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Phosphorus Acid Azides

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Data on the synthesis and the chemical and physical properties of phosphorus acid azides are surveyed. The bibliography includes 100 references.

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I. INTRODUCTION

Although the first phosphorus acid azides (PAA) were described in 1953,[1,2] the bulk of the studies on their synthesis and their properties have been carried out during the last 15–20 years. The synthesis of PAA has been greatly developed and the ready availability and in the vast majority of cases also the high stability of these compounds have been demonstrated, which constitutes their advantageous features compared with other azides, for example, aryl azides.

The chemical properties of PAA are very close to those of aryl, alkyl, and sulphonyl azides. PAA readily undergo the Staudinger reaction. Interaction of PAA with phosphorus(III) derivatives has led to the full availability of a new class of phosphorimido-compounds–substances containing the $\rangle P{=}N{-}P(X)\langle$ group, where X = O or S. The photolysis of PAA results in the formation of nitrenes capable of various reactions; in particular, in certain cases the groups attached to the phosphorus atom migrate to the nitrogen atom, i.e. a reaction analogous to the Curtius reaction takes place. PAA add to unsaturated compounds. On the other hand, the azide group in PAA exhibits the properties of a pseudohalogen and is capable of being substituted by other groups in reactions with nucleophiles. The study of the chemical properties of PAA established detailed differences between them and other azides, for example, sulphonyl azides. Thus, in terms of the number of reactions, PAA occupy one of the first places among phosphorus acid derivatives.

Recently one of the PAA, namely diphenyl phosphorazidate (diphenyl azidophosphate), has found extensive applications in organic synthesis, the synthesis of peptides, alkyl azides, etc.

There are a few reviews on PAA.[3–5] The first review[3] deals only with azides with a phosphorus–carbon bond. The last review[5] is the most complete but it covers the literature only up to 1973. The fundamental monographs[6,7] on organophosphorus compounds deal only briefly with PAA. It therefore became necessary to write the present review, which deals with the PAA synthesis, indicating the methods of synthesis, the yields, and the constants.

II. SYNTHESIS

The principal method of synthesising PAA involves the replacement of the chlorine atom in the corresponding chlorides by the azide group. The methods based on the employment of phosphorus acid anhydrides and hydrazides have been developed only slightly.

1. Synthesis from Phosphorus Acid Chlorides

Metal azides (principally sodium azide and more rarely lithium azide) or organoelemental azides in which the azide group is partly mobile (trimethylsilyl azide or PAA) are used to substitute the chlorine atom in phosphorus acid chlorides:

$$(RO)_2P(O)Cl + MN_3 \rightarrow (RO)_2P(O)N_3 + MCl,$$
$$(RO)_2P(S)Cl + MN_3 \rightarrow (RO)_2P(S)N_3 + MCl.$$

Various solvents have been proposed for sodium azide: acetone[1,8–10] (method *a*), pyridine[11–14] (method *b*), acetonitrile[9,15] (method *c*), DMF [16] (method *d*), water[2] (method *e*), ethanol[17] (method *f*), and methylene chloride[18] (method *g*). The reaction with lithium azide is carried out without a solvent[19], in acetonitrile[20,21] (method *h*), or in tetrahydrofuran (THF) [22] (method *i*). The most general method of synthesis of PAA proved to be the reaction with a concentrated solution of triethylammonium azide in chloroform[23,24] (method *j*). Tables 1–7 present the PAA synthesised with an indication of the method of synthesis, the yield, and the constants.

Table 1. Phosphorus(III) acid azides.

Formula	Method of synthesis	Yield, %	B.p., °C (mmHg)	M.p., °C	Refs.
$P(N_3)_3$	*c*	97	—	—	[25]
$[(iso\text{-}C_3H_7)_2]_2PN_3$	—	81	65—67 (0.01)	37—39	[26]
$(CF_3)_2PN_3$	—	—	—60 (1)	—	[19]
$(C_6H_5)_2PN_3$	*h*	—	—	13.6—13.8 (decomp.)	[20]

In the synthesis of diphenylphosphinic azide (I), the influence of the solvent on the rate of exchange of the chlorine atom was investigated:

$$(C_6H_5)_2P(O)Cl + NaN_3 \xrightarrow{\sim 20^\circ} (C_6H_5)_2P(O)N_3 + NaCl$$
(I)

The rate of reaction increases in the sequence benzene ≪ dioxan < THF ≪ pyridine[11].

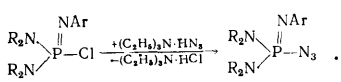
Method (a). Phosphorus acid chlorides react with sodium azide in acetone at room temperature or on prolonged refluxing. It cannot be claimed that the method is universal; for

example, when it is employed, the chlorine atom in dibutylphosphinic chloride is incompletely substituted by the azide group[23].

Method (b). Pyridine is the most universal solvent for the synthesis of PAA. The completion of the reaction can be monitored by analysis for chlorine. The advantages of this method are the mild reaction conditions (the reactants are stirred at room temperature) and the comparative ease of isolating the PAA. A possible side reaction involves the alkylation of pyridine by the PAA containing the RO groups (particularly in the case of the lower esters), which makes it necessary to limit contact between the reaction product and pyridine. Limitations to the method have also been found: in the case of *N,N,N',N'*,tetra-alkyl-*N''*-arylphosphoroamidimdic chlorides it is impossible to achieve a complete substitution of the chlorine atom by the azide group[52]. Apparently the accumulation of nitrogen atoms at the phosphorus atom and the associated extensive delocalisation of the effective positive charge significantly reduce the capacity of the halogen for substitution.

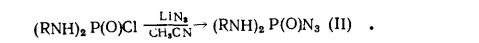
Method (d). The use of dimethylformamide (DMF) proved to be convenient in the synthesis of dialkyl phosphorazidothioates[16]. However, the PAA obtained must not be soluble in aqueous DMF (at the end of the reaction the mixture is diluted with water and the PAA is extracted with an organic solvent). It is noteworthy that, when an attempt was made to synthesise diarylphosphinic azides by this method, negative results were obtained[12].

Method (j). As already mentioned, this is the most universal method. Indeed its employment makes it possible to obtain PAA (for example, compounds 1, 2, and 3 in Table 6) from acid chlorides in which the chlorine atom is relatively inert.



Triethylammonium azide may prove useful in the synthesis of other PAA, which are difficult to obtain by other methods. The lack of side reactions, the complete substitution of chlorine in the acid chlorides by the azide group, and the mild reaction conditions are undoubted advantages of this method.

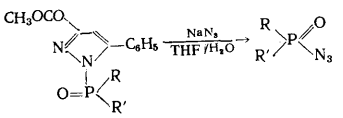
When *N,N'*-dialkylphosphorodiamidic chlorides were treated with lithium azide in acetonitrile at 50 °C, *N,N'*-dialkylphosphorodiamidic azides (II) were obtained in a low yield, decomposition being observed on boiling the solution[37]:

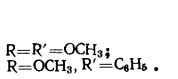


The employment of sodium azide in aqueous acetone also gives rise to a low yield of the azide (II).

2. Synthesis from Phosphorylpyrazoles

Certain PAA have been obtained from phosphorylpyrazoles in which the P–N bond is of the anhydride type[43]:





3. Synthesis from Phosphorus Acid Anhydrides

The reactions of phosphorus acid anhydrides with sodium azide, leading to the formation of PAA, can be illustrated schematically as follows[57]:

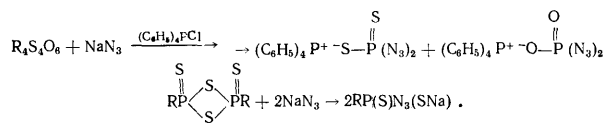


Table 2. Phosphoric acid azides.

Formula	Method of synthesis	Yield, %	B.p., °C (mmHg) or m.p., °C	n_D^{20}	d_4^{20}	Refs.
$(N_3)_3PO$	*c*	98	—	—	—	[25]
$CH_3OP(O)(N_3)_2$	*c*	87	—	—	—	[27]
$(CH_3)_2NP(O)(N_3)_2$	*c*	60	—	—	—	[27]
$CH_3OP(O)(ONa)N_3$	—	—	146—148	—	—	[28]
	a, e	—	221—225 (decomp.)	—	—	[29]
$(CH_3O)_2P(O)N_3$	*c**	35	79.5—81 (10)	1.4276	1.3013	[30]
$(C_2H_5O)_2P(O)N_3$	*a*	62.8	76—77 (4.5)	1.4260	1.1672	[30]
$(C_3H_7O)_2P(O)N_3$	*i*	90.5	64 (025)	1.4367	1.1029	[23]
$(iso\text{-}C_3H_7O)_2P(O)N_3$	*j*	92.4	62—64 (2)	1.4265	1.0824	[23]
$(C_4H_9O)_2P(O)N_3$	*j*	75.4	86—87 (0.5)	1.4372	1.0713	[23]
$(iso\text{-}C_4H_9O)_2P(O)N_3$	*b*	76	66.5 (0.2)	1.4325	1.0528	[31]
$(s\text{-}C_4H_9O)_2P(O)N_3$	*b*	68	54—55 (0.03)	1.4322	1.0592	[31]
	—	—	44—47	—	—	[29]
$(C_6H_5O)_2P(O)N_3$	*a*	90	157 (0.17)	—	—	[32]
$RO(C_6H_5NH)P(O)N_3$ (R = 2-adamantyl)	*a, e*	39	oil	—	—	[33]
$p\text{-}ClC_6H_4O(RHN)P(O)N_3$ (R = 1-adamantyl)	—	59	112—114	—	—	[33]
	a, e	49	93—95	—	—	[29]
	a, e	—	146—150	—	—	[29]
$[(CH_3)_2N]_2P(O)N_3$	*b***	75	93—94 (2)	1.4673 (21°)	—	[17]
$([CH_3)_2N]_2P(O)N_3 \cdot SbCl_5$	—	31	116	—	—	[34]
$[(C_2H_5)_2N]_2P(O)N_3$	*b*	88	76 (0.01)	2.4670	1.0504	[35]
$[CH_3(C_6H_5)N]_2P(O)N_3$	*a, e*	89	—	—	—	[34]
$(C_6H_5CH_2NH)_2P(O)N_3$	*a****	40	65—67	—	—	[36]
$(C_6H_{11}NH)_2P(O)N_3$	*a, e*	30	64—66 and 94—96	—	—	[36]
$(C_6H_5NH)_2P(O)N_3$	*c*	30	90—95	—	—	[36]
$[CH_2(CH_2)_3NP(O)N_3$	*a, e*	64	—	—	—	[36]
$[CH_2(CH_2)_3N](C_6H_5NH)P(O)N_3$	*a, e*	36	—	—	—	[37]
$[(CH_3)_2N]_2P(OCH_3)N_3^+SbCl_6^-$	—	35	141	—	—	[38]
$P(N_3)_5$	*c*	97	—	—	—	[25]

*The yield obtained by method *c* is 65%.

**The yield obtained by method *c* is 78.5%.

***The yield of the synthesis from $(C_6H_5CH_2NH)_2P(O)NHNH_2$ is 10%. [36]

Table 3. Phosphorothioic acid azides.

Formula	Method of synthesis	Yield, %	B.p., °C (mmHg) or m.p., °C	n_D^{20}	d_4^{20}	Refs.
$(CH_3O)_2P(S)N_3$	*a*	51	38—39 (0.5)	—	—	[1]
$(C_2H_5O)_2P(S)N_3$	*a*	—	60 (1.5)	—	—	[1]
	d	58	57—58 (1)	1.4720	1.1659	[16]
$[n\text{-}C_3H_7O)_2P(S)N_3$	*a*	—	77—78 (1)	—	—	[1]
$(iso\text{-}C_3H_7)_2P(S)N_3$	*d*	64	84—85 (6)	1.4630	1.0707	[16]
$(C_4H_9O)_2P(S)N_3$	*d*	65	88—89 (0.2)	1.4699	1.0789	[16]
$(изо\text{-}C_4H_9O)_2P(S)N_3$	*d*	56	67—70 (0.2)	1.4699	1.0789	
$(C_6H_5O)_2P(S)N_3$	*d*	35	25—27	—	—	[16]
$[(CH_3)_2N]_2P(S)N_3$	*b*	75	80 (1.5)	1.5177 (21)	—	[17]
	d	96	62 (0.01)	1.588	1.1 '28	[35]
$[(C_2H_5)_2N]_2P(S)N_3$	*d*	89	84 (0.01)	1.5018	1.0812	[35]
	a, e	91	177—178	—	—	[38]

Table 4. The azides of methyl- and phenyl-phosphonic and methyl- and phenyl-phosphonothioic acids.

Formula	Method of synthesis	Yield, %	B.p., °C (mmHg) or m.p., °C	n_D^{20}	d_4^{20}	Refs.
$CH_3P(O)(OC_2H_5)N_3$	*j*	78	39(0.1)	1.4480	1.1926	[39]
	b	63	36—37(1.5)	1.4460	1.1882	[31]
$CH_3P(O)(OC_6H_5)N_3$	*j*	92	80(0.04)	1.6289	1.2559	[39]
$ClCH_2P(O)(OC_2H_5)N_3$	*j*	84	74—75(0.05)	1.4750	1.3478	[39]
$ClCH_2P(O)(OC_6H_5)N_3$	*j*	74	117—118(0.06)	1.5420	1.3662	[39]
$CH_3P(O)(SC_2H_5)N_3$	*e*	43	78—79(1—2)	1.5190	1.2507	[40]
$CH_3P(O)[N(C_2H_5)_2]N_3$	—	80	76—77(0.03)	1.4680	1.0891	[41]
$CH_3P(O)(NH_6H_5)N_3$	—	99	—	1.5740	—	[41]
$CH_3P(O)(NHCOOCH_3)N_3$	—	66	82—83	—	—	[41]
$CH_3P(O)(NHCOOC_2H_5)N_3$	—	77	127—128	—	—	[42]
$CH_3P(O)(NHCOOC_3H_7\text{-iso})N_3$	—	77	114—115	—	—	[42]
$CH_3P(O)(NHCOOC_6H_5)N_3$	—	70	96—98	—	—	[41]
$CH_3P(O)(NHCONHC_6H_5)N_3$	—	—	158—166 (decomp.)	—	—	[42]
$CH_3P(O)(NHCONC_6H_4Cl\text{-}n)N_3$	—	—	164—166 (decomp.)	—	—	[42]
$CH_3P(O)(NCO)N_3$	—	52	49—50(0.04)	1.4835	1.3975	[41]
$CH_3P(O)(Cl)N_3$	*b*	67	46—47(0.03)	1.4850	1.4125	[41]
$CH_3P(O)(N_3)_2$	*b*	52	49—50(0.03)	1.4980	1.3826	[41]
$C_6H_5P(O)(OCH_3)N_3$	—	36*	95(0.01)	—	—	[43]
$C_6H_5P(O)[N(CH_3)_2]N_3$	*b*	—	86—88(0.001)	1.5473	—	[14]
$C_6H_5P(O)[N{=}P(C_6H_5)_3]N_3$	—	—	143—145	—	—	[14]
$C_6H_5P(O)(Cl)N_3$	—	—	66—67(0.75)	1.5636	—	[14]
$CH_3P(S)(OC_2H_5)N_3$	*b*	60.5	60(8)	1.4960	1.1572	[31]
$C_6H_5P(S)(N_3)_2$	*b*	—	—	—	—	[14]

*For the method of synthesis, see Section III, 1.

Table 5. The azides of phosphinic, phosphinothioic, and phosphinoselenoic acids.

Formula	Method of synthesis	Yield, %	B.p., °C (mmHg) or m.p., °C	n_D^{20}	d_4^{20}	Refs.
$(CH_3)_2P(O)N_3$	*b*	69	46—48(1); 14—16	—	—	[44]
$(CD_3)_2P(O)N_3$	*b*	74	48(1)	—	—	[45, 46]
$CH_3(C_2H_5)P(O)N_3$	*b*	—	32(10^{-2})	—	—	[45]
$CH_3(C_6H_5)P(O)N_3$	*b*	100	65(0.3)	—	—	[13, 45]
$(C_2H_5)_2P(O)N_3$	*b*	—	97(8)	—	—	[47]
$(C_2H_5)_2P(O)N_3$	*b*	85	97(8)	—	—	[44]
$(C_4H_9)_2P(O)N_3$	*b, c*	61	95(7)	—	—	[48]
$C_2H_5(C_6H_5)P(O)N_3$	*b*	—	—	—	—	[45]
$(iso\text{-}C_3H_7)_2P(O)N_3\cdot 0{,}15H_2O$	*b, d*	74	72—78(0.5)	—	—	[48]
$(C_4H_9)_2P(O)N_3$	*j*	40.9	78—79(0.2)	1.4648	1.0102	[23]
$(t\text{-}C_4H_9)_2P(O)N_3\cdot 0{,}35H_2O$	*b, d*	80	75—80(0.5)	—	—	[48]
$(CH_3)_2CCH(CH_3)C(CH_3)_2P(O)N_3$	*b*	65	80—82(0.2)	—	—	[49]
$CH_2C(CH_3)_2C(CH_3)_2P(O)N_3$	*d*	—	81(0.4)	—	—	[49]
$(CH_3)_2CCH_2C(CH_3)_2P(O)N_3$	*d*	84	95—100(2.5)	—	—	[49]
$(C_6H_5)_2P(O)N_3$	*b*	87	137—140 (0.05)	1.6077	1.23	[12]
$(C_6H_5)_2P(O)N_3$	*j*	74.3	95(10^{-4})	1.6080	1.2374	[23]
$(p\text{-}CH_3C_6H_4)_2P(O)N_3$	*b*	—	190—195(0.5)	—	—	[12]
$(p\text{-}ClC_6H_4)_2P(O)N_3$	*b*	—	160—165 (0.05)	1.6246	—	[12]
$B_{10}H_{10}C_2(C_6H_5PN_3)_2$	*f*	82	126—128	—	—	[50]
$B_{10}H_{10}C_2PN_3)_2$	*f*	81	150 (разл.)	—	—	[50]
$B_{10}H_{12}[(C_6H_5)_2PN_3]_2$	*f*	96	147	—	—	[51]
$(CH_3)_2P(S)N_3$	*a*	73	69—70	—	—	[44, 45]
$(CD_3)_2P(S)N_3$	*a*	95	72	—	—	[45, 46]
$CH_3(C_2H_5)P(S)N_3$	*a*	90.5	37—38(10^{-2})	—	—	[45]
$CH_3(C_6H_5)P(S)N_3$	*a*	—	—	—	—	[45]
$(C_2H_5)_2P(S)N_3$	*a*	87	70—71(1)	—	—	[44]
$C_2H_5(C_6H_5)P(S)N_3$	*a*	—	—	—	—	[45]
$(C_6H_5)_2P(S)N_3$	*b*	87.4	137—140 (0.05)	—	—	[12]
$(CH_3)_2P(Se)N_3$	*a*	71	69—70	—	—	[45, 46]
$CH_3(C_2H_5)P(Se)N_3$	*a*	50	47—48(10^{-2})	—	—	[45]
$CH_3(C_6H_5)P(Se)N_3$	*a*	—	—	—	—	[45]
$(C_2H_5)_2P(Se)N_3$	*a*	71	69—70	—	—	[45, 46]
$C_2H_5(C_6H_5)P(Se)N_3$	—	—	—	—	—	[45]
$(C_6H_5)_2P(Se)N_3$	*b*	45	25	—	—	[45, 46]

4. Synthesis from Phosphorus Acid Hydrazides

The azides (II) have been obtained in a very low yield by the reaction of *N,N'*-dialkylphosphorodiamidic hydrazides with nitrous acid:

$$(RNH)_2P(O)NHNH_2 + HNO_2 \rightarrow (RNH)_2P(O)N_3 + 2H_2O \ .$$
(II)

The use of the above reaction has not been extensively developed for the synthesis of PAA. Although the employment of dialkyl phosphorohydrazidothioates for the synthesis of dialkyl phosphorazidothioates has been described[58], methods *a* and *d* (from dialkyl phosphorochloridothioates) proved to be more convenient for their synthesis:

$$(RO)_2P(S)NHNH_2 + HNO_2 \rightarrow (RO)_2P(S)N_3 + 2H_2O \ ;$$
$$R = CH_3,\ C_2H_5,\ C_3H_7 \ .$$

When methyl hydrogen phosphorohydrazidate $CH_3OP(O).(NHNH_2)OH$ was treated with nitrous acid, only the evolution of nitrogen was observed; the expected azide $CH_3OP(O)(N_3).OH$ could not be obtained under these conditions[28].

Table 6. The azides of phosphorodiamidimidic and phosphinimidic acids.

№	Formula	Method of synthesis	Yield, %	B.p., °C (mmHg) or m.p., °C	n_D^{20}	d_4^{20}	Refs.
1	$[(CH_3)_2N]_2P(=NC_6H_5)N_3$	*j*	64.2	88—89(0.04)	1.5580	1.1270	[52]
2	$[(C_2H_5)_2N]_2P(=NC_6H_5)N_3$	*j*	60	72—74(10^{-4})	1.5390	1.0622	[52]
3	$[(C_2H_5)_2N]_2P(=NC_6H_4CH_3\text{-}p)N_3$	*j*	66	80—81(10^{-4})	1.5370	1.0511	[52]
4	$(C_6H_5)_2P(=NC_6H_5)N_3$	*i*	83	—	—	—	[22]
5	$(C_6H_5)_2P(=NSO_2C_6H_4CH_3\text{-}p)N_3$	*g*	76	84—85	—	—	[22]

5. Synthesis of Triazidophosphine and Phosphoric Triazide

The possibility of the formation of $P(N_3)_3$ and $PO(N_3)_3$ by the reaction of PCl_3 and $POCl_3$ with ammonium azide in liquid sulphur dioxide and the extremely high risk of their exploding were noted in the first communication[4] on the synthesis of these PAA. When $POCl_3$ is treated with ammonium azide in liquid SO_2 at −30 °C, a crystalline product is formed, but explodes when an attempt is made to isolate it.

In a later study[25] $P(N_3)_3$ and $PO(N_3)_3$ were obtained by the reaction of PCl_3 and $POCl_3$ with sodium azide in acetonitrile at −20 °C. After separating the precipitate by evaporating the filtrate at 0 °C, the azides were obtained in the form of readily hydrolysable liquids, which frequently explode on being heated to room temperature.

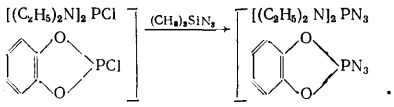
Table 7. The azides of cyclic λ^5-phosphazenes.

Formula	Method of synthesis	Yield, %	B.p., °C (mmHg) or m.p., °C	Refs.
$2,2\text{-}(H_2N)_2N_3P_3(N_3)_4\text{-}4,4,6,6$	*e*	—	81—82	[53]
$N_3P_3(C_6H_5)_5N_3$	—	—	153.5—155	[54]
$N_3P_3F_5N_3$	*a*	95	53(77)	[55]
$N_3P_3(N_3)_6$	*a, e*	~100	<−20	[56]
$N_4P_4F_7N_3$	*a*	65	54(40)	[55]

6. Phosphorus(III) Acid Azides

The azides of tervalent phosphorus acids are difficult to obtain. For this reason, the number of azides of this type isolated hitherto is small (Table 1). The azides are apparently formed readily from the corresponding chlorides and sodium azide or trimethylsilyl azide. The main cause of the difficulty of their isolation is their high reactivity, which

leads to the formation of cyclic and linear phosphonitriles as a result of self-condensation. Thus the use of trimethylsilyl azide in the reaction with chlorodiphenylphosphine under various conditions (variable temperature and solvents) did not yield azidodiphenylphosphine, but invariably led to the formation of its further transformation products[59]. The syntheses of the following azides are merely mentioned in the literature: $[(CH_3)_2N]_2PN_3$,[26] $(t\text{-}C_4H_9)_2PN_3$,[26] $\{[(CH_3)_3Si]_2N\}_2.PN_3$,[60] and $(C_6F_5)_2PN_3$.[61] Azidobis(diethylamino)phosphine[62] and *o*-phenylene phosphorazidite[63] were obtained in accordance with the following scheme:



These azides are stable only below 10–15 °C. The products of the self-condensation of *o*-phenylene phosphorazidite were obtained by the reaction of *o*-phenylene phosphorochlorodite with trimethylsilyl azide at 80 °C.[64]

III. CHEMICAL PROPERTIES

Two groups of reactions with participation of the azide group are most characteristic of PAA: reactions with phosphorus(III) compounds leading to the evolution of nitrogen, the formation of compounds with the fragment $\geq P=N-P(X)\leq$ (X = O or S) and the reaction in which the azide group reacts as a pseudohalogen (phosphorylation). Other reactions of PAA are noteworthy—pyrolysis, photolysis, and addition to unsaturated systems.

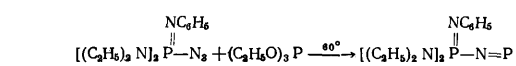
1. Reactions of PAA with Phosphorus(III) Compounds

The reactions of PAA with tervalent phosphorus compounds constitute an extension of the Staudinger reaction to PAA:

$$(RO)_2P(O)N_3 + (R'O)_3P \rightarrow (RO)_2P(O)N{=}P(OR')_3 + N_2 .$$

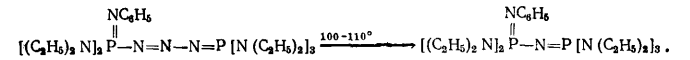
These reactions are general and, when the azide and the phosphorus(III) compounds are varied, many classes of phosphorimido-compounds, a considerable proportion of which cannot be synthesised by the Kirsanov reaction, can be obtained.

The rate of reaction depends on the structure of the reactants—of both the azide and the phosphorus(III) compound. Special kinetic studies of the influence of substituents in the azide molecule have still not been made, but it is known that *N,N,N',N'*-tetra-alkylphosphorodiamidic azides react with phosphorus(III) compounds more slowly than dialkyl phosphorazidates[35]. *N,N,N',N'*-Tetra-alkyl-*N''*-arylphosphorodiamidimidic azides react with particularly great difficulty, for example[52]:



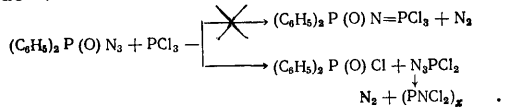
Azidobis(diethylamino)phosphine does not react with triethyl phosphite[63].

The mechanism of the reactions of PAA with phosphorus(III) compounds has not been investigated. By analogy with other azides (aryl azides and sulphonyl azides), the reaction presumably proceeds via triazenes, which decompose with evolution of nitrogen. The triazene has been isolated in only one instance and its heat treatment led to the formation of a phosphorimido-compound[52]:



The structure of the triazene was not investigated; the proposed structure is analogous to that of the triazenes formed from aryl and sulphonyl azides. A somewhat reduced (compared with aryl azides) reactivity in the reactions of PAA with phosphorus(III) compounds is noteworthy. In the case of PAA, the reaction are usually carried out at 50–60 °C,[31] while aryl azides react even at room temperature.

If the phosphorus(III) chloride is an acid chloride (phosphorus trichloride, chlorodiphenylphosphine), then the azide group is exchanged for the halogen in the reaction with PAA.[11,21] Thus a phosphonitrilic chloride polymer is formed in the reaction of diphenylphosphinic azide with phosphorus trichloride[11]:

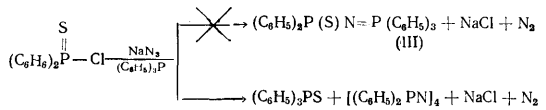


An analogous reaction is possible also in the case of chlorodiphenylphosphine[21]:

$$(I) + (C_6H_5)_2PCl \rightarrow (C_6H_5)_2PN_3 + (C_6H_5)_2P(O)Cl .$$

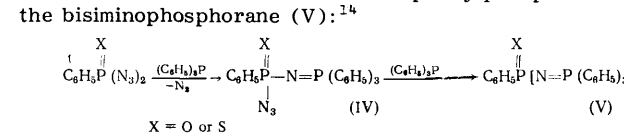
The main product proved to be $(C_6H_5)_2P(O)[N=P(C_6H_5)_2]_2Cl$ (yield 60%), whose formation can be represented as the result of a series of consecutive reactions of the azide (I) with $(C_6H_5)_2PN_3$ followed by the exchange of the N_3 group for Cl.

The reaction of diphenylphosphinothioic chloride with sodium azide and triphenylphosphine led to the isolation of the tetramer of diphenylphosphonitrile instead of the expected *N*-(diphenylphosphinothioylimino-*p,p,p*-triphenylphosphorane(III):[11]



Diphenylphosphinothioic chloride is apparently initially converted into chlorodiphenylphosphine, which then reacts with sodium azide.

In the presence of two azide groups in the PAA a stepwise reaction with triphenylphosphine is possible. Thus the azide (IV) can react further with triphenylphosphine to form the bisiminophosphorane (V):[14]

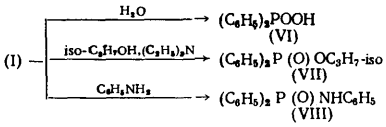


The reactions of various PAA with a wide variety of phosphorus(III) compounds, namely triphenylphosphine[11,14], the bisphosphines $(C_6H_5)_2P{-}X{-}P(C_6H_5)_2$ (X = *p*-C_6H_4 or *p*-$C_6H_4C_6H_4$-*p*),[14] alkyl dialkylphosphinites[23], dialkyl phosphonites[23], trialkyl phosphites[16,30,31], dialkyl phosphoramidites[31,35], alkyl phosphorodiamidites[35], and phosphorous triamides[31,35]. The reactions of PAA with trialkyl phosphorothioites have not been described.

2. Reactions of PAA involving the Azide Group as a Pseudohalogen

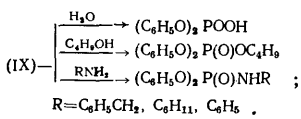
In the reactions of diphenylphosphinic azide with nucleophiles (water[11], isopropyl alcohol[11], and aniline[11,65]), its azide group is substituted with formation of diphenylphosphinic acid (VI), isopropyl diphenylphosphinate (VII),

and diphenylphosphinic anilide (VIII):



N-(Azidophenylphosphinylimino)-*p*,*p*,*p*-triphenylphosphorane $(C_6H_5)_3P{=}NP(O)(C_6H_5)N_3$,[14] diphenyl phosphorazidate (IX),[66] and diethyl phosphorazidate $(C_2H_5O)_2P(O)N_3$ (X) [8] are capable of undergoing similar reactions involving the substitution of the azide group.

Comparison of the reactivities of the last two azides in reactions with nucleophiles permits the conclusion that the mobility of the azide group in the azide (IX) is much greater than in the azide (X). The azide (IX) interacts with water and butanol on boiling. The azide (IX) reacts with aliphatic amines with self-heating, while the reaction with aniline is terminated after 3 h on refluxing in alcohol[66]:

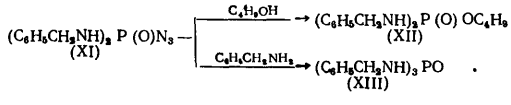


Diethyl phosphorazidate reacts with aniline under severe conditions (17.6 h at 185 °C). *N*-Phenylphosphoramidic acid $(HO)_2P(O)NC_6H_5$ was then isolated, evidently as a result of a secondary reaction involving the alkylation of aniline by the diethyl *N*-phenylphosphoramidate formed. Indeed, diethyl *N*-phenylphosphoramidate is rapidly converted into this acid on being refluxed in aniline[8].

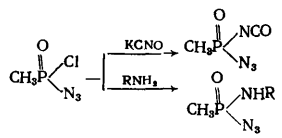
The solvolysis of diethylphosphinic azide in methanol takes place comparatively readily, while sterically hindered azides (di-isopropyl- and di-t-butylphosphinic azides) do not react with methanol in the course of 17 h at room temperature[48].

Although solutions of diaryl phosphorazidates in pyridine are readily hydrolysed by water in pyridine, the pure azides are hydrolysed only slowly in 0.5 *N* NaOH. The resistance of PAA to hydrolysis is noteworthy. It makes it possible to obtain them in an aqueous medium (method *e*). The ready hydrolysability of dimethyl phosphorazidothioate has been noted[44]. The kinetics of the hydrolysis and ammonolysis (in reactions with butylamine and benzylamine) of methyl phosphorazidate have been investigated. The formation of the corresponding phosphoramidates in this process has been demonstrated[28].

The azide group in phosphorodiamidic azides is more resistant to the action of nucleophiles. Thus *N*,*N*′-dibenzylphosphodiamidic azide (XI) reacts with butanol and benzylamine under severe conditions (for example, refluxing in butanol for 18 h), forming the ester (XII) and the triamide (XIII) respectively[36]:



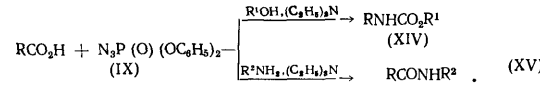
The azide group is less reactive than the chlorine atom in nucleophilic substitution reactions[42]:



PAA are more resistant to hydrolysis than the corresponding acid chlorides[44].

The reaction of the azide group as a pseudohalogen constitutes the basis of the modification of the Curtius reaction with participation of the readily available diphenyl phosphorazidate; this reaction has found extensive applications recently. Diethyl phosphorazidate was used initially[67], but the azide (IX) gave better results.

Thus the urethane (XIV) or the amide (XV) is formed from carboxylic acids, depending on the reactants employed under the reaction conditions[32]:



The urethanes (XIV) are obtained by refluxing equimolar amounts of a carboxylic acid, triethylamine, and the azide (IX) in the presence of a hydroxy-compound. This modification of the Curtius reaction† proved successful, since it is carried out under more or less neutral conditions and in the absence of oxidants (highly alkaline or acid media of the kind necessary for the Hofmann or Schmidt reactions are not required). In addition, it is possible to employ acids which do not enter into the Schmidt reaction (for example, pyridine-2-carboxylic acid). Table 8 presents certain results of the application of the azide (IX) in the syntheses of urethanes.

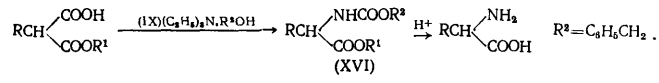
Table 8. The modified Curtius reaction involving the use of diphenyl phosphorazidate (R^1CH = t-C_4H_9OH).[68]

RCO_2H	Reaction time, h	Reaction product	Yield, %
$C_6H_5CH_2CO_2H$ *	20	$C_6H_5CH_2NHCO_2C_2H_5$	51**
$C_6H_5CH_2CH_2CO_2H$	25	$C_6H_5CH_2CH_2NHCO_2C_4H_9$-t	61
		C_6H_5—$CH_2CH_2NHCON_3$	3
$C_6H_5CH{=}CHCO_2H$	5	$C_6H_5CH{=}CHNHCO_2C_4H_9$-t	70
α-$HO_2CC_5H_4N$	23	α-{t-C_4H_9OCONH}C_5H_4N	73
p-$NO_2C_6H_4CO_2H$	20	*p*-$NO_2C_6H_4NHCO_2C_4H_9$-t	84
o-$NO_2C_6H_4CO_2H$	15	*o*-$NO_2C_6H_4NHCO_2C_4H_9$-t	90
$C_6H_5CO_2H$	21.5	$C_6H_5NHCO_2C_4H_9$-t	44
		$C_6H_5NHCON_3$	16
		$(C_6H_5NH)_2CO$	14

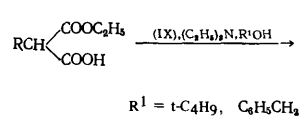
*R^1OH = C_2H_5OH.

**Diethyl phosphorazidate was used.

The attempt to convert the monoester of malonic acid into an aminoacid made it possible to obtain the ester (XVI) only when benzyl alcohol was used[69] and the latter must be added after refluxing a mixture of the azide (IX) and triethylamine for 1 h:



When a mixture of acid, the azide (IX), triethylamine, and alcohol is refluxed, the esters (XVII) are formed invariably[69,70]:

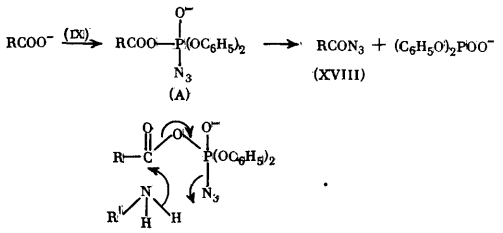


R^1 = t-C_4H_9, $C_6H_5CH_2$.

†The reaction under consideration is in a certain sense similar to the Schmidt reaction, but, from the standpoint of the mechanism (see below), the authors[68] regard it as a "modification of the Curtius reaction".

The mechanism of the reactions of substituted malonic acid monoesters with the azide (IX) and alcohols has been investigated and a scheme has been proposed whereby one can account for the different ways in which this reaction takes place[71].

Although the azide (IX) has found extensive applications, the mechanism of its reactions has not been established[72]. It may be that the intermediate (A) reacts intermolecularly with the amine or on dissociation gives rise to the acid azide (XVIII), which is converted into the amide (XV) as a result of bimolecular nucleophilic attack:



However, according to the authors of a review[5], the formation of the azide (VIII) has been insufficiently proved and the following mechanism can be considered for the formation of the amides (XV):

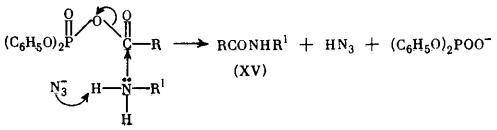
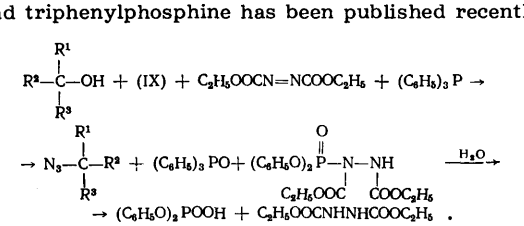


Table 9. The conversion of alcohols into azides using diphenyl phosphorazidate.

Alcohol	Azide	Yield, %
3β-Cholestanol	3α-Azidocholestane	78
Cholesterol	3α-Azido-5-cholestane	80—85
5α-Androsten-3β-ol-17-one	3α-Azido-5α-androsten-17-one	68
3α-Cholestanol	No reaction	—
5α-Androstan-17β-ol-3-one	No reaction	—
Cyclohexanol	Cyclohexyl azide	60
Decyl alcohol	Decyl azide	68
2-Menthol	(+)-Menthyl azide	90

The azide (IX) was used successfully to synthesise peptides in a high yield and without racemisation[32,68,73]. For example, the reaction of *N*-benzoxycarbonyl-L-leucyl-L-leucine with the hydrochloride of the methyl ester of L-valyl-L-phenylalanine has been achieved with a yield of 87%.[32]

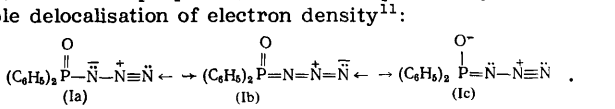
An elegant method of converting alcohols into azides by the reaction of the azide (IX), the diethyl ester of azodicarboxylic acid, and triphenylphosphine has been published recently[74]:



The reaction is stereospecific and makes it possible to obtain azides with high yields (Table 9).

3. Pyrolysis of PAA

The relatively high thermal stability of PAA, much higher than that of aryl and sulphonyl azides, has been noted. There is no satisfactory explanation of this phenomenon in the literature. The high thermal stability of diphenylphosphinic azide, for which different resonance structures (Ia–Ic) have been proposed, has been explained by the possible delocalisation of electron density[11]:



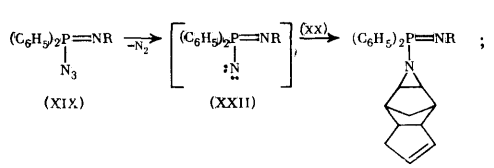
For thermally stable phosphorodiamidic azides, the possibility of a strong p_π–d_π conjugation between the α-nitrogen atom of the azide group and the phosphorus atom, has been noted[17].

Diphenyl phosphorazidate partly decomposes at 165 °C, darkens at 175 °C, and decomposes rapidly at 230 °C.[66] The extreme instability of the PAA in which there are several azide groups [triazidophosphine[4,25], phosphoric triazide[4,25], penta-azidophosphorane[25], and the azide $N_3P_3(N_3)_6$ [56]] should be noted.

Phenylphosphonic diazide and phenylphosphonothioic diazide decompose explosively above 80 °C,[14] while azidoperfluorodimethylphosphine explodes at 2–25 °C.[19] *N,N,N',N'*-Tetra-alkyl-*N''*-arylphosphorodiamidimidic azides decompose slowly at 150 °C with evolution of nitrogen[52]. For diphenylphosphinic azide, this temperature is above 137 °C.

Azidodiphenylphosphine decomposes at approximately 13.7 °C and is converted into the phosphonitrile $[(C_6H_5)_2PN]_x$. When attempts are made to vacuum distill (1 mmHg) diphenylphosphinothioic azide and diphenylphosphinoselenoic azide, they decompose[44]. All other PAA are stable on vacuum distillation and prolonged storage.

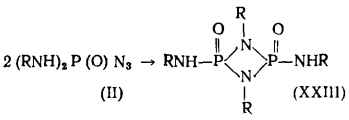
The evolution of nitrogen from the azide (XIX) has been noted only at 200 °C and in the presence of copper powder at 110 °C. In the presence of dicyclopentadiene (XX), a crystalline adduct (XXI) was obtained. It is formed when the nitrene (XXII) adds to dicyclopentadiene[75]:



Various insertion reactions are characteristic of the nitrene formed on pyrolysis of sulphonyl azide[76]. It is known[77,78] that arenesulphonyl azides react with aromatic compounds at 105–120 °C to form *N*-aryl substituted arenesulphonamides. Under these conditions and also in the presence of azobisisobutyronitrile, diphenylphosphinic azide does not undergo this type of reaction[11]. Nor does it enter into the reaction with pyridine characteristic of sulphonyl azides[78,79]. The reduced reactivity of the azide group at the phosphorus atom has also been manifested by the fact that the azide (I) does not undergo a reaction of the type of the Schmidt rearrangement on treatment with boron trifluoride in ethereal solution (refluxing for 48 h).[11]

The above insertion reactions could not be carried out for phosphorodiamidic azides either[36]. Prolonged heating of the azides (II) *in vacuo* or in the presence of inert solvents at 150–200 °C leads to the formation of the imido-amides

RNHP(O)=NR, which have been isolated in the form of the dimers (XXIII):[5,36]



(II) (XXIII)

On pyrolysis (1 h, 380 °C) of diphenylphosphinic azide, the phenyl group is seen to migrate from the phosphorus atom to the nitrogen atoms[80] (aniline was detected among the hydrolysis products), but the structure of the reaction product was not investigated in detail[3].

4. Photolysis of PAA

The aim of studies on the photolysis of PAA was the detection of nitrene, the investigation of its reactions involving insertion into a C–H bond, and its capacity for rearrangements.

The photolysis of diethyl phosphorazidate, diphenyl phosphorazidate, and *N,N,N',N'*-tetramethylphosphorodiamidic azide (XXIV)[81] was investigated [the resistance of the azide (XXIV) to ultraviolet irradiation in benzene had been noted previously[17]]. The photolysis of a 0.01 M solution of diethyl phosphorazidate in cyclohexane yielded diethyl *N*-cyclohexylphosphoramidate (yield 88%) and ethyl phosphoramidate (12%). Both products are formed as a result of the attack of diethylphosphorylnitrene on the solvent. No products indicating a rearrangement of the nitrene were detected.

The results of the photolysis of phenyl azidoformate in cyclohexane are presented as a comparison—the yield of *N*-cyclohexylurethane, formed as a result of the insertion of the nitrene in a solvent molecule, was only 19%. The study of the products of the photolysis of the azides (IX) and (X) in 2-methylbutane showed that phosphorylnitrenes do not exhibit a very pronounced selectivity with respect to insertion in a C–H bond of the kind observed for nitrenes formed from $C_2H_5OC(O)N_3$, $t\text{-}C_4H_9C(O)N_3$, and $C_6H_5N_3$ (the products of insertion in a C–H bond involving a tertiary cation atom are formed preferentially in the last case)[81]:

$$(RO)_2P(O)\ddot{N} + (CH_3)_2CHCH_2CH_3 \rightarrow (RO)_2P(O)NHR^1;\ R=C_2H_5,\ C_6H_5;$$

(a) $R^1=CH_2CH(CH_3)CH_2CH_3$, (b) $R^1=(CH_3)_2CHCH_2CH_2$; (c) $R^1=(CH_3)_2CHCH(CH_3)$

(d) $R^1=CH_3CH_2C(CH_3)_2$.

For example, in the case of the azide (X) the product ratios are (XXVd):(XXVc):[(XXVa) + (XXVb)] = 6.0:4.3:1.0.

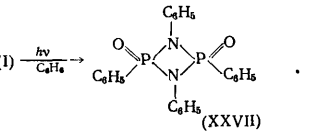
The high reactivity and low selectivity of phosphorylnitrenes were also observed on irradiation of a solution of the azide (X) in t-butyl alcohol[81]. Whereas the photolysis of ethyl azidoformate in t-butyl alcohol gives rise only to the product of the insertion in the O–H bond on photolysis, the product of the insertion in the C–H bond, namely the amide (XXVI), was also detected in the photolysis of the azide (X):

$$(C_2H_5O)_2P(O)\ddot{N} + (CH_3)_3COH \rightarrow \underset{(XXVI)\ (35\%)}{(C_2H_5O)_2P(O)NHCH_2C(CH_3)_2OH} +$$

$$[+\ \underset{(33\%)}{(C_2H_5O)_2P(O)NHOC(CH_3)_3} + \underset{(27\%)}{(C_2H_5O)_2P(O)NH_2}.$$

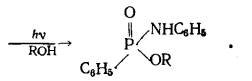
The phenyl[65], alkyl[48], and dimethylamide groups [in the photolysis of the azide (XXIV)][81] were found to migrate in phosphorylnitrenes from the phosphorus to the nitrogen atom, i.e. the photolysis of PAA is found to entail a rearrangement similar to the Curtius rearrangement. Derivatives of metaphosphonimidates# and an imidometaphosphate with the $O{=}\overset{|}{P}{=}N-$ fragment, which can dimerise or react with substances having a mobile hydrogen atom, are formed as intermediates.

Thus diphenylphosphinic azide gives rise to the diazadiphosphatidine (XXVII) on irradiation for 12 h (at 253.7 Å) in benzene:



(XXVII)

If the irradiation of the azide (I) is carried out in the presence of alcohols, then alkyl phenylphosphonanilidates are obtained[65]:



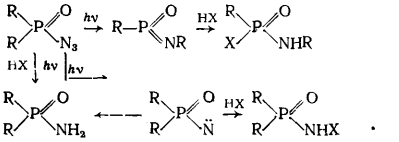
In other media the products of the addition of ethylene glycol, aniline, and methyl iodide to the metaphosphonimidate were obtained.

The photolysis of PAA has been studied in greatest detail in relation to di-t-butylphosphinic azide, di-isopropylphosphinic azide, and diethylphosphinic azide in various alcohols and in t-butylamine[48]. The results of the investigation are compiled in Table 10.

Table 10. Photolysis of dialkylphosphinic azides $R_3P(O)N_3$ in protic solvents[48].

№	Azide	Solvent (HX)	Yield, %		Other products
			$RP(O)(X)NHR$	$R_2P(O)NH_2$	
1	$(t\text{-}C_4H_9)_2P(O)N_3$	CH_3OH	71	—	$(t\text{-}C_4H_9)_2P(O)NHOCH_3$ (8%)
2	$(t\text{-}C_4H_9)_2P(O)N_3$	C_2H_5OH	62	24	none
3	$(t\text{-}C_4H_9)_2P(O)N_3$	iso-C_3H_7OH	27	64	none
4	$(t\text{-}C_4H_9)_2P(O)N_3$	$t\text{-}C_4H_9OH$	63	6.5	$(t\text{-}C_4H_9)_2P(O)NHCO_4H_9\text{-}t$
5	$(t\text{-}C_4H_9)_2P(O)N_3$	$t\text{-}C_4H_9NH_2$	74	—	none
6	$(iso\text{-}C_3H_7)_2P(O)N_3$	CH_3OH	71	5	$(iso\text{-}C_3H_7)_2P(O)NHOCH_3$
7	$(iso\text{-}C_3H_7)_2P(O)N_3$	C_2H_5OH	38	46	none
8	$(iso\text{-}C_3H_7)_2P(O)N_3$	$(t\text{-}C_3H_7OH$	—	87	none
9	$(iso\text{-}C_3H_7)_2P(O)N_3$	$(iso\text{-}C_4H_9NH_2$	74	—	none

The reactions can be illustrated schematically as follows:

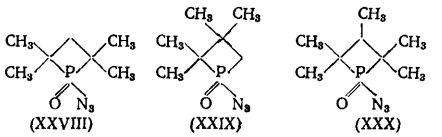


The addition of alcohols or t-butylamine to metaphosphonimidates results in the formation of alkyl *N*-alkylphosphonamidates or alkyl *N*-alkyl-*N'*-t-butylphosphonodiamidates. On passing from methanol to ethanol, the formation of dialkylphosphinic amides $R_2P(O)NH_2$ (compounds 2 and 7, Table 10) is observed, their yields increasing when the reaction is carried out in isopropyl alcohol (compounds 3 and 8), which can be accounted for by the ease of abstraction of hydrogen

#An analogy has been noted between the metaphosphonimidates and the isocyanates formed in the Curtius rearrangement of acyl azides[48].

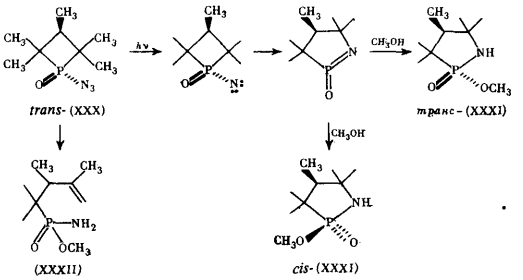
from the latter alcohol; the rate of the decomposition of the azide is several times greater than in methanol.

The migration of the alkyl group from phosphorus to nitrogen has also been observed in the nitrenes formed on photolysis of 1-azido-2,2,4,4-tetramethylphosphetan 1-oxide (XXVIII),[49] 1-azido-2,2,3,3-tetramethylphosphetan 1-oxide (XXIX),[49,82] and 1-azido-2,2,3,4,4-pentamethylphosphetan 1-oxide (XXX),[49,82,83] in methanol:



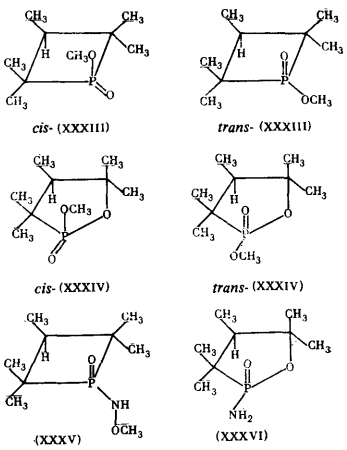
(XXVIII) (XXIX) (XXX)

The *trans*- and *cis*-isomers of compound (XXXI) and also compound (XXXII) have been obtained from the *trans*-isomer of compound (XXX):[49,82]



trans-(XXX) *trans*-(XXXI) (XXXII) *cis*-(XXXI)

The formation of the *cis*- and *trans*-isomers of compounds (XXXI), (XXXIII), (XXXIV), (XXXV), and (XXXVI) was demonstrated in a more detailed study[83] of the products of the photolysis of the *trans*-phosphetan (XXX):

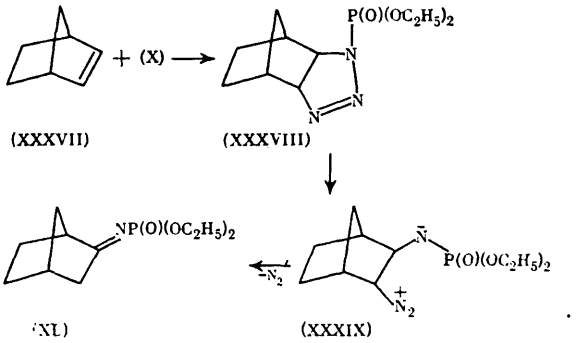


cis-(XXXIII) *trans*-(XXXIII) *cis*-(XXXIV) *trans*-(XXXIV) (XXXV) (XXXVI)

5. Reactions of PAA with Unsaturated Compounds (1,3-Dipolar Cycloaddition)

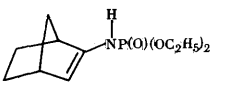
It has been shown in a number of studies[9,10,84-89] that PAA add to unsaturated compounds analogously to aryl azides and the azides of carboxylic acids.

In relation to the addition of diethyl phosphorazidate to norbornene (XXXVII),[89] it has been suggested that the reaction proceeds via an intermediate triazoline (XXXVII), which is formed as the result of the 1,3-dipolar cycloaddition and is subsequently converted into the dipolar ion (XXXIX), which decomposes with formation of *N*-(2-norbornylidene)-phosphoramidate (XL):



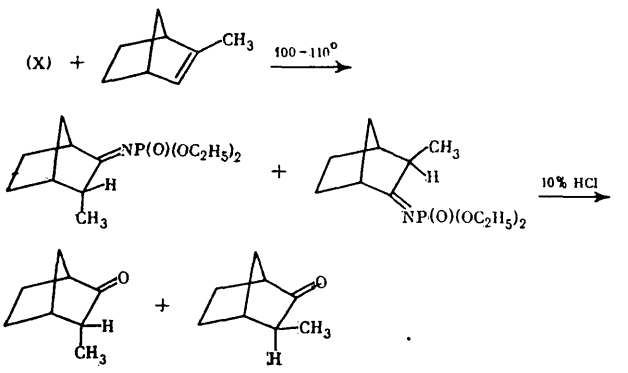
(XXXVII) (XXXVIII) (XL) (XXXIX)

A small amount (<5%) of the phosphoramidate

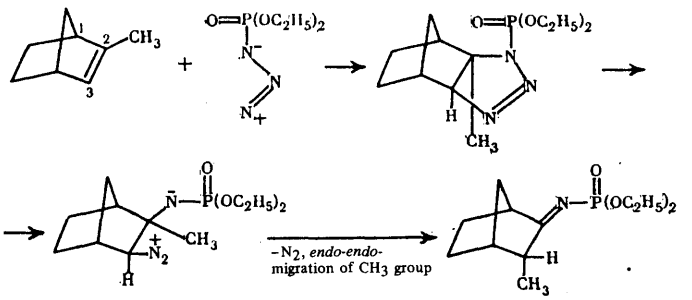


is also formed. The study of the reaction of norbornene deuterated in the 5- and 6-positions with the azide (X) led to the conclusion that the norbornyl skeleton does not rearrange. Dimethyl phosphorazidate reacts with compound (XXXVII) like the azide (X).[85]

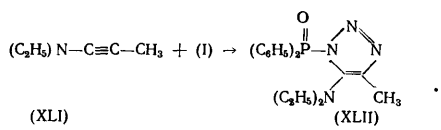
When the azide (X) adds to 2-methyl-2-norbornene, a mixture of diethyl *N*-(*endo*-3-methyl-2-norbornylidene)-phosphoramidate and diethyl *N*-(*exo*-2-methyl-3-norbornylidene)phosphoramidate is formed, but could not be resolved. However, after the hydrolysis of this mixture, *endo*-3-methyl-2-norbornanone (86%) and *exo*-3-methyl-2-norbornanone (14%) were isolated:



The intermediate triazolines were not isolated, since they are rapidly converted into phosphorylated imines as a result of the 3,2-*endo*-migration of the methyl group (the main reaction pathway) and the elimination of a nitrogen molecule[87]:

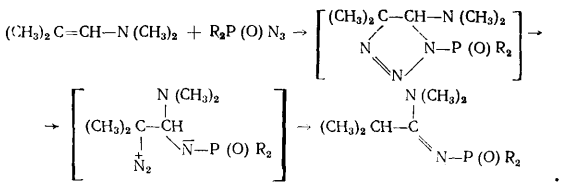


PAA react similarly with activated alkynes. Thus 1-(diethylamino)propyne (XLI) reacts with diphenylphosphinic azide in boiling benzene to form the triazole (XLII):[90]

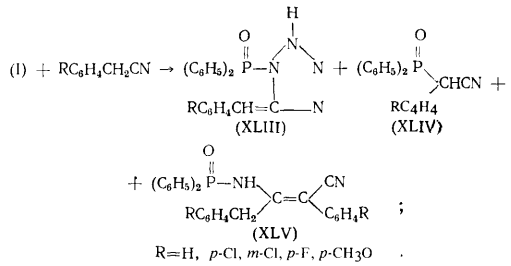


(XLI) (XLII)

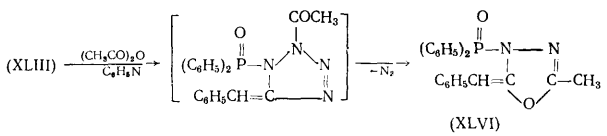
The reactions of PAA with enamines give rise to high yields of phosphorylated amidines[9]:



The interaction of the azide (I) with substituted phenylacetonitriles led to the synthesis of the phosphorylated tetrazoline (XLIII), the nitrole (XLIV), and the enaminonitrile (XLV):[86]

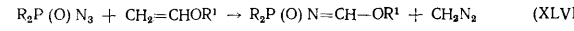


The acylation of compound (XLIII) and subsequent heating yielded the phosphorylated oxadiazoline (XLVI):

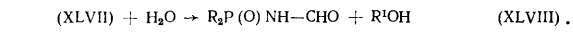


(XLVI)

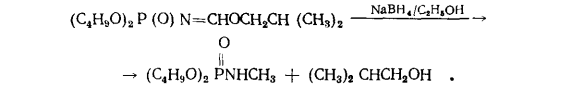
The reaction of PAA with vinyl ethers led to the formation of *N*-phosphorylated imines (XLVII) and phosphorylated triazolines, which were not expected[10]:



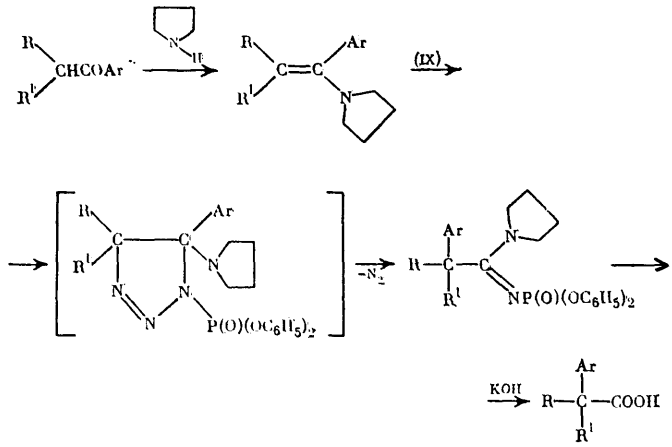
Hydrolysis of compound (XLVII) under mild conditions leads to the formation of *N*-formylphosphoramidates (XLVIII) and alcohols:



The structure of compounds (XLVII) was confirmed in a study of the reaction with sodium tetrahydroborate, which involves the dissociation of the C–O bond:

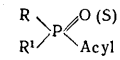


A method has been proposed for the conversion of alkyl aryl ketones into α-arylalkanecarboxylic acids using pyrrolidine and diphenyl phosphorazidate[91]. These reactions can be illustrated by the following scheme, in which the addition of the azide (IX) to the C=C double bond is postulated:



IV. PHYSIOLOGICAL ACTIVITY

Since the azide group in PAA has the properties of a pseudohalogen, the PAA fully satisfy the formula proposed by Schrader[92] for insecticides:



Indeed the first PAA [1,2] were patented as insecticides (dialkyl phosphorazidothioates—contact insecticides[1,93,94]; *N,N,N',N'*-tetramethylphosphorodiamidic azide—an effective systemic insecticide used against aphids).

Certain PAA exhibit a considerable toxicity for warm blooded animals. A strong miotic activity of diethyl phosphorazidate has been noted[8,30]. At the same time appropriate precautions made it possible to carry out an extensive research into this compound.

The toxicity and the anticholinesterase activity of certain phosphonamidic azides—derivatives of methylphosphonic acid have been investigated (Table 11).[42] The toxicity depends significantly on the structure of the amide component of the molecule—it has a maximum for the anilide group at the phosphorus atom.

Table 11. The toxicity and anticholinesterase activity of *N*-phenyl-*N*-alkoxycarbonyl-, and arylcarbamoyl-methylphosphonamidic azides[42].

Compound	Toxicity, mg kg^{-1}		I^*_{50}, moles
	LD_{50}	LD_{100}	
$CH_3P(O)(N_3)NHC_6H_5$	2.692	5	$4.5\cdot10^{-7}$
$CH_3P(O)(N_3)NHCOOCH_3$	1.39	5	$3.0\cdot10^{-6}$
$CH_3P(O)(N_3)NHCOOC_2H_5$	83.18	100	$8.0\cdot10^{-5}$
$CH_3P(O)(N_3)NHCOOC_3H_7$-iso	20.89	25	$4.0\cdot10^{-6}$
$CH_3P(O)(N_3)NHCONHC_6H_5$	851.1	1000	$1.0\cdot10^{-2}$
$CH_3P(O)(N_3)NHCONHC_6H_4Cl$-*p*	952.0	1000	$1.0\cdot10^{-2}$

*I_{50} represents the molar concentrations of the inhibitor which cause a 50% suppression of enzyme activity in 5 min.

The following series based on the dependence of the toxicity on the structure of the alkoxy-group has been observed for alkoxycarbonylamido-substituted PAA: methoxy > isopropoxy > ethoxy. Amido-substituted derivatives of ureidoazidomethylphosphonic acid exhibit a minimal toxicity.

V. PHYSICAL PROPERTIES

1. Infrared and Raman Spectra

PAA are characterised by an intense absorption band corresponding to the antisymmetric N–N stretching vibrations in the N_3 group. The band, which occurs at 2138–2195 cm^{-1} (3,25, 44–46) has a higher frequency than for organic azides (in the vicinity of 2130 cm^{-1})[95]. As for organic azides, the corresponding symmetrical vibrations have a much lower frequency and their absorption bands are much less intense.

Various types of vibrations characteristic of PAA have been examined in detail in a dissertation[45]. Some of them, localised either in the group of nitrogen atoms or in the group of phosphorus and nitrogen atoms, will be presented here.

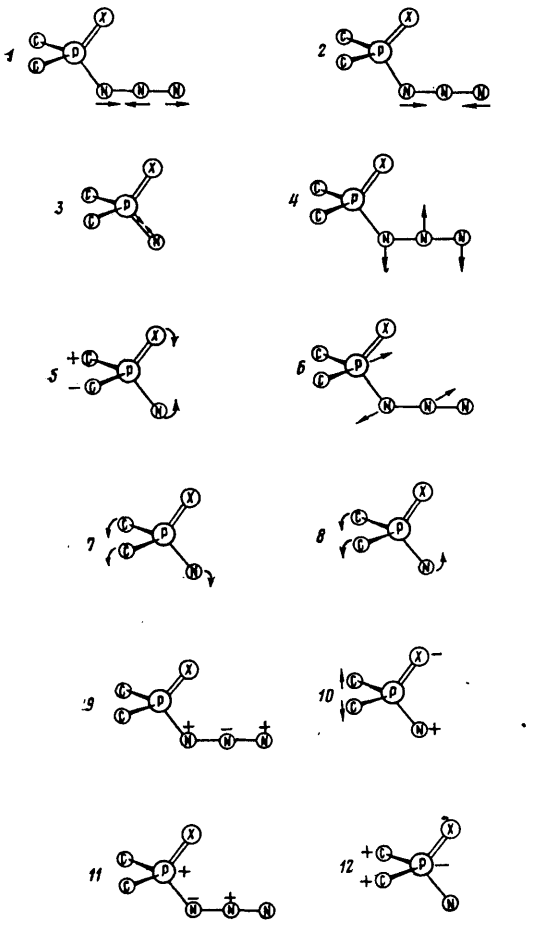


Figure 1. The types of vibrations of the $C_2P(X)N_2$ (X = O, S, or Se) fragment characteristic of PAA;[45] 1) $\nu_{as}(N_3)$; 2) $\nu_s(N_3)$; 3) ν(P–N); 4) $\delta(N_3)$; 5) $\delta[C_2P(X)N]$; 6) δ(P–N–N); 7) $\delta(C_2PN)$; 8) $\rho(C_2PN)$; 9) $\gamma(N_3)$; 10) $\tau[C_2P(X)N]$; 11) γ(P–N–N); 12) $\omega[C_2P(X)N]$.

The first group (Fig.1, *1–8*) includes stretching and deformation vibrations symmetrical relative to the plane. They must be active both in the infrared absorption and Raman spectra; in the latter case they should give rise to polarised lines.

In the second group (Fig.1, *9–12*) the stretching and deformation vibrations are antisymmetric relative to the plane; they are also active in the infrared absorption spectra, while in the Raman spectra depolarised lines correspond to them.

Table 12 presents the infrared and Raman spectroscopic data for dimethylphosphinic azide[44]. The insignificant ν_{as} intensity in the Raman spectrum is noteworthy (Fig.2). The antisymmetric vibration characteristic of PAA can be used for analytical purposes. When PAA were allowed to react with phosphorus(III) compounds, the end of the reaction was inferred from the disappearance of the azide band in the infrared spectrum of the reaction mixture[31].

Table 12. The wavenumbers (ν, cm^{-1}) in the vibrational spectra of dimethylphosphinic azide[44].

i.r.	Raman	Assignment	i.r.	Raman	Assignment
3397 w.	—	$\nu_{as} + \nu_s(N_3)$	554 v.s.	552 v.s.	ν (P—N) + $\delta(N_3)$
2521 w.	—	$2 \times \nu_s(N_3)$	393 s.	399 m.	$\delta[C_2P(O)N]$
2143 v.s.	2150 m.	$\nu_{as}(N_3)$	317 v.w.	312 m.	$\omega(PC_2N)$
1268 v.s.	1269 m.	$\nu_s(N_3)$	260 m.	258 s.	$\rho[C_2P(O)N]$
735 s.	732 w.	ν (P—N)+ $\delta(N_3)$	—	142 s.	$\tau[C_2P(O)N]$

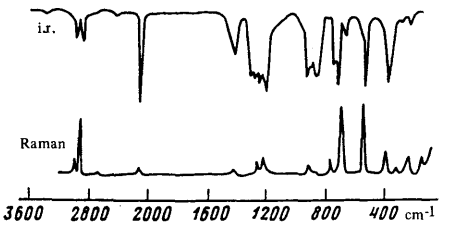
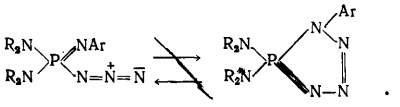


Figure 2. Infrared and Raman spectra of dimethylphosphinic azide[44].

The study of the infrared spectra of PAA confirmed their structure. The relative intensity of the azide absorption band at 2140 cm^{-1} in the spectra of *N,N,N',N'*-tetra-alkyl-*N''*-arylphosphorodiamidimidic azides is independent of the solvent (CCl_4, dioxan, and pyridine). This disproves the possibility of the azido-tetrazole tautomerism[52]:



A similar tautomerism has been ruled out for phosphinimidic acid azides $[(C_6H_5)_2P(=NR)N_3]$ [22,96,97] and diethyl phosphorazidate[8].

2. NMR Spectra and Mass Spectra

The chemical shifts of the signals in the ^1H, ^{13}C, and ^{31}P NMR spectra of PAA and the corresponding chlorides have been compared[28,44–46]. The ^{14}N NMR data for certain PAA and ^{15}N NMR data for isotope-substituted PAA have been published[98].

Mass-spectrometric data for PAA have also been published[44-46]. In the mass spectra of dimethylphosphinic azide $(CH_3)_2P(O)N_3$ and its deuterated analogue $(CD_3)_2P(O)N_3$, the fundamental peaks 77 $[(CH_3)_2PO^+]$ and 83 $[(CD_3)_2PO^+]$ correspond to the loss of the entire nitrogen $(M^+ - 42)$.[45] It is noteworthy that the fundamental peak in the mass spectrum of phenyl azide corresponds to the loss of molecular nitrogen $(M^+ - 28)$.[99]

3. The Atomic Refraction of the N_3 Group

The atomic refraction of the N_3 group in PAA has come to be assumed to be 9.61 cm^3 (calculated from the results of Gilyarov and coworkers[23,31]; the Eisenlohr numbers have been used for the atomic refractions of other elements), i.e. it is close to the atomic refraction of the N_3 group in alkyl and aryl azides[100].

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The advances in PAA chemistry are evident. Like any vigorously developing field of study, the chemistry of PAA involves many unsolved problems, some of which have been formulated in this review. It has now become necessary to manufacture in the USSR diphenyl phosphorazidate, the employment of which in the "modified Curtius reaction" instead of nitrous acid will undoubtedly prove useful in organic synthesis.

It may be hoped that this review will stimulate interest in the chemistry of PAA and this will assist in its further development.

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