An Electron Spin Resonance Study of Phosphoranyl Radicals derived from Tetra-alkyl Esters of Phosphorous Phosphoric Anhydride $(RO)_2POP(O)(OR)_2$

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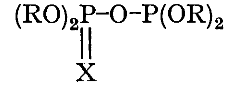
A series of phosphoranyl radicals with the general structure $(RO)_2P(X)O\dot{P}(OR)_3$ (X = O or S) have been studied in solution using e.s.r. spectroscopy. The phosphoranyl radicals were produced by addition of photochemically generated t-butoxyl radicals to $(RO)_2P(X)OP(OR)_2$ (X = O or S) or diethoxyphosphoryloxyl radicals $(EtO)_2P(O)O\cdot$ to $(RO)_3P$ (X = O). The e.s.r. spectra of these phosphoranyl radicals are consistent with a trigonal bipyramidal structure, and the apicophilicity of $(RO)_2P(O)O$ is greater than that of RO. The spectrum of the cyclic radical $\overline{OCH_2CH_2O\dot{P}}(OBu^t)OP(O)(OEt)_2$ shows that apical and equatorial endocyclic alkoxy-substituents undergo rapid exchange. The β-scission of $(EtO)_2Bu^tO\dot{P}OP(O)(OEt)_2$ at −60° to give t-butyl radicals is 40 times slower than that of $(EtO)_3\dot{P}OBu^t$.

THE synthesis and reactions of mixed P^{III}–P^{V} anhydrides of the type (I; X = O) have been studied fairly extensively, mainly by Michalski and his co-workers.[1]



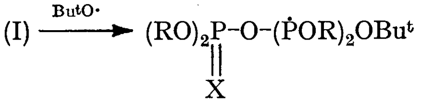
$$(RO)_2\underset{\underset{X}{\|}}{P}\text{-O-}P(OR)_2$$

(I)

The majority of the reactions of (I) which have been examined so far appear to proceed by heterolytic mechanisms. However it seemed to us that homolytic pathways were also feasible in some cases because of the high reactivity of phosphorus(III) compounds towards free radicals [*e.g.* equation (1)].[2]

$$(EtO)_3P + Bu^tO\cdot \longrightarrow (EtO)_3\dot{P}OBu^t \qquad (1)$$

The biochemical significance of phosphorylating agents (*e.g.* ADP and ATP) is of course well known, although the behaviour of the free-radical species which might be generated from such compounds (for example as a result of radiation damage) has received little attention. Phosphoranyl radicals of the type (II), derived from (I; X = O or S) by homolytic addition to the trivalent phosphorus atom, provide useful models for the species which may be produced in the biochemical systems.



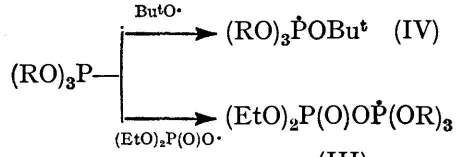
$$(I) \xrightarrow{Bu^tO\cdot} (RO)_2\underset{\underset{X}{\|}}{P}\text{-O-}(\dot{P}OR)_2OBu^t \qquad (2)$$

(II)

RESULTS AND DISCUSSION

Phosphoranyl radicals of the type (II) were generated by high intensity u.v. irradiation of cyclopropane solutions containing di-t-butyl peroxide and (I) whilst the samples were in the cavity of an e.s.r. spectrometer [equation (2)].[3] Similar species (III) were produced by photolysis of diethoxyphosphoryl t-butyl peroxide in the presence of a trialkyl phosphite, when superimposed spectra of (III) and (IV) were detected.

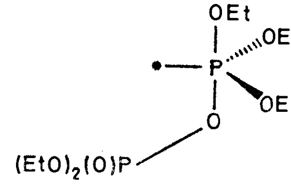
$$(EtO)_2P(O)OOBu^t \xrightarrow{h\nu} (EtO)_2P(O)O\cdot + \cdot OBu^t \quad (3)$$



$$(RO)_3P \begin{cases} \xrightarrow{Bu^tO\cdot} (RO)_3\dot{P}OBu^t & (IV) \\ \xrightarrow[(EtO)_2P(O)O\cdot]{} (EtO)_2P(O)O\dot{P}(OR)_3 & (III) \end{cases} \quad (4)$$

The results are collected in the Table.

All the phosphoranyl radicals listed in the Table exhibit very large hyperfine splittings from the tetravalent phosphorus, consistent with trigonal bipyramidal structures,[3,4,†] as shown for (V).



(V)

The P^{IV} hyperfine splitting for (V) and similar radicals is substantially larger than that[7] for $(EtO)_3\dot{P}OBu^t$ [a(P) 890 G at −70°] and is similar to that[8] for $(EtO)_2(Bu^tO)\dot{P}Cl$ [a(P) 1 034 G at −60°] in which the chlorine substituent occupies an apical site. The relative magnitudes of these coupling constants are in accord[3,8] with the higher electronegativity of $(EtO)_2P(O)O$ compared with RO, and there seems little doubt that the diethoxyphosphoryloxy-group is more apicophilic than an alkoxy-substituent.

When the tetravalent phosphorus atom is contained

[†] For convenience, the unpaired electron is shown centred on phosphorus in an equatorially directed orbital. The precise electronic structures of phosphoranyl radicals, which will depend markedly on the nature of the ligands, have still to be established.[5,6]

[1] (*a*) J. Michalski and T. Modro, *Bull. Acad. polon. Sci., Sér. Sci. chim.*, 1962, **10**, 327; *Roczniki Chem.*, 1964, **38**, 123; (*b*) J. Mikołajczyk, J. Michalski, and A. Zwierzak, *Chem. Comm.*, 1971, 1257; (*c*) J. Michalski and J. Mikołajczyk, *Bull. Acad. polon. Sci., Sér. Sci. chim.*, 1966, **15**, 829; (*d*) J. Mikołajczyk, J. Michalski, and A. Zwierzak, *Z. Naturforsch.*, 1973, **28*b***, 620.

[2] A. G. Davies, D. Griller, and B. P. Roberts, *Angew. Chem. Internat. Edn.*, 1971, **10**, 738.

[3] R. W. Dennis and B. P. Roberts, *J.C.S. Perkin II*, 1975, 140.

[4] P. J. Krusic, W. Mahler, and J. K. Kochi, *J. Amer. Chem. Soc.*, 1972, **94**, 6033.

[5] T. Gillbro and F. Williams, *J. Amer. Chem. Soc.*, 1974, **96**, 5032.

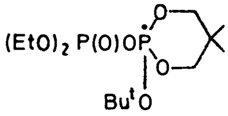
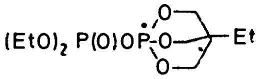
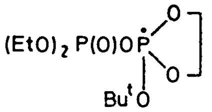
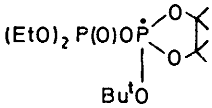
[6] A. Hudson and J. T. Wiffen, *Chem. Phys. Letters*, 1974, **29**, 113.

[7] A. G. Davies, D. Griller, and B. P. Roberts, *J.C.S. Perkin II*, 1972, 993, 2224.

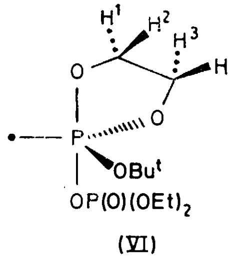
[8] D. Griller and B. P. Roberts, *J.C.S. Perkin II*, 1973, 1339.

in a five-membered ring system, the latter is assumed to bridge apical and equatorial ligand sites.[3] The hyperfine splitting constant of the pentavalent phosphorus is small and exhibits a temperature dependence which is especially marked for the cyclic radicals (VI) and (VII).

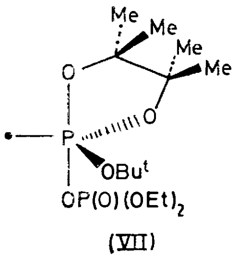
E.s.r. spectroscopic parameters for radicals of the type $(RO)_2P(X)O\dot{P}(OR)_3$ in cyclopropane solvent

Phosphoranyl radical	Source [a]	T/°C	Hyperfine splittings (G) $a(\mathrm{P^{IV}})$ [b]	$a(\mathrm{P^{V}})$	a(H)
$(EtO)_2P(O)O\dot{P}(OEt)_2OBu^t$	A	−80	1 036	6.0 [c]	
$(EtO)_2P(O)O\dot{P}(OEt)_3$	B	−80	1 039	5.7	
$(NeO)_2P(O)O\dot{P}(ONe)_2OBu^t$ [d]	A	−121	1 049	5.6	
	A [e]	−20	1 069	5.4	
	B	−80	1 138	6.1 [f]	
	A	−85	1 030	4.2 [g]	4.2 [g] (1 H)
	A	−100	1 028	4.7 [h]	
$(EtO)_2P(S)O\dot{P}(OEt)_2OBu^t$	A	−121	905		
$(NeO)_2P(S)O\dot{P}(ONe)_2OBu^t$	A	−125	910		
$[(EtO)_2P(O)O]_2\dot{P}(OEt)_2$	C	−60	1 123	5.0 (2 P)	

[a] A = Appropriate $\mathrm{P^{III}}$–$\mathrm{P^{V}}$ anhydride + $Bu^tO\cdot$; B = appropriate trialkyl phosphite + $(EtO)_2P(O)O\cdot$; C = $(EtO)_2P(O)OP(OEt)_2$ + $(EtO)_2P(O)O\cdot$. [b] Calculated using the Breit–Rabi equation: all g factors were 2.003 ± 0.001. [c] $a(\mathrm{P^{V}})$ 5.8 G (−28°). [d] Ne ≡ neopentyl. [e] In toluene solvent. [f] $a(\mathrm{P^{V}})$ 5.2 (−50°), 4.5 G (−10°). [g] $a(\mathrm{P^{V}})$ decreases with increase in temperature and the spectrum shows the effects of ring proton exchange (see text). [h] $a(\mathrm{P^{V}})$ 4.3 (−68°), 3.7 G (−19°).



(VI)

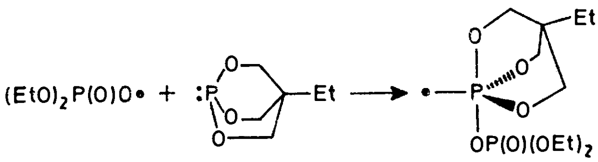


(VII)

The origin of this temperature dependence is uncertain, but a reasonable explanation would appear to be that rotation about the $\mathrm{P^{IV}}$–$\mathrm{OP^{V}}$ bond is restricted, and that the observed coupling constant represents the average over the different rotameric states. It seems likely that the mechanism of spin transmission is predominantly hyperconjugative, with the most stable conformation about the $\mathrm{P^{IV}}$–O bond being that illustrated for (V).

The assignment of the dialkoxyphosphoryloxy-group to an apical ligand site is supported by the magnitude of $a(\mathrm{P^{V}})$ in the radical (VIII), which was generated by addition of $(EtO)_2P(O)O\cdot$ to the caged phosphite (IX), in which the addendum radical must become an apical substituent.

Previous work [3,4] has shown that isotropic splittings from magnetic nuclei attached directly or indirectly to phosphorus(IV) in phosphoranyl radicals are larger if the substituent is apical than if it is equatorial. The value of $a(\mathrm{P^{V}})$ in (VIII) also exhibits temperature dependence (6.1 at −80, 4.5 G at −10°), discounting the possibility that this effect is associated with exchange of the diethoxyphosphoryloxy-group between apical and equatorial sites.



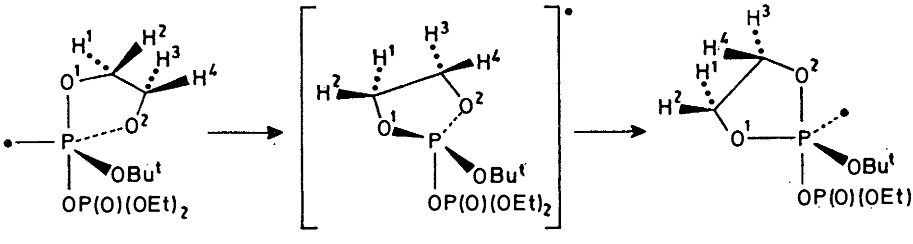
(5)

(IX) (VIII)

It is more difficult to be certain about the relative apicophilicities of $(RO)_2P(S)O$ and RO, but it seems reasonable that the phosphorus-containing ligand will be the more apicophilic. No P^V hyperfine splitting could be resolved for $(RO)_2P(S)O\dot{P}(OR)_2OBu^t$, although the lines were very broad (Γ *ca.* 15 G *).

The e.s.r. spectrum of the radical (VI), which shows hyperfine splitting from ring protons (see Table), exhibits temperature dependent line-shape effects. At −85°, apart from the large P^{IV} hyperfine splitting, the spectrum of (VI) exhibits coupling with the ligand phosphorus [$a(P^V)$ 4.2 G] and one ring proton (probably[3] H^1) [a(H) 4.2 G], giving rise to a 1 : 2 : 1 triplet pattern (Γ 1.7 G). At −16°, four lines of equal amplitude were apparent [$a(P^V)$ 3.0; a(H) 4.2 G (1 H)], but at +28° the e.s.r. spectrum appeared as a 1 : 3 : 3 : 1 quartet (Γ 1.2 G), consistent with coupling to two apparently equivalent ring protons [$a(P^V)$ 2.1; a(H) 2.1 G (2 H)]. The high temperature spectrum results from rapid exchange of H^1 with one of the other ring protons, which we believe[9] to be H^3. Because of the similarity of $a(P^V)$ and a(H), and the temperature dependence of the former, exact rate constants for the exchange process were not obtainable by computer simulation; however the exchange rate constant must be close to 10^8 s^{-1} at 10 °C.

The mechanism of ligand exchange (*P*4 mechanism[3]) shown in equation (6) appears rather attractive at the present state of our knowledge, although permutationally equivalent mechanisms cannot be excluded.



(6)

(VI) (X)

The exocyclic ligands in (VI) differ considerably in electronegativity and probably in apicophilicity (see above), and thus the exchange of these ligands by a similar mechanism is unlikely to be responsible for the observed line-shape effects. The exchange of endocyclic alkoxy-ligands in (VI) is slower than that of exocyclic apical and equatorial alkoxy-substituents in similar phosphoranyl radicals[3] (k_{exch} *ca.* 10^8 s^{-1} at −100°). This is in agreement with our previous observations[3] concerning phosphoranyl radicals with nitrogen and oxygen ligands, and indicates that formation of the transition state (X) is less favourable when the exchanging ligands form part of a five-membered ring system.

Fragmentation of Phosphoranyl Radicals.—Above *ca.* −50°, the e.s.r. spectrum of the t-butyl radical was detected immediately after commencement of photolysis of di-t-butyl peroxide in the presence of the tetra-alkyl esters of phosphorous phosphoric anhydride (I; X = O). The major source of t-butyl radicals in these systems is presumably the β-scission of the primary phosphoranyl radical adduct to give the corresponding pyrophosphate [equation (7)].

$$(RO)_2P(O)O\dot{P}(OR)_2OBu^t \longrightarrow (RO)_2P(O)OP(O)(OR)_2 + Bu^{t}\cdot \quad (7)$$

The spectrum of the primary phosphoranyl radical was detectable at much higher temperatures than was that of $(EtO)_3\dot{P}OBu^t$, providing further evidence[8] for the retarding effect of substituents more electronegative than RO on the rate of β-scission. At −60°, the first-order rate constant for the decay of the e.s.r. signal of $(EtO)_2P(O)O\dot{P}(OEt)_2OBu^t$ when the photolysis was interrupted was 10.2 s^{-1}, whilst the corresponding rate constant[10] for the β-scission $(EtO)_3\dot{P}OBu^t$ at −60° is 420 s^{-1}.

Soon after commencement of photolysis, for all the compounds studied, the spectra of tetra-alkoxyphosphoranyl radicals (XI) became apparent. The origin of these secondary-product radicals is not clear, since it appears unlikely that competing α-scission [equation (8)] of the primary phosphoranyl radical could occur readily under our conditions. The P^{IV}–OP^V bond is probably not weaker than the P^{IV}–OR bond,† and it seems likely that α-scission of $\dot{P}(OR)_4$ is endothermic by *ca.* 80—90 kJ mol^{-1}.[11] The build-up in the intensity of

$$(RO)_2P(X)O\dot{P}(OR)_2OBu^t \xrightarrow{\alpha\text{-scission}} (RO)_2P(X)O\cdot + Bu^tOP(OR)_2 \quad (8)$$

$$Bu^tOP(OR)_2 + Bu^tO\cdot \longrightarrow \underset{\text{(XI)}}{(Bu^tO)_2\dot{P}(OR)_2} \quad (9)$$

the spectrum of (XI) was particularly rapid in experiments involving (I; X = S). Alternative sources of trialkyl phosphite in these systems may be suggested, but speculation is not warranted at present.

EXPERIMENTAL

The techniques for obtaining e.s.r. spectra during continuous u.v. irradiation of samples have been described,[3] as

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* The symbol Γ is used to denote the peak–peak linewidth of the first-derivative e.s.r. spectrum.

† $(EtO)_2P(O)OOBu^t$ can be distilled at 75° without decomposition with cleavage of the O–O bond.[12] If the radical $(EtO)_2P(O)O\cdot$ possessed appreciable resonance stabilisation this would not be possible.

[9] J. W. Cooper and B. P. Roberts, unpublished work.

[10] G. B. Watts, D. Griller, and K. U. Ingold, *J. Amer. Chem. Soc.*, 1972, **94**, 8784.

[11] J. W. Cooper and B. P. Roberts, *J.C.S. Perkin II*, 1976, 808.

[12] G. Sosnovsky and E. H. Zarei, *Synthesis*, 1972, **4**, 202.

have the methods for measurement of radical life-times.[3] Samples were prepared in 4 mm o.d. Suprasil tubes using standard vacuum-line techniques. For reactions involving $(EtO)_2P(O)OOBu^t$ the peroxide (75 µl) was syringed onto the trialkyl phosphite (*ca.* 100 mg) contained in the sample tube and frozen in liquid nitrogen, cyclopropane (*ca.* 600 µl) was then condensed in, and the tube sealed under vacuum in the normal way. Diethyl peroxide and azomethane reacted with (I; X = O or S) before photolysis, even at low temperatures.

Synthesis of Mixed Anhydrides.—Dialkyl hydrogen phosphates were prepared by oxidation of dialkyl phosphites with potassium permanganate.[13] 2-Chloro-4,4,5,5-tetramethyl-1,3,2-dioxaphospholan was prepared by the reaction of pinacol with phosphorus trichloride,[14,15] and dineopentyl chlorophosphite was obtained from neopentyl alcohol and phosphorus trichloride.[16]

The following tetra-alkyl esters of phosphorous phosphoric anhydride were prepared as described by Michalski and his co-workers [1c,d,17] (^{31}P n.m.r. data for neat liquids with chemical shifts relative to 85% H_3PO_4): $(EtO)_2P(O)OP(OEt)_2$, $\delta(P^V)$ +10.3 p.p.m., $\delta(P^{III})$ −128.8 p.p.m. ($^2J_{P-O-P}$ 10.5 Hz); $(EtO)_2P(O)O\overline{P\cdot O\cdot CH_2\cdot CMe_2\cdot CH_2\cdot O}$, $\delta(P^V)$ +10.5 p.p.m., $\delta(P^{III})$ −109.0 p.p.m. ($^2J_{P-O-P}$ 13.5 Hz); $(EtO)_2O\overline{P\cdot O\cdot CH_2\cdot CH_2\cdot O}$, $\delta(P^V)$ +11.0 p.p.m., $\delta(P^{III})$ −123.0 p.p.m. ($^2J_{P-O-P}$ 27.5 Hz).

OO-*Dineopentylphosphorous* OO-*dineopentylphosphoric anhydride* was prepared by dropwise addition of dineopentyl chlorophosphite (12.02 g, 0.05 mol) to a stirred solution of dineopentyl hydrogen phosphate (11.9 g, 0.05 mol) and pyridine (3.95 g, 0.05 mol) in benzene (30 ml), with efficient cooling to maintain the reaction mixture at room temperature. After the addition, the reaction mixture was stirred for 1 h at room temperature, pyridine hydrochloride was removed by filtration and washed with benzene (30 ml), and the solvent was removed to yield *anhydride* (22 g, 99%) (Found: C, 56.3; H, 10.0; P, 13.8. $C_{20}H_{49}O_6P_2$ requires C, 56.6; H, 10.0; P, 14.0%), ^{31}P n.m.r. $\delta(P^V)$ +10.0 p.p.m., $\delta(P^{III})$ −128 p.p.m. ($^2J_{P-O-P}$ 14.5 Hz).

1-*Diethoxyphosphoryloxy*-4,4,5,5-*tetramethyl*-1,3,2-*dioxaphospholanyl* was prepared in a similar way from diethyl hydrogen phosphate (5.95 g, 0.025 mol) and 2-chloro-4,4,5,5-tetramethyl-1,3,2-dioxaphospholan (3.17 g, 0.025 mol). The product was purified by distillation, b.p. 95—98° at 0.01 mmHg, yield 6.0 g (80%) (Found: C, 39.7; H, 7.1; P, 20.4. $C_{10}H_{22}O_6P_2$ requires C, 40.0; H, 7.1; P, 20.7%), ^{31}P n.m.r., $\delta(P^V)$ +10.2 p.p.m., $\delta(P^{III})$ −131.2 p.p.m. ($^2J_{P-O-P}$ 12 Hz).

OO-*Diethylphosphorous* OO-*diethylthiophosphoric anhydride* was similarly prepared from diethyl hydrogen phosphorothioate (8.5 g, 0.05 mol, prepared from diethyl phosphite and sulphur [18]), pyridine (3.9 g, 0.05 mol), and diethyl chlorophosphite (7.8 g, 0.05 mol), b.p. 77—80° at 0.05 mmHg, yield 10.2 g (70%) (Found: C, 33.3; H, 6.8; P, 21.6. $C_8H_{20}O_5PS$ requires C, 33.1; H, 6.9; P, 21.4%), ^{31}P n.m.r., $\delta(P^V)$ −57.0 p.p.m., $\delta(P^{III})$ −129.2 p.p.m., P^V–P^{III} coupling was not resolved.

OO-*Dineopentylphosphorous* OO-*dineopentylthiophosphoric anhydride* was obtained from dineopentyl hydrogen phosphorothioate [18] (6.35 g, 0.025 mol), pyridine (1.97 g, 0.025 mol), and dineopentyl chlorophosphite (5.21 g, 0.025 mol). The product was not distilled, yield 11.2 g (98%) (Found: C, 52.3; H, 9.5; P, 13.5. $C_{20}H_{44}O_5PS$ requires C, 52.5; H, 9.6; P, 13.8%), ^{31}P n.m.r., $\delta(P^V)$ −57.8 p.p.m., $\delta(P^{III})$ −128.3 p.p.m.

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