

Novelties in the Enhancement of the Process of Polyfluoriaromatic Compounds Obtaining *via* Potassium Fluoride Action on Polyfluoroarenes

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Abstract

The complex of problems and directions is considered concerning an accelerated development of the methods for the synthesis of fluorine containing benzene derivatives through the action of potassium fluoride on chlorine containing arenes. The use of interphase transfer catalysts (such as hexaethylguanidinium chloride, quarternary ammonium and phosphonium salts, tetra(diethylamino)phosphonium and tetraphenylphosphonium bromides) is shown to be efficient for the obtaining of monofluoro benzene derivatives and polyfluoroaromatic compounds *via* the action of potassium fluoride on monochloroarenes and polychloroarenes. It is established that the catalytic participation of polyethers (such as dimethyl ether of tetraethyleneglycol, 18-crown-6) in the processes of fluorodechlorination is limited to an increase in the concentration of an “active” fluoride ion. Possibilities are considered for the application of mechanochemical technology for the synthesis of fluoroaromatic compounds via the substitution of chlorine by fluorine in solid phase of chloroaromatic compounds, alkali and alkali-earth metal fluorides as well as composite mixtures based on them.

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1. INTRODUCTION

The progress of modern chemistry and the use of its achievements in practice are inseparably linked with and substantially caused by the advances in the development of the methods for synthesis and industrial production of new chemical substances. This is connected with the fact that organic compounds and materials based on them exhibit a considerably great variety of structural and physicochemical properties in comparison with traditional inorganic products and metals. A highly important place amongst the former is occupied by fluorine con-

taining organic compounds. Due to unique properties and the features of chemical behaviour, they can be used in order to solve some basic theoretical problems of chemistry as well as the tasks of industry and medicine [1–3]. The accumulation of fluorine atoms within the carbon skeleton of a molecule results in the formation of qualitatively new properties those provide the creation of new fluorinated materials. A widespread application was found with polyfluorinated compounds of aliphatic series whereas polyfluoroaromatic derivatives are to a lesser degree used in practice up till now.

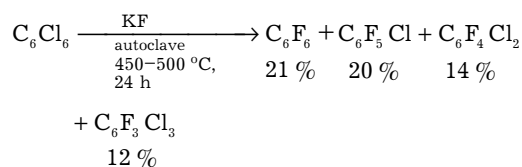
It was believed that polyfluoroaromatic derivatives exhibit no biological activity and consequently they are of no practical value. However in the course of time it has become clear that such is not the case.

With the development of the methods for obtaining of polyfluoroaromatic compounds the area of their practical application began to extend. So, polyfluorobenzoic acids are widely used in the preparation of synthetic antibiotics (fluoroquinolones). Pentafluorobrombenzene is used for the synthesis of tris(pentafluorophenyl)boron that is applied as a component in the manufacturing of highly efficient catalysts for ethylene and propylene polymerisation as well as for the preparation of stable compounds with C-Xe bond. Octafluorotoluene is used as a semi product in the synthesis of fluoroelastomers for aircraft industry, and as an oxygen carrier (being a part of "blue blood"), etc.

Chemical properties of polyfluoroaromatic compounds have formed an active area of research after a brilliant development under the direction of N. N. Vorozhtsov Jr. and G. G. Yakobson and industrial realisation in the USSR of a simple and convenient method for hexafluorobenzene to obtain, consisting in the substitution of chlorine atoms in polychloroarenes by fluorine atoms under the action of potassium fluoride [4-6]. This has opened almost unlimited possibilities for the creation of new materials based polyfluoroaromatics [7].

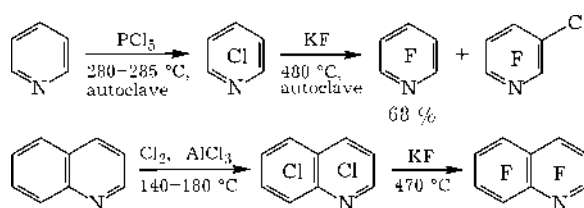
In the modern development of the chemistry of polyfluoroaromatic compounds two basic tendencies could be assigned. The first one is connected with enhancing the above mentioned synthesis technique as well as searching for new methods for the synthesis of polyfluoroaromatic derivatives. The second tendency is caused by an increased interest to elementorganic compounds containing the pentafluorophenyl ring, as well as by the revealing of the specific properties due to the influence of fluorine atoms of substituents on the properties of these substances.

The method of hexafluorobenzene [4, 5] and octafluoronaphthalene [6] obtaining is based on the action of anhydrous potassium fluoride on hexachlorobenzene and octachloronaphthalene with no solvent in a rotating pressure reactor (autoclave) at 450-500 °C.

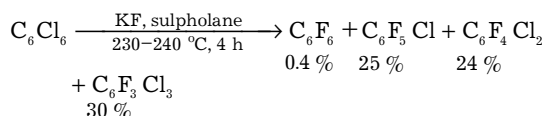


In a similar manner decafluorodiphenyl [6], decafluoropyrene [8], as well as difluoroanhydrides of tetrafluorophthalic [9] and tetrafluoroterephthalic [10] acids were obtained.

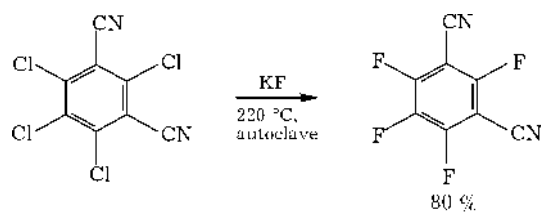
The method was extended into heterocyclic compounds, for example into pyridine derivatives [11-13] and quinoline [14].



The reaction occurs in such solvents as formamide or sulpholane as well, at atmospheric pressure. For example, in sulpholane medium at 230-240 °C the same mixture of products is formed as with the use of "dry" method. However the yield of hexafluorobenzene amounted only to 0.4 %, and the yield of octafluoronaphthalene was 52 %.



Japanese researchers actively used sulpholane as a solvent, and polychlorobenzonitriles as initial substrates. So, under the action of potassium fluoride dry powder on pentachlorobenzonitrile in sulpholane or benzonitrile at 300-315 °C and continuous stirring for 18 h pentafluorobenzonitrile is obtained with the yield exceeding 85 % [15]. The action of potassium fluoride at 220 °C on tetrachlorophthalonitrile [16] or tetrachloroisophthalonitrile [17]



Scheme 1.

results in the formation of corresponding tetrafluoroderivatives (Scheme 1).

The matching of the system of solvents allows substantial increasing the yield of perfluoro derivatives of aromatic series. As an example, the data could be presented on the interaction of potassium fluoride with chloro derivatives in the presence of crown ethers or sulpholane in a perfluoroperhydrophenantrene solution (b. p. at 215 °C) (Table 1) [15, 18].

The principal cause of low yield as well as of the necessity to operate at high temperatures consists in low solubility of potassium and caesium fluorides in polar aprotic solvents such as sulpholane, N-methylpyrrolidone, dimethyl formamide. In this connection the Halex methodology is efficient only in the case of activated benzene derivatives being of little use for the substrates unstable with respect to elevated temperature. Furthermore, the extraction of a target product is often complicated, whereas environmentally dangerous solvents are not processed then forming waste products.

In detail the problem of the synthesis of polyfluoroaromatic compounds is expounded in monographs [1–3, 7] and a review [19].

Despite of the progress in the realisation of this process in industry, the development of the chemistry of polyfluoroaromatic compounds

was restrained due to an imperfection of the technology of polychlorobenzenes fluorination by potassium fluoride (Halex process) as well as due to high expenses for its manufacture. In this connection, scientists proceeded with searching for novel methods and with improving the known technique of the obtaining both hexafluorobenzene, and octafluoronaphtalene. There are several basic fields indicated as it follows.

1. Improving the method of hexafluorobenzene obtaining with the use of interphase transfer catalysts, the preparation of potassium fluoride with a highly developed surface as well as the use of high-boiling aprotic solvents.

2. Application of physical effects for the acceleration of the process of chlorine by fluorine replacement and for the reduction of reaction temperature.

3. The use of elementary fluorine both others fluoridizing agents for the fluorination of polyhalogenebenzenes with subsequent dehalogenation under the action of metals.

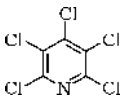
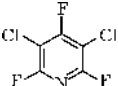
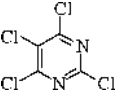
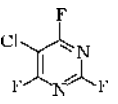
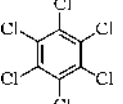
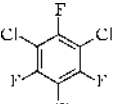
4. The synthesis of fluoroaromatic compounds basing on industrial freons and polyfluoroolefines.

5. The use of essentially new solvents or the systems such as ionic liquids.

In the present review an attempt is made to concentrate the main attention on the discussion of the crucial question such as the pathways of intensifying the technology for the production of hexafluorobenzene and some its derivatives.

TABLE 1

Fluorination of chloro derivatives of organic compounds with KF in perfluoroperhydrophenantrene solution (190 °C, 15 h) [18]

Substrate	Reaction product	Yield, %
		84 ^a 59 ^b
		91 ^a 71 ^b
		60 ^c 83 ^b

^a 18-crown-6.

^b Tetrahydrothiophene 1,1-dioxide (25 %).

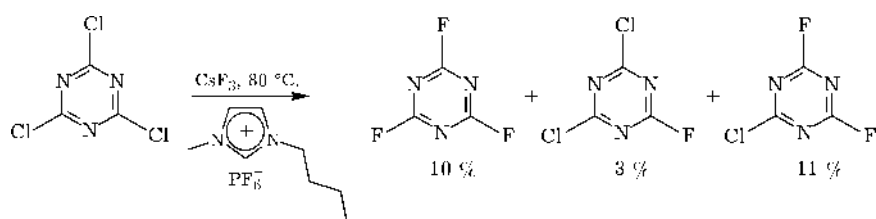
^c 217 h.

2. ENHANCEMENT OF CHLORINE BY FLUORINE SUBSTITUTION IN AROMATIC SERIES WITH THE USE OF INTERPHASE PROCESS CATALYSTS

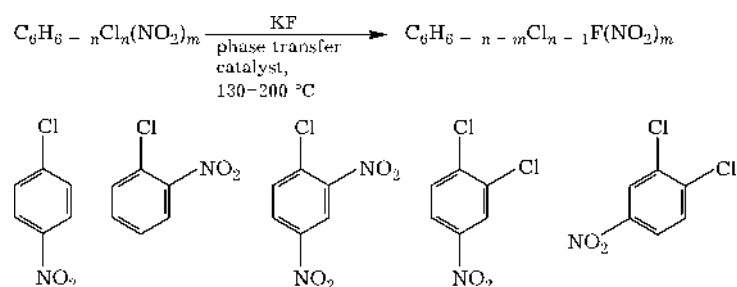
A considerable step forward for the last years in the enhancement of the process of chloroaromatic compounds fluorodechlorination through the action of alkali metal fluorides is the reaction carrying out for the series of oligochloroaromatic and polychloroaromatic compounds in the presence of interphase transfer catalysts and high-boiling organic solvents [20–25].

2.1. Reactions of benzene monochloro derivatives with potassium fluoride

The data for the reactions of benzene monochloro and dichloro derivatives with po-



Scheme 2.



Scheme 3.

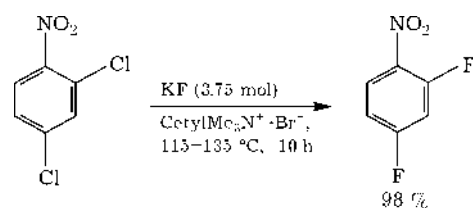
tassium fluoride were discussed repeatedly; therefore only several examples should be given. To take an example, the synthesis of 4-fluorobenzonitrile [26] and trifluoro-*s*-triazine [27, 28] *via* potassium fluoride action with the use of catalysts is considered. So, as a result of the reaction of 4-chlorobenzonitrile with KF in 1,3-dimethyl-2-imidazolidone at 280 °C and 0.4 at pressure during 2 h, the obtaining of 4-fluorobenzonitrile was observed with the yield of 89.5 % (99 % purity product). The reaction of trichloro-*s*-triazine with CsF at 80 °C in the presence of an ionic liquid such as hexafluorophosphonium salt of 1,3-methylbutylimidazolium resulted in the formation of trifluoro-*s*-triazine (the yield of 10 %) alongside with monofluorosubstituted and difluorosubstituted products (Scheme 2).

Practically, of the greatest interest is the application of interphase transfer catalysts without the use of solvents. In this case there is no necessity to isolate reaction products from solvent, as well as to recycle the latter. Generally, quarternary phosphonium salts, hexaethylguanidinium chloride, tetrakis(diethylamino)phosphonium bromide, dialkyl ethers of polyethyleneglycol and crown ethers are used in particular for chlorobenzenes, containing NO₂ group. It was shown that interphase transfer catalysts (such as crown ethers, tri(oxoalkyl)amines, quarternary ammonium and phosphonium salts) are efficient in the processes of flu-

orodechlorination of chlorine-containing nitroarenes in the absence of aprotic solvents [29]. The yield of end products ranges from 55 to 95 %. A 20 % surplus of KF, 0.5–2 mol. % of the catalyst with respect to KF is used. At the temperature of 160–180 °C the reactions occur during 0.5–8 h (Scheme 3). The action of the catalyst consists in its ability to efficiently transfer a fluoride ion from solid potassium fluoride to a liquid organic media. As a rule, such catalysts exhibit high thermal stability (up to 280 °C), good solubility in an organic liquid phase and low cost that allows their commercial using.

Under the conditions of this reaction only one chlorine atom is substituted located in a *para*-position with respect to nitro group. It is established that quarternary ammonium and phosphonium salts are the most efficient catalysts. However, at the temperature exceeding 150 °C the reactivity of ammonium salts is reduced, which is apparently caused by their low thermal stability [29].

By the example of the substitution of chlorine by fluorine in 2,4-dichloronitrobenzene the use of quarternary ammonium salts (such as cetyltrimethylammonium [30] and tetramethylammonium chloride [26]) was shown to be efficient.



The synthesis of compounds such as $YArF_wCl_{(x-w)}R$ ($Y = F, Cl, Br, NO_2, CN, CF_3, CHO, COOX, SO_2X; n = 1-10, Ar = Ph, pyridyl, naphthyl$) was carried out through the interaction of chlorine-containing derivatives $A_xArCl_yR_z$ with an alkali metal fluoride, the mixture of alkali metal fluorides both in an organic solvent and without the latter in the presence of either one of quarternary ammonium compounds $R^1R^2R^3R^4N^+ \cdot X^-$ or a mixture of these compounds as a catalyst at 50–200 °C [31, 32]. Ethylene glycol oligomers or 18-crown-6 were used as solvents. It should be noted that in this process both monofluoro derivatives, and polyfluorinated aromatic compounds can be obtained.

Quarternary phosphonium salts ($Ph_4P^+ \cdot Cl^-$) are also efficient in the substitution of chlorine by fluorine due to KF action on 2,4-dinitrochlorobenzene [33, 34] and 5-nitro-2-chloropyridine [34] (Table 2). A significant role is played by a solvent, too.

Electron accepting groups, such as CF_3 [35], $COOR$ [18] (Tables 3 and 4), activate the process of chlorine by fluorine exchange in the benzene ring, but the yield of substitution products in this case is low. In the case when the chlorine atom in the benzene ring is located in *ortho*- and *para*-positions with respect to such substituents, there is an efficient exchange of chlorine by fluorine, though the temperature

of such process is high enough. At a *meta*-position of chlorine the reaction proceeds slowly. It was shown that in the presence of phosphonium salts the rate of the substitution of chlorine by fluorine grows irrespective of the number of chlorine atoms in the benzene ring [18]. The data on fluorodechlorination of benzo-trifluoride derivatives [35] are presented in Table 3.

The catalysts such as Ph_4PBr , $(n-Bu)_4PBr$ и $Ph_4P \cdot HF_2$ are efficient within the temperature range of 180–200 °C. They are well soluble in polar solvents and are thermally stable [36], however, because of high cost they have found no technological application.

A similar picture is observed for the esters of chlorine-containing benzoic acids, too (Table 4) [11]. However it should be noted that the full exchange of chlorine atoms in a benzene ring is not always possible and, as a rule, mixtures difficult to separate are formed during this process.

In these processes the activating role in the exchange of chlorine by fluorine is played by crown ethers [37].

The efficiency of the use of catalysts for the Halex process to be carried out determined the necessity of synthesis of various phosphorus (V) derivatives involving, as a rule, several nitrogen-containing substituents such as $(R_2N)_4PX$ those are used within the temperature range

TABLE 2

Effect of interphase transfer catalyst of on the chlorine by fluorine substitution reaction rate in monochloro derivatives of benzene and pyridine [34]

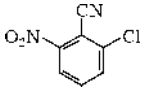
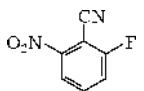
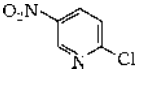
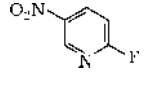
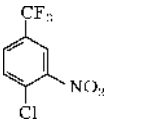
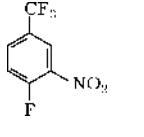
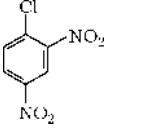
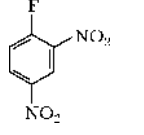
Substrate	Product	$\frac{k(Ph_4PBr/MeCN)}{k(MeCN)}$	$\frac{k(Ph_4PBr/sulpholane)}{k(sulpholane)}$
		146	2.8
		160	6.3
		200	4.4
		144	3.3

TABLE 3

Fluorodechlorination of chlorobenzotrifluorides under the action of KF in the presence of catalysts [35]

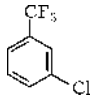
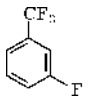
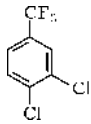
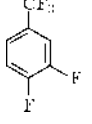
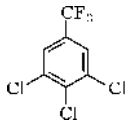
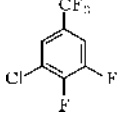
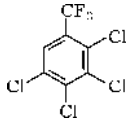
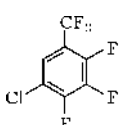
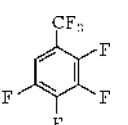
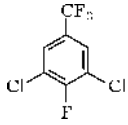
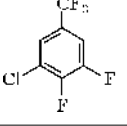
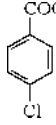
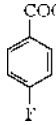
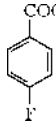
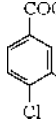
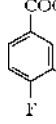
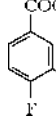
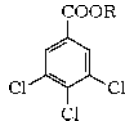
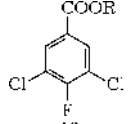
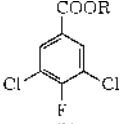
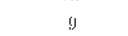
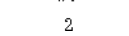
Substrate	Reaction conditions	Product
	$\text{Ph}_4\text{P}^+ \cdot \text{Br}^-$, 230 °C, 10 h	 5 %
	$\text{Ph}_4\text{P}^+ \cdot \text{Br}^-$, 185 °C, 18 h	 13 %
	$\text{Me}_4\text{N}^+ \cdot \text{Cl}^-$, 165 °C, 16 h	 67 %
	$\text{Ph}_4\text{P}^+ \cdot \text{Br}^-$, 230 °C, 10 h	 56 %  21 %
	$\text{Ph}_4\text{P}^+ \cdot \text{Br}^-$, 230 °C, 10 h	 70 %

TABLE 4

Fluorodechlorination of some derivatives of benzoic acid esters [18]

Substrate	Reaction conditions			Product
	T, °C	Time, h	Catalyst	
	190	5.5	B	 10 %
	210	5.5	B	 10 %
	190	5.5	A	 79 %
	190	5.5	B	 91 %
	190	6.0	A	 12 %
	190	6.0	B	 84 %
				 9  2

Note. R = $\text{CH}_2\text{C}(\text{CH}_3)_3$, A = $\text{Ph}_4\text{P}^+ \cdot \text{Br}^-$, B = $(\text{CH}_3)_2\text{N}^+ \text{---} \text{C}_5\text{H}_4 \text{---} \text{N}^+ \text{---} \text{C}(\text{C}_2\text{H}_5) \text{---} \text{C}_4\text{H}_9 \text{---} \text{Cl}^-$.

of 200–240 °C (Table 5 [38–40]). So, the action of KF on 4-nitrochlorobenzene in the presence of tetrakis(dimethylamino)-phosphonium bromide in DMSO at 180 °C during 5 h results in the formation of 4-nitrofluorobenzene with the yield of 86 % at 100 % conversion [39]. However, since all the catalysts of this type are toxic, it would be appropriate to use phosphorus compounds containing cyclic amines [41–43]. For example, the authors of [41] had been used bis(2-methoxyethyl)aminotris-(pyrrolidino)phosphonium chloride.

The salts on the base of aminophosphazene such as 1,1,1,3,3,3-hexapyrrolidinodiphosphazocanium chloride and 1,1,1,3,3,3-hexapiperidinodiphosphazocanium chloride represent efficient catalysts for the substitution of chlorine by fluorine under the action of alkali metal fluorides or ammonium fluoride [39]. So, the reaction of 2,5-dichloro-2,4,6-trifluoropyridine with KF in

the sulpholane–chlorobenzene system of solvents at 215 °C in the presence of these salts results in the formation of 3-chloro-2,4,5,6-tetrafluoropyridine (the yield of 75 %) and pentafluoropyridine (the yield of 24 %) [44].

Amidophosphonium salts such as $[(R^1R^2)N]_4P^+ \cdot Hal^-$ are also reactive in this process; in the presence of electron accepting substituents in the benzene ring the presence of these salts results in the formation of fluoro derivatives with a high yield [41, 45].

The presence of two nitro groups in the benzene ring promotes the exchange of chlorine

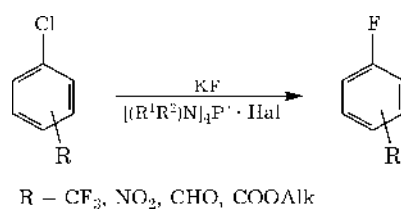


TABLE 5

Fluorination of benzene chloro derivatives by potassium fluoride in the presence of catalysts [40]

Substrate	Solvent (vol. %)	Catalyst (mol. %)	T, °C	Time, h	Yield (conversion degree), %
6		Ph ₄ PBr (1.3)	190	10	(30)
		(Et ₂ N) ₄ PBr (1)	180	20	88
		(Et ₂ N) ₄ PBr (1.3)	190	10	(30)
	Sulpholane (70)	Ph ₄ PBr (1.6)	180	5	(40)
	Sulpholane (130)	Ph ₄ PBr (1.6)	180	6	60 (71)
	Sulpholane (250)	Ph ₄ PBr (1.6)	180	4	80 (94)
	Me ₂ SO (130)	CNC (1.0)	170	5	96
	Me ₂ SO (130)	(Et ₂ N) ₄ PBr (1.0)	170	6	93
7	Me ₂ SO (130)	Ph ₄ PBr (1.0)	170	6	89
		Ph ₄ PBr (2.5)	180	24	72 (100)
		CNC (2.5)	180	24	63 (100)
		(Et ₂ N) ₃ PNPPh ₃ Br (2.5)	180	24	54 (100)
		(Et ₂ N) ₄ PBr (2)	165	20	69 (88)
8	Sulpholane (150)	–	200	9	30
	Sulpholane (150)	Ph ₄ PBr (2.0)	180	7	(5)
	Sulpholane (10)	CNC (1.5)	175	24	5
	Me ₂ SO (10)	CNC (1.5)	175	24	20
	Sulpholane (100)	CNC (1.5)	175	24	54
	Sulpholane (100)	CNC (1.5)	190	15	49
	DMI (100)	CNC (1.5)	180	24	75
	DMI (100)	(Et ₂ N) ₃ PNPPh ₃ Br (1.5)	180	24	(30)

by fluorine under the action of KF, however, the process occurs at high temperature. At the same time the use of tetraphenylphosphonium chloride as a catalyst allows lowering the temperature of the process [33].

Carrying out of the process of the exchange of chlorine by fluorine in *para*-chloronitrobenzene **6** is efficient in bipolar aprotic solvents in the presence of Ph₄PBr and **4** (Table 5).

In the presence of two chlorine atoms in the benzene ring, as a rule, formation of difluoro derivatives occurs. For example, in the case when 2,6-dichlorobenzaldehyde **7** is used (see Table 5) 2,6-difluorobenzaldehyde is ob-

tained, an important semi product for the manufacture of herbicides [40].

A similar result is obtained for chloroanhydride of 2,4-dichlorobenzoic acid **8** too (see Table 5) [40].

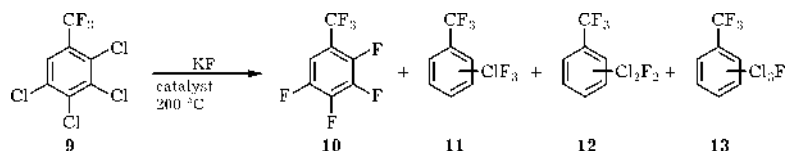
Much more complicated picture is observed in the fluorination of tetrachlorobenzotrifluoride **9**. In this case the fluorination level varies depending on the catalyst used (Table 6) [46].

Efficient catalysts were found for the manufacture of 1,3,5-trifluorobenzene by means of fluorination of 1,3,5-trichlorobenzene **14** using potassium fluoride (Table 7) [46].

So, 2,3,4-trifluoro-5-chloro-1-trifluoromethylbenzene was obtained with the yield of 85 %

TABLE 6

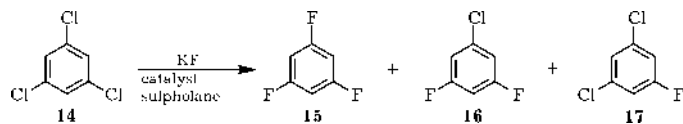
Synthesis of tetrafluorobenzotrifluoride from tetrachlorobenzotrifluoride [46]



Catalyst (mol. %)	T, °C	Composition of reaction mixture, %				
		9	10	11	12	13
<p>1 (1.5)</p> <p>R¹ = Me R² + R³ -CH₂-CH₂-</p>	200	0	0	5	66	29
<p>2 (1.5)</p> <p>R¹ = Me R² - R³ - -CH₂-CH₂- R⁴ Et</p>	200	0	1	24	70	5
<p>3 (1.5)</p> <p>R¹ - Ph, R² - Et, R³ - Ph, R⁴ - Me</p>	200	4	0	4	0	0
<p>4 (1.9)</p>	200	0	84	17	0	0
<p>5 (1.9)</p>	200	0	67	33	0	0
Ph ₄ PBr (1.5)	200	19	0	0	19	62
(Et ₂ N) ₃ PNPPh ₃ Br (1.5)	200	4	0	4	54	38
Ph ₄ PBr (1.9)	200	0	1	6	78	14
(Et ₂ N) ₃ PNPPh ₃ Br (1.9)	200	0	9	51	40	14

TABLE 7

Obtaining of 1,3,5-trifluorobenzene *via* the action of potassium fluoride on 1,3,5-trichlorobenzene in the presence of catalysts [46]



Catalyst (mol. %)	T, °C	Composition of reaction mixture, %				
		14	15	16	17	Residue
4 (5)	200	1	18	61	20	1
(Me ₂ N) ₃ PNPPh ₃ Br (5)	200	1	15	60	20	5
4 (5)	230	0	87	8	1	4
(Me ₂ N) ₃ PNPPh ₃ Br (5)	230	0	46	46	2	6

when 2,3,5-trichloro-1-trifluoromethylbenzene heated in sulpholane at 210 °C in the presence of Et₄PBr at a pressure of 2.2 bar in a pressure reactor [47]. The efficiency of the process increased with the use of fine-dispersed anhydrous potassium fluoride and tetrakis(diethyl-amido)phosphonium bromide (R₂N)₄P⁺ · Br⁻ [48, 49].

Successful realisation of the reaction of fluorodechlorination of chloroaromatic compounds by potassium fluoride depends on a variety of factors. The major role among them is played by potassium fluoride surface and the reactivity of a substrate. By the example of the substitution of chlorine by fluorine in the benzene ring containing NO₂ group, potassium fluoride has been tested prepared using various methods as it follows: 1) high-temperature drying by the spraying of aqueous KF solution (fine-dispersed powder) [50]; 2) sputtering onto CaF₂ [51]; 3) recrystallising from methyl alcohol [30]; 4) drying through freezing [52]. In all the cases due to reduction of crystal sizes the specific surface of KF increases, which results in a substantial increase of its reactivity in nucleophilic substitution reactions. A solvent might play an important role in this process.

2.2. Reactions of polychloroarenes with potassium fluoride

Taking into account a commercial value of hexafluorobenzene, the data its obtaining are published mainly in the patents sometimes poorly revealing the essence of the technologies suggested. Nevertheless, the efficiency of the

application of catalysts for the enhancement of the known technique of hexafluorobenzene obtaining is obvious. In this case it is advantageous to soften severe conditions of the synthesis or to abandon the use of solvents at all. It is established that the greatest catalytic efficiency (as interphase transfer catalysts) is shown by quarternary ammonium salts, guanidinium derivatives, quarternary phosphonium salts, cryptates, crown ethers and polyesters [33–37, 53, 54].

The catalysts can participate in the acceleration of the reaction of chloroaromatic substrata fluorodechlorination at different stages of the process. Firstly, they might increase KF concentration in a liquid phase; secondly, reducing the activation energy of the reaction due to the participation in stabilization of an intermediate σ -complex, they could promote an increase in the reactivity of catalytic system [48]. The addition of promoters to the catalytic system those represent the compounds of heterocyclic and aromatic series, ethers, substituted amides of organic acids, *etc.* is favourable for the increase in the rate of the substitution of chlorine by fluorine as well as the yield of end products [54]. Under these conditions the compounds of general formula such as C₆F₄XY (X = F, Cl, CF₃, CCl₃, CN, COR; Y = F, H, Cl, CF₃, CCl₃, CN, COR) have been obtained with a high yield [54]. The ratio between quaternary tetraamidophosphonium salt and the promotor ranges from 100 : 1 to (5–20) : 1, and the ratio of alkali metal fluoride to quaternary tetraamidophosphonium salt varies within the range from 1000 : 1 to 10 : 1.

The method was found to be so efficient that the Albemarle Company has patented a technology for the synthesis of fluorinated aromatic compounds, allowing to increase the yield of end-products at lower temperature and at more moderate pressure in comparison with a usual method as well as to reduce the duration of the reaction [55, 56]. Moreover, various benzene derivatives are already being obtained on this base and, first of all, pentafluorobromobenzene.

The authors of [57] have demonstrated that potassium fluoride applied onto calcium or barium fluoride, exhibits high reactivity in the reaction of hexachlorobenzene fluorination. Simultaneous use of such potassium fluoride and a quaternary phosphonium salt (such as tetrakis(diethylamino)phosphonium bromide) results in a substantial increase in the efficiency of chlorine by fluorine substitution process. From the data presented in Table 8 it can be seen that at 230 °C (during 42.5 h) with the use of potassium fluoride dried up by spraying, the products of fluorination are formed with an overall yield amounting only to 6 %. At the same time, with the use of potassium fluoride applied onto calcium fluoride, under similar conditions a mixture of the products of consecutive chlorine substitution by fluorine is formed with a high yield though the main product is tetrachlorodifluorobenzene (46 %).

The substitution of chlorine by fluorine in hexachlorobenzene under the action of KF occurs to a considerable degree more readily with the use of tetrakis(diethylamino) phosphonium bromide: as an interphase transfer catalyst at

the temperature of 230 °C: in 42.5 h the products of the reaction contain 13.5 % of chloropentafluorobenzene, 37 % of dichlorotetrafluorobenzene and 45 % of the main product such as trichlorotrifluorobenzene. With a higher rate the process of hexachlorobenzene fluorination occurs with the use of potassium fluoride, applied onto CaF₂ (see Table 8). The results obtained can be a consequence of fluorination both on a solid surface, and within an organic phase, and the factors promoting the increase in the sorption of reactants on a solid surface (pressure, the nature of a substrate), should result in the increase in the rate of exchange.

The compounds such as N,N',N''-hexasubstituted guanidinium chlorides appeared efficient in the obtaining of hexafluorobenzene [48, 58]. So, in the presence of this catalyst hexafluorobenzene was obtained from hexafluorobenzene and KF at 160–170 °C with the yield of ~90 %.

Ammonium salts such as [(RR'N)₂CNR²R³]⁺ · X⁻ (R-R³ is either alkyl C₁₋₇, or cycloalkyl C₅₋₈) or hexaethylguanidinium chloride [59] have been used as the catalysts. The carrying out of the reaction at 160–170 °C results in the formation of the mixture consisting of 91 % hexafluorobenzene and 9 % incompletely fluorinated fluorochlorobenzenes. The overall yield of hexafluorobenzene amounts to 88.4 %.

A higher efficiency is exhibited by quaternary phosphonium salts, which has determined their wider use as well as the interest in the studies on exchange processes with their participation. So, pentafluoro derivatives of benzene such C₆F_nX_{6-n} (X = F, Cl, CF₃, CN;

TABLE 8

Reaction of potassium fluoride with hexachlorobenzene (230 °C, 42.5 h) [57]

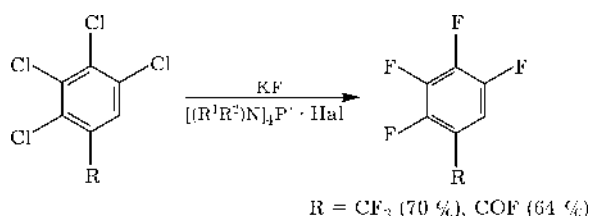
Loading of reagents, mol			T, °C	Time, h	Composition of reaction mixture, %					
C ₆ Cl ₆	KF	Catalyst			C ₆ F ₅ Cl	C ₆ F ₄ Cl ₂	C ₆ F ₃ Cl ₃	C ₆ F ₂ Cl ₄	C ₆ FCl ₅	C ₆ Cl ₆
2.37	19.66	—	230	42.5	—	—	—	1	5	94
2.37	17.7	CaF ₂	230	39	—	5.5	21	46	21	65
2.37	17.7	BaF ₂	230	39	—	9.5	39.5	50	1	—
1.75	11	CaF ₂ *	220	18	24.8	45	30	—	—	—
2.37	19.66	*	220	24	13.5	37	45	4	—	—
**	11	*	150	4.5	23.1	77				
**	11	CaF ₂ *	150	4.5	24	76				

*Tetrakis(diethylamino)phosphonium bromide.

**C₆F₄Cl₂.

$n = 1-5$) are obtained by heating of corresponding halogen-containing aromatic compounds with alkali metal fluorides of in the liquid phase in the presence of tetrakis(diethylamido)phosphonium bromide in the media of the products of incomplete fluorination of an initial substrate with simultaneous withdrawal of target products at 150–200 °C [60, 61]. In this case the technological process is to a considerable degree simplified and the yield of polyfluoroaromatic compounds increases.

As the result of the process of hexachlorobenzene fluorination by potassium fluoride in benzonitrile (the weight of the catalyst amounted to 12 g against 115 g of hexachlorobenzene) at 200 °C during 5.5 h a mixture was obtained containing 24.4 % of hexafluorobenzene, 39.9 % of pentafluorochlorobenzene, 21 % of the mixture of tetrafluorodichlorobenzenes and 8 % of the mixture of trifluorotrchlorobenzenes [49]. The efficiency of this catalyst was also noted by the authors of [40, 62] by the example of hexachlorobenzene and partially fluorinated chlorobenzenes. It should be noted that the presence of several chlorine atoms in the benzene ring does not interfere with the course of the exchange reaction [40].



2.3. Role of solvent in the reactions of polychloroarenes with potassium fluoride

When dimethyl ether of tetraethyleneglycol and 18-crown-6 are used, the efficiency of catalysis depends on the nature of a substrate: the isomeric compositions of trifluorotrchlorobenzenes formed in sulpholane media both using these catalysts and without their application at the identical conversion level are to a considerable degree coinciding [63], being close, in its turn, to the isomeric composition after the fluorination of trifluorotrchlorobenzenes by potassium fluoride at 350 °C. The authors of [63] consider the acceleration of the replace-

ment of chlorine by fluorine mainly occurs due to a nucleophilic nature of the fluoride ion from potassium fluoride.

Fluorodechlorination of tetrafluorodichlorobenzene with KF in the presence of catalytic amounts of diglym, tetraglym or 18-crown-6 occurs slowly (in 6 h only the traces of pentafluorochlorobenzene are revealed) [48]. The combination of hexaethylguanidinium chloride with polyesters results in appreciable increase in the reactivity of the catalytic system (the conversion level of tetrafluorodichlorobenzene is doubled). It should be emphasized that the authors of [57] have also noted a similar increase in reactivity due to the addition of polyester to KF, applied onto an inert support (CaF_2 , BaF_2) while hexachlorobenzene fluorination (Fig. 1).

The catalytic effect with the use of polyesters as catalysts could be explained from the point of the increase in current concentration of an "active" fluoride ion, which would result in the acceleration of fluorodechlorination [48]. With the use of other catalysts, the catalytic effect is of a somewhat different nature being connected not only with an increase in the concentration of an «active» fluoride ion, but also with a significant participation of these catalysts in the stabilization of anionic s -complexes. Apparently, due to more efficient stabilization of the intermediate σ -complex, the activation energy value of the fluorodechlorination reaction with the participation of these catalysts is reduced [48].

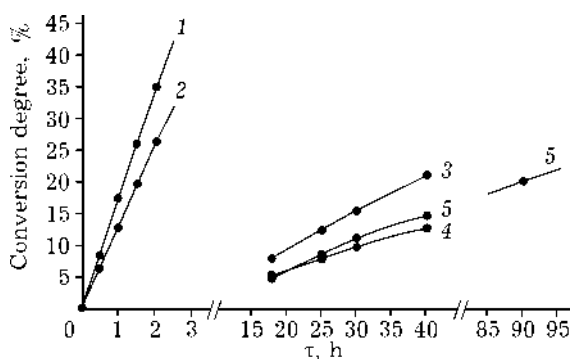


Fig. 1. Dependence of the conversion level on reaction time (the molar ratio $C_6Cl_2F_4 : KF : \text{catalyst} = 1 : 1 : 0.05$) [64]: 1 - hexaethylguanidinium chloride, 2 - tetra(diethylamino)phosphonium bromide, 3 - 18-crown-6, 4 - dimethyl ether of tetraethyleneglycol, 5 - sulpholane (the mass ratio $C_6Cl_3F_3 : \text{sulpholane} = 1 : 1$).

At the same time, with the use of tetra(diethylamido)phosphonium bromide and hexaethylguanidinium chloride as catalysts, the difference in isomeric compositions in comparison with a non-catalytic type comes into prominence already at 8.5 % conversion level and substantially increases at the conversion level amounting to 20 %. The manifestation of the catalytic effect of these catalysts to a considerable degree depends on the nature of a substrate, which might be connected with the difference in the mechanisms of the processes occurring [59].

According to modern concepts, the process of the fluorodechlorination of chloroaromatic compounds by potassium fluoride occurs both on the surface of solid phase, and within the ω -phase immediately adjacent to the surface of KF [7]. In both the cases the catalytic effect is ascribed to an increase in the reactivity of KF. In the first case the process is believed to occur due to more efficient coordination of the substrate on the surface of potassium fluoride, being in the second case to all appearance caused by the formation of unconsolidated ion pairs between the catalyst and fluoride ion [7].

It is supposed, that fluorodechlorination of polyfluorochlorobenzenes occurs according to the addition-detachment mechanism of with intermediate formation of anionic σ -complex [65]. As this takes place, it is believed that the difference in the rate of fluorination for catalytic and non-catalytic reactions could be connected not only with the influence of the catalyst on the increase in the concentration of an "active" fluoride ion, but also with the stabilization of a corresponding σ -complex. In the event that the participation of catalyst in the acceleration of fluorodechlorination is limited with the increase in the current concentration of an "active" fluoride ion, the catalytic effect would depend only slightly on nature of a substrate. On the contrary, when the catalyst participates in the stabilization of an intermediate σ -complex, the fluorodechlorination reaction might be expected to occur with higher acceleration for more reactive substrates than for less reactive ones.

The authors of [66] have studied the influence of various catalysts on the process of the fluorodechlorination of trifluorotrchlorobenzenes and demonstrated that the maximal conversion rate value for the latter is observed with

the use of tetra(diethylamido)phosphonium bromide and hexaethylguanidinium chloride as catalysts, and to the least degree efficiently the reaction occurs in sulpholane media with no use of catalyst (see Fig. 1). Furthermore, the reactivity decreases in the following series of isomers: 1,2,4- $F_3C_6Cl_3$ > 1,2,3- $F_3C_6Cl_3$ > 1,3,5- $F_3C_6Cl_3$, that is according to the influence of fluorine and chlorine atoms on the stabilization of an anionic σ -complex [65, 66].

The data presented bear the witness to the efficiency of the use of catalysts in the obtaining of fluoroaromatic compounds through the action of alkali metal fluorides on chlorine-containing aromatic compounds.

3. MECHANOCHEMICAL METHOD FOR HEXAFLUOROBENZENE OBTAINING

One of the ways to increase the efficiency of the process of aromatic compounds fluorodechlorination consists in supporting the process with a physical effect. So, by the example of reaction of nucleophilic chlorine by fluorine substitution, a fundamental possibility is demonstrated for the realisation of solid-phase synthesis of fluorinated aromatic compounds under the conditions of mechanochemical activation, as well as for the process enhancement via the use of liquid-phase fluorination due to the application of a preliminary activated fluoridizing agent. An important role is played here by KF preparation, in particular, by an increase of its microdispersity.

The authors of [64, 67-69] for to increase the efficiency of potassium fluoride action used a mechanochemical processing. It was shown that the carrying out of the reaction of hexachlorobenzene, octachloronaphtalene, pentachloropyridine with KF or with other alkali or alkali earth metal fluorides as well as with the mixture of salts (KF-CaF₂, K₂CO₃-CaF₂ [70]) on their base at 350-500 °C in a planetary type frictional activator (APF-1M planetary type mill) under the conditions promoting mechanochemical activation of KF (acceleration of 40g, activation time of 20 min), resulted in obtaining the mixture of chlorofluorobenzenes, octafluoronaphtalene and pentafluoropyridine, respectively.

The mechanical activation of KF results in the acceleration of fluorination process and al-

lows to increase the yield of polyfluorinated benzenes or to reduce the time of reaction [64, 67]. Octachloronaphtalene is the most easily fluorinated, and the fluorination of hexachlorobenzene occurs most difficultly. So, for 120 min of the activation the conversion level for the transformation of octachloronaphtalene into corresponding fluoroderivatives has reached 75 % whereas for the same time the similar parameter for hexachlorobenzene has amounted to only 22 %. As the duration of the processing increased an increase was observed in the conversion level as well as in the substitution degree. The use of the fluorides of other metals in this reaction has demonstrated, that the reactivity of a fluoridizing agent grows from LiF to CsF and from CaF_2 to BaF_2 .

For the isolation of individual products the mixture was collected and rectified in a usual manner. This approach allows to reduce the duration of the process, to reduce surplus of KF used, to reduce the amount of waste products. It has been revealed that in the systems of $\text{KF}-\text{CaF}_2$, as well as $\text{K}_2\text{CO}_3-\text{CaF}_2$ the formation occurs of mixed fluoride KCaF_3 , a new fluoridizing agent with an increased reactivity. So, with the use of a composite $\text{KF} + \text{CaF}_2$ mixture the reaction of pentachloropyridine fluorination proceeds almost to completion for 30 min only, whereas with the use of KF the yield of products in 120 min amounts to 35.8 %, and in the case of CaF_2 the yield is 14.8 %. The mixed fluoride demonstrates higher fluoridizing ability in comparison with KF not only in mechanochemical, but also to a greater extent in the liquid-phase fluorination process [70].

The use of the fluoridizing agent (KF and KCaF_3) has allowed obtaining 3-chloro-4-fluoronitrobenzene from 3,4-dichloronitrobenzene at 150 °C in sulpholane media [67].

4. CONCLUSION

The data reported in the present review allow ascertaining an increased interest of researchers to the chemistry of polyfluoroaromatic compounds. It is reasonable that the extension of the area of scientific exploration has resulted in serious achievements as well as in the opening up new fields of the practical use

of such chemical species. One might expect this review to draw attention not only of the experts in the field of synthesising fluorinated organic compounds, but also of those who are engaged in production for realising further practical activities in targeted synthesis of the materials important for engineering.

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