Preparation and Ultraviolet Spectra of Tri-2-heteroarylphosphine Oxides[1,2]

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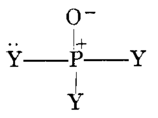
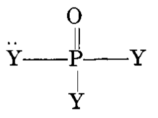
Tri-2-pyrryl- (IVa), tri-2-(1-methylpyrryl)- (IVb), tri-2-thienyl- (V), and tri-2-furylphosphine oxides (VI) have been prepared and characterized. The ultraviolet absorption spectra of IVa, IVb, and VI afford evidence for a moderately strong d_π–p_π resonance interaction between the heteroaromatic ring and the phosphonyl grouping. In the thienyl analog (V), such interaction is either very weak or nonexistent. The interactions observed are significantly stronger than those previously reported in phenyl phosphonyl compounds.

The occurrence of π-bonding involving the overlap of a phosphorus d-orbital with a p-orbital of an adjacent atom is firmly established for a number of tetracovalent phosphonyl compounds (I).[4] This bonding is conventionally expressed in terms of canonical structures such as II and III. The primary instances in which the occurrence of such dp_π bonding has been demonstrated conclusively are those cases in which nonbonding electrons of electronegative atoms ($Y = O, N, S, Cl$, etc.) are donated to the empty phosphorus d-orbital. Ample evidence for such bonding has been provided by chemical, thermochemical, and physical (primarily infrared, Raman, and nuclear quadrupole resonance spectroscopy) studies.[4a,b] However, evidence for the comparable interaction utilizing the donor properties of a π-bond system (Y = aryl and vinyl) has, until recently, been meager. In an extensive study, Jaffé, Freedman, and Doak[5] examined the ultraviolet absorption spectra of triphenylphosphine oxide[5a,b] and a number of phenylphosphonic acids containing chloro[5a] and nitro[5c] substituents and found evidence of only very weak $d\pi$–$p\pi$ bond formation, *i.e.*, bathochromic shifts of <10 mμ relative to the parent arene. A similar weak interaction between a phosphonyl group and a vinyl group has been postulated from comparisons of the infrared spectra of vinyl and allylphosphonates.[6]



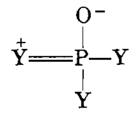
$$\ddot{Y}-\overset{\overset{O^-}{|}}{\underset{\underset{Y}{|}}{P^+}}-Y$$

I



$$\ddot{Y}-\overset{\overset{O}{\|}}{\underset{\underset{Y}{|}}{P}}-Y$$

II

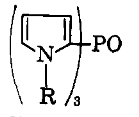


$$\overset{+}{Y}=\overset{\overset{O^-}{|}}{\underset{\underset{Y}{|}}{P}}-Y$$

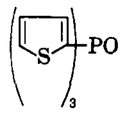
III

Although the evidence cited above indicates only a modest interaction between π-bonds and phosphonyl groups, Craig showed by quantum mechanical calculations that such bonding should be common and important.[7] In 1960, Berlin and Butler[8] suggested the much greater probability of observing such interactions in aryl–phosphonyl structures in which the aryl groups contained powerful electron-donor substituents, in contrast to the compounds studied by Jaffé, *et al.*[5] In order to investigate the possibility of such bonding in favorable cases, we have undertaken the examination of a series of triarylphosphine oxides in which the aryl groups meet the above criterion of donor power. Since the completion of this study, evidence for $d\pi$–$p\pi$ bonding has been obtained from studies of the dipole moments and ultraviolet spectra of substituted triphenylphosphine oxides and phenylphosphonium salts with suitable nuclear substituents (dimethylamino, methoxyl, etc.).[9–11]

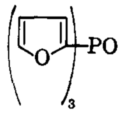
Katritzky[12,13a] has shown that the pyrryl, furyl, and thienyl ring systems are stronger electron donors than unsubstituted phenyl rings. Thus, the present study was directed toward the synthesis of the heteroarylphosphine oxides IV–VI and determination of their absorption spectra.



IVa, R = H
b, R = CH_3



V



VI

Each of the four phosphine oxides was prepared by conventional procedures.[8] Reaction of excess 2-pyrryl- and 2-thienylmagnesium bromides and 2-furyllithium with phosphorus oxychloride led to the formation of IVa, V, and VI in acceptable yields. Mingoia had previously reported the preparation of IVa by a similar reaction, but the product was a poorly characterized amorphous solid and the validity of the preparation is questionable.[14] Burger and Dawson have prepared V by the reaction of 2-thienylmagnesium bro-

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[1] A portion of these results was presented in the form of a preliminary communication: C. E. Griffin and R. A. Polsky, *J. Org. Chem.*, **26**, 4772 (1961).

[2] This study was supported in part by a research grant (CY-5338) from the National Cancer Institute, Public Health Service, and by an American Cancer Society Institutional Grant to the University of Pittsburgh.

[3] (a) Taken in part from the M.S. Thesis of R. P. P., University of Pittsburgh, 1961; (b) National Science Foundation Undergraduate Research Participant, 1961–1962.

[4] For summaries of the evidence regarding such interactions, see (a) R. F. Hudson, "Advances in Inorganic Chemistry and Radiochemistry," Vol. 5, H. J. Emeleus and A. G. Sharpe, Ed., Academic Press Inc., New York, N. Y., 1963, p. 347; (b) J. R. VanWazer, "Phosphorus and Its Compounds," Vol. I, Interscience Publishers, Inc., New York, N. Y., 1958; (c) A. B. Burg, "Inorganic Polymers," Chemical Society Special Publication No. 15, London, 1961, pp. 18–31.

[5] (a) H. H. Jaffé and L. D. Freedman, *J. Am. Chem. Soc.*, **74**, 1069, 2930 (1952); (b) H. H. Jaffé, *J. Chem. Phys.*, **22**, 1430 (1954); (c) L. D. Freedman and G. O. Doak, *J. Am. Chem. Soc.*, **77**, 6221 (1955); (d) L. D. Freedman, *ibid.*, **77**, 6223 (1955); (e) H. H. Jaffé and M. Orchin, "Theory and Applications of Ultraviolet Spectroscopy," John Wiley and Sons, Inc., New York, N. Y., 1962, pp. 497–501.

[6] R. G. Gillis, J. F. Horwood, and G. L. White, *J. Am. Chem. Soc.*, **80**, 2999 (1958).

[7] D. P. Craig, A. Macoll, R. S. Nyholm, L. E. Orgel, and L. E. Sutton, *J. Chem. Soc.*, 332 (1954); D. P. Craig and E. A. Magnusson, *ibid.*, 4895 (1956); see ref. 4a for a discussion of the symmetry of $d\pi$–$p\pi$ bonds in phosphonyl compounds.

[8] K. D. Berlin and G. B. Butler, *Chem. Rev.*, **60**, 243 (1960).

[9] H. Goetz, F. Nerdel, and K. H. Wiechel, *Ann.*, **665**, 1 (1963).

[10] G. P. Schiemenz, IUPAC Symposium on Organo-Phosphorus Compounds, Heidelberg, Germany, May 1964.

[11] The ultraviolet absorption spectra of a number of phosphine oxides and phosphonium salts possessing a range of *para* substituents have been examined recently and provide further and conclusive evidence for $d\pi$–$p\pi$ interactions (H. H. Hsieh, Ph.D. Thesis, University of Pittsburgh, 1964). These results will be published in detail in a separate communication.

[12] A. R. Katritzky, *Quart. Rev.* (London), **13**, 353 (1959).

[13] (a) A. R. Katritzky and A. P. Ambler in "Physical Methods in Heterocyclic Chemistry," Vol. II, A. R. Katritzky, Ed., Academic Press Inc., New York, N. Y., 1963, p. 161; (b) R. F. M. White, ref. 13a, p. 103.

[14] Q. Mingoia, *Gazz. chim. ital.*, **62**, 333 (1932).

TABLE I

ULTRAVIOLET ABSORPTION SPECTRA OF HETEROARYLPHOSPHINE OXIDES AND MODEL STRUCTURES[a]

Compd.	Band A[b]		Band B[b]		
	λ_{max}, mμ	$\epsilon_{max} \times 10^{-3}$	λ_{max}, mμ	$\epsilon_{max} \times 10^{-3}$	$\Delta\lambda$[c]
Pyrrole	183[d]	. . .	211[d]	15.0	. . .
	. . .	. . .	208[e]	7.3	. . .
IVa	. . .	. . .	237.5	11.6	29.5
			240 (sh)	11.4	. . .
N–CH_3 pyrrole	. . .	. . .	213	6.7	. . .
IVb	218	8.4	243	12.9	35
2-CHO pyrrole	252	5.0	289.5	16.6	78.5
2-COOH pyrrole	228	4.6	258	12.6	47
Thiophene[f,g]	. . .	. . .	231	7.1	. . .
V	. . .	. . .	238	33.2	7
			250 (sh)	28.0	. . .
2-Br thiophene	. . .	. . .	235.5	9.1	4.5
2-CN thiophene	. . .	. . .	243	9.3	12
2-CHO thiophene	265	10.5	278.5	6.5	47.5
2-COOH thiophene	249	11.5	268.5	8.2	37.5
Furan[d]	191	*ca.* 5.8[h]	205	6.4	. . .
VI	. . .	. . .	238	33.6	33
2-CHO furan	227	3.0	272	13.2	67
2-COOH furan	214	3.8	242.5	10.7	37.5

[a] All spectra were recorded in ethanol unless otherwise noted. The spectra of IVa, IVb, V, VI, and N-methyl pyrrole were determined in this study. The remaining values were taken from the compilation of Jaffé and Orchin.[5e] [b] Band designations are those of Andrisano and Pappalardo.[18] [c] $\Delta\lambda = \lambda_{max} - \lambda_{max}$ (parent arene). [d] Spectrum recorded in vapor state. [e] R. L. Hinman and S. Theodoropulos, *J. Org. Chem.*, **28**, 3052 (1963). [f] Spectrum recorded in hexane. [g] In the vapor state, a series of three electronic transitions is observed in the 200–260-mμ region; *cf.* G. Milazzo, *Gazz. chim. ital.*, **28**, 835 (1948); W. C. Price and A. D. Walsh, *Proc. Roy. Soc.* (London), **A179**, 201 (1941). In solution, only the band at 231 mμ is observed at $\lambda > 210$ mμ. [h] K. Watanabe and T. Nakayama, *J. Chem. Phys.*, **29**, 48 (1958).

mide and diethyl chlorophosphate.[15] IVb was best prepared by the reaction of 1-methylpyrryllithium with diethyl chlorophosphate; attempted reactions with phosphorus oxychloride led to lower isolated yields of IVb. IVb could also be prepared by direct methylation of the sodium salt of IVa in inert solvents. All products gave satisfactory elemental analyses and their infrared spectra showed the absorptions characteristic of the appropriate 2-substituted heterocycles.[12,13a] The assigned structures were further substantiated by proton magnetic resonance (p.m.r.) studies. The p.m.r. spectrum of IVa in $CDCl_3$ showed multiplets at $\tau = 2.83$, 3.18, and 3.67 p.p.m. assignable by intensities as the N-, 5-, and 3,4-protons. Similarly, IVb showed multiplets ($CDCl_3$) at $\tau = 3.20$ (5-H) and 4.0 p.p.m. (3,4-H) and a singlet at $\tau = 6.17$ p.p.m. (N–CH_3). A suitable model structure, 2-pyrrolecarboxaldehyde, shows multiplets (acetone) at $\tau = 2.7$ (5-H), 3.0 (3-H), and 3.7 p.p.m. (4-H).[13b] The relative integrated intensities for the absorptions of IVa as well as its conversion to IVb by methylation establish the absence of N-phosphorylation during preparation. The p.m.r. spectra of V and VI were similarly in accord with postulated structures.[16]

The ultraviolet absorption data for compounds IV–VI and a number of model pyrroles, thiophenes, and furans are listed in Table I and Figures 1 and 2. Although the parent heterocycles, pyrrole and N-methylpyrrole, show no intense bands with $\lambda > 213$ mμ, IVa and IVb have intense bands at 237.5 and 248 mμ, respectively. It is well established that a substituent acting only inductively on an aromatic ring will not produce a change in the general appearance of the spectrum, although minor bathochromic shifts and slight hyperchromism may be expected.[17] The appearance of a new and intense band in the spectra of IVa and IVb relative to the parent arenes is indicative of a conjugative interaction (dπ–pπ bonding) between the phosphonyl group and the π-electrons of the pyrrole ring. For pyrroles containing substituents in the 2-position capable of conjugation, two intense bands are observed at 228–252 mμ (ϵ 3700–5000) and 263–289.5 mμ (ϵ 12,600–16,600),[17a,18,19] designated as bands A and B, respectively, by Andrisano and Pappalardo.[18] These bands probably represent bathochromic shifts of the 183- and 211-mμ bands of pyrrole. Since only a single intense band is observed in the spectrum of IVa, it is probable that this band is related to band B; in the spectrum of IVb, a second, lower intensity band is observed at 218 mμ and probably corresponds to band A. The hypsochromic shift observed for IVa and IVb relative to the 2-carboxy- and 2-formylpyrroles indicates the degree of dπ–pπ interaction to be much weaker in IVa and IVb. However, the pronounced change in the general appearance of the spectra and the development of intense bands at 237.5 and 248 mμ is strongly indicative of dπ–pπ bondings and indicates that such bonding is much more appreciable in heteroaryl than in phenyl phosphonyl structures.[5]

Similar conclusions may be drawn from the spectrum of tri-2-furylphosphine oxide (VI). The intense band at 238 mμ represents a 33-mμ bathochromic shift of the primary band of the parent arene. For furans possessing 2-substituents capable of conjugation, the same considerations hold as in the case of substituted pyr-

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(15) A. Burger and N. D. Dawson, *J. Org. Chem.*, **16**, 1250 (1951).

(16) A detailed analysis of the four spin systems (ABCX) represented by IVb, V, and VI employing double resonance techniques is in progress. The p.m.r. spectra cited above were determined with a Varian Associates A-60 spectrometer (probe temperature 27°) using tetramethylsilane as an internal standard.

(17) (a) H. H. Jaffé and M. Orchin, ref. 5e, pp. 256–266, 347–353; (b) J. N. Murrell, "The Theory of the Electronic Spectra of Organic Molecules," Methuen and Company, Ltd., London, 1963.

(18) R. Adrisano and G. Pappalardo, *Gazz. chim. ital.*, **85**, 1430 (1955).

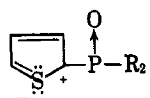
(19) B. Elpern and F. C. Nachod, *J. Am. Chem. Soc.*, **72**, 3379 (1950).

roles, namely the development of bands at 214–227 mμ (ε 2300–5400) and 242–272 mμ (ε 10,700–13,500),[17a,18] designated as bands A and B.[18] As in the cases of IVa and IVb, the 238-mμ band of VI probably corresponds to band B. This assignment is supported by its molar absorptivity (ε 33,600) which is approximately three times that observed for 2-formyl- and 2-carboxyfurans. In this instance, the bathochromic shift relative to the parent arene is almost as large as that produced by a carboxyl group (2-furoic acid, $\Delta\lambda$ = 27.5 mμ).

Conjugative interaction in the case of tri-2-thienylphosphine oxide (V) is less apparent than in the cases cited above. The bathochromic shift (7 mμ) relative to thiophene is only slightly greater than that produced by a typical inductive substituent (2-bromothiophene, $\Delta\lambda$ = 4.5 mμ) and much less than shifts produced by carbonyl substituents ($\Delta\lambda$ = 37.5–47.5 mμ). In this case $d\pi$–$p\pi$ bonding is either nonexistent or of approximately the same order as observed in phenyl phosphonyl structures.[5]

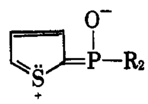
The results cited in this study substantiate the predictions of Craig[7] and Berlin and Butler[8] and support the conclusions drawn by Goetz[9] and Schiemenz[10] regarding $d\pi$–$p\pi$ bonding in aryl phosphonyl structures. A comparison of $\Delta\lambda$-values for IVa, IVb, and VI with $\Delta\lambda$-values for model structures indicates the phosphonyl group to be only slightly less effective than the carboxyl group in conjugation with an electron-donor aromatic system. It is recognized that comparisons of $\Delta\lambda$-values for the prediction of structural changes in molecules of different chemical types, *e.g.*, IVa and 2-formylpyrrole, can only be used in a qualitative sense. Dipolar contributions, possible interactions between the three arene groups,[20] and the possible dependence of inductive effects on the number of substituents on the auxochrome may make appreciable contributions to $\Delta\lambda$-values.

The difference in the behavior of the thienyl compound (V) follows the general behavior observed in the spectra of the five-membered heteroaromatics. It has been observed that the resemblance of the spectra of these aryl systems to benzene derivatives increases in the order furan, pyrrole, thiophene, and that the thienyl ring functions as a relatively weak donor.[12,17a] Additionally, the sulfur atom of V may function as an acceptor through its low-lying d-orbitals[17a]; such d-orbital participation would be expected to give rise to canonical structures such as VII. The contribution of such structures would oppose the donor effects of the sulfur atom (VIII) and would result in a decrease in effective conjugation of the ring with the phosphonyl group and a small bathochromic shift. In the cases of the furyl and pyrryl analogs, only donor activity is possible for the heteroatom. The extreme sensitivity of $d\pi$–$p\pi$ bonding to donor ability in the heteroarylphosphine oxides has been borne out in studies of *para*-substituted phenylphosphine oxides.[9,11]



R=2-thienyl

VII



VIII

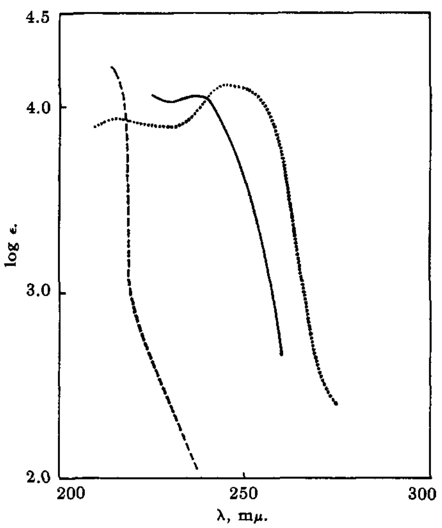


Figure 1.—Absorption spectra of pyrrole (———), tri-2-pyrrylphosphine oxide (IVa) (———), and tri-2-(1-methylpyrryl)phosphine oxide (IVb) (......).

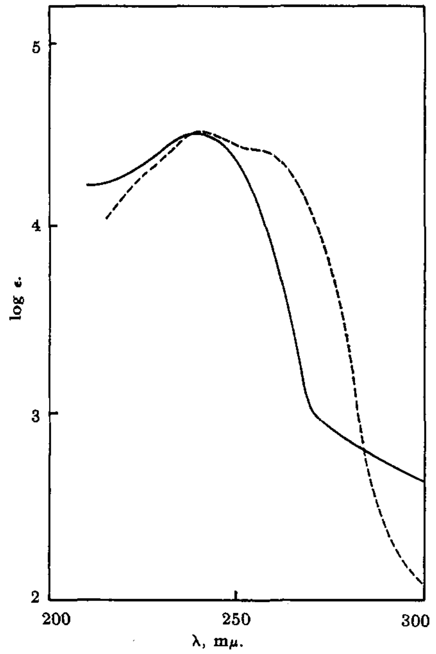


Figure 2.—Absorption spectra of tri-2-furylphosphine oxide (VI) (———) and tri-2-thienylphosphine oxide (V) (———).

On the basis of these studies, no distinction between a ground and an excited state interaction can be drawn. Baliah and Subbarayan studied the ultraviolet absorption spectra of triphenyl-, tri-*p*-tolyl-, and tri-*p*-anisylphosphine oxides in cyclohexane and ethanol solutions and concluded from the lack of solvent shifts that the ground and excited states possessed essentially equal zwitterionic character.[21a] The limited solubilities of IVa and IVb, V, and VI did not allow determination of spectra in nonpolar solvents. Studies of the dipole moments of *p*-dimethylamino- and *p*-methoxyphenyldiphenylphosphine oxides are indicative of a modest ground state $d\pi$–$p\pi$ interaction.[9] However, recent

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[20] It is probable that interactions between the three aryl groups are negligible since it has been shown in triphenylphosphine oxides that each substituted phenyl group makes an essentially independent and additive contribution to the absorption maximum.[11] Similar conclusions have been reached by other investigators from studies of phosphine oxides and phosphines: ref. 5e and H. Schindlbauer, *Monatsch. Chem.*, **94**, 99 (1963).

[21] (a) V. Baliah and P. Subbarayan, *J. Org. Chem.*, **25**, 1833 (1960); (b) M. W. Lister and R. Marson, *Can. J. Chem.*, **42**, 1817 (1964); (c) P. Haake, W. B. Miller, and D. A. Tyssee, *J. Am. Chem. Soc.*, **86**, 3577 (1964).

studies based on diamagnetic susceptibilities[21b] and the dependence of C^{13}–H coupling constants on substituent electronegativities[21c] indicate the phosphoryl bond of trialkylphosphine oxides to be almost totally devoid of semipolar character. If triarylphosphine oxides behave similarly, ground state interactions would appear to be unlikely. A distinction must await more detailed studies.

Experimental[22]

Tri-2-pyrrylphosphine Oxide (IVa).—Pyrrylmagnesium bromide was prepared by the gradual addition of a solution of 33.5 g. of pyrrole (0.5 mole) in 125 ml. of absolute ether to a solution of 0.5 mole of ethylmagnesium bromide in 125 ml. of absolute ether; the solutions were maintained at ice-bath temperatures throughout addition. After addition was completed, the solution was allowed to come to room temperature and was refluxed for 2 hr. A solution of 15.4 g. (0.1 mole) of phosphorus oxychloride in 125 ml. of ether was added to the refluxing Grignard solution; after the addition was completed (1 hr.), the reaction mixture was refluxed for 5.5 hr. and hydrolyzed over a mixture of ice and 1:1 aqueous hydrochloric acid. The ethereal layer was separated rapidly, washed with dilute sodium bicarbonate until neutral, and dried over anhydrous magnesium sulfate. Removal of the ether under reduced pressure gave 10.5 g. (42%) of a colorless solid, m.p. 125–128°; the solid was dissolved in 95% ethanol and precipitated with water until a constant melting point, 136–137°, was obtained.

Anal. Calcd. for $C_{12}H_{12}N_3OP$: C, 58.76; H, 4.93; N, 17.13. Found: C, 58.45, 58.51; H, 5.00, 5.09; N, 17.31, 17.25.

The ultraviolet spectrum of IVa showed maxima at 237.5 mμ (ϵ 11,600) and 240 sh (11,400), and a minimum at 232 (11,100). The infrared spectrum showed bands at the following frequencies (cm.$^{-1}$): 3413 w, 3165 s, 1724 w, 1587 m, 1462 s, 1414 m, 1381 s, 1289 s, 1135 m, 1071 s, 942 m, 883 m, 867 m ($CHCl_3$ solution); and 1255 m, 1189 m, 1092 w, 1055 m, 1041 m, 724 s (CCl_4 solution).

The aqueous solution from the hydrochloric acid hydrolysis contained a suspended black solid (3.6 g.) which was removed by filtration and slurried with 10% aqueous sodium hydroxide. No material was isolated on acidification of the basic extract. The infrared spectrum of the black solid showed the presence of IVa, but none could be isolated by attempted recrystallization of the solid. Hydrolysis of the reaction mixture with 10% hydrochloric acid and with saturated ammonium chloride led to lower isolated yields of IVa.

Tri-2-(1-methylpyrryl)phosphine Oxide (IVb).—An ethereal solution (100 ml.) of 1-methylpyrryllithium (0.25 mole) was prepared according to the procedure of Shirley, *et al.*[23]; after formation of the lithio reagent was completed, the solution was diluted with ether to a volume of 300 ml. and added slowly, with stirring, to a gently refluxing solution of 17.0 g. (0.10 mole) of diethyl chlorophosphate in 300 ml. of absolute ether. After addition was completed, the reaction mixture was refluxed for 3 hr. and hydrolyzed by pouring over ice; the ether layer was separated and the aqueous solution was extracted with ether. The combined ethereal extracts were washed with water, dried over magnesium sulfate, and reduced in volume to give 15 ml. of a brown oil. The aqueous solution was made basic with 10% aqueous sodium hydroxide and extracted with methylene chloride; after drying over magnesium sulfate, the methylene chloride solution extract was reduced in volume to give an additional 3 ml. of brown oil. The combined oils were fractionally distilled to give 5.3 g. (27.6%) of a yellow semisolid material, b.p. 150–170° (0.7 mm.), and a yellow oil, b.p. 122–190° (4.0 mm.). The yellow semisolid was purified by dissolution in ether and precipitation with pentane until a crystalline material of constant melting point, 136–137.5°, was obtained.

Anal. Calcd. for $C_{15}H_{18}N_3OP$: C, 62.71; H, 6.31; N, 14.63. Found: C, 62.85, 62.79; H, 6.25, 6.38; N, 14.59, 14.53.

The ultraviolet spectrum of IVb showed maxima at 218 mμ (ϵ 8430) and 248 (12,900) and a minimum at 227 (8040). The infrared spectrum showed bands at the following frequencies (cm.$^{-1}$): 2445 w, 1706 w, 1672 m, 1639 w, 1543 m, 1513 s, 1453 s, 1408 s, 1397 s, 1359 s, 1292 s, 1170 s, 1142 s, 1107 s, 1087 s, 887 m ($CHCl_3$ solution); and 1217 m, 1182 s, 1054 m, 1004 m (CCl_4 solution).

The infrared spectrum of the yellow oil indicated it to be a complex mixture, possibly containing some IVb and diethyl 2-(1-methylpyrryl)phosphonate; however, attempted isolation of IVb from the oil by recrystallization was unsuccessful. The phosphine oxide could also be prepared, although in lower yields, by the reaction of an excess of 1-methylpyrryllithium with phosphorus oxychloride in ether, hexane, or tetrahydrofuran.

N-Methylation of IVa.—A solution containing 1.2 g. of IVa (0.005 mole) and 0.0165 mole of sodium ethoxide in 75 ml. of absolute ether was refluxed for 2 hr.; a colorless solid was slowly deposited during the course of the reaction. The solid was removed by filtration, washed twice with absolute ether, and dried under vacuum. The solid was suspended in a solution of 2.4 g. of methyl iodide (0.0165 mole) in 100 ml. of dry toluene and the reaction mixture was refluxed for 2 hr. The reaction mixture was extracted with three 10-ml. portions of boiling water; the combined extracts were cooled to 0–5° to give 0.55 g. (40%) of tri-2-(1-methylpyrryl)phosphine oxide (IVb) which was identical in all respects with an authentic sample. All the operations preceding the final extraction were carried out in either a drybox or in apparatus suitably protected against moisture.

IVa could also be converted to IVb in comparable yield by reaction with sodium in xylene followed by methylation with dimethyl sulfate following the general procedure of Corwin and Quattlebaum.[24]

Tri-2-thienylphosphine Oxide (V).—A solution of the Grignard reagent prepared from 36.0 g. (0.225 mole) of 2-bromothiophene and 5.4 g. (0.225 g.-atom) of magnesium turnings in a total volume of 75 ml. of dry ether was treated with a solution of 6.8 g. (0.045 mole) of phosphorus oxychloride in 25 ml. of dry ether. After dropwise addition was completed (20 min)., the reaction mixture was refluxed for 5 hr. and hydrolyzed with a mixture of ice and concentrated hydrochloric acid. After separation of the ethereal layer, the aqueous layer was extracted with ether; the combined ether extracts were concentrated to give a dark solid which was crystallized from aqueous ethanol. Recrystallization from water gave 5.6 g. (42%) of V, which was recrystallized from aqueous ethanol to give a material of constant m.p. 130–130.5° (lit.[15] m.p. 129–130°).

Anal. Calcd. for $C_{12}H_9OPS_3$: C, 48.63; H, 3.06; P, 10.45. Found: C, 48.45; H, 3.09; P, 10.59.

The ultraviolet spectrum of V showed a maximum of 238 mμ (ϵ 33,200) and a shoulder at 250 (28,000). The infrared spectrum showed bands at 1401 m, 1335 w, 1230 m, 1192 s, 1098 m, 1017 s, 858 m, 758 w, 748 w, and 727 s cm.$^{-1}$ ($CHCl_3$ solution).

Attempted formation of V by reaction of 2-thienyllithium[25] and phosphorus oxychloride was less successful; a 24.2% yield of V was isolated.

Tri-2-furylphosphine Oxide (VI).—2-Furyllithium was prepared by the procedure of Ramanathan and Levine.[26] A solution of 38.0 g. of butyllithium[27] (0.475 mole) in hexane diluted with 60 ml. of dry ether was treated at −20° with a solution of 32.0 g. of furan (0.470 mole) in 50 ml. of dry ether. After warming to room temperature, the reaction mixture was refluxed for 4 hr. with constant stirring. The reaction mixture was cooled to 25° and a solution of 18.4 g. (0.12 mole) of phosphorus oxychloride in 80 ml. of dry ether was added dropwise with constant stirring over a period of 50 min.; the exothermic reaction caused refluxing throughout the period of addition. The reaction mixture was refluxed for an additional 3 hr., stirred with an equal volume of dilute aqueous sodium carbonate, filtered to remove insoluble material, and extracted with ether. The ethereal solu-

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[22] Melting points are uncorrected. Microanalyses were performed by Galbraith Microanalytical Laboratories, Knoxville, Tenn. Infrared spectra were recorded on a Perkin-Elmer Model 21 spectrophotometer and ultraviolet spectra were determined as dilute solutions (3–7 × 10^{-5} *M*) in 95% ethanol on a Cary Model 14 spectrophotometer.

[23] D. A. Shirley, B. H. Gross, and P. A. Roussel, *J. Org. Chem.*, **20**, 225 (1955).

[24] A. H. Corwin and W. M. Quattlebaum, Jr., *J. Am. Chem. Soc.*, **58**, 1081 (1936).

[25] R. A. Benkeser and R. B. Currie, *ibid.*, **70**, 1780 (1948).

[26] V. Ramanathan and R. Levine, *J. Org. Chem.*, **27**, 1216 (1962).

[27] The butyllithium as a 14.9% solution in hexane (Foote Mineral Co., Inc.) was transferred by means of a 50-ml. hypodermic syringe and was kept under a nitrogen atmosphere at all times.

tion was separated, washed with water, and evaporated to give a yellow crystalline residue. The residue was recrystallized by dissolution in the minimum amount of boiling water and cooling to 0–5° to give 5.25 g. (18.4%) of VI, m.p. 113.5–114°.

Anal. Calcd. for $C_{12}H_9O_4P$: C, 58.15; H, 3.63; P, 12.49. Found: C, 58.21; H, 3.80; P, 12.36.

The ultraviolet spectrum of VI showed a maximum at 238 mμ (ε 33,600). The infrared spectrum showed bands at the following frequencies (cm.$^{-1}$): 3009 w, 1555 m, 1210 s, 1179 m, 1164 m, 1131 s, 1123 m, 1059 w, 1021 s, 1007 s, 914 s, 905 w, 878 m, 831 w, 792 w, 778 m, 753 s, 722 s (Nujol mull); and 2960 m, 1590 w, 1459 s, 1369 m, 1228 w, 1203 w ($CHCl_3$ solution).

Oxidation of Phosphites and Phosphines *via* Quaternary Phosphonium Salts

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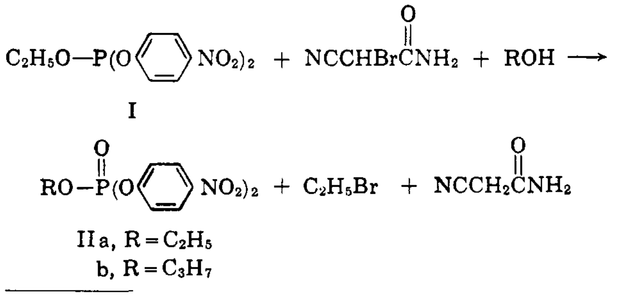
When phosphorylation of *n*-propyl alcohol by means of ethyl di-*p*-nitrophenyl phosphite (I) and monobromocyanoacetamide was tried, *n*-propyl di-*p*-nitrophenyl phosphate (IIa) and, unexpectedly, ethyl di-*p*-nitrophenyl phosphate (IIb) were obtained. The result can be best explained by assuming an initial formation of a quaternary phosphonium salt (IV) as an intermediate, from which the phosphates are formed by elimination of the alkyl bromides. The direction of the reaction may depend on the stability of the alkyl cation eliminated. This hypothesis was confirmed by the formation of triethyl phosphate in a 72% yield from the reaction of triethyl phosphite with monobromocyanoacetamide and benzyl alcohol. In view of this result, several alkyl and aryl phosphites were successfully oxidized by means of monobromocyanoacetamide with either benzyl alcohol or allyl alcohol, as were phosphines. Similarly, some cyclic phosphites, such as ethyl ethylene phosphite and ethyl propylene phosphite, were oxidized and gave the corresponding cyclic phosphates in good yields. The reaction was further extended to oxidation of diethyl phosphite, and diethyl phosphate was obtained in quantitative yield.

The preceding papers[1,2] describe a selective phosphorylation of alcohols and phosphates by means of monobromocyanoacetamide or monobromomalonamide with trialkyl phosphites, forming mixed esters of phosphoric acid and unsymmetrical pyrophosphates.

Further, the methods were successfully applied to the synthesis of some naturally occurring phosphorus derivatives.[3] In those experiments, tribenzyl phosphite was employed since the benzyl group can be readily removed from the resulting phosphates by catalytic hydrogenation after phosphorylation has been performed.

Another phosphite, ethyl di-*p*-nitrophenyl phosphite, was prepared and treated with monobromocyanoacetamide and alcohols in order to determine if it too would be effective in the reactions described above. The ethyl group of the phosphite would be expected to be split off as ethyl bromide in the first stage of the reaction, and the *p*-nitrophenyl group would be readily removed by the subsequent alkaline hydrolysis of the resulting phosphates under mild conditions[4] to yield the expected alkyl dihydrogen phosphates.

When ethyl alcohol was added to a suspension of equimolar amounts of ethyl di-*p*-nitrophenyl phosphite (I) and monobromocyanoacetamide in ether, ethyl di-*p*-nitrophenyl phosphate (IIa) was obtained in a 73% yield as expected (eq. 1).

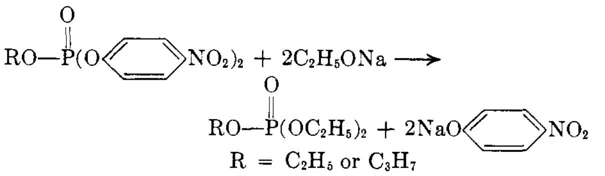


I

(1)

IIa, R = C_2H_5
b, R = C_3H_7

However, when phosphorylation of *n*-propyl alcohol was attempted in the same manner, there was obtained a colorless crystalline compound which could not be purified by recrystallization. When this product (A was allowed to react with sodium ethoxide under the assumption that the *p*-nitrophenyl group might be replaced by the ethyl group according to eq. 2, a liquid with b.p. 107–108° at 15 mm. was obtained. This substance showed two peaks by gas chromatography, one of which was identified as *n*-propyl diethyl phosphate and the other as triethyl phosphate. The ratio of the amounts of *n*-propyl diethyl phosphate and triethyl phosphate was about 2:3. The result shows that the unpurified product (A) consists of *n*-propyl di-*p*-nitrophenyl phosphate and ethyl di-*p*-nitrophenyl phosphate.



(2)

The formation of ethyl di-*p*-nitrophenyl phosphate can be explained by assuming an initial formation of quaternary phosphonium salt III from the phosphite and monobromocyanoacetamide. The intermediate III is then converted to IV by the reaction with an alcohol (eq. 3). The intermediate IV thus formed has two possible paths for decomposition: (1) the formation of *n*-propyl di-*p*-nitrophenyl phosphate by the elimination of ethyl bromide (phosphorylation of *n*-propyl alcohol) and (2) the formation of ethyl di-*p*-nitrophenyl phosphate by the elimination of *n*-propyl bromide (oxidation of ethyl di-*p*-nitrophenyl phosphite) as shown in eq. 4. The direction of the reaction may depend on the stability of the alkyl cation eliminated.

For the purpose of elucidating the proposed mechanism and of oxidizing only the phosphite, benzyl alcohol was employed in the place of *n*-propyl alcohol in the above experiment. When monobromocyano-

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