Conformational Equilibria of Phosphoranes with 5-Alkyl-Substituted 1,3,2-Dioxaphosphorinane Rings Attached Diequatorially to Five-Coordinated Phosphorus. Are Boat/Twist Conformations Populated?

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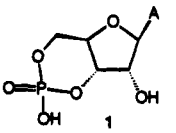
Abstract: The conformational equilibria of 1,3,2-dioxaphosphorinanes **4**−**8**, featuring diequatorial attachment of the ring to five-coordinate phosphorus, were perturbed by a series of substituents at C5 (Me, Ph, *t*-Bu). Unlike the analogous phosphoranes that feature equatorial/apical ring attachment and populate *boat/twist conformations* even when unbiased by ring substituents, no ^{1}H NMR evidence could be found for population of a nonchair conformation, even in the presence of an axial 5-*t*-Bu (**8**). The failure to readily form boat/twist conformations also is contradictory to their known ease of population by 1,3,2-dioxaphosphorinanes containing three- or four-coordinate phosphorus. Both steric and stereoelectronic rationales are offered for this highly significant but hitherto unrecognized conformational property of 1,3,2-dioxaphosphorinane rings attached diequatorially to five-coordinate phosphorus. Perturbation of a *chair*−*chair equilibrium* (**A** ⇌ **B**) was observed that allowed the determination of conformational energies (*A* values, kcal/mol, in C_6D_6) for the groups at C5: Me, 0.8; Ph, 1.6; *t*-Bu, 1.7. These values are similar to those for C5 substituents on 1,3-dioxane rings with the exception of 5-Ph (*A* value 1.0 kcal/mol for 1,3-dioxane). The similarity of the *A* values for the Ph and *t*-Bu substituents in the 1,3,2-dioxaphosphorinane ring is tentatively assigned to increased steric repulsions present when the 5-Ph is axial because of the apical P−O bond of the five-coordinate phosphorus.

Introduction

Several laboratories have recently published NMR and X-ray crystallographic studies of the structures of six-membered rings containing five-coordinated phosphorus, especially those involving the 1,3,2-dioxaphosphorinane ring.[1,2] One interest in such molecules is derived from their potential as analogs for the transition state or intermediate in enzymic hydrolysis of adenosine 3′,5′-cyclic monophosphate, cAMP (**1**).



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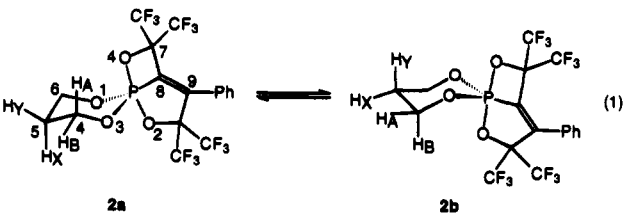
Recently we reported the study of phosphorane **2**.[1n,r] The X-ray structure of **2** showed its 1,3,2-dioxaphosphorinane ring to be attached to phosphorus in diequatorial fashion and to be in chair conformation **2a** (eq 1). The $^3J_{HP}$ values from proton



2a **2b** (1)

NMR analysis indicated that a single chair conformer is primarily populated in solution, presumably conformation **2a**. The X-ray structure corresponding to **2a** showed the P−O2 bond to be close to perpendicular to the equatorial plane, nicely defined by O1, O3, C8, and P. However, the apical P−O4 bond of the four-membered ring is tilted away from the six-membered ring and from colinearity with the P−O2 bond by 17°. Moreover, the P−O4 bond is lengthened to 1.80 Å. Both effects should reduce the 1,3-syn axial-like repulsive interactions of the P−O4 bond with the axial ring hydrogens at C4 and C6 in **2a**. Furthermore, for phosphorane **3b**, in which the apical P−O2 bond of the five-membered ring is syn to the axial CH_2O ring hydrogens, X-ray crystallography[1r] shows the six-membered ring

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(1) (a) Schomburg, D.; Hacklin, H.; Röschenthaler, G.-V. *Phosphorus Sulfur* **1988**, *35*, 241. (b) Yu, J. H.; Bentrude, W. G. *J. Am. Chem. Soc.* **1988**, *110*, 7897. (c) Yu, J. H.; Bentrude, W. G. *Tetrahedron Lett.* **1989**, *30*, 2195. (d) Bentrude, W. G.; Yu, J. H.; Sopchik, A. E. *Phosphorus Sulfur* **1990**, *51/52*, 73. (e) Yu, J. H.; Sopchik, A. E.; Arif, A. M.; Bentrude, W. G. *J. Org. Chem.* **1990**, *55*, 3444. (f) Yu, J. H.; Arif, A. M.; Bentrude, W. G. *J. Am. Chem. Soc.* **1990**, *112*, 7451. (g) Broeders, N. L. H. L.; Koole, L. H.; Buck, H. M. *J. Am. Chem. Soc.* **1990**, *112*, 7475. (h) Burton, S. D.; Kumara Swamy, K. C.; Holmes, J. M.; Day, R. O.; Holmes, R. R. *J. Am. Chem. Soc.* **1990**, *112*, 6104. (i) Kumara Swamy, K. C.; Day, R. O.; Holmes, J. M.; Holmes, R. R. *J. Am. Chem. Soc.* **1990**, *112*, 6095. (j) Kumara Swamy, K. C.; Burton, S. D.; Holmes, J. M.; Day, R. O.; Holmes, R. R. *Phosphorus Sulfur* **1990**, *53*, 437. (k) Day, R. O.; Kumara Swamy, K. C.; Fairchild, L.; Holmes, R. R.; Holmes, J. M. *J. Am. Chem. Soc.* **1991**, *113*, 1627. (l) Holmes, R. R.; Kumara Swamy, K. C.; Holmes, J. M.; Day, R. O. *Inorg. Chem.* **1991**, *30*, 1052. (m) Hans, J.; Day, R. O.; Howe, L.; Holmes, R. R. *Inorg. Chem.* **1991**, *30*, 3132. (n) Huang, Y.; Arif, A. M.; Bentrude, W. G. *J. Am. Chem. Soc.* **1991**, *113*, 7800. (o) Yu, J.; Sopchik, A. E.; Arif, A. M.; Bentrude, W. G.; Röschenthaler, G.-V. *Hetereoatom Chem.* **1991**, *2*, 177. (p) Hans, J.; Day, R. O.; Howe, L.; Holmes, R. R. *Inorg. Chem.* **1992**, *31*, 1279. (q) Huang, Y.; Sopchik, A. E., Arif, A.; Bentrude, W. G. *Heteroatom Chem.* **1993**, *4*, 271. (r) Huang, Y.; Sopchik, A. E., Arif, A.; Bentrude, W. G. *J. Am. Chem. Soc.* **1993**, *115*, 4031. (s) Huang, Y.; Arif, A.; Bentrude, W. G. *Phosphorus, Sulfur Silicon* **1995**, *103*, 225.

(2) For reviews, see: (a) Holmes, R. R.; Day, R. O.; Deiters, J. A.; Kumara Swamy, K. C.; Holmes, J. M.; Hans, J.; Burton, S. D.; Prakasha, T. K. In *Phosphorus Chemistry, Developments in American Science*; ACS Symposium Series 486; Walsh, E. N., Griffith, E. J., Parry, R. W., Quin, L. D., Eds.; American Chemical Society: Washington, D.C.; 1992, Chapter 11. (b) Bentrude, W. G. in *Phosphorus-31 NMR Spectral Properties in Compound Characterization and Structural Analysis*; Quin, L. D., Verkade, J. G., Eds.; VCH Publishers: New York, 1994; pp 41−53. (c) Bentrude, W. G. In *Conformational Studies of Six-Membered Ring Carbocycles and Heterocycles*; Juaristi, E., Ed.; VCH: New York, 1995; Chapter 7.

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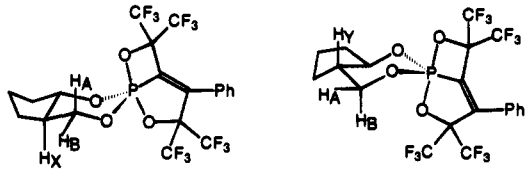
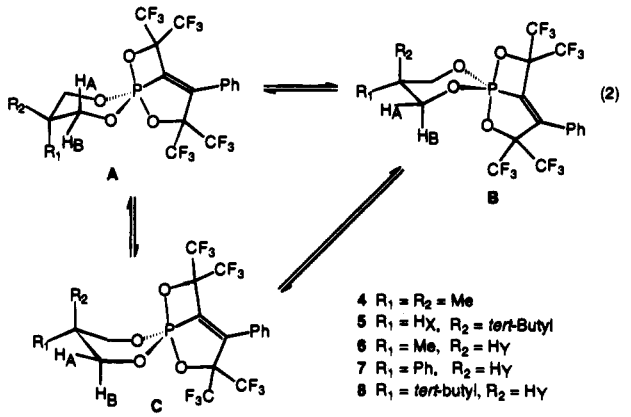
to be flattened about phosphorus compared to the ring in diastereomer **3a**, in apparent response to P−O2 steric repulsion. Occupation of the chair form by both **3a** and **3b** in solution was clearly seen from the measured $^3J_{HP}$ and $^3J_{HH}$ values (e.g. for **3a**, J_{AP} = 1.3 Hz, J_{BP} = 28.5 Hz, J_{AX} = 11.6 Hz, J_{BX} = 4.4 Hz).[1r]



3a **3b**

Though J_{AP} (5.5 Hz) and J_{BP} (25.0 Hz) for **2** clearly demonstrate the predominance of one chair conformer, presumably **2a**, J_{AP} is large enough to suggest the presence of a small population of **2b**.[1r] To investigate further this chair−chair equilibrium, expressed by **A** ⇌ **B** (eq 2) and the possible population of twist/boat forms (**C**−**E**), we have prepared phosphoranes **4**−**8** and studied their conformational properties

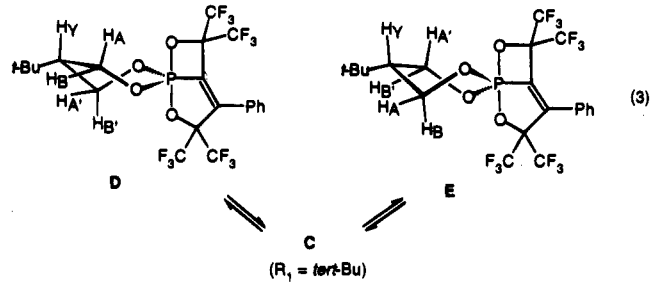


(2)

4 $R_1 = R_2$ = Me
5 R_1 = Hx, R_2 = *tert*-Butyl
6 R_1 = Me, R_2 = Hy
7 R_1 = Ph, R_2 = Hy
8 R_1 = *tert*-butyl, R_2 = Hy

by ^{1}H NMR spectroscopy. The 5-*tert*-butyl group, with an *A* value of 1.4−1.8 kcal/mol in 1,3-dioxanes[3] and six-membered ring cyclic sulfites,[4] biases the conformational equilibria of 1,3-dioxanes,[3] 1,3,2-dioxaphosphorinanes,[5] and 1,3,2-oxazaphosphorinanes[6] away from chair forms with the *tert*-butyl axial. As noted above, 1,3-*syn* axial-like interactions involving the apical substituent on phosphorus in conformer **B** (**2b**) are larger than those in conformer **A** (**2a**).[1r] Phosphorane **5**, therefore, might be expected to be more strongly biased toward population of chair conformer **A** than is **2**. By contrast for phosphoranes **6**−**8**, conformation **A** would be predicted to be depopulated, compared to **2** and **4**, as a result of the 1,3-*syn* axial repulsions generated by the axial R_1 in conformation **A**. Indeed, we find that the population of **A** decreases with an increase in steric size of R_1 in the order **6** (64%) > **7** (31%) > **8** (26%).

Highly significant is the fact that the *tert*-butyl group at C5 typically does not readily assume the axial position (**A**) in analogous chair-form 1,3,2-dioxa- and oxazaphosphoranes involving three- or four-coordinate phosphorus.[2b,c,5-8] Instead, it becomes pseudoequatorial in a predominant population of a *boat or twist conformation analogous to* ***C***, ***D***, *and* ***E*** (eq 3).



D **E**

C
(R_1 = *tert*-Bu)

(3)

Moreover, the large number of recently investigated phosphoranes whose 1,3,2-dioxaphosphorinane rings are attached to phosphorus in *apical/equatorial* rather than diequatorial fashion, with very few exceptions, preferentially *occupy twist/boat conformations both in solution and in the crystal, even without the driving force of a substituent at C5.*[1,2] By contrast, we will show that the coupling constants, determined for the series **6**−**8**, all can be accommodated by the equilibrium **A** ⇌ **B** *without inclusion of twist/boat forms* ***C***, ***D***, *and* ***E***. The failure of twist or boat conformers to be populated defines an *important conformational property* of 1,3,2-dioxaphosphorinane rings that are attached *diequatorially* to five-coordinate phosphorus *that has not been previously recognized.*

Results

Preparations. The syntheses of phosphoranes **4**−**8** are shown in Scheme 1. Phosphorane **4** was prepared from 5,5-dimethyl-2-phenylethynyl phosphonite **9** on reaction with hexafluoroacetone, a route reported previously for **2**.[1r] Reaction of the requisite *cis*-2-chloro-1,3,2-dioxaphosphorinanes with phenylacetylide proceeded with inversion at phosphorus to give **10t**−**12t** as the major and highly predominant trans diastereomers. (Cis and trans designations refer to the relation of the alkyl substituent R_1 and the 2-(2-phenylethynyl) substitutent and are readily derived from relative ^{31}P NMR chemical shifts.[8]) Without further purification, these products were reacted with hexafluoroacetone to prepare moderate isolated yields (30−40%) of phosphoranes **6**−**8** possessing retained geometry about phosphorus. Analogously, **10c**, formed on distillation of **10t**, yielded **5**. Phosphoranes **5**, **7**, and **8** were obtained as pure single diastereomers, while **6** was the dominant product coisolated along with its diastereomer (ratio 89/11, ^{31}P NMR). (The ^{1}H resonances for **6** were well separated from those of its diastereomer and readily yielded the necessary coupling constants.) The structure assigned to **5** has been confirmed by X-ray

(3) (a) Eliel, E. L.; Knoeber, M. C. *J. Am. Chem. Soc.* **1968**, *90*, 3444. (b) Riddell, F. G.; Robinson, M. J. T. *Tetrahedron* **1967**, *23*, 3417.

(4) (a) Van Woerden, H. F.; Cerfontain, H.; Green, C. H.; Reijerkerk, R. J. *Tetrahedron Lett.* **1968**, 6107. (b) Van Woerden, H. F.; Havinga, E. *Recl. Trav. Chim. Pays-Bas* **1967**, 341.

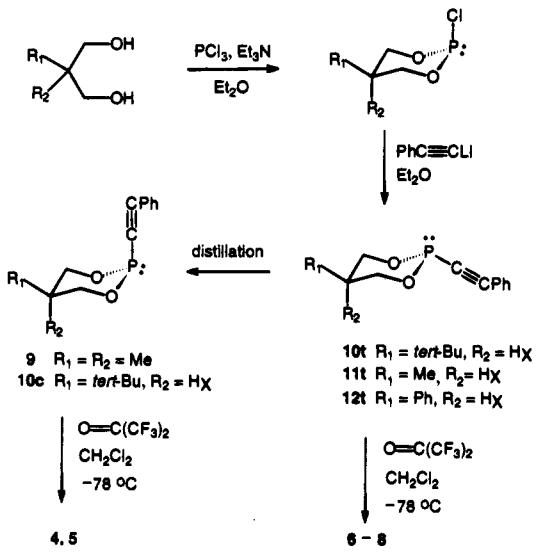
(5) (a) Bentrude, W. G.; Hargis, J. H. *J. Am. Chem. Soc.* **1970**, *92*, 7136. (b) Bentrude, W. G.; Yee, K. C. *J. Chem. Soc., Chem. Commun.* **1972**, 169. Values from iterative computer simulation with the LAOCN5 program are J_{AP} = 10.2 Hz, J_{BP} = 10.1 Hz, J_{AY} = 5.3 Hz, J_{BY} = 10.3 Hz. (Tan, H.-W. unpublished results.) (c) Bentrude, W. G.; Tan, H.-W.; Yee, K. C. *J. Am. Chem. Soc.* **1975**, *97*, 573.

(6) (a) Huang, Y.; Yu, J.; Bentrude, W. G. *J. Org. Chem.* **1995**, *60*, 4767. (b) Huang, Y.; Arif, A. M.; Bentrude, W. G. *J. Org. Chem.* **1993**, *58*, 6235. (c) Bentrude, W. G.; Setzer, W. N.; Sopchik, A. E.; Chandrasekaran, S.; Ashby, M. T. *J. Am. Chem. Soc.* **1988**, *110*, 7119. (d) Setzer, W. N.; Sopchik, A. E.; Bentrude, W. G. *J. Am. Chem. Soc.* **1985**, *107*, 2083. (e) Bentrude, W. G.; Day, R. O.; Holmes, J. M.; Quin, G. S.; Setzer, W. N.; Sopchik, A. E.; Holmes, R. R. *J. Am. Chem. Soc.* **1984**, *106*, 106. (f) Holmes, R. R.; Day, R. O.; Setzer, W. N.; Sopchik, A. E.; Bentrude, W. G. *J. Am. Chem. Soc.* **1984**, *106*, 2353. (g) Bajwa, G. S.; Chandrasekaran, S.; Hargis, J. H.; Sopchik, A. E.; Blatter, D.; Bentrude, W. G. *J. Am. Chem. Soc.* **1982**, *104*, 6385.

(7) Day, R. O.; Bentrude, W. G.; Yee, K. C.; Setzer, W. N.; Deiters, J. A.; Holmes, R. R. *J. Am. Chem. Soc.* **1984**, *106*, 103.

(8) For recent reviews of the conformational analysis of 1,3,2-dioxaphosphorinanes, see refs 2a−c and (a) Setzer, W. N.; Bentrude, W. G. In *Phosphorus-31 NMR in Stereochemical Analysis*; Verkade, J. G., Quin, L. D., Eds.; VCH Publishers: New York, 1987; Chapter 11. (b) Setzer, W. N. *Trends Org. Chem.* **1991**, 2, 215. (c) Nifant'ev, E. E.; Sorokin, S. F.; Borisenko, A. A. *J. Gen. Chem. U.S.S.R., Ser. Chem.* **1984**, 1481. (d) Arshinova, R. P. *Russ. Chem. Rev.* **1984**, *53*, 351. (e) Nifant'ev, E. E.; Zavalishina, A. I. *Russ. Chem. Rev.* **1982**, *51*, 1601. (f) Maryanoff, B. E.; Hutchins, R. O.; Maryanoff. C. S. *Top. Stereochem.* **1979**, *11*, 187.

Scheme 1



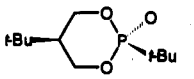
crystallography[1s] as have, as noted earlier, those for **2** and the related phosphoranes **3a** and **3b**.[1n,r]

^{1}H NMR Parameters and Structures of 4−8. The pertinent coupling constants and chemical shifts for the protons attached to the six-membered ring of **4−8**, determined at 300 MHz, are tabulated in Table 1. Also recorded for comparison are values for phosphorane **2** (see the Experimental Section for details of spectral analysis).

The *tert*-butyl substituent of phosphorane **5** is unmistakably assigned the equatorial position from the combination of J_{HH} values: J_{AX} = 11.8 Hz and J_{BX} = 4.4 Hz. The chair conformation of the ring for **5** is deduced from the observed combination of small J_{AP} (2.4 Hz) and large J_{BP} (29.1 Hz). Similar couplings have been noted for other 1,3,2-dioxaphosphorinane chair-form rings containing five-coordinate phosphorus, e.g. **3a** and **3b** and related phosphoranes.[1n,r] The large difference in the J_{HP} values for **5**, and particularly the large size of J_{BP}, are consistent with the essentially total population by **5** of a *single* chair conformation, **A** (eq 2). This form is favored by the equatorial preference of the 5-*tert*-butyl as well as by the preferred positioning in **A** of the P−O4 bond.

By comparison to **5**, phosphoranes **2** and **4** in C_6D_6 feature somewhat reduced J_{BP} couplings (25.0 Hz for **2** and **4**) along with increased J_{AP} values (5.5 Hz for **2** and 6.1 Hz for **4**). The obvious explanation is that for **2** chair form **A** (**2a**) is primarily populated, but a minor amount of **B** (**2b**) is in equilibrium with **A** (**2a**). The same argument applies to phosphorane **4**. The presence of an equilibrium is confirmed by the small increase in the minor conformer population of phosphoranes **2** and **4** when solvent polarity is increased. Thus, in CD_3CN the value of J_{BP} decreases (23.4 Hz for **2** and 23.3 Hz for **4**) while J_{AP} increases (7.0 Hz for **2** and 7.6 Hz for **4**). The equilibrium for series **6−8** is progressively shifted toward conformer **B** by relief of 1,3-syn axial repulsions involving the axial R_1 in **A** in the order for R_1: Me < Ph < *t*-Bu. This is seen in the steady increase in J_{AP} and decrease in J_{BP} which are concomitant with an increase in J_{BY}. The dominant chair form changes from **A** for **6** to **B** for **7** and **8**. The dominance of **B** in the equilibrium for **7** and **8** is confirmed by the reversal of the proton chemical shift order for H_A and H_B compared to that for **2** and **4−6**. As will be shown below, the observed J_{HP} values for **2**, **4**, and **6−8** can be used to estimate the equilibrium constant for **A** ⇌ **B** using reasonable assumed J_{HP} values for the conformers **A** and **B** *without the inclusion of twist or boat conformations such as C.*

In fact, the lack of measureable population of **C** by **5−8** can be readily established simply by examination of the coupling constants for **8**, which would have the greatest driving force toward depopulation of **A** because of the destabilization associated with the axial **5**-*t*-Bu. Indeed, an equilibrium featuring a major contribution of boat form **C** *would have*, as recorded (Table 1), a reasonably large value for J_{BY}. (This is also expected if a large fraction of **B** is populated.) Likewise, for twist forms (**D** and **E**) that are rapidly equilibrated via **C** (eq 3), J_{BY} would be equal to the value in **C** (or **B**) in one form (**E**) and somewhat reduced in the other (**D**), but nonetheless rather large on a time-averaged basis. A reasonable range for J_{BY} for **C** or a pair of rapidly equilibrating enantiomeric twist forms is 10−12 Hz. A good approximation of the time-averaged J_{BY} for the twist forms **D** and **E** comes from the corresponding *cis*-2,5-di-*tert*-butyl-2-oxo-1,3,2-dioxaphosphorinane, **13** (J_{BY} = 10 Hz), which, based on its J_{HH} and J_{HP} values, populates twist conformations.[5b] This means that for the measured J_{BY} for **8** to be 9.1 Hz, of the order 80% or more of **C** (or **D** ⇌ **E**) would need to be populated in equilibrium with **A**.



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However, it can readily be shown that if, for example, a 20 ⇌ 80 **A** ⇌ **C** (or **D**/**E**) equilibrium were present, the observed 20.3 Hz value for J_{AP} for **8** (Table 1) *cannot be accommodated.* Thus, for *cis*-2,5-di-*tert*-butyl-2-oxo-1,3,2-dioxaphosphorinane (**13**), approximately equal J_{AP} and J_{BP} values of 10 Hz are found.[5b] The 10 Hz couplings are the average of those of the pseudoaxial and pseudoequatorial H_A and H_B of the two rapidly interconverting twist forms analogous to **D** and **E**. If the corrresponding HCOP dihedral angles in these conformations are of the order 70° and 170°, then J_{HP} values of approximately 1−2 and 18−20 Hz, respectively, would be reasonable, based on known Karplus curves.[8b] These numbers are similar to those found for axial and equatorial CH_2 protons for such six-membered rings in the chair conformation and are consistent with the time-averaged values of 10 Hz observed for **13**.[5b] By analogy, J_{AP} (2.4 Hz) and J_{BP} (29.1 Hz) for **5** should approximate those for twist forms **D** and **E** equilibrating via **C**. Equal, time-averaged J_{AP} and J_{BP} values of about 16 Hz are thus predicted. Clearly, a coupling of the magnitude 20.3 Hz for J_{AP} of **8** cannot be obtained by even total population of twist forms **D** and **E** equilibrating through **C**.

Moreover, although a full Karplus-like curve has by no means been defined for 1,3,2-dioxaphosphorinanes, the values of J_{HP} seen for the equatorial (∠H−C−O−P ≈ 180°) and axial (∠H−C−O−P ≈ 60°) protons of chair-form **5** suggest that J_{HP} values for the approximately equivalent protons of **C** (∠H−C−O−P ≈ 120°) would be considerably less than the 16 Hz estimated for **D** ⇌ **E**. Thus, even complete population of **C** would not provide a J_{AP} value as high as the observed 20.3 Hz. Furthermore, total population of either **C** or **D** ⇌ **E** would result in a value of J_{BP} commensurate in size to J_{AP} which is totally inconsistent with the 9.2 Hz J_{BP} value actually measured for **8**.

Chair−Chair Equilibrium (A ⇌ B) Constants for 2 and 4−8. Since both the pseudoaxial P−O of the four-membered ring and the equatorial *t*-Bu of **5** bias that molecule toward conformation **A** (eq 2), its coupling constants can be assumed to be very close to those of ring **A**. (In fact, as noted above, the couplings J_{AP}, J_{BP}, and J_{AX} of **3a**[1r] are similar to those of **5**, which is evidence for the occupation by **5** of a single chair conformer.) In conformer **B** the axial-like P−O bond of the

Table 1. Pertinent ^{1}H NMR Parameters for Compounds **2** and **4**–**8**[a]

		J, Hz							δ, ppm			
compd	solvent	AP	BP	Σ	AX	AY	BX	BY	A	B	X	Y
2[b]	C_6D_6	5.5	25.0	30.5	11.4	2.9	4.7	3.2	4.13	3.62	1.44	0.57
2	CD_3CN	7.0	23.4	30.4	10.8	2.9	4.6	3.9	4.65	4.47	2.33	1.95
4	C_6D_6	6.1	25.0	31.1					4.12	3.45		
4	CD_3CN	7.6	23.3	30.9					4.36	4.07		
5	C_6D_6	2.4	29.1	31.5	11.8		4.4		4.43	3.88	1.71	
6	C_6D_6	10.8	19.2	30.0		3.4		5.1	4.17	3.71		1.20
7	C_6D_6	19.1	10.3	29.4		4.6		8.7	4.15	4.48		2.76
8	C_6D_6	20.3	9.2	29.5		4.5		9.1	4.09	4.35		1.44

[a] At 300 MHz, ambient temperature. All spectra were simulated with a LAOCN5 program. [b] References 1n,r.

Table 2. Estimated Equilibrium Constants (K = **B**/**A**) at 25 °C

		% **A** based on obsd					
compd	solvent	J_{AP}	J_{BP}	% **A** av	K	$\Delta G°$ (kcal/mol)	$-\Delta\Delta G°$ [a] (kcal/mol)
2	C_6D_6	87	85	86	0.16	1.1	0.0
2	CD_3CN	80	79	80	0.25	0.8	0.3
4	C_6D_6	84	85	85	0.18	1.0	0.1
4	CD_3CN	78	79	79	0.27	0.8	0.3
6	C_6D_6	64	64	64	0.56	0.3	0.8
7	C_6D_6	29	32	31	2.2	−0.5	1.6
8	C_6D_6	24	28	26	2.9	−0.6	1.7

[a] Corresponds to A values for 5-substituents Me, Ph, and t-Bu in C_6D_6 for **6**, **7**, and **8**.

five-membered ring destabilizes the chair-form ring and in phosphorane **3b** leads to some flattening of the 1,3,2-dioxaphosphorinane ring about phosphorus in the structure determined by X-ray crystallography.[1r] It seems reasonable that the $^3J_{HP}$ values for **3b** should appropriately model the $^3J_{HP}$ values for **B**. Thus, for conformers **A** and **B** it can be assumed that J_{AP}(**A**) = 2.4 Hz, J_{AP}(**B**) = 25.8 Hz, and J_{BP}(**A**) = 29.1 Hz, J_{BP}(**B**) = 1.4 Hz. The mole fractions of conformers **A**, N(**A**), and **B**, N(**B**), for phosphoranes **2** and **4**–**8** were estimated as follows:

$$N(\mathbf{A})J_{AP}(\mathbf{A}) + N(\mathbf{B})J_{AP}(\mathbf{B}) = J_{AP}(\text{obsd})$$

$$N(\mathbf{A}) + N(\mathbf{B}) = 1$$

therefore

$$N(\mathbf{A}) = \frac{J_{AP}(\text{obsd}) - J_{AP}(\mathbf{B})}{J_{AP}(\mathbf{A}) - J_{AP}(\mathbf{B})}$$

similarly

$$N(\mathbf{A}) = \frac{J_{BP}(\text{obsd}) - J_{BP}(\mathbf{B})}{J_{BP}(\mathbf{A}) - J_{BP}(\mathbf{B})}$$

The calculated results are recorded in Table 2. The reduction in J_{BP} assumed for conformation **B**, as mentioned above, is consistent with the observed ring flattening in X-ray structure of **3b**. However, the sum of the J_{HP} values for **3b** (27.2 Hz) is considerably below that observed for **8** (29.5 Hz) for which **B** is highly populated. Thus J_{AP} may be reduced in **3b** to an unusual degree by the five/six-membered ring fusion. The use of a somewhat small assumed value of J_{AP} for **B** may be responsible for the poorer agreement between the percentages of conformer **A** (Table 2) calculated independently from J_{AP} and J_{BP} when the population of **B** is large (phosphoranes **7** and **8**). Indeed, if the assumed J_{AP} for **B** is increased to 27.5 Hz (J_{AP} + J_{BP} = 28.9 Hz), the estimated population of **A**, based on J_{AP}(obsd) of **8**, is increased to 28%, in fortuitously precise agreement with the value calculated from J_{BP}(obsd). The population of **A** estimated for **7** is similarly raised to 33 from 29%. However, the average values of Table 2 for **7** and **8** (31 and 26%, repectively) are no doubt within experimental error of the averages of 32 and 28% obtained with the larger J_{AP}(**B**) (27.5 Hz) and have no important effect on K, $\Delta G°$, and $\Delta\Delta G°$ of Table 2.

Discussion

Absence of Boat/Twist Forms. It is very significant that no evidence for the population of boat or twist forms (**C**) is found even for **7** and **8**. This is in spite of the fact that the A value for the 5-t-Bu of Table 2 is of the order it is when attached to C5 of 1,3-dioxanes and six-membered ring sulfites.[4] For both three- and four-coordinate phosphorus containing 1,3,2-dioxaphosphorinane[5] and 1,3,2-oxazaphosphorinane rings,[6] the free energy increase for conversion of a chair conformation to a boat/twist form (1–2 kcal/mol) is comparable to or even less than the free energy increase accompanying placement of a 5-t-Bu group axial. Twist/boat forms with pseudoequatorial 5-t-Bu, therefore, normally are found to be highly populated for monocyclic 1,3,2-dioxaphosphorinane rings containing either three- or four-coordinate phosphorus instead of chair conformers with axial 5-t-Bu groups.[2b,c,5–8] Moreover, the three- and four-coordinate analogs of **3a** and **3b** show high populations of twist conformations in response to steric and stereoelectronic driving forces of the order 1–3 kcal/mol from substituents on phosphorus.[9]

Two factors seem likely to be responsible for the apparently relatively high energy of twist or boat forms of 1,3,2-dioxaphosphorinane rings attached diequatorially to five-coordinate phosphorus. *First*, although well-parameterized molecular mechanics programs for five-coordinate phosphorus are not available, one needs only inspect Dreiding models of the rings in question to see that the approximate trigonal bipyramidal geometry about phosphorus places even the apical P–O4 bond of **C**, **D**, or **E** in close proximity to the bowsprit hydrogen (R_2 = H) at C5 (eqs 2 and 3). *This interaction would raise the energy of boat or twist forms above that of such conformations in analogous 1,3,2-dioxaphosphorinane rings containing three- and four-coordinate phosphorus.* In the latter rings in a twist or boat form similar to **C**, **D**, or **E**, pseudoaxial P=O, and P–X

(9) Gorenstein, D. G.; Rowell, R. *J. Am. Chem. Soc.* **1979**, *101*, 4925. Gorenstein, D. G.; Rowell, R.; Findlay, J. *J. Am Chem. Soc.* **1980**, *102*, 5077. Bouchu, D.; Dreux, J. *Tetrahedron Lett.* **1980**, *21*, 2513. Sopchik, A. E.; Bentrude, W. G. *Tetrahedron Lett.* **1980**, *21*, 4679. Rowell, R.; Gorenstein, D. G. *J. Am. Chem. Soc.* **1981**, *103*, 5894. Bouchu, D. *Phosphorus Sulfur Silicon* **1983**, *15*, 33. Taira, K.; Gorenstein, D. G. *Tetrahedron Lett.* **1986**, *42*, 229. Nelson, K. A.; Bentrude, W. G.; Setzer, W. N.; Hutchinson, J. P. *J. Am. Chem. Soc.* **1987**, *109*, 4058. Hermans, R. J. M.; Buck, H. M. *J. Org. Chem.* **1987**, *52*, 5150. Hermans, R. J. M.; Buck, H. M. *Recl. Trav. Chim. Pays-Bas* **1988**, *107*, 82. Yang, J.-C.; Shah, D. O.; Rao, N. U. M.; Freeman, W. A.; Sosnovsky, G.; Gorenstein, D. G. *Tetrahedron* **1988**, *44*, 6305. Sopchik, A. E.; Beres, J.; Tomasz. J.; Bentrude, W. G. *J. Org. Chem.* **1991**, *56*, 5911. Nelson, K. A.; Bentrude, W. G. *Carbohydr. Res.* **1992**, *234*, 141.

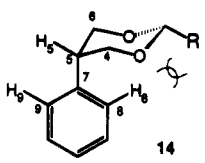
bonds and the P lone pair on tetrahedral or pyramidal phosphorus will be pointed less directly toward the analogous bowsprit, pseudoaxial hydrogen. *Second*, when there is apical/equatorial attachment of such a ring, it has been proposed that a major driving force toward the preferential population of the boat or twist conformation arises from the fact that in that conformation the 2p lone pair on the *equatorial* ring oxygen is in the equatorial plane of the TBP structure.[10] There it confers stability to that form by backbonding into the phosphorus orbital system.[11] It also is clear from Dreiding models that in conformations **C**, **D**, and **E** or any other boat or twist conformation the lone pair in the 2p orbital on ring oxygen *cannot be placed in the equatorial plane in question.*

Conformational Equilibrium A ⇌ B. Examination of the $\Delta G°$ values recorded in Table 2 for **2** and **4** reveals that including the pseudoaxial, apical P−O bond on five-coordinate phosphorus in a five-membered ring (conformation **B** (**2b**)) destabilizes that form by about 1 kcal/mol (C_6D_6 solvent) with respect to the alternative chair, **A** (**2a**). In **A** the apical P−O4 in the four-membered ring has been shown by X-ray crystallography to be moved away from the axial ring hydrogens at C4 and C6 and to be increased in length.[1n] This quite reasonably then leads in solution to predominate populations of **A** in the otherwise sterically unrestricted systems, **2** and **4** ($\Delta G°$ = 1.0, 1.1 kcal/mol, C_6D_6). Previous X-ray crystallographic work showed that **2** is in form **2a** in the solid state.[1n]

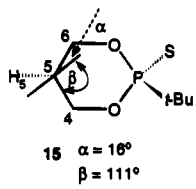
Placement of an *axial* substituent on C5 of **A** (**6**−**8**) generates a 1,3-syn axial repulsion that drives the equilibrium **A** ⇌ **B** toward **B** in the order *t*-Bu > Ph > Me. Comparisons of $\Delta\Delta G°$ for these groups (Table 2) assigns to these groups *A* values (benzene) of 0.8 (Me), 1.6 (Ph), and 1.7 (*t*-Bu) kcal/mol. If the impetus of favorable reorientation of both the apical P−O and the 5-*t*-Bu is present at the same time (1.1 + 1.7 kcal/mol, C_6D_6), only **A** should be populated, as is seen for **5**. The *A* values for the 5-substitutents in the equilibrium **A** ⇌ **B** can be compared to those for the corresponding 1,3-dioxanes: Me (0.8,[3a] 0.9[3b] kcal/mol); Ph (1.0 kcal/mol[3a]); *t*-Bu (1.4,[3a] 1.7[3b] kcal/mol). The differences in the values reported for a given substituent apparently reflect a systematic variation in their determinations in two research groups and perhaps the use of $CHCl_3$ solvent by one group[3b] and Et_2O by the other.[3a] The 0.3 kcal/mol difference for the 5-*t*-Bu was the largest noted. For the series Me, Et, *i*-Pr a systematic difference of 0.1 kcal/mol was noted. There is no doubt that the 5-*t*-Bu is significantly larger than the 5-Ph.

Notably, the *A* value for the 5-phenyl substituent of **7** is *close to that of the 5-tert-butyl* of **8** and somewhat larger than it is in the 1,3-dioxane system.[3] Presumably, this increase arises primarily from interactions that occur when the 5-phenyl substituent is axial. A key interaction, present in 1,3-dioxanes and in 1,3,2-dioxaphosphorinanes, is that between the axial 5-alkyl group and ring oxygen lone pairs. That these repulsions are of lower energy than 1,3-syn axial repulsions involving axial hydrogens in cyclohexanes is clear from the reduced *A* values for alkyl and phenyl substituents at C5 of 1,3-dioxanes[3] and the analogous six-membered ring sulfites.[4]

Molecular mechanics calculations predict that an axial phenyl will assume a conformation that is perpendicular to the symmetry plane of the chair-form cyclohexane ring and thus avoids 1,3-syn axial repulsions with cyclohexane ring hydrogens.[12] By contrast for 1,3-dioxanes and related rings, a parallel conformation, depicted by **14**, can be more readily assumed. Indeed, an unpublished X-ray crystal structure of *cis*-2-*tert*-butyl-2-thio-5-phenyl-1,3,2-dioxaphosphorinane[13] shows the axial 5-phenyl to be positioned as in **15**, a conformation



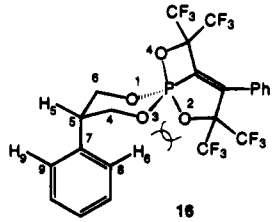
14



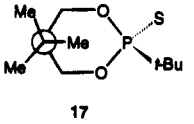
15 α = 16°
β = 111°

intermediate between parallel and perpendicular. Eclipsed C9−H5 and C6−C8 interactions are avoided. Simultaneously, the distance (3.27 Å) between the ortho hydrogen (H8) of the phenyl ring and a methyl of the 2-*tert*-butyl is reduced to very near the van der Waals radius sum (3.20 Å)[15] for methyl (2.0 Å)[14] and hydrogen (1.20 Å).[15]

For **7** in conformation **A**, a severe cross-ring repulsive interaction with the apical P−O bond is potentially present (structure **16**). Indeed, when an axial 5-phenyl is attached to the 5-carbon of the X-ray structure of **2a**,[1n] the bond angles C4−C5−C7 and C6−C5−C7 are made equal to those in X-ray structure of **15**[13] and the torsion angles are fixed such that the phenyl exactly bisects the six-membered ring,[16] as shown in **16**, the distances H8···O2 and H8···O1/O3 are only 2.29 and 2.48 Å, respectively. These are much less than the van der Waals radius sum of 2.72 Å for H (1.20 Å) and oxygen (1.52 Å), and **16** is clearly a high-energy conformation. If the angles α and β (**15**) are changed in **16** to 30° and 103°, respectively, the H···O distance *increases* to 2.95 Å for H8···O2, but the distance H8···O1 *decreases* to 2.10 Å. When angles α and β are made equal to those in the X-ray structure of **15**, the H8−O2 distance is 3.17 Å, well beyond the van der Waals sum (2.72 Å), but the H8−O1 distance is still only 2.15 Å.[16] The 16° value for angle α, as noted above, reduces the cross-ring *tert*-butyl···H8 interaction in **15** and likely is an unrealistically low value for **16**. The above considerations suggest to us that optimization of steric interactions involving the axial phenyl of **16** (**7**) results in a value of α considerably greater than 16°. The difficulty in avoiding either a severe H8···O2 or H8···O1 repulsion leads to an *A* value (1.6 kcal/mol) for the 5-phenyl substituent increased by about 0.5 kcal/mol compared to that reported for 1,3-dioxane (1.0 kcal/mol). In the latter case the H8···O1 repulsion can be avoided in a conformation like **16** since the C−H bond at C2 of a 1,3-dioxane most assuredly will not be within van der Waals distance of H8.



16



17

(10) Trippett, S. *Pure Appl. Chem.* **1974**, *40*, 595. For structures that illustrate the difference in orientation of the oxygen lone pair in apical and equatorial positions of a boat/twist ring, see ref 1e.

(11) (a) Hoffmann, R.; Howell, J. M.; Muetterties, E. L. *J. Am. Chem. Soc.* **1972**, *94*, 3047. (b) Szobata, J. S.; Holmes, R. R. *Inorg. Chem.* **1977**, *16*, 2299 and references cited therein.

(12) Allinger, N. C.; Tribble, M. T. *Tetrahedron Lett.* **1971**, 3259. Allinger, N. L. personal communication cited in Hodgson, D. J.; Rychlewska, U. Eliel, E. L.; Manoharan, M.; Knox, D. E.; Olefirowitcz, E. M. *J. Org. Chem.* **1985**, *50*, 4838.

(13) Newton, M. G.; Tan, H.-W.; Bentrude, W. G. Unpublished results.

(14) Pauling, L. *The Nature of the Chemical Bond*, 3rd ed.; Cornell University Press: Ithaca, 1960; p 260.

(15) Bondi, A. *J. Phys. Chem.* **1964**, *68*, 441.

(16) These structures were modeled using the Alchemy II program by which internuclear distances also were measured.

As a model for conformation **A** of **8**, the previously published X-ray crystal structure of **17** can be used.[17] The *tert*-butyl conformation was seen to be as shown in **17**. When the *tert*-butyl group is attached to the X-ray structure of **2** (**2a**), and the angles C4−C5−C7 and C6−C5−C7 as well as the torsion angles about the *tert*-butyl−C5 bond are made identical to those in the X-ray structure of **17**,[17] the C···O2 internuclear distance for the methyl directed into the ring was measured to be 3.43 Å.[16] This is very close to the van der Waal's sum (3.5 Å) for a methyl (2.0 Å)[14] and oxygen atom (1.52 Å).[15] By contrast, as was noted above, when the 5-phenyl of the X-ray model of **7** (**16**) bisects the ring, the H8···O2 distance is only 2.29 Å (van der Waals sum, 2.72 Å). It appears, therefore, that the 5-phenyl substituent is intrinsically more susceptible to an increase in its *A* value in 1,3-dioxaphosphorinane rings that contain five-coordinated phosphorus. Attempts at more extensive analysis of these effects are presently unwarranted and await molecular mechanics calculations once programs parameterized for phosphorus-containing molecules become readily available.

Conclusions

The equilibrium **A** ⇌ **B** (eq 2) is readily perturbed by the replacement in equation 1 of H_Y by *t*-Bu (**5**) or H_X by *t*-Bu (**8**), Me (**6**), or Ph (**7**). Conformational energies (*A* values) for axial 5-R substituents in **6**−**8** were shown to follow the relative size order: *t*-Bu (1.7 kcal/mol) > Ph (1.6 kcal/mol) > Me (0.8 kcal/mol). The significant, approximately 0.5 kcal/mol, increase in *A* value for 5-Ph in this ring system, compared to what has been reported for 1,3-dioxanes,[3a] may reflect the proximity of the apical P−O2 bond in **A** to the axial 5-phenyl. No evidence is found for depopulation of chair conformations **A** or **B** in favor of boat/twist form **C**, **D**, or **E**. This contrasts strikingly with the known *preference* of 1,3,2-dioxaphosphorinane rings attached in apical/equatorial fashion to five-coordinated phosphorus to occupy boat/twist conformations and the ease of population of boat/twist forms by 1,3,2-dioxaphosphorinanes containing three- or four-coordinate phosphorus. A reasonable understanding of the failure of the rings of the present study to populate nonchair conformations (**C**, **D**, **E**) comes from the realization that in these conformations the apical P−O4 bond would experience severe repulsive interactions with the pseudo-axial bowsprit hydrogen at C5 (eq 2, R_2 = H in **C**). Furthermore, when the ring is diequatorially attached to phosphorus, the electron lone pair in the 2p orbital on the equatorial oxygen cannot be positioned to back bond with phosphorus *in any nonchair conformation.*

Experimental Section

Materials. Commercial solvents and reagents were used as received unless otherwise noted. Ethyl ether and tetrahydrofuran were dried over sodium and 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 ^{1}H NMR spectra were recorded on a Varian Unity-300 spectrometer. Although the spectra are technically second-order AA′BB′XY (Y = P) spin systems, they are generally well dispersed and analyzable as ABXY systems. All spectra then were simulated with the aid of the LAOCN5 simulation program. Simulated spectra included cross-ring second-order splittings which are not reported as they do not assist in the analysis of conformational equilibria. ^{13}C NMR and ^{31}P NMR spectra were taken on Varian XL-300 and Unity-300 spectrometers operated with full proton decoupling ({^{1}H}). ^{1}H and ^{13}C NMR chemical shifts are recorded in parts per million (δ, ppm) relative to internal tetramethylsilane (TMS) added to the sample or from absorbances of deuterated solvent peaks with known chemical shifts relative to TMS. The individual protons or carbons, designated H_A, C1, etc., correspond to the structures shown in the text. Standard empirical calculations were used for the assignments of the phenyl carbons.[18] ^{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 Table 1 are recorded in this section.

Mass spectra were recorded on a Finnigan MAT 95 instrument operated in the negative chemical ionization ($^-$CI) mode. GLC spectra were taken on a Varian 3300 gas chromatograph equipped with an 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.

Preparation of 2-Chloro-5,5-dimethyl-1,3,2-dioxaphosphorinane. A solution of 2,2-dimethyl-1,3-propanediol (8.90 g, 95.0 mmol, recrystallized from THF) and triethylamine (19.2 g, 0.190 mol) in 100 mL of dry diethyl ether and a solution of phosphorus trichloride (13.3 g, 95.0 mmol) in 100 mL of dry diethyl ether were added dropwise and simultaneously to 500 mL of dry diethyl ether at 0 °C with rapid stirring. The resulting mixture was allowed to warm to room temperature and continuously stirred overnight. The salt was filtered away by Schlenk techniques, and the solvent was removed by rotary evaporation. The residue was short-path distilled to give 12.3 g of a colorless liquid (73.2 mmol, 77% yield): bp 46−47 °C (1.6 mmHg) (lit.[19] bp 87−88 °C (36 mmHg)).

Preparation of *cis*-2-Chloro-5-methyl-1,3,2-dioxaphosphorinane. By a procedure directly analogous to that for the above 5,5-dimethyl compound, the reaction of 2-methyl-1,3-propanediol (3.64 g, 40.0 mmol), triethylamine (8.10 g, 80.0 mmol), and phosphorus trichloride (5.61 g, 40 mmol) in 300 mL of THF gave 4.10 g of a colorless liquid containing cis and trans diastereomers in 83/17 (cis/trans) ratio (^{31}P and ^{1}H NMR) (26.5 mmol, 66% yield): bp 56−57 °C (4.7 mmHg); ^{31}P NMR (121 MHz, $CDCl_3$, {^{1}H}) δ 147.9 (s, cis), 154.14 (s, trans); ^{1}H NMR (300 MHz, $CDCl_3$) *cis*-diastereomer δ 0.81 (d, 3 H, CH_3, J_{HH} = 6.9 Hz), 2.45 (dttq, 1 H, CHCH$_3$, J_{AX} = 11.8 Hz, J_{BX} = 4.4 Hz, J_{PX} = −0.9 Hz, J_{HH} = 6.9 Hz), 3.93 (ddd, 2 H, H_B, J_{AB} = - 11.0 Hz, J_{BX} = 4.4 Hz, J_{BP} = 11.0 Hz), 4.18 (ddd, 2 H, H_A, J_{AB} = - 11.0 Hz, J_{AX} = 11.8 Hz, J_{AP} = 5.6 Hz); *trans*-diastereomer δ 1.40 (d, 3 H, CH_3, J_{HH} = 7.1 Hz), 1.85−2.01 (m, 1 H, CHCH$_3$), 3.72−3.80 (m, 2 H, H_B), 4.75−4.81 (m, 2 H, H_A).

Preparation of 2-(2-Phenylethynyl)-5,5-dimethyl-1,3,2-dioxaphosphorinane (9). By a procedure analogous to that described in literature for the precursor to **2**,[1n,r] the reaction of 2-chloro-5,5-dimethyl-1,3,2-dioxaphosphorinane (10.0 g, 59.3 mmol) and lithium phenylacetylide (59.3 mmol, 59.3 mL, 1.0 M in THF) in 300 mL of diethyl ether gave 12.8 g of a white solid (54.6 mmol, 92% yield): mp 68−69 °C; ^{31}P NMR (121 MHz, $CDCl_3$, {^{1}H}) δ 116.5 (s); ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.77, 1.27 (two s, 6 H, C(CH_3)$_2$), 3.62 (dd, 2 H, H_B, $^2J_{AB}$ = -10.5 Hz, $^3J_{BP}$ = 9.7 Hz), 4.22 (dd, 2 H, H_A, $^2J_{AB}$ = -10.5 Hz, $^3J_{AP}$ = 3.5 Hz), 7.37, 7.51 (2 m, 5 H, C_6H_5); ^{13}C NMR (75 MHz, $CDCl_3$, {^{1}H}) δ 22.5, 22.7, 33.6 (d, $^3J_{PC}$ = 4.5 Hz), 73.9 (d, $^2J_{PC}$ = 3.7 Hz), 88.5 (d, $^1J_{PC}$ = 69.6 Hz), 105.5 (d, $^2J_{PC}$ = 3.1 Hz), 121.6 (d, *ipso*-Ph, $^3J_{PC}$ = 2.6 Hz), 128.4 (*m*-Ph), 129.4 (*p*-Ph), 131.9 (d, *o*-Ph, $^4J_{PC}$ = 2.0 Hz). Anal. Calcd for $C_{13}H_{15}O_2P$: C, 66.66; H, 6.46. Found: C, 66.64; H, 6.47. Analogous procedures gave **10c**, **10t**, **11t**, and **12t**.

Preparation of 2-(2-Phenylethynyl)-5-*tert*-butyl-1,3,2-dioxaphosphorinane (10t and 10c). The reaction of 2-chloro-5-*tert*-butyl-1,3,2-dioxaphosphorinane[5a] (1.89 g, 9.60 mmol) with lithium phenylacetylide (6.30 mmol, 6.3 mL, 1.0 M in THF) in 25 mL of dry THF gave 2.31 g of product as an oil which in a freezer (about −20 °C) became a solid (8.80 mmol, 91% yield) that was predominately (^{31}P NMR) **10t**, the trans diastereomer. On Kugelrohr distillation, air bath temperature 80−90 °C (0.05 mmHg), the cis diastereomer, **10c**, was formed: ^{31}P NMR (121 MHz, $CDCl_3$, {^{1}H}) δ 118.4 (s); ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.93 (s, 9 H, C(CH_3)$_3$), 2.07 (dtt, 1 H, H_X, $^4J_{PX}$ = −1.1 Hz, $^3J_{AX}$ = 11.4 Hz, $^3J_{BX}$ = 4.0 Hz), 4.20 (ddd, 2 H, H_B, $^2J_{AB}$ = −10.1 Hz,

(17) Warrent, R. W.; Caughlan, C. N.; Hargis, J. H.; Yee, K. C.; Bentrude, W. G. *J. Org. Chem.* **1978**, *43*, 4266.

(18) Silverstein, R. M.; Bassler, C. G.; Morrill, T. C. *Spectrometric Identification of Organic Compounds*, 4th ed.; Wiley: New York, 1981; Chapter 5, pp 265−266.

(19) White, D. W.; Bertrand, R. D.; McEwen, G. K.; Verkade, J. G. *J. Am. Chem. Soc.* **1970**, *92*, 7125.

$^3J_{BP}$ = 9.5 Hz, $^3J_{BX}$ = 4.0 Hz), 4.40 (ddd, 2 H, H_A, $^2J_{AB}$ = −10.1 Hz, $^3J_{AP}$ = 3.5 Hz, $^3J_{AX}$ = 11.4 Hz), 7.37, 7.51 (2 m, 5 H, C_6H_5); ^{13}C NMR (75 MHz, $CDCl_3$, {^{1}H}) δ 27.3 (s,), 29.6 (s), 46.5 (d, $^3J_{PC5}$ = 4.7 Hz), 66.4 (d, $^2J_{PC}$ = 3.1 Hz), 88.6 (d, $^1J_{PC}$ = 69.7 Hz), 105.6 (d, $^2J_{PC}$ = 3.6 Hz), 121.6 (d, *ipso*-Ph, $^3J_{PC}$ = 2.5 Hz), 128.3 (*m*-Ph), 129.3 (*p*-Ph), 131.8 (*o*-Ph, $^4J_{PC}$ = 2.0 Hz). Anal. Calcd for $C_{15}H_{19}O_2P$: C, 68.69; H, 7.30. Found: C, 68.43; H, 7.40.

Preparation of 2-(2-Phenylethynyl)-5,5-dimethyl-1,3,2-dioxaphosphorinane Hexafluoroacetone Adduct (4). According to the procedure reported for **2**,[1n,r] reaction of 2-(2-phenylethynyl)-5,5-dimethyl-1,3,2-dioxaphosphorinane (**9**) (2.20 g, 9.50 mmol) and hexafluoroacetone in 10 mL of dichloromethane gave white solid crude product which was recrystallized from diethyl ether/*n*-pentane in a freezer (about −20 °C) to give 3.85 g of white crystals (6.80 mmol, 72% yield): mp 129−130 °C; ^{31}P NMR (121 MHz, C_6D_6, {^{1}H}) δ −1.45 (s); ^{1}H NMR (300 MHz, C_6D_6) δ 0.19, 0.85 (two s, 6 H, $C(CH_3)_2$), 3.45 (dd, 2 H, H_B, $^2J_{AB}$ = −10.4 Hz), 4.12 (dd, 2 H, H_A, $^2J_{AB}$ = −10.4 Hz), 6.96, 7.14 (2 m, 5 H, C_6H_5); ^{13}C NMR (75 MHz, $CDCl_3$, {^{1}H}) δ 21.1, 22.6, 34.2 (d, $^3J_{PC5}$ = 7.7 Hz), 76.5 (d, $^2J_{PC}$ = 6.5 Hz), 121.1 (dq, $^3J_{PC}$ = 3.5 Hz, $^1J_{CF}$ = 287.5 Hz), 121.4 (dq, $^3J_{PC}$ = 12.6 Hz, $^1J_{CF}$ = 286.0 Hz), 127.5 (s, *m*-Ph), 128.2 (*o*-Ph), 130.1 (*p*-Ph), 148.1 (d, *ipso*-Ph, $^3J_{PC}$ = 10.1 Hz). The remaining carbon signals were too weak to be assigned accurate chemical shifts. Anal. Calcd for $C_{19}H_{15}F_{12}O_4P$: C, 40.30; H, 2.67; P, 5.47. Found: C, 40.21; H, 2.64; P, 5.11. Phosphoranes **5**−**8** were prepared analogously.

Preparation of 2-(2-Phenylethynyl)-5-*tert*-butyl-1,3,2-dioxaphosphorinane Hexafluoroacetone Adduct (5). The reaction of *cis*-2-(2-phenylethynyl)-5-*tert*-butyl-1,3,2-dioxaphosphorinane (**10c**) (2.20 g, 8.40 mmol) with hexafluoroacetone in 10 mL of dichloromethane gave a white solid product which was recrystallized from diethyl ether/*n*-pentane in a freezer (about −20 °C) to give 4.20 g of white crystals of the single diastereomer, **5** (7.10 mmol, 85% yield): mp 131.5−132.5 °C; ^{31}P NMR (121 MHz, C_6D_6, {^{1}H}) δ 0.00 (s); ^{1}H NMR (300 MHz, C_6D_6) δ 0.35 (s, 9 H, $C(CH_3)_3$), 1.72 (dtt, 1 H, H_X, $^4J_{XP}$ = −1.1 Hz), 3.89 (ddd, 2 H, H_B, $^2J_{AB}$ = −10.5 Hz), 4.43 (ddd, 2 H, H_A, $^2J_{AB}$ = −10.5 Hz), 6.97, 7.18 (2 m, 5 H, C_6H_5); ^{13}C NMR (75 MHz, $CDCl_3$, {^{1}H}) δ 27.8, 31.2, 45.8 (d, $^3J_{PC}$ = 7.3 Hz), 69.3 (d, C_4, C_6, $^2J_{PC}$ = 6.6 Hz), 121.1 (dq, CF_3, $^3J_{PC}$ = 4.3 Hz, $^1J_{CF}$ = 288.4 Hz), 121.5 (dq, $^3J_{PC}$ = 12.2 Hz, $^1J_{CF}$ = 286.2 Hz), 127.5 (*m*-Ph), 128.1 (*o*-Ph), 130.1 (*p*-Ph), 148.0 (d, *ipso*-Ph, $^3J_{PC}$ = 10.7 Hz). The remaining carbon signals were too weak to be assigned accurate chemical shifts; MS (negative methane CI spectrum at 120 eV) m/z (relative intensity) 594 (M^+, 98), 193 (100). Anal. Calcd for $C_{17}H_{11}F_{12}O_4P$: C, 42.44; H, 3.22; P, 5.21. Found: C, 42.33; H, 3.21; P, 4.79.

Preparation of 2-(2-Phenylethynyl)-5-methyl-1,3,2-dioxaphosphorinane Hexafluoroacetone Adduct (6). Reaction of 2-chloro-5-methyl-1,3,2-dioxaphosphorinane (1.00 g, 6.50 mmol) and lithium phenylacetylide (6.50 mmol) in 30 mL of diethyl ether gave crude product 2-(2-phenylethynyl)-5-methyl-1,3,2-dioxaphosphorinane, **11**, in 15/85 (cis/trans) ratio (^{31}P NMR) which was reacted immediately with hexafluoroacetone according to the procedures given above. The crude product was purified by flash column chromatography (eluent: 10% ethyl acetate in hexane) to yield 1.10 g of a white solid containing the two diastereomers in a 11/89 cis/trans ratio (^{31}P NMR) (1.99 mmol, 31% yield): mp 124−125 °C. The major diastereomer is designated as **6**: ^{31}P NMR(121 MHz, C_6D_6, {^{1}H}) major diastereomer, δ −1.92 (s); minor diastereomer, δ −0.77 (s); ^{1}H NMR (300 MHz, C_6D_6) major diastereomer: δ 0.58 (d, 3 H, CH_3, $^3J_{HH}$ = 3.2 Hz), 1.20 (m, 1 H, H_Y, $^4J_{YP}$ = −2.5 Hz), 3.66 (ddd, 2 H, H_B, $^2J_{AB}$ = −10.8 Hz), 4.17 (dd, 2 H, H_A, $^2J_{AB}$ = −10.8 Hz), 6.90−7.00, 7.16−7.23 (m, 5 H, C_6H_5); ^{13}C NMR (75 MHz, $CDCl_3$, {^{1}H}) major diastereomer: δ 13.0, 32.0 (d, $^3J_{PC}$ = 8.3 Hz), 72.7 (d, $^2J_{PC}$ = 6.7 Hz), 121.1 (q, $^1J_{CF}$ = 285.3 Hz), 121.3 (q, CF_3, $^1J_{CF}$ = 285.3 Hz), 127.4 (*m*-Ph), 128.1 (*o*-Ph), 130.1 (*p*-Ph), 147.9 (d, *ipso*-Ph, $^3J_{PC}$ = 8.8 Hz). The remaining carbon signals were too weak to be assigned accurate chemical shifts. Anal. Calcd for $C_{18}H_{13}F_{12}O_4P$: C, 39.14; H, 2.37. Found: C, 38.97; H, 2.44.

Preparation of 2-(2-Phenylethynyl)-5-phenyl-1,3,2-dioxaphosphorinane Hexafluoroacetone adduct (7). Reaction of 2-chloro-5-phenyl-1,3,2-dioxaphosphorinane[20] (0.79 g, 3.65 mmol) in 20 mL of diethyl ether and lithium phenylacetylide (3.65 mmol) gave a crude product *trans*-2-(2-phenylethynyl)-5-phenyl-1,3,2-dioxaphosphorinane), **12t**, which was reacted immediately with hexafluoroacetone to yield 0.87 g of colorless needles (1.42 mmol, 39% yield) of a single diastereomer designated **7** (^{31}P NMR): mp 129−130 °C; ^{31}P NMR-(121 MHz, C_6D_6, {^{1}H}) δ −3.82 (s); ^{1}H NMR (300 MHz, C_6D_6) δ 2.76 (dtt, 1 H, H_Y, $^4J_{YP}$ = −1.7 Hz), 4.15 (ddd, 2 H, H_B, $^2J_{AB}$ = −10.9 Hz), 4.49 (ddd, 2 H, H_A, $^2J_{AB}$ = −10.9 Hz), 6.90−7.00 (m, 5 H, C_6H_5), 7.16 (bs, 5 H, CHC_6H_5); ^{13}C NMR (75 MHz, $CDCl_3$, {^{1}H}) δ 43.3 (d, $^3J_{PC}$ = 8.3 Hz), 71.7 (d, C_4, C_6, $^2J_{PC}$ = 7.5 Hz), 127.3 (*m*-Ph), 128.2 (*o*-Ph), 130.2 (*p*-Ph), 148.0 (d, *ipso*-Ph, $^3J_{PC}$ = 7.2 Hz), 128.02, 128.38, 129.23, 135.30. The remaining carbon signals were too weak to be assigned accurate chemical shifts. Anal. Calcd for $C_{23}H_{15}F_{12}O_4P$: C, 44.96; H, 2.46. Found: C, 45.02; H, 2.47.

Preparation of 2-(2-Phenylethynyl)-5-*tert*-butyl-1,3,2-dioxaphosphorinane Hexafluoroacetone Adduct (8). As reported above for the preparation of **10c**, reaction of 2-chloro-5-*tert*-butyl-1,3,2-dioxaphosphorinane (1.06 g, 5.39 mmol) and lithium phenylacetylide (5.4 mmol) in 20 mL of diethyl ether gave crude product, predominately *trans*-2-(2-phenylethynyl)-5-*tert*-butyl-1,3,2-dioxaphosphorinane (**10t**), which was reacted immediatedly with hexafluoroacetone to give 0.95 g of colorless crystals of the single diastereomer, **8** (1.60 mmol, 30% yield): mp 138−139 °C; ^{31}P NMR(121 MHz, C_6D_6, {^{1}H}) δ −3.18 (s); ^{1}H NMR (300 MHz, C_6D_6) δ 0.49 (s, 9 H, $C(CH3)_3$), 1.43 (dtt, 1 H, H_Y, $^4J_{YP}$ = −1.7 Hz), 4.08 (ddd, 2 H, H_B, $^2J_{AB}$ = −11.1 Hz), 4.34 (ddd, 2 H, H_A, $^2J_{AB}$ = −11.1 Hz), 6.96, 7.18 (2 m, 5 H, C_6H_5); ^{13}C NMR (75 MHz, $CDCl_3$, {^{1}H}) δ 27.8, 31.4, 45.7 (d, $^3J_{PC}$ = 6.9 Hz), 69.8 (d, $^2J_{PC}$ = 7.5 Hz), 120.9 (q, $^1J_{CF}$ = 284.7 Hz), 121.1 (q, $^1J_{CF}$ = 285.3 Hz), 127.3 (*m*-Ph), 128.1 (*o*-Ph), 130.0 (*p*-Ph), 147.7 (d, *ipso*-Ph, $^3J_{PC}$ = 7.3 Hz). The remaining carbon signals were too weak to be assigned accurate chemical shifts. Anal. Calcd for $C_{21}H_{19}F_{12}O_4P$: C, 42.44; H, 3.22. Found: C, 42.51; H, 3.24.

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(20) Bergesen, K.; Albriktsen, P. *Acta Chem. Scand.* **1972**, *26*, 1680.