NMR and X-ray Evidence for the Chair Conformation of Six-Membered Rings Attached Diequatorially to Five-Coordinate Phosphorus. Implications for Reported Transition-State Analogs of Nucleoside Cyclic 3′,5′-Monophosphate Hydrolysis

Yande Huang, Alan E. Sopchik, Atta M. Arif, and Wesley G. Bentrude*

Contribution from the Department of Chemistry, University of Utah, Salt Lake City, Utah 84112

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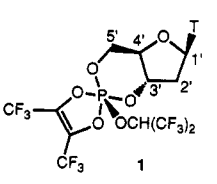
Abstract: A series of phosphoranes, **5**, **6a**, **6b**, and **7a**, has been prepared and structurally characterized by ^{1}H NMR spectroscopy and/or X-ray crystallography. In the crystalline state, **5a**, **6a**, and **6b** feature five-coordinate phosphorus bonded in a somewhat distorted, trigonal bipyramidal fashion. The phosphorus-containing six-membered ring is attached to phosphorus diequatorially and is in the chair conformation. ^{1}H NMR coupling constants reveal that for all four phosphoranes a chair-form ring, rather than a boat or twist conformation, also is populated in solution. The six-membered ring for **5** in solution is primarily in conformation **5a** (ca. 90%) in equilibrium with **5b** (ca. 10%). Arguments are presented to explain the greater stability of **5a** in terms of reduced steric repulsion between its axial-like four-membered ring oxygen with the axial hydrogens of the phosphorus-containing ring compared to that of the analogous oxygen of the five-membered ring in **5b**. The trans-fused ring structures of **6a**, **6b**, and **7a** are closely related to the previously reported phosphoranes **1–3**, prepared as transition-state analogs for the hydrolysis of cAMP. The results of the present paper render highly unlikely the assertion that thymidine-based phosphorane **3** populates in solution measurable amounts of a permutational isomer with its ring attached to phosphorus in diequatorial fashion. Structural aspects of the five-membered rings of phosphoranes **6a**, **6b**, and **7a** also are discussed.

Introduction

In recent years, a number of studies have been published that were targeted at determining the preference of a 1,3,2-dioxaphosphorinane ring containing five-coordinate phosphorus for apical/equatorial vs diequatorial attachment to phosphorus.[1] In a few instances, molecules such as **1–3** (T = thymin-1-yl) have been studied that approximate structurally the transition state for phosphodiesterase-catalyzed hydrolysis of adenosine cyclic 3′,5′-monophosphate. For **1** and **2** the ring was assigned an apical/equatorial attachment to phosphorus.[1f,g] By contrast, for **3**, from consideration of the vicinal proton coupling constants within the $CH_3OCH_2CH_2O$ substituent, it was postulated[1g] that there exists in solution a large, but unspecified, proportion of molecules with the ring bonded diequatorially to phosphorus.

A second key issue is the conformation of the six-membered ring in question. In nearly all cases,[2] the 1,3,2-dioxaphosphorinane ring bonded in apical/equatorial fashion to phosphorus has been found to be in a *nonchair twist or boat conformation.* This assignment was also given to the six-membered rings of **1**[1f] and **2**.[1g] MNDO calculations[1g] on molecule **4**, with trigonal bipyramidal geometry restrictions about phosphorus, predicted that the lowest-energy form of the diequatorial permutamer of **4** should involve phosphorus at the flattened end of a *half chair.* Nonetheless, the coupling constants for the protons at carbon 5′ ($H5'_a$ and $H5'_b$), which are diagnostic of the ring conformation, were nearly identical for **1–3**.[1f,g] (See designations of protons in structures **6a** and **6b**.) It was indeed acknowledged[1g] that the conformations populated by **3** must be twist forms.



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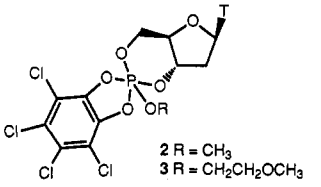

2 R = CH_3
3 R = $CH_2CH_2OCH_3$

Recently we published preliminary results[1n] of a study of **5**, a molecule featuring a bicyclic ring system that forces the 1,3,2-dioxaphosphorinane ring to be diequatorial. (The carbons and protons of the 1,3,2-dioxaphosphorinane ring of **5a** are numbered to correspond to the equivalent atoms of phosphoranes **6** and **7a** for easy comparisons of spectral and X-ray crystallographic data to be discussed later.) X-ray crystallographic evidence (Figure 1) showed that the phosphorus-containing ring of **5a**, the conformer isolated, is indeed attached in diequatorial fashion and, most significantly, is in the *chair* rather than the *twist* conformation. The predominant population of a single chair conformer,[1n] presumably **5a**, in solution was shown clearly[1n] by ^{1}H NMR spectroscopy. We interpreted this result to rule out the presence of measurable amounts of permutamer with diequatorial ring attachment for phosphorane **3** if it is assumed that such a ring, like that of **5**, would be in the chair conformation. The

(1) (a) Schomburg, D.; Hacklin, H.; Röschenthaler, G.-V. *Phosphorus, Sulfur Silicon Relat. Elem.* **1988**, *35*, 241–246. (b) Yu, J. H.; Bentrude, W. G. *J. Am. Chem. Soc.* **1988**, *110*, 7897–7899. (c) Yu, J. H.; Bentrude, W. G. *Tetrahedron Lett.* **1989**, *30*, 2195–2198. (d) Bentrude, W. G.; Yu, J. H.; Sopchik, A. E. *Phosphorus, Sulfur Silicon Relat. Elem.* **1990**, *51/52*, 73–76. (e) Yu, J. H.; Sopchik, A. E.; Arif, A. M.; Bentrude, W. G. *J. Org. Chem.* **1990**, *55*, 3444–3446. (f) Yu, J. H.; Arif, A. M.; Bentrude, W. G. *J. Am. Chem. Soc.* **1990**, *112*, 7451–7461. (g) Broeders, N. L. H. L.; Koole, K. H.; Buck, H. M. *J. Am. Chem. Soc.* **1990**, *112*, 7475–7482. (h) Burton, S. D.; Kumara Swamy, K. C.; Holmes, J. M.; Day, R. O.; Holmes, R. R. *J. Am. Chem. Soc.* **1990**, *112*, 6104–6115. (i) Kumara Swamy, K. C.; Day, R. O.; Holmes, J. M.; Holmes, R. R. *J. Am. Chem. Soc.* **1990**, *112*, 6095–6103. (j) Kumara Swamy, K. C.; Burton, S. D.; Holmes, J. M.; Day, R. O.; Holmes, R. R. *Phosphorus Sulfur Silicon Relat. Elem.* **1990**, *53*, 437–455. (k) Day, R. O.; Kumara Swamy, K. C.; Fairchild, L.; Holmes, J. M.; Holmes, R. R. *J. Am. Chem. Soc.* **1991**, *113*, 1627–1635. (l) Hans, J.; Day, R. O.; Howe, L.; Holmes, R. R. *Inorg. Chem.* **1991**, *30*, 3132–3140. (m) Holmes, R. R.; Kumara Swamy, K. C.; Holmes, J. M.; Day, R. O. *Inorg. Chem.* **1991**, *30*, 1052–1062. (n) Huang, Y.; Arif, A. M.; Bentrude, W. G. *J. Am. Chem. Soc.* **1991**, *113*, 7800–7802. (o) Yu, J.; Sopchik, A. E.; Arif, A. M.; Bentrude, W. G.; Röschenthaler, G.-V. *Hetereoat. Chem.* **1991**, *2*, 177–185. (p) Hans, J.; Day, R. O.; Howe, L.; Holmes, R. R. *Inorg. Chem.* **1992**, *31*, 1279–1285.

(2) For exceptions involving apical/equatorial chair conformation, see ref 1k and 1l.

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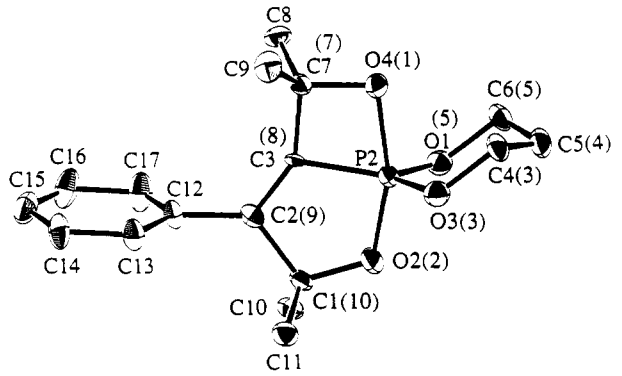
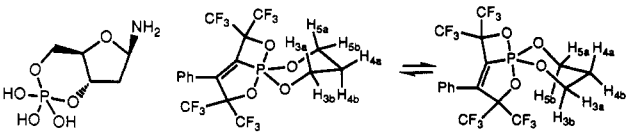


Figure 1. ORTEP diagram for **5a**.

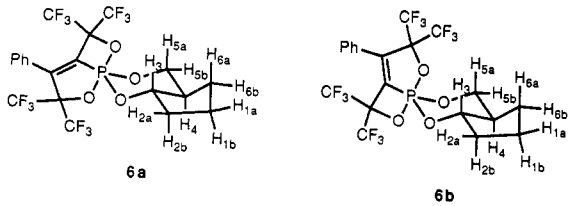
closely similar values of the observed coupling constants in question, previously reported for **1–3**,[1f,g] could only arise if the diequatorially attached 1,3,2-phosphorinane ring of **3** were to populate a *twist* conformation.



4 **5a** **5b**

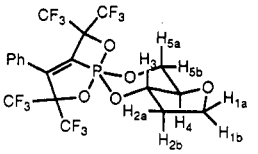
We noted[1n] by way of caution, however, that the six-membered ring of **5** exists in the crystal (Figure 1), and presumably also in solution, in the lower-energy chair conformation, **5a**, of the two available to it (**5a** ⇄ **5b**). In **5a** and **5b**, the oxygens of the four- and five-membered rings, respectively, are essentially axial-like substituents on phosphorus contained in a six-membered ring. However, the apical O–P–O bond angle in the essentially trigonal bipyramidal structure was not 180° but 162.3(2)°. More importantly, the axial-like oxygen of the four-membered ring of **5a** was tilted strongly away from perpendicularity to the equatorial plane (O–P–C angle within the four-membered ring = 73.4(2)°) and away from the six-membered ring. By contrast, the O–P–C angle in the five-membered ring was 89.0(3)°, very nearly perpendicular to the equatorial plane. Consequently, the repulsive 1,3-syn-axial-like interactions between that oxygen and the axial hydrogens of the OCH_2 portions of the 1,3,2-dioxaphosphorinane ring would be less severe in conformation **5a** than in **5b**.

To test further the possibility of the population of twist or boat conformations by diequatorially attached rings like that of **5**, we prepared phosphorane **6** which exists as two diastereomers, **6a** and **6b**. Phosphoranes **6a** and **6b** approximate the structure of

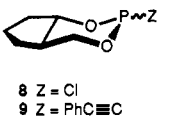


6a **6b**

the nucleoside-based molecules, **1–3**, more closely than does **5**. In **6a** and **6b**, 1,3-syn-axial-like repulsions cannot be relieved by conformational change to a lower-energy chair form as in **5a** ⇄ **5b**. Both diastereomers of **6** were isolated and characterized fully by ^1H NMR spectroscopy and X-ray crystallography. Indeed, both **6a** and **6b** feature a 1,3,2-phosphorinane ring that is *diequatorially bonded to near-trigonal-bipyramidal phosphorus*; and for both diastereomers, *the ring is in the chair conformation.* The same is found to be true for **7a** which, therefore, excludes the possibility[3] that the 4′-oxygen could influence the conformation or mode of attachment of the 1,3,2-dioxaphosphorinane ring. Therefore, the permutational isomer of phosphorane **3** having its 1,3,2-dioxaphosphorinane ring diequatorially attached to phosphorus would almost certainly also have that ring in the *chair* conformation. As will be explained in detail, the ^1H coupling constants (J_{HP}) reported for **3**[1g] are *totally inconsistent with the population of measurable amounts of such a structure with a diequatorial ring.*



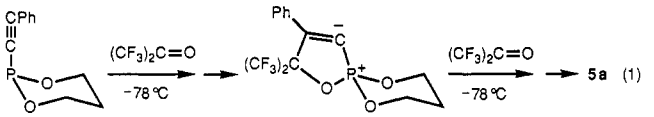
7a



8 Z = Cl
9 Z = PhC≡C

Results

1. Preparations of 5, 6a, 6b, and 7a. The preparation of **5** by use of the known reaction[4] of acetylenic phosphonites with hexafluoroacetone is shown in eq 1. Phosphoranes **6a** and **6b** were obtained in analogous fashion. Racemic phosphonites were used in all instances. A single enantiomer that corresponds to the enantiomer of naturally occurring nucleosides is depicted.



(1)

The precursor to **6a**, phosphonite **9**, was formed from reaction of phosphorochloridite **8** with lithium 2-phenylacetylide. The (2-phenylethynyl)phosphonite, **9**, was isolated on distillation as a single diastereomer with respect to configuration at phosphorus (^{31}P NMR), predictably the more thermodynamically stable one with the 2-phenylethynyl axial on phosphorus.[5] However, both phosphorochloridite **8** and phosphonite **9** were *diastereomeric about the ring fusion*, the ratio of desired trans diastereomer to cis-fused material being 3/1 (^{31}P NMR). Reaction of **9** with hexafluoroacetone gave crystalline product phosphorane (3/1 ratio of ring diastereomers, as shown by ^{31}P NMR) in 98% crude yield (>95% pure by ^{31}P NMR) as a mixture of diastereomeric phosphoranes. The desired trans fused-ring product, **6a**, was isolated from a portion of this mixture by HPLC on SiO_2 (EtOAc/*n*-hexane = 1/20).

To obtain **6b**, phosphorochloridite **8** was reacted with lithium 2-phenylacetylide at ambient temperature, as in the first step of the preparation of **6a**. (In this instance, the diol precursor to **8** has been isolated as the pure diastereomer with transoid ring fusion.) Filtration of the product solution, rapid evaporation of solvent, and immediate reaction of unpurified **9** with hexafluoroacetone were followed by flash-column chromatography of the solid product and then crystallization from ethyl acetate/*n*-hexane solution to afford **6b** in 18% yield. (No attempt was made to optimize the isolated yield of **6b**.) Both **6a** and **6b** are stable as shown by their stability toward HPLC and column chromatographic conditions.

(3) van Ool, P. J. J. M.; Buck, H. M. *Recl. Trav. Chim. Pays-Bas* **1984**, *103*, 119–122.

(4) (a) Aly, H. A. E.; Barlow, J. H.; Russell, D. R.; Smith, D. J. H.; Swindles, M.; Trippett, S. *J. Chem. Soc. Chem. Commun.* **1976**, 449–450. (b) Trishin, Ju, G.; Konovalova, I. V.; Burangulova, R. N.; Burnaeva, L. A.; Chistokletov, V. N.; Pudovik, A. N. *Tetrahedron Lett.* **1989**, *30*, 577–580. (c) Trishin, Yu. G.; Konovalova, I. V.; Burangulova, R. N.; Burnaeva, L. A.; Chistokletov, V. N.; Pudovik, A. N. *Zh. Obshch. Khim.* **1988**, *58*, 2434–2441.

(5) Bentrude, W. G.; Setzer, W. N. In *^{31}P NMR Spectroscopy in Stereochemical Analysis: Organic Compounds and Metal Complexes*; Verkade, J. G., Quin, L. D., Eds.; VCH: Deerfield Beach, FL, 1987; Chapter 11.

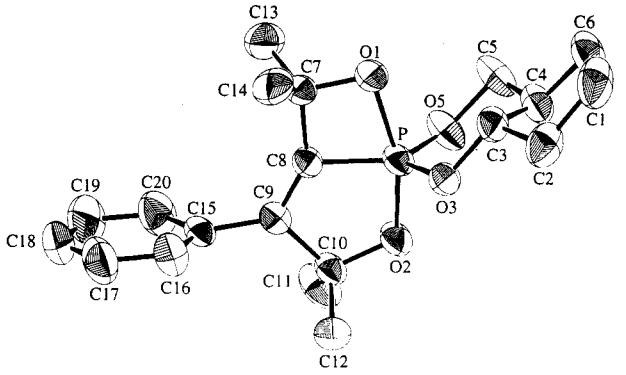


Figure 2. ORTEP diagram for **6a**.

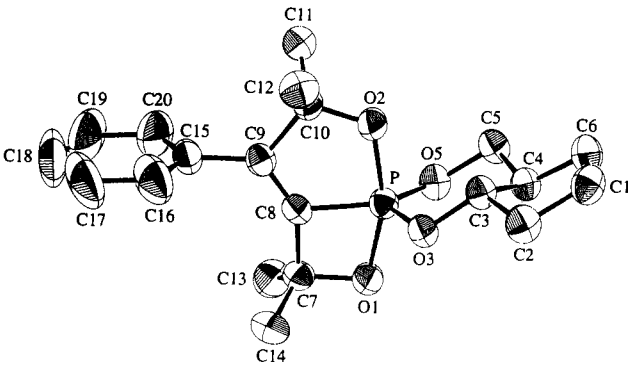


Figure 3. ORTEP diagram for **6b**.

Evidently, the configuration at phosphorus of phosphonite **9** is largely retained in its conversion to **6a** and **6b**, as is reasonable from the mechanism for the formation of **6** that can be readily envisaged (reaction 1). Initial nucleophilic attack by the phosphorus of the phosphonite on the carbonyl oxygen of CF_3COCF_3 to form an ylide intermediate is followed by reaction of that adduct with a second mole of ketone and subsequent cyclization to **6**. The relatively short reaction time at room temperature was designed to give predominantly the diastereomer of **9** with the 2-phenylethynyl equatorial on phosphorus and, subsequently, phosphorane **6b**. By contrast, distillation of **9** established the predominance of the thermodynamically favored diastereomer of **9** (2-phenylethynyl group axial) and led to the stereochemistry at phosphorus found for **6a**.

Phosphorane **7a** was prepared similarly from its phosphonite precursor, obtained as a single diastereomer with the 2-phenylethynyl group on phosphorus axial. Its configuration at phosphorus was based on the assumed stereochemistry of the reaction. The other diastereomer, **7b** (not shown), could not be obtained because of the unavailability of the phosphorochloridite, which, unlike **8**, could not be obtained by cyclization of 1′,2′-deoxyribose with PCl_3.

2. X-ray Crystallography. Figures 1, 2, and 3 display ORTEP perspective views for **5a**, **6a**, and **6b**, respectively. Pertinent crystal data for these phosphoranes are recorded in Table I. For purposes of comparison, selected bond distances for the three are listed in Table II, which bond angles of interest are compared in Table III. Table IV shows selected torsion angles for the series. In Figure 1 (ORTEP drawing of **5a**), the atom numbering system for the ORTEP drawings of **6a** and **6b** is shown in parentheses alongside the numbers based on the nomenclature of the ring system. For ease of comparison with those of **6a** and **6b**, the parameters for **5a** in Tables II–IV employ the numbers of Figure 1 in parentheses.

The ORTEP drawings clearly show the transoid fusion of the five- and six-membered rings of phosphoranes **6a** and **6b**. Most striking are the unmistakable chair conformations of the six-membered rings of *all three phosphoranes* (Figures 1–3). Atoms bonded to phosphorus are arranged in a somewhat distorted trigonal bipyramidal fashion. Atoms P, C8, O3, and O5 are virtually in the same equatorial plane as indicated by the sums of the bond angles about phosphorus in that plane of 359.3–359.4°. The atoms in the equatorial plane are very slightly distorted toward a pyramidal geometry about phosphorus. In all cases, the displacement of phosphorus from the plane through C8, O3, and O5 is only 0.08 Å, which corresponds to a slightly less than 3° deviation from planarity. In the very shallow pyramid, O3 and O5 move in the direction of apical O1 of the four-membered ring. The O1–P–O2 bond angles for all three

Table I. Crystal Data for **5a** at −125 °C and **6a** and **6b** at Ambient Temperature

compound	**5a**	**6a**	**6b**
mol formula	$PF_{12}O_4C_{17}H_{11}$	$PF_{12}O_4C_{20}H_{15}$	$PF_{12}O_4C_{20}H_{15}$
mol wt	538.23	578.295	578.295
space group	$Pca2_1$ (No. 29)	$P\bar{1}$ (No. 2)	$P\bar{1}$ (No. 2)
crystal system	orthorhombic	triclinic	triclinic
cell dimensions			
a, Å	13.232(2)	9.378(2)	11.441(3)
b, Å	8.562(3)	10.142(3)	7.123(3)
c, Å	17.570(5)	12.804(2)	14.345(3)
α, deg		98.41(2)	101.58(3)
β, deg		109.28(2)	91.69(2)
γ, deg		93.00(2)	95.40(3)
v, Å^3	1990.46	1130.49	1138.76
Z	4.0	2.0	2.0
D_{calcd}, g/cm^3	1.796	1.699	1.686
radiation, Å	λ (Mo) 0.70930	λ (Mo) 0.70930	λ (Mo) 0.70930
2θ range, deg	4.00–60.00	4.00–60.00	4.00–60.00
scan technique	$\theta/2\theta$	$\theta/2\theta$	$\theta/2\theta$
scan width, deg	1.0000 + 0.3500 tan θ	0.8000 + 0.3400 tan θ	0.8000 + 0.3400 tan θ
no. of reflections used	3284	6569	4246
absorption coeff, cm^{-1}	2.642	2.387	2.369
data to parameter ratio	7.179	8.782	9.829
shift to error ratio	0.005	0.000	0.001
R	0.0676	0.0488	0.0641
R_w	0.0768	0.0589	0.0660

Table II. Selected Bond Distances (Å) for **5a**, **6a**, and **6b**[a]

	compound		
atoms	**5a**	**6a**	**6b**
P–O1	1.799(5)	1.810(2)	1.741(3)
P–O2	1.675(5)	1.677(2)	1.742(3)
P–O3	1.576(5)	1.571(2)	1.566(3)
P–O5	1.568(5)	1.566(2)	1.581(3)
P–C8	1.785(6)	1.767(3)	1.777(4)
O3–C3	1.466(8)	1.474(3)	1.468(5)
O5–C5	1.469(8)	1.482(3)	1.476(5)

[a] Estimated standard deviations in parentheses.

Table III. Selected Bond Angles in Degrees for **5a**, **6a**, and **6b**[a]

	compound		
atoms	**5a**	**6a**	**6b**
O1–P–O2	162.3(2)	161.6(1)	161.1(2)
O1–P–O3	96.0(3)	96.6(1)	96.0(2)
O1–P–O5	94.9(2)	94.5(1)	93.4(2)
O1–P–C8	73.4(2)	73.8(1)	74.6(2)
O2–P–O3	94.4(3)	96.1(1)	97.3(2)
O2–P–O5	95.3(3)	94.0(1)	95.0(2)
O2–P–C8	89.0(3)	88.3(1)	86.9(2)
O3–P–O5	108.1(3)	108.2(1)	108.6(2)
O3–P–C8	127.2(3)	121.6(1)	121.6(2)
O5–P–C8	124.1(3)	129.5(1)	129.2(2)
P–O3–C3	116.1(4)	113.1(2)	114.3(3)
P–O5–C5	116.3(4)	117.6(2)	118.4(3)

[a] Estimated standard deviations in parentheses.

Table IV. Selected Torsion Angles in Degrees for **5a**, **6a**, and **6b**[a]

atoms	compound		
	5a	**6a**	**6b**
P–O1–C7–C8	−1.67 (0.48)	−1.44 (0.19)	−1.22 (0.33)
P–C8–C9–C10	−0.14 (0.76)	−1.95 (0.32)	−0.78 (0.53)
P–O2–C10–C9	0.66 (0.74)	2.62 (0.28)	2.28 (0.48)
P–O3–C3–C4	−52.83 (0.75)	−55.15 (0.28)	−53.93 (0.42)
P–O3–C3–C2		−171.33 (0.22)	−171.24 (0.34)
P–O5–C5–C4	51.59 (0.77)	52.43 (0.32)	51.00 (0.45)
P–O3–C3–H5	66.65 (0.70)	67.97 (0.26)	68.10 (0.42)
P–O5–C5–H7	−68.79 (0.70)	−67.07 (0.33)	−68.66 (0.47)
P–O5–C5–H8	177.12 (0.55)	172.02 (0.22)	171.68 (0.31)
H5–C3–C4–H6	−176.52 (0.71)	−168.00 (0.29)	−168.35 (0.40)
H6–C4–C5–H7	−178.26 (0.73)	−173.22 (0.29)	−176.12 (0.50)
H6–C4–C5–H8	−61.76 (1.03)	−52.74 (0.35)	−57.24 (0.50)
H1–C1–C2–H3		95.75 (0.41)	98.21 (0.58)
H1–C1–C2–H4		−27.47 (0.48)	−22.99 (0.69)
H2–C1–C2–H3		−24.65 (0.48)	−21.97 (0.67)
H2–C1–C2–H4		−147.88 (0.35)	−143.16 (0.49)
H3–C2–C3–H5		42.25 (0.42)	41.29 (0.60)
H4–C2–C3–H5		165.87 (0.30)	161.83 (0.42)
H1–C1–C6–H9		−3.19 (0.50)	−6.32 (0.65)
H1–C1–C6–H10		−124.84 (0.38)	−126.68 (0.49)
H2–C1–C6–H9		117.83 (0.38)	112.41 (0.52)
H2–C1–C6–H10		−3.82 (0.48)	−7.96 (0.62)
H6–C4–C6–H9		25.33 (0.44)	29.68 (0.64)
H6–C4–C6–H10		148.50 (0.32)	149.72 (0.44)

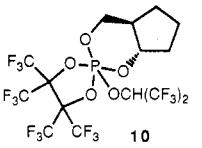
[a] Estimated standard deviations in parentheses.

phosphoranes are considerably less than 180° (161–162°). Of particular note is the angle O2–P–C8, 86.9–89.0°. This places the oxygen, O2, of the five-membered ring in all cases much more nearly perpendicular to the best plane through P and the equatorial atoms than it places the corresponding oxygen, O1, of the four-membered ring for which the angle O1–P–C8 ranges 73.4–73.8°. Axial-like O2 is obviously likely to engender greater syn-axial-like 1,3-interactions with H3 and H5a in **5b** and **6b** than will O1 in **5a** and **6a**.

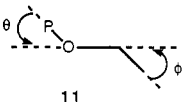
Significantly, the 1,3,2-dioxaphosphorinane ring readily accommodates diequatorial six-membered ring attachment with an *O3–P–O5 angle of 108° in all three cases*. For **5a** the P–O–C angles within the six-membered ring are reduced to about 116°, a value below the approximately 120° bond angles found[1f] for such rings bonded at apical and equatorial positions to five-coordinate phosphorus. The corresponding angles about O3 and O5 for **6a** and **6b** are unequal, as is usual for 1,3,2-dioxaphosphorinane rings trans-fused to five-membered rings,[1f,6] and they are reduced from those found[1f] previously for the analogous phosphorane, **10**, with the six-membered ring attached to phosphorus in apical/equatorial fashion. Thus, angle P–O5–C5 for the apical P–O bond of **10** is 122.5(3)° compared to the 117.6-(2)° and 118.4(3)° values measured for **6a** and **6b**, respectively. Similarly, for **10** the angle P–O3–C3 was 121.2(3)°, while for **6a** and **6b** Table III records 113.1(2)° and 114.3(3)° angles, respectively. The relatively large difference in P–O3–C3 and P–O5–C5 angles is reminiscent of the chair-form rings of phosphate and phosphoramidate derivatives of nucleoside cyclic 3′,5′-monophosphates.[6]

Another important feature of these molecules is the apical-like P–O bond of the four-membered ring which is lengthened to 1.80–1.81 Å for **5a** and **6a** from the 1.68-Å value recorded for the corresponding apical P–O bond in the five-membered rings of those phosphoranes (Table II). (Interestingly, the length of the same P–O bond in the four-membered ring is decreased to 1.74 Å in **6b**.) As previously noted, this bond is bent away from the equatorial plane by 18–19°, as revealed by the O1–P–O2 (161.1–162.3°) and O1–P–C8 angles (73.5–74.6°) of the three phosphoranes. A similar lengthening is seen for bond P–O2 of compound **6b** (1.74 vs 1.68 Å in **6a**). That bond, however, remains essentially perpendicular to the equatorial plane. The lengths of the remaining P–O bonds are unexceptional. As would be predicted, apical bonds are longer than equatorial ones. The equatorial P–O bond lengths for **5a**, **6a**, and **6b** (1.57–1.58 Å) are the same as the equatorial P–O bond distance for **10**, 1.58 Å.[1f]

Further insight into the conformations of these molecules arises from consideration of interplanar angles. One may define three planes as follows: O3–P–O5; the best plane through O3–O5–C5–C3; and C5–C4–C3. The interplane angles of interest are defined in structure **11**. The puckering at the phosphorus end of the ring is measured by θ. For the molecules in question, values of θ are 40.3° (**5a**), 42.4° (**6a**), and 38.0° (**6b**). Most probably the increased 1,3-syn-axial-like repulsions between O2 of **6b** and the axial hydrogens at C3 and C5 further flatten the ring, as seen in the 4° decrease in θ for **6b** compared to that of **6a**. Nonetheless, the ring remains in the *chair* form. The C4 end of these rings with ϕ values of 52.9° (**5a**), 53.7° (**6a**), and 55.9 (**6b**) is more like that of a cyclohexane. The greater flattening at P, compared to the carbon end of the ring, is found generally for 1,3,2-dioxaphosphorinanes,[7] probably as a consequence of the relatively long lengths of P–O bonds. The flattening is further increased for four-coordinate phosphorus when groups such as Me_2N, Me, etc., are placed axial on phosphorus.[7]



10



11

The four- and five-membered rings of the bicyclic system lie essentially in the same plane. The angles between the best planes formed by these rings are on the order of 2–3° with calculated errors of almost 2° for **6a** and **6b** and 6.4° for **5a**. Conformational features of the five-membered rings of **6a** and **6b** will be discussed later in connection with their ^{1}H NMR spectra.

3. ^{1}H NMR Spectroscopy of 5, 6a, 6b, and 7a. Table V contains the ^{1}H NMR parameters for the phosphorus-containing rings of phosphoranes **5**, **6a**, **6b**, and **7a**. The designations for the ring protons of **5a** and **5b** are made to correspond to those for **6a**, **6b**, and **7a** for ease of comparison. The chemical shifts of the protons of the six-membered ring of **5** are widely enough separated at 300 MHz to give first-order spectra, from which the appropriate parameters are easily obtained. Protons H5a, H5b, H3, and H4 of **6a**, **6b**, and **7a** also are well dispersed at 500 MHz. First-order spectra are seen as well for the protons of the five-membered rings of the phosphoranes under study. Protons H3 and H4 are common to both rings. The spectrum of the five-membered ring of **7a** was analyzed with the aid of computer-simulation techniques to obtain reliable parameters.

For **6a** and **6b**, H4 also is coupled to protons H6a and H6b. Even though the resonances remain well-separated, the complexity of the splitting patterns required that certain subspectra of these carbocyclic five-membered ring phosphoranes be iteratively refined by use of the LAOCN5 NMR simulation program. (See Experimental Section for details.) This task was complicated by the fact that the number of spins exceeds the capacity of the LAOCN5 program. Furthermore, assignments of sets of peaks to specific protons were not straightforward, especially in the H1, H2, and H6 areas, but were determined by 2D COSY techniques. Additionally, some of the resonances are rather broad with few assignable lines. Nonetheless, rms errors and probable errors in coupling constants and δ values are low. These results

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Table V. ^{1}H NMR Parameters for the 1,3,2-Dioxaphosphorinane Rings of Phosphoranes **5–7**[a]

		J, Hz							δ, ppm			
compd	solvent	5aP	5bP	3P	4P	34	45a	45b	3	4	5a	5b
1[b]	$(CD_3)_2CO$	27.6	<0.2	<0.2	<0.2	9.3	9.7	6.9	5.10	4.23	4.36	4.69
2[c]	CD_2Cl_2	27.0	1.3			9.2	9.2	7.2	4.76	3.98	4.20	4.73
3[c]	CD_2Cl_2	27.4	0.6			9.1	9.1	7.3	4.82	4.00	4.23	4.75
5[d]	C_6D_6	5.5	25.0	5.5[d] (3aP)	−1.4[d] (4bP)	11.4[d] (3a4b)	11.4	4.7	4.13[d] (3a)	1.44[d] (4b)	4.13	3.62
6a	C_6D_6	1.3	28.5	1.0	−0.6	10.7	11.6	4.4	4.44	1.71	4.20	3.81
6b	C_6D_6	1.4	25.8	1.0	−0.6	10.6	11.6	4.5	4.54	1.83	4.25	3.91
7a	C_6D_6	1.6	28.6	1.7	−0.9	9.7	10.8	4.5	4.56	*e*	4.38	4.04
7a	CD_3CN	1.8	28.5	1.8	−0.9	9.3	10.9	4.6	4.84	3.89	4.58	4.69
10[b]	C_6D_6	26.4	2.7	<0.2	<0.2	10.3	10.6	7.6	3.72	1.47	3.19	3.97

[a] At 500 MHz except for **5**, 26 °C. [b] Reference 1f. [c] Reference 1g. [d] At 300 MHz, ambient temperature; $\delta_3 = \delta_{3a}$, $\delta_4 = \delta_{4b}$; $J_{3P} = J_{3aP}$, $J_{4P} = J_{4bP}$, $J_{34} = J_{3a4b}$; $\delta_{4a} = 0.57$ ppm; $J_{4aP} = -3.0$ Hz, $J_{3b5b} = -1.3$ Hz; $J_{3a5b} = J_{3b5a} = -0.7$ Hz; $J_{4a5a} = 2.9$ Hz; $J_{4a5b} = 3.2$ Hz. [e] Overlapped with five-membered ring protons.

Table VI. J_{HH} Values for the Five-Membered Saturated Rings of Phosphoranes **6–7**[a]

		J, Hz															
compd	solvent	1a2a	1a2b	1a6a	1a6b	1b2a	1b2b	1b6a	1b6b	1a1b	2a2b	2a3	2b3	34	6a6b	46a	46b	2aP
6a[b]	C_6D_6	8.7	8.6	11.0	2.5	2.5	11.4	7.8	9.6	−13.5	−11.9	7.1	11.3	10.7	−12.6	12.6	7.2	−0.8
6b[b]	C_6D_6	8.7	8.6	11.0	2.5	2.5	11.4	7.8	9.6	−13.5	−11.9	7.1	11.3	10.6	−12.6	12.6	7.2	−0.8
7a[c]	CD_3CN	7.3	8.8			2.6	10.2			−8.8	−10.9	7.4	10.9	9.3				−0.9
12[d]	C_6D_6	7.5	8.6			3.5	10.3			−9.2	−11.8	7.8	10.2	9.2				
1[d]	$(CD_3)_2CO$					3.2	9.4				−13.4	8.0	9.6	9.3				
cTMP[e]	D_2O					2.4	8.9				−13.3	8.0	10.8	9.2				

[a] At 500 MHz, +26 °C. [b] Resonances for **6a** and **6b** were simulated and partially iterated using the LAOCN5 spectral analysis program. See Experimental Section for details; rms protons 1b and 2b 0.228; protons 6a and 6b 0.125. [c] Also determined for **7a**: $J_{1bP} = 1.1$ Hz; $J_{2bP} = -0.7$ Hz. [d] Reference 1f. [e] Reference 8a.

appear in Table VI. The coupling constants for the five-membered ring portions of **6a** and **6b** are nearly identical.

(a) Conformations of the Phosphorus-Containing Rings. The chair structure of the six-membered ring of **5** is evident from the *J* values of Table V. The protons H3a and H5a (chemical shift but not magnetically equivalent) display large couplings to H4b ($J = 11.4$ Hz) as evidence of their diaxial relationship (Karplus relation for vicinal J_{HH}). Predictably, the couplings of H3b and H5b to H4a and H4b are small. Most significant are the very large values for J_{3bP} and J_{5bP} (25.0 Hz), which reveal the antiperiplanar relationship of these protons to phosphorus, and the relatively small 5.5-Hz coupling J_{5aP}. This combination of coupling constants (J_{HH} and J_{HP}) *is unique for the chair conformation* and has been noted for thymidine-based 3′,5′-cyclic three- and four-coordinate phosphorus compounds and related bicyclic systems[5,8] that contain the 1,3,2-dioxaphosphorinane ring system. Presumably, the specific conformation *primarily* populated in solution is **5a** as it is in the crystal (Figure 1). Evidence that **5a** should be the lower-energy conformer is seen in the previously noted greater flattening of the ring of **6b** relative to that of **6a** and other features of the X-ray structures of **5a**, **6a**, and **6b**.

As for **5**, the key coupling constants for **6a**, **6b**, and **7a** are the large J_{45a} (10.8–11.6 Hz) and small J_{5aP} (1.3–1.8 Hz). These couplings identify H5a and implicate the *chair conformation for the 1,3,2-dioxaphosphorinane ring*. This assignment is confirmed unmistakably by the large J_{HP} values noted (25.8–28.6 Hz) for equatorial H5b together with the small value of J_{45b} (4.4–4.6 Hz). In all three of these phosphoranes, J_{34} is reasonably large (9.3–10.7 Hz), which reflects the trans fusion of the ring junction. By contrast, phosphoranes **1–3** display coupling constants that are only consistent with the population of *twist conformations* by their six-membered rings.[8] Most diagnostic of the twist form are the combination of large J_{45a} and simultaneously large J_{5aP}, which are unique for that conformation.[8] In none of these sorts of ring systems, regardless of the coordination number of phosphorus, are J_{3P} and J_{34} of value in assigning conformation. They remain essentially invariant with conformation as predicted by inspection of Dreiding models of these rings in either the chair or twist conformation.

There are some variations in the J_{HP} values in this series of phosphoranes. The increase in J_{5aP} for **5** to 5.5 Hz suggests the population of a small percentage of conformer **5b** along with the dominant one, **5a**. However, the size of J_{4b5a} (11.4 Hz) is large enough that at least 90% of **5** must populate **5a**, based on reasonable assumed values for J_{4b5a} of 12.5 Hz in form **5a** and 3.0 Hz in form **5b**.[9] A 90/10 ratio of **5a**/**5b** population also would account for the observed couplings of J_{5aP} and J_{5bP} for **5** if one time-averages assumed J_{HP} values of 28.5 Hz for equatorial H5b in **5a** and 1.5 Hz for axial H5b in **5b**. (These couplings (J_{HP}) are approximately the numbers found for **6a**, **6b**, and **7a**, all of which presumably are entirely in the chair conformation shown.) This equilibrium will be more fully explored in a separate publication, utilizing a phosphorane analogous to **5** but with a *tert*-butyl and other groups opposite phosphorus on the six-membered ring.

For phosphorane **6b**, J_{5bP} is reduced, but J_{5aP} is not increased. Here, of course, conformational equilibria between two chair forms is not possible. Substantial equilibration of the chair form with a twist conformation would *increase* J_{5aP}, but this is not observed. It seems most likely, therefore, that the reduction in J_{5bP} observed for **6b** is related to the reduction in the interplane angle θ depicted in **11**. It is surprising that the torsion angles

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Table VII. ^{1}H NMR Chemical Shifts for the Five-Membered Saturated Rings of Phosphoranes **6–7**[a]

compd	solvent	δ, ppm 6a	6b	1a	1b	2a	2b	3	4
6a[b]	C_6D_6	0.38	0.83	1.09	0.95	1.57	1.36	4.45	1.71
6b[b]	C_6D_6	0.42	0.87	1.11	0.97	1.65	1.38	4.54	1.83
7a	CD_3CN			4.15	4.24	2.47	2.30	4.84	3.89
12[c]	C_6D_6			3.36	3.40	1.34	1.21	3.78	3.31
1[c]	$(CD_3)_2CO$				6.30	2.68	2.62	5.10	4.23
cTMP[d]	D_2O				6.30	2.50	2.59	4.70	3.91

[a] At 500 MHz, 26 °C. [b] Resonances for **6a** and **6b** were simulated and partially iterated using the spectral analysis LAOCN5 program. See Experimental Section for details. [c] Reference 1f. [d] Reference 8a.

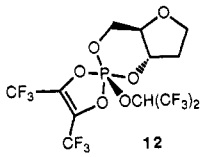
Table VIII. Torsion Angles in Degrees for the Five-Membered Rings of Phosphoranes **6a**, **6b**, and **10**[a]

compd	C1–C6 ν_0	C1–C2 ν_1	C2–C3 ν_2	C3–C4 ν_3	C4–C6 ν_4
6a	−7.3	−21.6	43.1	−47.9	32.8
6b	−3.8	−26.0	47.4	−50.5	32.1
10[1f]	−14.1	−15.1	38.5	−48.0	37.7

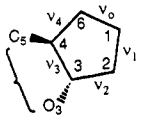
[a] See structure **13** for assignments of angles.

P–O–C–H5b (P–O5–C5–H7 of Table IV) for **6a** and **6b** are essentially identical, as Dreiding models suggest a reduction in J_{5bP} on decrease of θ. The hydrogens in question were not located in the X-ray analysis but were added using standard C–H bond lengths and C–C–H bond angles and may not reflect accurately actual differences in the angle in question.

(b) Conformations of the Five-Membered Rings. The coupling constants for the five-membered ring of **7a** are closely comparable to those published earlier[1f] for **12**, which are reproduced in Table VII along with ^{1}H NMR data for cyclic thymidine 3′,5′-monophosphate (cTMP)[8a] and the thymidine-based phosphorane **1**.[1f] Based on the recorded coupling constants, the 2′-deoxyribose



12



13

ring of cTMP was assigned[10] the narrow range of conformations designated $_4E$–$^3T_4$.[10,11] It had previously been found that the conformations of such rings are essentially unaffected by the coordination number at phosphorus and whether the ring is in a chair or twist conformation.[1f] The similarity of the coupling constants of **7a** and **12** shows that the 2′-deoxyribose ring conformation also is insensitive to whether the 1,3,2-dioxaphosphorinane ring containing five-coordinate phosphorus is attached diequatorially or apically/equatorially. The increase in the coupling J_{1b2b} for **7a** and **12**, compared to that for **1** and cTMP, suggests that the conformations of **7a** and **12** are displaced toward the $_4E$ (C4-exo) form.[10,11]

The X-ray crystal structures for **6a** and **6b** show their carbocyclic rings to have rather similar conformations. The designated torsion angles are given in Table VIII. Structure **13** assigns the angles of interest according to the IUPAC convention for nucleosides.[11] The very small values of ν_0 (−3.8° and 7.3°) place these rings at close to the ^3E envelope conformation (C3-endo). In a recent compilation[6] of ribose ring torsion angles for nucleoside cyclic 3′,5′-monophosphates, -phosphate triesters, and -phosphoramidates, ν_0 was seen to vary from 3° to −30.8° or essentially over the range from ^3E to $_4E$. cAMP and cIMP were the only molecules at the $_4E$ extreme. Crystal-packing effects seem to be important factors in these variations, which could not be correlated with the nature of the nucleobase or the 2′-substituent (H or OH).

By way of comparison, the published X-ray structure[1f] of phosphorane **10**, determined in this laboratory, showed its carbocyclic five-membered ring to be in twist form $^3T_4$. The near equality of angles ν_0 and ν_1 (Table VIII) attests to this conclusion. Though small, the range of ring pseudorotational motion available to the 2′-deoxyribose-like and carbocyclic rings of cyclic nucleotides, their derivatives, and analogs is real. Since the conformations of these five-membered rings are likely perturbed by crystal-packing forces, the solid-state conformation need not necessarily be present in solution. (The X-ray structure of a phosphorane similar to **10** was reported by the Holmes group.[1m])

Dreiding models for **6a** and **6b** readily show the ease with which conformations over the range ^3E–$_4E$ can be attained. In this range of conformations, one expects the J_{HH} values for J_{2b3} (11.3 Hz) and J_{2a3} (7.1 Hz) to be similar to those of cTMP and related molecules (Table VI), which allows the ready assignment of H2a and H2b. Expectedly, for **6a** and **6b** the couplings J_{1b2a} and J_{1b2b} also are similar to those of the other compounds of Table VI. For **6a** and **6b**, coupling constants involving H6a and H6b, not present in the ribose-like rings, yield further conformational information. The torsion-angle relationships of H6a and H6b to H4, as seen from Dreiding models, are essentially identical to those of H2a and H2b to H3. This allows assignment of H6a and H6b from the coupling constants J_{46a} (similar to J_{2b3}) and J_{46b} (similar to J_{2a3}) to be made easily.

In addition, in the $^3T_4$ conformation, unlike the ^3E and $_4E$ forms, none of the adjacent hydrogens on C1, C2, or C6 eclipse one another, including the pairs H1a, H1b and H6a, H6b. Furthermore, examination of a Dreiding model in the $^3T_4$ conformation predicts the symmetry of coupling constants noted for **6a** and **6b**; i.e., proton–proton couplings J_{1b2a}, J_{1b2b} and J_{1a6a}, J_{1a6b}; and similarly couplings J_{1a2a}, J_{1a2b} and J_{1b6a}, J_{1b6b}. As previously noted, the reported[1f] X-ray crystal structure of **10** shows the carbocyclic ring to be in the $^3T_4$ conformation. If one indeed uses the H–C–C–H torsion angles from that structure and standard Karplus curves, the values, and particularly the relative sizes of $^3J_{HH}$ predicted for the five-membered ring hydrogens of **6a** and **6b**, are in qualitative accord with the experimental ones. A more detailed analysis of the conformations of these rings, including calculation of precise torsion angles, is not warranted. The clear conclusion, however, is that the conformations of the carbocyclic rings of **6a** and **6b** are slightly different in the two different phases. In solution, the ring has moved an additional 7–10° along the pseudorotational pathway close to the $^3T_4$ conformation from a conformation only 4–7° away from the ^3E form.

Discussion

A series of five-coordinate phosphorus containing molecules, **5–7**, with phosphorus part of a 1,3,2-dioxaphosphorinane ring was prepared. This ring is constrained in **5–7** by the bicyclic ring system to be attached diequatorially to five-coordinate phosphorus. A combination of X-ray crystallography and ^{1}H NMR analysis shows that in the crystal and in solution *the six-membered ring is in a chair rather than twist or boat conformation.* This contrasts to the finding for 1,3,2-dioxaphosphorinanes containing five-coordinate phosphorus with the ring attached to phosphorus in apical/equatorial fashion that with few exceptions[2], a *twist or boat conformation* is preferred energetically.[1]

For **5a**, **6a**, and **7a**, the apical oxygen on phosphorus is part of a strained four-membered ring and, as a result, is pulled away from perpendicularity to the equatorial plane, and the P–O1 bond is lengthened in **5a** and **6a** to 1.80 Å. This oxygen, therefore, is not in position to maximally destabilize the chair form postulated by way of 1,3-syn-axial-like repulsions with H3 and H5a. For

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this reason, conformation **5a** is strongly favored over **5b** (**5a**/**5b** ≈ 9/1). These effects also may allow the chair form of **6a** to be more stable than the nonchair twist or boat conformation. However, **6b** is in the chair conformation form as well, even though the apical oxygen is part of a five-membered ring subjected to maximal repulsive interactions with H3 and H5a. As a result, the extent of ring flattening observed is greater for **6b** than for **6a**. The apical oxygen–H3 and –H5a distances in the crystal for **6b** are 2.348 and 2.511 Å, respectively. For the less-flattened **6a**, the two distances are 2.225 and 2.377 Å, respectively. All are shorter than the sum of the van der Waals distances for hydrogen (1.20 Å) and oxygen (1.52 Å).[12] Interestingly, the apical O···axial H internuclear distances are *greater* for **6b** than for **6a**. This is in spite of the fact that **6a** has the apical ring oxygen of the four-membered ring opposite H3a and H5a. Most likely the energy curves that express the concomitant relief of O/H repulsions and increase in ring strain on ring flattening are different for **6a** and **6b**. The apical bond of the five-membered ring of **6b** is considerably longer (1.74 Å) than that of **6a** (1.68 Å), which also increases the O···H internuclear distance and reduces strain.

The X-ray crystal structure of **10**,[1f] which has the apical/equatorial six-membered ring in a *twist* conformation, shows that the p orbital lone pair electrons on ring oxygen O3 lie very nearly in the equatorial plane of the trigonal bipyramidal, phosphorus bonding system, which should lend stability to the twist form via back-bonding.[13] Indeed this is the interaction suggested by Trippett[14] as being most responsible for the relative stability of *twist* conformers for such rings attached in apical/equatorial fashion. By contrast, Dreiding models show that this orientation of an oxygen lone pair would be very difficult for the twist form of a *diequatorially* attached ring to attain. This may be an important factor in the lack of relative stability of the twist conformation of such a ring when it is diequatorially attached.

An important goal of the research reported in this paper was to provide a basis on which to evaluate the assertion[1g] that **3** in solution is subject to an equilibrium that involves measurable, though not quantitatively defined, amounts of a permutamer with the phosphorus-containing ring attached diequatorially to phosphorus. The present work shows that such a diequatorial ring in **5a**, **6a**, **6b**, and **7a** *exists in a chair conformation.* Quite obviously, the set of coupling constants for the P, H5a, H5b, and H4 system of spins for chair-form **5a**, **6a**, **6b**, and **7a** (Table V) are very different from those recorded earlier (Table V) for **1** and **2**, both of which were assigned[1f,g] to *twist conformations alone.* Unless **5a**, **6a**, **6b**, and **7a** all represent special cases, permutamers of **3** with the phosphorus-containing ring attached to phosphorus diequatorially will be in the chair conformation. The essential invariance of the coupling constants J_{5aP}, J_{5bP}, J_{45a}, and J_{45b} for **1**, **2**, and **3** shows that they all populate rings that are in the same conformation, the twist form. *Therefore, it is highly unlikely that 3 (or 1 or 2) populates measurable amounts of a permutational isomer with a diequatorially attached ring.* Indeed, if so little as 7% of diequatorial, chair-form **3** were present, the observed coupling J_{5bP} would be at least 2 Hz. This would be true if J_{5bP} is 28–29 Hz for chair-form, diequatorial **3**, as was found for **6a** and **7a** (J_{5bP} = 28.5 Hz, Table V), even if J_{5bP} for the apical equatorial ring were 0 Hz. The finding that the vicinal coupling constant pattern of the protons of the $CH_3OCH_2CH_2O$ group is like that observed for five-coordinate phosphorus-containing molecules for which the $CH_3OCH_2CH_2O$ is forced to be apical must be, in this instance, *coincidental and not diagnostic of the position of attachment of the ring.*

It had also been predicted[1g] by MNDO calculations that the phosphorus-containing ring of model structure **4** with diequatorial ring attachment to phosphorus would place that ring in a half-chair conformation. This sort of ring flattening would be expected if the endocyclic O–P–O angle were fixed at 120°, as it was in the MNDO minimizations.[1g] However, the above X-ray structures demonstrate that the endocyclic O–P–O angle is about 108°. This means that the angle in question can be contracted from 120° to allow the chair conformation, with its inherent puckering of the ring about phosphorus, to be assumed. This conformation, thereby becomes of lower energy than the half chair. Future work in this laboratory will be focused on determining the conformations of diequatorially attached rings in phosphoranes more symmetrically substituted about phosphorus. It also will be of interest to see whether equatorial alkoxy substituents not part of a ring in molecules otherwise identical to **5** and **6** also feature contracted equatorial O–P–O angles.

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Experimental Section

Materials. Commercial solvents and reagents were used as received unless otherwise noted. Ethyl ether and tetrahydrofuran were dried over sodium. Ethyl acetate was dried over calcium hydride. All were freshly distilled before use. Other solvents were OmniSolv grade from EM Industries Inc. All reagents were purchased from Aldrich Chemical Co. in 95–99% purity.

Spectral and Physical Data. Fourier-transformed ^1H NMR spectra were recorded on Varian Unity-300 and VXR-500 spectrometers. Poorly dispersed spectra or those with complicated multiple splittings were analyzed with the aid of the LAOCN5 program. ^{13}C NMR and ^{31}P NMR spectra were taken on Varian XL-300 and Unity-300 spectrometers operated with full proton decoupling, designated $\{^1H\}$. APT (attached proton test) spectra were used for line assignments of ^{13}C NMR spectra when necessary. ^1H and ^{13}C NMR chemical shifts are recorded in δ (ppm) relative to internal tetramethylsilane or deuterated solvent peaks. The individual proton or carbon is designated H_{1a}, C_1, etc. The numbers correspond to the structures shown in the text. ^{31}P chemical shifts are reported in δ (ppm) downfield (+) and upfield (–) relative to external 85% H_3PO_4. Detailed NMR parameters not given in Tables V–VII are recorded in this section.

The approaches to the determination of the spectral parameters for **6a** and **6b** were the same. The following applies specifically to **6a**. First, reasonable parameters for protons H_{1a}–H_{6b}, formula **6a**, were varied by trial and error until an excellent visual fit of computer-generated absorption frequencies and intensities to those of the experimental spectra of protons H_{1a}, H_{2a}, and H_{2b} were obtained. The values for J_{1a2a}, J_{1b2a}, J_{2a2b}, J_{2a3}, J_{1b6a}, and J_{1b6b} were then fixed. These J values, plus reasonable chemical shifts for all seven protons, were entered in the LAOCN5 program. The subspectra of protons H_{1b} and H_{2b}, well separated in chemical shift, were iteratively refined by assigning the specific transitions within their spectra and then allowing variation in all couplings except for those previously fixed for proton H_{2a} and in all chemical shifts except for the protons H_{1b} and H_{2b}. These refinements yielded probable errors in the range of 0.02–0.04 Hz in J and 0.02 Hz in δ (rms error, 0.228). With the parameters for protons H_{1b}, H_{2a}, and H_{2b} held constant, the δ values for protons H_{6a} and H_{6b} along with the coupling constants to protons H_{1a} and H_4 were allowed to vary to generate interactively refined values (ranges of probable errors in J, 0.02–0.04 Hz; in δ, 0.02 Hz; rms error, 0.104). The spectrum for proton H_{1a} in both instances possessed a minimum of well-defined features that made line assignments very ambiguous. However, by use of the various coupling constants involving proton H_{1a}, but derived in refinement of other subspectra, the spectrum of proton H_{1a} was very well simulated. For **6b**, very similar probable errors and rms were obtained.

Crystallographic data were collected on an Enraf–Nonius CAD4 diffractometer at –125 °C for **5a** (from diethyl ether/*n*-pentane) and at ambient temperature for **6a** and **6b** (both from *n*-hexane/ethyl acetate). Cell constants were obtained from 25 reflections within $15° < 2\theta < 30°$. Space groups of Table I were determined from subsequent least squares refinement. Standard reflections showed no decay during data collection. Lorentz and polarization corrections, and an empirical absorption correction, based on a series of ψ scans, were applied to the data. The structures were solved by direct methods techniques with a SDP/VAX package. Non-hydrogen atoms were refined with anisotropic thermal parameters. Hydrogen atoms were calculated and added to the structure

factor calculations but were not refined. Scattering factors[15] and Δ′ and Δ″ factors[16] were taken from the literature. A more-detailed description of the previous procedures has been published.[1f]

Mass spectra were recorded on a Finnigan MAT 95 instrument operated in the negative chemical ionization (CI) mode. GLC analyses were done on a Varian 3300 gas chromatograph equipped with a HP-5 capillary column (25 m × 0.32 mm) and flame ionization detection. Elemental analyses were performed by Atlantic Microlab, Inc., Norcross, GA. Melting points are uncorrected.

General Procedure for the Reactions of Phosphonites with Hexafluoroacetone. A flask equipped with a stopcock, a dry ice–acetone condenser, and a flow control adapter connected to an argon line was charged with phosphonite (1 equiv) and dichloromethane. Hexafluoroacetone (approximately 5 equiv) was condensed into a pressure tube cooled in liquid nitrogen. The pressure tube was slowly warmed so that the hexafluoroacetone was vaporized and transferred dropwise through the side arm of the dry ice–acetone condenser to the phosphonite solution cooled to −78 °C by a dry ice–acetone bath. Following the hexafluoroacetone addition, the argon line was switched to the side arm of the dry ice–acetone condenser. The cooling bath was removed, and the reaction mixture was allowed to reflux at <0 °C for about 3 h. The solvent and unreacted hexafluoroacetone were removed under reduced pressure to give the crude product phosphorane.

Preparation of 2-(2-Phenylethynyl)-1,3,2-dioxaphosphorinane (14). To a solution of 2-chloro-1,3,2-dioxaphosphorinane[17] (3.39 g, 24.1 mmol) in 150 mL of dry diethyl ether was added dropwise a solution of lithium phenylacetylide (1.0 M in THF, 24.1 mL, 24.1 mmol) at room temperature with rapid stirring. Stirring was continued overnight. The solvent was removed under reduced pressure, and the residue was Kugelrohr-distilled to give a colorless liquid (98.5% GLC pure) that was short-path distilled to give 3.29 g of pure product (20.0 mmol, 83% yield): bp 95–96 °C at 0.05 mmHg; ^{31}P NMR (121 MHz, $CDCl_3$, $\{^1H\}$) δ 123.43 (s); ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.57 (ddtt, 1 H, H_{4a}, $^3J_{3a4a} = {}^3J_{5a4a} = 2.3$ Hz, $^3J_{3b4a} = {}^3J_{5b4a} = 1.8$ Hz, $^2J_{4a4b} = -14.3$ Hz, $^4J_{4aP} = -2.1$ Hz), 2.50 (ddtt, 1 H, H_{4b}, $^3J_{3a4b} = {}^3J_{5a4b} = 13.1$ Hz, $^3J_{3b4b} = {}^3J_{5b4b} = 4.5$ Hz, $^4J_{4bP} = -1.2$ Hz, $^2J_{4a4b} = -14.3$ Hz), 4.08 (dddddd, 2 H, H_{3b}, H_{5b}, $^2J_{3a3b} = {}^2J_{5a5b} = -11.4$ Hz, $^4J_{3a5b} = {}^4J_{3b5a} = -0.7$ Hz, $^4J_{3b5b} = -1.25$ Hz, $^3J_{3bP} = {}^3J_{5bP} = 9.5$ Hz, $^3J_{3b4b} = {}^3J_{5b4b} = 1.8$ Hz, $^3J_{3b4a} = {}^3J_{5b4a} = 4.5$ Hz), 4.59 (ddddd, 2 H, H_{3a}, H_{5a}, $^3J_{3aP} = {}^3J_{5aP} = 3.5$ Hz, $^2J_{3a3b} = {}^2J_{5a5b} = -11.4$ Hz, $^3J_{3a4a} = {}^3J_{5a4a} = 2.3$ Hz, $^3J_{3a4b} = {}^3J_{5a4b} = 13.1$ Hz, $^4J_{3a5b} = {}^4J_{3b5a} = -0.7$ Hz), 7.32–7.39, 7.51–7.55 (m, 5 H, C_6H_5); ^{13}C NMR (75 MHz, $CDCl_3$, $\{^1H\}$) δ 33.56 (d, 1 C, C_5, $^3J_{PC} = 4.5$ Hz), 73.87 (d, 2 C, C_4, C_6, $^2J_{PC} = 3.7$ Hz), 88.65 (d, 1 C, PC, $^1J_{PC} = 69.2$ Hz), 105.95 (d, 1 C, PCC, $^2J_{PC} = 3.2$ Hz), 121.52 (d, 1 C, *ipso*-Ph, $^3J_{PC} = 2.6$ Hz), 128.34 (s, 2 C, *m*-Ph), 129.34 (s, 1 C, *p*-Ph), 131.78 (d, 2 C, *o*-Ph, $^4J_{PC} = 2.0$ Hz). Anal. Calcd for $C_{11}H_{11}O_2P$: C, 64.08; H, 5.38. Found: C, 63.90; H, 5.37.

Preparation of 2-(2-Phenylethynyl)-1,3,2-dioxaphosphorinane–Hexafluoroacetone Adduct (5). To a solution of 2-(2-phenylethynyl)-1,3,2-dioxaphosphorinane (2.61 g, 12.7 mmol) in 10 mL of dichloromethane was added dropwise hexafluoroacetone at −78 °C, as described in the general procedure. The solid residue was recrystallized from diethyl ether/*n*-pentane at freezer temperatures to give 6.2 g of white crystals (11.5 mmol, 91% yield): mp 147–148 °C; ^{31}P NMR (121 MHz, $CDCl_3$, $\{^1H\}$) δ −1.36 (s); ^{1}H NMR (300 MHz, C_6D_6) δ 0.57 (ddtt, 1 H, H_{4a}), 1.44 (ddtt, 1 H, H_{4b}), 3.62 (dddddd, 2 H, H_{3b}, H_{5b}), 4.13 (ddddd, 2 H, H_{3a}, H_{5a}), 6.93–6.98, 7.12–7.15 (m, 5 H, C_6H_5); ^{13}C NMR (75 MHz, $CDCl_3$, $\{^1H\}$) δ 27.44 (d, 1, C, C_5, $^3J_{PC} = 8.9$ Hz), 67.35 (d, 2 C, C_4, C_6, $^2J_{PC} = 6.6$ Hz), 121.06 (dq, 2 C, CF_3, $^2J_{PC} = 3.8$ Hz, $^1J_{CF} = 288.3$ Hz), 121.39 (dq, 2 C, CF_3, $^2J_{PC} = 12.5$ Hz, $^1J_{CF} = 286.1$ Hz), 127.43 (s, 2 C, *m*-Ph), 128.16 (s, 2 C, *o*-Ph), 130.12 (s, 1 C, *p*-Ph), 147.96 (d, 1 C, *ipso*-Ph, $^3J_{PC} = 10.1$ Hz). The remaining signals were too weak to be assigned. Anal. Calcd for $C_{17}H_{11}F_{12}O_4P$: C, 37.93; H, 2.06. Found: C, 37.97; H, 2.09.

Preparation of Bis(dimethylamino)chlorophosphine (15). To a stirred solution of triethylamine (34.8 g, 0.344 mol) in 400 mL of dichloromethane at 0 °C was added dropwise a solution of phosphorus trichloride (23.6 g, 0.172 mol) in 100 mL of dichloromethane. Liquified dimethylamine (15.5 g, 0.344 mol) was bubbled simultaneously into the reaction solution. The resulting mixture was stirred at 0 °C for 1 h and then slowly warmed to room temperature over a 4-h period. The solvent was removed by rotary evaporation. The residue was taken up with diethyl ether (300 mL), and the salt was removed by Schlenk techniques. The ether was removed by rotary evaporation. The residue was distilled through a 2-in. Vigreux column to give 14.2 g of product, 97% pure (^{1}H NMR) (89.1 mmol, 52% yield, bp 52–53 °C at 3.0 mmHg), which was used without further purification: ^{31}P NMR (121 MHz, $CDCl_3$, $\{^1H\}$) δ 163.5 (s) (lit.[18] δ 160.2 (C_6D_6)); ^{2}H NMR (300 MHz, $CDCl_3$) δ 2.72 (d, 6 H, $N(CH_3)_2$, $^3J_{PH} = 12.2$ Hz).

Preparation of Bis(dimethylamino)(2-phenylethynyl)phosphine (16). By a procedure directly analogous to that for the preparation of **14**, reaction of bis(dimethylamino)chlorophosphine (4.50 g, 97%, 29.1 mmol) in 120 mL of dry diethyl ether and lithium phenylacetylide (1.0 M solution in THF, 27.7 mL, 27.7 mmol) at room temperature gave 4.53 g of product as an oil (20.6 mmol, 74% yield): bp 93–94 °C at 0.025 mmHg (lit.[19] bp 125 °C at 1 mmHg); ^{31}P NMR (121 MHz, $CDCl_3$, $\{^1H\}$) δ 69.95 (s); ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.80 (d, 12 H, CH_3, $^3J_{PH} = 10.2$ Hz), 7.28–7.32, 7.46–7.50 (m, 5 H, C_6H_5).

Preparation of 3β-(2-Phenylethynyl)-2,4,7-trioxa-3-phosphabicyclo[4.3.0]nonane (17). A solution of bis(dimethylamino)(2-phenylethynyl)-phosphine (2.61 g, 11.9 mmol) and *trans*-2-(hydroxymethyl)-3-hydroxytetrahydrofuran[20] (1.40 g, 11.9 mmol) in 50 mL of acetonitrile was refluxed under an argon atmosphere for 1 day. The solvent was evaporated under reduced pressure. The low-boiling impurities were removed in a Kugelrohr apparatus (at about 100 °C, 0.025 mmHg). The brown residue (2.82 g, 95% GLC pure, 10.7 mmol, 91% crude yield) was not further purified (product decomposed at higher temperature): ^{31}P NMR (121 MHz, $CDCl_3$, $\{^1H\}$) δ 115.31 (s); ^{13}C NMR (75 MHz, $CDCl_3$, $\{^1H\}$) δ 29.31 (s, 1 C, C_2), 63.40 (s, 1 C, C_1). The following unassigned signals correspond to carbons C_3, C_4, and C_5: 69.92 (d, 1 C, $J_{PC} = 5.7$ Hz), 73.56 (d, 1 C, $J_{PC} = 6.6$ Hz), 75.95 (d, 1 C, $J_{PC} = 2.0$ Hz).

Preparation of 3β-(2-Phenylethynyl)-2,4,7-trioxa-3-phosphabicyclo[4.3.0]nonane–Hexafluoroacetone Adduct (7). To a solution of 3β-(2-phenylethynyl)-2,4,7-trioxa-3-phosphabicyclo[4.3.0]nonane (**17**) (2.69 g, 95%, 10.2 mmol) in 10 mL of dichloromethane was added dropwise hexafluoroacetone at −78 °C, as described in the general procedure. The crude product was taken up with ethyl acetate, purified by flash-column chromatography (eluant: 10% ethyl acetate/*n*-hexane), and crystallized from *n*-hexane at freezer temperatures to give 1.75 g of white crystals (3.0 mmol, 29% yield): mp 152–152.5 °C; ^{31}P NMR (121 MHz, C_6D_6, $\{^1H\}$) δ 0.71 (s); ^{1}H NMR (500 MHz, C_6D_6) δ 1.40–1.52 (m, 2 H, H_{2a}, H_{2b}), 3.26–3.36 (m, 3 H, H_{1a}, H_{1b}, H_4), 4.04 (ddd, 1 H, H_{5b}), 4.38 (ddd, 1 H, H_{5a}), 4.56 (dddd, 1 H, H_3), 6.95–6.97, 7.12–7.14 (m, 5 H, C_6H_5); ^{1}H NMR (500 MHz, CD_3CN, ^{31}P coupled and decoupled) δ 2.30 (ddddd, 1 H, H_{2b}), 2.47 (ddddd, 1 H, H_{2a}), 3.89 (dddd, 1 H, H_4), 4.15 (ddd, 1 H, H_{1a}), 4.24 (dddd, 1 H, H_{1b}), 4.58 (ddd, 1 H, H_{5a}), 4.69 (ddd, 1 H, H_{5b}), 4.84 (dddd, 1 H, H_3), 7.32–7.34, 7.58–7.67 (m, 5 H, C_6H_5); ^{13}C NMR (125 MHz, $CDCl_3$, $\{^1H\}$) δ 29.06 (d, 1 C, C_2, $^3J_{PC} = 9.7$ Hz), 66.71 (s, 1 C, C_1), 69.53 (d, 1 C, C_5, $^2J_{PC} = 7.6$ Hz), 74.61 (d, 1 C, C_4, $^3J_{PC} = 6.7$ Hz), 77.65 (d, 1 C, C_3, $^2J_{PC} = 5.5$ Hz), 120.94 (dq, 2 C, CF_3, $^3J_{PC} = 3.0$ Hz, $^1J_{CF} = 288.4$ Hz), 121.29 (dq, 2 C, CF_3, $^3J_{PC} = 12.6$ Hz, $^1J_{CF} = 286.1$ Hz), 127.43 (s, 2 C, *o*-Ph), 128.22 (s, 2 C, *m*-Ph), 130.24 (s, 1 C, *p*-Ph), 148.83 (d, 1 C, *ipso*-Ph, $^3J_{PC} = 10.9$ Hz). The remaining signals were too weak to be assigned. Anal. Calcd for $C_{19}H_{13}F_{12}O_5P$: C, 39.32; H, 2.26. Found: C, 39.28; H, 2.29.

Preparation of *trans*-(2-Hydroxymethyl)cyclopentanol (18). To a stirred solution of THF (400 mL) were added slowly $AlCl_3$ (4.40 g, 32.3 mmol) and $LiAlH_4$ (4.20 g, 106 mmol) at room temperature. After being stirred for 30 min, the mixture was cooled to 0 °C and ethyl 2-oxocyclopentanecarboxylate (11.6 g, 70.5 mmol) in 100 mL of dry THF was added dropwise. The resulting mixture was warmed to room temperature, continuously stirred for 1 day, and then quenched at 0 °C by slow, dropwise addition of a solution of water (9.0 mL, 162 mmol) in 90 mL of THF. The resulting mixture was warmed to room temperature and continuously stirred for 30 min. The salts were removed by filtration and continuously extracted with THF by means of a Soxhlet apparatus. The combined filtrate and extract were dried over anhydrous Na_2SO_4. GLC showed that both the cis and trans diols (trans/cis = 2.2) were

(15) Cromer, D. T.; Waber, J. T. *International Tables for X-ray Crystallography*; Kynoch Press: Birmingham, England, 1974; Vol. IX, Table 2.2B.

(16) Cromer, D. T., ref 15, Vol. IV, Table 2.3.1.

(17) Prepared from phosphorus trichloride and 1,3-propanediol in the presence of triethylamine in THF under the conditions for the preparation of 2-chloro-5-*tert*-butyl-1,3,2-dioxaphosphorinane: Bentrude, W. G.; Hargis, J. H. *J. Am. Chem. Soc.* **1970**, *92*, 7136–7144.

(18) Bentrude, W. G.; Setzer, W. N.; Sopchik, A. E.; Chandrasekaran, S.; Ashby, M. T. *J. Am. Chem. Soc.* **1988**, *110*, 7119–7127, and references therein.

(19) Charrier, C.; Simonnin, M.-P. *C. R. Hebd. Seances Acad. Sci.* **1967**, *264*, 995–997.

(20) Prepared from 2-deoxy-D-ribose: Eritja, R.; Walker, P. A.; Randall, S. K.; Goodman, M. F.; Karplan, B. E. *Nucleosides Nucleotides* **1987**, *6*, 803–814.

formed. The solvent was removed, and the residue was short-path distilled to give 4.31 g of a colorless oil (37.1 mmol, 53% yield), bp 86–88 °C at 0.025 mmHg. Separation of the cis and trans diastereomers was accomplished by the literature procedure[21] to give 2.6 g of pure trans diol (22.4 mmol, 60.4% yield, 32% total yield), bp 94–95 °C at 0.025 mmHg (lit.[21] bp 96–99 °C at 1 mmHg).

Preparation of 3β-Chloro-2,4-dioxa-3-phosphabicyclo[4.3.0]nonane (19). A solution of *trans*-(2-hydroxymethyl)cyclopentanol (2.96 g, 25.5 mmol) and triethylamine (5.16 g, 7.1 mL, 51.0 mmol) in 50 mL of dry THF and a solution of phosphorus trichloride (3.57 g, 2.3 mL, 25.5 mmol) in 50 mL of dry THF were simultaneously added dropwise to 100 mL of dry THF at 0 °C with rapid stirring. The resulting mixture was refluxed for 40 h. The salt was removed by Schlenk techniques, and the solvent was removed by rotary evaporation. The residue was Kugelrohr distilled to give 2.37 g of product as an oil (13.1 mmol, 51% yield): bp 63–64 °C at 0.05 mmHg; ^{31}P NMR (121 MHz, $CDCl_3$, {^{1}H}) δ 145.76 (s); ^{13}C NMR (75 MHz, $CDCl_3$, {^{1}H}) δ 16.49 (s, 1 C, C_1), 23.31 (d, 1 C, C_6, $^3J_{PC}$ = 1.9 Hz), 29.42 (s, 1 C, C_2), 43.51 (d, 1 C, C_4, $^3J_{PC}$ = 4.4 Hz), 70.25 (d, 1 C, C_5, $^2J_{PC}$ = 4.8 Hz), 74.97 (s, 1 C, C_3).

Preparation of 3β-(2-Phenylethynyl)-2,4-dioxa-3-phosphabicyclo-[4.3.0]nonane (20). By a procedure directly analogous to the preparation of **14**, the reaction of 3β-chloro-2,4-dioxa-3-phosphabicyclo[4.3.0]nonane (1.85 g, 10.2 mmol) containing two products diastereomeric about the ring fusion from the cis/trans-diol precursors (the ratio of the desired trans diastereomer to the cis-fused one being 3/1 (^{31}P NMR)) gave 1.30 g of a yellowish, thick liquid containing cis and trans diastereomers (4.9 mmol, 48% yield, cis/trans = 1/3 (^{31}P NMR)): air bath temperature 70–80 °C at 0.05 mmHg; ^{31}P NMR (121 MHz, $CDCl_3$, {^{1}H}) δ 113.96 (s, trans diastereomer), 116.43 (s, cis diastereomer); ^{13}C NMR (75 MHz, $CDCl_3$, {^{1}H}) trans diastereomer δ 17.76 (s, 1 C, C_1), 25.73 (s, 1 C, C_6), 30.61 (s, 1 C, C_2) 39.21 (d, 1 C, C_4, $^3J_{PC}$ = 14.5 Hz), 72.06 (d, 1 C, C_5, $^2J_{PC}$ = 4.5 Hz), 76.54 (s, 1 C, C_3), 93.37 (d, 1 C, PC*C*, $^1J_{PC}$ = 80.9 Hz), 104.78 (d, 1 C, PC*C*, $^2J_{PC}$ = 3.6 Hz), 121.74 (d, 1 C, *ipso*-Ph, $^3J_{PC}$ = 2.6 Hz), 128.26 (s, 2 C, *m*-Ph), 129.22 (s, 1 C, *p*-Ph), 131.69 (d, 2 C, *o*-Ph, $^4J_{PC}$ = 2.0 Hz).

Preparation of 3β-(2-Phenylethynyl)-2,4-dioxa-3-phosphabicyclo-[4.3.0]nonane–Hexafluoroacetone Adduct (6a). To a solution of the above 3β-(2-phenylethynyl)-2,4-dioxa-3-phosphabicyclo[4.3.0]nonane (**20**) (1.27 g, 4.8 mmol, cis/trans = 1/3) in 5 mL of dichloromethane was added dropwise hexafluoroacetone at −78 °C, as described in the general procedure. The crystalline product phosphorane (3/1 ratio of diastereomers, as shown by ^{31}P NMR, 2.71 g, 4.7 mmol, 98% crude yield) was recrystallized from diethyl ether/*n*-pentane in the freezer to give a mixture of products isomeric about the ring fusion (trans/cis = 4/1, ^{31}P NMR). The pure trans diastereomer was obtained by HPLC techniques (eluant: *n*-hexane/ethyl acetate = 20/1) and crystallized from *n*-hexane/ethyl acetate at freezer temperatures: mp 140–141 °C; GLC/MS, negative CI mode (relative intensity) cis diastereomers, *m/z* 578 (100), 177 (63), 579 (20), 509 (7); trans diastereomers, *m/z* 578 (100), 177 (29), 579 (21), 509 (11); ^{31}P NMR (121 MHz, C_6D_6, {^{1}H}) δ −0.18 (s, trans diastereomer), −2.24 (s, cis diastereomer); ^{1}H NMR (500 MHz, C_6D_6) δ 0.38 (dddd, 1 H, H_{6a}), 0.83 (dddd, 1 H, H_{6b}), 1.09 (ddddd, 1 H, H_{1a}), 0.95 (ddddd, 1 H, H_{1b}), 1.57 (ddddd, 1 H, H_{2a}), 1.36 (dddd, 1 H, H_{2b}), 1.71 (dddddd, 1 H, H_4), 3.81 (ddd, 1 H, H_{5b}), 4.20 (ddd, 1 H, H_{5a}), 4.45 (dddd, 1 H, H_3), 6.93–6.98, 7.14–7.18 (m, 5 H, C_6H_5); ^{13}C NMR (75 MHz, $CDCl_3$, {^{1}H}) δ 18.53 (s, 1 C, C_1), 21.41 (s, 1 C, C_6), 28.88 (d, 1 C, C_2, $^3J_{PC}$ = 9.5 Hz), 44.25 (d, 1 C, C_4, $^3J_{PC}$ = 6.6 Hz), 71.69 (d, 1 C, C_5, $^2J_{PC}$ = 6.6 Hz), 81.42 (d, 1 C, C_3, $^2J_{PC}$ = 6.2 Hz), 120.98 (dq, 2 C, *C*F_3, $^3J_{PC}$ = 4.2 Hz, $^1J_{CF}$ = 284.5 Hz), 121.44 (q, 2 C, *C*F_3, $^3J_{PC}$ = 12.8 Hz, $^1J_{CF}$ = 286.0 Hz), 127.43 (s, 2 C, *o*-Ph), 128.07 (s, 2 C, *m*-Ph), 123.00 (s, 1 C, *p*-Ph), 147.79 (d, 1 C, *ipso*-Ph, $^3J_{PC}$ = 10.7 Hz). The remaining signals were too weak to be assigned. Anal. Calcd for $C_{20}H_{15}F_{12}O_4P$: C, 41.54; H, 2.61. Found: C, 41.49; H, 2.57.

Preparation of 3α-(2-Phenylethynyl)-2,4-dioxa-3-phosphabicyclo-[4.3.0]nonane–Hexafluoroacetone Adduct (6b). To a solution of pure trans ring-fused 3β-chloro-2,4-dioxa-3-phosphabicyclo[4.3.0]nonane (**19**) (2.37 g, 13.1 mmol) in 60 mL of dry diethyl ether was added dropwise a solution of lithium phenylacetylide (1.0 M in THF, 13.1 mL, 13.1 mmol) at room temperature with rapid stirring. The resulting mixture was continuously stirred for 4 h. The LiCl salt was removed by Schlenk techniques, and the solvent was evaporated in vacuo without heating. The residue (3α-(2-phenylethynyl)-2,4-dioxa-3-phosphabicyclo[4.3.0]nonane), without purification, was immediately taken up with 10 mL of dichloromethane. To this solution was added hexafluoroacetone at −78 °C, as described in the general procedure. The crude product was taken up with ethyl acetate and purified by flash-column chromatography (eluant: ethyl acetate/*n*-hexane = 1/20). Solvent evaporation at room temperature gave crystalline material contaminated with a yellow color that was washed away with *n*-hexane. A total of 1.4 g of white crystals was obtained (2.4 mmol, 18% yield, mp 148.5–149.0 °C). No attempt was made to optimize the product yield: ^{31}P NMR (121 MHz, C_6D_6, {^{1}H}) δ −4.16 (s); ^{1}H NMR (500 MHz, C_6D_6) δ 0.42 (dddd, 1 H, H_{6a}), 0.87 (dddd, 1 H, H_{6b}), 1.11 (ddddd, 1 H, H_{1a}), 0.97 (ddddd, 1 H, H_{1b}), 1.65 (ddddd, 1 H, H_{2a}), 1.38 (dddd, 1 H, H_{2b}), 1.83 (dddddd, 1 H, H_4), 3.91 (ddd, 1 H, H_{5b}), 4.25 (ddd, 1 H, H_{5a}), 4.54 (dddd, 1 H, H_3), 6.96–6.99, 7.16–7.19 (m, 5 H, C_6H_5); ^{13}C NMR (75 MHz, $CDCl_3$, {^{1}H}) δ 18.47 (s, 1 C, C_1), 21.48 (s, 1 C, C_6), 29.16 (d, 1 C, C_2, $^3J_{PC}$ = 8.6 Hz), 44.61 (d, 1 C, C_4, $^3J_{PC}$ = 6.3 Hz), 72.85 (d, 1 C, C_5, $^2J_{PC}$ = 8.0 Hz), 82.63 (d, 1 C, C_3, $^2J_{PC}$ = 7.2 Hz), 120.86 (dq, 2 C, *C*F_3, $^3J_{PC}$ = 15.0 Hz, $^1J_{CF}$ = 285.5 Hz), 121.91 (q, 2 C, *C*F_3, $^3J_{PC}$ < 0.5 Hz, $^1J_{CF}$ = 288.8 Hz), 127.28 (s, 2 C, *o*-Ph), 128.07 (s, 2 C, *m*-Ph), 129.98 (s, 1 C, *p*-Ph), 147.48 (d, 1 C, *ipso*-Ph, $^3J_{PC}$ = 7.1 Hz). The remaining signals were too weak to be assigned. Anal. Calcd for $C_{20}H_{15}F_{12}O_4P$: C, 41.54; H, 2.61. Found: C, 41.50; H, 2.59.

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Supplementary Material Available: Full tables of crystal data, hydrogen atom parameters, bond distances, bond angles, torsion angles, least squares planes, anisotropic thermal parameters, and positional parameters (50 pages); tables of observed and calculated structure factors (31 pages). Ordering information is given on any current masthead page.

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