Carbon-Phosphorus Heterocycles. Synthesis and Conformational Analysis of Alkyl-Substituted 1,2,6-Triphenyl-4-phosphorinanones and Derivatives

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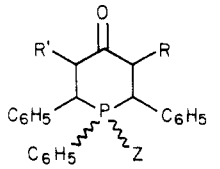
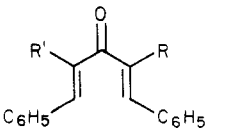
A series of substituted phosphorinanones has been prepared, and a conformational analysis has been performed on all of the systems via ^1H, ^{13}C, and ^{31}P NMR techniques. All of the compounds appear to be chair forms in solution as evidenced by the chemical shifts and coupling constants. 1,2,6-Triphenyl-3-methyl-4-phosphorinanone (**1a'**) was obtained via a condensation of bis(hydroxymethyl)phenylphosphine and 1,5-diphenyl-2-methyl-1,4-pentadien-3-one in boiling pyridine. Only **1a'** could be isolated from the reaction under these conditions. Oxidation and sulfurization afforded the corresponding oxide and sulfide which also were biased in solution at room temperature. 1,2,6-Triphenyl-3,5-dimethyl-4-phosphorinanone (**1d'**) was prepared in similar fashion by using 1,5-diphenyl-2,4-dimethyl-1,4-pentadien-3-one under the same conditions as cited previously. This phosphine, **1d'**, was the lone product via NMR examination of the mixture and was also biased, as were the corresponding oxide and sulfide obtained by the methods cited above. Deuteration of the 3,5-positions in **1a'** removed the H-H vicinal couplings in these systems and permitted structure diagnosis with respect to assigning the C-CH_3 bonds as being equatorial. Moreover, the C(2)-C_6H_5 bond and the C(6)-C_6H_5 bond were established as of the equatorial type not only in **1a'** but in all derivatives thereof. However, in **1d'** and its oxide and sulfide, the C(2)-C_6H_5 bond was axial. ^{13}C NMR shifts and J_{PC} couplings for all of the compounds were correlated where possible with related data from 1-*r*,*cis*-2(a),*trans*-6(e)-triphenyl-4-phosphorinanone 1-sulfide, the structure of which was established by X-ray diffraction work in the previous paper. Relaxation measurements (T_1 values) were employed where possible to make ^{13}C NMR assignments as well. Amino-substituted derivatives were obtained for 1,2,6-triphenyl-3-methyl-4-phosphorinanone and characterized. Oximation of the same phosphine did not result in oxidation of the phosphorus atom apparently because of steric hindrance, although oxidation had been reported in simple phosphorinanones. These highly substituted phosphorinanones are the first recorded, along with their ^{13}C NMR spectral properties.

4-Phosphorinanones are of active interest[1] and of potential value as synthons for construction of large polynuclear carbon-phosphorus (C-P) systems as well as for novel, fused heterocyclics.[2] As cited in the previous paper[3] and except for the analysis therein, stereochemical data available on C-substituted phosphorinanones is almost nonexistent. We report herein the synthesis of **1a-f** starting from **2a** or **2b**. Treatment of **2a** or **2b** with bis(hydroxymethyl)phenylphosphine[4] in boiling pyridine (under N_2) gave ketones **1a** and **1d** in yields of 39.7% and 62.6%, respectively. Surprisingly, dienone **2b** and phenylphosphine did not react under the above conditions or under those reported for the synthesis of 1,2,6-triphenyl-4-phosphorinanone.[1b]



1a, Z = lone pair; R = CH_3; R' = H
b, Z = O; R = CH_3; R' = H
c, Z = S; R = CH_3; R' = H
d, Z = lone pair; R = R' = CH_3
e, Z = O; R = R' = CH_3
f, Z = S; R = R' = CH_3



2a, R = CH_3; R' = H
b, R = R' = CH_3

Oxidation of **1a** and **1d** with *m*-chloroperbenzoic acid (MCPA) in cold acetone gave oxides **1b** and **1e**, respectively. Interestingly, attempted oxidation of **1a** with 30% hydrogen peroxide gave a lower yield of **1b** than had been obtained with MCPA. Similarly, sulfurization of **1a** and **1d** in boiling toluene afforded sulfides **1c** and **1f** as expected. The yields in all cases were only moderate to good, however, presumably because of the steric hindrance around the phosphorus atom.

That hindrance at C(4) is also present is supported by the observation that oximation of **1a** required boiling in alcohol for several hours to give an oxime tentatively identified as **3**. A ^{31}P NMR signal was recorded at -4.37 ppm from a solution (in Me_2SO-d_6), and one tentatively concludes that **3** has an equatorial C_6H_5-P bond.

No ^{31}P NMR signal was detected downfield from the standard in the solution of **3** as would be expected if oxidation had occurred at phosphorus. Oxidation at phosphorus in *P*-alkyl-4-phosphorinanones during oximation had been noted previously.[1o] Poor solubility in organic solvents precluded a useful ^1H or ^{13}C NMR analysis of **3**.

(1) (a) S. D. Venkataramu, K. D. Berlin, S. E. Ealick, J. R. Baker, S. Nichols, and D. van der Helm, *Phosphorus Sulfur*, **7**, 133 (1979); (b) G. D. Macdonell, Ph.D. Dissertation, Oklahoma State University, 1978; (c) S. D. Venkataramu, G. D. Macdonell, W. R. Purdum, M. El-Deek, and K. D. Berlin, *Chem. Rev.*, **77**, 121 (1977); (d) S. I. Featherman and L. D. Quin, *J. Am. Chem. Soc.*, **97**, 4349 (1975); (e) J. J. Breen, S. O. Lee, and L. D. Quin, *J. Org. Chem.*, **40**, 2245 (1975); (f) I. N. Azerbaev, B. M. Butin, and Y. Borjakov, *J. Gen. Chem. USSR (Engl. Transl.)*, **45**, 1696 (1975); (g) S. I. Featherman, S. O. Lee, and L. D. Quin, *J. Org. Chem.*, **39**, 2899 (1974); (h) I. D. Blackburne, A. R. Katritzky, D. M. Read, R. Bodalski, and K. Pietrusiewicz, *J. Chem. Soc., Perkin Trans. 2*, 1155 (1974); (i) T. E. Snider, D. L. Morris, K. C. Srivastava, and K. D. Berlin, *Org. Synth.*, **53**, 98 (1977); (j) S. I. Featherman and L. D. Quin, *Tetrahedron Lett.*, 1955 (1973); (k) L. D. Quin and J. H. Somers, *J. Org. Chem.*, **37**, 1217 (1972); (l) A. T. McPhail, J. J. Breen, and L. D. Quin, *J. Am. Chem. Soc.*, **93**, 2574 (1971); (m) D. M. Hellwege and K. D. Berlin, *Top. Phosphorus Chem.*, **6**, 1 (1969). (n) H. E. Shook, Jr., and L. D. Quin, *J. Am. Chem. Soc.*, **89**, 1841 (1967); (o) M. D. Martz and L. D. Quin, *J. Org. Chem.* **34**, 3195 (1969); (p) R. P. Welcher and N. E. Day, *ibid.*, **27**, 1824 (1962).

(2) (a) F. Asinger, A. Saus, and E. Michel, *Monatsh. Chem.*, **99**, 1695 (1968); (b) G. Markl, D. E. Fischer, and H. O. Olbrich, *Tetrahedron Lett.*, 645 (1970); (c) J. B. Rampal and K. D. Berlin, unpublished results.

(3) J. B. Rampal, G. D. Macdonell, K. D. Berlin, J. P. Edasery, A. Rahman, D. van der Helm, and K. M. Pietrusiewicz, *J. Org. Chem.*, previous paper in this issue.

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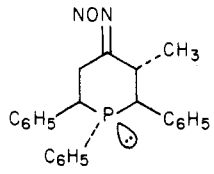

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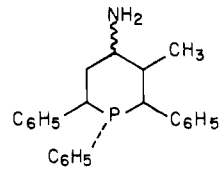

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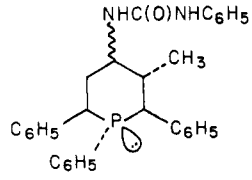
In Me_2SO-d_6, a signal was observed at δ 0.9 for the methyl protons ($^3J_{HH}$ = 6 Hz). The remaining spectrum was very complex because of signal overlap and P–H coupling.

Reduction of oxime **3** with excess $LiAlH_4$ in dry THF gave a gum from which pure amine **4** could not be obtained despite a variety of purification techniques applied to do so. However, a solution of crude **4** in absolute ethanol was warmed on a steam bath and was then treated with phenyl isocyanate. After 10 min, the solution was cooled and the crystalline urea derivative **5** was obtained in good yield.



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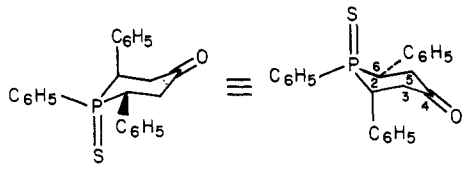

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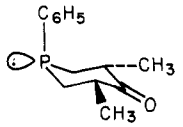
Amino groups substituted on saturated phosphorinane systems are apparently rare as none were uncovered in a literature search. Acetone-d_6 proved the best solvent for **5**, but the ^{1}H NMR spectrum was again complex because of severe overlap of signals and P–H coupling. In fact, the spectrum appeared to have sets of signals indicating two compounds presumably due to epimers at C(4). Two ^{31}P signals at −5.5 and −6.4 ppm (2.8:1) support our contention that the geometry at phosphorus was not changed appreciably. Unfortunately all attempts to separate the mixture failed.

^{1}H NMR Analysis

In view of the NMR analysis and X-ray diffraction study reported on the phosphine sulfide **6** in the previous paper,[3] it was possible to make useful correlations of shift data with structure for members of **1**. Conformational and structural analyses of highly substituted phorphorinanones have heretofore been sparsely reported with a few exceptions.[1c-h,j,p,5] Dienones **2a**[6] and **2b**[7] and bis(hydroxymethyl)phenylphosphine in dry, boiling pyridine produced only **1a** and **1d**, respectively. Long periods of heating **1a** in pyridine did not cause a change in the structure as the starting material could be recovered unchanged. Thus, we concluded that **1a** is the thermodynamic isomer under the conditions employed.

^{1}H NMR data in Table II demonstrate that **1a–c** had one signal each for the methyl protons in the range of δ 0.97–1.05 and broad multiplets for the remaining ring protons at δ 2.70–4.10. It has been noted that 3,5-dimethyl-1-phenyl-4-phosphorinanone had signals at δ 0.98 and 1.08, although it was not clear which assignment was for **7** and which was for **8**.[1h] That both methyl groups were



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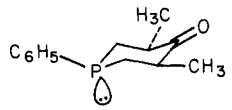

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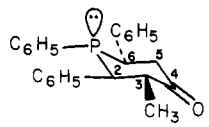
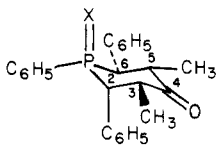
in equatorial positions seems reasonable from the accompanying equilibration studies.[1h] In our dimethyl-substituted systems **1d–f**, two signals were observed at δ 0.95 and 1.45 (**1d**), 1.00 and 1.65 (**1e**), and 1.10 and 1.65 (**1f**). It seems untenable that such a downfield shift for the one signal results from protons on an axial methyl group (an isomer of **7** or **8** with an equatorial and axial methyl group reportedly gave a signal at δ 1.24[1h]). Consequently, the signals at δ 1.45 (**1d**), 1.65 (**1e**), and 1.65 (**1f**) appear to be defended best for protons on the methyl group at C(3) as shown in conformers **1d′–f′**. The deshielding for the

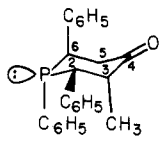


1a′, X = lone pair
b′, X = O
c′, X = S

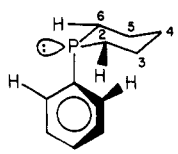


1d′, X = lone pair
e′, X = O
f′, X = S

CH_3–C(3) proton signal apparently arises from the gauche, axial phenyl group at C(2). In view of the very similar $^3J_{HCCH_3}$ couplings (6 or 7 Hz) in the spectra of **1a′–f′** (the $^3J_{HCCH_3}$ in **7** or **8** and related systems with equatorial CH_3 was 6–6.5 Hz[1h]), we tentatively suggest that all methyl groups are in equatorial positions in the major conformer present in solution in all of our examples. This situation avoids two separate interactions of the 1,3 type which would obtain if a conformer such as **1a″** were to be con-



1a″



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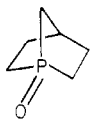
sidered. Quin has pointed out[1d] that an axial P–C_6H_5 bond in phosphorinane **9** causes the phenyl group to be displaced from the ring-to-phosphorus bond to relieve interactions of the ortho hydrogens and equatorial H(2) and H(6) protons. One might well expect severe interactions between the ortho hydrogens of the P–C_6H_5 and the C_6H_5–C(2) groups attached by an equatorial bond in **1a″**. This is also supported by an examination of a Courtauld model of **1a″**. Extreme crowding in the latter appeared to force all three phenyl groups into slightly irregular arrangements rather than permit H···H interactions as described. The situation was worse in a model with three C–C_6H_5 equatorial bonds.

Rather limited solubility and severe overlapping of signals prevented a useful ^{1}H NMR study of **1b′** but a series of experiments was feasible with **1c′**. Treatment of **1c′** in dioxane with D_2O and $NaOCH_3$ gave the 3,5,5-tri-

(5) (a) J. B. Lambert and S. I. Featherman, *Chem. Rev.*, **75**, 611 (1975); (b) D. E. C. Corbridge, "The Structural Chemistry of Phosphorus", Elsevier, Amsterdam, 1974.
(6) (a) K. Ramalingam, K. D. Berlin, R. A. Loghry, D. van der Helm, and N. Satyamurthy, *J. Org. Chem.*, **44**, 477 (1979); (b) G. Harries and G. H. Muller, *Ber. Dtsch. Chem. Ges.*, **35**, 966 (1902).
(7) P. Yates, N. Yoda, W. Brown, and B. Mann, *J. Am. Chem. Soc.*, **80**, 202 (1958).

deuterated derivative. The ^1H NMR spectrum of the latter showed a doublet at δ 4.08 ($^2J_{PH}$ = 5.5 Hz) which we have assigned to an *axially positioned* H(2). Irradiation of ^{31}P at 59 004 Hz upfield caused the doublet to collapse to a singlet, confirming that the coupling was to phosphorus. Irradiation at δ 1.02 (^1H resonance of the methyl group) showed only a slight change in the signal at δ 4.08 which suggested perhaps some *virtual coupling* was present but substantiated that the signal at δ 4.08 was *not* that of H(3).

The deuterated analogue of **1c′** also showed a doublet at δ 3.68 ($^2J_{PH}$ = 6.0 Hz) which collapsed to a singlet when ^{31}P was irradiated at 59 004 Hz upfield. We assigned the signal at δ 3.68 to H(6) which we believe is attached to C(6) by an *axial* bond. Moreover, H(6) should be coupled to H(5) (multiplet centered at δ 2.72–3.18) and should disappear from the ^1H NMR spectrum of the deuterated analogue which was observed. The signal pattern for $H(5)_a$ was *not* disturbed by irradiation at δ 1.02 (protons for the methyl group) but collapsed to a broadened doublet when irradiation occurred for ^{31}P at 60 001 Hz upfield. We surmise that, fortuitously, trans-diaxial $^3J_{H(5)_aH(6)_a}$ and geminal $^2J_{H(5)_aH(5)_e}$ were nearly identical in size (ca. 10 Hz) and larger than $^2J_{PH}$. It is well-known that, in general, $^2J_{PH} > {}^3J_{PH}$ in simple *P*-oxides and *P*-sulfides[8] and in some cyclic *P*-oxides such as **10**.[9] In view of $^2J_{HH}$ = 10 Hz, we

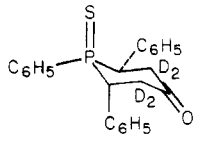


10, $^2J_{PH}$ = 9.4 Hz; $^3J_{PH}$ = 28 Hz

conclude that the C_6H_5–C(6) bond is quite probably equatorial in **1c′** since the vicinal proton coupling between $H(6)_a$ and $H(5)_a$ is of the correct magnitude. Moreover, the geminal coupling is also *not* unreasonable for $^2J_{H(5)_aH(5)_e}$. The signal for $H(5)_e$ at approximately δ 4.06 was obscured partially by overlap with the signals for H(2) and H(3). Upon deuteration of **1c′**, the signal at δ 4.06 was lost, confirming that the $H(5)_e$ proton resides on the carbon α to the C=O group. Irradiation of ^{31}P at 60 001 Hz upfield caused the signal at δ 4.06 to simplify only since residual geminal and vicinal H···H couplings were present along with partial overlap with signals for H(2) and H(3) as stated previously.

Deuteration of **1c′** caused the loss of the signal at δ 3.86 (multiplet) assigned to $H(3)_a$. Irradiation at δ 1.02 (protons for the methyl group) caused near collapse of the multiplet at 3.86 to a broadened singlet, but the signal pattern for $H(6)_a$ was near enough to overlap. When irradiation was effected at δ 3.86, the signal for the methyl protons [CH_3–$C(3)_a$] collapsed to a singlet.

As a reference compound, **6** was deuterated at C(3) and C(5) to give **11**; the ^1H NMR spectrum showed a doublet



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at δ 3.84 ($^2J_{PH(6)_a}$ = 20 Hz) and at δ 4.22 ($^2J_{PH(2)_e}$ = 6.5 Hz). The extremely large coupling between phosphorus and $H(6)_a$ is not easily understood, and we found no adequate model in the literature for comparison. Upon radiation of the ^{31}P signal upfield at 59 851 Hz, both signals became singlets at δ 3.86 and 4.23, respectively, confirming that the protons were on carbons α to the P=S group. The difference in $^2J_{PH(2)}$ is evidence for the H(2) and H(6) atoms to be attached to carbon by axial and equatorial bonds, respectively. In contrast, $^2J_{PCH(2)}$ and $^2J_{PCH(6)}$ values of the deuterated analogue of **1c′** were nearly identical (5.5 vs. 6.0 Hz), and C(2)–H(2) and C(6)–H(6) are both axial bonds.

Hence, these above data, in our opinion, strongly support the structure **1c′**. The ^{13}C NMR spectral analysis to be discussed later was complicated by overlapping of signals and P–C couplings but also was supportive. A calculation of the PCH bond angles in **6** revealed values of near 104° from the X-ray diffraction data.[3] Thus, the $^2J_{PH}$ couplings of 20 and 6.5 Hz are some of the first recorded for which the angle was known, at least in the solid state of the phosphorinanone.

Again in the 3,5-dimethyl-substituted family **1e′–f′**, the sulfur member **1f′** proved to have the best solubility properties (although of only moderate solubility) and ^1H NMR resonance pattern for analysis. A slightly broadened signal at δ 4.28 collapsed to a doublet ($^3J_{H(2)_eH(3)_a}$ = 6.0 Hz) when ^{31}P was irradiated at 59 965 Hz upfield and was assigned to $H(2)_e$. Similarly, the signal at δ 3.74 for $H(6)_a$ collapsed to a doublet ($^3J_{H(6)_aH(5)_a}$ = 13 Hz) centered at δ 3.73 upon irradiation of ^{31}P. This coupling value is certainly in accord with a trans, vicinal (axial) H(6)–C–C–H(5) coupling. These data, of course, are consistent with the C–CH_3 bonds being *equatorial* along with the C(6)–C_6H_5 bond and are also supportive of the C(2)–C_6H_5 bond as being *axial*.

Irradiation at δ 4.08 (the multiplet signal was centered at approximately δ 4.20) in a sample of **1f′** caused the doublet at δ 1.10 [C(5)–CH_3] to collapse to a singlet. Thus, the ^1H signal for H(5) is near δ 4.20. The corresponding signal for C(3)–CH_3 in **1c′** occurred at δ 1.02. When irradiation was effected at δ 3.49 (multiplet centered at about δ 3.44), the signal for C(3)–CH_3 collapsed to a singlet. Thus H(3) has a signal near δ 3.44.

Taken on the whole, these data support the structure of **1f′**, and we feel that the *P*-oxide **1e′** has the same structure. As can be seen from Table II, the ^1H NMR patterns for **1e′** were more complex but parallel those for **1f′** as those of **1b′** parallel those of the sulfide **1c′**.

^{31}P NMR Analysis

In Table II, the ^{31}P NMR data revealed one signal for **1a′–f′**. On the basis of the lone ^{31}P signals as well the ^1H and ^{13}C NMR analyses, we conclude that **1a′–f′** are highly biased systems in $DCCl_3$. In Table II it is clear that the extreme difference in ^{31}P NMR signals for **1a′** and **1d′** reflects significant environmental differences around phosphorus. It is our contention that these data support our configurational assignments at P, C(2), and C(6) in both of these phosphines. A similar situation can be detected when the ^{31}P signal for **1c′** is compared with that for **1f′**. The difference between **1b′** and **1e′** is real but less in magnitude.

^{13}C NMR Analysis

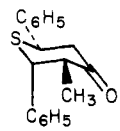
Analysis of the ^{13}C spectra of **1a′–f′** proved interesting and instructive to a degree. Because of limited solubilities as well as the P–C coupling which resulted in partial overlapping of signals, it was not possible to make unequivocal assignments of all the carbon resonances in each system. Unfortunately, these parameters also prevented,

(8) (a) J. B. Hendrickson, B. L. Maddox, J. J. Sim, and H. D. Kaesz, *Tetrahedron*, 26, 449 (1964); (b) M. J. Gallagher, *Aust. J. Chem.*, 21, 1197 (1968).

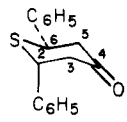
(9) R. B. Wetzel and G. L. Kenyon, *J. Am. Chem. Soc.*, 94, 9230 (1972).

for the most part, performance of useful T_1 measurements to verify ^{13}C signals.[10] Table III contains a listing of the carbon chemical shifts for **1a'-f'** and **6** (for comparison purposes) with some assignments along with $^1J_{PC}$, $^2J_{PC}$, and $^3J_{PC}$ values.

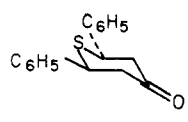
In view of the complexity of the ^{13}C spectra taken at 25.2 Hz, the discussion will be initiated with the spectra of **1c'** and **6** since the best data were available for these molecules and **6** has been examined by X-ray techniques.[3] Moreover, the data serve as a guide by which comparisons could be made with similar data from **1a',b',d'-f'**. Although ring carbons with axial C_6H_5–C bonds in cyclohexanes appear to be less deshielded than the ring carbon attached to equatorial C_6H_5–C bonds,[11] steric effects around the P atom in our systems require a different diagnosis as will be shown. We have assumed that a carbon adjacent to a carbon atom with an axial C_6H_5–C group is more shielded than the corresponding carbon adjacent to an equatorial C_6H_5–C group (as in **6**), a situation which has been observed in methylcyclohexanes.[12] Although no analogous phosphorinanones could be found in the literature, *r*-2, *trans*-6-diphenyl-*cis*-3-methyl-4-thianone (**12**) has been



12



13



14

examined by X-ray diffraction and ^{13}C NMR analysis.[13] In **12**, the equatorial C–CH_3 bond was on the same side of the ring as the axial C_6H_5–C bond, which suggested the situation persisted because under the reaction conditions (which we assume favor the formation of the kinetic product) a system with vicinal C–CH_3 and C–C_6H_5 groups with *equatorial bonds* may experience severe nonbonded interactions. Unfortunately, ^{13}C NMR analysis of **12** was somewhat tentative with respect to ring carbon assignments, but the signal for C(2) in the trans isomer **13** was at 43.78 ppm and for the cis isomer **14** at 48.15 ppm. Certainly **13** undergoes ring reversal at room temperature, so the shift for C(2) is an average value. We propose that this shift is primarily due to a γ_a-shielding effect of the axial C_6H_5–C(2) bond on C(6).[14] However, in **1a'-c'** the nearly identical $^2J_{PCH(2)}$ and $^2J_{PCH(6)}$ values preclude, in our opinion, such a *trans arrangement* of the two phenyl groups at C(2) and C(6). Moreover, the known trans arrangement of the phenyl groups at C(2) and C(6) in **6** is supported by the large difference in $^2J_{PCH}$ couplings in the deuterated analogue as discussed previously.

In **1c'**, a study of the relaxation properties of the ring carbons demonstrated that C(5) had the shortest T_1 value (Table III) in $DCCl_3$ as expected since C(5) has the most protons directly attached of any ring carbon. Thus, the doublet centered at 44.51 ppm ($^2J_{PC}$ = 2.29 Hz) could be assigned with reasonable confidence in **1c'**. The signal for C(5) in **6** occurred at 44.95 ppm ($^2J_{PC}$ = 2.89 Hz). Analogy with the ^{13}C signals at 48.15 ppm for C(2) in **14** tentatively allowed C(2) in **1c'** to be assigned the signal at 52.98 ppm ($^1J_{PC}$ = 43.48 Hz), the additional downfield shift being the result of the deshielding effect of the methyl group at C(3). The remarkable upfield shift for the doublet for C(6) [with equatorial C_6H_5–C(6)] in **6** at 38.00 ppm ($^1J_{PC}$ = 44.85 Hz) is a γ_a effect and is not result of the presence **1c'** which has C(6) at lower field [45.84 ppm ($^1J_{PC}$ = 44.05 Hz)]. In **6**, C(3) had a signal at 43.02 ppm ($^2J_{PC}$ = 2.95 Hz) and in **1c'** at 46.21 ppm ($^2J_{PC}$ = 1.36 Hz), the latter being deshielded by the methyl group. To be sure, the $^2J_{PC(3,5)}$ couplings were smaller in **1c'** than might be expected on the basis of other works[1e,g,j,15] which indicate a usual $^2J_{PC}$ value of 5–8 Hz in 1-alkyl(or aryl)-4-phosphorinanone 1-sulfides with an *axial* P=S arrangement. We take the smaller values of 2.29 Hz [C(5)] and 1.36 Hz [C(3)] in **1c'** and 2.89 Hz [C(5)] and 2.95 Hz [C(3)] in **6** as supportive of our previous supposition that severe nonbonded interactions are operative because of the three phenyl groups at positions 1, 2, and 6. Quin has noted that as the substituent on phosphorus increases in size in a series of phosphorinane sulfides there is a decrease in $^2J_{PC(3,5)}$.[1g] Analysis of the crystal structure of **6** has shown that the C_6H_5 groups at phosphorus and at C(2) are nearly parallel to the plane through P, S, C(4), and O while the C_6H_5 group bonded to C(6) (equatorial C_6H_5–C) makes an angle of 65° with this plane. Consequently, there is surely increased restricted rotation and crowding at phosphorus in **1c'** compared to that in **6**, and this very probably distorts the periplanar arrangement of the C_6H_5–P and C(2)–C(3) bonds which in turn likely alters $^2J_{PC}$. Although we tentatively suggest that increased crowding around phosphorus in phosphorinane systems reduces $^2J_{PC(3,5)}$, no systematic study has been recorded in this family of carbon–phosphorus heterocycles. It is noteworthy that the ring P–C bonds in solid **6**[3] were 1.853 Å [P–C(2); C(2) bonded to an axial C_6H_5 group] and 1.840 Å while 1-phenyl-4-phosphorinanone 1-sulfide had values of 1.818 and 1.814 Å.[1a] This also supports our contention for crowding around phosphorus in **1a-f** as well as in **6**.

In the simple phosphine **1a'** (Table III), we deduce that C(2) (equatorial C_6H_5–C bond) has a signal at 52.71 ppm ($^1J_{PC}$ = 13.88 Hz) while the signal for C(6) (equatorial C_6H_5–C bond) occurs at 44.86 ppm ($^1J_{PC}$ = 12.44 Hz). In addition, C(3) and C(5) have resonances at 49.79 ppm ($^2J_{PC}$ = 14.04 Hz) and 48.67 ppm ($^2J_{PC}$ = 14.60 Hz), respectively. Again, C(2) has *two* β-deshielding groups (equatorial C_6H_5–P and C(3)–CH_3) while C(6) has only one β-deshielding group (equatorial C_6H_5–P). Indeed, the same arguments can be made for **1c'** and, in essence, are the result of the substituents on phosphorus as well as on carbon. The dimethyl-substituted phosphine **1d'** has clean signals at 52.47 ppm ($^1J_{PC}$ = 12.75 Hz) and 47.57 ppm ($^1J_{PC}$ = 13.93 Hz) which we tentatively assign to C(2) (axial C_6H_5–C) and C(6), respectively, in analogy with the other systems discussed and because of the γ_a effect on C(6) which causes it to be shifted upfield.[14] In the sulfide **1f'**, C(2) and C(6) exhibit signals at 52.59 ppm ($^1J_{PC}$ = 44.84 Hz) and 47.26 ppm ($^1J_{PC}$ = 45.48 Hz), respectively, again for the reasons already cited. Regarding C(3) and C(5) in phosphine **1d'**, the resonances are at 52.58 ppm ($^2J_{PC}$ = 7.38 Hz) and 44.84 ppm ($^2J_{PC}$ = 13.24 Hz) but cannot be assigned unequivocally. Although one might assume C(3),

(10) Measurements of T_1 values for carbon atoms in degassed samples of **1a-c** were performed by using the FIRFT method for standard techniques. See D. Canet, G. C. Levy, and I. R. Peat, *J. Magn. Reson.*, 18, 199 (1975). See also K. Ramarajan, Ph.D. Dissertation, Oklahoma State University, May 1980.

(11) The ^{13}C signal for C(1) in *cis*-1-phenyl-4-*tert*-butylcyclohexane (axial C–C_6H_5 bond) and *trans*-1-phenyl-4-*tert*-butylcyclohexane (equatorial C–C_6H_5 bond) was at 36.4 and 44.6 ppm, respectively. We thank Dr. E. Eliel for these data prior to publication. See Eusebio Juaristi, Ph.D. Dissertation, University of North Carolina, 1977.

(12) (a) D. K. Dalling and D. M. Grant, *J. Am. Chem. Soc.*, 89, 6612 (1967). (b) For a summary see J. B. Stothers, "Carbon-13 NMR Spectroscopy", Academic Press, New York, 1972, Chapter 11.

(13) K. Ramalingam, K. D. Berlin, N. Satyamurthy, and R. Sivakumar, *J. Org. Chem.*, 44, 471 (1979).

(14) E. L. Eliel and K. M. Pietrusiewicz, *Top. Carbon-13 NMR Spectrosc.*, 3, 171 (1979).

(15) (a) G. D. Macdonell, K. D. Berlin, J. R. Baker, S. E. Ealick, D. van der Helm, and K. L. Marsi, *J. Am. Chem. Soc.*, 100, 4535 (1978).

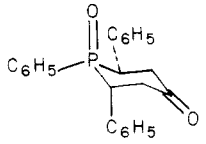
Table I. Physical Properties of the Phosphorinanones and Derivatives

compd	mp, °C	yield, %	analyses (calcd), % C	H	P	N
1a′	210–211	39.70	80.34 (80.45)	6.42 (6.35)	9.00 (8.66)	
1b′	289–291	52.6	76.71 (77.00)	6.12 (6.15)	8.00 (8.29)	
1c′[a,b]	246–247	78	74.30 (73.85)	6.07 (5.90)	7.79 (7.95)	
1d′	145–146	62.6	80.50 (80.64)	6.86 (6.72)	8.27 (8.33)	
1e′	296–297	74.3	76.91 (77.32)	6.39 (6.44)	7.91 (7.99)	
1f′[c]	255–256	46.8				
3	244–245	81.7	77.10 (77.21)	6.67 (6.43)	8.41 (8.31)	3.65 (3.75)
5	212–215	78			6.46 (6.48)	5.66 (5.86)

[a] Since the elemental analysis proved somewhat difficult, peak matching of M^+ was performed; m/e (M^+) 390.1207, found m/e 390.1207. [b] Sulfur analysis, found 7.89, calcd 8.81. [c] Mass spectral peak matching for M^+ gave m/e (M^+) 404.1363, found m/e 404.1360.

being adjacent to the axial C(2)–C_6H_5 bond, might be more shielded than C(5),[12] comparison of the ^{13}C spectrum of **1d′** with that of *r*-2,*trans*-6-diphenyl-*cis*-3-methyl-1-phenyl-4-phosphorinanone shows C(3) in the latter to absorb at 52.14 ppm ($^2J_{PC}$ = 7.44 Hz) and C(5) at 44.31 ppm ($^2J_{PC}$ = 13.16 Hz).[16] Thus C(3) in **1d′** must experience a deshielding effect. In sulfide **1f′**, C(3) and C(5) have signals tentatively assigned at 51.21 ppm ($^2J_{PC}$ = 1.97 Hz) and 42.28 ppm ($^2J_{PC}$ = 0.0 Hz). Similar trends are observed for oxide **1e′**.

Because of the similarities in shieldings as well as J_{PC} couplings, our assignments for ^{13}C resonances in **1a′,b′,d′–f′** were much more difficult and only partially successful. By analogy with the shifts and couplings for ^{13}C signals in **1c′**, it was observed that the resonances for the oxide **1b′** followed a similar pattern. The shift for C(5) in **1b′** was at the highest field of the ring carbons at 42.61 ppm ($^2J_{PC}$ 3.64 Hz) while C(3) was partially obscured at 46.48 ppm by overlap with one line of the doublet centered at 46.87 ppm ($^1J_{PC}$ = 56.49 Hz) for C(2). The position of C(6) at 45.28 ppm ($^1J_{PC}$ = 60.39 Hz) was at higher field than that for C(2) because the latter had the equatorial CH_3–C(3) bond. We noted that the ^{13}C NMR resonances[3] for oxide **1b′** followed only part of the pattern observed with **15**.



15

The low-field signal at 46.43 ppm ($^1J_{PC}$ = 56.66 Hz) for C(2) in **15** parallels that [46.87 ppm ($^1J_{PC}$ = 56.49 Hz)] found in **1b′**. The small deshielding effect on C(2) by the CH_3 group in **1b′** may result from a difference in crowding around the phosphorus in the oxides. This also is similar to the signal pattern for C(2) at 52.50 ppm ($^1J_{PC}$ = 61.05 Hz) in **1e′**.

On the whole, these ^{13}C NMR data appear to support the structure **1a′–f′**. The examples are the first recorded for highly P- and C-substituted phosphorinanones. Work is continuing on unraveling the relationship of angular deformation in phosphorinanes with J_{PH} and J_{PC} couplings for structure diagnosis.

Experimental Section

General Data. Melting points were determined with a Thomas-Hoover capillary apparatus and are uncorrected. The ^1H, ^{13}C, and ^{31}P NMR data were obtained on a Varian XL-100 NMR spectrometer equipped with a Nicolet TT-100 PFT accessory operating at 100.1 MHz with tetramethylsilane (Me_4Si) as internal standard for ^1H NMR, at 25.2 MHz (with Me_4Si) for ^{13}C, and at 40.5 MHz (with 85% H_3PO_4) for ^{31}P. The ^{13}C and ^{31}P NMR spectra were obtained by operating in the FT mode utilizing broad-band proton decoupling. Infrared spectral data were obtained on a Beckman IR-5A unit. Mass spectral data were collected on a CEC Model 21-110B HR mass spectrometer. Elemental analyses were performed by Galbraith Laboratories.

Starting Materials. Reagents (commercially available) were purified before use where necessary. Solvents were reagent grade and were dried over sodium where required. 2-Methyl-1,5-diphenyl-1,4-pentadien-3-one (**2a**)[6] and bis(hydroxymethyl)-phenylphosphine[4] were prepared by known methods.

Preparation of 1,2,6-Triphenyl-4-phosphorinanone 1-Sulfide (6). Compound **6** was prepared by a known method; mp 240–242 °C (lit.[3] mp 240–242 °C).

2,4-Dimethyl-1,5-diphenyl-1,4-pentadien-3-one (2b). This compound (mp 128 °C) was obtained by a known method:[7,17] ^1H NMR ($DCCl_3$) δ 2.20 (s, 3 H, CH_3), 7.15–7.25 (m, 2 H, vinylic H), 7.25–7.45 (m, 5 H, Ar H).

Synthesis of 3-Methyl-1,2,6-triphenyl-4-phosphorinanone (1a). Bis(hydroxymethyl)phenylphosphine[4] (10.3 g, 0.0606 mol) and 15 g (0.06 mol) of 2-methyl-1,5-diphenyl-1,4-pentadien-3-one (**2a**)[6b] were dissolved in dry pyridine (25 mL) under N_2. The reaction mixture was gently boiled for 20 h. What appeared to be paraformaldehyde was observed to form on the walls of the flask. After the reaction mixture was cooled, pyridine was removed on a rotary evaporator, and a solid mass formed. This solid was dissolved in a minimum of CH_3CN, and the solution was filtered. The filtrate, on cooling, gave white needles which were recrystallized (CH_3CN) to give 8.6 g (39.7%) of **1a′**: mp 210–211 °C; mass spectrum, m/e 358 (M^+). Spectral data and physical properties are given in Tables I–III.

Condensation of the ketone **2a′** with phenylphosphine (Pressure Chemical Co.) gave a lower yield (~27%) of **1a** even after the mixture was stirred at room temperature for 48 h. The yield of **1a** was not improved with heating.

The oxime derivative of ketone **1a′** was prepared as follows. Ketone **1a′** (1.0 g, 0.00279 mol) was dissolved in absolute C_2H_5OH (50 mL). Then H_2NOH·HCl (0.4 g, 0.0057 mol) and pyridine (1 mL) were added, and the solution was heated for 3 h. This solution was evaporated to dryness, and the solid obtained was repeatedly recrystallized (absolute C_2H_5OH) to give 0.85 g (81.7%) of white crystalline **3**, mp 244–245 °C.

Synthesis of *N*-Phenyl-*N′*-(3-methyl-1,2,6-triphenyl)-4-phosphorinylurea. Oxime **3** (1.0 g, 0.00249 mol) was dissolved in dry THF (50 mL), and the solution was added to a stirred suspension of $LiAlH_4$ (0.94 g, 0.0249 mol) in THF (10 mL) at 0 °C. This reaction mixture was then boiled for 4 h followed by stirring at room temperature overnight. Excess hydride was carefully destroyed by dropwise addition of 10 mL of 4:1 CH_3C-O_2CH_3–H_2O. The solid in the resulting mixture were filtered off and washed with portions of THF (3 × 15 mL). Upon evaporation of the combined organic fractions, a viscous oil remained. This crude amine was taken up in absolute C_2H_5OH (5 mL), and the resulting solution was warmed (10 min) on a steam bath. To this was added dropwise phenyl isocyanate (0.385 g, 0.0032 mol), and the resulting solution was warmed (10 min). Upon cooling, the

(16) Unpublished results of N. Satyamurthy, J. B. Rampal, and K. D. Berlin.

(17) (a) C. W. Shoppe and B. J. A. Cooke, *J. Chem. Soc., Perkin Trans.* 1, 1026 (1973); (b) F. R. Japp and W. Maitland, *J. Chem. Soc.*, 85, 1473 (1904).

Table II. IR and ^1H and ^{31}P NMR Data

compd	IR, cm^{-1} [a]	^1H NMR [b,c]	^{31}P NMR [d]
1a′	1700, 1440, 1320, 1220, 1075, 830, 795, 745, 700	0.97 (d, 3 H, CH_3, J = 6 Hz), 2.70–3.60 (m, 5 H, H(2), H(3), H(5), H(6)), 6.85–8.40 (m, 5 H, Ar H)	−0.92
1b′	1165, 850, 785, 695	1.05 (d, 3 H, CH_3, J = 6 Hz), 3.00–4.08 (m, 5 H, H(2), H(3), H(5), H(6)), 6.70–7.50 (m, 15 H, Ar H)	32.30
1c′	1710, 1450, 1230, 1085, 795, 750, 700	1.02 (d, 3 H, CH_3, J = 6 Hz), 2.72–4.10 (m, 5 H, H(2), H(3), H(5), H(6)), 6.70–7.50 (m, 15 H, Ar H)	53.70
1d′	1700, 1450, 1070, 960, 795, 750, 700	0.95 (d, 3 H, 5-CH_3, J = 6 Hz), 1.45 (d, 3 H, 3-CH_3, J = 6 Hz), 2.80–3.90 (m, 4 H, H(2), H(3), H(5), H(6)), 6.95–7.45 (m, 15 H, Ar H)	−21.34
1e′	1710, 1440, 1180, 965, 855, 795, 750, 700	1.00 (d, 3 H, 5-CH_3, J = 7 Hz), 1.65 (d, 3 H, 3-CH_3, J = 7 Hz), 3.00–4.20 (m, 4 H, H(2), H(3), H(5), H(6)), 7.00–7.70 (m, 15 H, Ar H)	31.67
1f′	1710, 1440, 1190, 1110, 965, 850, 800, 750, 700	1.10 (d, 3 H, 5-CH_3, J = 6 Hz), 1.65 (d, 3 H, 3-CH_3, J = 7 Hz), 3.20–4.40 (m, 4 H, H(2), H(3), H(5), H(6)), 7.00–7.80 (m, 15 H, Ar H)	44.85
3	3280, 1665, 1440, 1040 950, 770, 750, 700	0.90 (d, 3 H, CH_3, J = 6 Hz), 3.00–3.80 (m, 5 H, H(2), H(3), H(5), H(6)), 7.00–7.40 (m, 15 H, Ar H)	−4.37
5	3325, 1639, 1440, 1230, 745, 695,	0.83 (d, 3 H, CH_3, J = 6 Hz), 2.50–3.60 (m, 6 H, H(2), H(3), H(4), H(5), H(6)), 4.50 (m, 2 H, NH), 6.60–7.60 (m, 20 H, Ar H)	−5.49 (2.80), −6.40 (1.00)

[a] KBr pellets. [b] In parts per million from Me_4Si. [c] In $DCCl_3$; except 3 (Me_2SO-d_6) and 5 (acetone-d_6). [d] In parts per million from 85% H_3PO_4.

Table III. ^{13}C NMR Data in $DCCl_3$

compd	shift, [b] ppm (J_{PC}, Hz)				
	C(2,6)	C(3,5)	C(4)	3-CH_3	5-CH_3
1a′	52.71 (13.88), 44.86 (12.44)	49.79 (14.04), 48.67 (14.60)	209.65 (2.15)	13.13 (5.47)	
1b′	46.87 (56.49), 45.28 (60.39)	46.48 (0.0), 42.61 (3.64)	209.19 (7.10)	13.36 (8.82)	
1c′	52.98 (43.48), 45.84 (44.05)	46.21 (1.36), 44.51 (2.29)[a]	207.84 (1.40)	12.72 (10.20)	
1d′	52.47 (12.75), 47.57 (13.93)	52.58 (7.38), 44.84 (13.24)	213.69	13.81 (9.67)	13.43 (2.07)
1e′	52.50 (61.05), 46.92 (61.89)	41.41 (3.63), 52.95 (4.38)	212.00	14.46 (2.88)	13.34 (9.57)
1f′	52.59 (44.84), 47.26 (45.48)	42.28 (0.0), 51.21 (1.97)	211.90 (3.71)	13.88 (2.23)	13.92 (10.27)
6	51.53 (41.83), 38.00 (44.85)	43.02 (2.95), 44.95 (2.89)	207.10 (5.45)		

[a] T_1 values of 0.801 ± 0.21 and 0.767 ± 0.07 s for each of the doublets measured as described in the literature.[10] [b] From $(CH_3)_4Si$.

solution deposited a crystalline product which was recrystallized (C_2H_5OH/H_2O) to give 5: 1.0 g (78%); mp 212–215 °C. Mass spectral analysis gave m/e 478 (M^+). Other data are given in Tables I and II.

A solution of 5 in acetone-d_6 showed two ^{31}P NMR signals at −5.5 and −6.4 ppm (2.8:1) which suggest the presence of two isomers. All attempts at fractional crystallization from several solvents and chromatography over acid-washed alumina did not prove fruitful in separating the isomers.

3-Methyl-1,2,6-triphenyl-4-phosphorinanone 1-Oxide (1b′). Ketone **1a** (0.2 g, 0.000 55 mol) was dissolved in acetone (25 mL). This solution was cooled in ice, and then was added, dropwise with stirring, 0.12 g (0.0007 mol) of *m*-chloroperbenzoic acid (MCPA) in 5 mL of dry ether. The reaction mixture was stirred for another 0.5 h. Evaporation of the solvent left a solid mass which was washed with ether (3 × 10 mL) to remove excess MCPA. The residue was recrystallized (absolute C_2H_5OH) to give 0.11 g (52.6%) of **1b′**, mp 289–291 °C. Spectral data are given in Tables I–III.

Oxidation of ketophosphine **1a′** with 30% H_2O_2 (Mallinckrodt, analytical reagent) gave **1b′** in a lower yield (46%).

3-Methyl-1,2,6-triphenyl-4-phosphorinanone 1-Sulfide (1c′). Ketone **1a** (0.2 g, 0.000 55 mol) and sulfur (0.02 g, 0.000 62 mol) dissolved in toluene (25 mL) were placed in a 50-mL flask fitted with a condenser and magnetic stirrer. The reaction mixture was gently boiled for 16 h under N_2. The solution was filtered, and evaporation of the solvent gave a solid mass, which was recrystallized (absolute C_2H_5OH) to give 0.17 g (78%) of **1c′**, mp 246–247 °C. Spectral and physical data are given in Tables I–III.

3,5-Dimethyl-1,2,6-triphenyl-4-phosphorinanone (1d′). Bis(hydroxymethyl)phenylphosphine[4] (1.5 g, 0.0088 mol) and 2.25 g (0.0086 mol) of 2,4-dimethyl-1,5-diphenyl-1,4-pentadien-3-one (**2b**)[7,15] were dissolved in pyridine (20 mL). This solution was boiled for 4 h under N_2 on an oil bath. After the reaction mixture was cooled and the solvent evaporated, a residue formed which was taken up in absolute C_2H_5OH (20 mL). The resulting solution was kept overnight in the refrigerator. A white solid formed and was recrystallized (absolute C_2H_5OH) to give 2 g (62.6%) of **1d′**, mp 145–146 °C. Spectral and physical data are given in Tables I–III.

Attempted formation of ketone **1d′** with phenylphosphine and **2b** was unsuccessful under the conditions cited previously.

3,5-Dimethyl-1,2,6-triphenyl-4-phosphorinanone 1-Oxide (1e′). Ketone **1d′** (0.4 g, 0.001 075 mol) was dissolved in acetone (20 mL). To the ice-cooled solution was added, dropwise with stirring, 0.2 g (0.001 16 mol) of MCPA in 5 mL of dry ether. Then this solution was boiled for 4 h, and the remaining procedure was identical with that described previously in the preparation of **1b′**. Recrystallization (absolute C_2H_5OH) of the product gave white crystalline **1e′**: 0.31 g (74.3%); mp 296–297 °C. Spectral and physical data are given in Tables I–III.

3,5-Dimethyl-1,2,6-triphenyl-4-phosphorinanone 1-Sulfide (1f′). Ketone **1d′** (0.5 g, 0.001 34 mol) and sulfur (0.043 g, 0.001 34 mol) were added to toluene (25 mL). The mixture was boiled for 4 h under N_2, and the remaining procedure was like that described previously to prepare **1c′**. A white solid formed and was recrystallized (absolute C_2H_5OH) to give **1f′**: 0.245 g (48.8%); mp 255–256 °C. Spectral and physical data are given in Tables I–III.

1,2,6-Triphenyl-3-methyl-3,5,5-trideuteriophosphorinan-4-one 1-Sulfide. Compound **1c′** (0.0195 g, 0.05 mmol) was dissolved in dry dioxane (3 mL), and to this was added 0.5 mL of deuterium oxide and sodium methoxide (0.0032 g, 0.6 mmol). The mixture boiled with stirring under N_2 for 24 h. Upon cooling, the mixture was extracted with $HCCl_3$ (3 × 10 mL). The $HCCl_3$ layer was washed with deuterium oxide (1 mL) and then dried (Na_2SO_4). The solvent was evaporated, and a solid mass formed,

which was recrystallized (CH_3OH) to give 0.01 g (61%) of the deuterated analogue of **1c'**: mp 239–240 °C; *m/e* 393.1395 (M^+; calcd 393.1380).

1,2,6-Triphenyl-3,3,5,5-tetradeuteriophosphorinan-4-one 1-Sulfide. Ketone **6** (0.0376 g 0.0001 mol) was dissolved in dry dioxane (3 mL), and to this were added 0.5 mL of deuterium oxide and sodium methoxide (0.0064 g, 0.12 mmol). The mixture was boiled with stirring under N_2 for 24 h. Upon cooling, the mixture was extracted with $HCCl_3$ (3 × 10 mL). The $HCCl_3$ layer was washed with deuterium oxide (1 mL) and dried (Na_2SO_4). The solvent was evaporated to leave a solid mass which was recrystallized (CH_3OH) to give 0.035 g (92.1%) of the deuterated analogue of **6**: mp 239–240 °C; *m/e* 380.1289 (M^+; calcd 380.1301).

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Registry No. **1a'**, 76173-27-8; **1b'**, 76173-28-9; **1c'**, 76173-29-0; **1d'**, 76173-30-3; **1e'**, 76173-31-4; **1f'**, 76173-32-5; **2a**, 14164-67-1; **2b**, 42124-16-3; **3**, 76173-33-6; **5**, 76173-34-7; **6**, 76156-75-7; **11**, 76173-35-8; bis(hydroxymethyl)phenylphosphine, 3127-08-0; phenylphosphine, 638-21-1; **1c'** deuterated derivative, 76190-19-7.

Restricted Rotation in Hydroxyphenyl Ketones and Formaldehydes

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Barriers to rotation about the carbonyl carbon to phenyl carbon bond in phenyl ketones and formaldehydes are determined by a detailed line-shape analysis of the proton magnetic resonances which arise from hydroxyl groups substituted at the 2- and 6-positions of the phenyl ring. Enthalpies of activation for 2,4,6 derivatives of benzaldehyde and acetophenone are determined to be 8.0 and 6.9 kcal/mol, respectively. Although full line-shape analyses were not possible for the 2,6-dihydroxy derivatives of benzaldehyde and acetophenone, activation enthalpies are estimated to have upper limits of 6 kcal/mol. The effects of intermolecular exchange on the hydroxyl resonances are also reported as a function of water concentration. The experimental barriers to internal rotation are then compared with those obtained by using molecular orbital theory at the PRDDO level of approximation. Theoretical barriers are higher than experimental ones by at least 50%, suggesting significant solvent effects on the barriers.

In the absence of exchange the proton magnetic resonance (^1H NMR) spectrum of 2,4,6-trihydroxybenzaldehyde (III) or 2,4,6-trihydroxyacetophenone (IV) should contain three separate hydroxyl peaks. Under standard conditions, however, such peaks are either extremely broad or distinct peaks are not observed at all.[2]

The line broadening is due to the exchange of hydroxyl protons between various magnetic environments and can be slowed by using a dry solvent and/or by lowering the temperature of the sample. The former procedure lowers the rate of intermolecular exchange, while the latter lowers the rates of both intermolecular and intramolecular exchange.[3]

In this work we take advantage of the large chemical shifts associated with hydrogen bonding to study the kinetics of intramolecular exchange in compounds such as III and IV. At low temperature, two widely separated peaks are observed for the *o*-hydroxyls due to their different magnetic environments, one hydrogen-bonded the other not. As expected, an increase in sample temperature broadens and merges the *o*-hydroxyl peaks. Analysis of the exchange-broadened spectra yields rates and activation parameters for the exchange process. In order to gain insight concerning the details of this exchange process, we used approximate MO theory to explore the potential energy surface for intramolecular rearrangements in these and similar compounds.

Methods

2,4,6-Trihydroxybenzaldehyde (Pfaltz and Bauer) and 2,6-dihydroxyacetophenone (Pfaltz and Bauer) were obtained and used without further purification. 2,4,6-Trihydroxyacetophenone (Aldrich) was obtained as a monohydrate. It was dried by heating at 120 °C for 3 days. 2,6-Dihydroxybenzaldehyde was synthesized from 7-hydroxy-4-methylcoumarin (Aldrich) according to the method of Parikh and Thakor.[4]

Solutions of samples in deuterioacetone were placed in precision NMR tubes (Wilmad). NMR spectra were recorded at 60 MHz on a Perkin-Elmer R-12B spectrometer fitted with a variable-temperature probe. Temperature calibration was checked by recording the NMR spectrum of a methanol sample which possesses two signals whose chemical shift difference is temperature dependent.[5]

Rate constants for compounds III and IV were determined by fitting the experimental exchange-broadened spectra with theoretical spectra generated by using the classical two-site exchange theory.[6,7] From the low-temperature spectra the chemical shift difference $\Delta\nu$ between the *o*-hydroxyls of III was found to be very temperature dependent ($d(\Delta\nu)/dT = 0.70$ Hz/K). A linear extrapolation of $\Delta\nu$ was thus used in fitting the exchange-broadened spectra. Generally, the effective relaxation times were obtained from the line width of the *p*-hydroxyl resonance, except at higher temperatures where the *p*-hydroxyl signal was clearly broadened by intermolecular exchange (see

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