C. **Ethyl N-Benzyl-N-(3-hydroxy-2-butyl)-3-aminopropionate (2e).**—A solution of 18.0 g (0.10 mole) of **1e** in 50 ml of ethyl acrylate containing a small amount of polymerization inhibitor was refluxed overnight and stripped *in vacuo*. The residue was taken up in petroleum ether, the insoluble gum was separated and discarded, and the solution was treated with decolorizing carbon. Solvent evaporation furnished 18.6 g of product **2e** (66% yield) of 90% vpc purity. An infrared spectrum was compatible with the desired structure.

D. **Ethyl N-Benzyl-N-(3-chloro-2-butyl)-3-aminopropionate (3e).**—Treatment of **2e** by the general thionyl chloride procedure furnished a 95% yield of product of 90% vpc purity. The crude material was used directly for subsequent cyclization.

E. **1-Benzyl-2-methylazetidine (5e).**—The general cyclization procedure furnished only a 19% yield of product **5e**, bp 106–108° (23 mm).

Anal. Calcd for $C_{11}H_{15}N$: C, 82.0; H, 9.3; N, 8.7. Found: C, 81.9; H, 9.3; N, 8.4.

After the evolution of the desired product ceased, the vacuum was increased to 0.10 mm and the resulting distillate was collected, bp 153° (1.1 mm).

Anal. Calcd for $C_{16}H_{24}ClNO_2$: C, 64.6; H, 8.1; Cl, 11.9; N, 4.7. Found: C, 64.9; H, 8.2; Cl, 12.0; N, 4.7.

This chloride, which proved to be isomeric with starting material **3d**, had an nmr and mass spectrum compatible with the structure of ethyl 3-(N-benzyl-N-3-chlorobutylamino)propionate.

Preparation of 1,1-Di-*n*-pentylazetidinium Iodide (12).—A solution of 7.0 g (0.030 mole) of 3-(N,N-di-*n*-pentyl)aminopropyl chloride and 5.0 g (0.033 mole) of sodium iodide in 50 ml of acetonitrile was refluxed for 16 hr. The solvent was evaporated and the residue was taken up in chloroform and filtered to remove the insoluble, inorganic residue. Evaporation of the chloroform and crystallization of the residue from acetone–ethyl ether furnished 3.1 g of **12**, mp 64–66°.

Anal. Calcd for $C_{13}H_{28}IN$: C, 48.0; H, 8.7; I, 39.0. Found: C, 47.8; H, 8.5; I, 38.8.

Attempted Quaternization of 1-(2-Carbethoxyethyl)azetidine and 1-Benzylazetidine.—Equimolar mixtures of either **5a** or **5b** and *n*-butyl *p*-toluenesulfonate, after standing at room temperature overnight, produced a viscous gum. Vapor phase chromatography of these products showed no **5**; however, nearly all of the *n*-butyl *p*-toluenesulfonate remained unchanged. It was found that as little as 0.1 mole of *n*-butyl *p*-toluenesulfonate per mole of **5a** or **5b** caused a conversion to nonvolatile products with infrared spectra very similar to those of the parent azetidines **5a** or **5b**.

Registry No.—**5a**, 7730-42-9; **7a**, 503-29-7; **6a**, 7730-43-0; **5b**, 7730-44-1; 1-(*p*-toluenesulfonamido)azetidine, 7730-45-2; picrate of **7a**, 7730-46-3; **7b**, 7730-47-4; picrate of **7b**, 7730-36-1; **2c**, 7775-87-3; **5c**, 7042-17-3; **7c**, 7042-16-2; **5d**, 7730-39-4; **5e**, 7730-40-7; **12**, 7730-41-8; **10**, 7730-35-0.

Acknowledgment.—The author wishes to acknowledge the technical assistance of Mr. William C. Perkins, and Dr. O. E. Schupp, for his assistance in the gas chromatography.

Steric Effects in P^{31} Nuclear Magnetic Resonance

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Received October 20, 1966

Several series of esters of the acids of phosphorus in which a bulky tertiary alkyl ester group was replaced successively with an ethyl (or methyl) group were prepared and analyzed by P^{31} nuclear magnetic resonance. For the esters of quadruply connected phosphorus (trialkyl phosphates, thiophosphates, selenophosphates, and dialkyl phosphonates), replacement of the bulky tertiary alkyl ester group by an ethyl or methyl group gave a nearly linear downfield shift. However, in the case of triply connected phosphorus (the trialkyl phosphites), the first replacement of the bulky tertiary alkyl ester group gave a large upfield increase in chemical shift followed by the usual downfield progression. This is interpreted on the basis of the quantum-mechanical theory of P^{31} chemical shifts in terms of fractional-degree bond-angle changes.

As part of a study[2] of *t*-butyl phosphites carried out several years ago, it was noted that the P^{31} nuclear magnetic resonance (nmr) chemical shift did not vary linearly across the substitution series of compounds $P(OC_2H_5)_{3-i}[OC(CH_3)_3]_i$, for i = 0, 1, 2, and 3, as is the case for most mixed-ester systems. As a result, a number of compounds were prepared for an investigation of the effect of bulky alkyl groups on the P^{31} chemical shifts of completely esterified phosphorus-based acids. These data have not been reported until now, pending the elucidation of the theory of P^{31} chemical shifts.[3,4]

Experimental Section

Nmr Spectra.—A Varian HR-60 high-resolution spectrometer using a Model V-4311 fixed-frequency radiofrequency unit operating at 24.288 Mc was used for the P^{31} nmr measurements. Referencing (with positive shifts being upfield) was done by audio side-band modulation, using as external references 85% H_3PO_4 (chemical shift, δ = 0.0 ppm) and triphenyl phosphite, $(C_6H_5O)_3P$ (chemical shift, δ = 126.8 ppm), sealed in 1-mm-o.d. capillary tubes inserted in the sample. Peak positions were reproducible to within ±0.1–0.2 ppm. Unless indicated otherwise, published chemical shifts that were pertinent were redetermined in order to give maximum consistency in the comparisons given here.

Synthesis of Esters.—Tri-*t*-butyl phosphite ($\delta_P = -138.2$ ppm and $\delta_H = 1.34$ ppm, the latter being internally referenced from tetramethylsilane), phosphate ($\delta_P = +13.3$ ppm, $\delta_H = -1.46$ ppm), thiophosphate ($\delta_P = -41.2$ ppm, $\delta_H = -1.53$ ppm), selenophosphate ($\delta_P = -31.1$ ppm, $\delta_H = -1.57$ ppm), and di-*t*-butyl phosphonate ($\delta_P = +3.8$ ppm, $\delta_H = -1.45$ ppm and $J_{H-P} = 678$ cps) were prepared according to the procedures already described.[2] The mixed esters of phosphorous acid were made by analogous procedures from $(RO)_2PCl$ or $(RO)PCl_2$ (where R = CH_3 or C_2H_5) and the branched alcohol in ether as solvent, using triethylamine as the base. The mixed esters of the phosphates, thiophosphates, selenophosphates, and phosphonates were obtained by the oxidation of the corresponding trivalent esters with oxygen, sulfur, or selenium, as were the esters derived from *t*-pentyl or 1,1-dimethylallyl alcohol, acetone cyanohydrin, and neopentyl, *sec*-butyl, or isopropyl alcohol. Of the compounds prepared for this study, the following appear to be new to the literature: $[CH_3(C_2H_5)CHO]_2P(OC_2H_5)$, $\delta_P = -138.4$ ppm; $[CH_3(C_2H_5)CHO]_3P$, $\delta_P = -139.1$; $[(CH_3)_3CCH_2O]P(OC_2H_5)_2$, $\delta_P = -137.2$ ppm; $[(CH_3)_3CCH_2O]_2P(OC_2H_5)$, $\delta_P = -137.2$ ppm; $[(CH_3)_3CO]P(OC_2H_5)_2$, $\delta_P = -134.0$ ppm; $[(CH_3)_3CO]_2P(OC_2H_5)$, $\delta_P = -131.1$ ppm; $[(C_2H_5)(CH_3)_2CO]_3P$, $\delta_P = -138.6$ ppm; $[(CH_2{=}CH)(CH_3)_2CO]P(OC_2H_5)_2$, $\delta_P = -133.9$ ppm; $[(CH_2{=}CH)(CH_3)_2CO]_2P$-

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[1] Hooker Research Center, Niagara Falls, N. Y. 14302.

[2] V. Mark and J. R. Van Wazer, *J. Org. Chem.*, **29**, 1006 (1964).

[3] J. H. Letcher and J. R. Van Wazer, *J. Chem. Phys.*, **44**, 815 (1966). Owing to a clerical error, the values of *f*(3) and *f*(4) on pp 825, 826, and 829 were incorrectly given and should be 0.018 and 0.0067, respectively.

[4] J. H. Letcher and J. R. Van Wazer, *ibid.*, **44**, 2916 (1966).

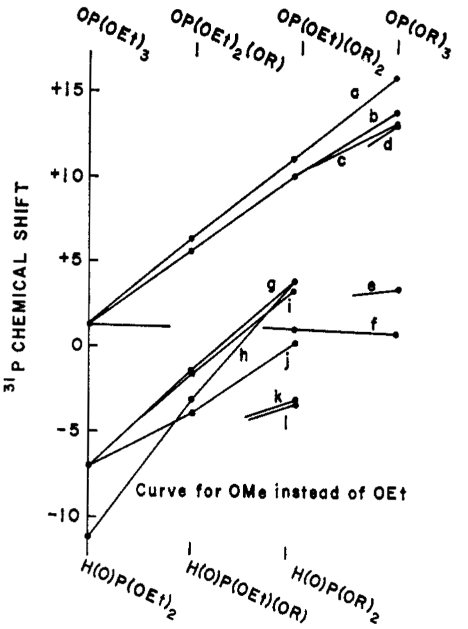

Figure 1.—Variation of P^{31} chemical shift for some ester-substituted ethyl phosphates, $OP(OC_2H_5)_i(OR)_{3-i}$, and phosphonates, $H(O)P(OC_2H_5)_i(OR)_{2-i}$. In the case of the phosphates, R = $(N{\equiv}C)(CH_3)_2C$ for line a; R = $(CH_3)_3C$ for b; R = $(H_2C{=}CH)(CH_3)_2C$ for c; R = $(C_2H_5)(CH_3)_2C$ for d; R = $(CH_3)_2CH$ for e; and R = $(CH_3)_3CCH_2$ for f. In the case of the phosphonates, R = $(CH_3)_3C$ for line g; R = $(H_2C{=}CH)(CH_3)_2C$ for i; R = $(N{\equiv}C)(CH_3)_2C$ for j; R = $(CH_3)_2CH$ for k; and R = $(C_2H_5)(CH_3)_2C$ for l. Line h corresponds to the series of methyl *t*-butyl phosphonates, $H(O)P(OCH_3)_i[OC(CH_3)_3]_{2-i}$.

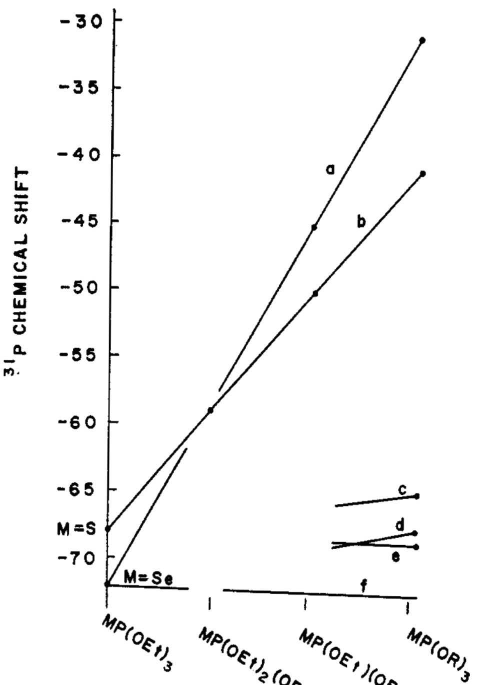

Figure 2.—Variation of P^{31} chemical shifts for some ester-substituted ethyl thiophosphates, $SP(OC_2H_5)_i(OR)_{3-i}$, and selenophosphates, $SeP(OC_2H_5)_i(OR)_{3-i}$. In the case of the thiophosphates, R = $(CH_3)_3C$ for line b; R = $(CH_3)_2CH$ for c; and *R* = $(CH_3)_3CCH_2$ for e. In the case of the selenophosphates, R = $(CH_3)_3C$ for line a; R = $(CH_3)_2CH$ for d; and R = $(CH_3)_3CCH_2$ for f.

(OC_2H_5), $\delta_P = -132.1$ ppm; $[(CH_2{=}CH)(CH_3)_2CO]_3P$, $\delta_P = -140.2$ ppm; $[(CH_3)_2CHO]_2P(OC_2H_5)$, $\delta_P = -137.3$ ppm; $[(CH_3)_2CHO]P(O)(OC_2H_5)_2$, $\delta_P = -137.2$ ppm; $[(N{\equiv}C)(CH_3)_2CO]P(OCH_2CH_3)_2$, $\delta_P = -136.4$ ppm; $[(N{\equiv}C)(CH_3)_2CO]_2P(OCH_2CH_3)$, $\delta_P = -135.6$ ppm; $[(CH_3)_3CO]_2P(O)(OC_2H_5)$, $\delta_P = +10.0$ ppm; $[(CH_3)_3CO]P(O)(OC_2H_5)_2$, $\delta_P = +5.5$ ppm; $[(C_2H_5)(CH_3)_2CO]_3PO$, $\delta_P = +12.9$ ppm; $[(H_2C{=}CH)(CH_3)_2CO]_2P(O)(OC_2H_5)$, $\delta_P = +10.0$ ppm; $[(H_2C{=}CH)(CH_3)_2CO]_3PO$, $\delta_P = +13.1$ ppm; $[(N{\equiv}C)(CH_3)_2CO]P(O)(OC_2H_5)_2$, $\delta_P = +6.3$ ppm; $[(N{\equiv}C)(CH_3)_2CO]_2P(O)(OC_2H_5)$, $\delta_P = +11.0$ ppm; $[(N{\equiv}C)(CH_3)_2CO]_3PO$, $\delta_P = +15.4$ ppm; $[(CH_3)_3CO]P(O)H(OCH_3)$, $\delta_P = -3.2$ ppm, $J_{HP} = 690$ cps; $[(C_2H_5)(CH_3)_2CO]_2P(O)H$, $\delta_P = +3.5$ ppm, $J_{HP} = 680$ cps; $[(H_2C{=}CH)(CH_3)_2CO]P(O)H(OC_2H_5)$, $\delta_P = -1.7$ ppm, $J_{HP} = 685$ cps; $[(H_2C{=}CH)(CH_3)_2CO]_2P(O)H$, $\delta_P = +3.2$ ppm, $J_{HP} = 690$ cps; $[(N{\equiv}C)(CH_3)_2CO]P(O)H(OC_2H_5)$, $\delta_P = -3.9$ ppm, $J_{HP} = 720$ cps; $[(N{\equiv}C)(CH_3)_2CO]_2P(O)H$, $\delta_P = +0.1$ ppm, $J_{HP} = 730$ cps; $[(CH_3)_3CO]P(O)H(OC_2H_5)$, $\delta_P = -1.4$ ppm, $J_{HP} = 680$ cps; $[(CH_3)_3CCH_2O]_3PS$, $\delta_P = -68.5$ ppm; $[(CH_3)_3CO]P(S)(OC_2H_5)_2$, $\delta_P = -59.0$ ppm; $[(CH_3)_3CO]_2P(S)(OC_2H_5)$, $\delta_P = -50.2$ ppm; $[(CH_3)_2CHO]_3PSe$, $\delta_P = -67.9$ ppm; $[(CH_3)_3CCH_2O]_3PSe$, $\delta_P = -72.6$ ppm; and $[(CH_3)_3CO]_2P(Se)(OC_2H_5)$, $\delta_P = -45.2$ ppm.

Compounds, the syntheses of which had already been given in the literature, have the following nmr constants: $[(CH_3)_3CCH_2O]_3P$, $\delta_P = -137.8$ ppm; $[(CH_3)_2CHO]_3P$, $\delta_P = -137.5$ ppm; $[N{\equiv}C(CH_3)_2CO]_3P$, $\delta_P = -143.5$ ppm; $[(CH_3)_3CO]_2P(OCH_3)$, $\delta_P = -130.5$ ppm; $(CH_3O)_3P$, $\delta_P = -139.6$ ppm; $(CH_3CH_2O)_3P$, $\delta_P = -137.1$ ppm; $[(CH_3)_2CHO]_3PO$, $\delta_P = +3.2$ ppm; $[(CH_3)_3CCH_2O]_3PO$, $\delta_P = +0.6$ ppm; $[(CH_3)_3CCH_2O]_2P(O)(OCH_2CH_3)$, $\delta_P = +1.0$ ppm; $(CH_3CH_2O]_3PO$, $\delta_P = +1.2$ ppm; $[(CH_3)_2CHO]_2P(O)H$, $\delta_P = -3.2$ ppm, $J_{HP} = 685$ cps; $(CH_3CH_2O)_2P(O)H$, $\delta_P = -7.1$ ppm, $J_{HP} = 690$ cps; $(CH_3O)_2P(O)H$, $\delta_P = -11.3$ ppm, $J_{HP} = 703$ cps; $(CH_3CH_2O)_3PS$, $\delta_P = -68.0$ ppm; $(CH_3CH_2O)_3PSe$, $\delta_P = -72.1$ ppm.

Results

The chemical shift obtained by replacing a bulky alkyl group by an ethyl (or, in one case, a methyl) group in either trialkyl phosphate or dialkyl phosphonate is shown in Figure 1, in which it should be noted that the shifts vary essentially linearly with increased substitution of the two series of phosphates and four series of phosphonates, where all of the mixed esters were prepared and studied. Similarly, such linear behavior is found for the successive replacement of ethyl by tertiary butyl groups in the thiophosphates and selenophosphates, as shown in Figure 2. The successive replacement of the first two ethyl groups of triethyl phosphite by a bulky alkyl group also results in a practically linear change in chemical shift, as shown by Figure 3. However, in the case where the bulky group is one in which a tertiary carbon is bonded to the bridging oxygen, there is a sudden decrease in chemical shift upon substituting the third bulky alkyl group for an ethyl or methyl group. This would reasonably be attributable to steric crowding.

Theory and Interpretation

According to the quantum-mechanical theory,[4] the difference in chemical shift ($\Delta\delta$) on stepwise substitution of one organic group (R) by another in the $P(OR)_3$, $OP(OR)_3$, $SP(OR)_3$, and similar structures may be related to the resulting change in the P–OR σ-bond polarity, the change in the total occupation number (n_π) of the d_π orbitals of the phosphorus, and the change in the angle (α) between the P–O bond of the RO group and the axis of the unshared pair of electrons of the trialkyl phosphites, the phosphoryl oxygen of the phosphates, the sulfur of the thiophosphates, etc.

On the basis of Coulson's treatment[5] of bond polari-

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[5] C. A. Coulson, "Valence," Corr 2nd ed, Oxford University Press, London, 1963, p 141.

ties, the average amount of charge, h_0, residing in the atomic orbitals of one atom (the P) of a two-atom bond (P–OR) may be estimated.

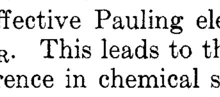
$$h_0 = 1.0 + 0.16(\chi_P - \chi_{OR}) + 0.035(\chi_P - \chi_O)^2 \qquad (1)$$

The polarity of a P–OR σ bond may thus be treated in terms of the effective Pauling electronegativity of the OR group, χ_{OR}. This leads to the following equation[6] for the difference in chemical shift ($\Delta\delta$) in parts per million resulting from stepwise substitution of one OR group by another in structures of C_{3v} symmetry

$$\Delta\delta = C'\cdot\Delta\chi_{OR} - 147k'\Delta n_\pi + A'\Delta\alpha \qquad (2)$$

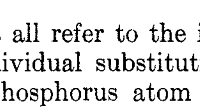
where the Δ terms all refer to the incremental change owing to each individual substitution, with n_π being in electrons per phosphorus atom and α in degrees. The parameter k' has a value of 1 for all quadruply connected phosphorus compounds and $k' = 2.6$ for triply connected phosphorus (*i.e.*, the trialkyl phosphites). For the $P(OR)_i(OR')_{3-i}$ structures, with $i = 0, 1, 2,$ or 3, $C' = -25$, and $A' = 21$; for $OP(OR)_i(OR')_{3-i}$, $C' = 60$ and $A' < 0.1$; for $SP(OR)_i(OR')_{3-i}$, $C' = 50$ and $A' = 1.1$; and for $O(H)P(OR)_i(OR')_{2-i}$, $C' = 40$ and $A' = 2.0$ (with α being measured from the P–H bond axis).[6]

The large value of A' for the $P(OR)_3$ structures as compared to the $OP(OR)_3$ molecules is demonstrated by the work of Verkade and King[7] which shows a $\Delta\delta$ of +6.8 ppm for going from $OP(OC_2H_5)_3$ to



$$\begin{array}{c} \mathrm{OCH_2} \\ \mathrm{OP{-}OCH_2{-}CCH_3} \\ \mathrm{OCH_2} \end{array}$$

compared with a $\Delta\delta$ of +45.6 ppm for going from $P(OC_2H_5)_3$ to



$$\begin{array}{c} \mathrm{OCH_2} \\ \mathrm{P{-}OCH_2{-}CCH_3} \\ \mathrm{OCH_2} \end{array}$$

If the $\Delta\delta$ value of +45.6 ppm were attributed in its entirety to a bond-angle change, eq 2 would show that the OPO angles in the bird-cage structure would be about 1° smaller than in the triethyl phosphite.

The quantum-mechanical calculations, which are approximated by eq 2, show that upon stepwise substitution of an OR by an OR′ group, the chemical shift will change quite linearly if the P–OR and P–OR′ bonds each exhibit a constant level of π-orbital occupation and if the bond angles α for the OR and for the OR′ group are each fixed and do not perturb each other. Since upon substitution of a *t*-butyl or other tertiary carbon group for an ethyl group such a linear change is observed for all but the trialkyl phosphites, we can probably assume that the π character of a given P–OR bond is not appreciably affected by the interchange in the same molecular structure of other P–OR bonds with P–OR′ bonds. This means that the observed nonlinearity in the chemical shifts of the substitution series of phosphites is attributable to small bond-angle perturbations upon substitution. This would not be observed for the structures based on other than triply connected phosphorus atoms because of the relatively small values of the constant A' corresponding to these molecules.

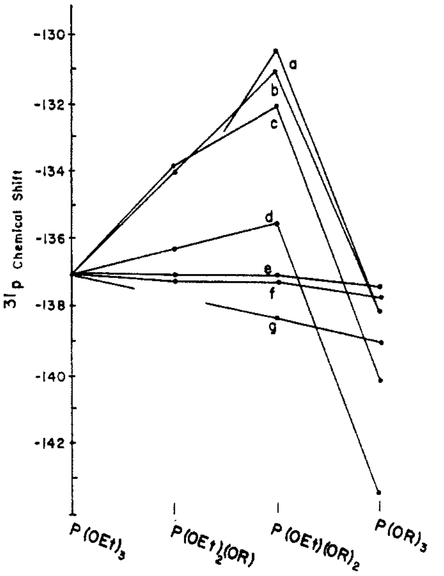


Figure 3.—Variations of P^{31} chemical shifts for some ester-substituted ethyl phosphites, $P(OC_2H_5)_i(OR)_{3-i}$. For line b, $R = (CH_3)_3C$; for c, $R = (CH_2{=}CH)(CH_3)_2C$; for d, $R = N{\equiv}C(CH_3)_2C$; for e, $R = (CH_3)_2CH$; for f, $R = (CH_3)_3CCH_2$; and for g, $R = CH_3(C_2H_5)CH$. Line a corresponds to the methyl *t*-butyl phosphites, $P(OCH_3)_i[OC(CH_3)_3]_{3-i}$.

By a linear extrapolation to $P(OR)_3$ of the straight line joining the $P(OEt)_3$ and $P(OEt)(OR_2)$ shifts in Figure 3, a value of $\Delta\delta$ of −10 ppm is found for this steric effect. From eq 2 it appears that this corresponds to a decrease in α of *ca.* 0.25° for *each* RO bond, owing to pushing out of the (RO)P(OR) angles.

Acknowledgment.—We wish to thank Dr. John H. Letcher for the computer program employed in calculating the values of A' and C' in eq 2.

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[6] These numbers are readily evaluated from the computer program or the graphs given in J. H. Letcher and J. R. Van Wazer, "Topics in Phosphorus Chemistry," Vol. 5, M. Grayson and E. J. Griffith, Ed., Interscience Publishers, Inc., New York, N. Y., Chapters 2 and 3, 1967.

[7] J. G. Verkade and R. W. King, *Inorg. Chem.*, **1**, 948 (1962); also see G. M. Blackburn, J. S. Cohen, and A. R. Todd, *Tetrahedron Letters*, **39**, 2873 (1964).