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Synthesis and Application of Polyfluorinated Organic Derivatives of Boron and Silicon for Preparation of Iodonium, Bromonium and Xenonium Salts

V. V. Bardin

N.N. Vorozhtsov Novosibirsk Institute of Organic Chemistry of the Siberian Branch of Russian Academy of Sciences, Novosibirsk, Russia

E-mail: bardin@nioch.nsc.ru (mailto:bardin@nioch.nsc.ru)

Abstract: Preparation of polyfluoroorganylsilanes, boranes and borates and their use for synthesis of salts $[R_FXeF_n][A]$, $[R_FR'_FBr][A]$ and $[R_FR'_FIF_n][A]$ are considered.

Keywords: Organoborates, organoboranes, organosilanes, iodonium salts, bromonium salts, xenonium salts

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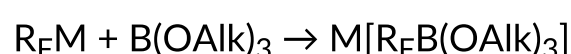
I. Introduction

Belonging to "borderline" sciences, which include typical particularities of every main direction and specific properties typical for only present field of sciences is the particularity of chemistry of polyfluorinated organoelement compounds. That to a full extent can be referred to organic derivatives of polyvalent iodine and bromine. Preparative methods and reactivity of these compounds are studied quite well and presented in numerous reviews and fundamental monographs. Their polyfluorinated analogues have been studied considerably less, and just recently the information regarding them has been systematized in review [1]. The first reliable data on synthesis of organoxenon compounds appeared in 1989 when two groups of German scientists had independently published the preparation of $[C_6F_5Xe][(C_6F_5)_nBF_{4-n}]$ salts [2, 3]. During research the availability of using the reactions of transfer of organic fragment R from silicon or boron atom onto xenon atom in XeF_2 molecule, iodine or bromine in $R'EF_2$ ($E = Br, I$; $R' = F$ or organic group) had been revealed. In the present review we have analyzed the application of these reactions in preparative synthesis of perfluoroorganylxenon (II, IV) salts, symmetrical and asymmetrical bromonium (III) and iodonium (III, V) salts with perfluorinated organic groups bonded to halogen atom.

II. Synthesis of Polyfluorinated Organylboranes, -borates and -silanes

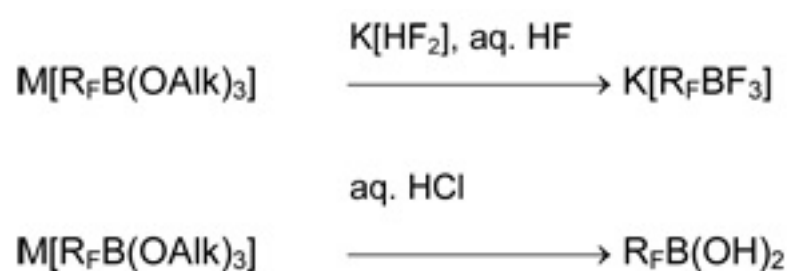
1. Boron Derivatives

Originally polyfluoroarylxenonium and -iodonium salts had been obtained from fluorocontaining triarylboranes. The synthetic procedure and particularly, the purification of these precursors was complex and the reaction products were salts of $[Ar_nBF_{4-n}]^-$ anions. The usage of boranes RBF_2 became an alternative route. A general scheme for preparation of RBF_2 was elaborated and it included synthesis of polyfluororganyl(alkoxy)borates and polyfluoroorganyl(fluoro)borates. The key process stage is nucleophilic addition of polyfluoroorganyllithium (or polyfluoroorganylmagnesium bromide) to tris(alkoxy)borane:

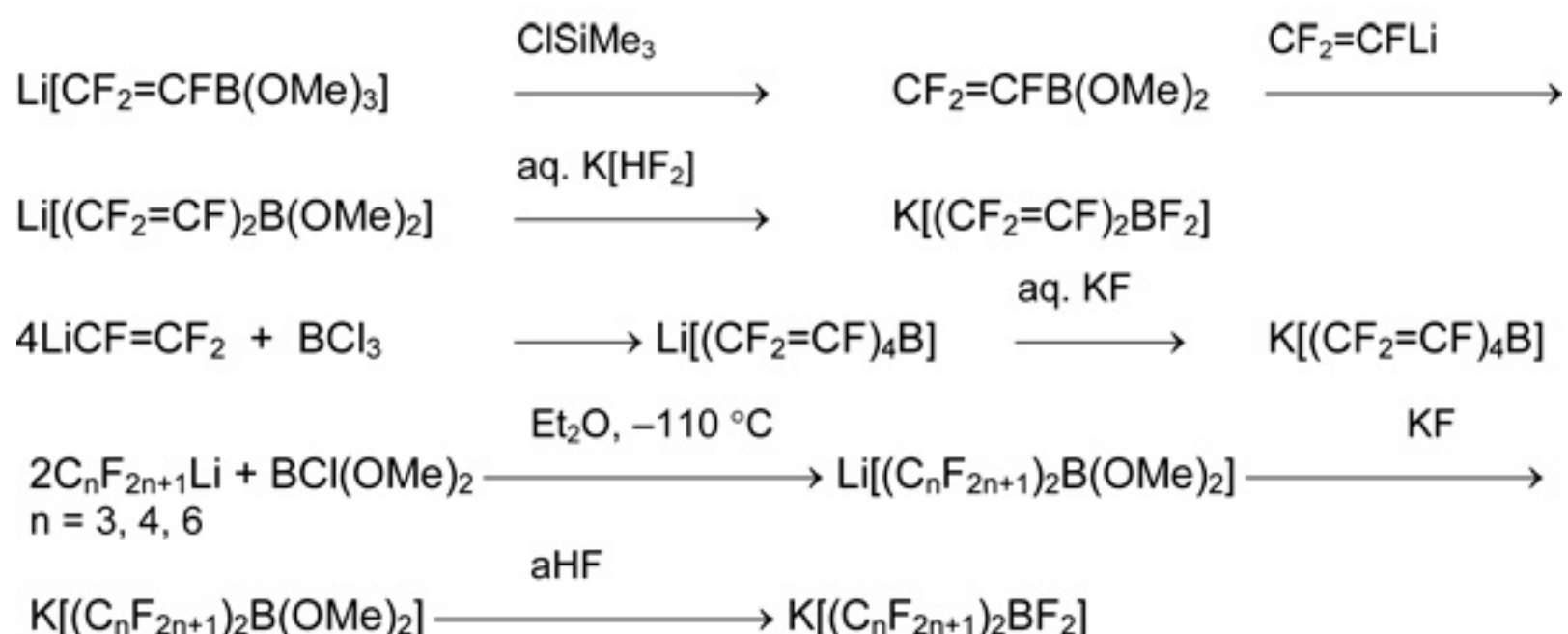


$M = Li, MgBr$; $R_F = C_nF_{2n+1}$, $RCF=CF$, $CF_2=CR$, $RC\equiv C$, $C_6H_nF_{5-n}$ ($n = 1-5$)

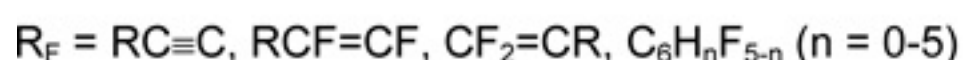
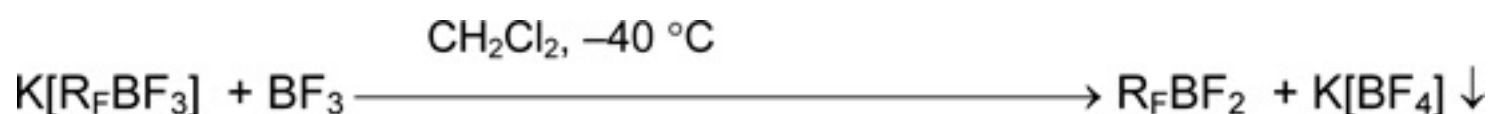
Salts $M[R_F B(OAlk)_3]$ can be isolated in their pure form [4-9], but to obtain derivatives of boric acid [8, 10] or fluoroborates [11-19] they are often used without isolation from solution.



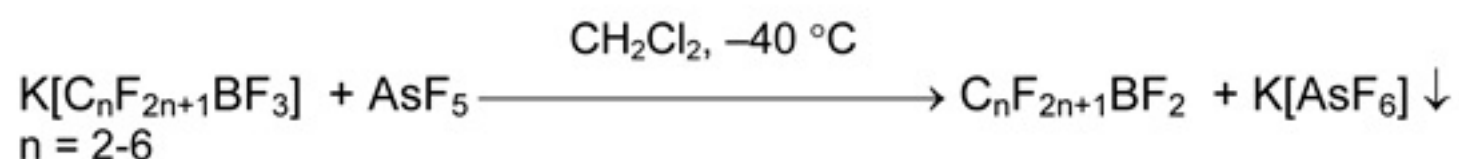
Based on this scheme, methods of preparation of organoboron compounds with 2-4 organic moieties at boron atom were developed [5, 18, 20].



The important property of organylfluoroborates is the ability to eliminate fluoride anion under the action of Lewis acid producing the corresponding organylfluoroboranes. Although the fluoride affinity of boranes $R_F BF_2$ in gaseous phase (pF^-) is 8.51 ($R_F = C_6F_5$), 8.0-9.0 ($R_F = CF_3CF=CF$), 8.90 ($R_F = CF_3C\equiv C$) and exceeds such one BF_3 (7.88) [21], the bubbling of boron trifluoride into suspension $K[R_F BF_3]$ in dichloromethane or polyfluorohydrocarbons results in formation of solution $R_F BF_2$ [11,12,16,17,22-24]. Presumably, the high energy of crystal lattice of precipitated $K[BF_4]$ is the driving force of the process.



To defluoridate perfluoroalkyltrifluoroborates to perfluoroalkyldifluoroboranes ($pF^- \sim 9.6$), the stronger Lewis acid like AsF_5 is required [14].

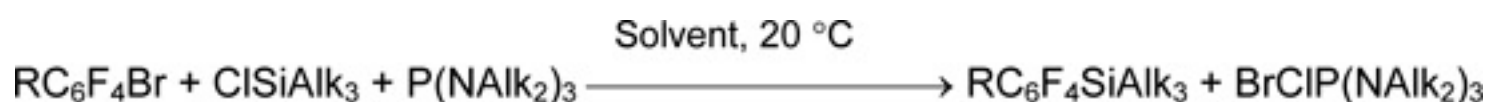


Organoyldifluoroboranes are well soluble in nonpolar solvents, and after decantation their solutions can be used for the further reactions. This method is applicable to boranes with hydrocarbon groups R and to their perfluorinated analogues [11, 12, 14, 16, 17, 22-24].

For more detailed discussion of reactivity of polyfluorinated fluoroboranes and fluoroborates see reviews [25, 26].

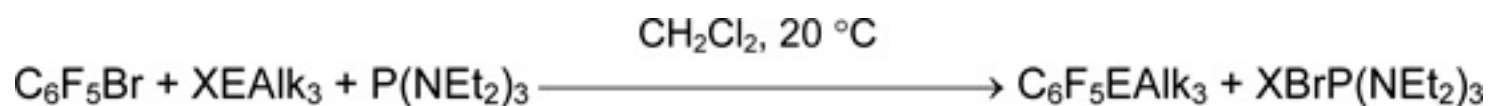
2. Silicon Derivatives

Polyfluoroarylsilanes $Ar_F SiAlk_3$ and $Ar_F SiF_3$ are the useful precursors. The reaction of polyfluoroaryl bromides and -iodides with $ClSiAlk_3$ and tris(dialkylamino)phosphines is suitable for the synthesis of the former. Target products $Ar_F SiAlk_3$ are formed fast at room temperature in aromatic hydrocarbons, ethers and esters (diethyl ether, diglyme, THF, ethyl acetate), dichloromethane or acetonitrile [27-31].



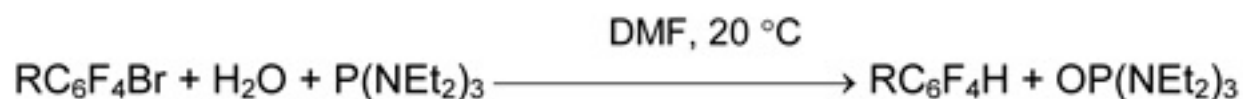
R = H, F, Cl, Br, I, CN, COOAlk, NO₂, CF₃, OCH₃, SiMe₃, GeEt₃

The use of trialkylgermanium, trialkyltin, and trialkyllead halogenides instead of ClSiAlk₃ allows obtaining the corresponding organoelement compounds.

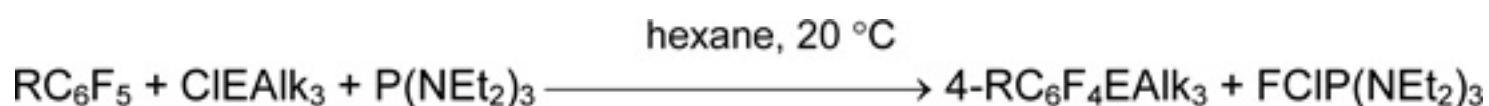


E = Ge, Sn, Pb; X = Cl, Br

It is interesting, that in the presence of protic substrates the substitution of halogen atom by hydrogen (reduction) occurs [27, 32].

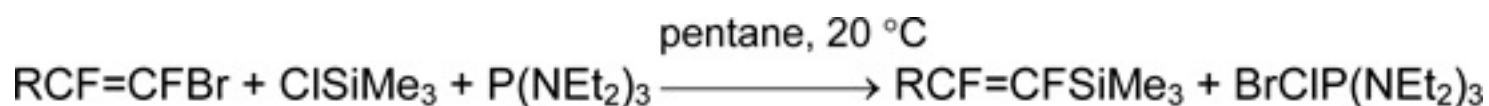


Hexafluorobenzene does not react with ClSiAlk₃ and P(NAIk₂)₃. However, the substitution of one fluorine atom in hexafluorobenzene by the more electron-withdrawing substituent facilitates reaction of silyldefluorination and germlyldefluorination like the substitution of bromine or iodine atoms [33, 34].



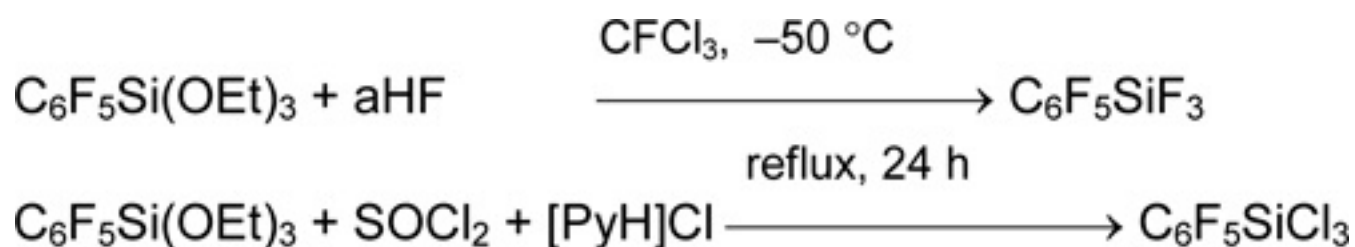
E = Si, Ge; R = CN, COOMe, NO₂, CF₃

Such reactions do not occur in the line of the non-fluorinated or less-fluorinated aromatic compounds. But this approach is suitable for the synthesis of perfluorinated alkenylsilanes and cycloalkenylsilanes [35].

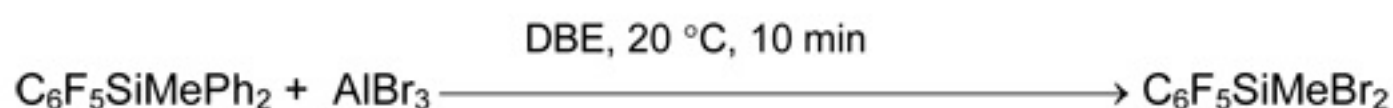
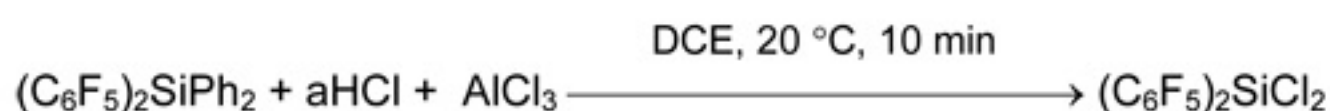
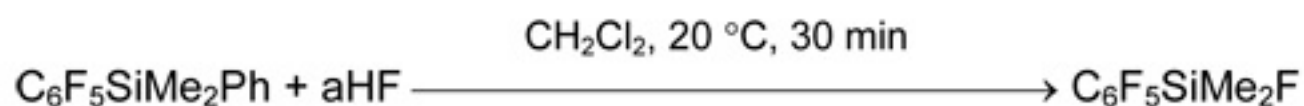


R = F, (CF₃)₂CF

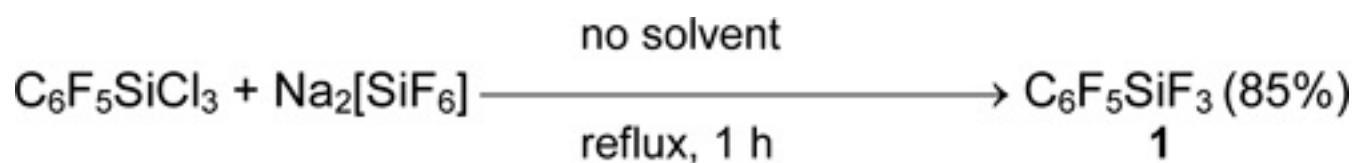
The attempts of pentafluorophenylation of SiCl₄, GeCl₄ and GeBr₄ using P(NEt₂)₃ did not lead to the desired result. The alternative methods based on substitution of ethoxy groups in comparatively available silane C₆F₅Si(OEt)₃ were elaborated for preparation of C₆F₅SiX₃ (X = F, Cl) [36].



It was offered to obtain pentafluorophenyl-containing fluoro-, chloro- and bromosilanes of common formula (C₆F₅)_nSiMe_mX_{4-n-m} by cleavage of Si-Ph bond in the corresponding phenylsilanes with anhydrous hydrogen fluoride HF (aHF) or HSO₃F (X = F), anhydrous HCl (aHCl) and AlCl₃ (X = Cl) or AlBr₃ in dibromomethane. The processes occur under mild conditions and with high yields [37, 38].



Aryl(fluoro)silanes and -germanes were prepared from the corresponding chloro- or bromoderivatives by the action of SbF₃, NbF₅ [36] or better, Na₂[SiF₆] [39].

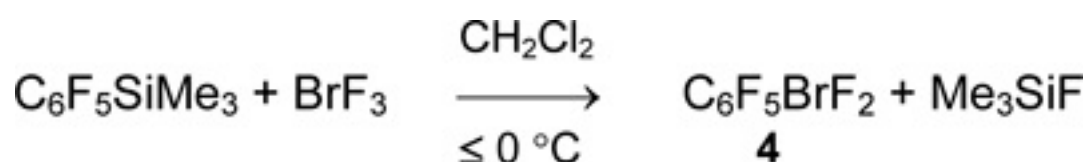


Silane 1 is weaker fluoride anion acceptor, than borane 2. Its fluoride anion affinity in gaseous phase (pF^-) is 7.45 with respect to 8.51 of borane $\text{C}_6\text{F}_5\text{BF}_2$. For comparison, the fluoride anion affinities of binary fluorides BF_3 and SiF_4 are 7.88 and 7.18, respectively. The substitution of fluorine atoms at heteroatom by alkyl groups significantly weakens the strength of Lewis acid. Thus, pF^- value of silane $\text{C}_6\text{F}_5\text{Si}(\text{CH}_3)_3$ is 4.92 [21].

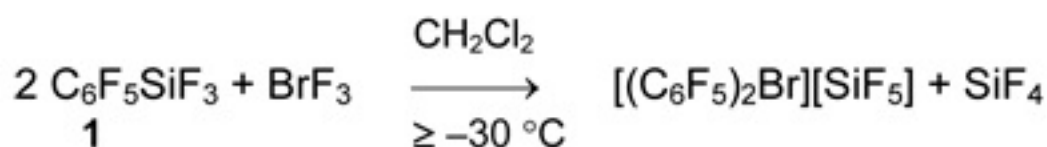
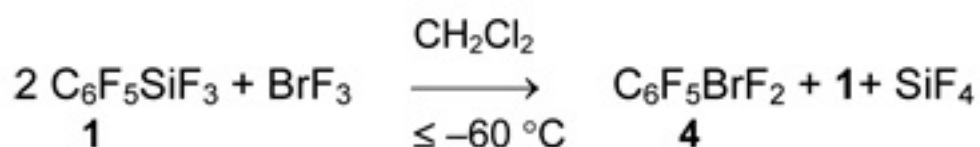
III. The Synthesis of Polyfluorinated Derivatives of Bromine (III, V), Iodine (III, V) and Xenon (II, IV)

1. Bromine (III) Derivatives

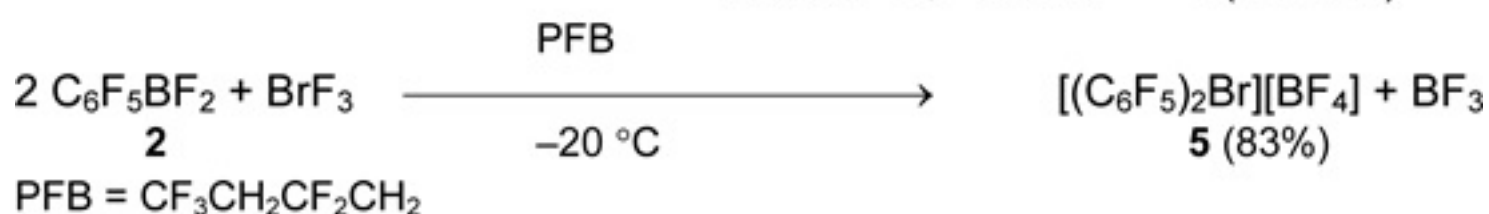
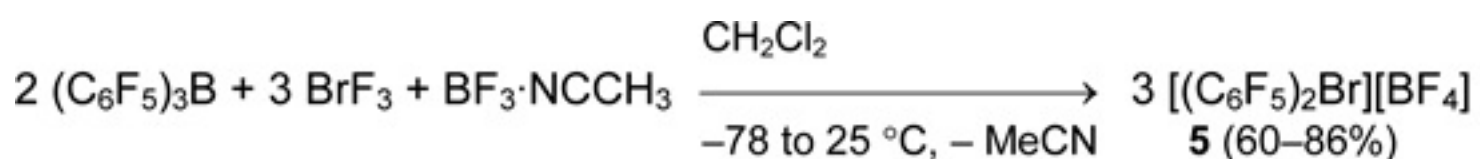
Pentafluorophenyldifluorobromane (4) was prepared by reaction of bromine trifluoride with $\text{C}_6\text{F}_5\text{SiMe}_3$ (3) (1 equiv.) in dichloromethane in 58% yield. Bis(pentafluorophenyl)bromonium salt does not form even in excess of $\text{C}_6\text{F}_5\text{SiMe}_3$ and in the presence of $\text{BF}_3 \cdot \text{OEt}_2$ [40].



Pentafluorophenyltrifluorosilane (1) reacts with BrF_3 in the same way at temperature below -60°C . The rate of the further reaction becomes significant at temperature above -30°C and as a result, salt $[(\text{C}_6\text{F}_5)_2\text{Br}][\text{SiF}_5]$ is obtained in 92% yield.



Polyfluoroorganylboranes are stronger fluoride anion acceptors (Chapter II.1) and their interaction with BrF_3 in weakly coordinating solvents gave symmetrical bis(perfluoroorganyl)bromonium salts.



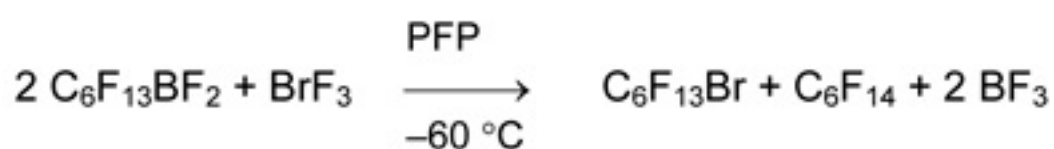
It should be noted, that salt 5 is formed even in equimolar reaction of pentafluorophenyldifluoroborane 2 with BrF_3 while the formation of $\text{C}_6\text{F}_5\text{BrF}_2$ was not registered at -60°C [40].

The method of preparation of bis(pentafluorophenyl)bromonium tetrafluoroborate was successfully applied for the synthesis of representative series of bis(perfluoroorganyl)bromonium salts containing alkenyl and alkynyl groups.

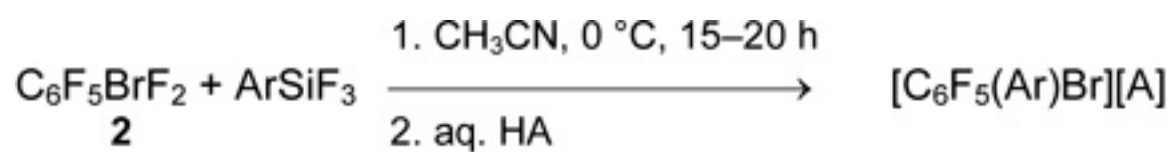


$\text{R}_\text{F} = \text{CF}_3\text{C}\equiv\text{C}$ (31%), *trans*- $\text{CF}_3\text{CF}=\text{CF}$ (>50%), *cis*- $\text{C}_2\text{F}_5\text{CF}=\text{CF}$ (>50%)
 $\text{PFP} = \text{CF}_3\text{CH}_2\text{CF}_2\text{H}$

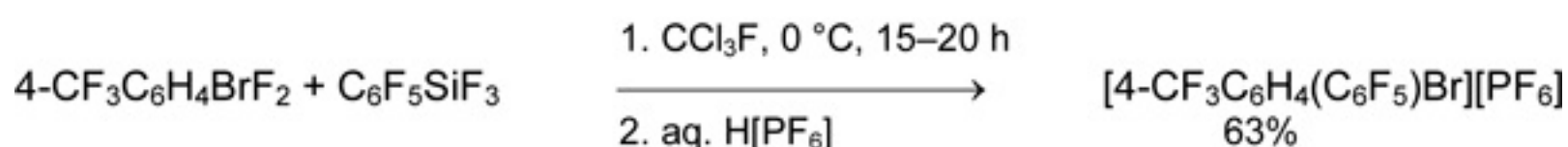
The attempt to obtain or detect bis(perfluorohexyl)bromonium salt in the reaction of $\text{C}_6\text{F}_{13}\text{BF}_2$ with BrF_3 failed.



The reactions of aryldifluorobromanes with aryltrifluorosilanes were used for preparation of asymmetrical fluorine-containing bis(aryl)bromonium salts [41].

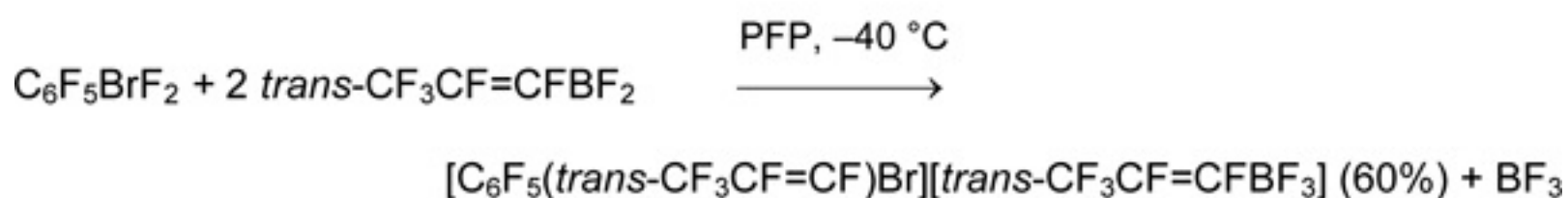


Ar = 4-CF₃C₆H₄ (67%), 4-FC₆H₄ (57%), C₆H₅ (31%);
A = BF₄, PF₆

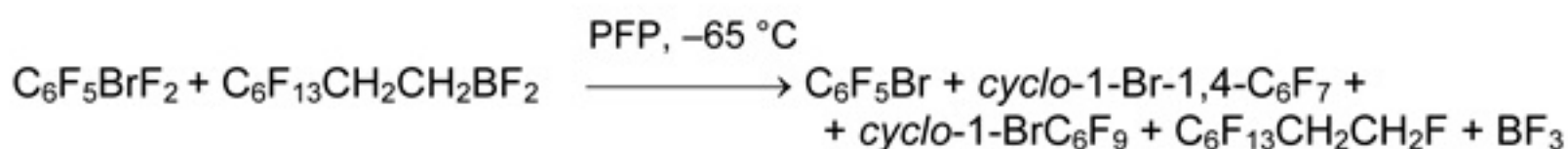


It can be expected, that aryldifluorobromanes will also react with alkenyl- and alkynyltrifluorosilanes, though the latter are low-available and there is no information on such research.

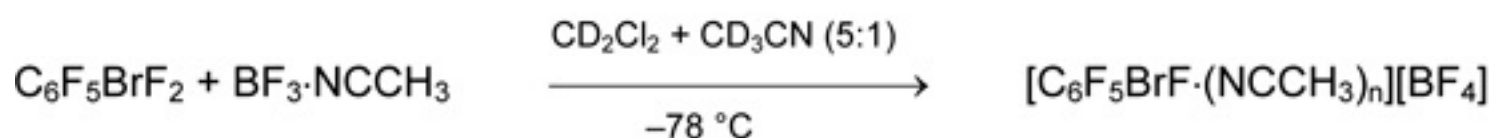
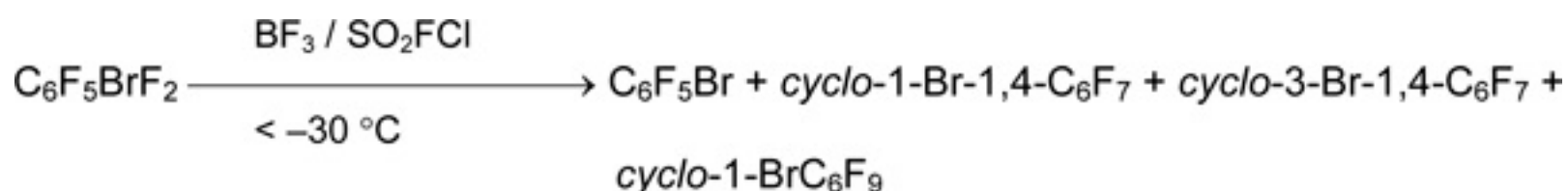
On the contrary, polyfluorinated alkenyldifluoroboranes and alkynyldifluoroboranes are easily available (Chapter II.1). Their reactions with bromanes ArBrF₂ gave the corresponding perfluoro(aryl)(alkenyl)bromonium and perfluoro(aryl)(alkynyl)bromonium salts.



Attempts to synthesize perfluorinated phenyl(hexyl)bromonium and (pentafluorophenyl)(1H,1H,2H,2H-tridecafluorooctyl)bromonium salts failed.

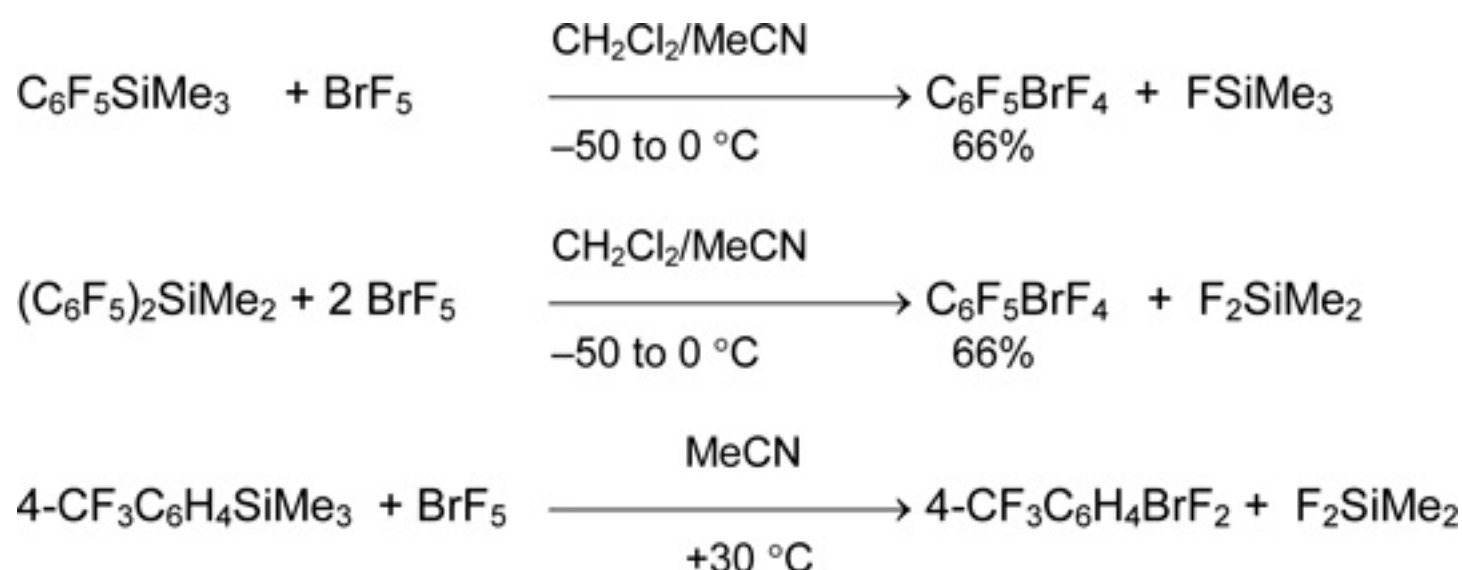


It should be noted, that organyl(fluoro)bromonium salts [RBrF][A] are not registered in the above reactions and are not described in literature. The interaction of C₆F₅BrF₂ with BF₃ in weakly coordinating solvent (SO₂Cl) and basic solvent (CD₃CN + CD₂Cl₂) was studied [42]. In the former case the fast decomposition of 4 with formation of C₆F₅Br and products of latter was observed. In second case a complex [C₆F₅BrF • (NCCH₃)_n][BF₄] (¹⁹F NMR) was found, which decomposed at heating up the solution to 22°C.

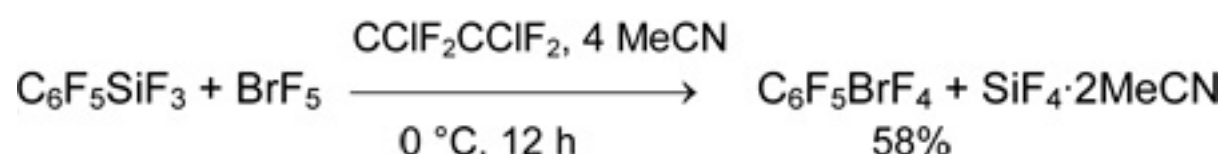


2. Bromine (V) Derivatives

In contrast to bromine (III) derivatives, organylbromane (V) salts are not described, but covalent arylbromanes ArBrF_4 are known. Pentafluorophenyltetrafluorobromane was obtained in 66% yield by reaction of pentafluorophenyltrimethylsilane with bromine pentafluoride in the presence of MeCN. Bis(pentafluorophenyl)dimethylsilane and 4-trifluoromethylphenyltrimethylsilane react in the same way [43].



The replacement of aryltrimethylsilane by aryltrifluorosilane (stronger Lewis acid) does not alter the reaction direction and the character of product. The only products of aromatic ring fluorination are formed in excess of base as well as without it [43, 44].

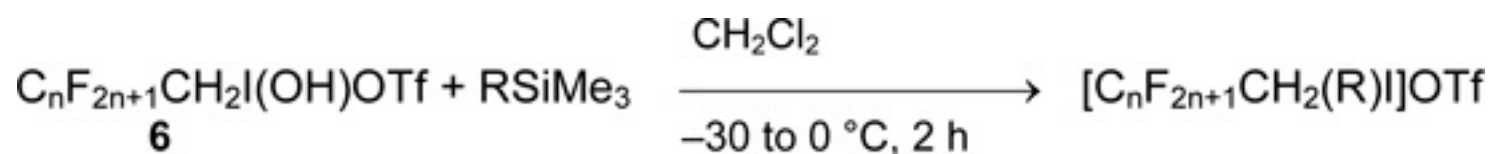


Bromane $3\text{-CF}_3\text{C}_6\text{H}_4\text{BrF}_4$ was synthesized from BrF_5 and complexes $3\text{-CF}_3\text{C}_6\text{H}_4\text{SiF}_3 \cdot 2\text{Py}$ or $(3\text{-CF}_3\text{C}_6\text{H}_4)_2\text{SiF}_2 \cdot 2\text{Py}$ using this method. At the same time, the corresponding aryltetrafluorobromanes $\text{FC}_6\text{H}_4\text{BrF}_4$ were formed from $2\text{-FC}_6\text{H}_4\text{SiF}_3 \cdot 2\text{Py}$ and $4\text{-FC}_6\text{H}_4\text{SiF}_3 \cdot 2\text{Py}$ in very low yield [43].



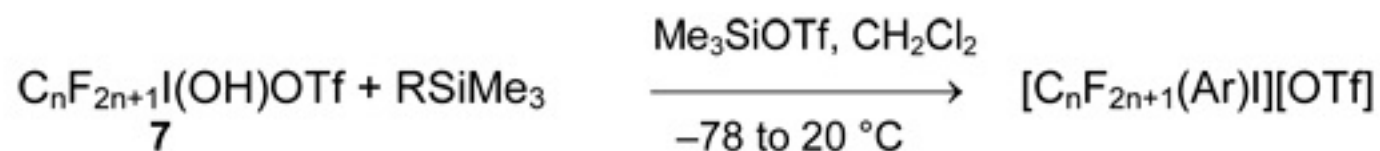
3. Iodine (III) Derivatives

The convenient preparative route to aryl(polyfluoroalkyl)iodonium and alkynyl(polyfluoroalkyl)iodonium salts was offered by Zhdankin [45-47]. It includes the treatment of polyfluoroalkyliodine derivatives (6) with aryltrimethylsilane or alkynyltrimethylsilane in dichloromethane.



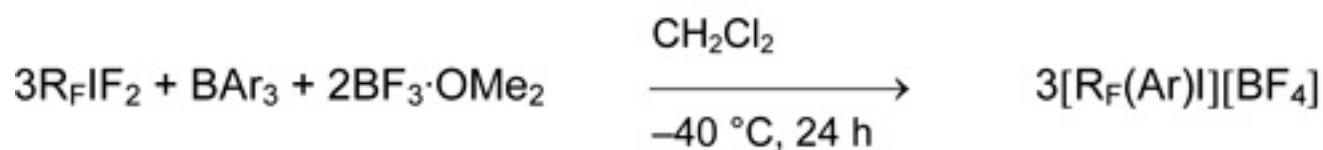
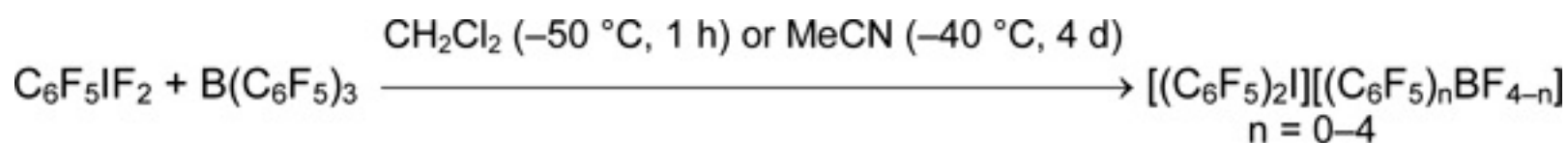
$n = 1, 2$; $\text{R} = \text{C}_6\text{H}_5, 2\text{-MeC}_6\text{H}_4, 4\text{-MeC}_6\text{H}_4, 4\text{-MeOC}_6\text{H}_4, 4\text{-Me}_3\text{SiC}_6\text{H}_4, 4\text{-ClC}_6\text{H}_4, \text{PhC}\equiv\text{C}, \text{t-BuC}\equiv\text{C}, \text{Me}_3\text{SiC}\equiv\text{C}$

Perfluoroalkyliodine (III) derivatives (7) are the less reactive and form the corresponding aryl(perfluoroalkyl)iodonium salts only in the presence of Me_3SiOTf . Alkynyltrimethylsilanes do not react with them.



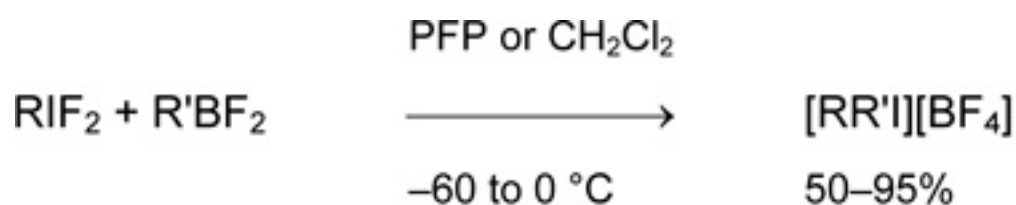
$n = 2, 3, 4, 6, 8$; $\text{R} = \text{C}_6\text{H}_5, 2\text{-MeC}_6\text{H}_4, 4\text{-MeC}_6\text{H}_4, 4\text{-MeOC}_6\text{H}_4, 4\text{-Me}_3\text{SiC}_6\text{H}_4, 4\text{-ClC}_6\text{H}_4$.

This method is limited by using of silanes RSiMe_3 with electron-donating substituent R. The more general method is based on interaction of organyldifluoroiodanes RIF_2 with triarylboranes or better organyldifluoroboranes R'BF_2 . In the first case aryl(polyfluoroaryl)iodonium salts are formed [48-50].



$\text{R}_\text{F} = \text{C}_6\text{F}_5, 2,6\text{-C}_6\text{F}_2\text{H}_3$; $\text{Ar} = 2\text{-FC}_6\text{H}_4, 3\text{-FC}_6\text{H}_4, 4\text{-FC}_6\text{H}_4, 2,6\text{-C}_6\text{F}_2\text{H}_3, 2,4,6\text{-C}_6\text{F}_3\text{H}_2, \text{C}_6\text{F}_5$

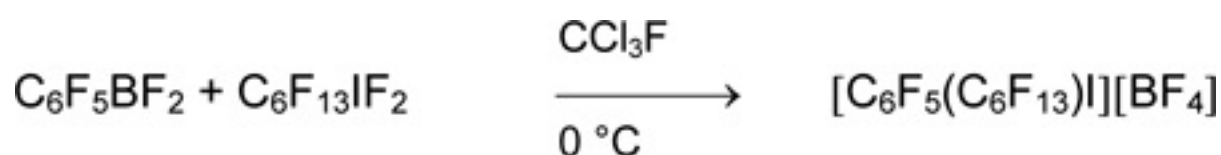
Using boranes, symmetrical and asymmetrical salts with aryl, alkenyl, and alkynyl groups in different combinations were formed. Moreover, different pairs of reagents $\text{RIF}_2/\text{R}'\text{BF}_2$ or $\text{R}'\text{IF}_2/\text{RBF}_2$ can be used in depend on their availability [4,21,51, 52].



$\text{R} = \text{C}_6\text{H}_5, 2\text{-FC}_6\text{H}_4, 3\text{-FC}_6\text{H}_4, 4\text{-FC}_6\text{H}_4, \text{C}_6\text{F}_5, (\text{CF}_3)_2\text{CFCF}=\text{CF}, \text{C}_4\text{F}_9, \text{CF}_3\text{CH}_2$;

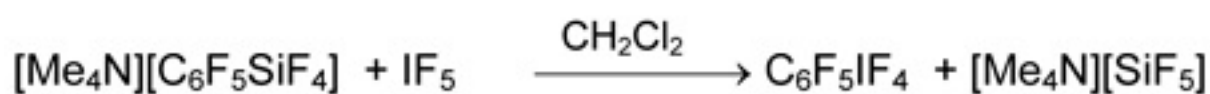
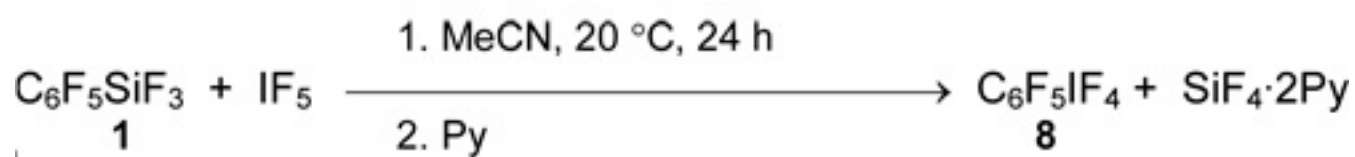
$\text{R}' = 2,6\text{-C}_6\text{F}_2\text{H}_3, 3,5\text{-C}_6\text{F}_2\text{H}_3, 2,4,6\text{-C}_6\text{F}_3\text{H}_2, 3,4,5\text{-C}_6\text{F}_3\text{H}_2, \text{C}_6\text{F}_5, 4\text{-C}_5\text{F}_4\text{N}, \text{CF}_2=\text{CF}, \text{trans-CF}_3\text{CF}=\text{CF}, (\text{CH}_3)_3\text{CC}\equiv\text{C}, \text{CF}_3\text{C}\equiv\text{C}, (\text{CF}_3)_2\text{CFC}\equiv\text{C}$

Using this method, perfluorinated aryl(alkyl)iodonium salt was obtained for the first time [53].

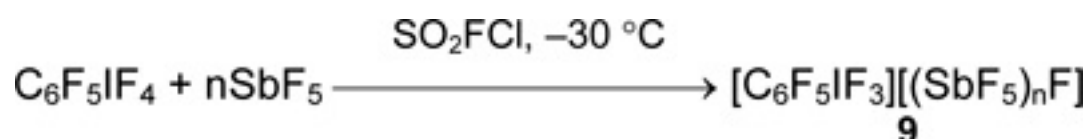


4. Iodine (V) Derivatives

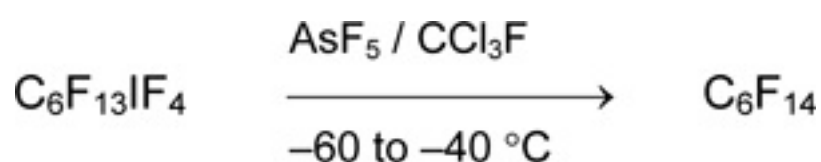
Silane 1 does not react with excess of neat IF_5 and its solutions in CH_2Cl_2 , fluorochlorocarbons or in anhydrous HF [36, 54], but in acetonitrile it produces pentafluorophenyltetrafluoroiodane (8) in quantitative yield [54]. This iodane was also obtained from tetramethylammonium pentafluorophenyltetrafluorosilicate [55].



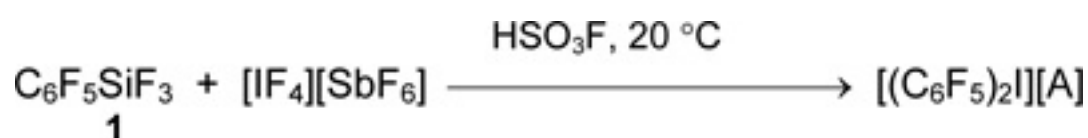
Pentafluorophenyltrifluoroiodonium salt 9 does not form here, but it can be generated by the action of SbF_5 in SO_2FCl [42, 56].



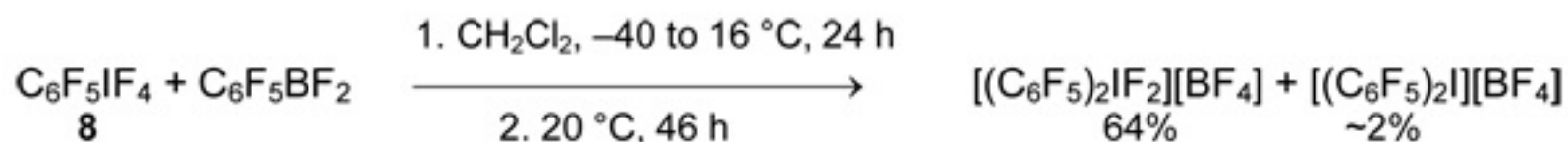
Perfluoroalkyltrifluoroiodonium salts are not described and apparently they are very unstable. For example, the treatment of perfluorohexyltetrafluoroiodane with arsenic pentafluoride leads to carbon-iodine bond cleavage and formation of perfluorohexane with quantitative yield [42].



It is interesting, that the action of $[\text{IF}_4][\text{SbF}_6]$ on silane 1 in fluorosulfonic acid results in formation of bis(pentafluorophenyl)iodonium salt instead of salt 9 [36].

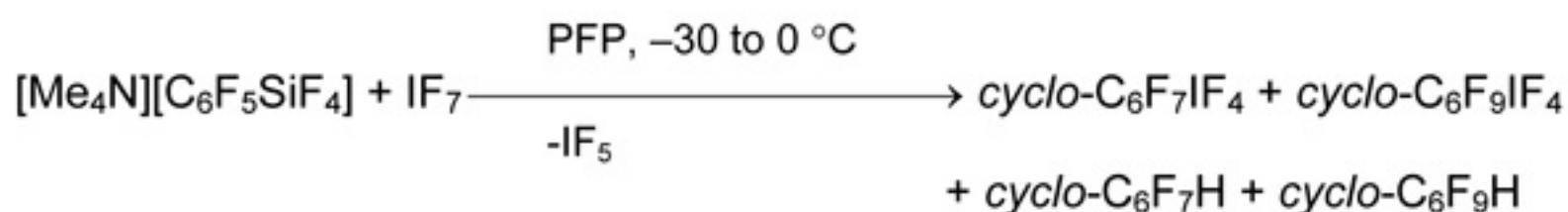
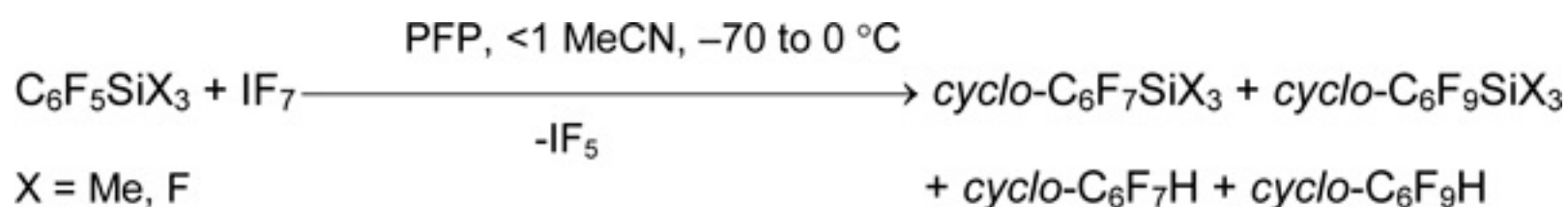


Borane 2 reacts with iodine pentafluoride in CH₂Cl₂ at 20°C very slowly producing a mixture of C₆F₅IF₄, [(C₆F₅)₂IF₂][BF₄] and by-products (C₆F₅I, C₆F₅H, CH₂ClF). Its reaction with iodane 8 occurs faster and leads to bis(pentafluorophenyl)difluoroiodonium tetrafluoroborate [57].

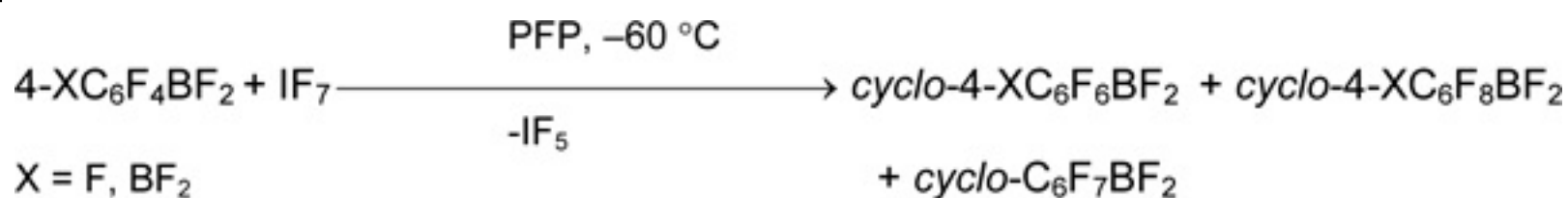


5. Approaches to Preparation of Iodine (VII) Derivatives

Inorganic iodine (VII) compounds are the less studied relative iodine (III) or iodine (V) derivatives, and organic iodine (VII) compounds are not described at all. Recently some approaches to R_FIF₆ based on using of organoboron and organosilicon synthones and IF₇ are studied [58]. In contrast to above considered cases, the reaction of iodine heptafluoride with C₆F₅SiMe₃ or C₆F₅SiF₃ in PFP produces only products of fluorine addition to aromatic ring. The substitution of silicon atom by iodine takes place in the reaction of [Me₄N][C₆F₅SiF₆] with IF₇ but the reaction products are iodine (V) derivatives.



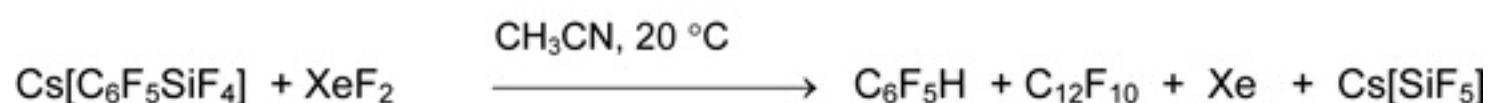
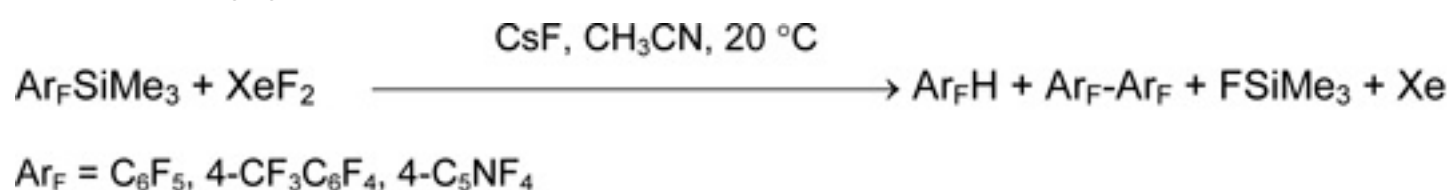
The reaction of IF₇ with borane 2 and even with perfluorodiborylbenzene, 1,4-C₆F₄(BF₂)₂, which contain two strong electron-withdrawing groups in tetrafluorophenyl ring [σ_I(BF₂) = 0.15, σ_R(BF₂) = 0.30, σ_m(BF₂) = 0.45, σ_p(BF₂) = 0.37] [11] proceeds in similar way.



The analysis of relative reaction rates of C₆F₅SiX₃ and C₆F₅BF₂ with HalF_n (Hal = Br, I; n = 3, 5) proved their decrease when n increases. It is one of more possible causes for the absence of bromine or silicon atom substitution for I(VII) atom. Notably the rate of iododeborylation by action of IF₇ is lower, than the rate of parallel polyfluoroaromatic ring fluorination reaction.

6. Xenon (II, IV) Derivatives

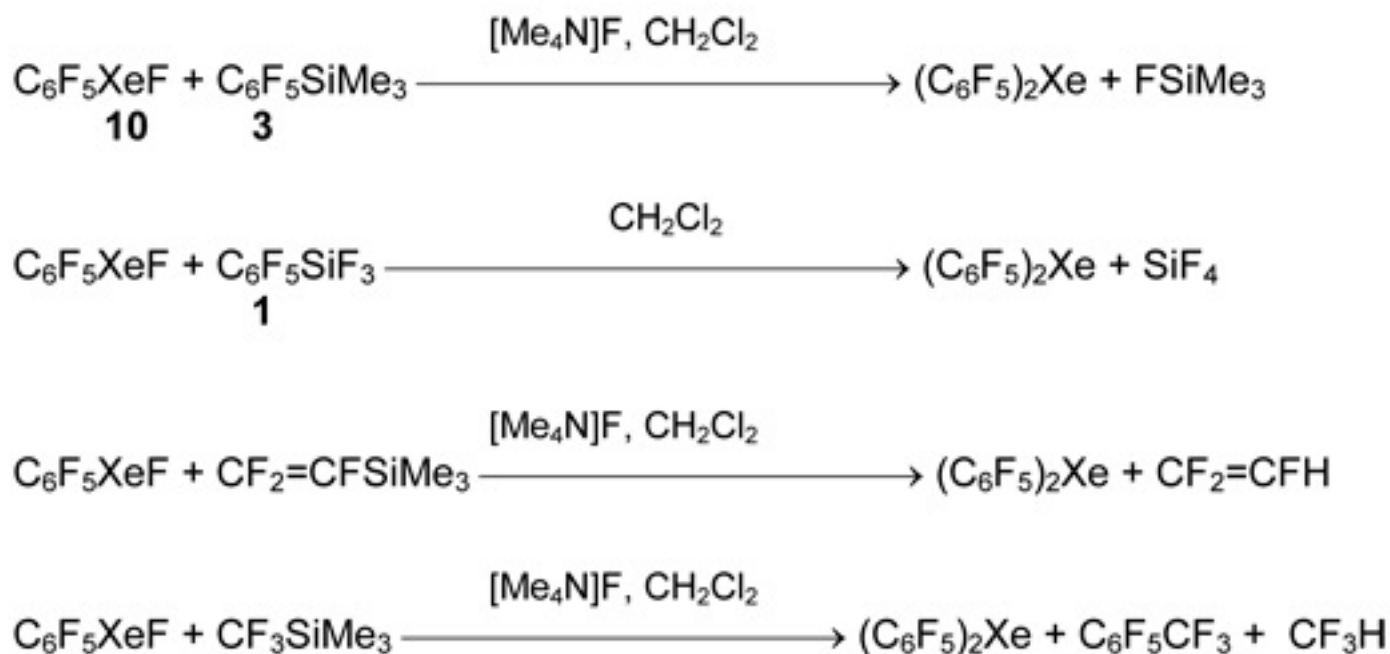
First publications on successive preparative synthesis of compounds with carbon-xenon bond were published in 1989 [2, 3]. Shortly before that publications communication [59] on reaction of perfluoroaryltrimethylsilanes Ar_FSiMe₃ with xenon difluoride over cesium fluoride at 20°C (heterogeneous reaction) appeared. Besides xenon and fluorotrimethylsilane, products were arenes and biaryls. The reaction of XeF₂ with Cs[C₆F₅SiF₄] goes analogously [55].



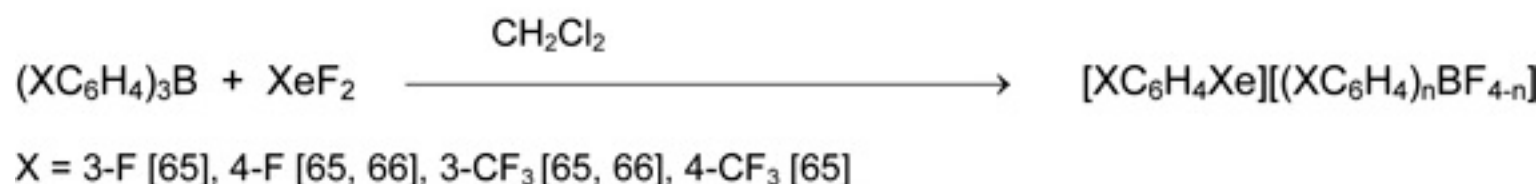
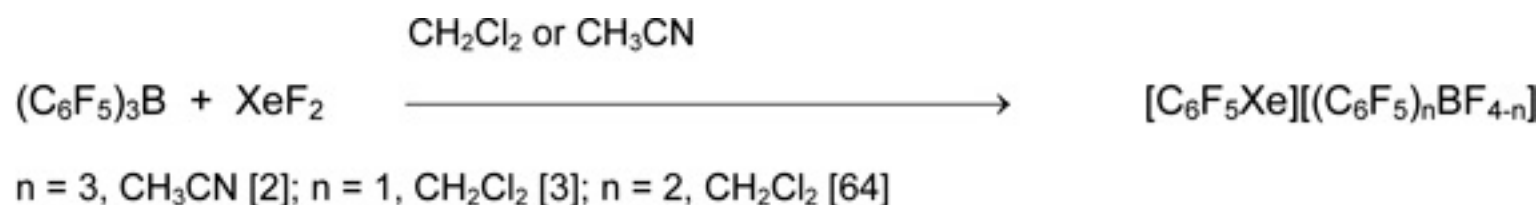
The formation of organoxenon compounds was not proved. The causes became clear later when properties of unambiguously prepared and characterized salts (like [C₆F₅Xe][AsF₆]) and covalent compounds (like C₆F₅XeF or (C₆F₅)₂Xe) had been studied. Indeed, organic compounds of two-coordinated xenon are significantly less stable, than the respective salts, and they dissociate in acetonitrile on radical mechanism producing C₆F₅H and C₁₂F₁₀ [60, 61]. When the reaction of C₆F₅SiMe₃ and XeF₂ in the presence of [Me₄N]F was performed by

heating homogeneous solution in MeCN-EtCN from -60 to -40 °C with further fast cooling, then C₆F₅XeF and (C₆F₅)₂Xe was registered with ¹⁹F and ¹²⁹Xe NMR spectroscopy. But xenon compounds with trifluoromethyl groups are unstable even at low temperature. Thus, under these conditions only hexafluoroethane, xenon and FSiMe₃ were formed from CF₃SiMe₃ [62].

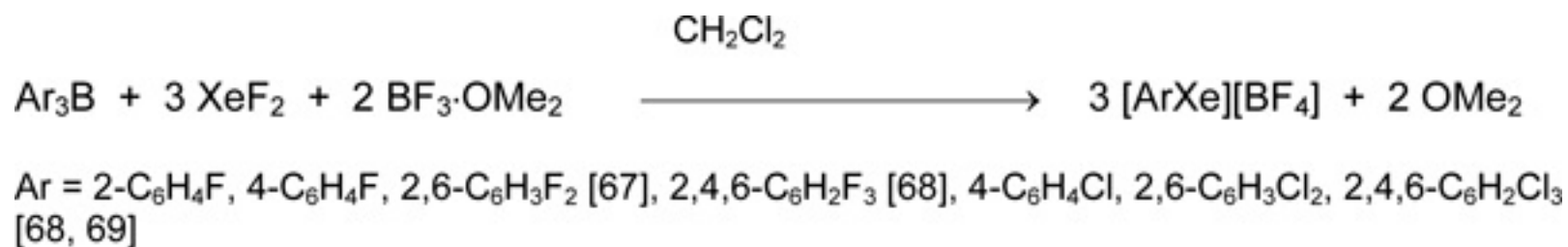
Similar approach was used for preparation of bis(pentafluorophenyl)xenon from pentafluorophenylfluoroxenon 10 and silanes 1 or 3. Unexpectedly, the formation of this compound was found in the reaction of 10 with silanes CF₃SiMe₃ and CF₂=CFSiMe₃ in the presence of [Me₄N]F [63].



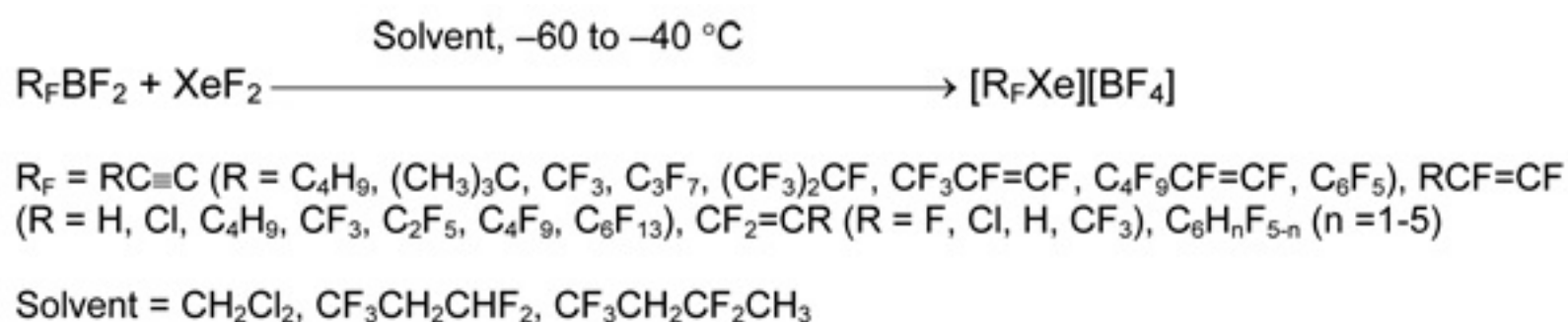
Practically useful results in preparative synthesis of organoxenon compounds were obtained when boron compounds were used as organic group carriers. Originally triarylboranes were used, but because of relatively high nucleophilicity of [(XC₆H₄)_nBF_{4-n}]⁻ anions, these salts decompose in solution at -60 to -20 °C.



The better result was obtained in the presence of boron trifluoride etherate. The role of the latter consists in replacement of relatively good fluoride anion donors, [Ar_nBF_{4-n}]⁻, by the low-nucleophilic anions [BF₄]⁻, which significantly increases the stability of [ArXe][A] salts.

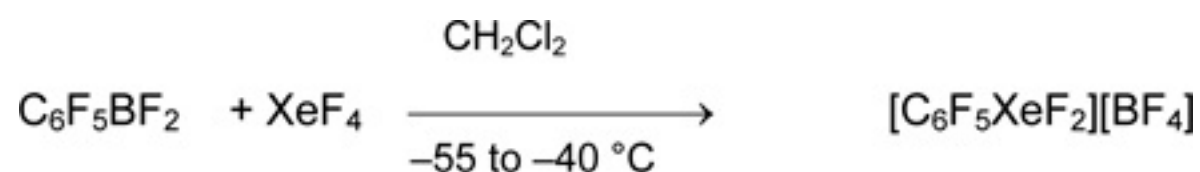


A significant progress in research of organoxenon compounds was achieved after usage of organyldifluoroboranes R_FBF₂ as sources of R_F. A simple and convenient preparative synthetic method to polyfluororganylxenon (II) tetrafluoroborates containing aryl, alkenyl, and alkynyl groups at xenon atom was elaborated [12, 16, 17, 70-75].

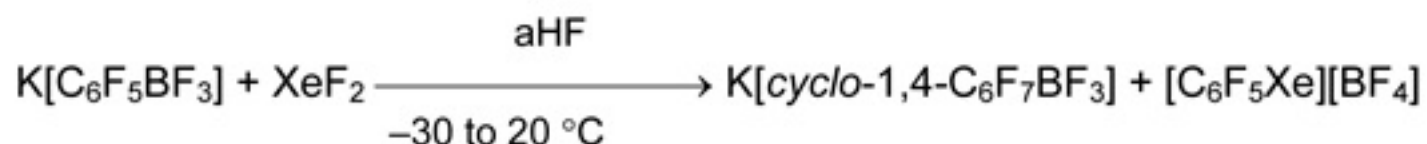


This method has some limitations. Thus, reaction of XeF₂ and 4-tetrafluoropyridyldifluoroborane gave presumably complex 4-C₅NF₄BF₂•XeF₂ [21] instead of expected tetrafluoropyridylxenonium (II) salt [21]. Alkylxenonium derivatives remain unknown: reaction of C₆F₁₃BF₂ and XeF₂ leads to perfluorohexane, xenon, and boron trifluoride, whereas from C₆H₁₃BF₂ and XeF₂ mainly hexyl fluoride was formed.

The reaction of borane 2 with xenon tetrafluoride proceeds significantly slower than with XeF₂ and produces pentafluorophenyldifluoroxenonium salt [76].



The alternative approach consists in electrophilic substitution of heteroatom of very good leaving group. In regards to that, a reaction of K[C₆F₅BF₃] and XeF₂ in anhydrous HF is representative, because the fluorine addition to aromatic ring proceeds simultaneously with the substitution of boron atom by xenon [77].



Detailed analysis of contemporary state of chemistry of organoxenon compounds see reviews [60, 61].

References (references.pdf)

Recommended for publication by Prof. V.E. Platonov