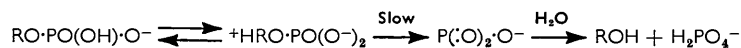**703.** *The Mechanism of Hydrolysis of Phosphorochloridates and Related Compounds. Part IV.* Phosphoryl Chloride.*

By R. F. HUDSON and G. MOSS.

The rates of hydrolysis of phosphoryl chloride and phosphorodichloridic acid were measured by various physical methods under varying conditions, and a reaction mechanism is proposed. The structural features promoting unimolecular heterolysis of P–X bonds are considered, and the mechanism of formation of the partial hydrolysis products of phosphoryl chloride is discussed.

MECHANISTIC studies[1] have shown that normally P–Cl fission proceeds by a bimolecular displacement similar to an S_N2 substitution at a saturated carbon atom, and several attempts[2] to detect intermediate diols by ^{18}O-exchange have been unsuccessful. However, in view of the stability of quinquecovalent phosphorus compounds, intermediates formed by addition probably have a transient existence during displacement reactions. Moreover, owing to the relatively high σ-bond energies and low $d_\pi–p_\pi$-conjugation energies[3] of the bonds in phosphorus compounds compared with those for carbon analogues, rate-determining (S_N1) ionisation is not normally found in phosphorus chemistry. This difference is shown by the stability of mono- and di-alkyl phosphates and the instability of alkyl hydrogen carbonates. Moreover, phosphorodichloridic acid can be prepared readily,[4] whereas chloroformic acid is unknown in the free state.

Ionisation mechanisms have, however, been proposed for certain phosphorus compounds containing strongly electron-releasing groups. Hall[5] suggested that tetra-alkyl phosphoroamidochloridates are hydrolysed by a rate-determining ionisation in a similar manner to carbamoyl chlorides,[6] but other workers[7] consider these reactions to be bimolecular displacements. However, in the ionic form several phosphorus compounds probably react by a unimolecular mechanism. For example, the hydrolysis of NN-dialkyl phosphorodiamidic chlorides[8] was discussed in the preceding paper. The hydrolysis of alkyl dihydrogen phosphates[9] is thought to involve a similar rate-determining stage:

$$RO\cdot PO(OH)\cdot O^- \underset{}{\overset{}{\rightleftharpoons}} \text{}^+HRO\cdot PO(O^-)_2 \xrightarrow{\text{Slow}} P(\text{:}O)_2\cdot O^- \xrightarrow{H_2O} ROH + H_2PO_4^-$$

In the following discussion, therefore, it will be assumed that the initial stage of the

* Part III, preceding paper.

[1] (a) Dostrovsky and Halmann, *J.*, 1953, 503; (b) Hudson and Keay, *J.*, 1960, 1859.
[2] Dostrovsky and Halmann, *J.*, 1956, 1004; Halmann, *J.*, 1959, 305.
[3] Jaffé, *J. Phys. Chem.*, 1954, **58**, 185; Craig, Maccoll, Nyholm, Orgel, and Sutton, *J.*, 1954, 332.
[4] Grunze, *Z. anorg. Chem.*, 1959, **298**, 152; Grunze and Thilo, *Angew. Chem.*, 1958, **70**, 73.
[5] Hall, *J. Org. Chem.*, 1956, **21**, 248.
[6] Hall, *J. Amer. Chem. Soc.*, 1955, **77**, 5993.
[7] Crunden and Hudson, *Chem. and Ind.*, 1959, 748; Westheimer and Samuel, *ibid.*, 1959, 51.
[8] Westheimer, *Chem. Soc. Spec. Publ.*, No. 8, 1957, 180; Crunden and Hudson, *Chem. and Ind.*, 1958, 1478; preceding paper.
[9] Butcher and Westheimer, *J. Amer. Chem. Soc.*, 1955, **77**, 2420; Vernon, *Chem. Soc. Spec. Publ.*, No. 8, 1957, 17.

hydrolysis of phosphoryl chloride proceeds by a bimolecular mechanism, and that rate-determining unimolecular processes are possible only for the anionic derivatives subsequently formed. This generalisation leads to the following series of possible reactions for the complete hydrolysis of phosphoryl chloride:

$$H_2O + POCl_3 \longrightarrow HO{\cdot}POCl_2 + HCl$$
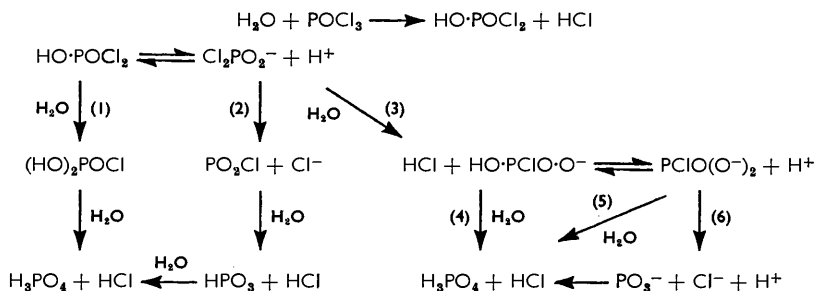
The first stage of the hydrolysis in dioxan–water mixtures (Table 1), the rate of which was measured by the stopped-flow procedure, gives two equivalents of acid and one of

TABLE 1.

Hydrolysis of phosphoryl chloride in dioxan containing 33·3% by volume of water.

$POCl_3$ $(10^{-3}M)$	Temp.	k_1 (sec.$^{-1}$)	k_1 (mean) * (sec.$^{-1}$)	Temp. (mean)	$POCl$ $(10^{-3}M)$	Temp.	k_1 (sec.$^{-1}$)	k_1 (mean) * (sec.$^{-1}$)	Temp. (mean)
1·9	26·7°	63·3 ⎤				0·97	25·1°	63·7 ⎤		
,,	26·3	65·5 ⎥	65·5	26·4°	,,	25·0	64·2 ⎥	62·4	25·0°
,,	26·5	64·9 ⎥			,,	,,	64·2 ⎥		
,,	26·2	68·9 ⎦			,,	24·8	57·3 ⎦		

* The effect of temperature on k_1 is probably relatively small (cf. the activation energy for Et_2PClO, 7·3 kcal./mole [1b]).

chloride ion (measured potentiometrically at a silver–silver chloride electrode). This initial reaction leads to the formation of phosphorodichloridic acid; this is found to be a strong acid, a $10^{-2}M$-solution having pH 2·0 immediately. This reaction with a half-life of the order of 10^{-2} sec. at 25° is followed by a slower process ($t_{\frac{1}{2}} \sim 250$ sec.), the rate of which is equal to that of hydrolysis of phosphorodichloridic acid.[4] The rate of acid production (from phosphorodichloridic acid) (followed by the automatic titrator) is similar to the rate of production of chloride ions followed potentiometrically (Table 2), and the two chlorine atoms are liberated simultaneously in acid and in alkaline solution.

TABLE 2.

Rate of hydrolysis of phosphorodichloridic acid in water at 25°.

$[Cl_2PO_2H]$ (M)	Conditions	10^3k_1 * (sec.$^{-1}$)	$[Cl_2PO_2H]$ $(10^{-3}M)$	10^3k_1 † (sec.$^{-1}$)
10^{-4}—10^{-5}	Solvolysis	3·06 ‡	5·3	4·20
7×10^{-5}	Solvolysis	3·14 ‡	9·1	4·31
1×10^{-2}	pH 4·0	3·11 §	6·1 **	4·29
8×10^{-3}	pH 7·0	3·21 §	3·5 **	4·03
7×10^{-3}	pH 7, 1·5N-KCl	6·26 §	**	3·69 ††
9×10^{-3}	pH 7, 1·5N-KBr	6·68 §	(§§)	3·66 ††

* The mean of the values from at least two separate experiments. ** Measurements made with phosphoryl chloride. ‡ Rate followed conductometrically. § Rate followed by the automatic titrator. † Rate followed potentiometrically (Ag/AgCl electrodes) in the presence of N-KNO₃. †† Measurements made at 22°. §§ With phosphoryl chloride +0·05N-NaOH.

Hydrolysis of Phosphorodichloridic Acid.—The rate of hydrolysis of phosphorodichloridic acid was similar in acidic and basic solution (Table 2), showing that the reaction does not involve the undissociated acid, so that mechanism (1) can be eliminated.

Moreover, sodium phenoxide and sodium nitrite, which are known to be very reactive

towards phosphorylating agents, had no effect on the rate of reaction, but pyridine and pyridine-4-aldehyde produced large rate-increases (Table 3). The ratio of the bimolecular

TABLE 3.

Rate of reaction of phosphorodichloridic acid with pyridine and pyridine-4-aldehyde.

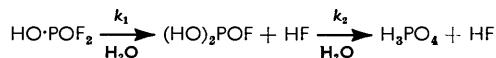| [Cl₂PO₂H] (10⁻³M)	[Amine] (10⁻²M)	10³k_1 (sec.⁻¹)	k_2 (l. mole⁻¹ sec.⁻¹)	k_2/k_w	[Cl₂PO₂H] (10⁻³M)	[Amine] (10⁻²M)	10³k_1 (sec.⁻¹)	k_2 (l. mole⁻¹ sec.⁻¹)	k_2/k_w
Pyridine at 28°.					*Pyridine-4-aldehyde at 25°.*				
2·7	2·5	11·75 } 12·25			2·6	1·9	7·06 } 7·14	0·152	2260
4·8	2·5	12·8 }	0·275	2750	5·0	1·9	7·22 }		
6·0	5·0	19·8	0·284		3·7	3·8	12·51 } 11·37	0·17	
5·5	—	5·63			5·4	3·8	10·23 }		

k_w = Second-order rate constant for the hydrolysis in water alone.

constants for the reactions with pyridine and with water ($\sim$3000) suggests that the hydrolysis proceeds by the bimolecular mechanism (3) and not by the ionisation process (2). The lack of reaction with phenoxide and nitrite ions is attributed to electrostatic repulsion, although it is noted that concentrated solutions of sodium hydroxide increase the rate of hydrolysis of phosphorodifluoridic acid.[10] The hydrolysis of the phosphorodichloridate ion exhibits a strong kinetic salt effect (Table 2), since the rate is increased to similar extents by potassium chloride and potassium bromide. This shows that the transition state is considerably more polar than the ground state, and it is probably similar in structure to the addition intermediate of the bimolecular mechanism, *i.e.*:
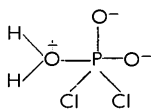
The simultaneous removal of both chlorine atoms from phosphorodichloridic acid shows that the rate of the second stage is either equal to, or considerably greater than, that of the first. Since the same overall rate is observed in acidic solution, where the chloro-acid exists predominantly in the singly ionised form, and in basic solution, where it exists entirely in the doubly ionised form, it follows that the second stage is considerably faster than the first.

This rate order is in contrast to that found for the corresponding fluoro-acids,[11] for which case $k_1 \gg k_2$ in the reactions:

$$\text{HO·POF}_2 \xrightarrow[\text{H}_2\text{O}]{k_1} (\text{HO})_2\text{POF} + \text{HF} \xrightarrow[\text{H}_2\text{O}]{k_2} \text{H}_3\text{PO}_4 + \text{HF}$$

Moreover, the rate of hydrolysis of phosphorofluoridic acid is increased by the addition of both acid and alkali, showing the hydrolysis to be bimolecular under all conditions. The increase in reactivity with decrease in pH is due to the greater reactivity towards water of the singly ionised form:

$$\text{F}^- + \text{HPO}_4{}^{2-} \xleftarrow{\text{HO}^-} \text{F·PO(O}^-)_2 \xrightleftharpoons{\text{H}^+} \text{F·PO(OH)·O}^- \xrightarrow{\text{H}_2\text{O}} (\text{HO})_2\text{PO·O}^- + \text{HF}$$

The bimolecular rate order $k_1 > k_2$ follows the increase in electron-release to the phosphorus atom, which reduces its electrophilic power. This decrease is also shown by the relative hydrolysis rates of the corresponding chloridates,[12] RO·POCl₂ $\gg$ (RO)₂POCl.
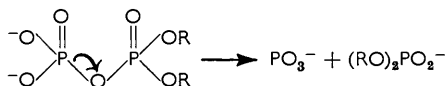
The reverse rate order for the chloro-acids suggests strongly that the reaction proceeds by an S_N1 type of process (mechanism 6) similar to that recently proposed by Brown and

[10] Devonshire, Ph.D. Thesis, Oklahoma 1954, quoted by Van Wazer, "Phosphorus and Its Compounds," Interscience Publ., Inc., New York, Vol. I, 1958, p. 814.
[11] Lange, *Ber.*, 1929, **62**, 786; Lange and Livingston, *J. Amer. Chem. Soc.*, 1950, **72**, 1280.
[12] Hudson and Saville, unpublished results.

Hamer [13a] to account for the catalysis of the hydrolysis of tetra-alkyl pyrophosphates by phosphate ions. The initial reaction leads to a dialkyl pyrophosphate,[13b] which hydrolyses very rapidly by the following suggested mechanism:

$$-O\diagdown \underset{\underset{-O\diagup}{}}{\overset{\overset{O}{\|}}{P}}\diagdown_{O}\diagup \underset{\overset{O}{\|}}{P}\diagup_{\diagdown OR}^{OR} \longrightarrow PO_3^- + (RO)_2PO_2^-$$
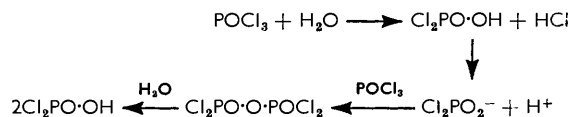
The difference in mechanism between the chlorides and anhydrides on the one hand, and the fluorides on the other, may be attributed to the high P–F bond-energy. Thus the d_π–p_π-conjugation which provides the energy to break the P–Cl and P–O bonds in the unimolecular reaction is too weak to break the P–F bond. The high electronegativity of the fluorine atom increases the positive charge on the phosphorus atom, assisting the bimolecular process.

As a result of these and previous observations, therefore, the conditions for the unimolecular heterolysis of P–X bonds are now fairly well established.

Partial Hydrolysis of Phosphoryl Chloride.—The present observations and the reaction mechanism proposed for the hydrolysis of phosphoryl chloride have an important bearing on the interpretation of the side reactions leading to partial hydrolysis products in media of low water content. The mixtures of reaction products have been investigated in detail in recent years,[14] and general schemes for their formation have been proposed. In order to deduce the probable mechanism by which the complex reaction mixture is produced, the following conclusions from the above discussion will be used as a basis: (1) Phosphoryl chloride is considerably more reactive than the other intermediates, except pyrophosphoryl chloride. (2) Phosphorodichloridic acid is a very strong acid, and the anion competes with water in further nucleophilic reactions, when their concentrations are comparable. (3) Reactions between negative ions are very slow and the following reaction can be neglected: $2Cl_2PO_2^- \longrightarrow Cl_2PO\cdot O\cdot POCl\cdot O^- + Cl^-$. (4) The following reaction will be slow compared with the reaction between the phosphorodichloridate ion and phosphoryl chloride, owing to the electronic effect of the hydroxyl group: $Cl_2PO_2^- + Cl_2PO\cdot OH \longrightarrow Cl_2PO\cdot O\cdot POCl\cdot O^- + HCl$.

The following reactions will therefore occur relatively rapidly:

$$POCl_3 + H_2O \longrightarrow Cl_2PO\cdot OH + HCl$$

$$\downarrow$$

$$2Cl_2PO\cdot OH \xleftarrow{\ H_2O\ } Cl_2PO\cdot O\cdot POCl_2 \xleftarrow{\ POCl_3\ } Cl_2PO_2^- + H^+$$

The initial reaction mixture thus consists almost entirely of phosphorodichloridic acid and pyrophosphoryl chloride, both of which may be obtained readily from the hydrolysates.[5,14]

The subsequent slower reactions will depend on the degree of dissociation of the phosphorodichloridic acid, and two possibilities, corresponding to complete dissociation and partial dissociation, respectively, will be considered.
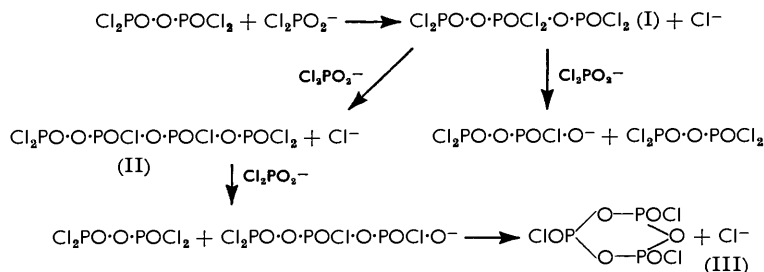
(a) *Complete dissociation.* Under these conditions, further reaction involves attack on pyrophosphoryl chloride by the phosphorodichloridate ion. Grunze [4] has shown that the hydrolysis of pyrophosphoryl chloride involves almost quantitative P–O fission, so that, by analogy, reaction with the phosphorodichloridate ion would simply lead to interchange, *viz.*:

$$Cl_2PO_2^- + Cl_2PO\cdot O\cdot POCl_2 \longrightarrow Cl_2PO\cdot O\cdot POCl_2 + Cl_2PO_2^-$$
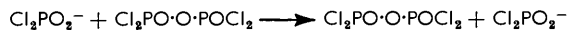
[13] (a) Brown and Hamer, *J.*, 1960, 1155; (b) Samuel and Silver, *J.*, 1961, 4321.
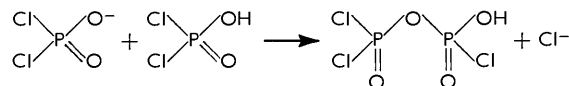[14] Roux, Thilo, Grunze, and Viscontini, *Helv. Chim. Acta*, 1955, **38**, 15; Van Wazer, *J. Amer. Chem. Soc.*, 1960, **82**, 5305.

Consequently, further reaction to form higher polyphosphoryl chlorides must proceed by a less favourable side reaction involving P–Cl fission, as follows:
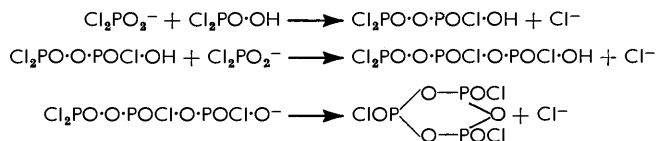
$$Cl_2PO \cdot O \cdot POCl_2 + Cl_2PO_2^- \longrightarrow Cl_2PO \cdot O \cdot POCl_2 \cdot O \cdot POCl_2 \text{ (I)} + Cl^-$$

$$\downarrow Cl_2PO_2^- \qquad \qquad \downarrow Cl_2PO_2^-$$

$$Cl_2PO \cdot O \cdot POCl \cdot O \cdot POCl \cdot O \cdot POCl_2 + Cl^- \qquad Cl_2PO \cdot O \cdot POCl \cdot O^- + Cl_2PO \cdot O \cdot POCl_2$$
(II)

$$\downarrow Cl_2PO_2^-$$

$$Cl_2PO \cdot O \cdot POCl_2 + Cl_2PO \cdot O \cdot POCl \cdot O \cdot POCl \cdot O^- \longrightarrow ClOP\underset{O-POCl}{\overset{O-POCl}{<}} \!\!> O + Cl^-$$
(III)

Intermediates of the kind (I), (II), and (III) have been isolated from the mixtures, and analogous sulphur derivatives [15] have been prepared by other methods. The mixtures subsequently recovered from a 1 : 1 mixture of water and phosphorus oxychloride consist mainly of ortho-, meta-, and pyro-phosphate, with relatively small quantities of the higher acids.[14]

(b) *Partial dissociation.* When the water concentration is low, the phosphorodichloridic acid may be partially dissociated according to the equilibrium: $H_2O + Cl_2PO_2H \rightleftharpoons H_3O^+ + Cl_2PO_2^-$. However, owing to the strong affinity of the proton for water, the reactivity of the latter will be greatly reduced, thus rendering the phosphorodichloridate ion relatively more nucleophilic. This ion may then react with the undissociated acid to initiate the following series of processes, similar to the scheme proposed by Roux *et al.*:[14]

$$\underset{Cl}{\overset{Cl}{>}}P\underset{O}{\overset{O^-}{<}} + \underset{Cl}{\overset{Cl}{>}}P\underset{O}{\overset{OH}{<}} \longrightarrow \underset{Cl}{\overset{Cl}{>}}P\underset{O}{\overset{O}{<}} \!\!\! P\underset{Cl}{\overset{OH}{<}} + Cl^-$$

This series of reactions would therefore lead to essentially the same products as are given in the previous scheme:

$$Cl_2PO_2^- + Cl_2PO \cdot OH \longrightarrow Cl_2PO \cdot O \cdot POCl \cdot OH + Cl^-$$

$$Cl_2PO \cdot O \cdot POCl \cdot OH + Cl_2PO_2^- \longrightarrow Cl_2PO \cdot O \cdot POCl \cdot O \cdot POCl \cdot OH + Cl^-$$

$$Cl_2PO \cdot O \cdot POCl \cdot O \cdot POCl \cdot O^- \longrightarrow ClOP\underset{O-POCl}{\overset{O-POCl}{<}} \!\!> O + Cl^-$$

EXPERIMENTAL

Preparation and Purification of Materials.—Dioxan was purified in the usual way and distilled before use (b. p. 101°).

Phosphoryl chloride was boiled for 2 hr. in a slow stream of dry nitrogen and distilled several times (b. p. 137·5°).

Phosphorodichloridic anhydride was prepared by the action of phosphoric oxide on freshly distilled phosphoryl chloride at 200° for 24 hr. under 50 atm. of carbon dioxide in an autoclave (yield 8%); it had b. p. 54°/0·22 mm. (lit.,[4] b. p. 90°/12 mm.) (Found: equiv., 31·6, 31·4. Calc.: equiv., 31·5).

Phosphorodichloridic acid was prepared by quantitative hydrolysis of the anhydride at −40°, according to the method of Grunze and Thilo [4] (Found: equiv., 33·8, 34·15. Calc.: equiv., 33·75).

Reaction Rates.—(a) The first stage of the hydrolysis was followed by the stopped-flow procedure in an apparatus similar to that described elsewhere,[16] the change in acid concentration with time being measured conductometrically. Phosphoryl chloride was stored in specially constructed weighing bottles, each with a long capillary neck sealed with a Polythene

[15] Rother, *Chem. Ber.*, 1960, **93**, 2217.
[16] Prince, *Trans. Faraday Soc.*, 1958, **54**, 838; Moss, Ph.D. Thesis, London, 1961.

cap. Small quantities could be introduced into dioxan by gently warming the base of the bottle. In this way, standard solutions of phosphoryl chloride in dioxan were made. These were protected from the atmosphere in the reservoir of the rate apparatus by means of close-fitting Polythene floats.

(*b*) The hydrolysis of phosphorodichloridic acid in water at 25° was followed by means of a Pye automatic titrator by a procedure previously described,[17] with a 250-ml. beaker as the reaction vessel. Phosphorodichloridic acid was weighed into a small intermediate storage vessel which could be immersed in the reaction medium. Before the acid was introduced, an equivalent of base was added to 100 ml. of water in the beaker, so that the reaction began in a medium of pH 7. For solvolyses in potassium chloride and potassium bromide solutions, and in the presence of pyridine, the titrant solution contained the same concentration of these as the reaction medium.

(*c*) The rates of the hydrolysis of phosphorodichloridic acid and of the second stage of the hydrolysis of phosphoryl chloride were also followed potentiometrically, with silver–silver chloride electrodes, by a balancing-cell method.[18] When phosphoryl chloride was used, slightly more than one-third of the calculated quantity of hydrochloric acid was added to the titration cell, and phosphoryl chloride was introduced through a microsyringe. The rate of reaction was then followed by adding single drops of acid and taking the time of each balance point. This procedure was adopted because the burette could not be read accurately in the time between the addition of successive drops in the early stage of the reaction.

Both chlorine atoms were removed simultaneously from phosphorodichloridic acid in all cases. The following is a typical analysis: wt. of $HO \cdot POCl_2$ taken = 0·036 g., 0·281 mmole; vol. of N-HCl used = 0·55 ml., 0·275 mmole.

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[17] Hudson and Loveday, *J.*, 1962, 1068.
[18] Hudson and Wardill, *J.*, 1950, 1729.