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New Types of Phosphorus-Containing Crown Ethers

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ABSTRACT: *The first phosphorus-containing crown ethers with regularly alternating arylene and phosphorus acid residues have been obtained. Structural peculiarities and some chemical properties of these compounds have been studied. Rhodium complexes of new phosphorus-containing macrocycles have been prepared.* © 1998 John Wiley & Sons, Inc. Heteroatom Chem 9: 643–649, 1998

INTRODUCTION

The discovery of crown ethers and the revelation of their unique chemical properties [1] stimulated investigations on complex macroheterocyclic compounds, including those containing phosphorus. Classic crown ethers, whose hydrocarbon components contain phosphorus functions, have been synthesized [2,3]. The design of molecular structures with phosphate and phosphonate functions in their skeletons has been achieved [4–6]. The oligomerizations of alkylene phosphites and amidophosphites have been carried out [7–9]. In these cases, mixtures of oligoalkylene cyclophosphites (amidophosphites) were formed. This approach did not result in the isolation of pure compounds.

We sought to design a new type of phosphorus-containing crown ether with regularly alternating symmetric arylene moieties and units of phosphorus acids. Resorcinol was used as the starting material, and molecular assemblage was used as the synthetic method. Another goal of the work was to study the structures of compounds obtained and their specific chemical characteristics depending on the ring size and other factors.

The plan of the syntheses involved an initial combination of resorcinol (**1**) with hexaalkyltriamides of phosphorus acid (**2**). At the first stage, this combination was used for obtaining linear oligonuclear intermediates with active peripheral groups. The identities and structures of these compounds were monitored by spectral methods. The second stage of each synthesis involved the cyclization of the intermediates by the phosphamine method [10,11].

The choice of resorcinol as the starting compound was made on the basis of important factors. Because the direct cyclophosphorylation of this diol by phosphamides is impossible, phosphorylations of resorcinol by phosphamides **2** with the formation of bisamidophosphites **3** were first performed [12].

The phosphamides **2** were chosen as the main reagents because of their high phosphorylating capacity [10] and because of the possibility for optimizing conditions for the selective, stepwise phosphorylation of the multiple phosphamide bonds [13].

The first goal of the work was the synthesis of cyclo-*tris*-resorcinolamidophosphites (**5**). For this purpose, a double phosphorylation of resorcinol by phosphamides **2** with the formation of bisamidophosphites **3** was first performed. The latter were isolated in pure form by high-vacuum distillation.

The bisamidophosphites **3** were then converted

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Dedicated to Prof. Robert R. Holmes on the occasion of his 70th birthday.
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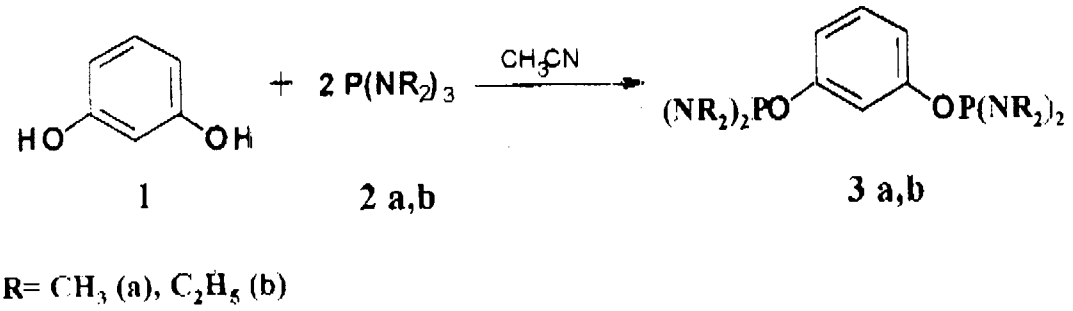
into the trinuclear diols (**4**) by reactions with resorcinol with the use of a 1:2 ratio of the reagents. The phosphorylation was monitored by means of ^{31}P NMR spectroscopy and TLC. For reliable identification, a portion of the product **4** was treated with sulfur.* The thiophosphoryl compound **7b** was isolated in pure form, and its structure was elucidated.

At the final step, trinuclear bisphenols **4**, without special purification, were cyclized by treatment with phosphotriamides **2** [13]. This phosphorylation yielded macroheterocycles **5** that were further characterized by conversion to sulfides **6**.

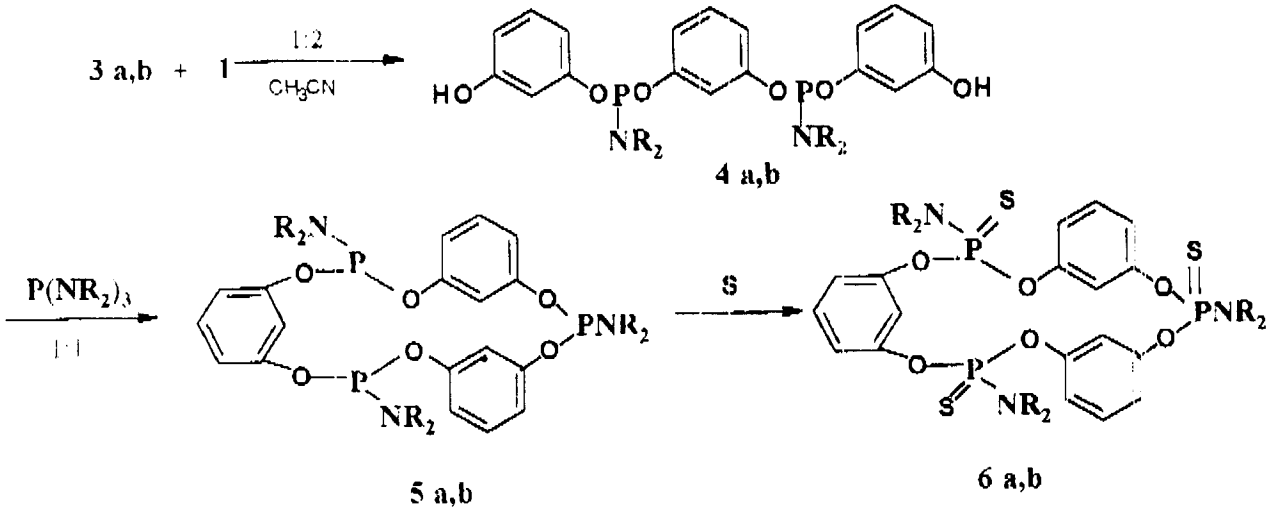
The occurrence of complete cyclization was confirmed by means of ^{31}P NMR spectroscopy of the thiophosphates **6**. The most interesting results were obtained with thiophosphate **6a** that was obtained in a relatively pure crystalline form. Two signals were observed in the ^{31}P NMR spectrum at 34°C, δ = 66.92 and 67.57, Δ 0.65 in a 1:2 ratio. By a decrease of the recording temperature to −60°C, an improvement of the resolution of the signals was achieved, with an increase of Δ to 0.9. In the proton spectra, two signals from amide and aromatic protons were observed in a 1:2 ratio, the former signals being well resolved and the latter broadened. These spectral data indicated that one phosphorus atom and aryl moiety differ in spatial arrangements from the others.

The recrystallization of compound **6a** from benzene resulted in crystals suitable for X-ray diffraction analysis. It was shown that the crystals contained molecules of **6a** and solvent of crystallization in a 1:1 ratio. The data for **6a** were refined in anisotropic approximation (hydrogen atoms not being refined) to R 0.044 and 0.072, respectively. It was found that all oxygen atoms were statistically randomized relative to the corresponding phosphorus atoms with a population of about 0.5, which resulted in the

*Product **4** has an unusual chemical nature. Its molecules contain phenolic hydroxyl groups and phosphamide functions, i.e., groups that can generally interact. However, we have found conditions wherein these groups did not realize their reciprocal activity. Under these conditions, product **4** can exist as an individual chemical entity.



SCHEME 1



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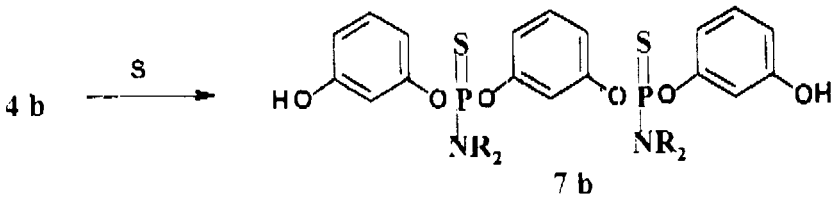


SCHEME 3

distortion of positional and heat parameters of the carbon atoms of the six-membered rings. Nevertheless, the general molecular configuration in the crystal may be thought of as having been determined unambiguously. It can be seen from Figure 1 that two aromatic rings are parallel to the central plane of the molecule and that the third ring deviates from this plane. The phosphorus atoms are also arranged differently: one phosphorus atom is over the plane, and the other two phosphorus atoms are under the ring plane. These data confirm our assumption, based on the spectral data, about the nonequivalence of the phosphorus atoms and aromatic units.

A subsequent stage of our investigation included the synthesis of tetranuclear crown ethers. For this purpose, we used the reaction between trinuclear bis-phenol **4** and bisphosphamide **3**.

The compounds produced were dense syrups. The N-CH_3 product was poorly soluble in common solvents. The ^{31}P NMR spectra of **8a** exhibited singlets in the range typical for monoamidoarylphosphites with aromatic substituents. However, two signals with a 1:1 ratio for **8a** and a 3:1 ratio for **8b** were observed in spectra recorded at -10°C. A conclusion can be drawn about the decreased straightness of the tetraphosphorus ring compounds compared with triphosphorus ones.

The sulfurization of **8a,b** gave solids that enabled us to characterize the tetramers obtained. Compounds **9a,b** were purified by chromatography. Compound **9a** was a solid with mp 66–67°C, which was 90°C lower than that for **6a**. This can be explained by the higher structural flexibility of this molecule compared with the more rigid trimer. Several signals close together (Δ 0.04) were observed in the ^{31}P NMR spectra at 34°C. The ^{1}H NMR spectra showed signals from all proton groups, but some broadening was observed, especially for aromatic protons. The molecular mass of **9a** was determined and supported its tetrameric structure.

Oxo derivatives **10a,11a,b** were obtained, purified, and characterized. The complex of urea with hydrogen peroxide was used as the oxidizing agent. The reaction proceeded rapidly under mild conditions.

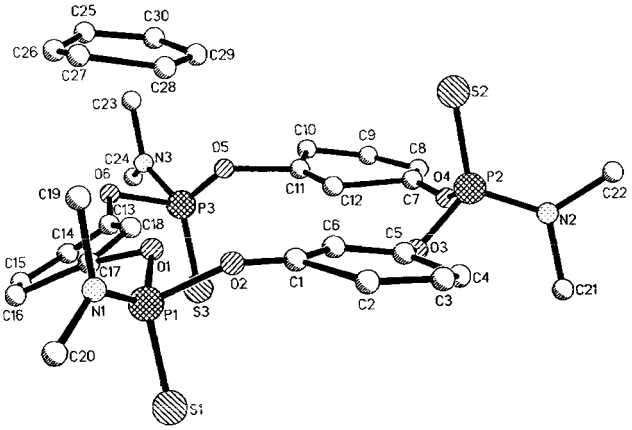


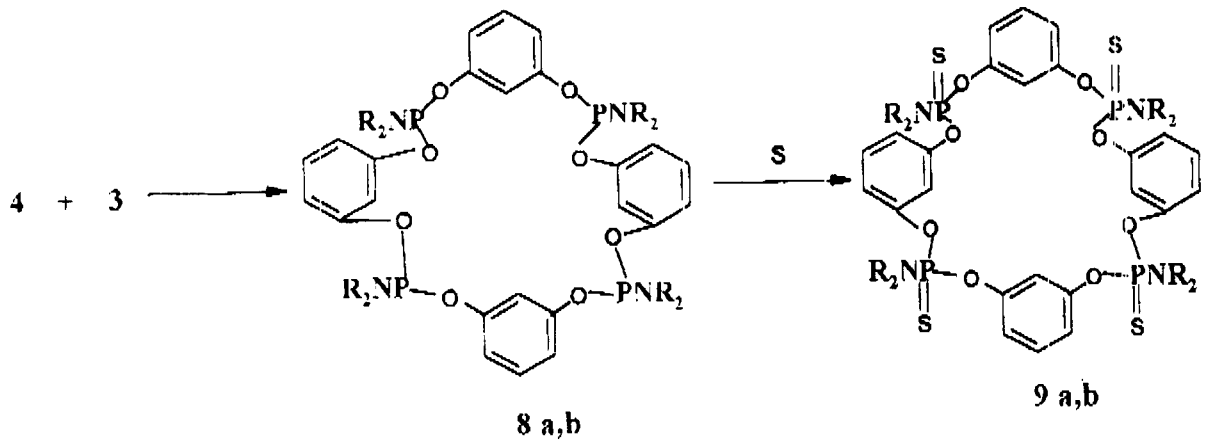
FIGURE 1 Molecular structure of **6a**.

A study of the coordination of new ligands **5a** and **8b** to monovalent rhodium has been initiated. Complexes **12a** and **13b** were obtained in methylene chloride at ligand-to-complexing agent ratios of 1:3 and 1:4, respectively.

The ^{31}P NMR spectrum of the tetranuclear complex **13** exhibited a doublet, whereas that of the trinuclear complex **12** displayed two doublets with a 1:2 intensity ratio, which indicates different spatial organizations of these systems. ^{1}H NMR spectra showed signals from all protons, but the signals of the trinuclear complex were broadened, and those of the tetranuclear complex were well resolved. The IR spectra of both complexes exhibited lines typical for carbonyl ligands at the rhodium atom.

EXPERIMENTAL

All syntheses were performed in dry solvents. Reactions were monitored by means of ^{31}P NMR spectroscopy and adsorption chromatography. ^{1}H NMR spectra of **3a,b; 7b; 9a,b; 11b; 13b** in C_6D_6 and **6a,b** in $CDCl_3$ were recorded on a Bruker AC-200 instrument at 200 MHz; those of **10a; 11a; 12a** in CD_2Cl_2 were recorded on a Bruker WH-250 instrument at 250 MHz. ^{31}P NMR spectra of **3a,b; 6a,b; 7b; 9a,b; 11b; 13b** in benzene and **10a; 11a; 12a** in methylene chloride were recorded on a Bruker WP-80SY in-



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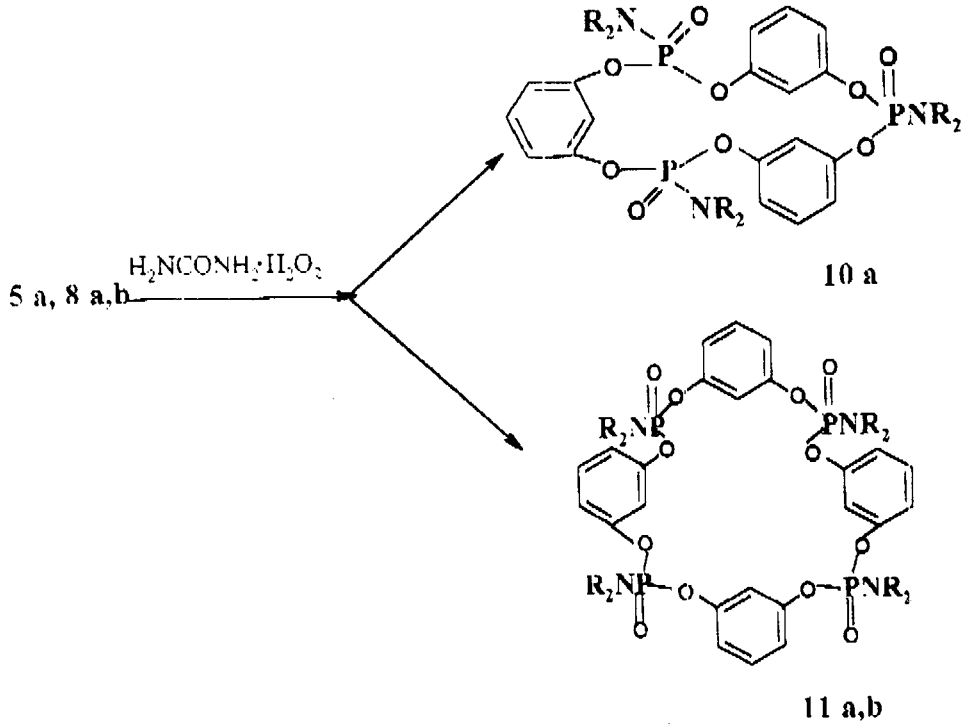
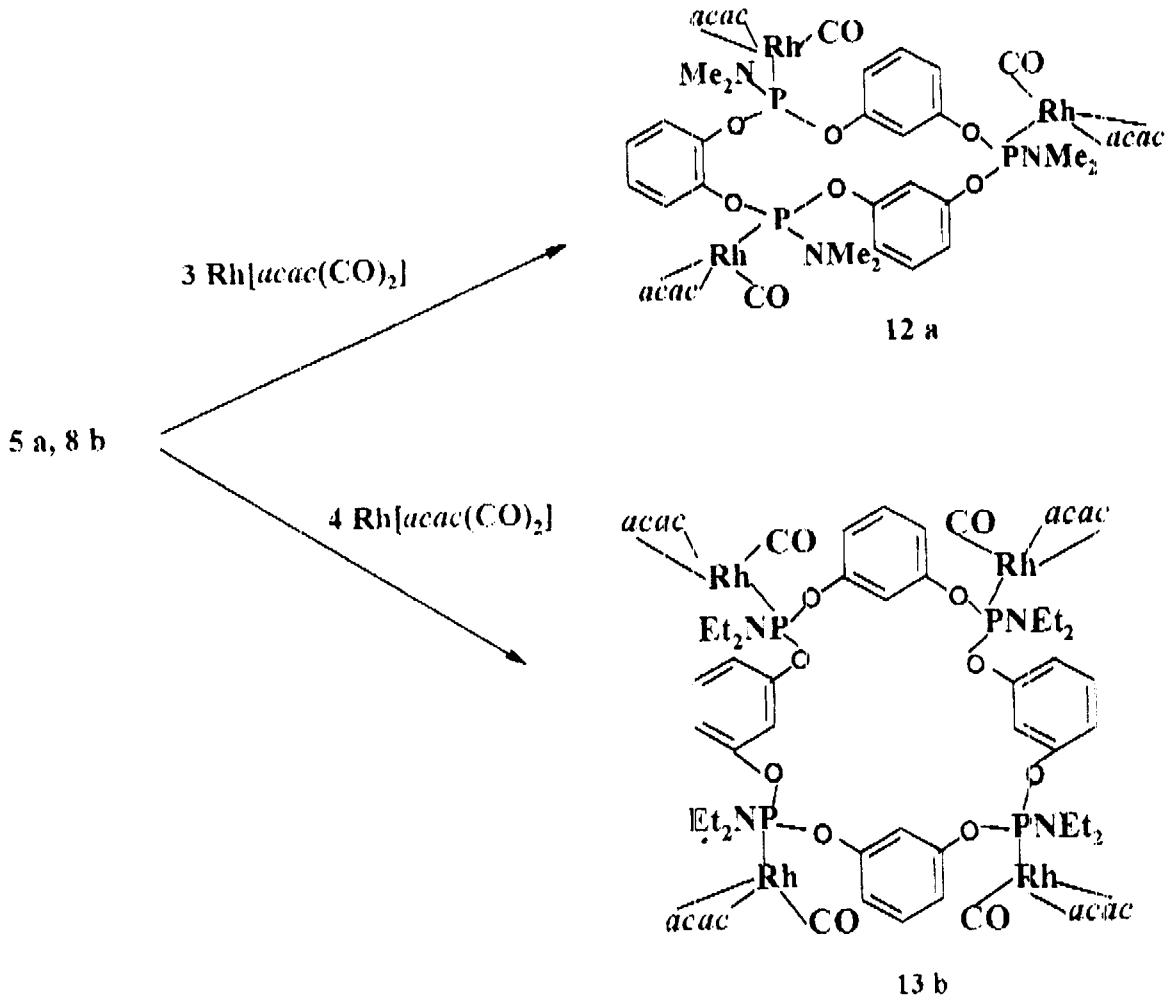


SCHEME 5

strument at 32.4 MHz (85% H_3PO_4 being used as an external standard).

IR spectra of **12a** and **13b** in methylene chloride were recorded on a Specord 75IR spectrometer in NaCl cells. The X-ray diffraction analysis was performed on a CAD-4 automatic diffractometer, Mo Kα radiation. Rhombic colorless crystal of **6a** ($C_{24}H_{30}N_3O_6P_3S_3$, M = 645.0), size 0.40 × 0.30 × 0.25 mm, orthorhombic, space group *P*na2(1), a = 15.138(3), b = 14.397(3), c = 16.25(3) A. V 3579.7 (12) A^3. Z = 4 (1.343 Mg/m^3). μ = 0.385 mm^{-1},-F(000) = 1512. $\theta/2\theta$ data collection, θ range 1.88 to 22.47° in $0 \le h \le 16$, $0 \le k \le 11$, $-17 \le l \le 0$, independent reflections: 1068 (R_{int} = 0.0000).

Refinement method: full-matrix least-squares on F^2, data/restraints/parameters: 1068/0/459, GoF on F^2 = 1.063, final R indices [$I > 2\theta(I)$]: R_1 = 0.0437, wR_2 = 0.1212, largest difference peak/hole: 0.292/ −0.223 e A^{-3}. Column chromatography was carried out on L 100/250 silica gel; TLC, on Silufol plates using benzene (A); benzene–dioxane 3:1 (B), 5:1 (C), and 10:1 (D); hexane–dioxane 3:1 (E) and chloro-



SCHEME 6

form–ethanol 5:1 (F) as eluants. The detection of compounds on Silufol plates was achieved using iodine vapor treatment, calcination, and the treatment with a 1% aqueous solution of $AgNO_3$.

Synthesis of 1,3-bis(tetraalkyldiamidophosphitoxybenzenes)

(**3a,b**): Each hexaalkyl-triamide of phosphorus acid (4.8 mmol) was added to a solution of 19.2 mmol of resorcinol in 96 mL of acetonitrile, the reaction mixture being kept at room temperature under periodic stirring for 24 hours. The solvent and excess triamide were then evaporated in vacuo, and the residue was distilled (bath temperature 145–160°C, 10^{-4} mmHg).

1,3-Bis(tetramethyldiamidophosphitoxybenzene) (**3a**). Yield, 5.98 g (90%); n_D^{26} 1.5228, R_f 0.6 (B). ^{1}NMR: 2.52 d (24H, CH_3, $^3J_{P\text{-}H}$ 9.39 Hz), 6.87 d, 6.98 s, 7.06 t (4H, CH). Anal calcd for $C_{14}H_{28}N_4O_2P_2$: P, 17.89. Found: P, 17.85.

1,3-Bis(tetraethyldiamidophosphitoxybenzene) (**3b**). Yield, 8.10 g (92%); n_D^{20} 1.5119, R_f 0.73 (B), 0.45 (E). ^{1}NMR: 1.05 t (24H, CH_3), 3.15 m (16H, CH_2), 6.9 d, 7.1 m, 7.2 m (4H, CH). ^{31}P NMR: 132.07. Anal calcd for $C_{22}H_{44}N_4O_2P_2$: P, 13.51. Found: P, 13.71.

Synthesis

(**6a,b**): Compound **3a,b** (1.4 mmol) was added to a solution of 2.8 mmol of resorcinol in 15 mL of acetonitrile; the reaction mixture was maintained under periodic stirring at room temperature for 2.5 hours. Next, each **2a,b** (1.4 mmol) was added to the solution obtained, and the mixture was kept under periodic stirring at room temperature for 2.5 hours. Aceto-

nitrile was removed, and the product (**6a,b**) was dissolved in 10 mL of benzene; 4.2 mmol of dry sulfur was added to the solution, and the mixture was stirred at room temperature for 2.5 hours. The solvent was then evaporated, and the residue was subjected to column chromatography, products being eluted with (A) for **6a** and 5:1 benzene–hexane for **6b**. The products were dried in vacuo for 3 hours (50°C, 1 mmHg).

Cyclo-[tris(*m-phenylenedimethylamidothionophosphate)] (***6a**). Yield, 0.43 g (56%); mp 153–154°C, R_f 0.72 (D) ^{1}NMR: 2.96 d (6H, CH_3, $^3J_{P\text{-}H}$ 11.95 Hz), 2.97 d (12H, CH_3, $^3J_{P\text{-}H}$ 11.97 Hz), 7.00 m, 7.04 m, 7.21 m (8H, CH). ^{31}P NMR: 66.90 s, 67.57 s. Anal calcd for $C_{24}H_{30}N_3O_6P_3S_3$: C, 44.65; H, 4.68; N, 6.51; P, 14.39; M 645. Found: C, 45.23; H, 4.58; N, 6.13; P, 14.54; M 620.

Cyclo-[tris(*m-phenylenediethylamidothionophosphate)] (***6b**). Yield, 0.426 g (48%); mp 117–118°C, R_f 0.54 (A), 0.7 (C). ^{1}NMR: 1.11 t (6H, CH_3), 1.20 d (12H, CH_3), 3.2 m, (12H, CH_2), 7.01 m, 7.12 m, 7.27 m (12H, CH). ^{31}P NMR: 66.21 s, 65.67 s. Anal calcd for $C_{30}H_{42}N_3O_6P_3S_3$: P, 12.73. Found: P, 12.85.

1,3-Bis(*m-hydroxyphenyldiethylamidothionophosphatoxy*) *benzene* (**7b**). Compound **3b** (0.96 g, 2.09 mmol) was added to a solution of 0.46 g (4.17 mmol) of resorcinol in 20 mL of acetonitrile, the reaction mixture being kept at room temperature under periodic stirring for 2.5 hours. A signal at δ = 141.04 was observed in the ^{31}P NMR spectrum of the reaction mixture. Sulfur (0.11 g, 6.27 mmol) was added, and the mixture was stirred at room temperature for 2 hours. The solvent was evaporated, and the residue was subjected to chromatography on silica gel, the product being eluted with benzene. Yield, 0.7 g (56%); viscous oil, R_f 0.83 (B). ^{1}NMR: 0.95 t (12H, CH_3), 3.22 m (8H, CH_2), 5.27 b, (2H, OH), 6.32 d, 6.51 d, 6.90 d, 7.20 *m*, 7.58 m (12H, CH). ^{31}P NMR: 66.84. Anal calcd for $C_{26}H_{34}N_2O_6P_2S_2$: P, 10.83. Found: P, 10.41.

Synthesis of cyclo-[tetra(*m-phenylenedialkylamidothionophosphates)] (***9a,b**)

Each resorcinol bistetraalkyldiamidophosphite **3a,b** (0.55 mmol) was added to a solution of 1.1 mmol of resorcinol in 6 mL of acetonitrile, the reaction mixture being kept at room temperature under periodic stirring for 24 hours. A singlet at δ = 140 was observed in the ^{31}P NMR spectrum of the reaction mixture. Each compound **3a,b** (0.55 mmol) was added to the solution obtained, and the mixture was stirred for 2 hours. Acetonitrile was evaporated in vacuo, and the residue was diluted with 5 mL of benzene; 2.2 mmol of dry sulfur was added to the solution, and the reaction mixture was stirred at room temperature for 2.5 hours. The solvent was removed in vacuo, and the residue was chromatographed on a column, **9a** being eluted with benzene and **9b** with 7:1 benzene–hexane. The products were dried in vacuo for 3 hours (55°C, 1 mmHg).

Cyclo-[tetra(*m-phenylenedimethylamidothionophosphate)] (***9a**). Yield, 0.346 g (73%); mp 66–67°C, R_f 0.67 (C). ^{1}NMR: 2.9 d b (24H, CH_3), 7.03 d b, 7.13 s b (16H, CH). ^{31}P NMR: 67.01–67.05. Anal calcd for $C_{40}H_{56}N_4O_8P_4S_4$: P, 14.39; M, 860. Found: P, 14.52; M, 899 (cryoscopy).

Cyclo-[tetra(*m-phenylenediethylamidothionophosphate)] (***9b**). Yield, 0.316 g (68%); viscous oil, R_f 0.74 (C). ^{1}NMR: 1.00 t (24H, CH_3), 3.32 m (16H, CH_2), 7.01 t, 7.19 d, 7.68 s (16H, CH). ^{31}P NMR: 66.21. Anal calcd for $C_{40}H_{56}N_4O_8P_4S_4$: P, 12.73. Found: P, 12.85.

Cyclo-[tris(*m-phenylenedimethylamidophosphate)]*

(**10a**): The complex $NH_2CONH_2 \cdot H_2O_2$ (0.04 g, 0.4 mmol) was added to a solution of 0.08 g (0.12 mmol) of **6a** in 5 mL of methylene chloride; the reaction mixture being kept at room temperature for 24 hours. The product was separated from urea and the biscyclophosphate by filtration; the solvent was evaporated, and the residue was washed with hexane and dried in vacuo for 4 hours (55°C, 1 mmHg). Yield, 0.075 g (82%); mp 47–48°C, R_f 0.0 (C), 0.76 (F). ^{1}NMR: 2.84 m (12H, CH_3), 2.88 m (6H, CH_3), 7.05 m (8H, CH), 7.29 m (4H, CH). ^{31}P NMR: 1.27. Anal calcd for $C_{24}H_{30}N_3O_9P_3$: P, 15.55. Found: P, 15.64.

Cyclo-[tetra(*m-phenylenedimethylamidophosphate)]*

(**11a**): The complex $NH_2CONH_2 \cdot H_2O_2$ (0.08 g, 0.85 mmol) was added to a solution of 0.156 g (0.21 mmol) of **8a** in 6 mL of methylene chloride; the reaction mixture being maintained under regular stirring at room temperature for 36 hours. The product was filtered off from the complex of urea with water; the solvent was evaporated, and the residue was washed with benzene and dried in vacuo for 3 hours (50°C, 1 mmHg). Yield, 0.15 g (89%); dense oil, R_f 0.0 (C), 0.64 (F). ^{1}NMR: 2.47 d b (24H, CH_3), 6.91 m b, 7.11 m b (16H, CH). ^{31}P NMR: 1.27. Anal calcd for $C_{32}H_{40}N_4O_{12}P_4$: P, 15.55. Found: P, 15.51.

Cyclo-[tetra(m-phenylenediethyl-amidophosphate)]

(**11b**): The complex $NH_2CONH_2 \cdot H_2O_2$ (0.026 g, 0.28 mmol) was added to a solution of 0.059 g (0.07 mmol) of **8b** in 3 mL of benzene; the reaction mixture being maintained under regular stirring at room temperature for 24 hours. The product was filtered off from the complex of urea with water; the solvent was evaporated, and the residue was washed with hexane and dried in vacuo for 3 hours (55°C, 1 mmHg). Yield, 0.077 g (90%); dense white oil, R_f 0.00 (C), 0.54 (F). ^{1}NMR: 0.83 t, b (24H, CH_3), 3.05 m b (16H, CH_2), 6.93 t b, 7.20 m b, 7.63 s b (16H, CH). ^{31}P NMR: 0.36. Anal calcd for $C_{40}H_{56}N_4O_{12}P_4$: P, 13.63. Found: P, 3.56.

μ-{Cyclo-[tris(m-phenylenedimethylamidophosphite)]}tris[acetyl-acetonatocarbonyl rhodium(I)]

(**12a**): The complex Rh[(acac)(CO_2)] (0.09 g, 0.35 mmol) was added to a solution of 0.064 g (0.12 mmol) of **5a** in 5 mL of methylene chloride under an argon atmosphere; the reaction mixture being at room temperature for 2 hours. The solvent was evaporated; the residue was washed with hexane and redissolved in methylene chloride. The solution was separated from an insoluble residue, and 0.2 mL of hexane was added. The residue was separated and dried in vacuo for 2.5 hours (45°C, 1 mmHg). Yield, 0.12 g (80%); light yellow powder, dp 140°C, R_f 0.00 (C), 0.8 (F). ^{1}NMR: 1.65 s (6H, CH_3 acac), 2.01 s (12H, CH_3 acac), 2.7 d b (6H, CH_3), 2.99 d b (12H, CH_3), 5.46 s (2H, CH acac), 5.58 s b (3H, CH acac), 7.13 m b, 7.29 m b (12H, CH). ^{31}P NMR: 134.89 d, $^1J_{P\text{-}Rh}$ 265.08, 134.42 d, $^1J_{Rh}$ 265.89. IR spectrum: *ν* 1990 (CO-Rh), 1510, 1570 (acac). Anal calcd for $C_{42}H_{63}N_3O_{12}P_3Rh_3$: P, 7.4. Found: P, 7.55.

μ-{Cyclo-[tetra(m-phenylenediethyl-amidophosphite)]} tetra[acetyl-acetonatocarbonyl rhodium (I)]

(**13b**): The complex Rh[(acac)(CO_2)] (0.1 g, 0.39 mmol) was added in portions to a solution of 0.082 g (0.13 mmol) of **5b** in 5 mL of benzene maintained under an argon atmosphere for 10 minutes. The reaction mixture was stirred at room temperature for 2 hours. The solvent was evaporated to a minimum, and the residue was washed with hexane and then redissolved in benzene. The solution was separated from an insoluble residue, and 0.2 mL of hexane was added. The residue was separated and dried in vacuo for 2.5 hours (45°C, 1 mmHg). Yield, 0.138 g (76%); light yellow powder, dp 140°C, R_f 0.00 (C), 0.95 (F). ^{1}NMR: 1.09 t (24H, CH_3), 1.7 s (12H, CH_3 acac), 1.90 s (12H, CH_3 acac), 3.62 m b (16H, CH_3), 5.33 s (4H, CH acac), 7.08 t b, 7.30 m b, 7.70 d b (16H, CH). ^{31}P NMR: 133.90 d, $^1J_{P\text{-}Rh}$ 263.23. IR spectrum: *ν* 1990 (CO-Rh), 1510, 1575 (acac). Anal calcd for $C_{64}H_{84}N_4O_{20}P_4Rh_4$: P, 7.42. Found: P, 7.53.

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