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The Reactivity of 1,3,2-Diheterophospholans and 1,3,2-Diheterophosphorinanes with a Tetracoordinate Phosphorus Atom

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The present state of research into the reactivities of 1,3,2-diheterophospholans and 1,3,2-diheterophosphorinanes with a tetracoordinate phosphorus atom, containing in five- and six-membered rings, two identical or two different hetero-atoms (O, S, or N) together with the phosphorus atom, is described. Attention is concentrated on the differences between the reactivities of cyclic and acyclic organophosphorus compounds with the same ligand environment of the phosphorus atom. The influence of the introduction of a phosphorus atom into the ring on the reactivity of cyclic compounds is demonstrated. The bibliography includes 189 references.

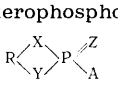
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I. INTRODUCTION

The last decade has been marked by increasing interest in cyclic esters, thioesters, amides, and amidoesters of phosphorus acids in which a tetracoordinate phosphorus atom is incorporated in a five- or six-membered ring—1,3,2-diheterophospholans and 1,3,2-diheterophosphorinanes. The importance of studies on organophosphorus compounds of this type is due primarily to the important role of cyclic phosphates in many biochemical processes. The considerable distortion of the geometry of the phosphorus tetrahedron in cyclic structures, particularly in five-membered structures, and the resulting changes in the nature of the intramolecular electronic interactions predetermine the known specificity of the reactivity of such molecules, differing significantly in many instances from the reactivity of their acyclic analogues. In addition, the rigidity of the cyclic fragment is responsible for certain limitations in the relative positions of the ligands at the phosphorus atom, imposing thereby its imprint on the stereochemical results of processes involving such molecules.

The aim of the present review is to examine and as far as possible describe systematically and survey the results of studies on the reactivities of 1,3,2-diheterophospholans and 1,3,2-diheterophosphorinanes having the general formula



R = 1,2- and 1,3-alkylene or 1,2- or 1,3-arylene; X, Y = O, S, NR'; Z = O, S, Se, NR'; A = = Alk; Ar, AlkO; ArO, AlkS, ArS, NR'_2, OH, SH, H .

Particular attention has been devoted to the deduction of the chemical consequences of the incorporation of a tetracoordinate phosphorus atom in the cyclic skeleton of the molecule; the reactivities of cyclic and acyclic compounds with the same ligand environment of the phosphorus atom have been compared.

Mainly synthetic aspects of the chemistry of 1,3,2-diheterophospholans and 1,3,2-diheterophosphorinanes have been considered in the available review literature[1]. Much attention has been devoted to studies of the stereochemical and conformational relations in these compounds[2-6] as well as the stereochemistry of nucleophilic substitution at the tetrahedral phosphorus atom in five-membered and six-membered phosphates and phosphonates[7].

For this reason, the results of preparative and stereochemical studies are used in the present review only to the extent that they are necessary for the interpretation of the specific features of the reactivities of cyclic phosphorus compounds. Cyclic derivatives of enediol phosphates, to the chemistry of which a recently published review is devoted[8], are not considered.

The only publication of the review type published in 1972, which discusses the characteristics of the reactivity of phosphorus-containing cyclic molecules, embraces the results of studies carried out mainly in the 1960s and deals with various types of phosphorus-containing heterocycles[9]. This review is concerned with experimental data published during the last ten years.

II. NUCLEOPHILIC SUBSTITUTION AT A TETRAHEDRAL PHOSPHORUS ATOM

1. 1,3,2-Diheterophospholans

The results of kinetic, stereochemical, thermochemical, and quantum-chemical studies and the investigation of the composition of the products of the hydrolysis of phosphorus(V) acids made it possible to formulate[10-13] the concept of trigonal-bipyramidal intermediates with the hydroxyphosphorane structure (the "hydroxyphosphorane concept" [12]), which constitutes the basis of the modern interpretation of the mechanism of nucleophilic substitution at a tetrahedral phosphorus atom. The use of the hydroxyphosphorane concept proved to be extremely fruitful in explaining the very marked acceleration (by a factor of millions) of the hydrolysis of five-membered cyclic phosphorus esters compared with their acyclic analogues.

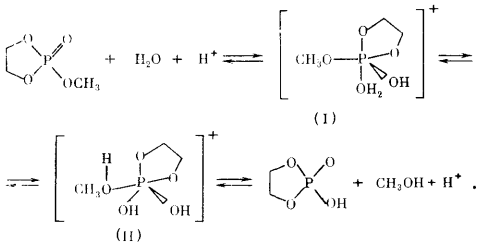
The hydrolysis of ethylene phosphate and its methyl ester takes place with the preferential opening of the five-membered ring; the exocyclic substitution product is formed in a smaller amount. However, both reactions are 10^6–10^8 times faster than the hydrolysis of trimethyl phosphate (see Westheimer's paper[10] and the literature quoted there). 2-Methoxy-2-oxo-1,2-oxaphospholan also hydrolyses very

rapidly and almost exclusively with the rupture of the endocyclic ester linkage, while the cyclic methyl tetramethylenephosphinate undergoes exocyclic hydrolysis at a rate close to that of the reactions of acyclic phosphorus esters.

Whereas the ease of the endocyclic rupture of the bonds on hydrolysis can be explained by the decrease of the strain in the five-membered rings within the framework of the $S_N2(P)$ concerted nucleophilic substitution mechanism[7,10], for the rapid exocyclic elimination of ester groups a satisfactory explanation has been obtained only on the hypothesis of an addition–elimination mechanism. When the nucleophile attacks the phosphorus atom, metastable trigonal-bipyramidal intermediates are formed whose stability and decomposition are regulated by the rules of the hydroxyphosphorane concept[12,14,15].

According to these rules, the addition of a nucleophile to the phosphorus atom leads to the formation of a phosphorane in which the attacking and leaving groups occupy axial (apical) positions. The strained five-membered rings containing the phosphorus atom then occupy one axial (a) and one equatorial (e) positions whereby a decrease of strain is achieved. The disposition of the ligands in the phosphorane obeys the polarity ("apicophilicity" [14]) rule—electron-accepting groups prefer a-positions and electron-donating groups prefer e-positions. Finally, the phosphoranes undergo ligand reorganisation (pseudorotation and permutation isomerisation), which is determined by the strain and apicophilicity rules[16–18].

From these standpoints, the rapid exocyclic hydrolysis of ethylene methyl phosphate in an acid medium can be readily accounted for by the conversion of the intermediate (I) into (II) as a consequence of pseudorotation, which results in the transfer of the leaving methoxy-group to the a-position[10,13]:

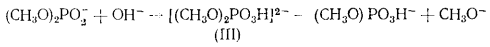


The endocyclic rupture of the bonds in the hydrolysis of the cyclic methyl propylenephosphinate is associated almost exclusively with the high energy barrier to the pseudorotation required to transfer the e-methoxy-group to the a-position; any permutation isomerisation causes the migration of an electron-donating endocyclic carbon atom to the a-position or the transfer of the five-membered ring to the e–e-position.

The slow hydrolysis of cyclic phosphinates is also due to the lack of pathways to the formation of low-energy hydroxyphosphoranes, because, as a result of pseudorotation, either the angle in the ring increases to 120° or one of the ring carbon atoms must substitute the oxygen atom in the a-position. The ring rupture on hydrolysis of ethylene methyl phosphate does not require pseudorotation, while substitution at the phosphorus atom can proceed via an intermediate resembling the transition state in a concerted S_N2 process†.

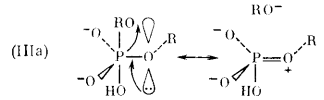
The main "driving force" of the rapid hydrolysis of ethylene phosphates is believed to be[10] ring strain. The heat of hydrolysis of ethylene phosphate exceeds by 20–25 kJ mol^{-1} that for acyclic phosphoric acid esters. On the other hand, the difference between the activation energies for the reactions of cyclic and acyclic phosphates reaches 40–45 kJ mol^{-1}, while the difference between the strain energies is 17–21 kJ mol^{-1} [19]; thus the high stabilisation (to the extent of almost 20–25 kJ mol^{-1}) of the cyclic transition state compared with the acyclic transition state (Fig. 1) cannot be explained solely from the standpoint of the strain in five-membered phosphorus-containing rings but is determined to a significant extent by stereoelectronic control or the orientation of the orbitals of the unshared electron pairs of the ligands[20].

Quantum-chemical calculations[20–22] of the potential energy cross-section of the model system

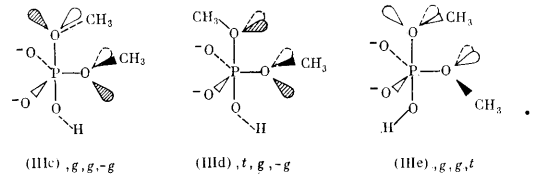


have shown that the reaction proceeds in two stages via intermediate (III) separated by activation barriers from the reactants and the reaction products. The energies of the transition state in both stages depend to a large extent on the conformations of the initial molecule of dimethyl phosphate and the molecule of the intermediate dimethoxyphosphorane and are subject to stereoelectronic control by the e-methoxy-group. This stereoelectronic effect is responsible for the selective weakening of the P–O ester linkages, which are in the *trans*-positions (antiperiplanar positions) relative to the unshared electron pairs of the adjacent oxygen atoms[21].

The nature of the stereoelectronic effect is explained within the framework of the anomeric effect[21,22]: the a-ester linkage P–OCH$_3$ is weakened in the molecule of compound (IIIa) for the *trans*-position (antiperiplanar position) of the orbital of the unshared electron pair of the e-oxygen atom. The e-ester linkage with the oxygen atom having the *trans*-unshared electron pair is stabilised. In other words, the resonance structure (IIIb) makes a significant contribution to the structure of the transition state:



The addition of OH$^-$ to the *gauche*, *gauche*-conformer of dimethyl phosphate leads to the intermediate (IIIc) (g, g, $-g$), while the ester in the *gauche*, *trans*-conformation can form the phosphoranes (IIId) (t, g, $-g$) and (IIIe) (g, g, t).



(IIIc), $g, g, -g$ (IIId), $t, g, -g$ (IIIe), g, g, t

†Strictly speaking it is in principle impossible to draw a boundary between the $S_N2(P)$ and addition–elimination mechanisms in an endocyclic substitution reaction involving the inversion of the configuration at the phosphorus atom. Most probably in such situations we are dealing with the limiting cases of the same mechanism[7].

Calculation showed that the energy of the trigonal-bipyramidal transition state depends on the orientation of the *e*-ester linkage[20-22]. For the two-stage nucleophilic substitution process at the tetrahedral phosphorus atom, in which both stages are partly rate-determining[21], the rotation about the *e*-ester linkage during the reaction is significant. Whereas the *trans*-disposition of the unshared electron pair of the *e*-oxygen atom relative to the P–OH bond being formed is favourable for the attack stage [there is an energy gain of ~17 kJ mol^{-1} in structure (IIIe)], the *trans*-orientation of the unshared electron pair of the *e*-oxygen atom relative to the P–OCH_3 *a*-bond is required for the weakening of the bond between the phosphorus atom and the leaving group [there is an energy gain of ~45 kJ mol^{-1} in structures (IIIc) and (IIId)]. Only on rotation about the *e*-ester linkage in the course of the reaction can the stereoelectronic effect lower the activation barrier in both stages and hence the overall activation barrier. A necessary condition for such "stereoelectronic catalysis" [21] is the formation of intermediate pentacoordinate structures whose lifetime is sufficient for a single rotation.

In cyclic systems of the type of ethylene phosphate, where the favourable *trans*-disposition of the unshared electron pair of the *e*-oxygen and the *a*-ester linkage being ruptured is enforced in the potential hydroxy-phosphorane, the stereoelectronic effect ensures the stabilisation of the five-membered cyclic transition states (~25 kJ mol^{-1}) compared with the acyclic transition states, as shown in Fig.1.[20,21].

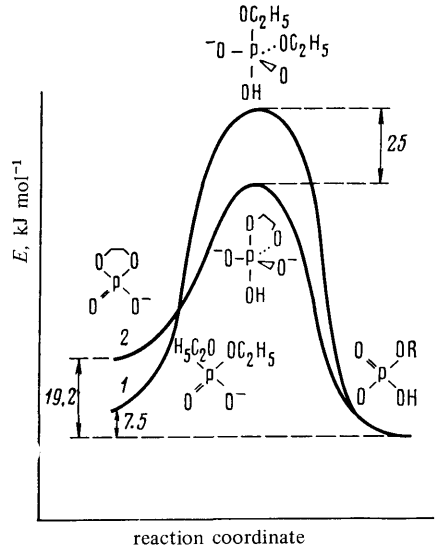


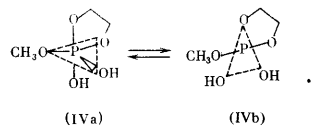
Figure 1. Reaction profiles of the OH^--catalysed hydrolysis of diethyl phosphate (curve *1*) and ethylene phosphate (curve *2*).[19]

The importance of the stereoelectronic control is confirmed by the considerable entropy contribution to the kinetic acceleration of the hydrolysis of five-membered cyclic phosphates[20]. Thus the entropy of activation for the latter is higher by almost 75 J mol^{-1} K^{-1} than for the acyclic ester[23]. Among all the possible conformations of the transition states in the hydrolysis of acyclic phosphates, only five undergo the interaction characteristic of *trans*-unshared electron pairs and the transition states of type (IIIc) or (IIId) are characterised by the lowest energy[20]. This requires the "freezing" of two rotational degrees of freedom about the acyclic ester linkages. The cyclic esters are already "frozen" in a suitable conformation with a low energy which is reflected in the difference between the activation entropies. The arrest of the free rotation about the ester linkages is responsible for the low negative entropies of activation for the acyclic esters (−143– −161 J mol^{-1} K^{-1}). In order to compensate for this unfavourable entropy, the stereoelectronic enthalpy gain must indeed be significant[20].

In the general case the reactivity of 1,3,2-diheterophospholans in nucleophilic substitution reactions at the tetrahedral phosphorus atom, the stereochemistry of these reactions (the retention or inversion of the configuration at the phosphorus atom), and the nature of the bond rupture (endocyclic or exocyclic) depend on many causes: on the presence or absence of catalysis (neutral, acid, or alkaline hydrolysis), on the type of heteroatoms linked to phosphorus, on the nature of the nucleophile and the leaving group, on the influence of the substituents in the five-membered ring, and on the nature of other electrophilic centres in the substrate molecule.

Kinetic studies and the investigation of the composition of the products of the hydrolysis as a result of the exocyclic and endocyclic substitution of the ester groups of ethylene methyl phosphate over a wide pH range in the medium[24] showed that the rate of reaction (Fig.2) and the *exo*/*endo* ratio (Fig.3) depend markedly on the nature of the catalysis.

If the ring rupture does not require pseudorotation, then the elimination of the methoxy-group is possible only after the conversion of the intermediate (IVa) into (IVb):



(IVa) (IVb)

In acid hydrolysis the intermediate phosphorane (IVa) is protonated by the *a*-oxygen atom[24], which prevents the conversion of compound (IVa) into (IVb), because the electronegative oxonium oxygen atom then migrates to the *e*-position. Therefore, with increase of the acidity of the medium, the fraction of the products formed as a result of ring rupture increases (Fig.3); the rate of reaction then varies linearly with the acid concentration (the left-hand branch of the curve in Fig.2).

The increase of the content of the cyclic product in dilute solutions (up to 50%, Fig.3) can be associated with the rate-determining pseudorotation in these instances[24]. In the regions where the pH is close to the value for a neutral medium, the rate of reaction is much lower and the fraction of the cyclic product reaches 25%.

In weak alkalis the intermediates exist in a monoanionic form with an anionic *e*-oxygen atom and pseudorotation giving rise to the anion of hydroxyphosphorinane (IVb) is in principle possible. The predominance of the endocyclic rupture in this instance can be accounted for by the fact that the rate of abstraction of the endocyclic *a*-oxygen atom is much higher than the rate of pseudorotation[24].

In a strongly alkaline solution the increase of the fraction of the cyclic product is most probably associated with the favourable energy of the permutation isomerisation of the

dianion of phosphorane (IVa) with an anionic α-substituent to the anion of the acid (IVb) in which both negatively charged oxygen atoms are located in the e-positions.

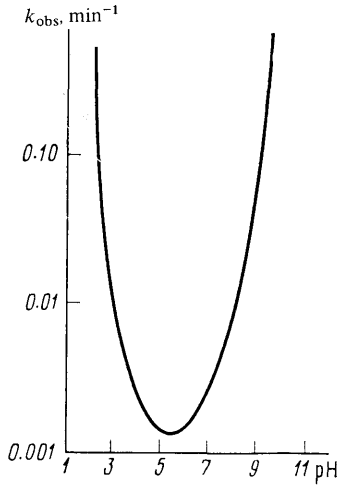


Figure 2. The rate of hydrolysis of ethylene methyl phosphate at 298 K.[24]

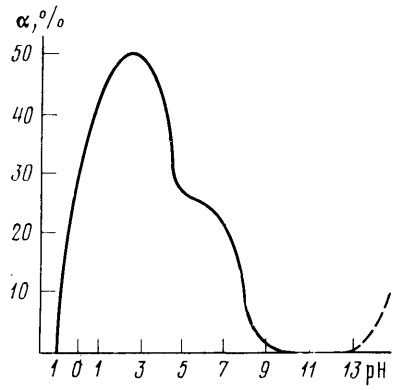


Figure 3. The pH profile of the hydrolysis products of ethylene methyl phosphate in water at 298 K;[24] α is the content of products formed as a result of exocyclic substitution.

The retention of the 1,3,2-diheterophospholan ring on hydrolysis and alcoholysis is observed fairly frequently [compounds (V), (VI), (VIII), (IX), (XIV), (XVIII), (XX), and (XXV) in Table 1]. 1,3,2-Dioxaphospholans and their benzo-derivatives react in a neutral solution with a limited amount of water with the preferential elimination of exocyclic groups [compounds (XIV) and (VIII) in Table 1];[25-27] the hydrolysis of the benzodiheterophospholan ring is a secondary process. On the other hand, there are data[28] indicating the exceptional hydrolytic instability of the benzodioxaphospholan ring. Thus the alcoholysis of phenyl phenylene phosphate (XVI) with ring opening under the influence of isobutyl alcohol takes place very rapidly at room temperature; 2-ethylpropanol reacts in 5 min, while 2,4-dimethyl-3-pentanol reacts in 2 h. After standing for a long time at room temperature, the acyclic alcoholysis products recyclise to alkyl phenylene phosphates. An analogous situation has been observed in the reaction of the phenylene phosphate anion (XV) with α-chymotrypsin[29].

These results show that both the ring opening products and the exocyclic substitution products can be formed as a result of secondary reactions and the assessment of the nature of the substitution (exocyclic or endocyclic) must be performed with some caution.

The hydrolysis and methanolysis of acyl ethylene phosphate (VII) also proceed with retention of the ethylene phosphate ring[30]. It is striking that nucleophilic substitution is in this case directed to the phosphoryl and not the carbonyl centre, which is apparently due to the unfavourable energetic features of the intermediate with a pentacoordinate phosphorus atom, analogous to compound (I). The rate of reaction of compound (VII) is much higher than that of its acyclic analogue—acetyl dimethyl phosphate.

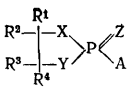
Preferential attack by nucleophiles on the phosphoryl rather than the carbonyl group has been observed in the alcoholysis, acidolysis, and aminolysis of 2,4-dioxo-1,3,2-diazaphospholans[31]. On the other hand, six-membered and acyclic acyl phosphates react with nucleophiles preferentially or fully via the acylation mechanism[32].

The relative ease of dissociation of the exocyclic and endocyclic ester linkages depends significantly on the degree of substitution of the ring carbon atoms. For example, in neutral media ethylene methyl phosphate hydrolyses almost completely with ring opening[24], while methyl tetramethylethylene phosphate (VI) forms methyl pinacolphosphoric acid under these conditions[33]. Alkaline hydrolysis takes place as a rule almost exclusively with the endocyclic rupture of ester linkages[24,33]. However, under these conditions too the dioxaphospholan fragment is ruptured preferentially at the P–O bond adjoining the least substituted carbon atom. Thus the endocyclic hydrolysis of compound (XVIII) takes place to the extent of 50% with rupture of the ester linkage involving the secondary carbon atom and to the extent of 20% with the rupture of the linkage involving the tertiary carbon atom[34].

It is most likely that the latter feature is associated with the fact that, on formation of the trigonal-bipyramidal intermediate, the oxygen atom linked to the least substituted (less electropositive and hence more apicophilic) carbon atom occupies preferentially the a-position for the a–e disposition of the five-membered ring. Naturally, this difference between the electronegativities of the ring carbon atoms is small and for this reason both ester linkages are ruptured.

Other conditions being equal, an increase in the number of alkyl substituents in the 1,3,2-diheterophospholan ring increases the hydrolytic stability of the cyclic skeleton of the molecule[35,36]. For example, it is known that the tendency of 1,3,2-dioxaphospholans to undergo reversible oligomerisation with ring opening is much greater for the unsubstituted cyclic compounds. The introduction of even one alkyl substituent at the ring carbon atoms sharply increases the stability of the molecules[37,38].

The greater stability of the substituted five-membered rings in hydrolysis reflects the tendency, common to small rings, to become stabilised with increase of the number of substituents[39,40], particularly in the presence of *gem*-dialkyl groups (the Ingold–Thorpe effect[41,42]).

Table 1. The rupture of bonds in the hydrolysis and alcoholysis of 1,3,2-diheterophospholans of the type .

No.	Compound								Reaction conditions	α, %	β, %	References
	R_1	R_2	R_3	R_4	X	Y	Z	A				
(V)	H	H	H	H	O	O	O	OCH_3	H_2O, 298 K, pH 2*	55	45 (P—O)	[10, 24]
(VI)	CH_3	CH_3	CH_3	CH_3	O	O	O	OCH_3	dioxan–H_2O (1 : 1), t_{room}, 0.1 M NaOH**		100 (P—O)	[31]
(VII)	H	H	H	H	O	O	O	$OCOCH_3$	H_2O, t_{room}, 15 s	100	—	[33]
(VIII)	—*o*-C_6H_4—				O	NH	O	OC_6H_5	THF, 3 M H_2O, t_{room}	85	—	[26]
(IX)	—*o*-C_6H_4—				O	O	O	HC_6H_5	ditto	64	—	[26]
(X)	—*o*-C_6H_4—				O	S	O	OC_6H_5	»	30	45 (P—S)	[26]
(XI)	—*o*-C_6H_4—				S	NH	O	OC_6H_5	»	8	0.7 (P—N); 78 (P—S)	[26]
(XII)	—*o*-C_6H_4—				NH	NH	O	NHC_6H_5	»	—	***	[26]
(XIII)	—*o*-C_6H_4—				NH	NH	O	$CH_2C_6H_5$	»	—	***	[26]
(XIV)	—*o*-C_6H_4—				NH	NH	O	OC_6H_5		27	51 (P—N)	[26]
									THF, 1 M CH_3OH, 2 h	48	17 (P—N)	[27]
(XV)	—*o*-C_6H_4—				O	O	O	O^-	α-chymotrypsin, pH 7, 298 K	—	100 (P—O)	[29]
(XVI)	—*o*-C_6H_4—				O	O	O	OC_6H_5	THF, 3 M H_2O, t_{room}***	68	21 (P—O)	[26]
(XVII)	H	H	H	H	NCH_3	O	O	OCH_3	H_2O, 0.01–0.005 M NaOH	0	60 (P—O); 40 (P—N)	[34]
(XVIII)	H	CH_3	H	H	O	O	O	$N(CH_3)_2$	ditto	30	20 (P—X); 50 (P—Y)	[34]
(XIX)	H	H	H	H	NC_6H_5	O	O	OCH_3	»	0	100 (P—O)	[34]
(XX)	H	H	H	H	NC_6H_5	O	O	OC_6H_5	»	91	4 (P—O); 5 (P—N)	[34]
(XXI)	H	H	H	H	NCH_3	O	O	C_6H_5	»	0	100 (P—O)	[43]
(XXII)	H	H	H	H	NC_6H_5	O	O	C_6H_5	»	0	100 (P—N)	[43]
(XXIII)	H	CH_3	H	C_6H_5	NCH_3	O	O	CH_3	RONa or HCl in ROH, t_{room}	0	100 (P—N)	[45]
(XXIV)	H	CH_3	H	C_6H_5	CH_3	O	Se	CH_3	ROH, t_{room}	0	100 (P—N)	[46]
(XXV)	H	CH_3	H	C_6H_5	CH_3	O	S	$N(C_2H_5)_2$	$NaOCH_3$ in CH_3OH*****	0	100 (P—N)	[47]
(XXVI)	H	CH_3	H	C_6H_5	NCH_3	O	S	CH_3	NaOR in ROH	—	100 (P—N)	[47]
(XXVII)	H	CH_3	H	C_6H_5	NCH_3	S	S	CH_3	ditto	—	100 (P—N)	[50]
(XXVIII)	H	CH_3	H	C_6H_5	NCH_3	S	O	OC_2H_5	»	—	100 (P—N)	[50]
(XXIX)	H	H	H	H	O	S	O	C_6H_5	0.1 *N* Na_2CO_3 in H_2O, 298 K	0	100 (P—O)	[55–57]
(XXX)	H	H	H	H	O	S	O	C_6H_5	ditto	0	100 (P—O)	[55–57]
(XXXI)	H	H	H	H	O	S	O	OCH_3	»	0	100 (P—S)	[55–57]

Note. α and β are the amounts of products formed as a result of the exocyclic and endocyclic ruptures respectively; the bond ruptured is indicated in brackets against the values of β.

*α = 17% and β = 83% (P—O) at pH 7 and α = 1% and β = 99% at pH 13 were obtained. **α = 100% was obtained for the 1:1 1,2-dimethoxyethane–H_2O system. ***Reaction does not occur. ****α = 10% and β = 90% (P—O) were obtained for the following conditions: $(CH_3)_2CHCH_2OH$, fast; $(C_2H_5)CHOH$, 5 min; $[(CH_3)_2CH]_2CHOH$, 2 h. *****t_{ki} = 20 min and α = 20% for the system comprising 3 moles of aqueous HCl in acetone.

If readily removed exocyclic substituents, for example aryloxy-substituents, are linked to the phosphorus atom, then the ring is retained and the rate of hydrolysis is described satisfactorily by the Hammett equation when the substituent in the leaving group is varied[44].

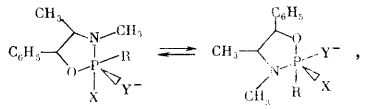
In the presence of unlike heteroatoms in the 1,3,2-diheterophospholan ring, nucleophilic substitution results in the preferential rupture of the bond between the phosphorus atom and the more apicophilic heteroatom or group. Alkaline hydrolysis of the cyclic phosphoramidate (XIX) and of the phosphonate (XXI) leads exclusively to the rupture of the endocyclic P—O bond, because the oxygen atom is more apicophilic than the NC_6H_5 group[34,43]. However, according to other data[45–47], the relative apicophilicities of the atoms can change following their incorporation in the heterocycle. The exclusive P—N rupture on alcoholysis of oxazaphospholans (XXIII)–(XXVIII) is attributed to the greater apicophilicity of the endocyclic nitrogen atom and the oxygen atom[45–47,51].

Thus the characteristic feature of cyclic aminoesters of phosphorus acids is the ease of the cleavage of the phosphamide linkages under the conditions of alkaline hydrolysis and alcoholysis. The alkaline hydrolysis of the phosphoramidates (XVII) and (XVIII) proceeds to the extent of 40 and 30% respectively with substitution of the amino-groups[34]. The base-catalysed hydrolysis of the phosphoramidate (XXII) [43] and the alcoholysis of the cyclic phosphorus derivatives (XXII)–(XXVI) based on (-)-ephedrine proceed wholly with dissociation of the P—N bond[45–48]. The rupture of the amide rather than the less stable thioester linkage has been observed in the hydrolysis[49] and alcoholysis[50] of the thiazaphospholans (XXVII) and (XXVIII), but the hydrolysis of compound (XI) in a neutral medium proceeds mainly with rupture of the P—S bond[26], while the exocyclic substitution of the phenoxy-group competes with the cleavage of the labile P—N bond in the oxathiaphospholan (X).

On the other hand, the acyclic amidoesters of phorphorus acids hydrolyse in alkaline solutions exclusively with liberation of the alcohol[34,44,51]. It has been suggested[52] that this difference is associated with the change in the nature of the P—N bond when it is incorporated in a rigid five-membered ring. The amino-group in acyclic phosphoramidates can "choose" the conformation in which there is maximum overlap of the orbital of the unshared electron pair of the nitrogen atom with the d orbitals of phorphorus, which strengthens the phosphamide linkage and lowers the electrophilicity of the phosphorus and the basicity of the nitrogen. When the P—N bond incorporated in a five-membered ring and the overlap weakens and hence the basicity of the nitrogen, the electrophilicity of the phosphorus, and the lability of the phosphamide linkage increase.

However, the interaction of alkyl(aryl)phosphonamidate, phosphinoselenoate, and phosphonamidothioate derivatives (XXIII), (XXIV), (XXVI), and (XXVII) of (-)-ephedrine

and (+)-pseudoephedrine with organolithium and organomagnesium compounds takes place with dissociation of the P–O and P–N bonds, the ratios of the reaction products depending both on the nature of the nucleophile and on the steric structure of the ring[7,51–53]. The difference from the reactions with oxygen-centred nucleophiles is associated with different barriers to the transformations of the intermediates (XXXII) and (XXXIII):



(XXXII) (XXXIII)

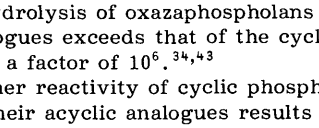
R=CH_3, C_6H_5; Y=O, S; X=OR, R, C_6H_5.

When X = OR, the pseudorotation (XXXII) ⇌ (XXXIII) is hindered, because the apicophilicity of the alkoxy-substituents is somewhat greater than that of the methyl or phenyl group; in such phosphoranes the α-elimination of the amino-group takes place. The apicophilicities of the group X (X = alkyl or aryl) and the equatorial substituents R are similar and pseudorotation and the subsequent heterolysis of the P–O bond compete with the endocyclic dissociation of the P–N bond. Furthermore, in many instances the nucleophile X can attack approximately equally readily the P–O and P–N groups from the rear. The interconversion energy of the intermediates is influenced by the nature and steric disposition of the ring substituents. In other words, there is a fine balance of all the factors which determine the nature of the rupture and the stereochemistry of the reaction involving substitution by organometallic nucleophiles[53].

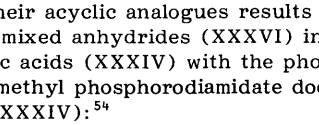
Acid hydrolysis of phosphoramidates takes place with substitution of the amino-group, because the nitrogen atom, being the most basic centre, is the first to be protonated, while the ammonium substituent is very readily eliminated. The insignificant contribution (5%) of the P–N dissociation in the hydrolysis of the phosphoramidate (XX) has been explained by general acid catalysis[44]. However, the exclusive P–N dissociation in the *N*-phenylphosphonate (XXII), where the nitrogen is less basic than in the *N*-methyl derivative (XXI), conflicts with this hypothesis. In order to account for this contradiction, a square-pyramidal structure of the intermediate has been proposed[43]. The full amides (XII) and (XIII) are not hydrolysed in a neutral medium.

The rate of hydrolysis of oxazaphospholans as well as their dioxa-analogues exceeds that of the cyclic phosphoramidates by a factor of 10^6.[34,43]

The much higher reactivity of cyclic phosphoramidates compared with their acyclic analogues results in the ready formation of the mixed anhydrides (XXXVI) in the reactions of arylphosphoric acids (XXXIV) with the phosphoramidate (XXXVI), while methyl phosphorodiamidate does not react with compound (XXXIV):[54]

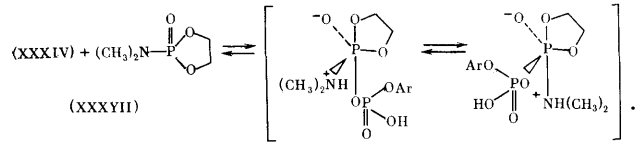


(XXXIV) (XXXV)



(XXXVI)

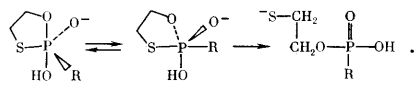
It is of interest that ethylene *N,N*-dimethylphosphoramidate (XXXVII) is also inert in this reaction; this is apparently associated with the unfavourable energetic features of the intermediate (XXXVIII) (in which the ammonium group characteristically assumes an equatorial position) or its rotational isomer (XXXIX) (where the electronegative hydroxyphosphoryl group is equatorial):



(XXXIV) + $(CH_3)_2N$–P(O)(O)(O) ⇌ [(XXXVIII) ⇌ (XXXIX)]

(XXXVII)

A difference between the types of endocyclic dissociations has also been established in the series of oxathiaphospholans (XXIX)–(XXXI).[55–57] The alkaline hydrolysis of ethylene methyl phosphorothiolate (XXXI) involves, like that of the acyclic thiolo-esters of phosphorus acids[56], the substitution of the thioester group with formation of compound (XLII), while the hydrolysis products of the phosphorothioate anion (XXIX) and of the phosphonothioate (XXX) are the β-hydroxyethyl thiolo-esters of the corresponding acids. This can be explained by the different capacities of the intermediates (XL) for pseudorotation in the presence of different substituents R:



(XL) (XL1) (XLII)

A necessary condition for the P–S dissociation is the transformation of the bipyramid (XL) into (XLI), which is allowed only for R = OCH_3. Such pseudorotation is difficult for R = O [compound (XXIX)] and C_6H_5 [compound (XXX)] (the less apicophilic groups should migrate to the α-position) and it cannot compete with the endocyclic dissociation of the P–O α-bond.

2. 1,3,2-Diheterophosphorinanes

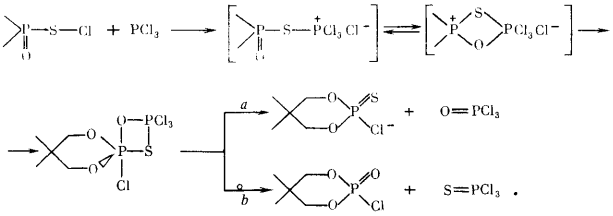
Nucleophilic substitution at the tetrahedral phosphorus atom incorporated in a six-membered 1,3,2-diheterophosphorinane ring does not involve a striking difference between the rates of reaction of cyclic and acyclic phosphorus acid esters of the kind observed in the series of 1,3,2-diheterophospholans. In contrast to the five-membered phosphorus-containing heterocycles, the six-membered heterocycles are more stable and in the presence at the phosphorus atom of a readily eliminated exocyclic group the substitution takes place with retention of the ring. The rate of exocyclic hydrolysis is very close to that of the analogous reactions of acyclic phosphates[7,10,58,59]. This is most probably associated with the absence of angular strain in the six-membered rings and with the similarity between the structure of the trigonal-bipyramidal intermediate, formed as a result of the addition of the nucleophile to the phosphorus atom, and the structure of the transition state in $S_N2(P)$ reactions (at any rate, in exocyclic nucleophilic substitution occurring with inversion of the configuration at the phosphorus atom[60]).

The formation of such intermediates presupposes that the six-membered ring is in the diequatorial position, which is energetically more favourable[11,12] than the a–e positions.

However, the arrangement in the phosphorane bipyramid of the six-membered rings in which a heteroatom is linked to the phosphorus atom is determined by the effect of the orientation of the unshared electron pairs of the heteroatom. The structure with the *a*–*e*-ring in the boat conformation has the lowest energy[7,60,61,62]. This conclusion agrees with the results of the X-ray diffraction analysis of the phosphorane containing the oxazaphosphorinane ring[61].

It has also been suggested that structures with the *e*–*e* and *a*–*e* disposition of the diheterophosphorinane ring have comparable energies[63,64]. On the other hand, the authors of recent investigations into the stereochemistry of nucleophilic substitution reactions of organophosphorus carbohydrate derivatives[65] question this claim on the grounds that the *a*–*e* disposition of the dioxaphosphorinane rings is thermodynamically preferred. This last factor is believed to be responsible[7,65] for the appreciably higher (by a factor ≳10) rate of ring opening in six-membered cyclic phosphates than was believed previously[10,58].

The *e*–*e* disposition of the six-membered ring is apparently the only one possible in the intermediate compounds in the reactions of cyclic phosphorylsulphenyl chlorides with phosphorus trichloride[66]. The reaction proceeds via the successive formation of quasi-phosphonium intermediates. The dicyclic phosphorane formed subsequently can decompose with abstraction of an oxygen atom from the four-membered ring or after the pseudorotation of the sulphur atom:



It is striking that acyclic phosphonosulphenyl chlorides undergo only deoxidation on treatment with phosphorus trichloride (pathway *a*). The lifetime of the phosphorane intermediate formed from the acyclic substrate is probably insufficiently long for the pseudorotation necessary for the occurrence of desulphurisation (pathway *b*).

It has been shown in a number of instances that, of the two enantiomeric 1,3,2-diheterophosphorinanes, the stereoisomer with the *a*-disposition of the P=X groups hydrolyses at a higher rate[20,60,67,68]. Thus 2-aryloxy-2-oxo-*trans*-5,6-tetramethylene-1,3,2-dioxaphosphorinanes with the P=O *e*-group hydrolyse 4–17 times more slowly than their epimers[60]. The difference between the energies of the ground states of the phosphorus-containing cyclic structures is responsible for this difference in behaviour: the P=O group occupies preferentially the *e*-position and the energy of isomers with this structure is lower by 6–8 kJ mol^{-1}. The difference between the energies of the transition states in these systems is very small (~0.8 kJ mol^{-1}). A similar difference between the reactivities of the stereoisomers has been observed in the hydrolysis of uridine 3,5-phosphates, where the difference between the energies of the ground states is ~3 kJ mol^{-1}.[69]

Endocyclic rupture occurs in 2-alkyl(aryl)-1,3,2-diheterophosphorinanes, in which the substitution of the exocyclic groups is impossible[7]. In those cases where a group difficult to eliminate is linked to the phosphorus atom, exocyclic cleavage competes with the ring opening[70,71]. In the series of *p*-substituted 5-chloromethyl-5-methyl-2-oxo-(phenoxy)-1,3,2-dioxaphosphorinanes the influence of the *p*-substituents on the reaction rate is not very significant, which is reflected in the constant $\rho = 0.95$ in the Hammett equation[7].

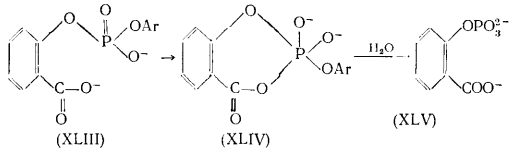
It has been suggested that the trigonal-bipyramidal intermediates formed initially in reactions with retention of the configuration at the phosphorus atom undergo pseudorotation[60,71,72]. An alternative explanation involves the formation of square-pyramidal intermediate structures[69,70].

As in the series of five-membered cyclic phosphates, the nature of the endocyclic dissociation of the phosphorus–heteroatom bonds in 1,3,2-diheterophosphorinanes depends on the nature of the heteroatoms in the ring and the substituents at the ring carbon atoms. The acid-catalysed hydrolysis of 1,3,2-oxazaphosphorinanes proceeds with dissociation of the P–N bond[7,73–75], while in reactions involving alkaline hydrolysis the stability of the P–N bond is intermediate between that of the stable acyclic amidoesters of phosphorus acids and that of the labile 1,3,2-oxazaphospholans[7,76,77].

The relative ease of the P–O and P–S dissociations in 1,3,2-oxathiaphosphorinane derivatives depends on the nature of the exocyclic substituents. Thus 2-ethoxy-2-oxo-1,3,2-oxathiaphosphorinanes undergo P–S cleavage in the CH_3ONa–CH_3OH system, while in the analogous methyl phosphonates the P–O bond is ruptured[7,70]. This result indicates an appreciable difference between the cyclic and acyclic phosphorus thiolo-compounds. As already stated, the acyclic thiolo-esters of phosphorus acids hydrolyse in the first place at the thioester linkage in all cases.

The influence of the substituents at the ring carbon atoms on the rate of nucleophilic substitution at a phosphorus atom incorporated in a six-membered ring has been studied in only a few instances[78–82]. The ester linkage with a secondary carbon atom is more labile in 1,3,2-dioxaphosphorinanes than the similar bond with a tertiary carbon atom[70]. The ease of ring opening in carbohydrate derivatives depends on the nature of the initial glucoside. In *trans*-joined 1,3,2-dioxaphosphorinanes derived from glucose the ring opening under the influence of Grignard reagents takes place under mild conditions; the *cis*-joined phosphate esters of galactose are fairly inert and react only after refluxing in benzene for 96 h.[78]

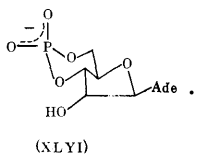
The acceleration of the reaction by a factor of 10^7–10^8 in the hydrolysis of aryl 2-carboxyphenyl phosphates (XLIII) in the region of pH 5, in which the *o*-carboxy group is ionised, has been explained by the intermediate formation of the phosphorane (XLIV), whose decomposition is responsible for the large effect in the formation of the monoaryl phosphate (XLV):[79]



(XLIII) (XLIV) (XLV)

The combined thermochemical, quantum-chemical, and stereochemical study[80–82] makes it possible to explain why the enthalpy of hydrolysis of six-membered cyclic adenosine 3′,5′-monophosphates (XLVI) is higher by ~33 kJ mol^{-1}

compared with trimethylene phosphate:



(XLVI)

It was established that ~21 kJ mol^{-1} corresponds to the strain induced by the ribofuranoside component of the molecule, *trans*-condensed relative to the phosphorus-containing ring. A definite proportion of the enthalpy difference (4.0–8.5 kJ mol^{-1}) is associated with the enforced fixation of the 5-alkoxy-substituent in the unfavourable *e*-position, which destabilises the system. Finally, 4–8 kJ mol^{-1} is due to the difference between the solvation energies of the reactants and products.

It has been shown that the enthalpies of hydrolysis of diethyl phosphate (~10.5 kJ mol^{-1}) and trimethylene phosphate (~16 kJ mol^{-1}) do not differ significantly[80].

The enthalpy of hydrolysis of cyclic phosphates can serve as a measure of the stability of the molecule in the synthesis of cyclic phosphates, for example, from the corresponding phosphorus acid dichlorides and diols[83]. The threshold of the enthalpy of hydrolysis above which cyclic phosphates lose their stability under the usual conditions (polymers and decomposition products are formed instead of the expected cyclic esters) is ~25 kJ mol^{-1}.

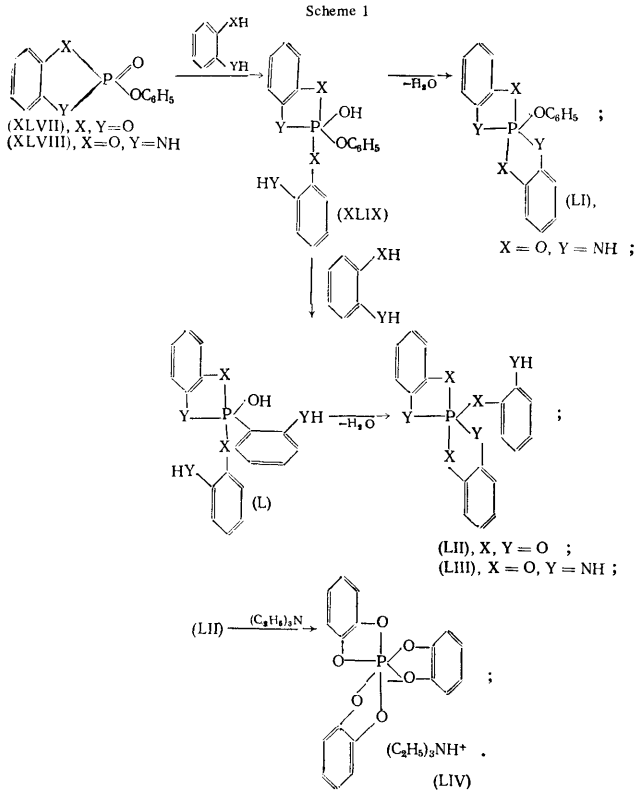
3. Nucleophilic Reactions with Increase of the Coordination Number of Phosphorus Atoms

A serious argument in support of the hydroxyphosphorinane concept was the detection of hydroxyphosphoranes formed in the course of the intramolecular and intermolecular nucleophilic substitution at a tetrahedral phosphorus atom. Direct evidence for the formation of hydroxyphosphorinane was obtained for the first time in a study of the interaction of phenyl phosphorodichloridate with catechol and *o*-aminophenol in the presence of triethylamine[84].

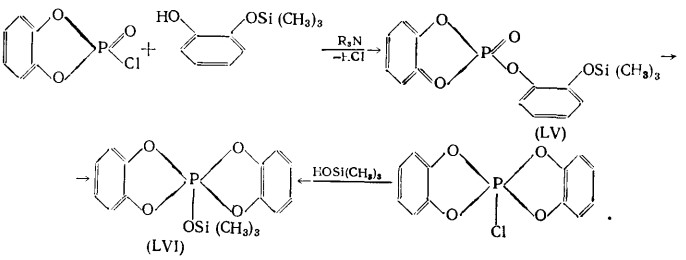
It was found that in the first case a salt of hexacoordinate phosphorus (LIV) is formed instead of the expected phenyl phenylene phosphate (XLVII). *o*-Aminophenol gives rise to small amounts of compounds (LI) and (LIII) with a phosphorane structure together with compound (LIV). The reaction of compound (XLVII) with catechol and *o*-aminophenol leads to analogous products. The formation of organophosphorus compounds with an increased coordination number is possible only as a result of the intermediate formation of the hydroxyphosphoranes (XLIX) and (L) via Scheme 1.

It was established subsequently that the formation of the phosphorane (LIV) is extremely characteristic of the reactions of catechol with 2-halogenobenzo-1,3,2-oxaphospholans containing an atom of tricoordinate, tetracoordinate, or pentacoordinate phosphorus in the ring[85,86].

Scheme 1

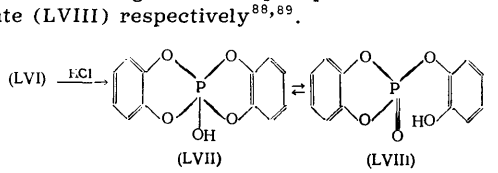


The reaction of phenylene phosphorochloridate with *o*-trimethylsiloxyphenol[87] in the presence of triethylamine leads to the phosphate (LV), which fully isomerises in aprotic solvents to spirotrimethylsiloxydiphenylenephosphorane (LVI); the latter can be obtained by specific synthesis from spirochlorodiphenylenephosphorane and trimethylsilanol:



The possibility of such silyl transfer apparently arises from the greater stability of the $(RO)_4P-O-SiR'_3$ system compared with $Ar-O-SiR'_3$.[87]

When silylphosphorane (LVI) reacts with anhydrous hydrogen chloride, a crystalline substance is formed, exhibiting features of a dynamic equilibrium in aprotic solvents: two signals in ^{31}P NMR spectra at −27 and +7 p.p.m. were assigned to the phosphorane (LVII) and the phosphate (LVIII) respectively[88,89].

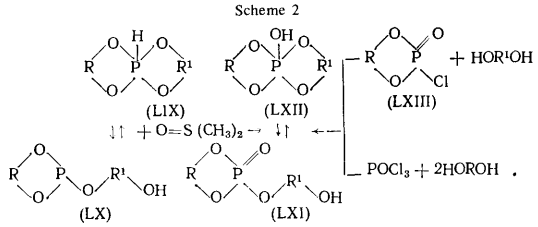


In the crystalline state this substance consists of the phosphate (LVIII). In acetonitrile at 225 K, the ratio of the quinquevalent and quadrivalent phosphorus forms $P^{V}:P^{IV}$ = 1.5:1, while in acetone it is 3:1.

The reaction of compound (LVIII) with diazomethane leads exclusively to methoxyspirodiphenylenephosphorane. Acylation yields 80% of 2-acetoxyphenyl phenylene phosphate and 20% of acetoxyspirodiphenylenephosphorane.

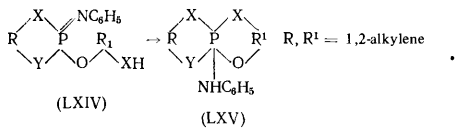
The phosphate–phosphorane tautomerism has been observed in the products of the oxidation of the prototropic system (LIX) ⇌ (LX) with dimethyl sulphoxide and also in the cyclic phosphates formed when alkylene phosphorochloridates (LXIII) or phosphoryl chloride react with diols[90–93] via Scheme 2:

Scheme 2

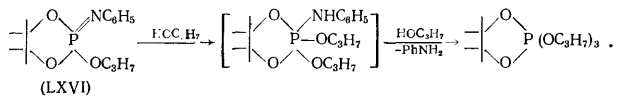


An increase in the number of substituents in five-membered rings and an increase of their electron-accepting capacity stabilise the phosphorus(V) form[93]. The equilibrium (LXI) ⇌ (LXII) shifts towards the hydroxyphosphorane with increase of the basicity of the medium[91].

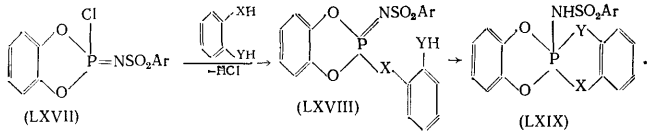
The intramolecular proton transfer from the functional group in the γ-position to the heteroatom in the P=X bond has been demonstrated in five-membered cyclic phosphorimidates[94,95]:



Although the phosphorimidate (LXIV), formed in the reaction of phosphites of type (LX) with phenyl azide, could not be identified, its transformation into compound (LXV) is modelled by the addition of an alcohol to the imide linkage of the phosphorimidate (LXVI):

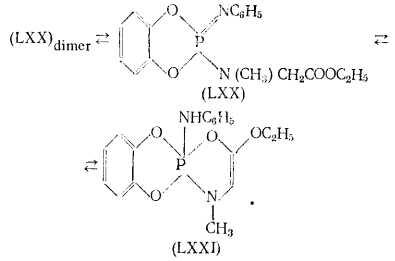


The interaction of 2-acylimino-2-chloro-4,5-benzo-1,3,2-dioxaphospholan (LXVII) with catechol, *o*-phenylenediamine, and *o*-aminophenol proceeds via a stage involving the formation of the phosphorimidate (LXVIII) with the subsequent intramolecular prototropic isomerisation to the spirophosphorane (LXIX):[96,97]

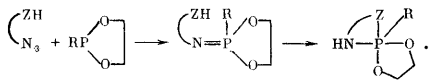


It was shown that the reactivity of the phosphorimidochloridate (LXVII) is higher than that of acyclic dialkoxychlorophosphazo-compounds[98].

An interesting case of reversible prototropic isomerisation was observed in the thermolysis of phosphoramidimidate (LXX), which is dimerised under the usual conditions (see below). When the dimer of the phospholan (LXX) is heated, it is converted into the monomeric form and then isomerises to the aminospirophosphorane (LXXI) with intramolecular proton transfer to the phosphorimide nitrogen atom[99]:

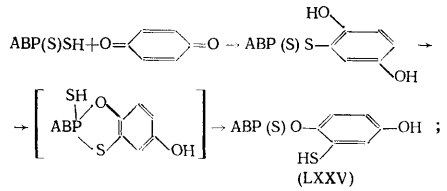


An analogous intramolecular prototropic process has been used to synthesise stable cyclic spirophosphoranes by the reaction of phosphites with bifunctional azides[100]:



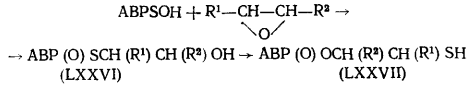
The driving force of the intramolecular nucleophilic attack by the nucleophilic functional group in the γ-position on the phosphorus atom is spirocyclisation, leading to stable spirophosphoranes[14,89,94,101]. Acyclic organophosphorus compounds with a 2-hydroxy(amino, mercapto)ester group do not form hydroxyphosphoranes which would be sufficiently stable for identification[101]. This reflects the well-known sequence based on the decrease of the stability of phosphoranes; spirocyclic > monocyclic > acyclic.[102]

The isomerisation of *S*-(2-hydroxyalkyl) esters of phosphorus thioacids probably also proceeds via the hydroxy(mercapto)phosphorane stage. At any rate, the much greater ease of the isomerisation of the esters of cyclic ω-hydroxy(mercapto)phosphates compared with the acyclic compounds can be associated with the more favourable energetic features of the bicyclic intermediates[103–105]. Thus the product of the addition of alkylene phosphorodithioic acids to *p*-quinone isomerises to the corresponding phosphoromonothioate (LXXV) so rapidly that under the usual conditions the adducts (LXXIII) and (LXXIV) cannot be isolated, while *O,O*-dialkyl *S*-(2,5-dihydroxyphenyl) phosphorodithioates (LXXII) isomerise only at an elevated temperature[103]:



(LXXII)), A=B=Alko (LXXIII), AB=OC $(CH_3)_2C(CH_3)_2O$ (LXXIV), AB=$OCH_2C(CH_3)_2CH_2O$.

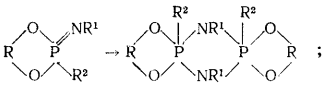
The stability of the products of the addition of phosphorus monothioacids to oxirans depends greatly on the nature of the substituents at the phosphorus atoms: whereas the acyclic *S*-(2-hydroxyalkyl) phosphorothioates (LXXVI) are fairly stable at room temperature, in the case of five-membered 2-hydroxyalkyl derivatives only the isomerisation products were detected—2-(2′-mercaptoalkyl)-2-oxo-1,3,2-dioxaphospholans (LXXVII). 2-Hydroxyalkyl phosphorothioates of the 1,3,2-dioxaphosphorinane series (LXXVI) can be detected by ^{31}P NMR.[104]



where AB = 1,2-dihydroxyalkylene. Evidently, the intermediate hydroxyphosphoranes with two five-membered rings have a lower energy than the intermediates with five- and six-membered rings, which are in turn more stable than the monocyclic phosphoranes.

It is striking that *S*-(3-hydroxyalkyl) phosphorothioates—the products of the addition of five-membered cyclic phosphoromonothioic acid to oxetans—are readily converted in ethereal solution into 3-mercaptoalkyl phosphates[105]. Derivatives of acyclic and six- and seven-membered cyclic acids do not isomerise under these conditions.

An increase of the coordination number of the phosphorus atom has been observed in the dimerisation of 2-imino-2-R-1,3,2-diheterophospholans and their 4,5-benzo-analogues[97,106] to 1,3-diaza-2,4-diphosphetidines:



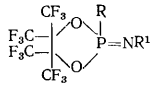
R = CH_2CH_2, *ortho*-C_6H_4 .

This process probably proceeds via a [2+2]-cycloaddition mechanism, but the dimerisation of the cyclic five-membered phosphorimidates obeys all the rules governing the nucleophilic substitution at the phosphorus atom. The presence of acyl groups at the nitrogen atom determines the stability of the monomeric form. If there is an aryl substituent at the nitrogen atom, then the capacity for dimerisation is determined by the nature of the substituents R^2: the dimethyl-amino-group attached to the phosphorus atom stabilises the monomer; weak electron-donating or electron-accepting groups at the phosphorus atom promote dimerisation. Acyclic phosphazo-compounds with the same environment around the phosphorus atom are monomeric[97].

A similar behaviour has been observed also in the series of 2-imino-4,5-benzo-1,3,2-dioxaphospholans[107,108]: regardless of the nature of the substituents at the phosphorus atom, the *N*-acyl derivatives are monomeric, while the *N*-aryl derivatives are dimeric. 2-Diethylamino-2-*N*-phenylimino-4,5-benzo-1,3,2-dioxaphospholan, which is involved in a monomer–dimer equilibrium in solutions, is an exception.

Evidently, the relative ease of the dimerisation of the five-membered cyclic phosphazo-compounds is ensured by the ring strain, which diminishes when the ring passes to the *a–e* position in the dimeric 1,3-diaza-2,4-diphosphetidine[106]. The greater tendency towards dimerisation by 4,5-benzo-derivatives can be accounted for by the greater strain in the condensed ring.

On the other hand, in the series of iminophospholan derivatives of perfluoropinacone (LXXVIII) the competing influence of the five-membered ring in the substituent at the phosphorus atom is manifested. Despite the presence of a bulky substituent in the imine fragment, which hinders dimerisation, compounds (LXXVIII) exist in the form of dimers, while the iminophospholan (LXXIX) is monomeric[109,110]:



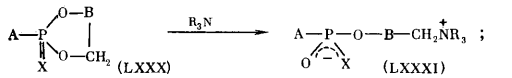
(LXXVIII), R=F; R^1 = t-C_4H_9, $Si(CH_3)_3$;
(LXXIX), R=N [$Si(CH_3)_3]_2$; R^1=$Si(CH_3)_3$.

The imino-derivatives of the 1,3,2-oxazaphospholan[97] and 1,3,2-dioxaphosphorinane[111] types are monomeric. In the latter case this is probably associated with the absence of ring strain in the six-membered ring.

III. NUCLEOPHILIC SUBSTITUTION AT A CARBON ATOM

Apart from the tetracoordinate phosphorus atom or together with the latter, a ring carbon atom or a carbon atom in an exocyclic ester group can serve as a centre of nucleophilic attack. The site of nucleophilic substitution is determined by the nature of the nucleophile and of the substituents at the ring carbon atoms and the carbon atoms of the exocyclic group.

The interaction of tertiary amines with 2-oxo-2-thiono-, and 2-selenono-1,3,2-dioxaphospholans and the corresponding phosphorinanes (LXXX) leads mainly to the formation of the inner salts (LXXXI):[112]



(LXXX) (LXXXI)

X=O, S, Se; A=R, RO, Ar, ArO, R_2N; B=CH_2, $(CH_2)_2$, *ortho*-C_6H_4 .

The rate of reaction is greatly influenced by the electronic properties of the exocyclic substituents. Under the usual conditions, the reaction terminates after several days for A = C_6H_5O and *p*-$NO_2C_6H_4O$ and after several months for A = R_2N.[113]

The ease of formation of the inner salts depends on the degree of ring substitution and the nature of the amine. In the series of 2-oxo-2-phenoxy-1,3,2-dioxaphospholans[114] salts of type (LXXXI) are formed only in the case of unsubstituted rings. Monomethylphospholan does not form inner salts in the reactions with methylamine and dimethylamine; attack is mainly directed to the phosphorus atom. Nucleophilic substitution at a ring carbon atom is even less marked for rings with a large number of methyl groups. In these reactions with amines one can postulate an S_N2 mechanism, which leads to ring opening and the formation of aminoalcohol derivatives (LXXXI): the reaction with the strong bases $(CH_3)_2NH$ and $(C_2H_5)_2NH$ is faster, whereas that with bases of moderate strength, namely pyridine and aniline, is slower. This mechanism apparently operates also in the reactions of unsubstituted rings. However, the fact that in the reaction of monomethylphospholan the nitrogen atom is linked to the methylated carbon atom suggests that the S_N1 mechanism is preferred[114].

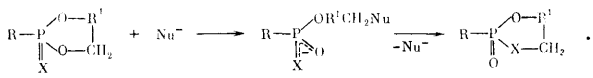
Exocyclic dealkylation by amines has been observed in 1,3,2-dioxaphospholan with alkoxy-substituents at the phosphorus atom[112,113]. Contrary to expectation, cyclic ammonium phosphates are formed also in the interaction of tertiary amines and pyridine with 4,5-dimethyl-2-oxo-2-phenoxy-1,3,2-dioxaphospholans and in the reaction of all the amines investigated with the phenyl ester of pinacone phosphate[114]. It has been suggested that in this case the amine attacks the phosphorus atom and the formation of phenylammonium cyclic phosphate is a result of a secondary disproportionation process arising in the first, phosphorane stage. Exocyclic dearylation also occurs when 5-chloromethyl-5-methyl-2-*p*-nitrophenoxy-2-oxo-1,3,2-dioxaphosphorinane reacts with sodium *p*-nitrophenoxide[115].

Thus an unsubstituted five-membered phosphate is attacked by amines at an endocyclic carbon atom. When the ring contains at least one methyl substituent, the reaction centre becomes either the carbon atom linked to the substituent or the phosphorus atom. A highly basic group attacks only the phosphorus atom; when the basicity is lower, there is competition between two electrophilic centres; interaction via the phosphorus atom can lead either to ring opening (in the case of strong bases) or to intramolecular disproportionation to ammonium phosphate[114]. The opening

of the phospholan ring under the influence of amines made it possible to develop a convenient method of synthesis of phosphorylcholines[116,117].

The endocyclic carbon atoms can undergo nucleophilic attack also by other nucleophiles, for example, by cyanide ions, with formation of 2-cyanoalkyl esters of phosphorus acid[118]. The substitution of the cyclic glycerol phosphates by phosphate anions has been used to synthesise glycerol phospholipids[119].

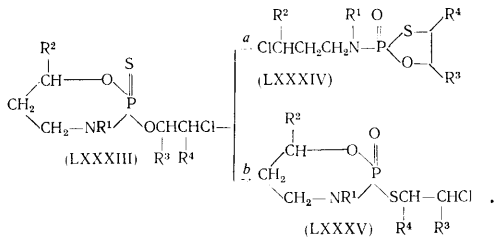
Nucleophilic substitution at a carbon atom in 2-selenono- and 2-thiono-2-R-1,3,2-dioxaphospholans and the corresponding phosphorinanes leads to selenone–selenol and thione–thiol isomerisation. The reaction proceeds via a stage involving the formation of the acyclic anions (LXXXII):



(LXXXII)

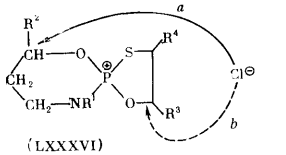
The isomerisation can take place under the influence of tertiary amines[113], tertiary phosphines[113,120], and iodide[121] and bromide[50] anions.

An interesting case of thermal thione–thiol isomerisation has been observed in the series of oxazaphosphorinanes with an exocyclic 2-chloroalkoxy-group (LXXXIII):



(LXXXIII) (LXXXIV) (LXXXV)

The reaction proceeds via two pathways (*a* and *b*) and leads to the products (LXXXIV) and (LXXXV), probably via the common intermediate (LXXXVI), which arises as a result of the intramolecular alkylation of the thiophosphoryl group:

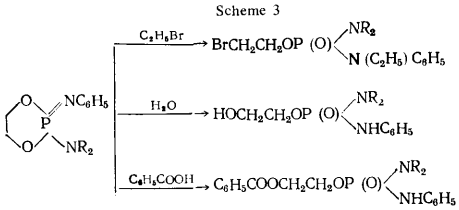


(LXXXVI)

In those cases where $R^2 = CH_3$ and $R^3 = R^4 = H$, the attack by the chloride anion proceeds via pathway *b* and the isomer with the oxazaphosphorinane structure (LXXXV) predominates in the mixture of products. On the other hand, the introduction of the methyl substituent into the chloroethyl group favours pathway *a*, which leads to the opening of the six-membered ring and to an increase of the content of the oxathiaphospholan (LXXXIV).[122]

Nucleophilic substitution at a ring carbon atom in 2-alkylamino-2-phenylimino-1,3,2-dioxaphospholans is accompanied by the imide–amide rearrangement[97,106] in accordance with Scheme 3:

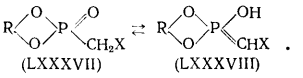
Scheme 3



Cyclic phosphorimidates are then more reactive than the acyclic derivative[97].

IV. COMPOUNDS WITH AN ACTIVE METHYLENE GROUP

Although the reactiviity of cyclic phosphonates with an active methylene group has been little studied[123], the available data indicate their unusual properties which are manifested both in their structures and in the characteristics of their reactions. Infrared spectroscopic and NMR studies on the phosphonates (LXXXVII) with $R = CH(CH_3)CH(CH_3)$ and $X = CN$ or $COOC_2H_5$ led to the discovery of the phosphonate–ylide tautomerism in the series of five-membered cyclic derivatives[124]:



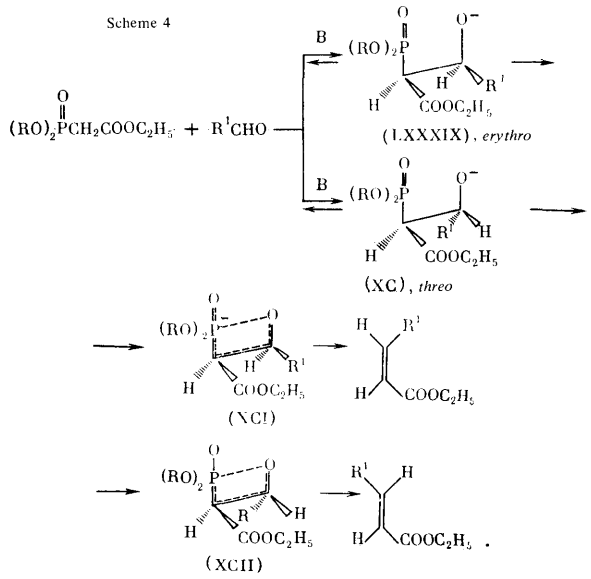
(LXXXVII) (LXXXVIII)

The ylide structure (LXXXVIII) was detected from the characteristic absorption of the OH group in the infrared region (3420–3460 cm^{-1}); the isomer ratio is 4:1 in favour of compound (LXXXVII) according to ^1H NMR data[124]. These compounds are titrated like strong monobasic acids and vigorously interact with diazoalkanes. The presence of the ylide formed is associated with the pronounced electron-accepting effect of the dioxaphospholan fragment (see Section V). The acyclic and six-membered cyclic esters and nitriles of phosphonoacetic acid are not converted into ylides and do not exhibit acid properties[124].

The incorporation of a phosphorus atom in the five- or six-membered rings of compounds (LXXXVII) alters appreciably the stereospecificity of the phosphonate modification of the Wittig reaction[125,126]. The reactions of acyclic organophosphorus compounds having an active methylene group with carbonyl compounds proceed preferentially with formation of *trans*-olefins[125–128]. This is attributed to the thermodynamic control of the reversible formation and interconversion of the *erythro*- and *threo*-betaines (LXXXIX) and (XC) and their decomposition to olefins.

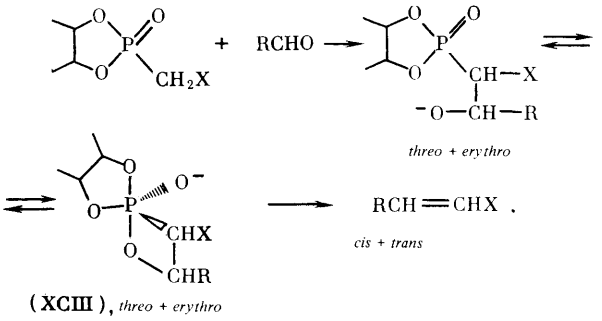
In acyclic systems the stability of the intermediate monocyclic phosphoranes of type (XCI) and (XCII, R = alkyl) is apparently insufficient to prevent the epimerisation of the phosphonates (LXXXIX) and (XC) preceding them (Scheme 4):[126,127]

Scheme 4



(LXXXIX), *erythro* (XC), *threo* (XCI) (XCII)

The alkoxides (LXXXIX) and (XC) obtained from five-membered cyclic phosphonates (LXXXVII), rapidly form the more stable spirophosphoranes (XCIII), which should prevent the interconversion of the *erythro*- and *threo*-intermediates and hence should favour the formation of appreciable amounts of *cis*-olefins (the ratio of *cis*- and *trans*-olefins in reactions of five-membered cyclic phosphonates is close to 60:40 [126]). The study of ^{31}P NMR spectra of the reaction mixture of compound (LXXXVII), where R = $CH(CH_3)CH(CH_3)$ and X = $COOC_2H_5$, with benzophenone and aryl cyclopropyl ketones made it possible to demonstrate the formation of a spirophosphetan of type (XCIII):[129]



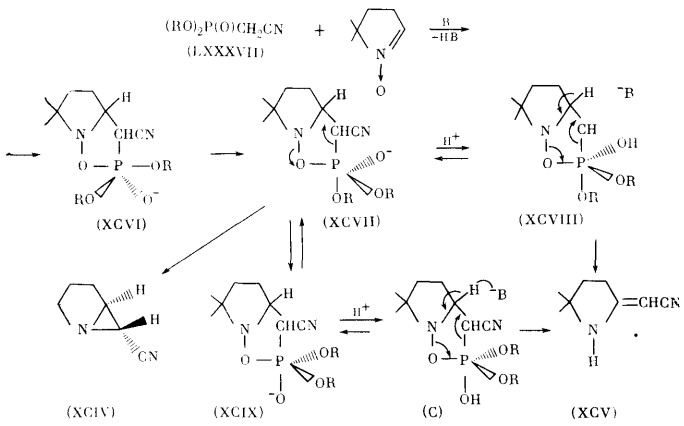
(XCIII), *threo + erythro*

Phosphonates of the dioxaphosphorinane series also produce considerable amounts of *cis*-olefins in these reactions[128], but their content is appreciably lower, which may be attributed to the lower stability of the intermediate phosphoranes with a six-membered ring than that of the compounds with a five-membered ring (the effect of the five-membered ring).

The size of the phosphorus-containing ring in phosphonates with an active methylene group influences also the reactions with nitrones. The interaction of acyclic phosphonates with nitrones in aprotic solvents leads to the preferential or exclusive formation of the aziridines (XCIV), while in protic solvents this reaction proceeds to the enamines (XCV) whose content increases with the acidity of the medium[130–132]. These results have been interpreted on the hypothesis that the intermediate (XCVI) participates in the process. The formation of the reaction product requires the transfer of a carbon atom in compound (XCVII) to the *a*-position via permutation isomerisation; the decomposition of compound (XCVIII) leads to the formation of an aziridine. Protonation neutralises compound (XCVII) and 1,2-elimination from compound (XCVIII) gives rise to the enamine (XCV).

The reaction of the five-membered phosphonate (LXXXVII), where R,R = $CH(CH_3)CH(CH_3)$, proceeds via the intermediates (XCVII) and (XCVIII), whose stabilisation is improved by virtue of the *a–e* disposition of the two five-membered rings. The decomposition of compound (XCVII) also leads to a single product of the reaction of 2-cyanomethyl-3,4-dimethyl-2-oxo-1,3,2-dioxaphospholan, namely the aziridine (XCIV).[133] In the six-membered 5,5-dimethyl-1,3,2-dioxaphosphorinane derivative (LXXXVII), where R,R = $CH_2C(CH_3)_2CH_2$, the *a–e* position of the six-membered ring in the boat conformation[61,62] gives rise to the unfavourable non-bonding 1,4-interaction of the *gem*-dimethyl groups with the substituent at the phosphorus atom. For this reason, the intermediate (XCIX) with an *e–e* ring in the chair conformation, where the oxide anion occupies the *a*-position, is preferable. It is known that the oxide anion in the *a*-position is a stronger base[13] and is rapidly protonated to compound (C) with subsequent β-elimination of an enamine. Under these conditions, the weaker base (XCVII) remains in the form of an anion (in the reactions of the five-membered phosphonate) and decomposes to aziridine (Scheme 5).

Scheme 5



In the reactions of the phosphonate (LXXXVII), where R,R = $CH(CH_3)CH(CH_3)$ and X = CN, the formation of a spirophosphorane, which gives rise to high-field signals (−35 and −36 p.p.m.) in ^{31}P NMR spectra, was demonstrated[134].

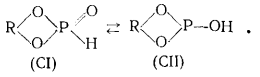
V. CYCLIC PHOSPHORUS ACIDS

1. Alkylenephosphorous Acids

The principal data on the methods of synthesis, stereochemical features, and certain reactions of alkylenephosphorous acids are presented in a recently published review[135]. We shall therefore consider below only the result of later studies and those which permit inferences about the chemical consequences of the incorporation of the hydrophosphoryl fragment in a five- or six-membered ring.

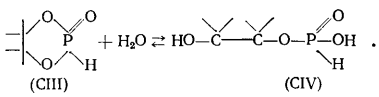
As in cyclic six-membered phosphates, among 1,3-alkylene phosphites, the stereoisomer with the P=O group in the *e*-position is more stable. Whereas in six-membered hydrophosphoryl compounds the conversion of the labile forms into stable forms takes place fairly readily, the analogous 1,3,2-dioxaphospholans do not tend to undergo the conversion readily[135].

The acid-base properties of alkylene phosphites and the influence of dihydroxyalkylene substituents on the diad tautomerism have been investigated:



The study of alkylenephosphorous acids in alcoholic[136] and aqueous alcoholic media[137] demonstrated the anomalously high acidity of the five-membered hydrophosphoryl compounds, which was explained by the presence of considerable amounts of the phosphite form (CII) and by the electron-accepting influence of the 1,2-dihydroxyalkylene groups. However, a detailed study of the acid–base properties of methyl pinacolphosphorous acid in aqueous organic solvents[138–140] made it possible to relate its high acidity to its ready

reversible hydrolysis to the monoalkyl phosphite (CIV), which is responsible for the highly acidic properties of the methyl pinacol phosphite:



(CIII) (CIV)

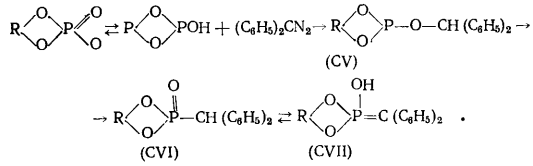
On the other hand, the reversibility of the hydrolysis of 2,3-butylene phosphite was not observed[139]; unusual ease of recyclisation is specific solely to the methyl pinacol phosphite derivative (the Ingold–Thorpe effect). A considerably smaller acidity has been found for 4,5-dimethyl-2-oxo-2-phenyl-1,3,2-dioxaphospholan[137]. Factors other than the contribution of structure (CIV) (for example, the CH acidity of the ring) probably play a role in this instance. The considerably smaller strength of methyl pinacol phosphorothious acid compared with the oxo-analogue is also striking (the pK_a in 50% ethanol are 4.76 and 2.37 respectively[141]); this difference is difficult to account for from the standpoint of hydrolysis, because the thiono-analogue of the acid (CIV) should be more acid or at least comparable in its acidity.

Possibly the protonated forms of compounds (CI) and (CII) contribute to the overall acidity of cyclic hydrophosphoryl compounds[137,141] and their formation is characteristic mainly of five-membered cyclic derivatives. The six-membered and acyclic hydrophosphoryl compounds have similar acid properties[137,139,141].

The contribution of the phosphite form to the equilibrium (CI) ⇌ (CII) involving five-membered alkylene phosphites is apparently less important than for the six-membered and acyclic derivatives[137]. In ethylene phosphoromonothiolite the content of form (CII) is estimated as ~30%;[142] catecholphosphorous acid exists in the condensed phase mainly in the phosphorus (III) form and both isomers are detected only in solutions[137].

The more marked tendency of five-membered alkylene phosphites to isomerise to the phorphorus(III) derivatives has been used to explain the characteristics of the chemical behaviour of these hydrophosphoryl compounds. Thus cyclic phosphorous and phosphorothious acids of the 1,3,2-dioxaphospholan series readily combine with sulphur in the absence of catalysts with formation of alkylenephosphoro-monothious and alkylenephosphorodithious acids[141]. Six-membered phosphorothioites combine with sulphur in the presence of bases[143]; this reaction is not characteristic of acyclic hydrothionophosphoryl compounds[144].

Fundamental differences between the reactivities of acyclic and cyclic hydrophosphoryl compounds have been noted for their reactions with diphenyldiazomethane. Whereas the former react with diazoalkanes only under severe conditions with formation of phosphorus–nitrogen derivatives[145,146], cyclic phosphates interact vigorously with diazo-derivatives, the reaction being accompanied by a rise of temperature and the evolution of nitrogen even in the cold[147]. The reaction proceeds via a stage involving the formation of diphenylmethyl phosphite (CV), which subsequently isomerises to the phosphonate (CVI) in equilibrium with the ylide (CVII):



(CV) (CVI) (CVII)

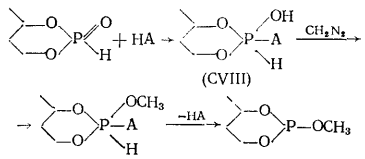
Kinetic studies of the two-stage formation of compound (CV) demonstrated the similarity of the mechanisms of the reactions of cyclic phosphites[148] and acids based on phosphorus in the highest oxidation state[149], which include the initial proton transfer and subsequent decomposition of the resulting ion pair:

$$HA + (C_6H_5)_2CN_2 \xrightarrow{k_1} HN_2C(C_6H_5)_2^+A^- \xrightarrow{k_2} \text{product.}$$

It was established that five-membered alkylene phosphites react faster by a factor of 3–12 than the six-membered derivatives and diphenyl phosphite, in conformity with the strengths of these acids. Measurement of the rate of consumption of the diazo-component and of the accumulation of nitrogen made it possible to compare the rates of the two stages. It was found that the rates of reaction measured by the two methods and the activation parameters are similar for the least reactive neopentyl- and diphenyl-phosphorous acids, i.e. $k_1 > k_2$. For the more acid 2,3-butylene phosphite, the rate of evolution of nitrogen is smaller by an order of magnitude than the rate of consumption of the diazo-compound[148]; in this case the slow stage of the process is the unimolecular decomposition of the ion pair ($k_2 > k_1$).

The intermediate formation of the diphenylmethyl phosphite (CV) has been demonstrated in the reaction of catechol phosphorous acid[147] and the capacity for the subsequent transformation into a phosphonate and an ylide was demonstrated in a study of compound (CV), obtained by the reaction of 2,3-butylene phosphorochloridite with diphenylmethanol.

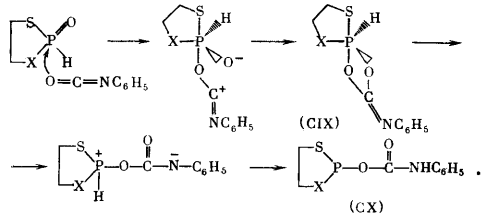
We may note that the interaction of 1,3-butylene phosphite with diazomethane in protic media has been attributed to the involvement of the phosphorane adduct (CVIII):[150]



(CVIII)

However, this mechanism does not explain the non-catalysed reaction of alkylene-phosphorous acids and phosphorothioites in aprotic media[148].

The addition of five-membered alkylenephosphorous acids to unsaturated systems also proceeds with a decrease of the coordination number of the phosphorus atom. Thus phenyl isocyanate combines with ethylene phosphoromono-thioites and phosphorodithioites with formation of the phosphorus(III) derivatives (CX),[142] probably via a mechanism involving the nucleophilic addition of the acid to the tautomeric form with a tervalent phosphorus atom or the addition of their conjugate alkylene phosphite anions to the C=N bond of phenyl isocyanate. An alternative mechanism presupposes nucleophilic attack by the carbonyl oxygen atom of the unsaturated reactant on the tetrahedral phosphorus atom in the alkylene phosphite[135]. This course of the reaction involves the formation of the intermediate (CIX) with a high energy, which is due to the considerable angular strain in the dioxaphosphetan ring incorporating an sp^2-hybridised carbon atom:



(CIX) (CX)

Adducts with a phosphite structure are formed as a result of the non-catalysed addition of catechol phosphorous acid to styrene, anethole, and butyl vinyl ether[151]. Phosphites isomerise more or less readily to phosphonates. Intermediates with phosphorus(III) could not be detected in the reactions of 2,3-butylene phosphite and phosphorothioite with butyl vinyl ether. It is noteworthy that acyclic phosphorous acids do not undergo heterolytic addition to compounds whose double bond is nucleophilic[152,153].

2. Quinquevalent Phosphorus Acids. The Electronic Influence of Dihydroxyalkylene Substituents

In contrast to the types of organophosphorus compounds examined above in which the reactive centre is mainly the phosphorus atom, the reaction of phosphorus(V) acids , where R = 1,2- or 1,3-alkylene and X,Y = O or S, are characterised by the involvement of the functional groups in the side chain, while the phosphorus-containing cyclic substituents exert a specific influence on them.

Cyclic phosphonic and phosphinic acids have on the whole acidities comparable to those of the acyclic phosphonates and phosphinates[154-159], although the strain in the five- and four-membered rings[154,155] leads to some enhancement of the acid properties.

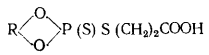
However, a number of acids of the 1,3,2-dioxaphospholan and 1,3,2-dioxaphosphorinane series were found to exhibit appreciable differences from the phosphinate derivatives in aqueous alcoholic media in which potentiometric studies were carried out[158].

Comparison of the pK_a of substituted six-membered phosphoric acids in aqueous ethanol solutions, absolute ethanol, and nitromethane permitted the hypothesis[156,157,159] that there is a possibility of the specific solvation of the dihydroxyalkylene substituents at the phosphorus atom in aqueous organic media. Calorimetric and spectroscopic studies[160] of the solvation of isotypical cyclic and acyclic phosphorus and carbon compounds led to the discovery of a difference between the types of solvation of the cyclic compounds, on the one hand, and the acyclic compounds, on the other; no anomaly was found in water–alcohol mixtures. Nevertheless the available data are still insufficient to infer the nature of this difference.

Cyclic phosphoromonothioic acids[161] are stronger in aqueous alcoholic media than their acyclic analogues[162], which may be due to a more significant contribution to the tautomeric thione–thiol equilibrium by the thiolo-form of cyclic phosphorothioates[161]. This hypothesis is consistent with the results of the determination of the oxidation-reduction potentials of the latter compounds in these solutions[163]. In solvents with a lower polarity the thiono-forms of cyclic phosphoromonothioic acids predominate[136].

Cyclic phosphorodithioic acids also exhibit stronger proton-donating properties in benzene and anisole than the acyclic acids[164]. However, in absolute ethanol the values of pK_a of alkylene phosphorodithioates are higher than for their analogues with an open-chain structure. This anomaly of the acid properties was explained by the conformational characteristics of these cyclic compounds. Thus the *cis*-disposition of the exocyclic S–H and P–S groups in dioxaphospholan derivatives makes the proton less mobile and the effective positive charge on the phosporus is "quenched" as a result of the solvation by ethanol molecules which are of suitable size[165]. Such *cis*-orientation in the triad P(S)SH predetermines the possibility of the formation of intramolecular hydrogen bonds in the molecules of five-membered cyclic phosphorodithioates[166].

The removal of the acid centre from the phosphorodithioate substituent in acids of the type



promotes a change in the mutual orientation of the functional groups and the manifestation of a greater electron-accepting capacity by 1,2-dihydroxyalkylene substituents compared with the alkoxy-substituents[167].

The study of the acid–base properties of the acids of phosphorus in the highest oxidation state is important for the determination of the electronic influence (σ^{ph}) of dihydroxyalkylene substituents at the phosphorus atom. However, the use of the ionisation constants of oxygen-based cyclic phosphates for the calculation of the σpH on the basis of Kabachnik's familiar standard series[168] proved to be impossible, because it was shown[156,157] that cyclic and acyclic phosphates are acids of different chemical types. Because of this, the values of σ^{ph} determined from this series do not exhibit the required constancy—they vary as the solvent is altered (Table 2, Nos.12–15).

Attempts have been made to determine the values of σ^{ph} of dihydroxyalkylene substituents from other reaction series: from the free energies of the association of cyclic phosphoryl compounds with *p*-fluorophenol[169], the basicity constants, ^{19}F NMR data for phosphorimidate compounds[170], and the stability constants of phosphinodithioyl complexes of cobalt[172]. Analysis of the results (Table 2) showed that invariant values of the σ^{ph} constants can be assigned only to alkylene (Nos.1 and 10) and dihydroxytetramethylene (No.20) substituents. For other 1,2- and 1,3-substituents, this is at present difficult to achieve.

One of the causes of the inadequately clear-cut quantitative ideas concerning the influence of these types of substituents at the phosphorus atom is the lack of exact views on the nature of the solvation and transolvation of the cyclic fragment containing a phosphorus atom. Admittedly, this factor cannot be decisive because the values of σ^{ph} for acyclic groups are fairly satisfactory in different reaction series and in media of different polarity[173].

One must also note the dependence of the σ^{ph} of the groups RX not only on the nature of the inductive and resonance components in the overall polar effect of substituents[173] but also on their steric influence[174-177]. This is apparently equally valid also as regards the groups X–R–Y at the phosphorus atom, although one cannot rule out the possibility that in the case of cyclic substituents hyperconjugation and field influences can be manifested together with the effects enumerated above.

On the other hand, there are data showing that the steric effect of dihydroxyalkylene substituents with sterically fixed configurations is less pronounced than the effect of two alkoxy-groups having the same number of carbon atoms[178].

Thus a realistic estimation of the relative contributions of the inductive, mesomeric, and structural components to the overall values of σ^{ph} for cyclic substituents at the phosphorus atom is at present fairly difficult. Only certain qualitative conclusions can be drawn from the available data (Table 2): the strained phospholan substituents have the most marked electron-accepting properties; the influence of the phosphorinane fragments is similar to the overall effect of two acyclic alkoxy-groups at the phosphorus atom.

It has been suggested that the enhancement of the electron-accepting effect of the 1,2-dihydroxyalkylene substituent at the phosphorus atom in a five-membered ring

Table 2. The values of σ^{ph} for cyclic substituents at the phosphorus atom.

№	Substituent A + B	From the pK_a for the acids ABPOOH					α	β	γ	References
		H_2O	50% C_2H_5OH	80% C_2H_5OH	95% C_2H_5OH	CH_3NO_2				
1	$-(CH_2)_4-$	−1.84	−1.62	−1.83*	−1.71	−1.77	−1.78	—	—	[157, 169]
2	$-O(CH_2)_3-$	—	—	—	—	—	−1.01	—	—	[169]
3	$-O(CH_2)_2N(CH_3)-$	—	—	—	—	−1.19**	—	−0.30	—	[170]
4	$-O(CH_2)_2N(C_6H_5)-$	—	—	—	—	−0.13**	—	+0.93	—	[170]
5	$-O(CH_2)_2N$ (iso-C_3H_7)—	—	—	—	—	—	−1.17	—	—	[169]
6	$-O(CH_2)_2O-$	—	—	—	—	—	+0.11	+0.90	—	[169, 170]
7	$-OCH(CH_3)CH_2O-$	—	—	—	—	—	−0.02	+0.75	+1.21	[139, 164, 170]
8	$-OCH(CH_3)CH(CH_3)O-$	—	—	—	—	—	—	—	+0.62	[164]
9	$-OC(CH_3)_2C(CH_3)_2O-$	—	—	—	—	—	−0.05	—	+0.10	[164, 169]
10	$-(CH_2)_5-$	−2.18	−1.95	−2.12	−1.97	−2.27	−2.26	—	—	[157, 169]
11	$-O(CH_2)_4-$	—	—	—	—	—	−1.44	—	—	[169]
12	$-O(CH_2)_3O-$	−0.87	−0.64	−0.25	−0.08	−0.14***	−0.56	+0.02	—	[157, 169]
13	$-OCH(CH_3)CH_2CH_2O-$	−0.75	−0.65	−0.42	−0.27	−0.20	−0.55	—	+1.06	[157, 169, 171]
14	$-OCH(C_6H_5)CH_2CH_2O-$	−0.67	−0.54	−0.18	+0.06	+0.01	−0.47	—	—	[157]
15	$-OCH_2C(CH_3)_2CH_2O-$	−0.67	−0.57	−0.19	0.00	−0.08	−0.46	—	+1.73	[157, 164, 169]
16	$-OCH$ (iso-C_3H_7)$C(CH_3)_2CH_2O-$	—	—	—	—	—	−0.54	—	—	[139]
17	$-O(CH_2)_3N$(iso-C_3H_7)-	—	—	—	—	—	−1.72	—	—	[169]
18	$-CH_2SCH_2-$	+0.195	—	—	—	—	—	—	—	[155]
19	$-N(t\text{-}C_4H_9)CH=C(t\text{-}C_4H_9)O-$	—	—	—	—	—	+0.5****	—	—	[172]
20	$-O(CH_2)_4O-$	−0.58	−0.66	−0.60	−0.39	−0.49	−0.72	—	—	[139]
21	$-O(CH_2)_2N$(iso-C_4H_9)-	—	—	—	—	—	−1.24	—	—	[139]

Note. α, β, and γ are the values of σ^{ph} found from the thermodynamic characteristics of the hydrogen-bonded complexes of cyclic phosphoryl compounds with *p*-fluorophenol, the chemical shift $\delta(^{19}F)$ of fluorine-substituted arylimides of cyclic phosphorus acids, and the stability constants of the cobalt complexes of phosphorus dithioacids respectively.

*The value of σ^{pH} found from the pK_a for the acids ABPSOH is −1.65.[161]

**Found from the basicity constants of the arylimides of cyclic phosphorus acids.

***The value of σ^{ph} found from the basicity constants of the arylimides of cyclic phosphorus acids is −0.61.[170]

****Found from the correlation between the values of σ and the stretching vibration frequencies of the phosphoryl groups ν(P–O) in the compounds ABP(O)R.

is associated with the rigid fixation of the oxygen atoms, which weakens the p_π–d_π interaction of the unshared electron pairs of the endocyclic oxygen atoms with the *d* orbitals of phosphorus[179]. This increases the electron density deficit at the tetracoordinate phosphorus atom and reduces the basicity and nucleophilicity of the trivalent phosphorus atom in a 1,3,2-dioxaphospholan ring. We may note that the more pronounced electron-accepting properties of the 1,2-dihydroxyalkylene group compared with two alkoxy-groups are also attributed to the decrease of the endocyclic P–O–C angles, which alters the hybridisation of the oxygen atom from sp^2 towards sp^3, and to a decrease of the π character of the ring P–O ester linkages[180].

The reactivity of phosphorus(V) acids has been studied more extensively in relation to phosphorus dithio-acids. In the general case, cyclic phosphorodithioates are more reactive than their acyclic analogues. Thus their reaction with diphenyldiazomethane is accompanied by a greater heat change[181], they add faster to acrylonitrile[182], and they are more reactive in the protodemetallation reaction of tetra-ethylstannane[184]. This is mainly associated with the greater strength of the cyclic dithio-acids compared with the acyclic analogues.

On the other hand, the complexes of transition metal ions nickel(II), cobalt(II), silver(II), and zinc(II) with cyclic phosphinodithioyl ligands are less stable than the complexes with dialkoxyphosphinyl ligands[172,185,186], which can be naturally accounted for by the greater electron-accepting capacity of the cyclic ligands. For the same reason, the alkylation of salts of cyclic dithio-acids[183] is much slower than that of the acyclic acids[187].

The kinetics of the addition of cyclic phosphorodithioates to α-substituted styrylphosphonates and ethyl acrylate are unusual[188,189]. Whereas acyclic phosphorodithioates interact with these unsaturated reagents via the bimolecular nucleophilic addition mechanism with 1,4-orientation of the dithio-acid with respect to the system of multiple bonds of the unsaturated reactant, in the case of the stronger cyclic dithio-acids the rate of reaction is described by a third-order equation: of first order with respect to the unsaturated reactant and of second order with respect to the acid. In the first stage a hydrogen-bonded complex of the dithio-acid with a protophilic centre of the unsaturated compound (P=O or C=O) is formed and then a second molecule of the cyclic phosphorodithioate adds to the multiple bond.

* * *

The data presented in this review demonstrate the wide variety of the reactivities of 1,3,2-diheterophospholans and 1,3,2-diheterophosphorinanes, expressed both in the anomalous rates of reaction and in the unusual pathways followed in the interactions, which are not characteristic of their acyclic analogues. The fairly considerable ease of the change in the coordination number of the phosphorus atom, $P^{IV} \rightleftharpoons P^{V}$–$P^{VI}$, due to the favourable thermodynamic features of the trigonal and tetragonal bipyramids of penta-coordinate and hexacoordinate phosphorus compounds containing five-membered heterocycles, has been demonstrated in relation to cyclic and particularly five-membered organophosphorus compounds. The study of the reactivity

of cyclic derivatives of phosphorus acids established the important role in chemical reactions of intermediates containing phosphorus atoms in the highest coordination states. This made it possible in its turn to consider the fine details of many biochemical processes occurring with participation of phosphate esters. On the other hand, the available information about the interconversion of phosphorus compounds with different coordination numbers revealed and explained the unity and wide variety of the chemistry of organophosphorus compounds.

REFERENCES

1. S.I.Malekin, Yu.L.Kruglyak, and I.V.Martynov, in "Khimiya Organicheskikh Soedinenii Fosfora" (The Chemistry of Organic Compounds of Phosphorus), by D.Purdela and R.Vylchanu, Izd.Khimiya, Moscow, 1972, p.637.
2. M.J.Gallagher, in "Stereochemistry of Heterocyclic Compounds" (Edited by W.L.F.Armarego), J.Wiley, New York, 1977, Part 2, p.339.
3. R.F.Hudson and J.G.Verkade, Tetrahedron Letters, 1975, 3231.
4. J.G.Verkade, Phosphorus and Sulfur, 1976, **2**, 215.
5. R.P.Arshinova, Symposium, "Stroenie i Reaktsionnaya Sposobnost' Organicheskikh Soedinenii" (The Structure and Reactivity of Organic Compounds) (Edited by B.A.Arbuzov), Izd.Nauka, Moscow, 1978, p.66.
6. R.P.Arshinova, Doctoral Thesis in Chemical Sciences, Ul'yanov-Lenin Kazan State University, Kazan, 1979.
7. C.R.Hall and T.D.Inch, Tetrahedron, 1980, **36**, 2059.
8. F.Ramirez, H.Okuzaki, and J.F.Marecek, Heterocycles, 1978, **11**, 631.
9. R.F.Hudson and C.Brown, Acc.Chem.Res., 1972, **5**, 204.
10. F.H.Westheimer, Acc.Chem.Res., 1968, **1**, 70.
11. D.Marquarding, F.Ramirez, I.Ugi, and P.Gillespie, Angew.Chem., 1973, **85**, 99.
12. F.Ramirez and I.Ugi, Bull.Soc.chim.France, 1974, 453.
13. F.H.Westheimer, Pure Appl.Chem., 1977, **49**, 1059.
14. S.Trippett, Pure Appl.Chem., 1974, **40**, 595.
15. S.Trippett, Phosphorus and Sulfur, 1976, **1**, 89.
16. I.Ugi, D.Marquarding, H.Klusacek, P.Gillespie, and F.Ramirez, Acc.Chem.Res., 1971, **4**, 288.
17. P.Gillespie, P.Hoffmann, H.Klusocek, D.Marquarding, S.Pfohl, F.Ramirez, E.A.Tsolis, and I.Ugi, Angew.Chem., 1971, **83**, 691.
18. B.A.Arbuzov and N.A.Polezhaeva, Uspekhi Khim., 1974, **43**, 933 [Russ.Chem.Rev., 1974(5)].
19. J.A.Gerlt, F.H.Westheimer, and J.M.Sturtevant, J.Biol.Chem., 1975, **250**, 5059.
20. D.G.Gorenstein, B.A.Luxon, J.B.Findlay, and R.Momii, J.Amer.Chem.Soc., 1977, **99**, 4170.
21. D.G.Gorenstein, B.A.Luxon, and J.B.Findlay, J.Amer.Chem.Soc., 1979, **101**, 5869.
22. D.G.Gorenstein, B.A.Luxon, and E.M.Goldfield, J.Amer.Chem.Soc., 1980, **102**, 1757.
23. C.Aksnes and K.Bergesen, Acta Chem.Scand., 1966, **20**, 2508.
24. R.Kluger, F.Covitz, E.Dennis, L.D.Williams, and F.H.Westheimer, J.Amer.Chem.Soc., 1969, **91**, 6066.
25. T.Koizumi, J.Yoshida, Y.Watanabe, and E.Yoshii, Chem.Pharm.Bull., 1975, 1381.
26. T.Koizumi, Y.Watanabe, Y.Yoshida, K.Takeda, and E.Yoshii, Tetrahedron Letters, 1977, 1913.
27. T.Koizumi, J.Agai, and E.Yoshii, Tetrahedron Letters, 1973, 4763.
28. F.Ramirez, J.R.Marecek, H.Tsuboi, H.Okazaki, and M.Novakowski, Phosphorus, 1976, **6**, 215.
29. E.T.Kaiser and T.W.S.Lee, J.Amer.Chem.Soc., 1971, **93**, 2351.
30. R.Kluger and P.Wasserstein, Tetrahedron Letters, 1974, 3451.
31. M.Mullez and M.Wakselman, Phosphorus and Sulphur, 1980, **8**, 41.
32. R.S.Edmundson, C.I.Forth, and T.A.Moran, J.Chem.Soc.C, 1971, 2452.
33. M.G.Newton, J.R.Cox, and J.A.Bertrand, J.Amer.Chem.Soc., 1966, **88**, 1503.
34. C.Brown, J.A.Boudreau, B.Hewitson, and R.F.Hudson, Chem.Comm., 1975, 504.
35. R.S.Edmundson, Chem.Ind.(London), 1967, 1809.
36. R.S.Edmundson and A.J.Lambie, J.Chem.Soc.B, 1967, 577.
37. E.E.Nifantev, I.S.Nasonovskii, A.V.Miklashevskii, A.I.Zavalishina, and E.I.Smirnova, Zhur.Org. Khim., 1975, **11**, 2206.
38. A.N.Pudovik, R.A.Cherkasov, and R.M.Kondrat'eva, Vysokomol.Soed., **9A**, 1118.
39. D.Houalla, M.Sanches, R.Wolf, and R.H.Osman, Tetrahedron Letters, 1978, 4675.
40. E.F.Perozzi and J.C.Martin, J.Amer.Chem.Soc., 1979, **101**, 1592.
41. R.M.Busley, C.K.Ingold, and J.F.Thorpe, J.Chem. Soc., 1915, **107**, 1080.
42. C.K.Ingold, J.Chem.Soc., 1921, **119**, 305.
43. J.A.Boudreau, C.Brown, and R.F.Hudson, Chem. Comm., 1975, 679.
44. C.Brown, J.A.Boudreau, B.Hewitson, and R.F.Hudson, J.Chem.Soc., Perkin Trans.II, 1976, 888.
45. D.B.Cooper, J.M.Harrison, and T.D.Inch, Tetrahedron Letters, 1974, 2697.
46. C.R.Hall and T.D.Inch, Tetrahedron Letters, 1976, 3645.
47. C.R.Hall and T.D.Inch, Tetrahedron Letters, 1977, 3761.
48. S.J.Abbott, S.R.Joness, S.A.Weinmann, F.M.Bockhoff, F.W.McLafferty, and J.R.Knowles, J.Amer.Chem.Soc., 1979, **101**, 4323.
49. J.Chenocult, M.Dreux, P.Savignac, and P.Chabrier, Compt.rend., 1971, **272C**, 955.
50. C.R.Hall and N.E.Williams, Tetrahedron Letters, 1980, 4959.
51. C.R.Hall, T.D.Inch, and J.W.Lawton, Tetrahedron Letters, 1979, 2729.
52. D.B.Cooper, C.R.Hall, J.M.Harrison, and T.D.Inch, J.Chem.Soc., Perkin Trans.I, 1977, 1969.
53. C.R.Hall and T.D.Inch, J.Polymer Chem., 1980, **54**, 469.
54. P.Chabrier and N.T.Thuong, Compt.rend., 1975, **281C**, 397.
55. D.C.Gay and N.K.Hammer, J.Chem.Soc.B, 1970, 1123.
56. D.C.Gay and N.K.Hammer, Chem.Comm., 1970, 1564.
57. D.C.Gay and N.K.Hammer, J.Chem.Soc., Perkin Trans.II, 1972, 929.
58. J.Emsley and D.Hall, "The Chemistry of Phosphorus", Harper and Row, London, 1976, p.330.

59. T.R.Fukuto and R.L.Metcalf, J.Medicin.Chem., 1965, **8**, 759.
60. D.G.Gorenstein, R.Rowell, and J.Findlay, J.Amer. Chem.Soc., 1980, **102**, 5077.
61. S.A.Bone, S.Trippett, and P.J.Whittle, J.Chem. Soc., Perkin Trans.I, 1977, 80.
62. J.H.Barlow, S.A.Bone, D.R.Russel, S.Trippett, and P.J.Whittle, Chem.Comm., 1976, 1031.
63. B.C.Chang, W.E.Conrad, D.B.Denney, D.Z.Denney, R.Edelman, R.L.Powell, and D.W.White, J.Amer. Chem.Soc., 1971, **93**, 4004.
64. W.Stez et al., Tetrahedron, 1973, **29**, 539.
65. J.M.Harrison and T.D.Inch, J.Chem.Soc., Perkin Trans.I, 1979, 2855.
66. Z.Omelanzuk et al., Tetrahedron, 1975, **31**, 2803.
67. Y.Margalit, G.Amitai, and Y.Ashani, Phosphorus and Sulphur, 1977, **3**, 315.
68. J.Engels and E.-J.Schlaeger, Medicin.Chem., 1977, **20**, 907.
69. J.Engels and J.Hotteiezer, Chem.Ber., 1977, **110**, 2019.
70. D.B.Cooper, J.M.Harrison, and T.D.Inch, J.Chem. Soc., Perkin Trans.I, 1974, 1058.
71. S.H.Gehrte and W.S.Wadsworth, J.Org.Chem., 1980, **45**, 3921.
72. M.Baumann and W.S.Wadsworth, J.Amer.Chem.Soc., 1978, **100**, 6388.
73. J.K.Chakrabarti and O.M.Friedman, J.Heterocycl. Chem., 1973, **10**, 55.
74. M.K.Grachev, V.A.Sukhanov, D.A.Predvoditelev, V.I.Shvets, and E.E.Nifant'ev, Zhur.Org.Khim., 1977, **13**, 1830.
75. T.D.Inch, G.J.Lewis, R.G.Wilkinson, and P.Watts, Chem.Comm., 1975, 500.
76. J.M.Harrison, T.L.Inch, and G.Lewis, J.Chem.Soc., Perkin Trans.I, 1975, 1892.
77. C.R.Hall and T.D.Inch, Phosphorus and Sulphur, 1979, **7**, 171.
78. D.B.Cooper, T.D.Inch, and G.I.Lewis, J.Chem. Soc., Perkin Trans.I, 1974, 1043.
79. S.A.Khan, A.J.Kirby, M.Wakselman, D.P.Horning, and J.M.Lewlor, J.Chem.Soc.B, 1970, 1182.
80. J.A.Gerlt, N.I.Gutterson, R.E.Drews, and J.A.Sokolow, J.Amer.Chem.Soc., 1980, **102**, 1665.
81. F.J.Marsh, P.Weiner, J.E.Dauglus, P.A.Kollman, G.L.Kennyon, and J.A.Gerlt, J.Amer.Chem.Soc., 1980, **102**, 1660.
82. J.A.Gerlt, N.I.Gutterson, P.Datta, B.Bellan, and C.L.Penney, J.Amer.Chem.Soc., 1980, **102**, 1655.
83. C.L.Penney and B.Belleau, Canad.J.Chem., 1978, **56**, 2396.
84. T.Koizumi, Y.Watanabe, Y.Yoshida, and E.Yoshii, Tetrahedron Letters, 1974, 1075.
85. J.Gloede and H.Gross, Tetrahedron Letters, 1976, 917.
86. M.Gallagher, A.Munoz, G.Gence, and M.Koening, Chem.Comm., 1976, 321.
87. F.Ramirez, M.Nowakowski, and J.F.Marecek, J.Amer.Chem.Soc., 1976, **98**, 4330.
88. F.Ramirez, M.Nowakowski, and J.F.Marecek, J.Amer.Chem.Soc., 1977, **99**, 4515.
89. R.Sarma, F.Ramirez, B.McKeever, M.Novakowski, and J.F.Marecek, J.Amer.Chem.Soc., 1978, **100**, 5391.
90. A.Munoz, M.Gallagher, A.Klaebe, and R.Wolf, Tetrahedron Letters, 1976, 673.
91. Chang Bui Cong, A.Munoz, M.Sanches, and A.Klaebe, Tetrahedron Letters, 1977, 1587.
92. A.Munoz, B.Garrigues, and M.Koening, Chem. Comm., 1978, 219.
93. A.Munoz, B.Garrigues, and M.Koening, "International Conference on Phosphorus Chemistry, Halle (Saale), GDR", 1979, p.139.
94. M.Sanches, J.F.Brazier, D.Houalla, and R.Wolf, "International Conference on Phosphorus Chemistry, Halle (Saale), GDR", 1979, p.123.
95. M.Sanches, J.F.Brazier, D.Houalla, and R.Wolf, Nouv.chim., 1979, **3**, 775.
96. V.P.Kukhar', E.V.Grishkun, and V.P.Rudavskii, Zhur.Obshch.Khim., 1978, **48**, 1424.
97. V.P.Kukhar and V.A.Gilyarov, Pure Appl.Chem., 1980, **52**, 891.
98. V.P.Kukhar', E.V.Grishkun, V.P.Rudavskii, and V.A.Gilyarov, Zhur.Obshch.Khim., 1980, **50**(7), 1477.
99. Yu.G.Gololobov, L.I.Nesterova, V.P.Kukhar', and V.I.Luk'yanchuk, Zhur.Obshch.Khim., 1981, **51**, 477.
100. J.I.G.Cadogan, J.Gosney, E.Henry, T.Naisby, B.Nay, N.J.Stenerd, and N.J.Tweddle, Chem. Comm., 1979, 189.
101. G.Kemp and S.Trippett, J.Chem.Soc., Perkin Trans.I, 1979, 879.
102. Y.Segatt and J.Granoth, J.Amer.Chem.Soc., 1978, **100**, 5131.
103. G.A.Kutyrev, A.A.Kutyrev, R.A.Cherkasov, and A.N.Pudovik, Dokl.Akad.Nauk SSSR, 1980, **256**, 601.
104. O.R.Nuretdinova and F.F.Guseva, Izv.Akad.Nauk SSSR, Ser.Khim., 1980, 2594.
105. O.N.Nuretdinova, Izv.Akad.Nauk SSSR, Ser. Khim., 1980, 477.
106. V.A.Gilyarov, N.A.Tikhonina, V.G.Andrianov, Yu.T.Struchkov, and M.I.Kabachnik, Zhur.Obshch. Khim., 1978, **48**, 732.
107. V.P.Kukhar', E.V.Grishkun, and V.P.Rudavskii, Zhur.Obshch.Khim., 1978, **48**, 1267.
108. V.P.Kukhar', E.V.Grishkun, and V.P.Rudavskii, Zhur.Obshch.Khim., 1978, **48**, 2657.
109. J.A.Gibson, G.V.Roschenthaler, D.Schomburg, and W.S.Sheldrick, Chem.Ber., 1978, **111**, 1887.
110. G.V.Roschenthaler, K.Sauerbrey, and R.Schmutzler, Chem.Ber., 1978, **111**, 3105.
111. W.Sted and A.Lopusinski, Tetrahedron, 1973, **29**, 547.
112. P.Chabrier, N.T.Thuong, and D.Lemaitre, Compt. rend., 1969, **268**, 1802.
113. H.P.Nguyen, N.T.Thuong, and P.Chabrier, Compt.rend., 1970, **271**, 1465.
114. M.Revel, J.Navech, and F.Mathis, Bull.Soc.chim. France, 1971, 105.
115. W.S.Wadsworth, S.Larsen, and H.L.Horten, J.Org.Chem., 1973, **38**, 256.
116. E.E.Nifant'ev and D.A.Predvoditelev, Bioorg. Khim., 1981, **7**, 1285.
117. H.P.Nguyen, N.T.Thuong, and P.Chabrier, Bull.Soc.chim.France, 1975, 2326.
118. N.T.Thuong and P.Chabrier, Compt.rend., 1972, **275C**, 1125.
119. J.S.Baran, D.D.Langford, and I.Laos, J.Org. Chem., 1977, **42**, 2260.
120. H.P.Nguyen, H.T.Thuong, and P.Chabrier, Compt. rend., 1971, **272C**, 1145.
121. H.P.Nguyen, H.T.Thuong, and P.Chabrier, Compt.rend., 1971, **272C**, 1588.
122. O.N.Nuretdinova, Izv.Akad.Nauk SSSR, Ser.Khim., 1976, 2107.

123. A.N.Pudovik and G.E.Yastrebova, Uspekhi Khim., 1970, **39**, 1190 [Russ.Chem.Rev., 1970(7)].
124. V.V.Ovchinnikov, V.M.Valitova, R.A.Cherkasov, and A.N.Pudovik, Zhur.Obshch.Khim., 1979, **49**, 2434.
125. E.Breuer and D.M.Bannet, Tetrahedron Letters, 1977, 1141.
126. E.Breuer and D.M.Bannet, Tetrahedron, 1978, **34**, 997.
127. B.Deschamps, J.P.Lampin, F.Mathey, and J.Seyden-Penne, Tetrahedron Letters, 1977, 1137.
128. J.Bontagy and R.Thomas, Chem.Rev., 1974, **74**, 87.
129. E.Breuer, S.Zbaida, and E.Segall, Tetrahedron Letters, 1979, 2203.
130. E.Breuer, S.Zbaida, J.Peso, and J.Ronnen-Braustein, Tetrahedron, 1977, **34**, 1145.
131. E.Breuer and S.Zbaida, J.Org.Chem., 1977, **42**, 1904.
132. S.Zbaida and E.Breuer, Tetrahedron, 1978, **34**, 1241.
133. S.Zbaida and E.Breuer, Chem.Comm., 1978, 6.
134. S.Zbaida and E.Breuer, Experientia, 1979, **35**, 851;
135. E.E.Nifant'ev, Uspekhi Khim., 1979, **48**, 1565 [Russ. Chem.Rev., 1979(9)].
136. V.V.Ovchinnikov, V.I.Galkin, R.A.Cherkasov, and A.N.Pudovik, Izv.Akad.Nauk SSSR, Ser. Khim., 1977, 2021.
137. V.V.Ovchinnikov, V.I.Galkin, E.G.Yarkova, L.E.Markova, R.A.Cherkasov, and A.N.Pudovik, Zhur.Obshch.Khim., 1978, **48**, 2424.
138. A.A.Kryuchkov, M.P.Komarova, A.G.Kozachenko, E.I.Matrosov, E.E.Nifant'ev, and M.I.Kabachnik, Izv.Akad.Nauk SSSR, Ser.Khim., 1979, 2456.
139. A.A.Kryuchkov, Abstracts of Candidate's Thesis in Chemical Sciences, Lomonosov Moscow State University, Moscow, 1979.
140. E.I.Matrosov, A.A.Krjuchkov, M.P.Komarova, and A.G.Kazachenko, "International Conference on Phosphorus Chemistry, Halle (Saale), GDR", 1979, p.228.
141. V.V.Ovchinnikov, V.I.Galkin, R.A.Cherkasov, and A.N.Pudovik, Zhur.Obshch.Khim., 1979, **49**, 1693.
142. E.E.Nifant'ev, A.I.Zavalishina, S.F.Sorokina, and A.A.Borisenko, Zhur.Obshch.Khim., 1976, **46**, 471.
143. D.A.Predvoditelev, D.N.Afanas'ev, and E.E.Nifant'ev, Zhur.Obshch.Khim., 1974, **44**, 2629.
144. M.I.Kabachnik and T.A.Mastryukova, Izv.Akad. Nauk SSSR, Otd.Khim.Nauk, 1953, 163.
145. V.A.Gilyarov, Symposium, "Khimiya i Primenenie Fosfororganicheskikh Soedinenii" (The Chemistry and Applications of Organophosphorus Compounds), Izd.Akad.Nauk SSSR, Moscow, 1957, p.275.
146. A.N.Pudovik and R.D.Gareev, Zhur.Obshch.Khim., 1975, **45**, 1674.
147. V.V.Ovchinnikov, V.I.Galkin, E.G.Yarkova, R.A.Cherkasov, and A.N.Pudovik, Dokl.Akad. Nauk SSSR, 1977, **235**, 118.
148. V.V.Ovchinnikov, V.I.Galkin, R.A.Cherkasov, and A.N.Pudovik, Dokl.Akad.Nauk SSSR, 1979, **249**, 128.
149. T.A.Mastryukov and M.I.Kabachnik, Izv.Akad. Nauk SSSR, Ser.Khim., 1978, 2040.
150. E.E.Nifant'ev, I.S.Masonovskii, and E.I.Matrosov, Zhur.Obshch.Khim., 1969, **39**, 1891.
151. V.V.Ovchinnikov, S.V.Cherezov, V.I.Galkin, R.A.Cherkasov, and A.N.Pudovik, Zhur.Obshch. Khim., 1980, **50**, 2615.
152. A.N.Pudovik, I.V.Gur'yanova, and E.A.Ishmaeva, Symposium, "Reaktsii i Metody Issledovaniya Organicheskikh Soedinenii" (Reactions and Methods for the Investigation of Organic Compounds), Izd. Khimiya, Moscow, 1968, Vol.19.
153. A.N.Pudovik and I.V.Konovalova, Synthesis, 1979, 81.
154. A.G.Cook and G.W.Mason, J.Org.Chem., 1972, **37**, 3342.
155. I.M.Shermergon, Abstracts of Doctoral Thesis in Chemical Sciences, Institute of General Chemistry of the Academy of Sciences of Ukrainian SSR, Kiev, 1977.
156. A.A.Kryuchkov, A.G.Kozachenko, and E.I.Matrosov, "Yubileinaya Konferentsiya po Khimii Fosfor-organicheskikh Soedinenii, Posvyashchennaya 100-Letyu so Dnya Rozhdeniya Akad.A.E.Arbuzova" (Jubilee Conference on the Chemistry of Organo-phosphorus Compounds Commemorating the 100th Anniversary of the Date of Birth of Academician A.E.Arbuzov), Izd.Inst.Obshch.Khim.Akad.Nauk Ukrain.SSR, Kiev, 1977, p.97.
157. A.A.Kryuchkov, A.G.Kozachenko, E.I.Matrosov, and M.I.Kabachnik, Izv.Akad.Nauk SSSR, Ser. Khim., 1978, 1985.
158. G.S.Mikhailova, Abstracts of Candidate's Thesis in Chemical Sciences, Lensovet Leningrad Technological Institute, Leningrad, 1978.
159. A.G.Kozachenko and A.A.Grigor'eva, "Tezisy Dokladov Vsesoyuznogo Molodezhnogo Kollokviuma im.A.E.Arbuzova 'Stroenie i Reaktsionnaya Sposobnost' Nekotorykh Elementoorganicheskikh Soedinenii' " (Abstracts of Reports at the All-Union Arbuzov Young Scientists' Colloquium on 'The Structure and Reactivity of Certain Organoelemental Compounds'), Izd.Inst.Org.Fiz.Khim.im.Arbuzova, Kazan, 1980, p.27.
160. V.V.Ovchinnikov, R.A.Cherkasov, and A.N.Pudovik, Dokl.Akad.Nauk SSSR, 1980, **255**, 1169.
161. V.V.Ovchinnikov, V.I.Galkin, R.A.Cherkasov, and A.N.Pudovik, Zhur.Obshch.Khim., 1977, **47**, 290.
162. T.A.Mastryukova and M.I.Kabachnik, Symposium, "Khimiya i Primenenie Fosfororganicheskikh Soedinenii" (The Chemistry and Applications of Organophosphorus Compounds), Izd.Akad.Nauk SSSR, Moscow, 1962, p.57.
163. V.V.Ovchinnikov, A.R.Garifzyanov, R.A.Cherkasov, and V.F.Toropova, Zhur.Obshch.Khim., 1980, **50**(1), 67.
164. R.A.Cherkasov, V.V.Ovchinnikov, E.I.Petrova, and V.F.Toropova, Symposium, "Khimiya Elementoorganicheskikh Soedinenii III–V Grupp" (The Chemistry of Organoelemental Compounds of Group III–V Elements), Zhur.Obshch.Khim. (Journal of General Chemistry), Izd.Nauka, Leningrad, 1976, p.114.
165. E.A.Ishmaeva, V.V.Ovchinnikov, R.A.Cherkasov, and A.N.Pudovik, Zhur.Obshch.Khim., 1975, **45**, 946.
166. R.R.Shagidullin, I.P.Lipatova, L.I.Vachugova, R.A.Cherkasov, and F.Kh.Khairutdinova, Izd. Akad.Nauk SSSR, Ser.Khim., 1972, 847.
167. V.V.Ovchinnikov, L.V.Kostakova, R.A.Cherkasov, and A.N.Pudovik, Reakts.Sposobn.Org.Soed., 1978, **15**, 2(54), 203.

168. M.I.Kabachnik, Dokl.Akad.Nauk SSSR, 1956, **110**, 393.
169. E.I.Matrosov, A.A.Kryuchkov, E.E.Nifant'ev, and M.I.Kabachnik, Izv.Akad.Nauk SSSR, Ser. Khim., 1977, 791.
170. M.I.Kabachnik, N.A.Tikhonina, V.A.Gilyarov, B.A.Korolev, M.A.Pudovik, L.K.Kibardina, and A.N.Pudovik, Zhur.Obshch.Khim. (in the Press).
171. G.A.Kalyagin, Yu.V.Balitskii, and I.E.Boldeskul, "Tezisy Dokladov Vsesoyuznogo Molodezhnogo Kollokviuma im.A.E.Arbuzova 'Sintez, Stroenie i Reaktsionnaya Sposobnost' Nekotorykh Elementoorganicheskikh Soedinenii' " (Abstracts of Reports at the All-Union Arbuzov Young Scientists' Colloquium on "The Synthesis, Structure, and Reactivity of Certain Organoelemental Compounds"), Izd.Inst.Org.Fiz.Khim.im.Arbuzova, Kazan, 1980, p.21.
172. V.F.Toropova, R.A.Cherkasov, N.I.Savel'eva, and E.I.Petrova, Zhur.Obshch.Khim., 1974, **44**, 531.
173. T.A.Mastryukova and M.I.Kabachnik, Uspekhi Khim., 1969, **38**, 1751 [Russ.Chem.Rev., 1969(10)].
174. B.I.Istomin, V.A.Baranskii, A.D.Lobanov, and E.F.Grechkin, Reakts.Sposobn.Org.Soed., 1975, 12, 69.
175. V.A.Baranskii and B.I.Istomin, Reakts.Sposobn. Org.Soed., 1975, **12**, 83.
176. M.Charton and B.J.Charton, J.Org.Chem., 1978, **43**, 2383.
177. L.F.Kasukhin and Yu.G.Gololobov, Reakts. Sposobn.Org.Soed., 1978, **15**, 477.
178. V.V.Ovchinnikov, A.R.Garifzyanov, R.A.Cherkasov, A.N.Pudovik, and V.F.Toropova, Reakts.Sposobn. Org.Soed., 1980, **16**, 1(61), 54.
179. A.N.Pudovik, R.A.Cherkasov, and V.V.Ovchinnikov, Zhur.Obshch.Khim., 1972, **42**, 2638.
180. D.S.Milbrath, J.P.Springer, J.C.Clardy, and J.G.Verkade, J.Amer.Chem.Soc., 1976, **98**, 5493.
181. V.V.Ovchinnikov, R.A.Cherkasov, and A.N.Pudovik, Izv.Akad.Nauk SSSR, Ser.Khim., 1980, 934.
182. R.A.Cherkasov, G.A.Kutyrev, V.V.Ovchinnikov, and A.N.Pudovik, Zhur.Obshch.Khim., 1976, **46**, 936.
183. R.A.Cherkasov, V.V.Ovchinnikov, and A.N.Pudovik, Zhur.Obshch.Khim., 1976, **46**, 957.
184. R.A.Cherkasov, N.V.Kashina, I.G.Lushchits, A.I.Vinokurov, and A.N.Pudovik, Zhur.Obshch. Khim., 1976, **46**, 781.
185. V.V.Ovchinnikov, A.R.Gerifzyanov, N.I.Savel'eva, and V.F.Toropova, Izv.Vys.Ucheb.Zaved., Khim.i Khim.Tekhnol., 1979, **22**, 654.
186. V.F.Toropova, R.A.Cherkasov, N.I.Savel'eva, L.A.Grigor'eva, I.V.Shergina, V.V.Ovchinnikov, and A.N.Pudovik, Zhur.Obshch.Khim., 1971, **41**, 1673.
187. M.I.Kabachnik, T.A.Mastryukova, G.A.Balueva, E.E.Kugucheva, A.E.Shipov, and T.A.Malent'eva, Zhur.Obshch.Khim., 1961, **31**(1), 140.
188. R.A.Cherkasov, Doctoral Thesis in Chemical Sciences, Ul'yanov-Lenin Kazan State University, Kazan, 1975.
189. R.A.Cherkasov, Symposium, "Stroenie i Reaktsionnaya Sposobnost' Organicheskikh Soedinenii" (The Structure and Reactivity of Organic Compounds) (Edited by B.A.Arbuzov), Izd.Nauka, Moscow, 1978, p.107.

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