CATALYTIC PHOSPHORYLATION OF POLYFLUORINATED ALCOHOLS COMMUNICATION 1. PREPARATION OF TRIPOLYFLUOROALKYL AND ARYL POLYFLUOROALKYL PHOSPHATES

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Polyfluoroalkyl phosphates are usually obtained by the reaction of phosphorus oxychloride or the appropriate chlorophosphate with polyfluorinated alcohols in the presence of tertiary amines in an inert solvent [1-4]. Only the preparation of polyfluoroalkyl phosphates by the reaction of phosphorus oxychloride or alkyl chlorophosphates with alcohols or a mixture of alcohols and phenols in the presence of aqueous sodium hydroxide solution is described in the literature [5]. The symmetrical fluorine-containing trialkyl phosphates can be obtained by the reaction of PCl₅ with polyfluorinated alcohols [6], or by the reaction of phosphorus oxychloride reacts with the alcoholates of alcohols in refluxing toluene [7]. We found that phosphorus oxychloride reacts with the alcoholates of polyfluorotrialkyl phosphates in 50-60% yield. However, a redistribution of the ester radicals occurs and a mixture of phosphates is formed when aryl chlorophosphates are reacted with the alcoholates of polyfluorinated alcohols.

Phosphorus oxychloride does not react with polyfluorinated alcohols in the absence of a hydrogen chloride acceptor [3]. It could be assumed that electrophilic agents of the Lewis acid type, which are capable of reacting with phosphorus oxychloride at the phosphoryl group and in this way increasing the effective positive charge of phosphorus, should facilitate nucleophilic substitution. Actually, it is known that some metals and their salts catalyze the reaction of phosphorus oxychloride with phenols: Mg, Ca, Al, or their chlorides [8]; $ZnCl_2$ [9]; $BaCl_2$, KCl, NaCl, RbCl, CsCl, CoCl₂ [10]. Boron trifluoride [11] and magnesium amalgam [12] catalyze the reaction of phosphorus oxychloride with alcohols, but acid phosphates are formed here, since the liberated hydrogen chloride cleaves the P-O-C bond.

Polyfluorotrialkyl phosphates are not cleaved by hydrogen chloride even on long heating. This made it possible to verify the catalytic action of metal salts during the phosphorylation of polyfluorinated alcohols. It proved that many salts of the metals of Groups I-III of the periodic system are effective catalysts [13, 14]. We made a more detailed study of the catalytic effect on the example of the phosphorus oxychloride

 $POCl_3 + 3CF_3CF_2CF_2CH_2OH \xrightarrow{c \text{ atalysts}} PO(OCH_2CF_2CF_2CF_3)_3 + 3HCl.$

A mixture of phosphorus oxychloride and 1,1-dihydroperfluorobutyl alcohol was heated in the presence of the catalyst and its effectiveness was determined on the basis of the yield of neutral phosphate. The most effective catalysts are the salts of the Group II metals of the periodic system (Table 1), in which connection the most convenient in the preparative sense are $CaCl_2$ and Mg. Magnesium dissolved in the reaction mixture and the actual catalyst is the formed $MgCl_2$. The phosphorylation can also proceed under milder conditions, for example, by diluting the reaction mixture with an excess of 1,1-dihydroperfluorobutyl alcohol or with absolute benzene.

The salts of the Group I metals of the periodic system are less effective than the salts of the Group II metals, although they can be used for preparative purposes. At first glance, catalysis of ammonium salts, for example, the triethyl- and tetraethylammonium chlorides, seems quite unusual, and in their

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Molar ratio POCl ₃		Reaction	Yield of neutral
:CF ₃ (CF ₂) ₂ CH ₂ OH	Catalyst 0.08 M/IM POCI3	time, h	phos - phate, %
1:6	Without catalyst	15	
1:0 1:3,4 $(+20 \text{ ml of absolute } C_6H_6)$	Mg (turnings)	15	75
1:3,4 1:3,4	Without catalyst KCl	15 8	Up to 16
1:3,4 1:3,4 1:3.4	Mg (turnings) MgCl(OH) MgCl	3,5-4	81
1:3,4 1:3,4	MgSO ₄ CaCl ₂	3-4 2	85 86
1:3,4 1:3,4 1:3 /	AICI ₃ Al (powder) 7nCL (granules)(0.12 M / 1 M	15 15	47 40
1:3,4	POCl ₃) NH ₄ Cl	9 8	84 44
1:3,4 1:3,4	[(C ₂ H ₅) ₃ NH]Cl [(C ₂ H ₅) ₄ N]Cl	$3,5-4 \\ 3,5$	88 86

TABLE 1. Phosphorylation of 1,1-Dihydroperfluorobutyl Alcohol with Phosphorus Oxychloride in the Presence of Catalysts

activity they approach some of the catalysts of Group II of the periodic system. The reaction proceeds very vigorously, but in a complicated manner, when $AlCl_3$ is used as the catalyst. Evidently, secondary reactions play an important role in this case, these reactions lead to a substantial reduction in the yield of the phosphate.

Two theories can be expressed regarding the mechanism of the catalytic phosphorylation of polyfluorinated alcohols. 1) Nucleophilic attack on the phosphorus oxychloride molecule is facilitated as the result of reaction between the catalyst and the phosphoryl group (Scheme 1). 2) The alcoholate is formed as the result of an equilibrium exchange reaction between the salt and the alcohol, which then reacts further in conventional manner (Scheme 2). An analogous scheme was proposed in [10] to explain the reaction between phosphorus oxychloride and phenols in a phosphorus oxychloride medium, in the presence of metal salts

> Scheme 1 $Cl_3PO + M^+ \rightleftharpoons Cl_3P = O \dots M^+ \leftrightarrow Cl_3P^+ \longrightarrow OM \xrightarrow{R_FOH} R_FOPOCl_2 + H^+ + M^+ + Cl^-$ Scheme 2 $M^+ + HOR_F \rightleftharpoons MOR_F + H^+$ $Cl_3PO + MOR_F \rightarrow R_FOPOCl_2 + MCl$

We give preference to Scheme 1, on the assumption that the catalytic effect is associated with the addition of the catalyst to the phosphoryl oxygen atom. This assumption is obvious for such salts as the chlorides of aluminum, zinc, and magnesium, which are typical Lewis acids. It is known that the halides of the Group I metals are capable of forming complexes of variable stability with tertiary phosphine oxides, while for the dioxides and sodium iodide such complexes were isolated in the crystalline state [15]. In the case of the ammonium salts the polarization of the phosphoryl group is apparently accomplished only via electrostatic interaction with the ionic pair of the salt. The possibility of forming complexes of this type was shown recently [16].

Employing the catalytic method developed for the phosphorylation of polyfluorinated alcohols, we synthesized a number of symmetrical polyfluoroalkyl phosphates, the constants of which are given in Table 2.

The reaction of aryl chlorophosphates with various polyfluorinated alcohols also proceeds easily when the reactants are heated in the presence of a catalyst. However, in this case the salts of the Group I metals are not sufficiently effective. The use of Mg and $CaCl_2$ makes it possible to obtain the aryl polyfluoroalkyl phosphates in up to 90% yield. The constants of the synthesized compounds are given in Table 3. It should be mentioned that the purity and individuality of the obtained products, and also the absence of

TABLE 2. Symmetrical Polyfluoroalkyl Phosphates (R_FO)₃PO

R _F	Yield,%*	Bp, °C (p, mm of Hg)	n_{D}^{20}	d_{4}^{20}	MR	
					found	calculated
$CF_{3}CH_{2}-\dagger$ $CF_{3}CF_{2}CH_{2}$ $CF_{3}CH_{2}CH_{2}$ $CF_{3}(CF_{2})_{2}CH_{2}-\ddagger$ $H(CF_{2})_{4}CH_{2}-**$	84 80 68 84 80	$\begin{array}{ c c c c c c c c c c c c c c c c c c c$	1,3208 1,3112 1,3532 1,3102 1,3336	1,5959 1,6501 1,4767 1,7108 1,7775	42,9 57,9 56,7 72,5 85,8	43,2 57,8 57,0 72,6 85,3

* Magnesium used as catalyst.

† From [2]: bp 74-75° (9 mm); n_D^{25} 1,3180; [6]: bp 186-189°; n_D^{20} 1,3198; d_4^{20} 1,5865. ‡ From [3]: bp 130° (21 mm); n_D^{20} 1,3108; d_{20}^{20} 1,716; [5]: bp 70° (0.7 mm); [6]: bp 220-223°; n_D^{20} 1,3110; d_4^{20} 1,7163.

** From [1]: bp 161° (7 mm); [6]: bp 295-302°; n_D^{20} 1,3340; d_4^{20} 1,7641.

TABLE 3. Mixed Aryl Polyfluoroalkyl Phosphates $(ArO)_{nP}(OR_F)_{3-n}$

						0	
Ar	R_{F}	n	Catalyst	Yield, %	Bp, °C (p, mm of Hg)	n_{D}^{20}	d_4^{20}
C ₆ H ₅ o-ClC ₆ H ₄ m-ClC ₆ H ₄ C ₆ H ₅ C ₆ H ₅	$CF_3(CF_2)_2CH_2 CF_3(CF_2)_2CH_2 CF_3$	1 1 1 2 2	Mg CaCl ₂ CaCl ₂ Mg Mg Mg	86 92 90 70 87 71		1,3722 1,3830 1,3843 1,4234 1,4239 1,4948	1,5745 1,6295 1,6174 1,3886 1,4206 1,3046

* From [5]: bp 93-96° (1 mm).

† From [5]: bp 127-130° (1 mm).

phenols among the reaction products, both testify against the phosphorylation mechanism, which postulates the formation of the alcoholate in the first step, since it should lead to a redistribution of the ester groups and the formation of a mixture of phosphates.

Attempts to use phosphorus thiotrichloride or hexachlorotriphosphazene as the phosphorylating agent, both without catalyst and in the presence of either magnesium or calcium chloride, proved unsuccessful. The absence of a catalytic effect when polyfluoroalkyl alcohols are phosphorylated with compounds that do not contain the phosphoryl group tends to corroborate our theory that it specifically takes an active part in the catalysis process.

EXPERIMENTAL METHOD

Reaction of Phosphorus Oxychloride with Alcoholates of

Polyfluorinated Alcohols

<u>Tri-(1,1-dihydroperfluoropropy</u>) Phosphate. To a solution of sodium 1,1-dihydroperfluoropropylate, prepared from 3.45 g of Na and 30.0 g of 1,1-dihydroperfluoropropyl alcohol, in 100 ml of absolute ether, with stirring and cooling, was added a solution of 7.6 g of POCl₃ in 30 ml of absolute ether in drops, after which the mixture was stirred at room temperature for 1 h and then allowed to stand overnight. Then the mixture was washed with water, dilute KOH solution, again with water to pH ~ 7, and dried over MgSO₄. Vacuum distillation gave 14.9 g (60% yield) of tri-(1,1-dihydroperfluoropropyl) phosphate with bp 67-68° (1.5 mm); n_{20}^{20} 1.3112; d_{40}^{20} 1.6501. Found: C 21.9, 21.7; H 1.2, 1.2; F 57.7, 57.9; P 6.2, 6.2%; MR 57.9. C₉H₆F₁₅O₄P. Calculated: C 21.9; H 1.2; F 57.7; P 6.3%; MR 57.8:

 $\begin{array}{c} {\rm Tri-(1,1-dihydroperfluorobutyl) \ Phosphate. \ In a similar manner, from 0.03 mole of POCl_3 and 0.09 \\ {\rm mole \ of \ sodium \ 1,1-dihydroperfluorobutylate \ was \ obtained \ tri-(1,1-dihydroperfluorobutyl) \ phosphate \ in \\ 48\% \ yield; \ bp \ 96-97^{\circ} \ (2.5 \ mm); \ n_D^{20} \ 1.3102; \ d_4^{20} \ 1.7108. \ \ Found: \ C \ 22.4, \ 22.3; \ H \ 0.8, \ 0.9; \ F \ 61.8, \ 61.9; \ P \\ 5.0, \ 4.7\%; \ MR \ 72.5. \ C_{12}H_6F_{21}O_4P. \ Calculated: \ C \ 22.4; \ H \ 0.9; \ F \ 61.9; \ P \ 4.8\%; \ MR \ 72.6. \end{array}$

Catalytic Phosphorylation of Polyfluorinated Alcohols

with Phosphorus Oxychloride

The yields and constants of the polyfluorotrialkyl phosphates are given in Table 2.

<u>Tri-(1,1-dihydroperfluorobutyl)</u> Phosphate. A mixture of 0.025 mole of POCl₃, 0.085 mole (or 0.15 mole) of 1,1-dihydroperfluorobutyl alcohol and 0.002 mole of catalyst was refluxed for several hours (bath temperature 135-140°C). Vacuum distillation gave tri-(1,1-dihydroperfluorobutyl) phosphate, the constants of which were identical with the constants of the product obtained by the reaction of POCl₃ with sodium 1,1-dihydroperfluorobutylate. The catalyst, the ratio of the reactants, the reaction time, and the yields are given in Table 1.

<u>Tri-(2,2,2-trifluoroethyl)</u> Phosphate. To 0.002 g-atom of Mg (turnings) are added 0.025 mole of POCl₃ and 0.085 mole of trifluoroethyl alcohol. The reaction began without the application of heat, and the temperature spontaneously rose up to approximately 65°, while the Mg dissolved completely. The bath temperature was raised gradually until the HCl evolution ceased (~140°, 4 h), after which the product was isolated by vacuum distillation. Found: C 21.3, 21.4; H 2.0, 2.1; F 49.2, 49.9; P 8.9, 8.9%. $C_{6}H_{6}F_{9}O_{4}P$. Calculated: C 20.9; H 1.8; F 49.7; P 9.0%.

 $\frac{\text{Tri-(3,3,3-trifluoropropyl) Phosphate.}_{\text{mole of 3,3,3-trifluoropropyl alcohol was heated up to 115° for 30 min and then vacuum distilled.}_{\text{Found: C 27.7, 27.9; H 3.3, 3.3; F 44.3, 44.0; P 8.0, 8.0\%. C_9H_{12}F_9O_4P.}$ Calculated: C 28.0; H 3.1; F 44.3; P 8.0%.

<u>Tri-(1,1-dihydroperfluoropropyl)</u> Phosphate. A mixture of 0.001 g-atom of Mg, 0.0125 mole of POCl₃, and 0.0425 mole of 1,1-dihydroperfluoropropyl alcohol was heated slowly until the HCl evolution ceased (~4 h, up to a bath temperature of ~140°). The reaction began above 50°. Vacuum distillation gave a product whose constants were identical with the constants of the tri-(1,1-dihydroperfluoropropyl) phosphate that was obtained by the reaction of POCl₃ with sodium 1,1-dihydroperfluoropropylate.

 $\frac{\text{Tri}-(1,1,5-\text{trihydroperfluoropentyl}) \text{ Phosphate.} A \text{ mixture of } 0.002 \text{ g-atom of Mg, } 0.025 \text{ mole of } POCl_3, \text{ and } 0.085 \text{ mole of } 1,1,5-\text{trihydroperfluoropentyl alcohol was gradually heated up to } \sim 165^{\circ} \text{ (bath temperature) for 4 h, and then it was vacuum distilled. Found: C 24.3, 24.5; H 1.2, 1.2; F 61.3, 61.2; P 4.1, 4.1\%. C_{15}H_9F_{24}O_4P. Calculated: C 24.3; H 1.2; F 61.6; P 4.2\%.}$

Catalytic Phosphorylation of Polyfluorinated Alcohols with

Aryl Chlorophosphates

The constants and yields of the obtained aryl polyfluoroalkyl phosphates are given in Table 3.

<u>Phenyl Di-(1,1-dihydroperfluorobutyl) Phosphate.</u> A mixture of 0.025 mole of phenyl dichlorophosphate and 0.06 mole of 1,1-dihydroperfluorobutyl alcohol was heated in the presence of 0.002 g-atom of Mg at 135-145° (bath temperature) until the HCl evolution ceased (~3 h), and then it was vacuum distilled. Found: C 31.3, 31.5; H 1.8, 2.0; P 5.8, 5.9%. $C_{14}H_9F_{14}O_4P$. Calculated: C 31.2; H 1.7; P 5.8%.

<u>o-Chlorophenyl Di-(1,1-dihydroperfluorobutyl)</u> Phosphate. In a similar manner, from 0.25 mole of o-chlorophenyl dichlorophosphate, 0.6 mole of 1,1-dihydroperfluorobutyl alcohol, and 0.002 mole of anhydrous CaCl₂ was obtained o-chlorophenyl di-(1,1-dihydroperfluorobutyl) phosphate. Found: C 29.2, 29.2; H 1.5, 1.7; F 46.5, 46.8; P 5.4, 5.5; Cl 5.5, 5.7%. C₁₄H₈F₁₄ClO₄P. Calculated: C 29.4; H 1.4; F 46.4; P 5.4; Cl 6.2%.

<u>m-Chlorophenyl Di-(1,1-dihydroperfluorobutyl) Phosphite.</u> From 0.05 mole of m-chlorophenyl dichlorophosphate, 0.12 mole of 1,1-dihydroperfluorobutyl alcohol, and 0.002 mole of anhydrous CaCl₂ was obtained m-chlorophenyl di-(1,1-dihydroperfluorobutyl) phosphate. Found: C 29.4, 29.4; H 1.4, 1.5; F 46.2, 46.5; P 5.4, 5.5; Cl 6.0, 5.9%. $C_{14}H_8F_{14}ClO_4P$. Calculated: C 29.4; H 1.4; F 46.4; P 5.4; Cl 6.2%.

<u>Phenyl Di-(3,3,3-trifluoropropyl)</u> Phosphate. To 0.002 g-atom of Mg were added 0.025 mole of phenyl dichlorophosphate and 0.06 mole of 3,3,3-trifluoropropyl alcohol. The evolution of HCl began immediately and the mixture warmed up. The bath temperature was gradually raised up to 135-145°, and then kept at this temperature for 1 h. The product was isolated by vacuum distillation. Found: C 39.7, 39.8; H 3.6, 3.8; F 31.2, 30.8; P 8.3, 8.2%. C₁₂H₁₃F₆O₄P. Calculated: C 39.4; H 3.6; F 31.1; P 8.5%.

Diphenyl (1,1-Dihydroperfluorobutyl) Phosphate. A mixture of 0.002 g-atom of Mg, 0.05 mole of diphenyl chlorophosphate, and 0.055 mole of 1,1-dihydroperfluorobutyl alcohol was heated until the HCl evolution ceased (~5 h), in which connection the bath temperature was gradually raised up to 175°, after which the reaction mixture was vacuum distilled. Found: C 44.4, 44.4; H 2.8, 2.7; F 30.7, 30.6; P 7.1, 7.2%. $C_{16}H_{12}F_7O_4P$. Calculated: C 44.5; H 2.8; F 30.8; P 7.2%.

Diphenyl (3,3,3-(1,1-Dihydroperfluorobutyl). A mixture of 0.05 mole of diphenyl chlorophosphate, 0.055 mole of 3,3,3-trifluoropropyl alcohol, and 0.002 g-atom of Mg was slowly heated up to 135-145° (bath temperature), after which it was kept at this temperature for 1.5 h and then vacuum distilled. Found: C 52.4, 52.5; H 4.2, 4.2; F 16.4, 16.3; P 8.9, 9.1%. C₁₅H₁₄F₃O₄P. Calculated: C 52.0; H 4.1; F 16.5; P 8.9%.

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CONCLUSIONS

1. A new method was developed for the catalytic phosphorylation of polyfluorinated alcohols.

2. In order to explain the catalytic action of the salts of metals of Groups I-III of the periodic system and of ammonium salts a scheme was proposed, which postulates reaction between the catalyst and the oxygen of the phosphoryl group, in this way facilitating nucleophilic substitution at the phosphorus atom.

3. A number of polyfluorotrialkyl phosphates and aryl polyfluoroalkyl phosphates was synthesized.

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