

Synthetic Methods and Reactions. 46.¹ Oxidation of Organic Compounds with Uranium Hexafluoride in Haloalkane Solutions

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Abstract: Uranium hexafluoride was found to be an active, yet selective, oxidizing agent for organic compounds. It is very effective in oxidizing methyl ethers, benzylic bromides, *N,N*-dimethylalkylamines, hydrazones, benzylic alcohols, and oximes to carbonyl compounds. Benzyl and benzhydryl ethers were cleaved to the parent alcohols. The intermediate oxonium ions formed in the oxidation of ethers were trapped with dithiols to yield 1,2-dithiolanes and 1,3-dithianes. The stability of the intermediate complexes was demonstrated by trapping experiments with *n*-butyllithium. Fluorination reactions with UF₆ were also studied.

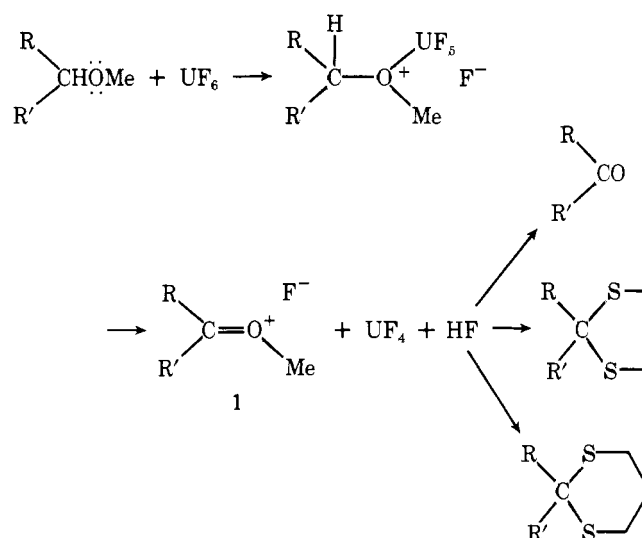
Uranium hexafluoride, depleted of fissionable ²³⁵U, contains less than 0.20% ²³⁵U, is a colorless compound which sublimates at 56.5 °C, with a vapor pressure of 120 mm at room temperature. As a by-product of enrichment plants it is abundantly available. Although historically UF₆ has been found to be a technologically difficult compound to handle in large quantities, it is easily transferred in relatively stable chlorofluorocarbons (Freon) or chlorohydrocarbon (methylene chloride or chloroform) solutions which do not attack glass. Conventional laboratory housekeeping and safety procedures normally used in the handling of any highly fluorinated inorganic compound and low radiation level radioisotope were found to be sufficient for routine experimentation. All experiments were performed in an efficient fume hood. Radiation levels were routinely checked but always found to be minimal.

The reactions of UF₆ with organic compounds have been previously unexplored. We have found UF₆ to be an efficient reagent for effecting the facile and selective oxidation of organic molecules. As these reactions carried out in haloalkane solutions generally are convenient, high-yield processes giving pure products the synthetic utility of the uranium hexafluoride oxidations is considerable and warranted a thorough investigation.

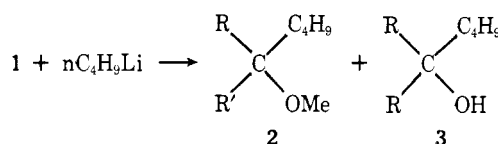
Results and Discussion

Oxidative Cleavage of Ethers. The oxidative cleavage of ethers is of increasing preparative use. Both Hg(II)² and Ag(II)³ will oxidize aryl methyl ethers to quinones. Trityl fluoroborate was effectively used by Barton to oxidatively cleave ketone acetals and ethers.^{4a} Jung has extended the use of trityl salts to oxidatively cleave silyl ethers,^{4b,c} while Doyle has developed the use of trityl salts to cleave trityl ethers.^{4d} Mukaiyama,^{5a,b} Ogawa,^{5c} and Ueno^{5d} have developed the oxidative cleavage of stannyl ethers. In our own laboratories, nitrosonium salts have been effectively used to cleave methyl ethers via hydride abstraction.

Ethers undergo oxidative cleavage upon addition to a Freon or chloroform (methylene chloride) solution of UF₆. The direction of the cleavage reaction is predictable, enhancing the utility of ethers (such as benzyl or benzhydryl) as protecting groups for alcohols. The oxidation of methyl ethers was regioselective. The reaction was considered to proceed through an initial complex of UF₆, a weak Lewis acid,⁶ with the non-bonded electrons of oxygen. Following the loss of a proton, U(VI) was reduced to U(IV) as UF₄ was displaced from the intermediate oxonium ion. The intermediate oxonium species **1** may be reacted with a variety of nucleophiles: water, 1,2-

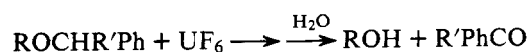


ethanedithiol or 1,3-propanedithiol to yield, respectively, ketones or aldehydes, 1,2-dithiolanes, and 1,3-dithianes (see Table III). The existence of **1** has been demonstrated by trapping with *n*-butyllithium to form both the butylated methyl ether **2** and the corresponding alcohol **3**. The stability of the



intermediate oxonium ion is sufficient to permit the exchange of solvent necessitated by the use of *n*-butyllithium.

Benzyl and benzhydryl ethers are cleaved to the parent alcohols and benzaldehyde or benzophenone, respectively. The



cleavage reaction may be successfully effected in the presence of other functionalities such as nitro groups, where hydrogenolytic procedures⁷ would be untenable (see Tables IV and V). The cleavage of ethers, in the course of deprotecting alcohols, has been well reviewed⁸ and generally requires the use of aggressive reagents and conditions.

UF₆ was not effective in cleaving allyl ethers, as the direction of cleavage was not predictable. The use of UF₆ to oxidatively cleave methyl ethers implies the use of methyl ethers as carbonyl synthons. Furthermore, trapping of the oxonium inter-

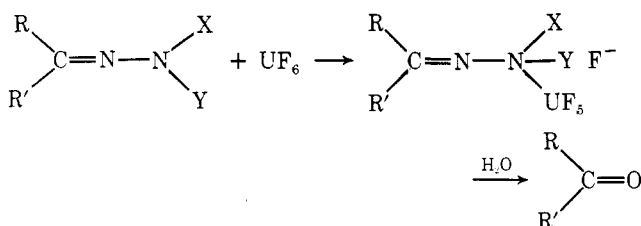
Table VIII. Oxidation of Hydrazones to Carbonyl Compounds with UF₆

carbonyl product	yield, %	carbonyl product	yield, %
<i>N,N</i> -Dimethylhydrazone		Tosylhydrazone	
propiophenone	49	acetophenone	96
benzaldehyde	41	isobutyrophenone	95
2-heptanone	56	cycloheptanone	95
4-methylcyclohexanone	69	cyclooctanone	76
4- <i>tert</i> -butylcyclohexanone	50	2-norbornanone	56
cyclohexanone	46	4-heptanone	66

Table IX. Oxidation of Carboxylic Acid Hydrazides with UF₆

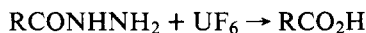
acid hydrazide	yield, %	acid hydrazide	yield, %
benzoic	30	terephthalic	9
<i>m</i> -nitrobenzoic	25	phenylacetic	34
<i>o</i> -nitrobenzoic	14	cyclohexane-carboxylic	55

Aqueous workup of the reaction of tosyl- or *N,N*-dimethylhydrazones with uranium hexafluoride regenerates the parent carbonyl compounds in good yield. Data are summarized in Table VIII. Although the mechanism of the reaction is not clear, it may proceed via hydrolysis of the intermediate ammonium salt, 4.



A variety of methods for the regeneration of carbonyl compounds from tosylhydrazones are known, such as by Pb(OAc)₄,¹⁷ NaOMe-Me₂SO,¹⁸ TiCl₃,¹⁹ NaOCl,²⁰ NBS-MeOH,²¹ and acetone.²² The *N,N*-dimethylhydrazone protecting group may be removed with MeI-OH⁻,²³ NaIO₄,^{15b} and Cu²⁺.²⁴ The regeneration of carbonyl compounds with UF₆, especially with tosylhydrazones, is as efficient as the other methods cited and could well be the method of choice.

Oxidation of Carboxylic Acid Hydrazides. Carboxylic acid hydrazides are oxidized to carboxylic acids by Ce(NH₄)₂(NO₃)₆,²⁵ and Pb(OAc)₄,²⁶ and are oxidized to aldehydes by K₃Fe(CN)₆.²⁷ Carboxylic acid hydrazides may be oxidized in fair yield with uranium hexafluoride (see Table IX).



The reaction proceeds slowly, hindered in large part by the poor solubility of the carboxylic acid hydrazides in the trichlorotrifluoroethane or chloroform solution. Consequently little can be said about the reaction.

Oxidation of Oximes. The preparation and degradation of oximes have been extensively studied. Oximes are generally prepared from the parent carbonyl compound. However, preparations not involving simple derivatization are also known, such as nitrosation of an active methylene group,²⁸ nitrosation of an α -halocarbonyl compound,²⁹ or condensation of a nitroalkene with an aldehyde.³⁰ The regeneration of the carbonyl function from oximes thus affords a ready ketone synthesis.

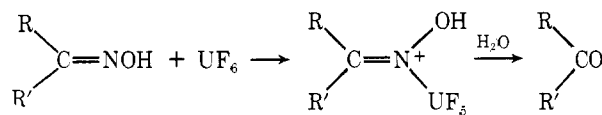
Table X. Oxidative Cleavage of Oximes with UF₆

oxime	yield, %	oxime	yield, %
cyclohexanone	64	benzaldehyde	50
4-heptanone	62	4-methoxybenzaldehyde	31
3-cyclohexene-carboxaldehyde	16	acetophenone	79

Table XI. Oxidation of Tertiary Amines to Carbonyl Compounds with UF₆

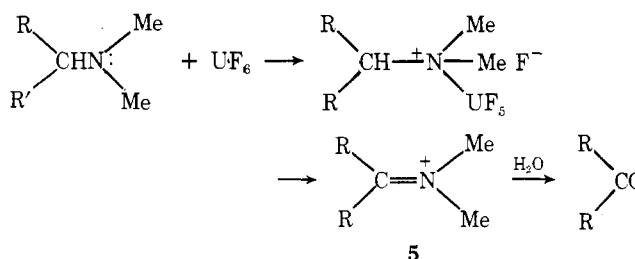
<i>N,N</i> -dimethyl-amine	carbonyl compound	yield, %
<i>n</i> -octyl	octaldehyde	33
<i>n</i> -decyl	decylaldehyde	63
cyclohexyl	cyclohexanone	16
adamantyl	adamantanone	21
4- <i>tert</i> -butyl-cyclohexyl	4- <i>tert</i> -butylcyclohexanone	70

Numerous methods are known for the regeneration of carbonyl compounds, including recent methods by Olah and Ho which are selective.³¹ It has now been found that chloroform solutions of oximes are oxidized by UF₆ to the corresponding carbonyl compound in fair to moderate yield (see Table X). The oxidation of oximes, however, was considerably slower than the reaction of hydrazones or ethers.



Oxidation of Tertiary Amines. The oxidation of amines has received considerable attention. The best known oxidative transformation of tertiary amines is the Sommelet reaction.³² Additionally, *N*-alkylmorpholine derivatives are oxidized by Hg(OAc)₂,³³ as are *N,N*-dialkylamines.³⁴ Tertiary amines may be oxidized by Cr^{VI},³⁵ and MnO₂,³⁶ whereas enamines are readily oxidized by Ti(OAc)₃,³⁷ as well as FeCl₃.³⁸

The oxidation of tertiary amines with uranium hexafluoride may be viewed as the nitrogen analogue of the oxidation of ethers. When *N,N*-dimethylamines are treated with UF₆, they are, upon hydrolysis, regioselectively oxidized to the corresponding carbonyl compound (see Table XI). The reaction is suggested to proceed through an intermediate iminium ion 5.



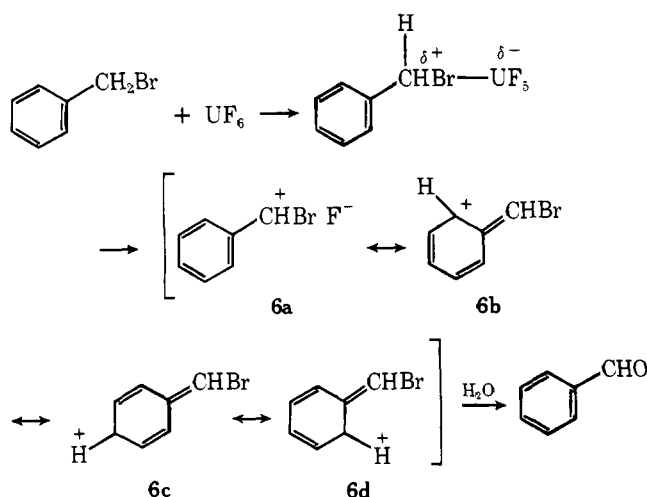
The oxidation of amines with UF₆ may be advantageous in that it proceeds well at room temperature and in nonaqueous media.

Reaction of Benzylic Bromides. The ability of uranium hexafluoride to oxidize organic functionalities involves complex formation between UF₆ and a nonbonded electron pair of the heteroatom in each reaction examined. Benzylic bromides expectedly also are excellent substrates and were oxidized via aqueous quenching to carbonyl compounds (see Table XII).

Table XII. Oxidation of Benzylic Bromides to Carbonyl Compounds with UF₆

bromide	carbonyl compd	yield, %
benzyl	benzaldehyde	24
diphenylmethyl	benzophenone	69
9-fluorenyl	fluorenone	75

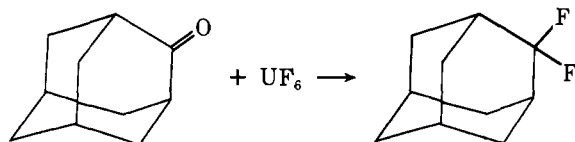
The reaction is suggested to involve the loss of a benzylic proton to form an intermediate brominium ion where the charge may be delocalized into the neighboring phenyl ring. Necessarily **6a** must be the major contributor, as on quenching benzalde-



hyde is formed. Oxidation, however, of either alkyl bromides or iodides with uranium hexafluoride was unsuccessful.

As a corollary to the above procedure, the oxidation of benzylic and alkyl bromides was attempted in the presence of an equivalent amount of ceric ammonium nitrate, Ce(NH₄)₂(NO₃)₆, a powerful 1-equiv oxidant.³⁹ Although initially insoluble, as the reaction proceeded ceric ammonium nitrate dissolved. Upon aqueous quenching, both nitrate esters and nitroalkanes were isolated. The data are summarized in Table XIII. The yield of nitroproducts was greatest with the benzylic halides, diminishing to almost exclusive nitrate ester formation in the reaction of the alkyl halides. The reaction is presumed to involve ligand exchange between Ce(NH₃)₆(NO₃)₆ and the UF₆-bromohydrocarbon complex.

Deoxygenative Fluorination of Adamantanone. In the course of the study of the reactivity of uranium hexafluoride with functionalized organic compounds, fluorination was infrequently observed. However, 2-adamantanone was fluorinated with a twofold excess of UF₆ in trichlorotrifluoromethane solution at 0 °C to form 2,2-difluoroadamantanone in 41% yield. Other nonenolizable ketones such as benzophenone and fluorenone failed to react.



Conclusions

It was found that uranium hexafluoride is an effective reagent for oxidizing a variety of organic functional groups. The reactions were easily carried out in haloalkane solvents generally at or below room temperature without specific precautions against hydrolysis of the reagent. Fluorination by UF₆ was observed in the reaction of aldehydes and adamantanone. The versatility of uranium hexafluoride and the facility with

Table XIII. Oxidation of Alkyl Bromides with UF₆ in the Presence of Ceric Ammonium Nitrate

bromide	product	yield, %
2-octyl	2-octyl nitrate	93
1-octyl	1-octyl nitrate	95
1-adamantyl	1-adamantyl nitrate	74
cyclohexyl	cyclohexyl nitrate	83
2-norbornyl	2-norbornyl nitrate	92
9-fluorenyl	9-nitrofluorene	12
	9-fluorenyl nitrate	11
2-methylbenzyl	2-methyl- α -nitrotoluene	56
4-bromobenzyl	4-bromobenzyl nitrate	32
	4-bromo- α -nitrotoluene	29

which it effects oxidative transformations make it a valuable new reagent.

Experimental Section

General. Capillary melting points were determined with either a Mettler FP-1 melting-point apparatus, a Gallenkamp melting-point apparatus, or a Fisher-Johns melting-point apparatus and are reported uncorrected. Boiling points were read from a thermometer in the distillation head and are reported uncorrected. Proton magnetic resonance (¹H NMR) spectra were recorded on either a Varian A60-A or A56/60 spectrometer. Infrared spectra (IR) were recorded on a Beckman IR-10 instrument either as thin films or as solutions in CCl₄. Mass spectra were obtained using a du Pont Model 21-4903 GC-MS spectrophotograph equipped with a 21-094 MS data system. The instrument was calibrated before each spectrum. The spectra were obtained at source temperatures of 160–180 °C at 70 eV. Carbonyl compounds were generally characterized wherever possible as their 2,4-dinitrophenylhydrazones. Alcohols were characterized as their 3,5-dinitrobenzoates. Elemental microanalyses were performed by Galbraith Laboratories, Inc., Knoxville, Tenn.

Methyl Ethers. Methyl ethers were generally prepared by the method of McKillop and Ford.⁴⁰

Phenethyl Methyl Ether. To 9.2 g (0.05 mol) of (2-bromoethyl)-benzene (Aldrich) dissolved in 100 mL of absolute methanol in a magnetically stirred 250-mL round-bottom flask equipped with a reflux condenser was added 18.7 g (0.05 mol) of mercuric fluoroborate in 15 mL of aqueous fluoroboric acid, prepared as follows. Yellow mercuric oxide (10.8 g, 0.05 mol) was added with stirring to 15 mL of 40% aqueous fluoroboric acid heated on a steam bath. When the yellow color of mercuric oxide disappeared, the cloudy solution was immediately used. After stirring with heating under reflux for 12 h, the reaction mixture was filtered and the filtrate quenched with 150 mL of water. After extraction of the aqueous solute with 200 mL of pentane in three portions, the combined extracts were washed with water and dried over anhydrous magnesium sulfate. Phenethyl methyl ether (1.81 g, 26% yield) was distilled, bp 91 °C (10 mm), from the crude product obtained by evaporation of the solvent.

***o*-Methylbenzyl Methyl Ether.** To 9.2 g (0.05 mol) of α -bromo-*o*-xylene (Aldrich) dissolved in 100 mL of absolute methanol in a magnetically stirred 250-mL round-bottom flask equipped with a reflux condenser was added 25 g (0.05 mol) of mercuric triflate in 75% aqueous trifluoromethanesulfonic acid prepared as follows. Yellow mercuric oxide (10.9 g, 0.05 mol) was added with stirring to 15 mL of trifluoromethanesulfonic acid prepared as follows. Yellow mercuric oxide (10.9 g, 0.05 mol) was added with stirring to 15 mL of trifluoromethanesulfonic acid (3 M) and 5 mL of water. The mixture was heated on a steam bath until the reaction of mercuric oxide was complete, as indicated by the disappearance of the characteristic yellow color of HgO. After stirring with heating under reflux for 12 h, the reaction was quenched with 150 mL of water and extracted with 200 mL of pentane in three portions. The combined extracts were washed with water and dried over anhydrous magnesium sulfate. *o*-Methylbenzyl methyl ether (2.75 g, 38% yield) was distilled, bp 53 °C (2 mm), from the crude oil obtained by evaporation of the solvent: IR (neat) 1110 (s, ROR) cm⁻¹.

Benzyl and Benzhydryl Ethers. Benzyl and benzhydryl ethers were generally prepared by the Williamson synthesis.⁴¹

Benzhydryl Methyl Ether. To 6.2 g (0.034 mol) of benzhydryl

(Aldrich) dissolved in 100 mL of absolute methanol in a 250-mL round-bottom flask equipped with reflux condenser was added 2 drops of trifluoromethanesulfonic acid. After heating under reflux for 48 h, the reaction was quenched with 150 mL of water and extracted with 200 mL of pentane in four portions. After washing with water and drying over anhydrous magnesium sulfate, the solvent was evaporated. Filtration of the crude oil dissolved in benzene through adsorbent alumina yielded 4.9 g (74% yield) of benzhydryl methyl ether.

***N,N*-Dimethylhydrazones.** *N,N*-Dimethylhydrazones were prepared by adding 0.1 mol of unsymmetrical *N,N*-dimethylhydrazine to 0.05 mol of carbonyl compound in a 100-mL round-bottom flask equipped with reflux condenser. After heating under reflux for ca. 12 h, the excess *N,N*-dimethylhydrazine was removed by rotary evaporation. The product oil was distilled to yield the product *N,N*-dimethylhydrazone.

***p*-Toluenesulfonylhydrazones.** *p*-Toluenesulfonylhydrazones were prepared in the usual manner.⁴¹

Carboxylic Acid Hydrazides. Carboxylic acid hydrazides were prepared in the usual manner by reaction of the ester with hydrazine hydrate.⁴¹

***N,N*-Dimethylalkylamines.** *N,N*-Dimethylalkylamines were prepared by the method of Icke, Wisegarver, and Alles.⁴² To 50 mL of 80% formic acid in a magnetically stirred 100-mL round-bottom flask equipped with a reflux condenser was slowly added 0.05 mol of alkyl amine followed by 8.1 g of 37% aqueous formaldehyde. The reaction was heated to 80–90 °C until gas evolution commenced. After 20 min without heating, the flask was again heated under reflux for 8–12 h. To the cooled solution was added ca. 100 mL of 4 N HCl, and the solution was rotary evaporated to yield a yellow oil. The free amine was liberated by the addition of 50–75 mL of water followed by 50 mL of 18 N NaOH solution. The organic phase was separated and the basic phase was extracted with 50 mL of benzene in two portions. The combined organic phases were washed with water and dried over anhydrous magnesium sulfate. Evaporation of the solvent yielded the *N,N*-dimethylamine, characterized by IR as being free of primary amine, which was used without further purification.

***N,N*-Dimethyladamantylamine.** *N,N*-Dimethyladamantylamine was prepared by the method of Borch.⁴³ To 3.24 g (0.04 mol) of dimethylamine hydrochloride dissolved in 25 mL of methanol in a 100-mL round-bottom flask was added 1.5 g of potassium hydroxide pellets. Upon dissolution of the KOH, 4.5 g (0.03 mol) of 2-adamantanone was added and the solution was stirred for 15 min. Sodium cyanoborohydride (0.63 g, 0.01 mol) was then added to 10 mL of methanol. After 30 min, ca. 2.0 g of KOH was dissolved in the reaction mixture. The reaction mixture was concentrated by rotary evaporation, and following the addition of 10 mL of aqueous sodium chloride the organic phase was separated. The aqueous phase was extracted with 30 mL of diethyl ether in two portions. The combined aqueous phases were extracted with 50 mL of 6 M HCl. The acid extracts were washed with diethyl ether and then cooled to 0 °C and basified with KOH. Extraction of the basic phase with 75 mL of diethyl ether in two portions, which were combined and washed with water and aqueous sodium chloride, yielded 2.20 g (41% yield) of *N,N*-dimethyladamantylamine: IR (neat) 2780 and 2830 (m, -CH_3) cm^{-1} .

Oximes. Oximes were prepared in the usual manner by reaction of hydroxylamine hydrochloride with a basic solution of the aldehyde or ketone. The crystalline derivatives were filtered, washed with cold methanol, and reacted without further purification.

Sublimation and Storage of Uranium Hexafluoride. UF_6 (obtained through DOE) was conveniently sublimed from the shipping cylinder under reduced pressure into a cold trap. Care need be taken only to ensure that blockage of the line does not occur, as UF_6 effects hydraulic rupture readily. The sublimed material generally formed colorless plates. Uranium hexafluoride was safely stored in Teflon TFE bottles at -20 °C indefinitely without noticeable hydrolysis. Halocarbon solutions were prepared in a dry box.

Oxidative Cleavage of Methyl Ethers to Carbonyl Compounds with UF_6 . In a typical procedure, an ice-cooled magnetically stirred solution of 3.52 g (0.01 mol) of UF_6 in 100 mL of 1,1,2-trichlorotrifluoroethane (Freon 113) was reacted with 1.28 g (0.01 mol) of cycloheptyl methyl ether, added dropwise in 10 mL of the same solvent. The reaction was allowed to proceed for 1 h and was quenched with 25 mL of water and the resultant uranyl salts were filtered. The organic phase was separated and dried over anhydrous magnesium sulfate. Evaporation of the solvent yielded 0.93 g (83% yield) of pure cycloheptanone: IR

(neat) 1700 (s, C=O) cm^{-1} . The compound was characterized as the 2,4-dinitrophenylhydrazone, mp 145 °C (lit. mp 148 °C).

Oxidative Cleavage of Methyl Ethers to 1,2-Dithiolanes with UF_6 . In a typical procedure, 1.22 g (0.01 mol) of benzyl methyl ether (Eastman) dissolved in 10 mL of Freon 113 was added dropwise to 5.2 g (0.015 mol) of UF_6 dissolved in 100 mL of the same solvent at 0 °C. After stirring at 0 °C for 30 min, followed by stirring for 15 min at room temperature, 0.96 g (0.012 mol) of 1,2-ethanedithiol was added to the reaction mixture. After suction filtration of the uranyl salts, the organic phase was washed with 10% aqueous NaOH to remove unreacted ethanedithiol and after drying the organic phase was concentrated to yield 0.96 g (53% yield) of benzyl-1,2-dithiolane.

Oxidative Cleavage of Methyl Ethers to 1,3-Dithianes with UF_6 . **Method A.** In a typical procedure, 0.85 g (0.05 mol) of *n*-decyl methyl ether dissolved in 10 mL of Freon 113 was added dropwise to 3.52 g (0.01 mol) of UF_6 dissolved in 40 mL of the same solvent at 0 °C. After stirring at 0 °C for 30 min, followed by stirring at room temperature for 15 min, the solvent was completely evaporated under reduced pressure. To the dried solids was added 2.0 g (0.02 mol) of 1,3-propanedithiol in 30 mL of nitromethane. After stirring for 1 h, the reaction was quenched with 50–75 mL of water. The product was extracted with 150 mL of benzene in three portions. The organic phase was washed with 10% aqueous sodium bicarbonate and water and was dried over anhydrous magnesium sulfate. Chromatography on adsorbent alumina with benzene of the crude oil obtained by evaporation of the solvent yielded 0.92 g (75%) of *n*-decyl-1,3-dithiane.

Method B. The procedure described above was followed without the evaporation of the solvent. 1,3-Propanedithiol (1.59 g, 0.015 mol) was added directly to the reaction mixture. After 1 h the uranyl salts were suction filtered, and the organic phase was washed with 10% aqueous sodium hydroxide and dried over anhydrous magnesium sulfate. Evaporation of the solvent yielded 0.77 g (63% yield) of *n*-decyl-1,3-dithiane.

Reaction of Intermediate Oxonium Ion 1 with *n*-Butyllithium. To 3.52 g (0.01 mol) of UF_6 dissolved in 60 mL of Freon 113 in a three-necked 250-mL round-bottom flask was added at 0 °C with stirring 1.22 g (0.01 mol) of benzyl methyl ether (Eastman) in 5 mL of the same solvent. After stirring for 30 min at 0 °C and 15 min at room temperature, the solvent was removed under reduced pressure. To the solid material remaining was added 50 mL of *n*-pentane, followed at -20 °C with stirring by 13 mL of 2.4 M solution of *n*-butyllithium in hexane (Ventron) (0.03 mol). After 1 h at -20 °C, the reaction mixture was warmed to room temperature and 50 mL of saturated ammonium chloride solution was added. The organic phase was separated and the aqueous phase was extracted with 100 mL of pentane in three portions. The combined organic phases were washed with water and dried in the usual manner. Evaporation of the solvent yielded 1.56 g of a crude oil which was purified by chromatography on ca. 30 g of Merck aluminum oxide 90 active. Elution with 200 mL of benzene yielded 0.23 g (13% yield) of 1-phenyl 1-pentylmethyl ether: IR (neat) 1105 (s, ROMe) 2950 (s, $\text{-CH}_2\text{-}$) cm^{-1} . Subsequent elution with 250 mL of chloroform yielded 1.23 g (75% yield) 1-phenyl-1-pentanol: IR (neat) 3370 (s, -OH), 2950 (s, $\text{-CH}_2\text{-}$) cm^{-1} .

Oxidative Cleavage of Benzyl Ethers to Alcohols with UF_6 . To 5.2 g (0.015 mol) of UF_6 dissolved in 100 mL of trichlorofluoromethane (Freon 11) at 0 °C was dropwise added 0.96 g (0.005 mol) *n*-hexylbenzyl ether in 10 mL of the same solvent. After stirring at 0 °C for 1 h, the reaction was warmed to room temperature and quenched with 75 mL of water. The uranyl salts were separated by suction filtration through Celite, and the organic phase was separated. After washing with water and drying in the usual manner, evaporation of the solvent yielded 0.4 g of the aldehyde-alcohol mixture. The alcohol was separated by chromatography on alumina with initially 200 mL of benzene followed by 200 mL of chloroform. Evaporation of the chloroform eluent yielded 0.20 g (44% yield) of *n*-hexyl alcohol and 3,5-dinitrobenzoate, mp 60–64 °C (lit. mp 61 °C).

Oxidative Cleavage of Benzhydryl Ethers to Alcohols with UF_6 . To 5.2 g (0.015 mol) of UF_6 dissolved in 100 mL of Freon 113 at 0 °C was dropwise added 1.50 g (0.005 mol) of *n*-octyl benzhydryl ether in 10 mL of the same solvent. After stirring at 0 °C for 1 h the reaction was warmed to room temperature and quenched with 75 mL of water. The usual workup followed by chromatography on alumina with benzene and chloroform yielded 0.20 g (31% yield) of 1-octanol [IR (neat) 3400 (s, -OH) cm^{-1}] and 3,5-dinitrobenzoate [mp 60–62 °C (lit. mp 62 °C)].

Oxidation of Benzylic Alcohols to Carbonyl Compounds with UF₆. To 3.52 g (0.01 mol) of UF₆ dissolved in 100 mL of Freon 113 was added 1.5 g (0.01 mol) of 1-phenyl-2-methyl-1-propanol slowly with vigorous stirring. After stirring at room temperature for 1 h, the reaction was quenched with 75 mL of water. Following filtration of the uranyl salts, the organic phase was separated, washed with water, and dried over anhydrous magnesium sulfate. Evaporation of the solvent yielded a crude oil which was purified by chromatography on alumina to yield 1.01 g (69% yield) of isobutyrophenone.

Oxidation of Benzyl Alcohol to Benzaldehyde and Benzoyl Fluoride with UF₆. To 5.2 g (0.015 mol) of UF₆ dissolved in 100 mL of Freon 113 was added dropwise at 0 °C under nitrogen 1.06 g (0.01 mol) of benzyl alcohol in 10 mL of the same solvent. The reaction was stirred at 0 °C for 1 h and was then allowed to warm to room temperature. The reaction was quenched with water and quickly worked up as previously described. A 1:2 mixture of benzaldehyde and benzoyl fluoride [0.55 g (~50% yield), as determined by IR, was isolated: IR (neat) 1805 (s, C=O), 1695 (s, C=O) cm⁻¹.

Oxidative Fluorination of Aldehydes with UF₆. To 5.2 g (0.015 mol) of UF₆ dissolved in 100 mL of Freon 113 was added dropwise at 0 °C 1.14 g (0.01 mol) of heptaldehyde dissolved in 10 mL of the same solvent. After stirring at 0 °C for 2 h the reaction mixture was suction filtered without quenching with water. The Freon solution was evaporated to yield 0.55 g (40% yield) of heptanoyl fluoride: IR (neat) 1840 (s, C=O) cm⁻¹.

Oxidative Cleavage of *N,N*-Dimethylhydrazones to Carbonyl Compounds with UF₆. To 3.52 g (0.01 mol) of UF₆ dissolved in 100 mL of Freon 113 was dropwise added 0.51 g (0.003 mol) of 2-methylcyclohexanone *N,N*-dimethylhydrazone. The reaction mixture was stirred at 0 °C for 2 h. After warming to room temperature, the reaction was quenched with 100 mL of H₂O. The uranyl salts were suction filtered, and the organic phase was separated, washed with water, and dried. Evaporation of the solvent yielded 0.23 g (69% yield) of 2-methylcyclohexanone characterized as a 2,4-dinitrophenylhydrazone, mp 140 °C (lit. mp 137 °C).

Oxidative Cleavage of Tosylhydrazones to Carbonyl Compounds with UF₆. To 1.7 g (0.005 mol) of UF₆ dissolved in 75 mL of Freon 113 was dropwise added 0.72 g (0.0025 mol) of acetophenone tosylhydrazone dissolved in 10 mL of chloroform. After stirring at 0 °C for 2 h, the reaction was warmed to room temperature and quenched with 50 mL of H₂O. The uranyl salts were suction filtered and the organic phase was separated. After washing with ca. 50 mL of 10% aqueous NaOH, followed by 50 mL of H₂O, the organic phase was dried in the usual manner. Evaporation of the solvent yielded 0.29 g (96% yield) of acetophenone, characterized as a 2,4-dinitrophenylhydrazone, mp 242 °C (lit. mp 250 °C).

Oxidation of Carboxylic Acid Hydrazides to Carboxylic Acids with UF₆. To 5.2 g (0.015 mol) of UF₆ dissolved in 100 mL of chloroform at 45 °C was added 0.68 g (0.005 mol) of benzoic acid hydrazide as a finely divided solid. After stirring the suspension at 45 °C for 3 h, the reaction was quenched with water. Filtration of the uranyl salts preceded separation of the organic phase. After washing with 10% aqueous HCl, the organic phase was dried in the usual manner and evaporated to yield 0.15 g (25% yield) of benzoic acid: mp 120 °C (lit. mp 122 °C); IR (Nujol) 1690 (s, C=O) cm⁻¹.

Oxidation of Oximes to Carbonyl Compounds with UF₆. To 5.2 g (0.015 mol) of UF₆ dissolved in 100 mL of Freon 113 was dropwise added 1.29 g (0.01 mol) of 4-heptanone oxime dissolved in 10 mL of chloroform. The reaction was gradually heated to 40 °C and then stirred for 4 h at 40 °C. After quenching with 75 mL of H₂O, the uranyl salts were filtered and the organic phase was separated. The organic phase was concentrated, after drying over anhydrous magnesium sulfate, to give the crude carbonyl compound. Chromatography on adsorbent alumina with benzene yielded 0.71 g (62% yield) of 4-heptanone, IR (neat) 1712 (s, C=O) cm⁻¹, characterized as a 2,4-dinitrophenylhydrazone, mp 61 °C (lit. mp 75 °C).

Oxidation of *N,N*-Dimethylamines to Carbonyl Compounds with UF₆. To 3.52 g (0.01 mol) of UF₆ dissolved in 100 mL of Freon 113 was dropwise added 0.91 g (0.005 mol) of *N,N*-dimethyl-2-adamantylamine in 10 mL of the same solvent. After stirring at 40 °C for 3 h, the reaction was quenched with 75 mL of H₂O. Suction filtration of the uranyl salts was followed by separation of the organic phase. The organic phase was washed with water and dried in the usual manner. Evaporation of the solvent yielded 0.16 g (21% yield) of adamantanone: IR (CCl₄) 1715 (s, C=O) cm⁻¹.

Oxidation of Benzylic Bromides to Carbonyl Compounds with UF₆.

To 3.52 g (0.01 mol) of UF₆ dissolved in 100 mL of Freon 113 was dropwise added 1.22 g (0.005 mol) of 9-bromofluorene in 20 mL of the same solvent. After stirring at 40 °C for 3 h, 25 mL of dimethyl sulfoxide was added to the reaction mixture, followed by 75 mL of water. The uranyl salts were suction filtered and the organic phase was separated and washed with water. After drying in the usual manner the solvent was evaporated to yield 0.680 g (76% yield) of 9-fluorenone, IR (CCl₄) 1720 (s, C=O) cm⁻¹, characterized as a 2,4-dinitrophenylhydrazone, mp 240 °C (lit. mp 237 °C).

Reaction of Adamantyl Bromide with UF₆-Ceric Ammonium Nitrate. To 3.52 g (0.01 mol) of UF₆ dissolved in 100 mL of Freon 113 was added dropwise 0.7 g (0.003 mol) of 1-adamantyl bromide (Aldrich) dissolved in 10 mL of the same solvent. After stirring at room temperature for 1 h, 5.5 g (0.01 mol) of ceric ammonium nitrate (G. Frederick Smith) was added to the reaction mixture. After stirring at room temperature for 2 h, the product was quenched with 75 mL of water. The uranyl salts were suction filtered and the organic phase was separated and washed with water. After drying in the usual manner, evaporation of the solvent yielded 0.730 g (74% yield) of adamantyl nitrate: IR (CCl₄) 1630 (–ONO₂) cm⁻¹. The mass spectra showed a molecular ion peak at *m/e* 197 and a base peak at *m/e* 135.

Reaction of 2-Methylbenzyl Chloride with UF₆-Ceric Ammonium Nitrate. To 3.52 g (0.01 mol) of UF₆ dissolved in 100 mL of Freon 113 was dropwise added 0.7 g (0.005 mol) of 2-methylbenzyl chloride in 10 mL of the same solvent. After stirring at room temperature for 30 min, 5.0 g (0.01 mol) of ceric ammonium nitrate was added to the solution. After stirring at room temperature for 2 h, the product was quenched with 75 mL of water. The uranyl salts were suction filtered, and the organic phase was separated and washed with water. After drying over anhydrous magnesium sulfate, evaporation of the solvent yielded 0.420 g (56% yield) of 2-methyl- α -nitrotoluene: IR (neat) 1530 (s, –NO₂) cm⁻¹.

Oxidative Fluorination of 2-Adamantanone with UF₆. To 3.52 g (0.01 mol) of UF₆ dissolved in 100 mL of Freon 113 at 0 °C was dropwise added 0.75 g (0.005 mol) of 2-adamantanone (Aldrich) in 15 mL of the same solvent. After stirring for 2 h at 0 °C, the reaction was quenched with 75 mL of water. The uranyl salts were suction filtered, and the organic phase was separated and washed with water. Evaporation of the solvent yielded 0.350 g (41% yield) of 2,2-difluoro-2-adamantanone which was purified by sublimation. Anal. Calcd: C, 69.7; H, 8.1; F, 22.1. Found: C, 69.7; H, 8.16; F, 22.03. The mass spectrum showed a molecular ion peak (base peak) at *m/e* 172.

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Stabilities of Carbonium Ions in Solution. 7. A Low-Temperature Calorimetric Approach to Enthalpies of Formation of Carbocations in Solution

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Abstract: This article describes the design and operation of a solution calorimeter suitable for studying fast reactions at temperatures from 0 to -100°C . This is applied to measuring enthalpies of reaction for alkyl halides (RX) with SbF_5 in several solvents of varying Lewis basicity: CH_2Cl_2 , SO_2 , SO_2ClF , and SO_2F_2 . ^1H NMR spectra obtained for the product solutions are consistent with those reported by Olah and others for the carbocations obtained under comparable conditions. Accordingly, the difference between the heat of solution of RX in the pure solvent and in solvent containing SbF_5 is taken to be the heat of ionization, ΔH_i , for conversion of RX to the carbocation. Using the ionization of *tert*-butyl chloride as a standard, it is shown that ΔH_i for this process is relatively insensitive to temperature changes (from 0 to -75°C) or to the ratio of RX/ SbF_5 (over a range from 135 to 0.5). Procedures for determining the heat of capturing the alkyl cations with $\text{Bu}_4\text{N}^+\text{Cl}^-$ are also described. Considerable effort was spent on purifying solvents and checking their purity after a serious discrepancy was found between replica experiments with different batches of SO_2ClF . The results of applying these methods to a variety of alkyl halides are presented in the accompanying paper where the effects of substituents and solvents on the energetics of carbonium ion formation are discussed.

Introduction

Several years ago, Dr. John Larsen in this laboratory reported preliminary calorimetric measurements^{2,3} of the heats of reaction of some olefins, arenes, and alcohols with "magic acid" (i.e., SbF_5 dissolved in HSO_3F) at low temperatures under conditions which were close to those where strong evidence for carbonium ion formation had been demonstrated by others.^{1,4-14} Although the reported results probably were sound, their precision was low and several attempts to extend the magic acid study to related compounds gave results which were not internally consistent. Side reactions, high viscosity, and low solubility caused serious problems.

In the ensuing years we have devoted considerable effort to the search for conditions and techniques which would permit reliable calorimetric study of the quantitative conversion of simple, saturated compounds to carbonium ions in solution. We have endeavored to conduct these experiments with as many checks on the authenticity of the presumed ionization process as possible. This report presents our thermochemical methodology and also describes several supporting tests for consistency and reproducibility. In the following paper we will present the results of applying our techniques to a series of

related compounds in four solvents of relatively low nucleophilicity. Comparison of those results with each other and with related published reports provides a number of other tests for internal consistency which strongly support the validity of the presumed ionization process.

Experimental Section

Sources and Purification of Compounds. Antimony pentafluoride was purchased from Cationics, Inc. It was refluxed for 6 h under reduced pressure, to remove gaseous impurities, followed by a triple distillation, bp 142°C ,³¹ in a flame-dried, all-glass apparatus. It was stored and handled under a dry nitrogen atmosphere in a drybox.

Methylene chloride (Fisher Scientific or Aldrich) was refluxed over sulfuric acid for 6 h followed by distillation, bp 40°C .¹⁵ The purity was greater than 99.9% by gas-liquid chromatography.

The nonreproducibility of results obtained from two separate shipments of SO_2ClF (Cationics) prompted us to test the purity of all three gases (SO_2 , SO_2F_2 , SO_2ClF) used as solvents for carbocation formation. In addition to checking the boiling point of each shipment of gas, its GLC trace and IR spectra were determined.

Sulfuryl fluoride and sulfur dioxide were purchased from Matheson Gas Products. The observed boiling points agreed with the respective literature values.¹⁵ Gas-liquid chromatography showed that SO_2 was