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Fluorine-containing α-Dicarbonyl Compounds and Their Derivatives

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The synthesis of fluorine-containing α-dicarbonyl compounds and their derivatives, their chemical properties (including the formation of heterocycles), and their applications are considered. Data emphasising their characteristic features due to the presence of fluorine atoms are presented.
The bibliography includes 97 references.

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I. INTRODUCTION

α-Dicarbonyl compounds (α-DCC), namely α-diketones, α-ketoaldehydes, α-ketoacids, and their derivatives are used in industry and in laboratory syntheses. The presence of the α-dicarbonyl group in compounds of this class is responsible for their high reactivity in relation to many types of reagents. They are also convenient objects for the study of certain theoretical problems of organic chemistry (rotational isomerism relative to a single C–C bond and the mutual influence of substituents). Among compounds of this type, biologically active substances, analytical reagents, and valuable monomers have been discovered. The introduction of fluorine atoms into α-DCC molecules leads in many instances to a change of the reactivity of the substances and the appearance of new aspects of their applications. At the present time extensive data have accumulated in the literature on fluorine-containing α-DCC but no surveys on this problem have been published†.

This review surveys the literature data on the synthesis, chemical reactions, and practical applications of fluorine-containing α-diketones, α-ketoaldehydes, α-ketoacids, and their derivatives. The literature up to 1980 inclusive is covered.

II. METHODS OF SYNTHESIS

The preparation of a fairly large number of fluorine-containing α-diketones, α-ketoaldehydes, α-ketoacids, and their derivatives by various methods has been described in the literature; these data can be conveniently divided into two groups: the preparation of α-diketones and aldehydes and the preparation of α-ketoacids and their derivatives.

1. Fluorine-containing α-Diketones and α-Ketoaldehydes

A number of methods for the synthesis of fluorine-containing α-DCC are based on reactions of substances in which the carbonyl group is linked to a halogen atom and fluoroalkyl or fluoroacyl groups (acid halides, ketones, and acid anhydrides). These methods as a rule involve radical processes (the abstraction of radicals, recombination of fluoroacyl radicals, or oxidation).

† Some information about α-DCC is available in reviews[1,2] devoted mainly to other problems.

1,4-Difluorobutane-2,3-dione and 1,4-dichloro-1,4-difluorobutane-2,3-dione have been obtained (in yields of 42 and 58% respectively) by the reaction of monofluro- or chlorofluoro-acetyl chlorides with iron pentacarbonyl in an autoclave at 180 °C.[3] Diacetyl is formed by this method in 86% yield[3]:

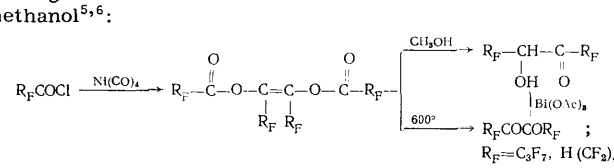
$$CHFXCOCl \xrightarrow[180°]{Fe(CO)_5} CHFXCOCOCHFX + CHFXCOF \ ; \quad X=H,Cl \ .$$

In the reactions of trifluoroacetyl and difluoroacetyl chlorides, perfluorodiacetyl and 1,1,4,4-tetrafluorobutane-2,3-dione are not formed, the degradation of the initial acid chlorides being observed with formation of iron fluorides, carbon, and small amounts of carbonyl fluoride and hexafluoroethane[3].

1,1,4,4-Tetrafluorobutane-2,3-dione and perfluorodiacetyl have been obtained by the reaction of difluoro- and trifluoroacetic anhydrides with iron pentacarbonyl (in yields of 11 and 6.5%).[4] Under the same conditions, diacetyl is formed from acetic anhydride in 90% yield[4]. Together with perfluorodiacetyl, the following compounds have been obtained from trifluoroacetic anhydride: iron trifluoroacetate, carbon monoxide, iron fluorides, trifluoroacetyl fluoride, hexafluorobut-2-en-2,3-diyl bistrifluoroacetate, and hexafluoroethane[4]. Analogous products are formed from difluoroacetic anhydride[4].

It is believed[3,4] that, with decrease of the fluorine content in the initial acid chlorides and anhydrides, the yield of acid fluorides falls, while that of α-diketones increases in connection with the decrease of the concentrations of iron fluorides in the reaction mixture.

When heptafluorobutyryl and ω-hydro-octafluorovaleryl chlorides react with nickel tetracarbonyl in benzonitrile at 25 °C, the corresponding enediol esters are formed in yields of 51 and 19%, the esters being converted into α-diketones by pyrolysis at 600 °C *in vacuo*[5,6]. The same α-diketones are formed on oxidation with bismuth triacetate of fluorine-containing α-ketonalcohols obtained from enediol esters and methanol[5,6]:

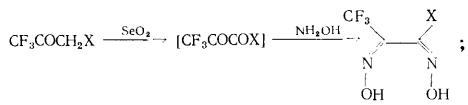


$$R_F = C_3F_7, \ H(CF_2)_4 \ .$$

The attempt to obtain decafluorobenzil from pentafluorobromo- or pentafluoroiodo-benzene and nickel tetracarbonyl in aprotic solvents was unsuccessful; the reaction products were only decafluorobiphenyl, decafluorobenzophenone, and pentafluorobenzene[7]. The authors[7] attribute the absence of

decafluorobenzil to the instability of the pentafluorobenzoyl radical, which decomposes before it can dimerise.

1,1,1-Trifluorobutane-2,3-dione and trifluoromethylglyoxyal are formed from ethyl trifluoromethyl ketone and trifluoroacetone when they are oxidised by selenium dioxide. However, these compounds could not be isolated in a pure state and they were characterised in the form of glyoximes[8]:



X=H, CH_3 .

The above method is apparently without value for the synthesis of fluorine-containing α-DCC, because the attempt to hydrolyse perfluorodipropylglyoxime was unsuccessful[9]. More interesting results were obtained on oxidation of benzyl fluoroalkyl ketones[10]:

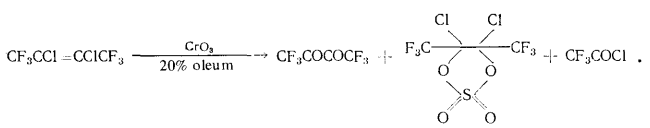
$$C_6H_5CH_2COC_3F_7 \xrightarrow{SeO_2} C_6H_5COCOC_3F_7 \ ;$$

$$C_6H_5CH_2CO(CF_2)_4COCH_2C_6H_5 \xrightarrow{SeO_2} C_6H_5COCO(CF_2)_4COCOC_6H_5 \ .$$

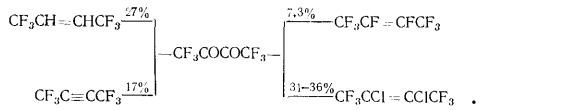
In certain studies on the photolysis of hexafluoroacetone the formation of perfluorodiacetyl on recombination of trifluoroacyl radicals was postulated[11,12]. Although perfluorodiacetyl was not isolated in the above studies[11,12], in the investigation of the flash photolysis of hexafluoroacetone at −78 °C it was identified[12] from the phosphorescence spectra in the presence of hexafluoroacetone.

$$CF_3COCF_3 \xrightarrow{h\nu} CF_3COCOCF_3 \ .$$

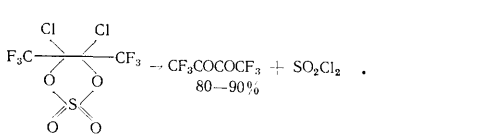
A large number of methods for the synthesis of fluorine-containing α-diketones, based on the reactions of compounds containing multiple bonds (fluoro-olefins, fluoroacetylenes, and fluoroallenes) have been described. Perfluorodiacetyl was synthesised for the first time by the oxidation of 2,3-dichlorohexafluorobut-2-ene with chromium trioxide in 20% oleum[13]. Trifluoroacetyl chloride and 2,3-dichloro-1,1,1,4,4,4-hexafluorobutylene sulphate are formed together with perfluorodiacetyl[13]:



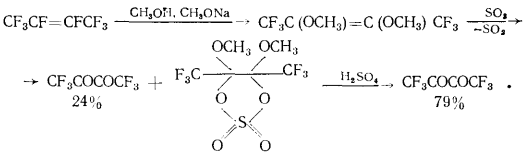
The above investigators studied the formation of perfluorodiacetyl in the oxidation of hexafluorobut-2-yne by chromium trioxide or potassium perchlorate in 20% oleum[14]:



2,3-Dichlorohexafluorobutylene sulphate, formed on oxidation of 2,3-dichlorohexafluorobut-2-ene, is converted into perfluorodiacetyl on treatment with catalytic amounts of triphenylphosphine, triphenyl phosphite, tributylamine, or pyridine[15]:

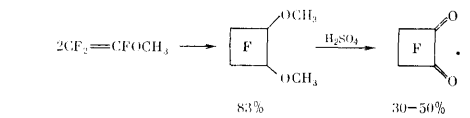


Perfluorodiacetyl has been obtained from perfluorobut-2-ene via hexafluoro-2,3-dimethoxybutylene sulphate[16,17], formed in the reaction of sulphur trioxide with vicinal dimethoxy-derivatives of hexafluorobut-2-ene:

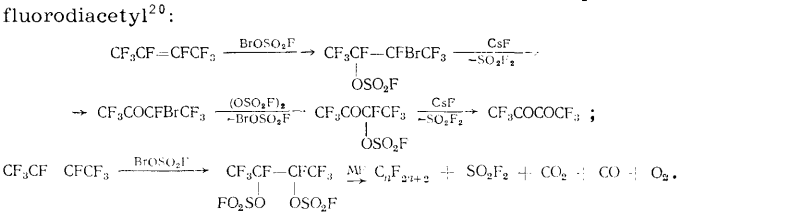


This is one of the best methods from the standpoint of the yields of products and the availability of the initial reactants. Unfortunately it is apparently not universal and is suitable only for the synthesis of perfluorodiacetyl, since, after the increase of the length of the fluoroalkyl residues, the reaction of the fluoro-olefin with sodium methoxide in methanol leads to the formation of mixtures of products[17].

Perfluorocyclobutane-1,2-dione has been synthesised in 30–50% yield on treatment of 1,2-dimethoxyperfluorocyclobutane with sulphuric acid[18]:

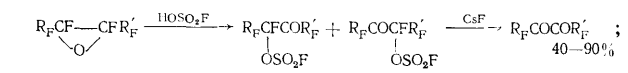


Treatment of perfluorobut-2-ene with bromine fluorosulphate yielded 2,3-di(fluorosulphate)perfluorobutane, whose treatment with alkali metal fluorides did not permit the isolation of perfluorodiacetyl[19]. However, in another study[20] the reaction of bromine fluorosulphate with perfluorobut-2-ene yielded 2-bromo-3-fluorosulphatoperfluorobutane, which is converted into 2-bromoperfluoro-2-butanone on treatment with a caesium fluoride. The reaction of the butanone with peroxydisulphuryl difluoride yields 3-fluorosulphatoperfluoro-2-butanone, which reacts with caesium fluoride to form perfluorodiacetyl[20]:



The method of synthesis of symmetrical and asymmetric perfluoro-α-diketones by the reaction of peroxydisulphuryl difluoride with internal fluoro-olefins and subsequent treatment of the products with caesium fluoride is of undoubted interest[21].

Perfluoro-α-ketofluorosulphate-derivatives have now become fairly readily available as a result of their synthesis from the epoxy-derivatives of internal fluoro-olefins and fluorosulphonic acid, which made it possible to obtain a large number of fluorine-containing α-diketones[22–24].



R_F=CF_3, C_2F_5, C_3F_7; R'_F=CF_3, C_2F_5, C_3F_7, $CF(CF_3)_2$.

The last two methods are the most general for the synthesis of aliphatic and alicyclic perfluoro- α-diketones[21–24].

Perfluoro-2,5-dimethylhexane-3,4-dione has been isolated in 28% yield together with perfluoro-2,4-dimethyl-3-pentanone on reaction of perfluoropropene with oxalyl difluoride under pressure in acetonitrile in the presence of potassium hydrogen difluoride[25]:

$$CF_3CF{=}CF_2 + FOC{-}COF \xrightarrow[28\%]{KHF_2} (CF_3)_2CFCOCOCF(CF_3)_2 + (CF_3)_2CFCOCF(CF_3)_2 \ .$$

An analogous but somewhat modified method, in which oxalyl dichloride can be used as the starting material, has also been proposed[26].

2-Chloroperfluoro-2-methylpentane-3,4-dione has been obtained with other products in 38% yield on treatment of tetrakis(trifluoromethyl)allene with nitrosyl chloride[27]:

$$(CF_3)_2C{=}C{=}C(CF_3)_2 \xrightarrow[180°]{NOCl} \underset{38\%}{CF_3COCOCCl(CF_3)_2} .$$

When hexafluorobut-2-yne or perfluorodiphenylacetylene reacts with bis(trifluoromethyl)nitroxide, perfluorodiacetyl or decafluorobenzil are formed in yields of 73% (for a 50% conversion) and 25% respectively[28]:

$$R_FC{\equiv}CR_F \xrightarrow{(CF_3)_2NO^\bullet} R_FCOCOR_F ;$$
$$R_F{=}CF_3,\ C_6F_5 .$$

Hexafluorobut-2-yne also gives rise to perfluorodiacetyl on reaction with perfluoromorpholine oxide[29]:

$$CF_3C{\equiv}CCF_3 \xrightarrow{\text{perfluoromorpholine-}O^\bullet} CF_3COCOCF_3 .$$

α-Diketones containing pentafluorophenyl groups are synthesised mainly with the aid of aromatic organometallic compounds. Decafluorobenzil is formed in 43–55% yield when pentafluorophenyl-lithium reacts with dimethyl oxalate at low temperatures (between −40° and −78 °C): [30]

$$C_6F_5Li + CH_3OOC-COOCH_3 \rightarrow C_6F_5COCOC_6F_5 .$$

Decafluorobenzil can be obtained in 26–32% yield from phenylcopper and oxalyl dichloride in ether[31]:

$$C_6F_5Li + CuBr \rightarrow C_6F_5Cu \xrightarrow{ClOC-COCl} C_6F_5COCOC_6F_5 .$$

Pentafluorobenzil can be obtained in 40% yield via the following mechanism[30]:

$$C_6F_5Li + C_6H_5C(OLi)(OC_2H_5)-CO_2C_2H_5 \rightarrow C_6F_5COCOC_6H_5 .$$

Pentachloropentafluorobenzil has been synthesised by the reaction of pentafluorophenyl-lithium with methyl pentachlorobenzoyl formate at −78 °C (yield 87%): [30]

$$C_6F_5Li + C_6Cl_5COCO_2CH_3 \rightarrow C_6F_5COCOC_6Cl_5 .$$

2. Fluorine-Containing α-Ketoacids and Their Derivatives

The main methods of synthesis of fluorine-containing α-ketoacids and their derivatives involve the interaction of the epoxy-derivatives of terminal fluoro-olefins and perfluoroazirines with nucleophiles (H_2O, ROH, RNH_2) or electrophiles (SO_2).

The hydrate of trifluoropyruvic acid has been obtained by treating epoxyhexafluoropropane with water[32,33]. This method proved to be general and has been used successfully to synthesise the hydrates of fluorine-containing α-ketoacids with longer fluoroalkyl residues from the corresponding epoxy-derivatives of higher fluoro-olefins[34,35]:

$$R_FCF(O)CF_2 \xrightarrow{H_2O} \underset{40-80\%}{R_FCOCO_2H\cdot H_2O} ,$$

$R_F{=}CF_3$ [32, 33]; C_2F_5 [34]; $H(CF_2)_n$, where n = 2, 4 [34], 6 [35]; C_4F_9 [34].

The synthesis of trifluoropyruvic acid by the hydrolysis of perfluoro-2-methyl-2*H*-azirine and perfluoro-3-methyl-2*H*-azirine has been described[36]:

$$CF_3CF(O)CF \xrightarrow[70°]{H_2O} [CF_3COCO_2H] \xrightarrow{C_6H_5NH_2} \underset{33\%}{CF_3COCO_2^-NH_3C_6H_5} .$$

The hydrate of trifluoropyruvic acid is formed on acid hydrolysis of α,α-diaminoperfluoropropionamide[37]:

$$CF_3CF(O)CF_2 + H_2NR \rightarrow CF_3C(NHR)_2CONHR \xrightarrow{H_2O,\ H_3PO_4} CF_3COCO_2H\cdot H_2O .$$

On the interaction with water, the fluoride of trifluoropyruvic acid yield trifluoropyruvic acid hydrate; the starting materials for the synthesis of the acid fluoride are epoxyhexafluoropropane and an aromatic carbonyl compound (benzophenone, acetophenone, benzaldehyde, etc.)[38–45]:

$$CF_3CF(O)CF_2 \xrightarrow{ArCOR} CF_3COCOF + CF_3COF \xrightarrow{H_2O} CF_3COCO_2H\cdot H_2O \xrightarrow{H_2SO_4} CF_3COCO_2H .$$

One must note that the mechanism of this reaction still remains obscure.

The fluoride of trifluoropyruvic acid has also been obtained from epoxyhexafluoropropane and sulphur trioxide at 150 °C with subsequent elimination of sulphuryl fluoride by treating the mixture of the addition products with caesium fluoride[46]:

$$CF_3CF(O)CF_2 \xrightarrow[150°]{SO_3} \underset{58\%\text{ of mixture}}{F_3C-CF(OSO_2O)-CF_2} + CF_3COCF_2OSO_2F \xrightarrow{CsF} CF_3COCOF .$$

Pyrolysis of 1-nitro-perfluoro-2-propyl nitrite in a flow system gives rise to trifluoropyruvyl fluoride in a yield of approximately 10%: [47]

$$O_2N-CF_2-CF(ONO)-CF_3 \xrightarrow{250°} CF_3COCOF + NO .$$

The study of the infrared spectra and of the temperature variation of the ^1H NMR spectra of solutions of hydrated fluorine-containing α-ketoacids showed that they exist in the form of fluoro-α,α-dihydroxyacids $R_FC(OH)_2COOH$. They differ in this respect from the usual fluorine-free α-ketoacids, which do not form stable hydrates capable of being isolated in a crystalline form[34].

On treatment of the hydrates of fluorine-containing α-ketoacids with phosphorus pentoxide, the anhydrous α-ketoacids are formed[35]. The alkyl esters of carboxylic 2-alkoxyperfluoroacids have been synthesised in high yields (50–96%) by the reaction of the epoxy-derivatives of terminal fluoro-olefins with alcohols[32,33,48–51]. Methyl tetrafluoro-2-methoxypropionate is converted on treatment with sulphuric acid at 140 °C into methyl trifluoropyruvate[48]. However, the alkyl esters of higher carboxylic 2-alkoxyfluoroacids give rise under these conditions to a mixture of alkyl esters of carboxylic fluoro-α-ketoacids and the products of the decarbonylation of the esters of the corresponding carboxylic fluoroacids[51]:

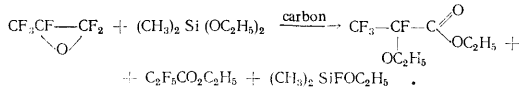
$$R_FCF(O)CF_2 \xrightarrow{ROH} R_FCF(OR)-C(=O)OR \xrightarrow{H_2SO_4} R_FCOCO_2R + RCO_2R + CO ;$$

R = alkyl, $R_F = CF_3$ (Ref.48; C_2F_5 (Ref.51); C_4F_9(Ref.51); $H(CF_2)_n$, where n = 2, 4 (Ref.51).

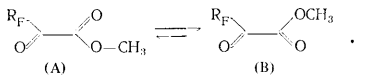
By reducing the reaction temperature to 100 °C or 60 °C (on replacing sulphuric acid with 20% oleum), it was possible to obtain the pure methyl esters of higher polyfluoro-α-ketoacids[51]. Methyl trifluoropyruvate has been obtained by treating the hydrate of trifluoropyruvic acid with diazomethane[48]:

$$CF_3-C(OH)(OH)-C(=O)OH \xrightarrow[-H_2O]{CH_2N_2} CF_3COCO_2CH_3 .$$

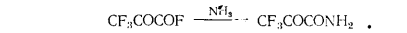
Ethyl 2-ethoxytetrafluoropropionate is formed when epoxyhexafluoropropane reacts with diethoxydimethylsilane[52]:



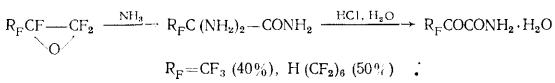
The study of the infrared spectra and dipole moments of solutions of the methyl esters of fluorine-containing α-ketoacids in carbon tetrachloride established that they exist in the form of equilibrium mixtures of the *trans*- and *cis*-conformers (A) and (B) with the *cis*-form predominating[53]. Pyruvate esters also consist of mixtures of the *cis*- and *trans*-conformers but with the *trans*-form predominating[54]. This difference is apparently due to the fact that the *cis*-forms of the esters of fluorine-containing α-ketoacids are less polar than the *trans*-forms, whereas in the case of the esters of hydrocarbon α-ketoacids the *trans*-form is less polar:



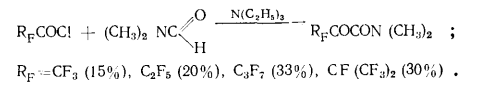
The amide of trifluoropyruvic acid has been obtained by the reaction of the corresponding acid fluoride with ammonia[38,40,43]:



Hydrolysis of the amides of carboxylic α,α-diaminofluoroacids leads to the hydrates of the amides of α-ketoacids[35]:



The synthesis of the dimethylamides of carboxylic fluoro-α-ketoacids by the reaction of the chlorides of carboxylic perfluoroacids with dimethylformamide in the presence of triethylamine has been described[55,56] (without triethylamine, the yields are much lower[55,56]):



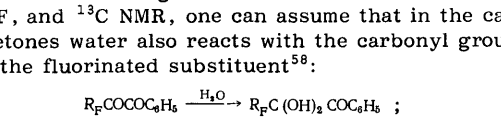
III. CHEMICAL REACTIONS

1. Anionoid Reactions

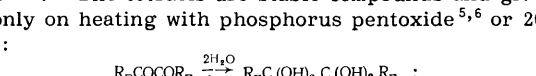
The majority of the studies in the chemistry of the fluorine-containing α-DCC have been associated with the investigation of anionoid reactions; they lead to different valuable α-DCC derivatives and make it possible to synthesise compounds with practically useful properties.

(a) The Interaction of α-DCC with Hydroxy-compounds

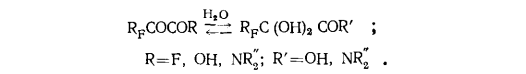
Fluorine-containing α-diketones with a fluoroalkyl substituent at one of the carbonyl groups and bis- α-diketones with an aliphatic fluorine-containing chain between the α-dicarbonyl groups combine with one molecule of water to form *gem*-ketodiols[10,57]. The site of addition has not been rigorously demonstrated but, by analogy with asymmetric β-diketones for which the addition of water to the carbonyl group linked to the fluorine-containing substituent has been established by ^1H, ^{19}F, and ^{13}C NMR, one can assume that in the case of the α-diketones water also reacts with the carbonyl group adjoining the fluorinated substituent[58]:



α-Diketones in which the fluoroalkyl groups are linked to both carbonyl groups combine with two water molecules to form tetraols[5,15]. The tetraols are stable compounds and give up water only on heating with phosphorus pentoxide[5,6] or 20% oleum[15]:

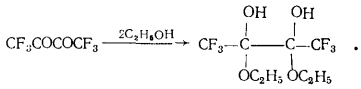


Fluorine-containing α-ketoacids[32,33,35,37], acid fluorides[37,38], and amides[35,55] also combine with a water molecule at the carbonyl group to form *gem*-dihydroxy-derivatives. The acid fluoride group is then hydrolysed to the carboxy-group:

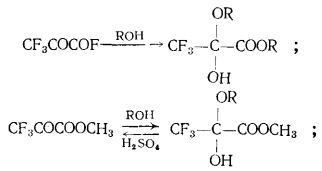


The derivatives of α,α-dihydroxy-acids are entirely stable compounds which give up water only on treatment with phosphorus pentoxide[47] or sulphuric acid[38], while the hydrocarbon α-ketoacids do not form stable hydrates.

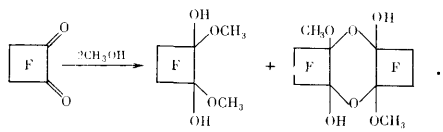
On interaction with ethanol, perfluorodiacetyl gives rise to a stable bishemiketal[14]:



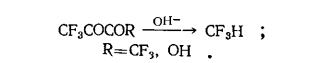
The methyl ester[37,60] and fluoride[61] of trifluoropyruvic acid react vigorously with alcohols, which leads to stable hemiketals. The hemiketal of methyl trifluoropyruvate can be decomposed by treatment with sulphuric acid[60]:



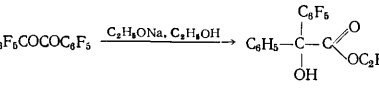
Perfluorocyclobutane-1,2-dione gives rise to a mixture of a bishemiketal and a dioxan on treatment with methanol[18]:



When aliphatic fluoro-α-diketones[14] and fluoro-α-ketoacids[33] are treated with aqueous alkali, they undergo the haloform decomposition with formation of trifluoromethane, like the fluorinated monoketones[59]:

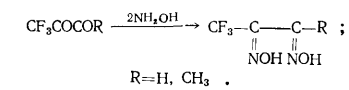


Fluorine-containing aromatic α-diketones in alcohol undergo a rearrangement in the presence of alkali metal alkoxides with migration of the pentafluorophenyl group[30]:



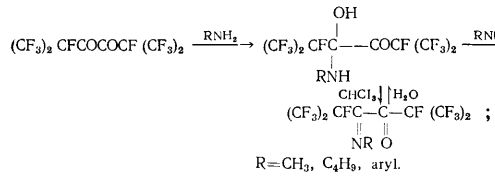
(b) The Interaction of α-DCC with Amino-Nucleophiles

The interaction of α-dicarbonyl compounds having one fluoroalkyl group with hydroxylamine yields dioximes, which readily form complexes with the nickel cation[8]:



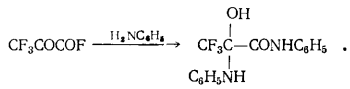
R=H, CH_3 .

Perfluoro-2,5-dimethylhexane-3,4-dione reacts with amines (with the reactants in proportions of 1:1) to form adducts which split off water on heating in chloroform and yield ketoimines[26]. However, on treatment with an excess of the amine, the α-diketone or its 1:1 adduct with the amine undergo the haloform decomposition with formation of 2-hydroperfluoropropane[26], which is apparently associated with the great stability of the leaving heptafluoroisopropyl anion:

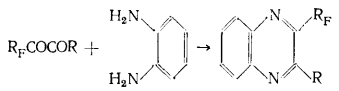


R=CH_3, C_4H_9, aryl.

When trifluoropyruvyl fluoride was allowed to react with aniline the anilide of α-hydroxy-α-phenylaminoperfluoropropionic acid was obtained[46]:

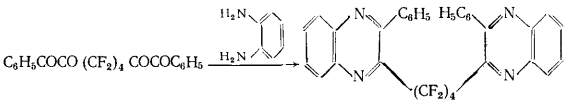


Fluorine-free α-diketones react with *o*-phenylenediamine (OPDA) to form 2,3-substituted quinoxalines[62]. This reaction has been studied vigorously also in the series of fluorine-containing α-DCC. Investigations showed that fluorine-containing α-diketones with fluoroalkyl substituents having a straight-chain structure and aromatic fluoro-substituents react with OPDA like the α-diketones of the hydrocarbon series and give rise to satisfactory yields of quinoxalines containing fluorinated substituents in the heterocyclic ring[5,8,10,14,30]. The reaction has been used successfully to identify fluorine-containing α-diketones, since the quinoxalines formed are readily purifiable crystalline substances.

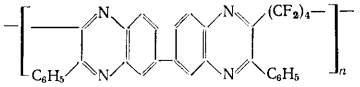


R_F=CF_3, R=H [8]; R_F=CF_3; R=CH_3 [8]; R_F=R=CF_3 [14]; R_F=C_3F_7, R=C_6H_5 [10]; R_F=R=C_3F_7 [5]; R_F=R=H$(CF_2)_4$ [5]; R_F=R=C_6F_5 [30] .

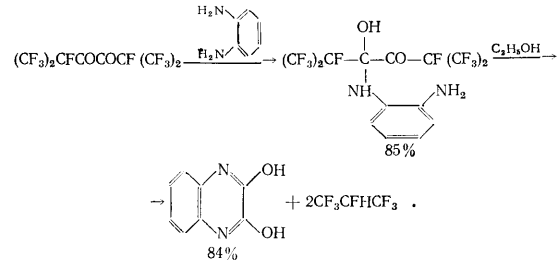
Fluorine-containing bis-α-diketones with an aliphatic fluorinated chain between the α-dicarbonyl groups also react with OPDA and give rise to bis-quinoxalines[57]:



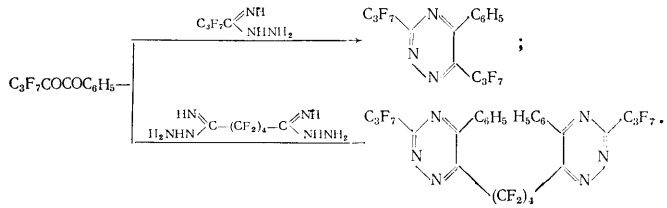
This synthesis has been used to obtain polyquinoxalines by the reaction of bis-α-diketones with tetra-aminobiphenyl[57]:



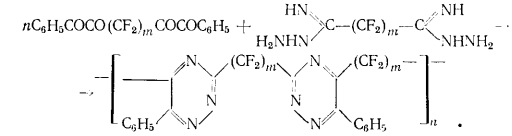
Perfluoro-2,5-dimethylhexane-3,4-dione reacts with OPDA in an unusual manner. Thus in acetonitrile at 0 °C the product is a 1:1 adduct, formed in 85% yield, which on heating in alcohol eliminates 2-hydroheptafluoropropane with formation of 2,3-dihydroxyquinoxaline[26,63]. This reaction pathway agrees also with the reactivity in relation to primary amines[26]; it too can be explained by the high stability of the leaving perfluoroisopropyl anion:



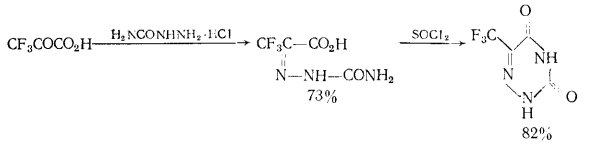
The interaction of fluorine-containing α-diketones with the imidoylhydrazides of carboxylic perfluoroacids, which leads to asymmetric triazines and bistriazines, has been described[10]:



If a bis-α-diketone and the bisimidoylhydrazide of a dicarboxylic perfluoroacid are introduced into the reaction, then fluorine-containing asymmetric polytriazines are formed[57]:



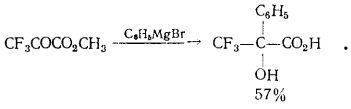
The interaction of trifluoropyruvic acid with semicarbazide hydrochloride in water yielded the semicarbazone of trifluoropyruvic acid, which is converted into 5-trifluoromethyl-6-azauracil on being refluxed with thionyl chloride[64]. The uracil has been used to synthesise nucleosides and nucleotides[64]:



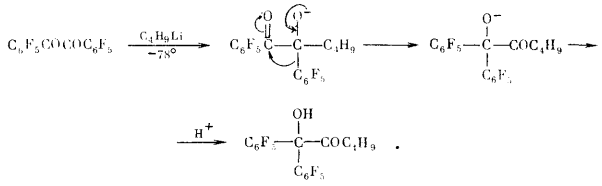
It follows from the available literature data on the interaction of α-DCC with hydroxy- and amino-nucleophiles that the introduction of fluorine into the α-DCC molecule reduces the electron density at the carbonyl carbon atoms, as a result of which they are capable of forming stable adducts via one or both carbonyl groups, which is not characteristic of fluorine-free α-DCC. The structure of the fluorinated substituent also has a considerable influence on the reactivity of the α-DCC. Thus the introduction of perfluoroisopropyl groups gives rise to an increased tendency of perfluoro-2,5-dimethylhexane-3,4-dione to undergo the haloform decomposition in the presence of bases[36,63].

(c) The Interaction of α-DCC with Organometallic Compounds

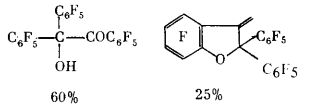
Treatment of methyl trifluoropyruvate with phenylmagnesium bromide and subsequent treatment of the reaction mixture with sulphuric acid and an alkali yielded α-hydroxy-α-trifluoromethyl phenylacetic acid[65]:



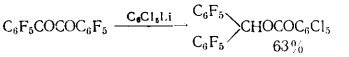
The reactions of alkyl- and aryl-lithium compounds with fluorine-containing aromatic α-diketones result in the formation of adducts, which undergo a rapid rearrangement with migration of the pentafluorophenyl group[30]. The structure of the final reaction products depends on the nature of the lithium derivative used. Thus, when decafluorobenzil was treated with butyl-lithium, 2-hydroxy-1,1-bis(pentafluorophenyl)-2-hexanone was obtained after acid hydrolysis[30]:



The interaction of decafluorobenzil with pentafluorophenyllithium leads to the formation of perfluoro-2-benzylbenzoin and perfluoro-2,2-diphenylbenzofuran-3-one (the latter is obtained as a result of the intramolecular nucleophilic substitution of the *ortho*-fluorine atom)[30]:



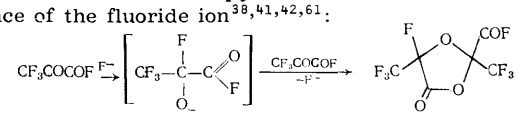
The reaction with pentachlorophenyl-lithium results in the formation of bispentafluorophenylmethyl pentachlorobenzoate[30]:



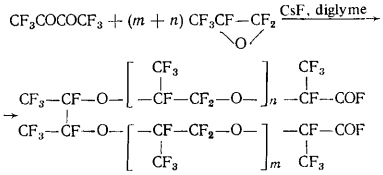
(d) Reactions with Participation of the Fluoride Anion

The reactions with participation of the fluoride anion are important for the chemistry of fluorinated carbonyl compounds[66,67]. However, hitherto only a limited number of reactions involving the fluoride ion in the series of fluorine-containing α-DCC are known.

The fluoride of trifluoropyruvic acid dimerises in the presence of the fluoride ion[38,41,42,61]:

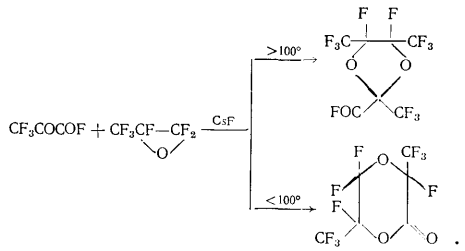


In the presence of caesium fluoride, perfluorodiacetyl reacts with epoxyhexafluoropropane in diglyme to form oligomeric products, both carbonyl groups of perfluorodiacetyl being involved in the reaction[69]:



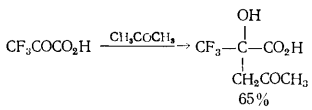
The acid fluoride groups of this oligomer were then converted into fluoroalkyl groups by reaction with elemental fluorine[69].

The interaction of epoxyhexafluoropropane with the fluoride of trifluoropyruvic acid and caesium fluoride leads to dioxolan or dioxan derivatives, depending on the temperature[38,40,43,44]:

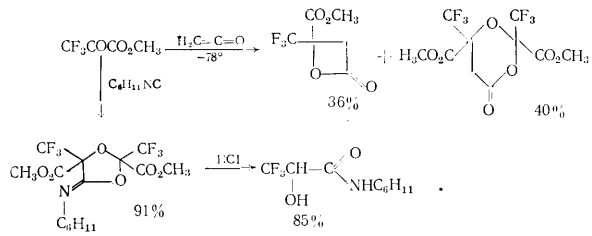


(e) Other Reactions of α-DCC with Participation of the Carbonyl Group

The condensation of trifluoropyruvic acid with acetone in water has been observed. The reaction in the formation of α-hydroxy-α-trifluoromethyl-γ-oxovaleric acid[32]:



When methyl trifluoropyruvate was allowed to react with keten, β-methoxycarbonyl-β-trifluoromethyl-β-propiolactone and 2,4-bis(methoxycarbonyl)-2,4-bis(trifluoromethyl)-1,3-dioxan-6-one were obtained[60]. Treatment of methyl trifluoropyruvate with cyclohexyl isocyanide in the same study[60] led to the isolation of a high yield of 5-cyclohexylimino-2,4-bis(methoxycarbonyl)-2,4-bis(trifluoromethyl)dioxolan, whose acid hydrolysis results in the formation of the cyclohexylamide of trifluorolactic acid:

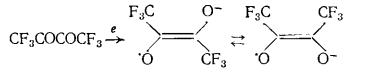


2. Oxidation-Reduction Reactions

The fluorine-free α-DCC are capable of undergoing oxidation-reduction reactions with participation of the carbonyl groups[70]. The oxidation-reduction reactions of polyfluoro-α-DCC with participation of the carbonyl groups (electrochemical reduction[71,72], interaction with metals and their salts[71,75], and interaction with phosphorus-containing reagents[77–86]) are also known.

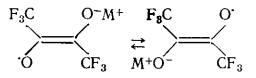
(a) Reduction of α-DCC

Like diacetyl, hexafluorodiacetyl is converted on electrochemical reduction in tetrahydrofuran (THF) (in the presence of an R_4N^+ cation) into a semidione radical-anion, which exists in the form of an equilibrium mixture of the *trans*- and *cis*-isomers (as shown with the aid of EPR).[71,72] The *trans/cis* ratio is 170 in THF and 120 in dimethyl sulphoxide (DMSO):[71,72]

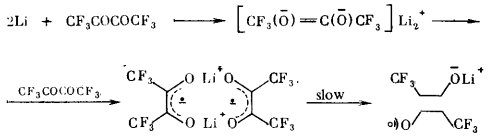


The *trans/cis* ratio for diacetyl in DMSO (in the presence of an R_4N^+ cation) is 35;[70] thus the introduction of fluorine shifts the equilibrium towards the *trans*-isomer.

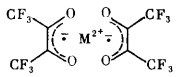
On interaction with alkali and alkaline earth metals in DMSO and THF, hexafluorodiacetyl is reduced to a radical-anion[71], which gives rise to several types of ion pairs with metal cations. If the counterions are Cs^+ and Rb^+, then the *trans*-isomer is formed preferentially (*trans/cis* = 150, DMSO, Rb^+; *trans/cis* > 200, THF, Cs^+);



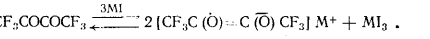
The mechanism of the interaction of hexafluorodiacetyl with lithium has been established by EPR[71]:



The formation of ion pairs on reduction of perfluorodiacetyl with alkaline earth metals (Ca, Sr, and Ba) in THF was demonstrated in the same study[71]:

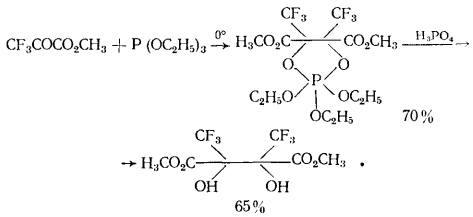


Hexafluorodiacetyl is also reduced on treatment with alkali metal iodides in solvents [in DMSO, hexamethylphosphoramide (HMP), and ethereal solvents] to a radical-anion, which forms ion pairs with alkali metal cations[72,74]. In DMSO and HMP the radical-anion exists mainly in the *trans*-form, (*trans/cis* > 100) and the ratio of the isomers is independent of the nature and the concentration of the counterion. The reduction takes place rapidly also in ethereal solvents when lithium iodide is used as the reductant[72], 1 : 1 ion pairs being formed. In the reaction involving treatment with sodium iodide, irradiation with light from a mercury lamp in a quartz cell is required[72]:



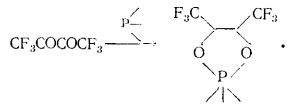
(b) The Interaction of α-DCC with Fluorine-Containing Reagents

The product of the reaction of methyl trifluoropyruvate with triethyl phosphite is a 2 : 1 adduct consisting of a cyclic phosphorane whose hydrolysis gives rise to a pinacone[60]:

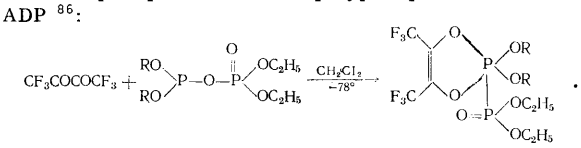


It is of interest that trifluoropyruvate reacts via one carbonyl group, like hexafluoroacetone, and not a diketone in which both carbonyl groups are reduced with formation of 1,3,2-dioxaphospholens[76].

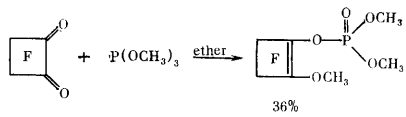
Numerous studies have been devoted to the investigation of the reactions of hexafluorodiacetyl with phosphorus(III) derivatives of different structure. A series of cyclic 1,3,2-dioxaphospholens have been obtained in this way with high yields[77–86]:



For example, hydroxyphosphoranes have been synthesised in this way from hexafluorodiacetyl and mixed anhydrides of phosphoric and phosphorous acids, which are models of the hypothetical intermediates formed in the addition of nucleophiles to the phosphorus atom in polyphosphates such as ATP and ADP [86]:

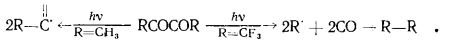


In reactions with phosphorus(III) derivatives, fluorine-containing aliphatic α-diketones behave mainly analogously to fluorine-free α-diketones[87]. It is of interest that the reaction of perfluorocyclobutane-1,2-dione with trimethyl phosphite yields dimethyl 3,3,4,4-tetrafluoro-2-methoxycyclobut-1-enyl phosphate[88].

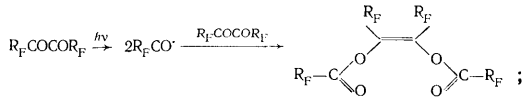


3. Radical Reactions

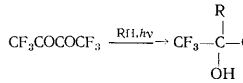
When hexafluorodiacetyl is irradiated with ultraviolet light in the vapour phase, it decomposes into trifluoromethyl radicals and carbon monoxide[89,90]. Irradiation of diacetyl at room temperature leads to the formation in the primary photochemical step of two acyl radicals, which then undergo a number of reactions[91]:



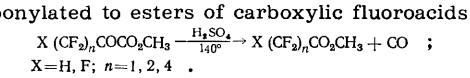
The study of the photolysis of hexafluorodiacetyl and tetrafluorodiacetyl in the liquid phase showed that the trifluoroacetyl radicals arising in the first stage can interact with the initial diketones to form diacetyl derivatives of enediols[4]:



When hexafluorodiacetyl is exposed to ultraviolet light in the presence of hydrocarbons, ketoalcohols and small amounts of CO are formed[90]:



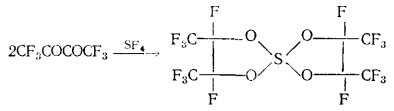
When the methyl esters of polyfluoro-α-ketoacids are heated above 140 °C in the presence of sulphuric acid, they are decarbonylated to esters of carboxylic fluoroacids[51]:



One must note that the available literature data are insufficient to reach conclusions concerning the pathways followed in the primary photochemical processes in the photolysis of fluorine-containing α-DCC.

4. Interaction with Sulphur Tetrafluoride

The unusual formation of a spirosulphuran (in a quantitative yield) on interaction of hexafluorodiacetyl with sulphur tetrafluoride (reactant ratio 2:1) has been observed[92]. The compound obtained is a stable crystalline substance whose structure has been determined by ^{19}F and ^{13}C NMR and by X-ray diffraction[92]. It is of interest that products of the fluorination of the carbonyl groups of hexafluorodiacetyl were not detected in the reaction mass, whereas in the series of hydrocarbon α-DCC such compounds are formed in high yields[92–96]:



IV. APPLICATIONS

Perfluorodiacetyl has been recommended as an antibacterial and fungicidal agent and also for imparting water- and dirt-repellent properties to cotton textiles[13]. The use of perfluorodiacetyl as a photoinitiator in radical polymerisation and also for the treatment of fabrics has been patented[16].

The fluoride of trifluoropyruvic acid and its cyclic dimer are used as soil fumigants and insecticides, which evolve hydrogen fluoride on contact with water[39,41].

The amide of trifluoropyruvic acid can be used as a dispersing agent and exhibits surface-active properties[41].

The fluoride of trifluoropyruvic acid serves as the starting material for the synthesis of perfluoro-derivatives of cyclic dioxans and dioxolans, which are chemically inert and thermally stable solvents[41]. This compound is used as the starting material for the synthesis of monomers and then polymers employed as adhesive films and films with irreversible gas permeability[45]. The latter can be used to separate different gases.

Glyoximes, which are used as reagents for nickel(II), have been obtained from 1,1,1-trifluorobutane-2,3-dione and trifluoromethylglyoxal[8].

Polymers with quinoxaline and triazine rings in the chain have been obtained from fluorine-containing bis-α-diketones having an aliphatic fluorine-containing chain between the α-dicarbonyl groups[57]. Fluorine-substituted benzils are used as the starting materials for the synthesis of anaesthetics and antihistamine preparations[97].

Analysis of the present state of research into the chemistry, properties, and applications of fluorine-containing α-dicarbonyl compounds (α-diketones, α-ketoaldehydes, α-ketoacids, and their derivatives) permits the conclusion that methods have been developed in recent years for their synthesis and their properties of practical value have been discovered. However, hitherto many problems of the chemistry of α-dicarbonyl compounds have been virtually uninvestigated. Thus there are almost no data on their reactions with electrophiles and few studies have been made on the radical processes and physicochemical properties of substances in this series; such studies would yield additional information about the influence of fluorine atoms on the reactivity of organic compounds.

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