{3}J_{HP}$ = 9.3 Hz, 6H, P-N-CH_3), 3.6 (br s, 4H, O-CH_2), 3.7 (br s, 4H, O-CH_2), 4.0 (br s, 4H, O-CH_2), 6.7–8.0 (m, 13H, C_6H_5, C_6H_3, and HC=N), 10.0 (br s, 2H, OH). ^{13}C NMR ($CDCl_3$): δ 30.4 (dq, $^{2}J_{CP}$ = 8.6 Hz, $^{1}J_{CH}$ = 139.5 Hz, P-N-CH_3), 68.6 (t, $^{1}J_{CH}$ = 144.3 Hz, O-CH_2), 69.0 (t, $^{1}J_{CH}$ = 142.0 Hz, O-CH_2), 70.1 (t, $^{1}J_{CH}$ = 141.2 Hz, O-CH_2), 115.6–133.4 (m, C_6H_5 and C_6H_3), 141.5 (dd, $^{3}J_{CP}$ = 12.3 Hz, $^{1}J_{CH}$ = 164.0 Hz, HC=N), 146.5 (m, C-OH or *C*-O-CH_2), 147.0 (m, C-OH or *C*-O-CH_2). IR (KBr) 1637 ($\nu_{C=N}$), 945 (ν_{P-N}), 657 ($\nu_{P=S}$) cm^{-1}. MS: *m/z* 585 [M + 1]$^+$. Anal. Calcd for $C_{28}H_{33}N_4O_6PS$: C, 57.52; H, 5.68; N, 9.58. Found: C, 57.95; H, 5.28; N, 9.21.

9b: yellow powder (3% yield). ^{31}P [^{1}H] NMR ($CDCl_3$): δ 78.5 (s). ^{1}H NMR ($CDCl_3$): δ 3.3 (d, $^{3}J_{HP}$ = 9.2 Hz, 6H, P-N-CH_3), 3.5 (m, 4H, O-CH_2), 3.7 (m, 4H, O-CH_2), 4.2 (m, 4H, O-CH_2), 6.7–7.9 (m, 13H, C_6H_5, C_6H_3, and HC=N), 9.6 (br s, 2H, OH). ^{13}C [^{1}H] NMR ($CDCl_3$): δ 30.2 (d, $^{2}J_{CP}$ = 10.2 Hz, P-N-CH_3), 69.1 (s, O-CH_2), 69.3 (s, O-CH_2), 70.3 (s, O-CH_2), 117.5–132.0 (m, C_6H_5 and C_6H_3), 140.2 (d, $^{3}J_{CP}$ = 12.0 Hz, HC=N), 146.3 (s, C-OH or *C*-O-CH_2), 147.5 (s, C-OH or *C*-O-CH_2). MS: *m/z* 585 [M + 1]$^+$.

Synthesis of Compounds 10a and 11a. To a solution of dialdehyde **6** (0.60 g, 1.74 mmol) or **7** (0.68 g, 1.74 mmol) in 10 mL of chloroform was added powdered phosphodihydrazide **4b** (0.37 g, 1.74 mmol) at room temperature. After stirring for 48 h, the solvent was evaporated and the resulting powder was washed with a 20 mL solution of dioxane.

10a: pale yellow powder (26% yield). ^{31}P [^{1}H] NMR ($CDCl_3$): δ 24.4 (s). ^{1}H NMR ($CDCl_3$): δ 3.2 (d, $^{3}J_{HP}$ = 9.3 Hz, 6H, P-N-CH_3), 3.6 (br s, 4H, O-CH_2), 3.9 (br s, 4H, O-CH_2), 6.7–8.0 (m, 13H, C_6H_5, C_6H_3, and HC=N), 9.9 (br s, 2H, OH). ^{13}C NMR ($CDCl_3$): δ 29.8 (dq, $^{2}J_{CP}$ = 7.6 Hz, $^{1}J_{CH}$ = 139.8 Hz, P-N-CH_3), 68.6 (t, $^{1}J_{CH}$ = 142.9 Hz, O-CH_2), 69.1 (t, $^{1}J_{CH}$ = 142.9 Hz, O-CH_2), 115.6–132.6 (m, C_6H_5 and C_6H_3), 140.6 (dd, $^{3}J_{CP}$ = 12.7 Hz, $^{1}J_{CH}$ = 153.0 Hz, HC=N), 146.4 (m, C-OH or *C*-O-CH_2), 147.0 (m, C-OH or *C*-O-CH_2). IR (KBr):

Scheme 6



1645 ($\nu_{C=N}$), 960 (ν_{P-N}), 1250 ($\nu_{P=O}$) cm^{-1}. MS: *m/z* 525 $[M + 1]^+$. Anal. Calcd for $C_{26}H_{29}N_4O_7P$: C, 59.54; H, 5.53; N, 10.69. Found: C, 59.17; H, 5.20; N, 10.88.

11a: pale yellow powder (24% yield). ^{31}P [^1H] NMR ($CDCl_3$): δ 24.3 (s). ^1H NMR ($CDCl_3$): δ 3.2 (d, $^3J_{HP}$ = 7.0 Hz, 6H, P-N-CH_3), 3.6 (br s, 4H, O-CH_2), 3.7 (br s, 4H, O-CH_2), 4.0 (br s, 4H, O-CH_2), 6.7–8.0 (m, 13H, C_6H_5, C_6H_3, and HC=N), 9.8 (br s, 2H, OH). ^{13}C NMR ($CDCl_3$): δ 29.8 (dq, $^2J_{CP}$ = 7.6 Hz, $^1J_{CH}$ = 139.8 Hz, P-N-CH_3), 68.6 (t, $^1J_{CH}$ = 146.0 Hz, O-CH_2), 69.1 (t, $^1J_{CH}$ = 146.0 Hz, O-CH_2), 70.0 (t, $^1J_{CH}$ = 146.0 Hz, O-CH_2), 115.6–132.3 (m, C_6H_5 and C_6H_3), 140.6 (dd, $^3J_{CP}$ = 13.0 Hz, $^1J_{CH}$ = 146.0 Hz, HC=N), 146.5 (m, C-OH or *C*-O-CH_2), 147.0 (m, C-OH or *C*-O-CH_2). MS: *m/z* 569 $[M + 1]^+$. Anal. Calcd for $C_{28}H_{33}N_4O_7P$: C, 59.15; H, 5.81; N, 9.86. Found: C, 58.96; H, 5.99; N, 10.10.

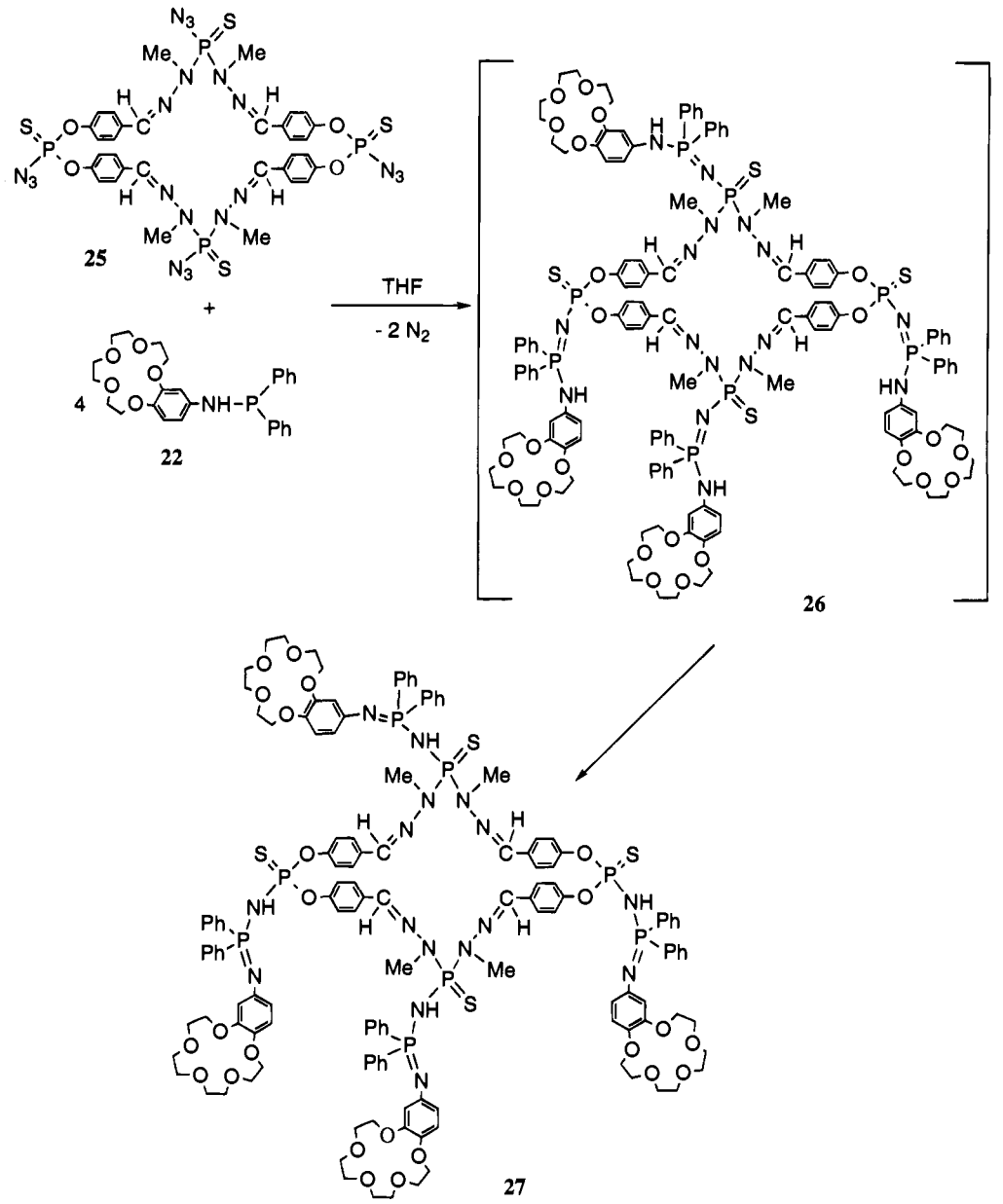
Synthesis of Compound 12. First Method. A solution of dialdehyde **7** (0.10 g, 0.256 mmol) in 10 mL of THF and a solution of phosphodihydrazide **4a** (0.06 g, 0.256 mmol) in 10 mL of methanol were added dropwise and simultaneously to a refluxing solution of Ba$(SO_3CF_3)_2$ (0.11 g, 0.256 mmol) in 20 mL of methanol. The resulting solution was refluxed for 3 h and then stirred overnight at room temperature. The solvent was evaporated, and the powder thus obtained was washed with methanol to give **12**.

Second Method. To a solution of macrocycle **9** (0.15 g, 0.257 mmol) in 20 mL of chloroform was added a solution of $Ba(SO_3CF_3)_2$ (0.11g, 0.257 mmol) in 10 mL of methanol. The mixture was refluxed for 3 days and then the solution evaporated to dryness. The resulting powder was washed with methanol to give pure **12**.

12: white powder (first method, 76% yield; second method, 86% yield). ^{31}P [^1H] NMR ($CDCl_3$): δ 75.3 (s) ppm. ^1H NMR ($CDCl_3$): δ 3.4 (d, $^3J_{HP}$ = 8.7 Hz, 6H, P-N-CH_3), 3.9 (br s, 4H, O-CH_2), 4.1 (br s, 4H, O-CH_2), 4.4 (br s, 4H, O-CH_2), 6.8–7.7 (m, 13H, C_6H_5, C_6H_3, and HC=N), 11.5 (br s, 2H, OH). ^{13}C [^1H] NMR ($CDCl_3$): δ 34.5 (d, $^2J_{CP}$ = 5.1 Hz, P-N-CH_3), 68.8 (s, O-CH_2), 71.1 (s, O-CH_2), 71.5 (s, O-CH_2), 121.1 (q, $^1J_{CF}$ = 250.0 Hz, CF_3), 114.9–134.7 (m, C_6H_5 and C_6H_3), 143.4 (d, $^3J_{CP}$ = 12.3 Hz, HC=N), 146.1 (s, C-OH or *C*-O-CH_2), 147.8 (s, C-OH or *C*-O-CH_2). ^{19}F [^1H] NMR ($CDCl_3$): δ −2.4. IR (KBr): 1300 (ν_{CF_3}), 1249–1031–638 (ν_{SO_3}) cm^{-1}. MS:[13] *m/z* 871 $[M - CF_3SO_3]^+$, 623 $[\mathbf{9a} + K]^+$. Anal. Calcd. for $C_{30}H_{33}BaF_6N_4O_7PS$:

(13) The ionization in electro spray technique is performed in the presence of potassium and sodium which displays barium from the complex.

Scheme 7



C, 35.32; H, 3.26; N, 5.49; Ba, 13.46; P, 3.03. Found: C, 35.27; H, 3.23; N, 5.41; Ba, 13.51; P, 2.98.

Synthesis of Compound 13. Same experimental procedure as for **12** (first method) was used with 1.17 g of **7** (3 mmol) in THF (30 mL), 0.642 g of **4b** (3 mmol) in methanol (30 mL), and 1.30 g of $Ba(SO_3CF_3)_2$ (3 mmol) in methanol (80 mL).

13: yellow powder (80% yield). ^{31}P [^1H] NMR (CD_3OD): δ 25.2 (s). ^1H NMR (CD_3OD): δ 3.21 (d, $^3J_{HP}$ = 7.2 Hz, 6H, P-N-CH_3), 3.67 (br s, 4H, O-CH_2), 3.85 (br s, 4H, O-CH_2), 4.03 (br s, 4H, O-CH_2), 6.60–8.0 (m, 13H, CH=N, C_6H_3, and C_6H_5). ^{13}C [^1H] NMR (CD_3OD): δ 32.3 (d, $^2J_{CP}$ = 6 Hz, P-N-CH_3), 68.5 (s, CH_2O), 70.6 (s, CH_2O), 71.3 (s, CH_2O), 114.3 (s, C_6H_3), 120.7 (s, *C*-CH=N), 121.8 (s, C_6H_3), 124.6 (s, C_6H_3), 131.1–135.8 (m, C_6H_5), 144.9 (d, $^3J_{CP}$ = 13.1 Hz, CH=N), 146.3 (s, *C*-O-CH_2 or *C*-OH), 148.0 (s, *C*-OH or *C*-O-CH_2). ^{19}F NMR [^1H] ($CDCl_3$): δ −2.7. IR (KBr): 1300 (ν_{CF_3}), 1242–1030–638 (ν_{SO_3}) cm^{-1}. MS:[13] *m/z* 855 $[M - CF_3SO_3]^+$, 607 $[9 + K]^+$, 353 $[M - 2CF_3SO_3]^{2+}$. Anal. Calcd for $C_{30}H_{33}BaF_6N_4O_{13}PS_2$: C, 35.88; H, 3.31; N, 5.58; Ba, 13.67; P, 3.08. Found: C, 35.92; H, 3.34; N, 5.57; Ba, 13.55; P, 3.13.

Synthesis of Compound 14. Same experimental procedure as for **13** was used with 1.039 g of **6** (3 mmol) and 0.690 g of **4a** (3 mmol). Crystals suitable for X-ray structure determination were grown in a CH_2Cl_2/ether (1/1) solution.

14: yellow powder (80% yield). ^{31}P [^1H] NMR (CD_3OD): δ 74 (s). ^1H NMR (CD_3COCD_3): δ 3.58 (d, $^3J_{HP}$ = 9.4 Hz, 6H, P-N-CH_3), 3.91 (br s, 4H, O-CH_2), 4.23 (br s, 4H, O-CH_2), 6.78–7.90 (m, 11H, C_6H_3 and C_6H_5), 8.10 (s, 2H, CH=N), 10.90 (s, 2H, OH) ppm; ^{13}C [^1H] NMR (CD_3COCD_3): δ 31.0 (d, $^2J_{PC}$ = 8.6 Hz, P-N-CH_3), 66.0 (s, CH_2), 67.2 (s, CH_2O), 113.2 (s, C_6H_3), 118.0 (d, $^1J_{PC}$ = 5.7 Hz, *Cipso* C_6H_5), 119.2 (s, *C*-CH=N and C_6H_3), 119.9 (s, C_6H_3), 123.1 (s, C_6H_3), 129.5–132.9 (m, C_6H_5), 143.0 (d, $^3J_{PC}$ = 11.8 Hz, CH=N), 145.67 (s, *C*-O-CH_2 or *C*-OH), 146.15 (s, *C*-OH or *C*-O-CH_2). ^{19}F [^1H] NMR ($CDCl_3$): δ −2.5. IR (KBr) 1305 (ν_{CF_3}), 1240–1032–637 (ν_{SO_3}) cm^{-1}. MS:[13] *m/z* 609 $[28 + Ba - 2CF_3SO_3]^{2+}$, 579 $[8 + K]^+$, 563 $[8 + Na]^+$. Anal. Calcd for $C_{158}H_{174}BaF_6N_{24}O_{36}P_6S_8{\cdot}C_3H_6Cl_6$: C, 49.16; H, 4.61; N, 8.56; Ba, 3.49; P, 4.72. Found: C, 48.94; H, 4.58; N, 8.47; Ba, 3.41; P, 4.64.

Synthesis of Compounds 15a,b. A solution of dialdehyde **7** (0.585 g, 1.5 mmol) in 50 mL of THF and a solution of phosphotrihydrazide **5a** (0.198 g, 1 mmol) or **5b** (0.182 g, 1 mmol) in 50 mL of methanol were added very slowly and simultaneously to 100 mL of methanol at room temperature. The mixture was stirred for 2 h, and then the solvent was evaporated and the resulting powder washed with a methanol/THF (1/1) solution. The residue was then extracted several times with a $CHCl_3/CH_3CN$ solution. Evaporation of the combined solutions gave **15a** or **15b**.

15a: white powder (65% yield). ^{31}P [^1H] NMR ($CDCl_3$): δ 71.2 (s). ^1H NMR ($CDCl_3$): δ 3.33 (d, $^3J_{HP}$ = 9.2 Hz, 6H, P-N-CH_3), 3.35 (d, $^3J_{HP}$ = 9.2 Hz, 12H, P-N-CH_3), 3.38–3.66 (m, 36H, CH_2), 6.64–6.93 (m, 18H, C_6H_3), 7.87 (br s, 6H, CH=N), 9.90 (s, 4H, OH), 10.33 (s, 2H, OH). ^{13}C [^1H] NMR ($CDCl_3$): δ 31.7 (d, $^2J_{CP}$ = 10.5 Hz, P-N-CH_3), 32.2 (d, $^2J_{CP}$ = 8.4 Hz, P-N-CH_3), 69.5–70.9 (m, O-CH_2), 117.1–118.9 (m, C_6H_3), 119.7 (s, *C*-CH=N), 120.0 (s, *C*-CH=N), 123.2 (s, C_6H_3), 141.9 (d, $^3J_{CP}$ = 13 Hz, *C*H=N), 141.9 (d, $^3J_{CP}$ = 14.1 Hz, CH=N), 146.9 (s, *C*-OH or *C*-O-CH_2), 147.0 (s, *C*-OH or *C*-O-CH_2), 148.1 (s, *C*-OH or *C*-O-CH_2), 148.2 (s, *C*-OH or *C*-O-CH_2). IR (KBr): 1645 ($\nu_{C=N}$), 963 (ν_{P-N}), 652 ($\nu_{P=S}$) cm^{-1}. MS: *m/z* 1459 [M + 1]$^+$. Anal. Calcd for $C_{66}H_{84}N_{12}O_{18}P_2S_2$: C, 54.31; H, 5.80; N, 11.51. Found: C, 54.27; H, 5.77; N, 11.50.

15b: white powder (80% yield). ^{31}P [^1H] NMR (THF): δ 11.2 (s). ^1H NMR ($CDCl_3$): δ 3.29 (d, $^3J_{HP}$ = 10.0 Hz, 6H, P-N-CH_3), 3.21 (d, $^3J_{HP}$ = 9.8 Hz, 12H, P-N-CH_3), 3.35–3.61 (m, 36H, CH_2), 6.59–6.90 (m, 18H, C_6H_3), 7.73 (br s, 6H, CH=N), 9.89 (s, 4H, OH), 10.25 (s, 2H, OH) ppm; ^{13}C [^1H] NMR ($CDCl_3$): δ 31.6 (d, $^2J_{CP}$ = 9.8 Hz, P-N-CH_3), 32.3 (d, $^2J_{CP}$ = 8.2 Hz, P-N-CH_3), 69.4–70.7 (m, CH_2), 116.8–119.0 (m, C_6H_3), 119.9 (s, *C*-CH=N), 121.0 (s, *C*-CH=N), 123.2 (s, C_6H_3), 140.8 (d, $^3J_{CP}$ = 13.9 Hz, CH=N), 142.0 (d, $^3J_{CP}$ = 12.7 Hz, CH=N), 146.9 (s, *C*-OH or *C*-O-CH_2), 147.1 (s, *C*-OH or *C*-O-CH_2), 148.3 (s, *C*-OH or *C*-O-CH_2), 148.5 (s, *C*-OH or *C*-O-CH_2). IR (KBr): 1643 ($\nu_{C=N}$), 965 (ν_{P-N}) cm^{-1}. MS: *m/z* 1427 [M + 1]$^+$. Anal. Calcd for $C_{66}H_{84}N_{12}O_{20}P_2$: C, 55.53; H, 5.93; N, 11.77. Found: C, 55.49; H, 5.91; N, 11.74.

Synthesis of Compound 16. A solution of dialdehyde **7** (0.781 g, 2 mmol) in 40 mL of THF and a solution of phosphotrihydrazide **5a** (0.396 g, 2 mmol) in 40 mL of methanol were added dropwise and simultaneously to 80 mL of methanol at room temperature. The mixture was stirred for 3 h, and then the solution was evaporated to dryness and the resulting powder washed with methanol.

16: white powder (30% yield). ^{31}P [^1H] NMR ($CDCl_3$): δ 76.4 (s). ^1H NMR ($CDCl_3$): δ 2.98 (d, $^3J_{HP}$ = 11.5 Hz, 3H, P-N-CH_3), 3.30 (d, $^3J_{HP}$ = 9 Hz, 6H, P-N-CH_3), 3.69 (br s, 4H, O-CH_2), 3.75 (br s, 4H, O-CH_2), 4.09 (br s, 4H, O-CH_2), 6.69–6.96 (m, 6H, C_6H_3), 7.78 (s, 2H, CH=N) ppm; ^{13}C [^1H] NMR (CD_3CN) δ 32.4 (d, $^2J_{PC}$ = 7.0 Hz, P-N(CH_3)N=), 41.3 (d, $^2J_{PC}$ = 10.0 Hz, P-N(*C*H_3)NH_2), 69.1 (s, CH_2O), 70.2 (s, CH_2O), 71.3 (s, CH_2O), 115.1 (s, C_6H_3), 119.7 (s, C_6H_3), 120.7 (s, *C*-CH=N and C_6H_3), 123.0 (s, C_6H_3), 142.7 (d, $^3J_{PC}$ = 14.0 Hz, CH=N), 147.9 (br s, *C*-OH and *C*-O-CH_2). MS: *m/z* 553 [M + 1]$^+$. Anal. Calcd for $C_{23}H_{33}N_6O_6P$: C, 49.98; H, 6.02; N, 15.21. Found: C, 50.06; H, 6.10; N, 10.17.

Synthesis of Compound 17. To a solution of 3-hydroxybenzaldehyde (2.44 g, 20 mmol) in 20 mL of THF was added freshly distillated triethylamine (2.8 mL, 20 mmol) at room temperature. This mixture was stirred for 30 min and then slowly added to a solution of thiophosphoryl chloride (1.01 mL, 10 mmol) in 20 mL of THF at −100 °C (bath temperature). The solution was stirred for 2 h at this temperature and then warmed to room temperature. After filtration, the solvent was evaporated and the resulting powder was washed with a chloroform/pentane (1/1) solution.

17. ^{31}P [^1H] NMR ($CDCl_3$): δ 57.9 (s) ppm; ^1H NMR ($CDCl_3$): δ 7.2–7.8 (m, 8H, C_6H_4), 9.8 (s, 2H, CHO).

Macrocycle 18. To a solution of dialdehyde **17** (10 mmol) prepared *in situ* in 30 mL of THF at −100 °C was rapidly added a solution of phosphodihydrazide **4a** (2.30 g, 10 mmol) in 90 mL of THF. The mixture was warmed at room temperature overnight, and then the solvent was evaporated.

18: pale yellow powder (90% yield). ^{31}P [^1H] NMR ($CDCl_3$): δ 78.5 (s, N-P-N), 57.3 (s, O-P-O). ^1H NMR ($CDCl_3$): δ 3.2 (d, $^3J_{HP}$ = 8 Hz, 6H, P-N-CH_3), 7.0–8.1 (m, 15H, C_6H_4, C_6H_5, CH=N). ^{13}C [^1H] NMR ($CDCl_3$): δ 30.8 (d, $^2J_{CP}$ = 10 Hz, P-N-CH_3), 112.0–137.2 (m, C_6H_5, C_6H_4 and HC=N), 149.7 (d, $^2J_{CP}$ = 10 Hz, C-O-P). MS: *m/z* 535 [M + 1]$^+$. Anal. Calcd for $C_{22}H_{21}ClN_4O_2P_2S_2$: C, 49.39; H, 3.95; N, 10.47. Found: C, 49.52; H, 4.12; N, 10.43.

Synthesis of Compound 19. A solution of phosphodihydrazide **4a** (2.30 g, 10 mmol) in 50 mL of dichloromethane was added to a solution of 4-hydroxybenzaldehyde (2.44 g, 20 mmol) in 50 mL of dichloromethane, in the presence of molecular sieves (4 Å). After stirring overnight at room temperature, the solution was filtered and the solvent evaporated. The dihydrazone thus obtained in quantitative yield was dissolved in 50 mL of THF and added dropwise to a suspension of sodium hydride (0.48 g, 20 mmol) in 20 mL of THF. The mixture was stirred for 3 h at room temperature, and an oil was obtained on the walls of the vessel. The solution was transferred and eliminated. The oil was recovered and washed with 10 mL of pentane.

19: brown powder (70% yield). ^{31}P [^1H] NMR (DMSO-d_6): δ 75.9 (s). ^1H NMR (DMSO-d_6): δ 3.2 (d, $^3J_{HP}$ = 11.2 Hz, 6H, P-N-CH_3), 6.3 (d, $^3J_{HH}$ = 8 Hz, 4H, C_6H_4), 7.2 (d, $^3J_{HH}$ = 8 Hz, 4H, C_6H_4), 7.6–8.2 (m, 7H, C_6H_5 and CH=N).

Synthesis of Compound 20. To a solution of macrocycle **18** (0.35 g, 0.66 mmol) in 20 mL of THF was added the diphenate **19** (0.151 g, 0.33 mmol of oil in 10 mL of THF). After stirring for 3 h at room temperature, the mixture was filtered and the solvent was evaporated. The resulting yellow powder was washed twice with 20 mL of methanol.

20: yellow powder (80% yield). ^{31}P [^1H] NMR ($CDCl_3$): δ 79.3 (s, N-P-N), 78.7 (s, N-P-N), 52.5 (s, O-P-O). ^1H NMR ($CDCl_3$): δ 2.8–3.2 (m, 18H, P-N-CH_3), 6.5–8.2 (m, 45H, C_6H_4, C_6H_5, and CH=N). ^{13}C [^1H] NMR ($CDCl_3$): δ 30.7 (d, $^2J_{CP}$ = 10.0 Hz, P-N-CH_3), 114.9–139.9 (m, C_6H_4, C_6H_5 and CH=N), 150.1 (d, $^2J_{CP}$ = 8.0 Hz, C-O-P). MS: *m/z* 1435 [M + 1]$^+$. Anal. Calcd for $C_{66}H_{84}N_{12}O_6P_5S_5$: C, 55.24; H, 4.42; N, 11.71. Found: C, 55.17; H, 4.36; N, 11.65.

Synthesis of Compound 21. To a solution of 4-hydroxybenzaldehyde (4.88 g, 40 mmol) in 80 mL of THF was added triethylamine (5.56 mL, 40 mmol). After stirring for 30 min, this mixture was added dropwise to a solution of thiophosphoryl chloride (2.02 mL, 20 mmol) in 60 mL of THF at −100 °C (bath temperature). The resulting mixture was stirred overnight while the temperature was allowed to raise up slowly at room temperature. After filtration, sodium azide (1.30 g, 20 mmol) was added at room temperature and the mixture was stirred for 24 h and then filtered. To this solution of dialdehyde was added *in situ* a solution of phosphodihydrazide **4a** (4.605 g, 20 mmol) in 100 mL of THF at room temperature and in the presence of molecular sieves (4 Å). After stirring for 3 h, the solution was filtered and the solvent was evaporated. Several washings with methanol gave pure **21**.

21: white powder (90% yield). ^{31}P [^1H] NMR ($CDCl_3$): δ 79.2 (s, N-P-N), 58.7 (s, O-P-O). ^1H NMR ($CDCl_3$): δ 3.2 (d, $^3J_{HP}$ = 9 Hz, 12H, P-N-CH_3), 6.7–8.2 (m, 30H, C_6H_4, C_6H_5, and CH=N). ^{13}C [^1H] NMR ($CDCl_3$): δ 31.2 (d, $^2J_{CP}$ = 9 Hz, P-N-CH_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, C-O-P). IR (KBr): 2161 (ν_{N_3}) cm^{-1}. MS: *m/z* 1083 [M + 1]$^+$. Anal. Calcd for $C_{44}H_{42}N_{14}O_4P_4S_4$: C, 48.79; H, 3.90; N, 18.10. Found: C, 48.69; H, 3.87; N, 18.06.

Synthesis of Compound 22. A mixture of triethylamine (0.074 mL, 0.53 mmol) and 4′-aminobenzo-15-crown-5 (0.150 g, 0.53 mmol) in 10 mL of dichloromethane was added to a solution of chlorodiphenylphosphine (0.095 mL, 0.53 mmol) in 10 mL of dichloromethane at −40 °C. After the addition, the mixture was stirred for 1 h at room temperature and then filtered. This product is unstable and was used *in situ* for further reactions.

22: pink powder (90% yield). ^{31}P [^1H] NMR (CH_2Cl_2): δ 70.7 (s).

Synthesis of Compound 24. To a solution of phosphine **22** synthesized *in situ* (0.42 mmol) in 15 mL of dichloromethane was added a solution of macrocycle **21** (0.23 g, 0.21 mmol) in 10 mL of dichloromethane. After stirring for 72 h at room temperature, the solvent was evaporated and the powder thus obtained was washed with a CH_2Cl_2/pentane mixture (1/4).

24: beige powder (86% yield). ^{31}P [^1H] NMR ($CDCl_3$): δ 79.1 (s, N-P-N), 48.9 (br d, $^2J_{PP}$ = 29 Hz, O-P-N), 10.7 (br d, $^2J_{PP}$ = 29 Hz, N=P-N). ^1H NMR ($CDCl_3$): δ 3.1–3.4 (m, 12H, P-N-CH_3), 3.5–4.2 (m, 32H, CH_2), 6.1–6.7 (m, 6H, C_6H_3), 6.9–8.2 (m, 50H, C_6H_4, C_6H_5, and CH=N). ^{13}C [^1H] NMR ($CDCl_3$): δ 30.6 (d, $^2J_{CP}$ = 9 Hz, P-N-CH_3), 68.0–70.1 (m, CH_2), 102.4 (s, C_6H_3), 107.1 (s, C_6H_3), 116.7 (s, C_6H_3), 114.6–134.5 (m, C_6H_3*ipso*, C_6H_5, C_6H_4, and CH=N), 149.3 (br s, *C*-O-CH_2), 151.5 (br d, $^2J_{CP}$ = 10 Hz, C-O-P) ppm. MS: *m/z* 1961 [M + 1]$^+$. Anal. Calcd for $C_{96}H_{102}N_{12}O_{14}P_6S_4$: C, 58.76; H, 5.24; N, 8.56. Found: C, 58.69; H, 5.12; N, 8.49.

Synthesis of Compound 25. Same procedure as for **21** was performed, using $N_3P(S)(NMeNH_2)_2$ instead of phosphodihydrazide **4a**. This functionalized phosphodihydrazide was obtained by addition of sodium azide (1.95 g, 30 mmol) to a mixture of dibenzo-18-crown-6

(0.72 g, 2 mmol) and $ClP(S)(NMeNH_2)_2$[14] (3.77 g, 20 mmol) in 100 mL of THF. The mixture was stirred for 4 days at room temperature and then filtered and evaporated to dryness. The white solid thus obtained was washed several times with toluene.

25: yellow powder (80% yield). ^{31}P [^1H] NMR ($CDCl_3$): δ 67.2 (s, N-P-N), 59.2 (s, O-P-O). ^1H NMR ($CDCl_3$): δ 3.2 (d, $^3J_{HP}$ = 9.6 Hz, 12H, P-N-CH_3), 6.8−7.8 (m, 20H, C_6H_4 and CH=N). ^{13}C [^1H] NMR ($CDCl_3$): δ 32.3 (d, $^2J_{CP}$ = 8.7 Hz, P-N-CH_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): 2150 and 2162 (ν_{N_3}) cm^{-1}. MS: *m/z* 1013 [M + 1]$^+$. Anal. Calcd for $C_{32}H_{32}N_{20}O_4P_4S_4$: C, 37.88; H, 3.18; N, 27.61. Found: C, 37.10; H, 3.20; N, 27.89.

Synthesis of Compound 27. To a solution of phosphine **22** synthesized *in situ* (1.72 mmol) in 20 mL of THF was added a solution of macrocycle **25** (0.435 g, 0.43 mmol) in 20 mL of THF at room temperature. After stirring for 5 days, the solvent was evaporated. The resulting powder was washed first with a dichloromethane/pentane solution and then with a THF/pentane solution.

27: beige powder (83% yield). ^{31}P [^1H] NMR (CH_2Cl_2): δ 54.2 (d, $^2J_{PP}$ = 20.9 Hz, N-P(S)-N), 49.2 (d, $^2J_{PP}$ = 28.5 Hz, O-P(S)-O), 10.3 (d, $^2J_{PP}$ = 28.5 Hz, N=P-N), 8.6 (d, $^2J_{PP}$ = 20.9 Hz, N=P-N). ^1H NMR ($CDCl_3$): δ 3.2 (d, $^3J_{HP}$ = 8.0 Hz, 12H, P-N-CH_3), 3.6−4.2 (m, 68H, NH and O-CH_2), 6.2−8.0 (m, 72H, C_6H_3, C_6H_4, C_6H_5, and CH=N). ^{13}C [^1H] NMR ($CDCl_3$): δ 32.5 (d, $^2J_{CP}$ = 10.0 Hz, P-N-CH_3), 68.6−70.7 (m, O-CH_2), 102.4 (s, C_6H_3), 107.2 (s, C_6H_3), 117.1 (s, C_6H_3), 114.8−132.3 (m, *C*-CH=N, C_6H_5, C_6H_4, and CH=N), 148.9 (br s, *C*-O-CH_2), 151.2 (br s, C-O-P). MS: *m/z* 2769 [M + 1]$^+$. Anal. Calcd for $C_{136}H_{152}N_{16}O_{24}P_8S_4$: C, 58.95; H, 5.53; N, 8.08. Found: C, 59.12; H, 5.61; N, 8.15.

Crystallographic Analyses for 14. A selected crystal was mounted on an automatic diffractometer. Unit cell dimensions with estimated standard deviations were obtained from least-squares refinements of the setting angles of 25 well-centered reflections. Three standard reflections were monitored periodically; they showed no change during data collection carried out at room temperature (21 °C). Crystallographic data and other pertinent information are summarized in Table 1. Corrections were made for Lorentz and polarization effects. Absorption corrections (Difabs)[15] were applied.

Computations were performed by using CRYSTALS[12] adapted to a PC. Atomic form factors for neutral Ba, P, S, N, Cl, O, F, and H atoms were taken from ref 16. The structure was solved by direct methods using the SHELX86 program.[17]

Although the macrocycle could be easily located, localization of the Ba atom and triflate anion group appeared to be difficult. The electron density observed for the Ba site on the inversion center appeared lower than the one expected for a 56-electron atom. These observations lead to consider a partial occupation of the Ba site. A multiplicity refinement of Ba atoms indicated that there is 0.7 Ba atom in the whole unit cell. Consequently, the triflate anion would also present a statistic arrangement with a total of 1.4 triflate in the unit cell. However, the electron density in the triflate region was broad and diffuse. The best model to fit with the electron density was to consider a mixup of SO_3CF_3 (0.35) and CH_2Cl_2 (0.5). Refinement of this model gave convergence at R = 0.069. The triflate and the dichloromethane were constrained to have chemically reasonable values (C−F = 1.30 Å, S−O = 1.40 Å, C−S = 1.80 Å, O−S−C = 109°, F−S−C = 109°, Cl−C−Cl = 109°).

The hydrogen atoms attached to the C atoms of the macrocycle were located on difference Fourier syntheses, but their coordinates were introduced in the refinement as fixed contributors in calculated positions and recalculated after each cycle. They were assigned isotropic thermal parameters 20% higher than those of the carbon to which they were attached. Hydrogens attached to O atoms were refined with an overall isotropic thermal parameter. Anisotropic temperature factors were introduced for all non-hydrogen atoms, except for the F and C atoms of the triflate and the C atoms of the CH_2Cl_2 solvent. Full-matrix least-squares refinements were carried out by minimizing the function $\Sigma_w(|F_o| - |F_c|)^2$, where F_o and F_c are the observed and calculated structure factors. Models reached convergence with $R = \Sigma(||F_o| - |F_c||)/\Sigma|F_o|$ and $R_w = [\Sigma_w(|F_o| - |F_c|)^2/\Sigma_w(F_o)^2]^{1/2}$ having values listed in Table 1. Criteria for a satisfactory complete analysis were the ratios of rms shifts to standard deviation being less than 0.1 and no significant features in final difference maps.

Acknowledgment. This work was supported by the CNRS (France).

Supplementary Material Available: Final fractional atomic coordinates, interatomic bond distances and bond angles, anisotropic thermal parameters, and idealized coordinates for H atoms (5 pages); tables of calculated and observed structure factors (16 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

JA943245I

(14) Majoral, J. P.; Kraemer, R.; Navech, J.; Mathis, F. *J. Chem. Soc. Perkin Trans. 1* **1976**, 2093.

(15) Walker, N.; Stuart, D. *Acta Crystallogr.* **1983**, *39*, 158.

(16) *International Tables for X-ray Crystallography*; Kynoch Press: Birmingham, England, 1974; Vol. IV.

(17) Sheldrick, G. M. *SHELXS86, Program for Crystal Structure Solution*; University of Göttingen: Göttingen, Germany, 1986.