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New Class of Bicyclic Oxyphosphoranes with an Oxaphosphorinane Ring: Molecular Structures and Activation Energies for Ligand Exchange[1]

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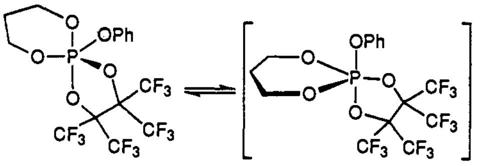
Abstract: Members of a new class of bicyclic oxyphosphorane compounds containing a six-membered oxaphosphorinane ring, $Me_2C(CH_2O)_2P(OC_{12}H_8)(OXyl)$ (**1**), $CH_2(MeCHO)_2P(OC_{12}H_8)(OXyl)$ (**2**), and $C_6H_4(CH_2O)_2P(OC_{12}H_8)(OXyl)$ (**3**), were synthesized in 85–90% yield by the oxidative addition reaction of a diol to the cyclic phosphine precursors. X-ray analysis revealed trigonal bipyramidal (TBP) geometries with the rings spanning axial–equatorial positions. ^{31}P NMR spectral data showed that pentacoordination was retained in solution. Variable-temperature ^{1}H NMR spectra recorded over the range of −90 to 85 °C supported intramolecular ligand exchange processes (pseudorotation) where each of the rings was required to be located in diequatorial positions in exchange intermediates. Application of a well-parametrized model treatment, including element effect and ring strain terms, resulted in excellent agreement between calculated and experimental activation energies for ligand exchange in **1–3**. Strain energies for diequatorial placement of rings in **1–3** follow the order dibenzo-fused oxaphosphorinane > dioxaphosphorinane > benzo-fused dioxaphosphepane. The results of this study have application to nucleophilic displacement reactions of cyclic phosphorus compounds involving oxyphosphorane intermediates, e.g., cAMP. **1** crystallizes in the triclinic space group $P\bar{1}$ with $a = 8.607(1)$ Å, $b = 16.817(2)$ Å, $c = 17.153(2)$ Å, $\alpha = 115.15(1)°$, $\beta = 90.78(1)°$, $\gamma = 91.46(1)°$, and $Z = 4$. **2** crystallizes in the monoclinic space group $P2_1/n$ with $a = 9.315(2)$ Å, $b = 17.422(3)$ Å, $c = 14.096(2)$ Å, $\beta = 102.04(1)°$, and $Z = 4$. **3** crystallizes in the monoclinic space group $P2_1/c$ with $a = 9.734(1)$ Å, $b = 27.769(4)$ Å, $c = 9.263(1)$ Å, $\beta = 113.17(1)°$, and $Z = 4$. The final conventional unweighted residuals are 0.037 (**1**), 0.040 (**2**), and 0.035 (**3**).

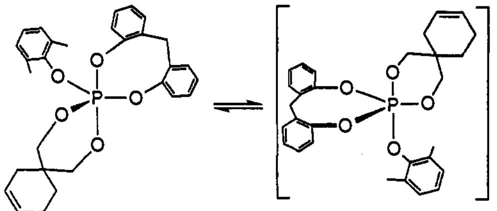
Introduction

Five-membered rings in pentacoordinated phosphorus molecules have been extensively studied.[2-5] However, recently oxyphosphoranes with larger cyclic components extending up to eight-membered rings have received increasing attention.[6-17] These cyclic pentaoxyphosphoranes are, in general, nonrigid molecules and exhibit intramolecular ligand exchange (pseudorotation) phenomena.[7,8,10,18-21] Variable-temperature NMR spectroscopic data generally show cessation of the intramolecular exchange processes at reduced temperatures from which activation energies have been derived. These values ($\Delta G^{\ddagger}$) are ascribed to a so-called low-temperature process and high-temperature process.[2] The former is associated with axial–equatorial rings usually present in ground-state structures undergoing ligand exchange via axial–equatorial ring reorientations, a–e → a–e, while the latter process is associated with the same type of ground-state structure exchanging via rings orienting in diequatorial sites of a trigonal bipyramid (TBP), a–e → e–e. The values ($\Delta G^{\ddagger}$) for the high-temperature process fall in the range of 6–13 kcal/mol[8,10,18,21,22] and are a function of the complexity of the exchanging molecule. For example, at extremes of this range are the trigonal bipyramidal molecules **A**[22] and **B**.[10]



A

$\Delta G^{\ddagger}$ = 6.1 kcal/mol [22]



B

$\Delta G^{\ddagger}$ = 12.9 kcal/mol [10]

The activation energies associated with this type of exchange process (a–e → e–e) for a series of six spirocyclic tetraoxyphos-

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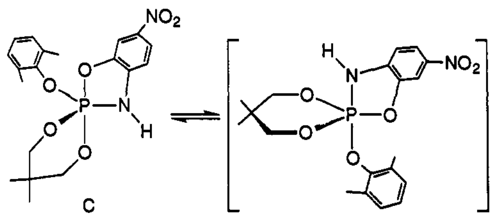
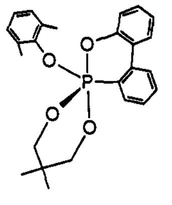
phoranes containing a six-membered ring as one cyclic component and a five-membered oxazaphospholane ring as the other cyclic component lie in the range 10.5–12.5 kcal/mol.[8,21] For example, exchange of C^8 is envisioned to occur by way of placement of the six-membered ring at diequatorial sites. This is postulated to occur to account for the coalescence of the $C_6H_3(Me)_2$ (T_c = −42 °C) and OCH_2 (T_c = −35 °C) proton signals on warming from −90 to +18 °C.[23]



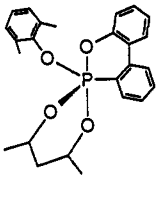
C

$\Delta G^{\ddagger}$ = 10.5–11.3 kcal/mol [8]

In the present study, a six-membered oxaphosphorinane ring was chosen in a series of bicyclic oxyphosphoranes, **1**–**3**, where



1



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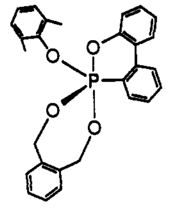

3

the other cyclic component varied in composition and ring size. It was anticipated that ligand exchange would allow placement of this ring in diequatorial sites as an exchange intermediate. This would allow us to compare relative energy differences for six-membered rings that are of the dioxaphosphorinane kind with those in this study that are of the oxaphosphorinane class.

The energies of six-membered e–e ring orientations compared to a–e ring placements in ground-state structures provide a means of assessing proposed c-AMP intermediates in enzymatic reactions involving phosphodiesterases and protein kinases. Literature reports on this topic presently favor active-site models in phosphodiesterase hydrolysis of c-AMP involving pentaoxyphosphoranes with the six-membered ring of c-AMP positioned in an a–e orientation,[6,24–26] whereas, in activation of protein kinases by c-AMP, e–e ring orientations in the pentaoxyphosphorane intermediates have been proposed at the active site.[24,27–29] Toward this end, the syntheses, X-ray structures, and variable-temperature NMR spectral measurements of **1**–**3** were undertaken and the results are reported here. These pentacoordinate phosphorus molecules represent a new class of cyclic oxyphosphoranes, as these are the first members to contain the six-membered oxaphosphorinane ring.

Experimental Section

Reagents and Procedures. Chemicals were obtained from Aldrich, Eastman Kodak Co., or Fluka and used without further purification. Solvents were of HPLC grade (Fisher Scientific). Further purification was done according to standard procedures.[30] ^1H and ^{31}P NMR spectra were recorded on a Varian XL 300 FT-NMR spectrometer. ^{31}P spectra were recorded at 23 °C. ^1H chemical shifts are reported in ppm relative to tetramethylsilane. Chemical shifts for ^{31}P NMR spectra in ppm were obtained by setting triphenyl phosphate[31] ($CDCl_3$) at −18.0 ppm and are referenced to 85% H_3PO_4 with negative shifts upfield. Temperature calibration for variable ^1H NMR measurements was accomplished by using methanol (below 25 °C) and ethylene glycol (above 25 °C) samples, respectively, with a calibration error of ±0.5 °C. Melting points are uncorrected. Phosphorus trichloride, 2,6-dimethylphenol and 1,2-benzenedimethanol were purchased from Aldrich, 2-phenylphenol was purchased from Eastman Kodak, and 2,2-dimethyl-1,3-propanediol and 2,4-pentanediol (mixture of racemic and meso forms) were purchased from Fluka. *N*-Chlorodiisopropylimine was prepared by a literature method.[32] Et_3N (Fisher Scientific) was distilled over KOH pellets prior to use. All of the reactions were carried out in a dry nitrogen atmosphere using standard Schlenk-type glassware.[33]

Syntheses. A. $P(OC_{12}H_8)(OXyl)$ (5). Following a procedure by Pastor et al.,[34] a mixture of phosphorus trichloride (20 mL, 31.5 g, 0.23 mol) and 2-phenylphenol (31.2 g, 0.18 mol) was heated gradually to 150 °C over a period of 5 h with continuous stirring. A slow sweep of nitrogen was maintained to facilitate the ready removal of evolved hydrogen chloride. The reaction flask containing the chlorophosphine precursor **4** was cooled to 25 °C, followed by the addition of 0.20 g of anhydrous zinc chloride. The temperature of the reaction mixture was increased to 250 °C over a period of 2 h and then cooled to 25 °C. The reaction mixture was dissolved in 250 mL of diethyl ether, and to it was added dropwise a mixture of 2,6-dimethylphenol (22.4 g, 0.18 mol) and Et_3N (25.6 mL, 18.6 g, 0.18 mol) in 200 mL of diethyl ether. The reaction mixture was stirred at 25 °C for 47 h. Triethylamine hydrochloride was removed by filtration followed by the evaporation of solvent from the filtrate under reduced pressure. The resulting oil was crystallized from a mixture of ether (100 mL) and hexane (50 mL) to give **5**; mp 113 °C (yield 40.3 g, 70%). ^1H NMR ($CDCl_3$, 23 °C): 2.20 (s, 6 H, $OC_6H_3(CH_3)_2$), 6.90–8.16 (complex multiplets, 11 H, H(Ar)). ^{31}P NMR ($CDCl_3$): 130.43. Anal. Calcd for $C_{20}H_{17}O_2P$: C, 75.0; H, 5.31. Found: C, 75.0; H, 5.27.

B. $Me_2C(CH_2O)_2P(OC_{12}H_8)(OXyl)$ (1). To a mixture of phosphine **5** (1.00 g, 3.13 mmol) and 2,2-dimethyl-1,3-propanediol (0.33 g, 3.13 mmol) in diethyl ether (100 mL) maintained at −70 °C was added dropwise a solution of *N*-chlorodiisopropylamine (0.46 mL, 0.42 g, 3.13 mmol) in 50 mL of diethyl ether over a period of 30 min with continued stirring. The reaction was brought to 25 °C and stirred at this temperature for 24 h. Solvent was removed completely under reduced pressure and the resulting solid extracted with a mixture of diethyl ether (150 mL) and hexane (50 mL). The amine hydrochloride was filtered, and the filtrate was concentrated by passing a slow stream of nitrogen over the solution. Crystallization occurred after the solution was left standing for 12 h to afford **1**; mp 149 °C (yield 1.12 g, 85%). ^1H NMR (toluene-d_8) at +80 °C: 0.64 (s, 6 H, ring methyl protons), 2.35 (shoulder, 6 H, $OC_6H_3(CH_3)_2$), 3.50 (s, slightly broad, 4 H, OCH_2), 6.80–8.50 (m, 11 H, H(Ar)). ^{31}P NMR ($CDCl_3$): −63.26. ^1H NMR ($CDCl_3$) at 25 °C: 0.69 (s, little

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Table 1. Crystallographic Data for Compounds **1**–**3**

	1	**2**	**3**
formula	$C_{25}H_{27}O_4P$	$C_{25}H_{27}O_4P$	$C_{28}H_{25}O_4P$
formula wt	422.466	422.466	456.483
cryst syst	triclinic	monoclinic	monoclinic
space group	$P\bar{1}$ (No. 2)	$P2_1/n$ (No. 14)	$P2_1/c$ (No. 14)
a (Å)	8.607(1)	9.315(2)	9.734(1)
b (Å)	16.817(2)	17.422(3)	27.769(4)
c (Å)	17.153(2)	14.096(2)	9.263(1)
α (deg)	115.15(1)		
β (deg)	90.78(1)	102.04(1)	113.17(1)
γ (deg)	91.46(1)		
V (Å^3)	2246(1)	2237(1)	2301.8(8)
Z	4	4	4
T (°C)	23 ± 2	23 ± 2	23 ± 2
λ (Å)	0.710 73	0.710 73	0.710 73
D_{calc} (g cm^{-3})	1.249	1.254	1.317
μ (cm^{-1})	1.443	1.449	1.462
$R(F_o)^a$	0.037	0.040	0.035
$R_w(F_o)^a$	0.048	0.048	0.045

^{a} $R = \sum||F_o| - |F_c||/\sum|F_o|$ and $R_w = \{\sum w(|F_o| - |F_c|)^2/\sum w|F_o|^2\}^{1/2}$.

shoulder, 3 H, ring methyl protons), 1.12 (s, little shoulder, 3 H, ring methyl protons), 2.26 (sh, $OC_6H_3(CH_3)_2$), 3.46 (slightly broad, $OC_6H_3(CH_3)_2$), 25% of the xylyloxy methyl protons are centered at 3.46 and the remaining 75% are centered at 2.26, 3.50–4.0 (br, 4 H, OCH_2), 6.60–8.38 (complex multiplets, 11 H, H(Ar)). ^1H NMR (toluene-d_8) at 25 °C: 0.40 (shoulder, 3 H, ring methyl protons), 0.85 (s, 3 H, ring methyl protons), 2.40 (s, $OC_6H_3(CH_3)_2$), 3.15 (br, $OC_6H_3(CH_3)_2$), 3.50 (br, OCH_2), 4.01 (br, OCH_2), 6.70–8.60 (complex multiplets, 11 H, H(Ar)). Anal. Calcd for $C_{25}H_{27}O_4P$: C, 71.09; H, 6.39. Found: C, 71.46; H, 6.40.

C. **$CH_2(MeCHO)_2P(OC_{12}H_8)(OXyl)$ (2).** Quantities used were as follows: phosphine **5** (1.00 g, 3.13 mmol), 2,4-pentanediol (0.34 mL, 0.33 g, 3.13 mmol), *N*-chlorodiisopropylamine (0.46 mL, 0.43 g, 3.13 mmol), and 150 mL of diethyl ether. The procedure used for the synthesis of **1** was followed; mp 145–147 °C (yield 1.19 g, 90%). ^{31}P NMR ($CDCl_3$): two distinct resonances at −64.21 and −65.60, with an intensity ratio of 1:2, respectively, attributable to the presence of two different isomers (as the diol used was a mixture of racemic and meso forms). Recrystallization of the compound in a mixture of diethyl ether (50 mL) and Skelly-F (25 mL) gave crystals of only one of the forms with a ^{31}P chemical shift of −66.20 (toluene-d_8). ^1H NMR (toluene-d_8) at +25 °C: 0.70 (s, ring methyl protons), 1.12–1.80 (br, ring methyl protons), 2.35 (less intense peak, $OC_6H_3(CH_3)_2$), 2.70 (slightly br, $OC_6H_3(CH_3)_2$), 3.60 (broad, 2 H, CH_2), 4.65 (broad, 2 H, CH), 6.70–8.60 (complex multiplets, 11 H, H(Ar)). ^1H NMR (toluene-d_8) at −3.4 °C: 0.75 (s, ring methyl protons), 1.0–1.30 (shoulder, ring methyl protons), 2.07 (s, $OC_6H_3(CH_3)_2$), 2.75 (s, $OC_6H_3(CH_3)_2$), 3.60 (br, CH_2), 4.70 (br, CH), 6.70–8.70 (br multiplets, 11 H, H(Ar)). Anal. Calcd for $C_{25}H_{27}O_4P$: C, 71.09; H, 6.39. Found: C, 70.86; H, 6.35.

D. **$C_6H_4(CH_2O)_2P(OC_{12}H_8)(OXyl)$ (3).** Quantities used were as follows: phosphine **5** (1.00 g, 3.13 mmol), 1,2-benzenedimethanol (0.432 g, 3.13 mmol), *N*-chlorodiisopropylamine (0.46 mL, 0.43 g, 3.13 mmol), and 150 mL of diethyl ether. The procedure used for the synthesis of **1** was followed; mp 179–181 °C (yield 1.43 g, 85%). ^{31}P NMR ($CDCl_3$): −63.03. ^1H NMR (toluene-d_8) at +85 °C: 2.00 (s, $OC_6H_3(CH_3)_2$), 5.15 (slightly broad, OCH_2), 6.6–8.6 (multiplets, H(Ar)). ^1H NMR (toluene-d_8) at +25 °C: 2.06 (s, 6 H, $OC_6H_3(CH_3)_2$), 3.80 (dd, OCH_2), 5.18 (m, OCH_2), 5.70 (dd, OCH_2), 6.48–8.60 (complex multiplets, 15 H, H(Ar)). ^1H NMR ($CDCl_3$) at +25 °C: 1.91 (s, 6 H, $OC_6H_3(CH_3)_2$), 4.24 (dd, OCH_2), 5.32–5.52 (m, OCH_2), 5.78 (dd, OCH_2), 6.51–8.46 (complex multiplets, 15 H, H(Ar)). Anal. Calcd for $C_{28}H_{25}O_4P$: C, 73.68; H, 5.48. Found: C, 73.55; H, 5.46.

X-Ray Experimental Section. All X-ray crystallographic studies were done using an Enraf-Nonius CAD4 diffractometer and graphite monochromated molybdenum radiation. Details of the experimental procedures have been described previously.[35]

Crystals were mounted in thin-walled glass capillaries which were sealed as a precaution against moisture sensitivity. Data were collected using the θ–2θ scan mode with $3° \leq 2\theta_{Mo\,K\alpha} \leq 43°$ for **1** and **2** and with $3° \leq 2\theta_{Mo\,K\alpha} \leq 50°$ for **3**. No corrections were made for absorption.

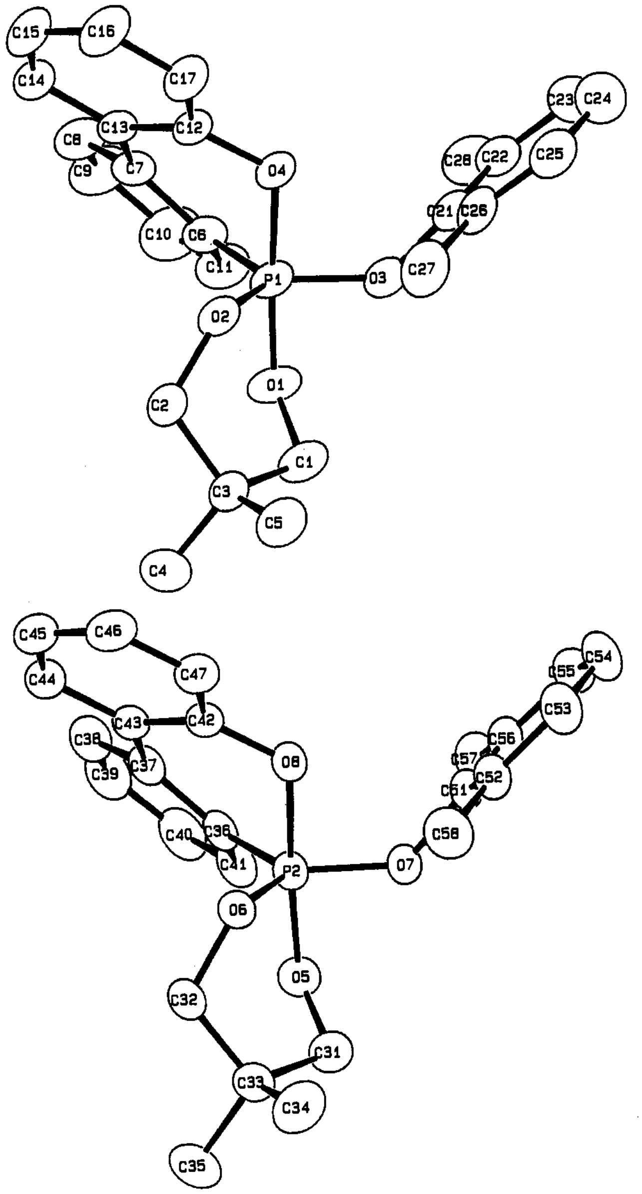

Figure 1. ORTEP plots of $Me_2C(CH_2O)_2P(OC_{12}H_8)(OXyl)$ (**1**) with thermal ellipsoids at the 30% probability level. Hydrogen atoms are omitted for clarity. (a) The independent molecule containing P1. (b) The independent molecule containing P2.

The structures were solved by use of direct methods and difference Fourier techniques and were refined by full-matrix least-squares.[36]

All computations were performed on a Microvax II computer using the Enraf-Nonius SDP system of programs. Crystallographic data are summarized in Table 1.

A. **X-Ray Study for $Me_2C(CH_2O)_2P(OC_{12}H_8)(OXyl)$ (1).** The somewhat irregular brick-shaped colorless crystal used for the X-ray study was cut from a striated sheet and had approximate dimensions of 0.30 × 0.43 × 0.50 mm^3. A total of 5126 independent reflections ($+h$, $\pm k$, $\pm l$) were measured. The 60 independent non-hydrogen atoms were refined anisotropically. Hydrogen atoms were included in the refinement as fixed isotropic scatterers (ideal positions or regularized difference Fourier positions for the xylyl methyl hydrogen atoms). The final refinement was based on the 3303 reflections with $I \geq 3\sigma_I$.

B. **X-Ray Study for $CH_2(MeCHO)_2P(OC_{12}H_8)(OXyl)$ (2).** The colorless crystal used for the study was cut from a larger mass and had approximate dimensions of 0.23 × 0.45 × 0.50 mm^3. A total of 2522 independent reflections ($+h$, $+k$, $\pm l$) were measured. The thirty independent non-hydrogen atoms were refined anisotropically. Hydrogen atoms were treated as described for **1**. The final refinement was based on the 1439 reflections with $I \geq 3\sigma_I$.

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(36) The function minimized was $\sum w(|F_o| - |F_c|)^2$, where $w^{1/2} = 2F_oLp/\sigma_I$.

Table 2. Selected Distances (Å) and Angles (deg) for $Me_2C(CH_2O)_2P(OC_{12}H_8)(OXyl)$ (**1**)[a]

	Distances		
P1–O1	1.662(3)	P2–C36	1.811(4)
P1–O2	1.592(3)	O1–C1	1.391(5)
P1–O3	1.603(2)	O2–C2	1.456(5)
P1–O4	1.710(2)	O3–C21	1.408(5)
P1–C6	1.809(3)	O4–C12	1.365(3)
P2–O5	1.657(2)	O5–C31	1.425(4)
P2–O6	1.608(2)	O6–C32	1.448(3)
P2–O7	1.608(3)	O7–C51	1.416(3)
P2–O8	1.712(2)	O8–C42	1.372(4)
	Angles		
O1–P1–O2	94.2(1)	O6–P2–O7	119.1(1)
O1–P1–O3	89.4(1)	O6–P2–O8	87.8(1)
O1–P1–O4	177.1(1)	O6–P2–C36	118.8(1)
O1–P1–C6	89.6(1)	O7–P2–O8	88.0(1)
O2–P1–O3	118.1(1)	O7–P2–C36	122.0(1)
O2–P1–O4	87.7(1)	O8–P2–C36	91.8(1)
O2–P1–C6	120.5(1)	P1–O1–C1	118.4(3)
O3–P1–O4	87.8(1)	P1–O2–C2	122.2(2)
O3–P1–C6	121.3(2)	P1–O3–C21	132.3(2)
O4–P1–C6	91.2(1)	P1–O4–C12	119.1(2)
O5–P2–O6	93.6(1)	P2–O5–C31	117.3(2)
O5–P2–O7	88.5(1)	P2–O6–C32	120.1(2)
O5–P2–O8	176.5(1)	P2–O7–C51	130.6(2)
O5–P2–C36	90.3(1)	P2–O8–C42	120.2(2)

[a] Estimated standard deviations in parentheses. The atom-labeling scheme is shown in Figure 1.

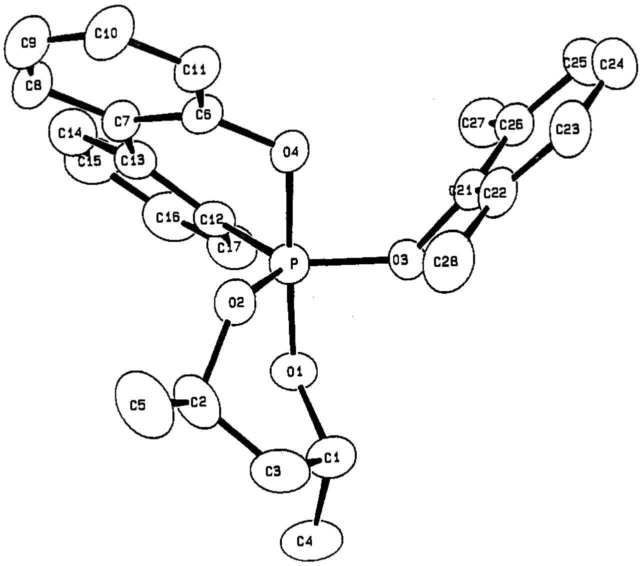

Figure 2. ORTEP plot of $CH_2(MeCHO)_2P(OC_{12}H_8)(OXyl)$ (**2**) with thermal ellipsoids at the 30% probability level. Hydrogen atoms are omitted for clarity.

C. X-Ray Study for $C_6H_4(CH_2O)P(OC_{12}H_8)(OXyl)$ (3). The colorless crystal used for the X-ray study was cut from a large polyfaceted crystal and had approximate dimensions of 0.25 × 0.30 × 0.63 mm^3. A total of 4030 independent reflections (+*h*, +*k*, ±*l*) were measured. The 33 independent non-hydrogen atoms were refined anisotropically. Hydrogen atoms were treated as described for **1**. The final refinement was based on the 2476 reflections with $I \geq 3\sigma_I$.

Table 3. Selected Distances (Å) and Angles (deg) for $CH_2(MeCHO)_2P(OC_{12}H_8)(OXyl)$ (**2**)[a]

	Distances		
P–O1	1.647(3)	O1–C1	1.446(5)
P–O2	1.592(3)	O2–C2	1.457(5)
P–O3	1.608(2)	O3–C21	1.397(4)
P–O4	1.716(3)	O4–C6	1.368(5)
P–C12	1.808(4)		
	Angles		
O1–P–O2	95.1(1)	O3–P–O4	88.2(1)
O1–P–O3	89.4(1)	O3–P–C12	123.7(2)
O1–P–O4	177.2(1)	O4–P–C12	90.0(2)
O1–P–C12	90.1(2)	P–O1–C1	123.2(3)
O2–P–O3	118.5(2)	P–O2–C2	122.3(3)
O2–P–O4	87.3(1)	P–O3–C21	130.5(2)
O2–P–C12	117.6(2)	P–O4–C6	117.8(2)

[a] Estimated standard deviations in parentheses. The atom-labeling scheme is shown in Figure 2.

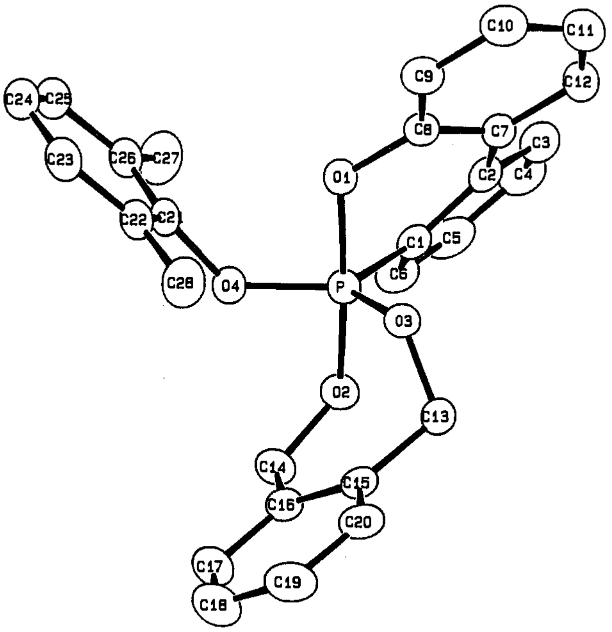

Figure 3. ORTEP plot of $C_6H_4(CH_2O)_2P(OC_{12}H_8)(OXyl)$ (**3**) with thermal ellipsoids at the 30% probability level. Hydrogen atoms are omitted for clarity.

Table 4. Selected Distances (Å) and Angles (deg) for $C_6H_4(CH_2O)_2P(OC_{12}H_8)(OXyl)$ (**3**)[a]

	Distances		
P–O1	1.709(2)	O1–C8	1.365(2)
P–O2	1.658(2)	O2–C14	1.426(2)
P–O3	1.605(2)	O3–C13	1.458(3)
P–O4	1.612(2)	O4–C21	1.406(3)
P–C1	1.815(2)		
	Angles		
O1–P–O2	175.84(8)	O3–P–O4	120.94(8)
O1–P–O3	87.41(8)	O3–P–C1	116.45(9)
O1–P–O4	87.17(8)	O4–P–C1	122.5(1)
O1–P–C1	91.82(9)	P–O1–C8	120.9(2)
O2–P–O3	95.10(9)	P–O2–C14	125.9(2)
O2–P–O4	88.69(8)	P–O3–C13	123.5(1)
O2–P–O1	90.0(1)	P–O4–C21	131.4(1)

[a] Estimated standard deviations in parentheses. The atom-labeling scheme is shown in Figure 3.

Results

The atom-labeling scheme and the molecular geometry for **1** are shown in the ORTEP plots of Figure 1a and b, while selected distances and angles are given in Table 2. The corresponding information for **2** is given in Figure 2 and Table 3, and that for **3** in Figure 3 and Table 4. Atomic coordinates, anisotropic thermal parameters, complete distances and angles, and hydrogen atom parameters are provided as supplementary material.

Discussion

Synthesis. The cyclic chlorophosphine precursor **4** was prepared by Cherynshev and co-workers[37] from the reaction of 2-phen-

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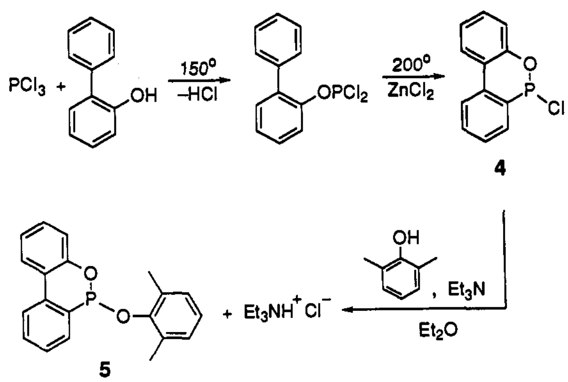
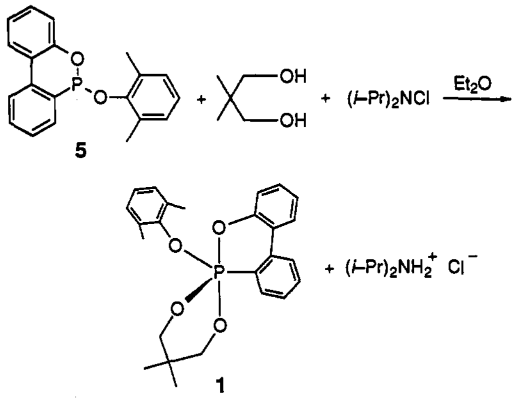
(37) Cherynshev, E. A.; Aksenov, V. I.; Ponomarev, V. V.; Golubstsov, S. A.; Bugerenko, E. F. *Zh. Obshch. Khim.* **1972**, *42*, 93; *Chem. Abstr.* **1972**, *77*, 34639.

Scheme 1



ylphenol and PCl_3 followed by cyclization using aluminium trichloride as a catalyst. A more convenient route described by Pastor and co-workers[34] was used here based on heating the reactants in the absence of solvent followed by a cyclization step in the presence of $ZnCl_2$ as a catalyst to give **4**. The latter chlorophosphine underwent halide displacement on reaction with 2,6-dimethylphenol *in situ* in diethyl ether at 25 °C using Et_3N as an acid acceptor to give **5** in 70% yield (Scheme 1). The new tricoordinate compound **5** was characterized by its ^{31}P NMR spectrum, which showed a single resonance at 130.4 ppm, and by its ^{1}H NMR spectrum, which showed a singlet at 2.20 ppm and a complex multiplet at 6.90–8.16 ppm. The features were assigned to the methyl protons of the xylyloxy group and to the protons of the aromatic components, respectively.

The new class of bicyclic oxyphosphoranes, **1**–**3**, was prepared in 85–90% yields from the reaction of **5** with the corresponding diols in the presence of *N*-chlorodiisopropylamine. The reaction is illustrated for the synthesis of **1** (eq 1).



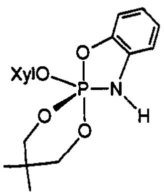
(1)

Structural Aspects. The molecular geometry about the phosphorus atom in all three compounds can be referred to as a trigonal bipyramid (TBP) where the ring systems all span axial–equatorial sites and where the carbon ligand atoms and the xylyloxy groups are in equatorial positions.

The ^{31}P NMR spectra of **1** and **3** revealed singlets at −63.3 and −63.0 ppm, respectively, which confirms the retention of five-coordinated structures in solution.

Since, in the preparation of **2**, the diol used was a mixture of racemic and meso forms, two diastereoisomers were present in the reaction mixture. This was evident in the ^{31}P NMR spectrum of the crude product. Two singlets were observed in the five-coordinate region in $CDCl_3$ solution, one at −64.2 ppm and another at −65.6 ppm, with an intensity ratio of 1:2. In growing crystals suitable for X-ray diffraction analysis, only one diastereoisomer was isolated, which was again evident in the ^{31}P NMR spectrum. Here only one signal was present, at −66.2 ppm, in toluene-d_8 solution. Determination of the structure showed that the crystals which were used in the X-ray study were of the racemic mixture.

For all three compounds, the P–C bond lengths appear to be scattered about a similar value and average 1.811(3) Å, with a range from 1.808(4) to 1.815(2) Å. Similarly, the P–O_{eq} bond lengths, including both the P–OXyl bonds and the P–O_{eq} bonds to the dioxa ring systems, average 1.604(3) Å, with a range from 1.592(3) to 1.612(2) Å. The P–O_{ax} bond lengths, however, fall into two distinct groups with the bond to the phenoxy oxygen atom of the oxaphosphorinane ring averaging 0.06 Å longer than the remaining P–O_{ax} bond. The P–O_{ax} phenoxy bond lengths average 1.712(2) Å with a range from 1.710(2) to 1.716(3) Å while the remaining P–O_{ax} bond lengths average 1.656(3) Å with a range from 1.647(3) to 1.662(3) Å. As expected, all of the P–O_{ax} bonds are longer than the P–O_{eq} bonds. The longer P–O_{ax} bond lengths to the phenoxy oxygen atoms in **1**–**3** are most likely associated with a greater ring strain for the relatively planar portion of the oxaphosphorinane ring system containing an sp^2 carbon atom compared to that in the more flexible six- and seven-membered dioxa ring systems. This is apparent in the following discussion. Indeed the average P–O axial bond length of 1.712 Å for the constrained oxaphosphorinane ring is close to that for P–O axial bond lengths of unsaturated five-membered rings attached a–e in oxyphosphorane molecules. An average P–O axial length of ten such molecules is 1.715 Å.[8,18,20,21] The considerably lower average value of 1.656 Å found for the P–O axial bond length to the more flexible six- and seven-membered rings in **1**–**3** compares with an average value of 1.643 Å for three non-hydrogen-bonded P–O axial bond lengths in tetraoxyphosphoranes of the type[8,21]



Accompanying the systematic difference in P–O_{ax} bond lengths for **1**–**3** is a slight displacement of the P atom out of the plane of the three equatorial ligand atoms in a direction toward the ligand atom with the shorter P–O_{ax} bond. For the molecule containing P1 of compound **1**, atom P1 is displaced by 0.031(1) Å from the plane defined by O2, O3, and C6 in a direction toward atom O1. The corresponding displacement for the molecule containing P2 is 0.023(1) Å. For compound **2** this value is 0.043(1) Å, and for compound **3** it is 0.036(1) Å.

Ring Conformation. The saturated six-membered rings in compounds **1** and **2** (Figures 4 and 5) have the typical somewhat twisted boat conformation,[6,18-20] with the axial oxygen atom and opposing carbon atom at the tips of the boat.

For the molecule containing P1 of compound **1**, the four atoms forming the base of the boat (P1, O2, C1, and C3) are coplanar to within ±0.103(3) Å, while atoms O1 and C2 are displaced from this plane in the same direction by distances of 0.617(2) and 0.534(4) Å, respectively. For the molecule containing P2 the corresponding values are ±0.113(3), 0.641(2), and 0.602(3) Å, and for compound **2** the values are ±0.032(4), 0.565(3), and 0.669(5) Å.

The boat conformation is thought to be assumed in order to position the ring so that the P–O_{eq}–C plane is close to perpendicular to the equatorial plane (i.e., dihedral angle of 90°). As discussed by Trippett,[22] this allows the lone electron pair of the equatorial oxygen atom to be located near the equatorial plane and presumably this effect enhances P–O_{eq} π bonding. The observed dihedral angle for the ring containing P1 of compound **1** is 71.4(2)°. For the molecule containing P2 the value is 68.7(2)°, and for compound **2** the value is 82.4(2)°.

The conformation of the seven-membered ring in compound **3** also conforms to this notion (Figure 3). If one considers a

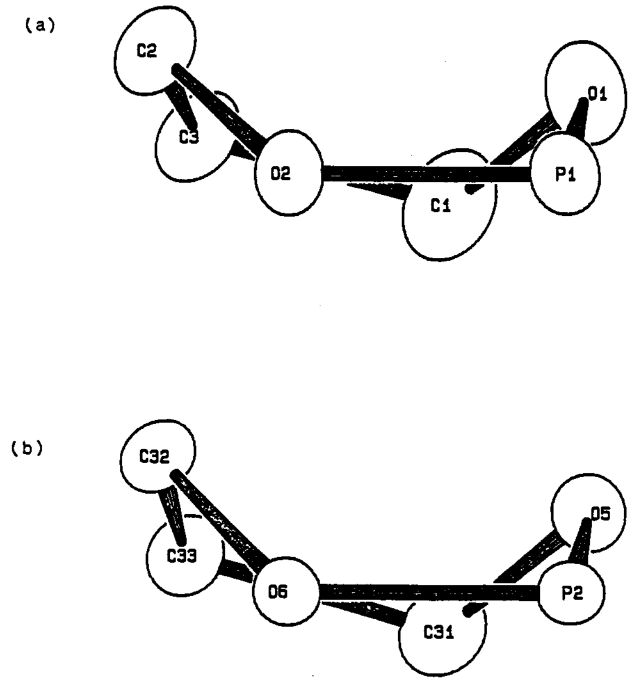


Figure 4. ORTEP plots showing the conformation of the saturated six-membered ring in **1** (a) for the independent molecule containing P1 and (b) for the independent molecule containing P2.

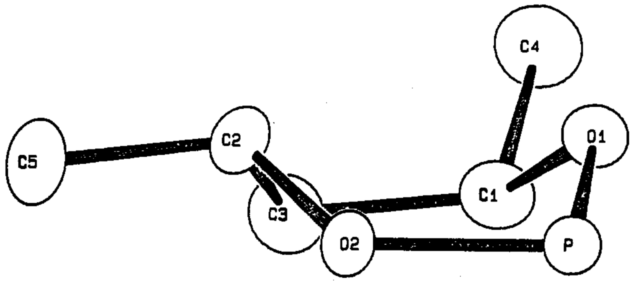


Figure 5. ORTEP plot showing the conformation of the saturated six-membered ring in **2**.

hypothetical six-membered ring comprised of P, O2, O3, C13, C14, and C15, then this ring has a boat conformation with the axial atom O2 and the opposing C13 at the tips of the boat. The four atoms forming the base of the boat (P, O3, C14, C15) are coplanar to within ±0.080(1) Å while atoms O2 and C13 are displaced from this plane in the same direction by distances of 0.654(2) and 0.799(2) Å, respectively. The dihedral angle between the plane defined by atoms P, O3, and C13 and the equatorial plane is 86.0(1)°.

The xylyloxy groups in all three compounds are also positioned in agreement with this notion. For the molecule containing P1 of compound **1**, the dihedral angle between the plane defined by $P-O_{eq}-C_{xylyl}$ (P1–O3–C21) and the equatorial plane is 86.2(2)°. For the molecule containing P2 the corresponding value is also 86.2(2)°. For compound **2** the value is 84.8(2)°, and for compound **3** the value is 87.1(2)°. The closer approach to 90° for the acyclic ligands is not surprising, since there are no ring constraints to interfere with the optimal geometry.

The conformation of the seven-membered ring in **3** (Figure 6) is not analogous to either of the conformations previously observed for this ring system in four-coordinated phosphorus compounds.[38-40] A chair form for three compounds containing this benzo-fused 1,3,2-dioxaphosphepane ring was demonstrated from X-ray analysis, e.g., **D**[38] and **E**,[39] while **F**[40] was unique and had the ring in a twist conformation.

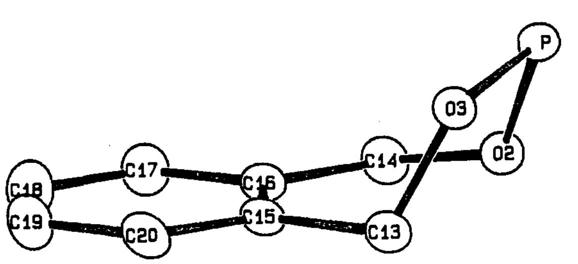
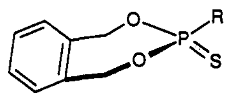
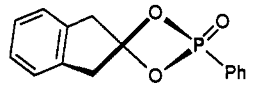


Figure 6. ORTEP plot showing the conformation of the seven-membered ring in **3**.



D (R = Me), **E** (R = NMe_2)



F

In solution, a variety of four-coordinated compounds of this type with a benzo-fused dioxaphosphepane ring[41] and either attached $P{=}S$ or $P{=}O$ groups have been studied by NMR,[42,43] dipole moment, and Kerr effect data.[44-47] These data suggest conformational equilibria between chair and flexible twist forms. The assumption of one of these conformations for this ring in **3** is precluded by the fact that the axial and equatorial oxygen atoms of the ring in the a–e sites of a TBP are *not* equivalent. In both the chair and the twist conformations previously reported for four-coordinated systems,[38-40] the oxygen atoms are chemically equivalent and geometrically equivalent by pseudo symmetry operations, i.e., mirror related in the chair form and twofold related in the twist form. In **3**, the axial atom O2 is nearly in the plane of the phenyl ring, while the equatorial atom O3 is very much displaced from this plane. The ring atoms constrained by the aromatic system (C13, C14, C15, and C16) are coplanar to within ±0.029(2) Å. Atoms O2, O3, and P are displaced from this plane in the same direction by distances of 0.233(2), 1.265(2), and 1.617(1) Å, respectively. In the chair form, one would expect both oxygen atoms to be displaced by about the same amount in the same direction, while in the twist form, one would expect them to be displaced by about the same amount in opposite directions with the phosphorus atom nearly in the plane.

The conformation of the unsaturated six-membered rings is the same for all three compounds (Figure 7) and can be referred to a slightly twisted half-chair in which the phosphorus atom is out of the plane of the remaining ring atoms. This type of ring system is very constrained, since all of the ring atoms are either members of a phenyl group or are constrained to lie more or less in the plane of one of the two phenyl groups. The nonplanar nature of the ring system is primarily a result of a rotation about the bond connecting the two phenyl rings and only slightly due to out of plane deformations. This rotation, as measured by the

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(41) (a) Quin, L. D. In *Conformational Analysis of Medium-Sized Heterocycles*; Glass, R. S., Ed.; VCH: Deerfield Beach, FL, 1988. (b) Gallagher, M. J. In *Phosphorus-31 NMR Spectroscopy in Stereochemical Analysis*; VCH: Deerfield Beach, FL, 1987.

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(45) Arbuzov, B. A.; Kadyrov, R. A.; Arshinova, R. P.; Klochkov, V. V.; Aganov, A. V. *Izv. Akad. Nauk SSSR. Ser. Khim.* **1985**, 1762.

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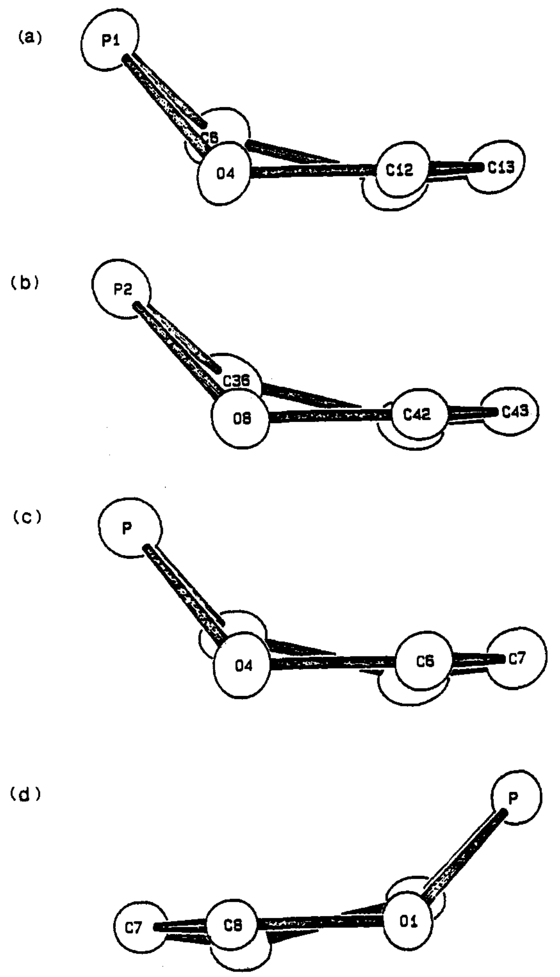

Figure 7. ORTEP plots showing the conformation of the unsaturated six-membered ring (a) for the molecule containing P1 of compound **1**, (b) for the molecule containing P2 of compound **1**, (c) for compound **2**, and (d) for compound **3**.

ring torsion angle about the bond connecting the two phenyl rings, is very similar for all compounds and ranges from 22.1(5)° to 23.6(5)°.

Variable-Temperature ^{1}H NMR Studies from −90 to 85 °C in Toluene-d_8. The ^{1}H NMR spectrum of **1** in Figure 8 exhibits two sharp singlet peaks at −73.8 °C at 0.45 and 0.90 ppm ($\Delta\nu = 144.7$ Hz) which are assigned to the protons of the two methyl groups appended to the dioxaphosphorinane ring. As the temperature is raised, the methyl proton signals noticeably broaden at 9.9 °C and coalesce at 35 °C. Above this temperature, a single peak emerges at 0.6 ppm which narrows as the upper limit of 80 °C is reached.

The xylyloxy methyl proton resonances are relatively sharp at −73.8 °C and appear at 2.15 and 2.95 ppm ($\Delta\nu = 228.7$ Hz). On raising the temperature, broadening occurs and the signals reach coalescence at −27.1 °C. Above this temperature, a broad singlet appears at 2.45 ppm which becomes narrower at 80 °C.

Further downfield, four broad peaks with some discernible splitting are present at −73.8 °C. These peaks are centered at 3.08 (sh), 3.21, 3.75, and 4.35 ppm and assigned to the four protons of the OCH_2 groups of the dioxaphosphorinane ring. Coalescence is reached at 32 °C, above which a single broad resonance emerges and is at 3.45 ppm at 80 °C. The aromatic protons appear as complex multiplets in the range 6.8–8.5 ppm.

For **2**, the ^{1}H NMR spectrum showed similar spectral behavior as that of **1**. Singlet proton signals appeared at 0.60 and 1.1 ppm at −73.8 °C and are assigned to the methyl groups appended to the dioxaphosphorinane ring. On warming, these coalesced at 67.4 °C and resulted in a single peak at 0.90 ppm at 85 °C.

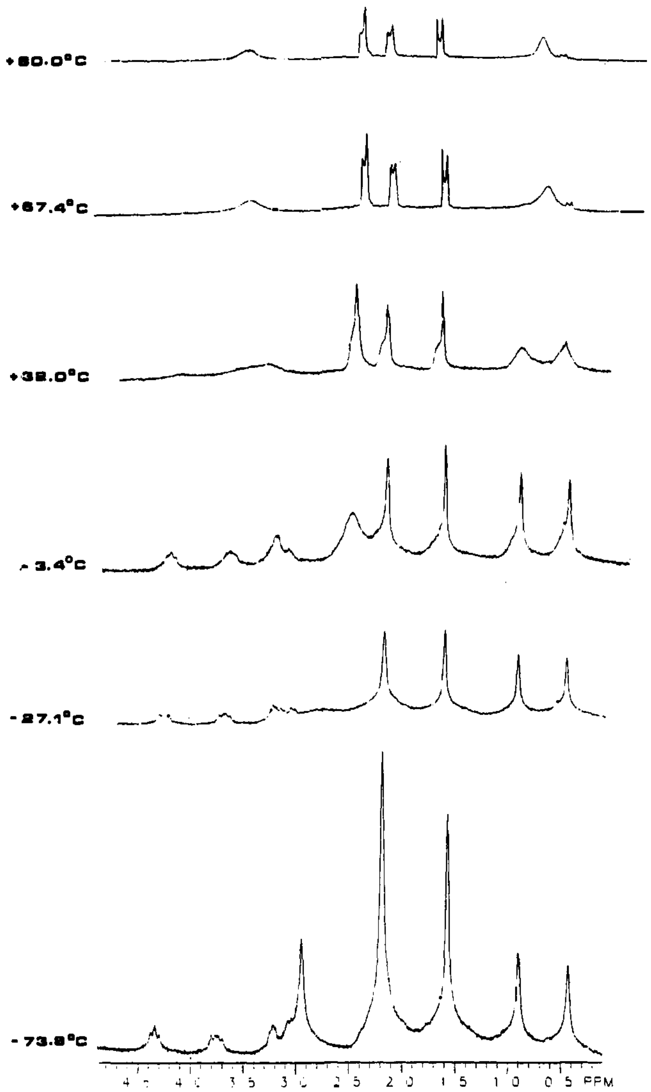

Figure 8. Partial ^{1}H NMR spectrum of **1** as a function of temperature. A small peak at 0.4 ppm is due to water in toluene-d_8. The signals at 1.6 and 2.1 ppm are due to water in toluene-d_8 and to toluene-d_8 itself, respectively.

The xylyloxy methyl signals of **2** appeared as two separate singlets, e.g., at 2.07 and 2.75 ppm at −3.4 °C, below the coalescence temperature of 42.2 °C and one signal at higher temperatures, at 2.30 ppm at 85 °C. The methylene protons (CH_2) and two methine protons (2 CH) appear as broad signals at 3.60 and 4.65 ppm, respectively, in the temperature range −74 to 42 °C. Coalescence occurs at 67.4 °C, but no signal emerges at higher temperatures. The aromatic protons give signals in the range 6.7–8.6 ppm.

The ^{1}H NMR spectrum for **3** shows only one signal for the xylyloxy methyl protons even at −90 °C. The signals from the four methylene protons are quite resolved at −3.4 °C, where doublets of doublets are present at 3.81, 5.17, and 5.72 ppm and a doublet is present at 5.24 ppm (Figure 9). This splitting is indicative of an ABX pattern, although at −27.1 °C the quartet at 3.81 ppm is further resolved into an AA′BB′X pattern due to evidence of long-range proton–proton coupling. The parameters for this peak are $^3J_{P\text{–}OCH} = 36.4$ Hz, $^2J_{H\text{–}H} = 13.0$ Hz, and $^5J_{H\text{–}H} = 2.9$ Hz, while, for the quartet at 5.72 ppm, $^3J_{P\text{–}OCH} = 15.6$ Hz, $^2J_{H\text{–}H} = 5.9$ Hz, and $^5J_{H\text{–}H} = 1.2$ Hz. Figure 10 shows the multiplet at 5.72 ppm under higher resolution. The $^5J_{H\text{–}H}$ coupling of 1.2 Hz is just apparent. The possible overlap of the other two multiplets at 5.17 and 5.24 ppm precludes coupling assignments. These four multiplet signals coalescence at 42.2 °C and result in a single broad resonance at 5.12 ppm at 85 °C. Table 5

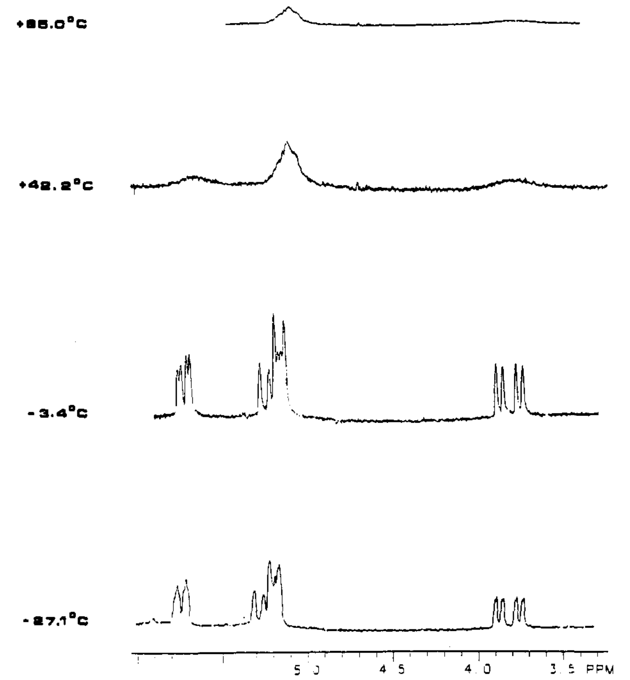

Figure 9. Variable-temperature ^{1}H NMR spectrum of **3** covering the ring methylene region.

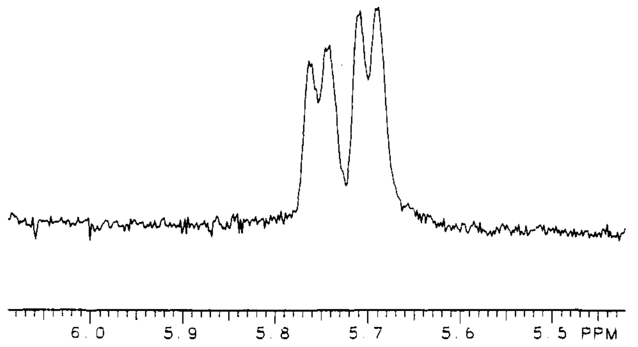

Figure 10. Expansion of the multiplet ^{1}H NMR signal of **3** at 5.72 ppm at -3.4 °C.

Table 5. Results from Variable-Temperature ^{1}H NMR Spectra to Calculate Ligand Exchange Barriers for the Bicyclic Oxyphosphoranes **1**–**3**

compd	no of signals	T_c (°C)	$\Delta\nu$ (Hz)	$\Delta G^\ddagger$ (kcal/mol)[a]
1	$\underline{Me_2}C(CH_2O)_2$, 2 → 1	35	144.7	14.5
	$C_6H_3\underline{Me_2}$, 2 → 1	27.1	228.7	11.3
	$2(OC\underline{H_2})$, 4 → 1	32		
2	$CH_2(\underline{Me}CHO)_2$, 2 → 1	67.4	146.3	16.1
	$C_6H_3\underline{Me_2}$, 2 → 1	42.2	189.6	14.7
3	$2(OCH_2)$, 4 → 1	42.2	607.8	14.0

[a] Values are estimated to be accurate to within ±1.5 kcal/mol. See ref 48.

summarizes these spectral data and lists activation energies for ligand exchange.[48]

Ligand Exchange Mechanism. The temperature-dependent spectra of these trigonal bipyramidal molecules are consistent with an intramolecular exchange process (Berry pseudorotation[49]) depicted in Figure 11, where the oxaphosphorinane ring and the dioxaphosphorinane ring traverse diequatorial positions in different exchange intermediates, those labeled **42** and **41**, respectively. Ligand exchange for **3** is represented by Figure 11, where the dioxaphosphorinane ring is replaced by the dioxaphosphepane ring. The labeling system here is the conventional one when referring to a topological representation[50,51] where the boldface pairs of numbers refer to the upper and lower axial atoms of trigonal bipyramids, respectively, with the equatorial atoms that are attached to phosphorus taking on numbers that increase in a counterclockwise fashion. The single boldface numbers between exchange intermediates represent pivotal ligands which become apical in intervening square pyramids (SPs) between adjacent trigonal bipyramids. The numbers in parentheses represent relative isomer energies and are given in kcal/mol, as described below.

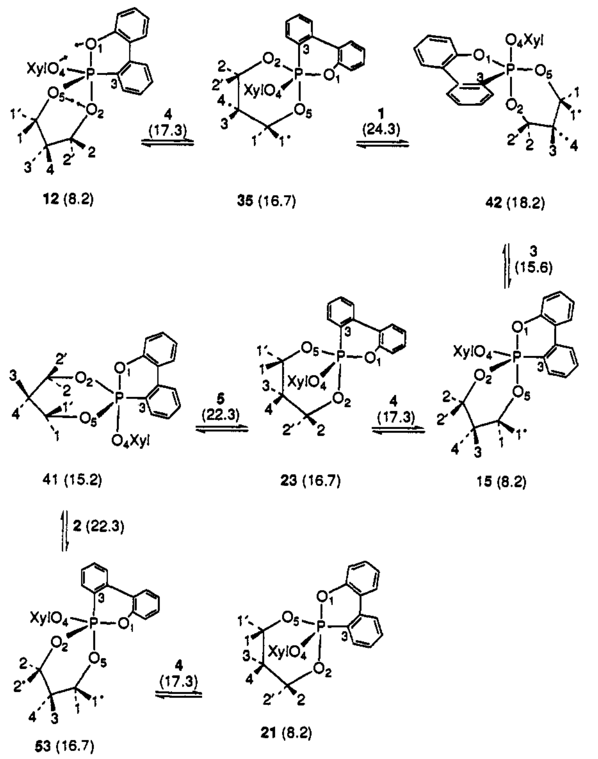

Figure 11. Isomerization pathway for intramolecular ligand exchange. Energies of all TBP and SP isomers are listed in parentheses in kcal/mol following boldface numbers identifying each isomer as discussed in the text.

Seven ligand interchanges are required to bring about equivalence of the four methylene protons of **1** and **3**, whereas, to achieve equivalence of the two ring methyls in the racemic form of the dioxo ring of **2** and the appended methyl groups in the dioxa ring of **1**, only three pseudorotations are required, **12** → **35** → **42** → **15**. The seven ligand exchanges that cause **12** to transform to **21** allow positions labeled 1 = 1′, 2 = 2′, and 3 = 4 in Figure 11. In going from **12** to **15**, 1′ = 2, 1 = 2′, and 3 = 4.

Rotation of the xylyl groups about the C–O bond equilibrates the two separate methyl proton signals. This rotational process appears to begin before the onset of pseudorotation, since coalescence occurs at lower temperatures for **1** and **2** even though the signal separation ($\Delta\nu$) is greater than that for the ring methyl signals. This is reflected in lower $\Delta G^\ddagger$ values for C–O xylyl group rotation. This process is occurring as far down as -90 °C for **3**, since only one signal is present in the ^{1}H spectrum which is invariant up to 85 °C.

To accomplish the intramolecular ligand exchange process in Figure 11 requires not only that C–O xylyl group bond rotation occurs concurrent with each of the Berry pseudorotational steps but also that each of the rings undergo conformational change based on the ring structures shown in Figures 1–7. These ring

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(48) Calculated from the equation $\Delta G^\ddagger = (4.57 \times 10^{-3})T_c(10.32 + \log(T_c\sqrt{2}/\pi\Delta\nu))$ following: Kessler, H. *Angew Chem.* **1970**, *82*, 237. See also ref 4.

(49) Berry, R. S. *J. Chem. Phys.* **1960**, *32*, 933.

(50) De Bruin, K. E.; Naumann, K.; Zon, G.; Mislow, K. *J. Am. Chem. Soc.* **1969**, *91*, 7031.

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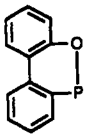
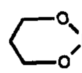
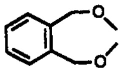
Table 6. Element Effect and Ring Strain Values for Use in Estimating Isomer Energies (kcal/mol)

Element Effect[a]

		TBP		SP	
	X^b	eq	ax	ap	bas
C	2	0.0	7.0	0.0	4.0
N	3.0	2.2	2.8	3.8	1.2
O	3.5	2.8	1.3	5.1	0.4

Ring Strain[c]

	TBP		SP	
ring type	ax–eq[d]	eq–eq	bas–bas[d]	ap–bas
	0	10	0	7
	0	7	0	5
	0	5	0	3.5

[a] To the sum of these element values for a SP 7.0 kcal/mol must be added to obtain the energy of an acyclic SP relative to a TBP isomer.[52,53] [b] Electronegativity values. [c] Ring strain values for rings spanning apical–basal sites of a SP (ideal angle of 105°) are estimated as approximately 0.7 of those for rings positioned in diequatorial sites of a TBP (ideal angle of 120°). [d] For rings in these positions with ideal angles at phosphorus of 90° (TBP) and 88° (SP), little strain is expected on the basis of values listed for five-membered rings.[52,53]

inversions and ring pseudorotations for the half-chair and boat conformations take place to maintain the structural integrity of the oxyphosphorane intermediates as they are traversed in the ligand exchange process.

On the basis of work on activation energies for an extensive variety of cyclic oxyphosphoranes containing five-membered rings,[2,3] a model approximation was developed[52] which can be extended here to include more recent work on larger ring sizes[6–13] and hence allow estimates of the relative energies of all the activated TBP and SP species involved in the ligand exchange process in Figure 11. These numbers in kcal/mol are listed in parentheses next to the numbers identifying each isomer undergoing exchange as shown in Figure 11. The isomer energies are listed for compounds **1** and **2**, which contain the six-membered dioxaphosphorinane ring.

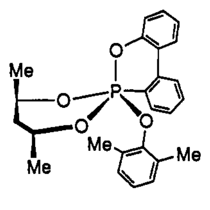
In arriving at these terms, element effects reflecting electronegativities of the attached atoms in each of the two positions of the TBP and SP are summed with a ring strain term, whose value is a function of the ring placement, and a term representing the inherent instability of a SP relative to a TBP for pentacoordinate phosphorus. These terms are summarized in Table 6, which also includes ring strain values for the six- and seven-membered rings encountered here. This model approximation is fully described elsewhere[52,53] and has been applied with considerable success in outlining reaction mechanisms of nucleophilic displacements at phosphorus.[3,4]

Ring strain values listed in Table 6 are estimated relative to activation energies and *ab-initio* calculations for saturated five- and six-membered rings.[54] Using Gaussian 93 with a 6-31G*//3-21G* basis set, an e–e ring orientation of the six-membered ring of $(OCH_2CH_2CH_2O)P(OH)_3$ is 8.7 kcal/mol less stable than the ring in an a–e orientation, while, for a comparable five-membered ring in $(OCH_2CH_2O)P(OH)_3$, the e–e ring orientation gives an isomer energy 22.9 kcal/mol higher than that of the isomer with the ring in an a–e orientation. Activation energies from NMR data[22] for ligand exchange of these same rings positioned diequatorially in $(O(CH_2)_nO)P(OC(CF_3)_2C(CF_3)_2O)$ compounds give 6.1 ($n = 3$) and 17.4 ($n = 2$) kcal/mol for the estimated energies relative to ground-state a–e ring orientations.

On the basis of the discussion in the section Ring Conformation, of the constraint in the oxaphosphorinane ring common to **1–3**, a value of 10 kcal/mol is indicated for an e–e site occupancy in a TBP. This value was obtained by comparing the more parametrized values of ring strain[52] for structurally similar five-membered rings in oxyphosphoranes. For e–e orientations of the saturated five-membered rings $(CH_2)_4P$ and $(OCH_2CH_2O)P$ in TBPs, ring strain values of 15 and 18 kcal/mol, respectively, have been established while 23 kcal/mol results for the e–e orientation of the unsaturated ring (OCH=CHO)P.[55] This increase due to ring unsaturation has been applied in a proportionate fashion to obtain the value of 10 kcal/mol for the corresponding unsaturated six-membered ring relative to the saturated counterpart.

A value of 5 kcal/mol in a similar proportionality is included in Table 6 for strain of the seven-membered ring of **3** in an e–e orientation. Previous work[11] has indicated the greater flexibility and ease of accommodation of saturated seven-membered rings in e–e positions compared to positioning saturated six-membered rings in this location of a TBP.

Referring to Figure 11, it is seen that the SP **1** represents the barrier state between the two TBP intermediates **35** and **42**. The energy of **1** (24.3 kcal/mol) relative to the energy estimated for the ground state **12** (8.2 kcal/mol) gives an energy difference of 16.1 kcal/mol for the barrier energy for ligand exchange. This compares very favorably with the 14.5 kcal/mol determined for the activation energy for ligand exchange of **1** on the basis of equilibration of the methyl proton signals of the dioxaphosphorinane ring (Table 5). The comparable exchange barrier for **2** from NMR data is 16.1 kcal/mol. This is consistent with a larger steric term for **2** compared to oxyphosphorane **1** due to the closer proximity of the xylyloxy methyl groups and the dioxaphosphorinane ring methyls of **2** that may be encountered in the exchange process in traversing the SP barrier state **1** between TBP **35** and TBP **42** intermediates of Figure 11.



SP Barrier state 1 for compound 2

The lower ΔG^* value for ligand exchange of **3** of 14.0 kcal/mol, obtained from coalescence of the four ring methylene proton signals, is in line with the greater ring flexibility of seven-membered rings compared to six-membered ones.[11] Calculation of the exchange barrier for phosphorane **3**, similar to that for **1** and **2** from Figure 11, gives 14.6 kcal/mol. This value is obtained from the sum of the element and ring strain terms listed in Table 6 and represents the difference between the energy of SP **4** and the energy of the ground-state structure **12**.

This method of estimating isomer energies from data in Table 6 when applied to tetraoxyphosphorane **C**[8] shown in the Introduction gives 9.1 kcal/mol higher energy for the TBP intermediate in the exchange process pictured with the dioxaphosphorinane ring in the e–e positions. An activation energy of 9.5 kcal/mol is calculated from the data in Table 6 for the associated SP barrier state.

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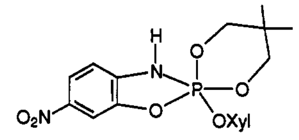
(52) Reference 3, pp 32–40.

(53) Holmes, R. R. *J. Am. Chem. Soc.* **1978**, *100*, 433–446.

(54) Holmes, R. R.; Deiters, J. A. *J. Am. Chem. Soc.*, submitted for publication.

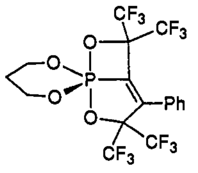
(55) Reference 3, p 36, Table 1.8.



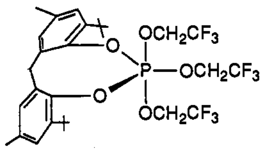
SP Barrier state for compound **C**

This value compares with the 10.5–11.3 kcal/mol range for activation energies determined experimentally for six related TBP structures.[8,21] Applying this method to cyclic pentaoxy structure **A**[22] in the Introduction gives 7.7 kcal/mol for the activation barrier for ligand exchange compared to 6.1 kcal/mol found experimentally. Here the SP barrier state has the six-membered ring spanning apical–basal positions. Insufficient data on the types of rings involved in **B**[10] are available to permit a similar calculation.

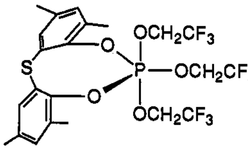
It is encouraging that structures have been determined for cyclic oxyphosphoranes that have six-[56] and eight-membered[9,11] rings in e–e sites compared to the more normally observed a–e ring orientations. Using special ring constraints, Bentrude and co-workers[56] isolated tetraoxyphosphorane **G** in this form, while we provided two examples of pentaoxyphosphoranes, **H**[9,11] and **I**,[11] having eight-membered rings so oriented. All of the structures were established by X-ray crystallography.



G

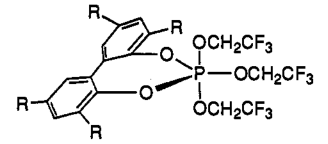


H

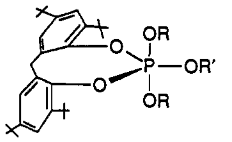


I

Although no oxyphosphoranes with seven-membered rings have been structurally characterized by X-ray diffraction, NMR studies by Denney and co-workers[57] have supported e–e ring orientations in **J** and **K** as well as other oxyphosphoranes with eight-membered ring systems, **L** and **M**, related to **H**.



J, R = *t*-Bu
K, R = H



L, R = R' = CH_2CF_3
M, R = CH_2CF_3; R' = C_2H_5

Conclusion

The results of the model calculations and activation energy comparisons indicate that a considerable level of confidence exists in applying the element and ring strain terms of Table 6 in related cyclic oxyphosphoranes containing six- and seven-membered rings involved in ligand exchange processes or applicable nucleophilic displacement reactions at phosphorus proceeding via pentacoordinate states. The results suggest that saturated six-membered rings situated diequatorially in TBP geometries of pentaoxyphosphoranes may be stabilized as ground-state structures and as such have relevance to cAMP mechanisms.

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Supplementary Material Available: Tables of atomic coordinates, anisotropic thermal parameters, bond lengths and angles, and hydrogen atom parameters for **1** (Tables S1–S4), **2** (Tables S5–S8), and **3** (Tables S9–S12) (37 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.

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(56) Huang, Y.; Arif, A. M.; Bentrude, W. G. *J. Am. Chem. Soc.* **1991**, *113*, 7800.

(57) Abdou, W. M.; Denney, D. B.; Denney, D. Z.; Pastor, S. D. *Phosphorus Sulfur Relat. Elem.* **1985**, *22*, 99.