Synthetic Methods and Reactions. 63.[1] Pyridinium Poly(hydrogen fluoride) (30% Pyridine–70% Hydrogen Fluoride): A Convenient Reagent for Organic Fluorination Reactions

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Pyridinium poly(hydrogen fluoride) (30% pyridine–70% hydrogen fluoride) reagent, a stabilized, less-volatile form of hydrogen fluoride, was found to be a convenient and effective fluorinating agent. Fluorination, halofluorination, nitrofluorination, and hydrofluorination of olefins were achieved using the reagent. The in situ diazotization and subsequent fluorinative dediazonization of α-amino acids, aminoarenes, and carbamates yielded α-fluorocarboxylic acids, aryl fluorides, and fluoroformates, respectively. Geminal dihalides and α-halo ketones were reacted with mercuric oxide in pyridinium poly(hydrogen fluoride) to form geminal difluorides and α-fluoro ketones. Solutions of alkali halides in pyridinium poly(hydrogen fluoride) were also found to be effective halogenating agents for aminoarenes, via in situ diazotization and subsequent nucleophilic dediazonization by the corresponding halides, as well as for alcohols, via S_N2 type displacement reactions. Diazo ketones and diazoalkanes also reacted smoothly with halide ions in pyridinium poly(hydrogen fluoride) solution to give the corresponding geminally halofluorinated compounds.

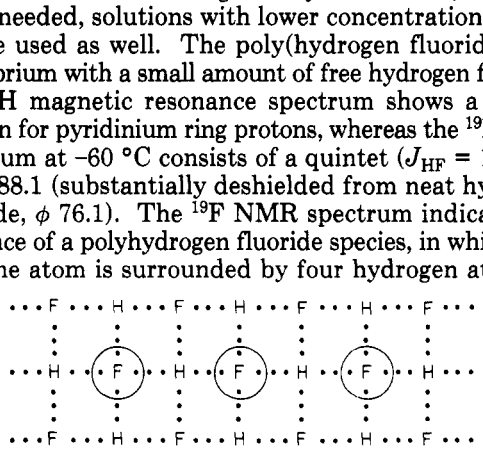
The preparation of organic fluoro compounds has stimulated considerable interest in the development of general and convenient fluorinating reagents.[2,3] Anhydrous hydrogen fluoride, one of the most inexpensive fluorinating agents, has been widely used, but its reactions generally require work under pressure due to its low boiling point (19.6 °C). To overcome the need to carry out fluorinations with anhydrous hydrogen fluoride at superatmospheric pressure, we studied the possibility of using less volatile complexes of HF with various *n*-donor bases. Hirschman's[4] use of the tetrahydrofuran–hydrogen fluoride system in 1955 was the first reported application of such a reagent. Subsequently, stable solutions of HF with amines,[5] amides,[6] carbamic acids and esters,[7] trialkyl phosphines,[8] and alcohols[9] were reported. These complexes, however, remained basically limited to specific fluorinations of organic compounds (mostly steroids), as is clear from the work of Jullien[5a] and Bergstrom,[5b] who employed isopropylamine and pyridine complexes.

Surprisingly and in contrast to the other pyridinium halides, pyridinium fluoride is difficult to prepare. Reacting pyridine with anhydrous hydrogen fluoride gives only bi- and polyhydrogen fluorides. Pyridinium fluoride was obtained, as we reported in 1960,[10] only by the reaction of pyridine with formyl fluoride, through the obvious decarbonylation of the intermediate *N*-formylpyridinium fluoride. These observations arose our continued interest in the pyridine–hydrogen fluoride system and its use as a fluorinating agent.

Having reported on its applicability in some preliminary communications,[1b] we now report in full the use of remarkably stable pyridinium poly(hydrogen fluoride) (30% pyridine–70% hydrogen fluoride) reagent as a convenient general purpose fluorinating agent.

Results and Discussion

Pyridine forms remarkably stable solutions with anhydrous hydrogen fluoride. The solution contains about 9 equiv of hydrogen fluoride to 1 equiv of pyridine (70% w/w HF, 30% w/w pyridine) and is stable up to 55 °C. This solution was utilized generally in our work, although, when needed, solutions with lower concentrations of HF can be used as well. The poly(hydrogen fluoride) is in equilibrium with a small amount of free hydrogen fluoride. The ^1H magnetic resonance spectrum shows a typical pattern for pyridinium ring protons, whereas the ^{19}F NMR spectrum at −60 °C consists of a quintet (J_{HF} = 120 Hz) at ϕ 188.1 (substantially deshielded from neat hydrogen fluoride, ϕ 76.1). The ^{19}F NMR spectrum indicates the presence of a polyhydrogen fluoride species, in which each fluorine atom is surrounded by four hydrogen atoms.



The observed coupling, J_{HF} = 120 Hz, is approximated by assuming $J_{(HF_2^-)_x} = {}^1/_4 J_{HF}$ and using the value reported by McLean and Mackor,[11] i.e., J_{HF} = 521 Hz in hydrogen fluoride to $J_{(HF)_xF^-}$ = 130 Hz. Neat liquid HF itself is well known to be highly associated.[12]

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Table I. Hydrofluorination of Alkenes and Alkynes with Hydrogen Fluoride-Pyridine Reagent

alkene or alkyne	reaction temp, °C	product	yield, %	bp, °C [mm], or (mp, °C)	lit. bp, °C [mm], or (mp, °C)
propene	20	isopropyl fluoride	35	−11 to −9	−9.4[13a]
cyclopropane	20	propyl fluoride	75	−3 to −1	−2.5[13a]
2-butene	0	*sec*-butyl fluoride	40	24-25	25.1[13a]
2-methylpropene	0	*tert*-butyl fluoride	60	11-13	12.1[13a]
cyclopentene	0	cyclopentyl fluoride	65	51-52 [300]	51-52 [300][13b]
cyclohexene	0	cyclohexyl fluoride	80	102-104	43.2 [100][13c]
norbornene	0	2-norbornyl fluoride	65	(56-59)	(56-59)[13d]
cycloheptene	0	cycloheptyl fluoride	90	70-71 [200]	
1-hexyne	0	2,2-difluorohexane	70	85-87	87.4[13e]
3-hexyne	0	3,3-difluorohexane	75	84-86	87.4[13e]

Table II. Iodofluorination of Alkenes and Alkynes

alkenes or alkynes	products	yield, % NIS[a]	yield, % I_2	bp, °C [mm], or (mp, °C)	lit. bp, °C [mm], or (mp, °C)
ethene	1-iodo-2-fluoroethane	23	25[b]	96-97	96.5-97[14]
propene	1-iodo-2-fluoropropane	32	40[b]	50 [20]	
2-methylpropene	1-iodo-2-fluoro-2-methylpropane	60	35	dec	dec[14b]
1-hexene	1-iodo-2-fluorohexane	70	35	72-75 [16]	75 [16][14]
3-hexene	3-iodo-4-fluorohexane	65	30	63-65 [15]	
cyclohexene	1-iodo-2-fluorocyclohexane	75	60	73-75 [10]	64 [9][14]
norbornene	7-*anti*-iodo-2-*exo*-fluoronorbornane	55	45	separated by gas chromatography	
	7-*syn*-iodo-2-*exo*-fluoronorbornane	30	25		
3-hexyne	3-iodo-4-fluorohex-3-ene	70	80[b]	62-65 [12]	
diphenylacetylene	1-iodo-2-fluoro-1,2-diphenylethene	90	90[b]	(128-30)	

[a] NIS = *N*-iodosuccinimide. [b] Diiodo compounds were exclusively formed.

Table III. Bromofluorination of Alkenes and Alkynes

alkenes or alkynes	products	yield, %	bp, °C [mm], or (mp, °C)	lit. bp, °C [mm], or (mp, °C)
ethene	1-bromo-2-fluoroethane	30	71.5	71.5[15a]
propene	1-bromo-2-fluoropropane	40	88.5	88.5[15a]
2-methylpropene	1-bromo-2-fluoro-2-methylpropane	85	95-96	95-96[15b]
1-hexene	1-bromo-2-fluorohexane	90, 80[a]	60-62 [18]	62 [18][15a]
3-hexene	3-bromo-4-fluorohexane	85	53-55 [15]	
cyclohexene	1-bromo-2-fluorocyclohexane	90	76-78 [16]	78 [16][15c]
norbornene	7-*anti*-bromo-2-*exo*-fluoronorbornane	43	separated by GC	
	7-*syn*-bromo-2-*exo*-fluoronorbornane	43		
2-butyne	2-bromo-3-fluorobut-2-ene	50	43-45 [200]	
3-hexyne	3-bromo-4-fluorohex-3-ene	85	55-57 [15]	37 [30][15d]
diphenylacetylene	1-bromo-2-fluoro-1,2-diphenylethene	95	(175-178)	100-103 [0.3][15e]

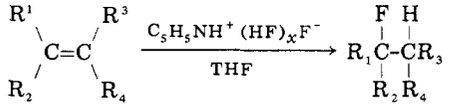
[a] Bromofluorination was performed, using equimolar amounts of bromine and silver nitrate.

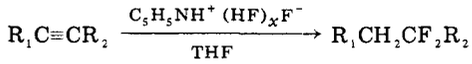
The stable 30% pyridine–70% hydrogen fluoride solution has been found to be extremely useful at atmospheric pressure as a general purpose fluorinating agent for varied additions to alkenes and alkynes, for effective deaminative and dediazonative halogenation reactions, as well as halogen substitution of hydroxyl groups and halogen exchange reactions.

It should be noted that other amine–poly(hydrogen fluoride) complexes, such as trimethylamine–, triethylamine–, substituted pyridine–, and triethanolamine–poly(hydrogen fluoride), are also applicable as sources of liquid hydrogen fluoride. For its convenience and inexpensiveness, however, our work, reported herein, was carried out only with pyridinium poly(hydrogen fluoride).

Hydrofluorination, Halofluorination, Nitrofluorination, and Fluorination of Alkenes

Although alkenes and alkynes are insoluble in pyridinium polyhydrogen fluoride, a tetrahydrofuran solution of these compounds when added to pyridinium polyhydrogen fluoride yields alkyl fluorides and alkyl difluorides, respectively, in typical Markowonikoff type additions (see Table I[13]).





Reactive branched alkenes may be reacted in this way with a minimum of polymerization. Additionally, it was found that cyclopropane is cleaved under the reaction conditions to form only *n*-propyl fluoride. The pyridinium poly(hydrogen fluoride) reagent, although slightly acidic, is nonetheless an excellent fluoride donor capturing the

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Table IV. Chlorofluorination of Alkenes and Alkynes

alkenes or alkynes	products	yield, %	bp, °C [mm], or (mp, °C)	lit. bp, °C [mm], or (mp, °C)
propene	1-chloro-2-fluoropropane	35	65-67	65-67[16a]
2-methylpropene	1-chloro-2-fluoro-2-methylpropane	60	71-73	71-73[16b]
1-hexene	1-chloro-2-fluorohexane	40	58-60 [45]	
3-hexene	3-chloro-4-fluorohexane	80	54-56 [45]	
cyclohexene	1-chloro-2-fluorocyclohexane	85	71-72 [42]	60-63 [15][16c]
norbornene	7-*anti*-chloro-2-*exo*-fluoronorbornane	30	separated by GC	
	7-*syn*-chloro-2-*exo*-fluoronorbornane	45		
3-hexyne	3-chloro-4-fluorohex-3-ene	70	38-40 [20]	
diphenylacetylene	1-chloro-2-fluoro-1,2-diphenylethane	95	(132-134)	

Table V. In Situ Fluorination of Alkenes

alkenes	products	yield, %	bp, °C [mm], or (mp, °C)	lit. bp, °C [mm], or (mp, °C)
2,3-dimethylbut-2-ene[a]	2,3-difluoro-2,3-dimethylbutane	60	dec	dec[17a]
3-hexene[b]	3,4-difluorohexane	75	40-42 [100]	
cyclohexene[b]	1,2-difluorocyclohexane	85	48-50 [100]	
stilbene[a]	1,2-difluoro-1,2-diphenylethane	95	70 dec	(128-130)[17b]

[a] *N*-Bromosuccinimide was used for the first step of the reaction. [b] *N*-Iodosuccinimide was used for the first step of the reaction.

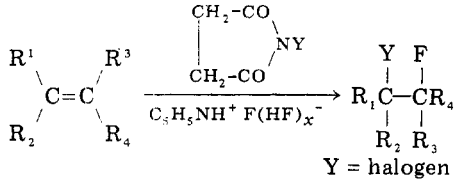
Table VI. Nitrofluorination of Alkenes

alkene	reaction temp, °C	reaction time, h	product	yield, %	bp, °C [mm], or (mp, °C)	lit. bp, °C [mm], or (mp, °C)
ethene	20	1	1-fluoro-2-nitroethane	60	60 [15]	60 [15][18a]
propene	20	1	2-fluoro-1-nitropropane	65	33 [4]	33 [4][18a]
2-butene	20	0.5	2-fluoro-3-nitrobutane	60	37 [4]	
1-hexene	0	1	2-fluoro-1-nitrohexane	65	45 [3]	
chloroethene	20	2	1-chloro-1-fluoro-2-nitroethane	40	41 [10]	41 [10][18a]
1,1-dichloroethene	20	2	1,1-dichloro-1-fluoro-2-nitroethane	45	48 [10]	48 [10][18a]
cyclohexene	0	1	1-fluoro-2-nitrocyclohexane	70	50 [3]	
	20	0.3		80		

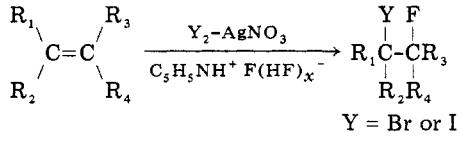
primary cation before any intramolecular rearrangement takes place. When alkenes are added in a similar manner

$$c\text{-}C_3H_6 \xrightarrow{C_5H_5NH^+\,F(HF)_x^-} CH_3CH_2CH_2F$$

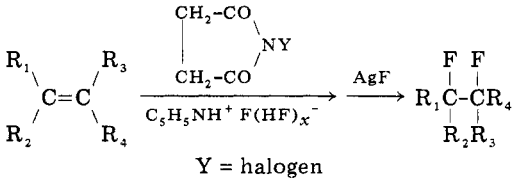
to a solution of pyridinium polyhydrogen fluoride containing *n*-halosuccinimide, the corresponding halofluorinated compounds are isolated (see Tables II–IV[14-14]).



In contrast to the reaction of alkynes to form germinally difluorinated compounds, only vinylic iodofluorine compounds are formed upon addition of alkynes to a solution of pyridinium poly(hydrogen fluoride) containing *N*-iodosuccinimide. Iodofluorination and bromofluorination of alkenes are also effected, using bromine or iodine with an equivalent amount of silver nitrate in the pyridinium poly(hydrogen fluoride) solution.



The halofluorination method can also be modified to prepare vicinal difluorides from the corresponding alkenes without isolation of the intermediate halofluorinated compounds. This is simply carried out by adding silver fluoride to the solution of α-halo-β-fluoroalkanes, effecting the exchange reaction in situ (see Table V[17]).



Fluoronitroalkanes can be conveniently prepared from olefins by a variation of the above procedures. The olefin is added to a solution of nitronium tetrafluoroborate dissolved in pyridinium poly(hydrogen fluoride).

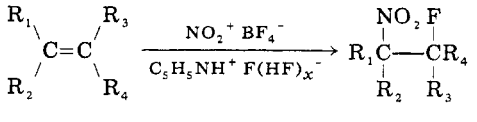


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Table VII. Preparation of Carbamyl Fluorides from Isocyanates

isocyanate	carbamyl fluoride	yield, %	bp, °C [mm], or (mp, °C)	lit. bp, °C [mm], or (mp, °C)
methyl isocyanate	methylcarbamyl fluoride	40	48-50 [6]	48 [6][19a]
phenyl isocyanate	phenylcarbamyl fluoride	58	(30-31)	(30-31)[19b]
o-tolyl isocyanate	*o*-tolylcarbamyl fluoride	52	(48)	
p-tolyl isocyanate	*p*-tolylcarbamyl fluoride	53	(57-58)	(58)[19b]

Table VIII. Preparation of Tertiary and Secondary Alkyl Fluorides from Alcohols

alcohol	temp, °C	reaction time, h	alkyl fluoride	yield, %	bp, °C [mm], or (mp, °C)	lit. bp, °C [mm], or (mp, °C)
isopropyl	50	3	isopropyl	30	−9 to −7	−9.4[20a]
sec-butyl	20	3	*sec*-butyl	70	25-26	25.1[20a]
tert-butyl	0	1	*tert*-butyl	50	12	12.1[20a]
3-ethyl-3-pentyl	0	0.5	3-ethyl-3-pentyl	95	30-33 [60]	45 [84][20b]
3-methyl-3-heptyl	0	2	3-methyl-3-heptyl	35	35 [40]	
3-methyl-4-heptyl	−70	0.5	3-methyl-4-heptyl	85		
cyclohexyl	20	2	cyclohexyl	99	100-102	43.2 [100][20c]
2-norbornyl	20	1	2-norbornyl	95	(56-59)	(56-59)[20d]
1-adamantyl	20	1	1-adamantyl	95	(210)	(210-212)[20e]
2-adamantyl	20	0.5	2-adamantyl	98	(254-255)	(254.5-254.8)[20f]
α-phenylethyl	20	0.5	α-phenylethyl	65	46 [15]	55-57 [12][20g]
triphenylmethyl	20	1	triphenylmethyl	76	(103-104)	(103-104[20h] dec)

β-Fluoronitroalkanes can be prepared in this manner from olefins without the accompanying problems of polymerization usually found in reactions conducted in anhydrous hydrogen fluoride (see Table VI[18]).

Hydrofluorination of Isocyanates

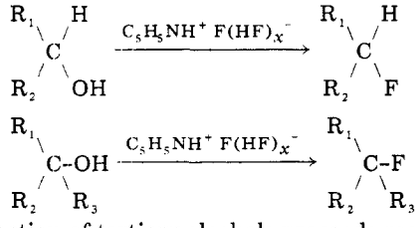
Aliphatic and aromatic isocyanates were reacted with pyridinium poly(hydrogen fluoride) at room temperature to give the corresponding carbamyl fluorides in good yields (see Table VII[19]).

$$RN{=}C{=}O \xrightarrow{C_5H_5NH^+\ F(HF)_x^-} RNHC(=O)F$$

R = aliphatic or aromatic

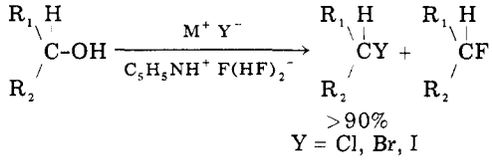
Fluorination and Halogenation of Alcohols

Reactive tertiary and secondary alcohols are readily fluorinated in pyridinium poly(hydrogen fluoride). The fluorides may be conveniently separated from the reaction media by extraction with cyclohexane or heptane, which forms an immiscible upper layer into which the formed fluorides are extracted.



The reaction of tertiary alcohols proceeds readily at low temperatures. Secondary alcohols, except isopropyl alcohol, which requires heating to 50 °C for the completion of the reaction, react at room temperature to give the corresponding alkyl fluorides in satisfactory yields (see Table VIII[20]).

Alcohols can also be reacted with other alkali halides in pyridinium poly(hydrogen fluoride) solution to give the corresponding alkyl halides (see Table IX[21]). Whereas secondary and tertiary alcohols themselves react with pyridinium poly(hydrogen fluoride) to give alkyl fluorides (vide supra), this reaction is much slower than the displacement reaction with halide ions (assisted by protolytic interaction of the hydroxyl moiety). This is evident by the fact that alkyl fluorides were formed in less than 10% yield, if at all, in the reaction of secondary and tertiary alcohols with alkali chlorides, bromides, and iodides. Primary alcohols were found to be unreactive with pyridinium poly(hydrogen fluoride) itself. However, the reaction proceeded smoothly in the presence of added fluoride, chloride, bromide, or iodide ion. This indicates that the monomeric fluoride ion is a strong nucleophile, whereas polymeric $F(HF)_x^-$ is a very weak one. The nature of alkali cations was found to have no particular effect on the reactions.



The reactions proceeded well at room temperature, and it was generally not necessary to heat the reaction mixtures. The S_N2 nature of the reactions was demonstrated by the preparation of neopentyl halides (1-halo-2,2-dimethylpropanes) from neopentyl alcohol without any

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Table IX. Preparation of Haloalkanes (R-Y) from Alcohols (R-OH) and Alkali Halides (MY) in Pyridinium Poly(hydrogen fluoride) Solution

R	alkali halide	yield, %	bp, °C [mm], or (mp, °C)	lit. bp, °C [mm], or (mp, °C)
n-hexyl	NaF	30	93	93.15 [753][21a]
n-octyl	NaF	49	140-141	142
2,2-dimethylpropyl	NaF	55		
	NaCl	40	82	82.5[21e]
	NH_4Br	70	105	104.8 [732][21d]
	KI	56	53-55 [55]	54-55 [55][21a]
cyclohexyl	NaF	51	43 [100]	43.2 [100][21e]
	NaCl	97	140-142	142[21a]
	NH_4Br	71	70-71 [32]	72 [32][21a]
	KI	80	68-69 [10]	69 [10][21a]
cyclopentyl	NaF	54	51-52 [300]	51-52 [300][21f]
	NaCl	71	114	114-115[21a]
	NH_4Br	55	138	137-139[21a]
	KI	85	76-78 [46]	78-79 [46][21a]
1-adamantyl	NaF	81	(210-211)	(210-212)[21j]
	NaCl	40	(154-156)	(152-6)[21h]
	NH_4Br	80	(119)	(119-120)[21i]
	KI	35	(76)	(76-77)[21j]
2-adamantyl	NaF	88	(254-255)	(254.5-254.8)[21k]
	NaCl	40	(194-194.5)	(193.8-194.8)[21l]
	NH_4Br	70	(139)	(139.1-139.6)
	KI	20	(47)	(46-48)[21m]
n-pentyl	NaCl	89	107-108	108.4[21a]
	NH_4Br	75	129	129.7[21a]
	KI	60	60-61 [20]	62 [20][21a]
2-methyl-1-butyl	NaCl	53	97-98	97-9[21a]
	NH_4Br	70	120-121	120-1[21a]
	KI	84	148	148[21a]
2-octyl	NaCl	75	55 [10]	55 [10-11][21a]
	NH_4Br	67	60-61 [3]	60 [3][21a]
	KI	85	94 [15]	95.6 [16][21a]
2-norbornyl	NaCl	83 (exo)	30-32 [8]	33 [8][21n]
	NH_4Br	57 (exo)	78-80 [28]	80 [28][21o]
	K	76 (exo)	87 [16]	87 [16][21p]
benzyl	NaCl	100	60-63 [8]	63 [8][21a]
	NH_4Br	94	126-127 [80]	127 [80][21a]
	KI	100	93 [10]	93 [10][21a]
tert-butyl	NaCl	70	(52)	(52)[21a]
	KI	44	(99-100)	(100[21a] dec)

Table X. Preparation of α-Fluorocarboxylic Acids (RCHFCOOH) from α-Amino Acids ($RCH(NH_2)COOH$) in Pyridinium Poly(hydrogen fluoride) (30% Pyridine-70% HF)-Sodium Nitrite

α-amino acid	R	yield, %	bp, °C [mm], or (mp, °C)	lit. bp, °C [mm], or (mp, °C)
glycine	H	38	163	162-165 [652][22a]
alanine	CH_3	96	65-66 [13]	66 [13][22a]
2-aminobutanoic acid	C_2H_5	80	90-90.5 [12]	77-77.5 [11][22a]
valine	*i*-C_3H_7	84	(38-39)	(35-40)[22a]
leucine	*i*-C_6H_9	88	95-96 [10]	95.5-96.5[22b]
isoleucine	*s*-C_4H_9	75	97-98 [10]	96.5-98.5 [10][22b]
phenylalanine	$C_6H_5CH_2$	98	(73-75)	(71-74)[22a]
tyrosine	*p*-HO-C_6H_4-CH_2	47	57 [0.5]	
serine	$HOCH_2$	80	(95-95.5)	(94.5-95.5)[22c]
threonine	$(H_3C)CH(HO)$	54		
aspartic acid	HOOC-CH_2	52	(141-143)	(144-145)[22d]
glutamic acid	HOOC-CH_2-CH_2	28	(105-107)	(104-107)[22a]

rearrangement to 2,3-dimethyl-2-halopropanes. Optically active compounds, such as *l*-2-methyl-1-butanol, did not racemize under the reaction conditions but gave inverted products. In the reactions of *l*-2-octanol, *d*-2-halooctanes were formed, again indicating the bimolecular nature of the displacement reaction.

Deaminative Fluorination and Halogenation

Deaminative halogenation reactions, whereby the amino group is displaced by fluoride or other halides, were studied in the case of α-amino acids, carbamates, and aminoarenes. The reaction of α-amino acids in pyridinium poly(hydrogen fluoride) solution with excess sodium nitrite led via in situ diazotization followed by nucleophilic dediazonization to the formation of 2-fluorocarboxylic acids in good to moderate yields (see Table X[22]).

$$RCHCO_2H \xrightarrow[NaNO_2]{C_5H_5NH^+(HF)_xF^-} \left[RCHCO_2H\right] \rightarrow RCHCO_2H$$

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Table XI. Preparation of Alkyl Fluoroformates (ROC(O)F) from Alkyl Carbamates ($ROC(O)NH_2$) in Pyridinium Poly(hydrogen fluoride)-Sodium Nitrite

R	yield, %	bp, °C [mm], or (mp, °C)	lit. bp, °C [mm], or (mp, °C)
CH_3	75	39-40	40[28a]
C_2H_5	31	56-57	57[28a]
n-C_3H_7	68	89-91	90-92[28a]
i-C_3H_7	75	79-82	81-82[28a]
n-C_4H_9	40	96-98	97-99[28a]
s-C_4H_9	75	92-93	92-93[28a]
i-C_4H_9	78	27 [0.1]	
t-C_4H_9	50	30 [20]	4 [15][28b]

The reaction proceeds well in the presence of other functionalities too, such as tyrosine, threonine, and glutamic acid (see Söll).[23] However, the reaction with glutamine was unsuccessful, due possibly to intramolecular competition for the intermediate, similar to that observed by Austin.[24]

2-Fluorocarboxylic acids, prepared in pyridinium poly(hydrogen fluoride) solution, were isolated by extraction (in some cases by continuous liquid–liquid extraction) of the quenched reaction mixture with ether and readily purified by distillation.

Treatment of alkyl carbamates, dissolved in pyridinium poly(hydrogen fluoride) solution, with an excess of sodium nitrite at room temperature resulted in the formation of the corresponding fluoroformates (see Table XI[28]).

$$ROC(O)NH_2 \xrightarrow[NaNO_2]{C_5H_5NH^+\,F(HF)_x^-} ROC(O)F$$

The reaction is considered to proceed via in situ diazotization followed by dediazonization.

The preparation of alkyl fluoroformates with pyridinium poly(hydrogen fluoride) from easily available carbamates eliminates the necessity of using phosgene or its derivatives in their preparation.

The deaminative introduction of a halogen into the aromatic nucleus is commonly accomplished via diazotization of the corresponding amines and decomposition of the diazonium salts[25] in the presence of suitable halide donors. For the preparation of specifically fluorinated aromatic compounds, the Schiemann's reaction has been the most widely used method.[26] The metal-catalyzed Sandmeyer[27] reaction is also widely used, but it is often accompanied by unwanted side reactions. When aminoarenes were diazotized in pyridinium poly(hydrogen fluoride) solution with sodium nitrite, subsequent dediazoniation resulted in formation of the corresponding fluoroarenes.

$$PhNH_2 \xrightarrow[NaNO_2]{C_5H_5NH^+\,(HF)_xF^-} PhF$$

The fluoroarenes formed were frequently isomerically pure compounds, as determined by gas chromatography (see Table XII[29]); however, it should be noted that, in some cases, the products contained a mixture of isomers. The mechanistic implications of this observation have been discussed elsewhere.[30] Pyridinium poly(hydrogen fluoride), in general, is a convenient medium for the preparation of fluoroarenes. The diazotization and dediazoniation reactions proceed smoothly at room or slightly higher temperatures and do not require isolation of the diazonium salt intermediate. The product fluoroarenes are generally formed in good yields.

Fluorination (Halofluorination) of Diazoalkanes and Diazo Ketones

The success of the reaction of diazonium compounds with nucleophiles in pyridinium polyhydrogen fluoride led to the study of the reactions of the neutral diazo compounds in the same medium, including reactions in the presence of added N-halosuccinimides. The chemistry and preparative utility of diazoalkanes has been thoroughly reviewed.[25a,d,31] α-Halogenated ketones and haloalkanes were successfully prepared by the reaction of diazo ketones and diazoalkanes with halide ions in pyridinium poly(hydrogen fluoride) solution at 0 °C.

$$RC(O)CHN_2 \xrightarrow[\substack{M\ X\\ N\ Y}]{C_5H_5NH^+\,(HF)_xF^-} RC(O)CHXY$$

Reactions in the absence of added halide ions resulted in the formation of the corresponding fluoro ketone or fluoroalkane (see Table XIII)[32]). Diazomethane, prepared from nitrosomethylurea,[31d,33] phenyldiazomethane, prepared from benzylhydrazine,[34] and commercially available diazoalkanes were reacted with solutions of N-halosuccinimides in pyridium poly(hydrogen fluoride) solution. The reaction of the aliphatic diazo compounds is now

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Table XII. Preparation of Fluoroarenes from Aminoarenes in Pyridinium Poly(hydrogen fluoride)-Sodium Nitrite

$R\text{-}C_6H_4NH_2$	$R\text{-}C_6H_4\text{-}X$	yield, %	isomer distribution[a] ortho	meta	para	bp, °C [mm], or (mp, °C)	lit. bp, °C [mm], or (mp, °C)
H	F	40				85	85.2[29a]
o-CH_3	F	63	100	0	0	114	114[29a]
m-CH_3	F	86	0	100	0	115	116[29a]
p-CH_3	F	90	0	0	100	116	116.6[29a]
o-NO_2	F	30	0	100	0	86 [19]	110-12 [22][29a]
m-NO_2	F	35	0	73	27	85-86 [19]	86 [19][29a]
p-NO_2	F	45	0	65	34	81 [12]	86.6 [14][29b]
o-CF_3	F	50	8	91	1	114	114.5 [750][29b]
m-CF_3	F	46	0	53	47	100	99.5-100.5 [762][29c]

[a] Isomer distributions were determined by gas chromatography.

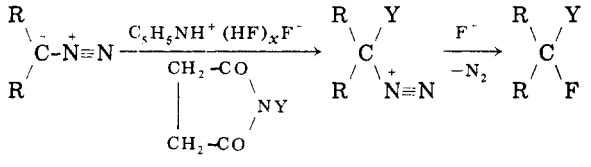
Table XIII. Dediazoniative Hydrofluorination and Halofluorination of Diazoalkanes and Diazo Ketones in Pyridinium Poly(hydrogen fluoride)

diazoalkane	N-halo-succinimide	product	yield, %	bp, °C [mm], or (mp, °C)	lit. bp, °C [mm], or (mp, °C)
Ph-CO-CHN_2		Ph-$COCH_2F$	51	62 [0.6]	65-70 [1][32a]
Ph-CO-CHN_2	Cl	Ph-COCHClF	49	(45)	91 [11][32b]
Ph-CO-CHN_2	Br	Ph-COCHBrF	63	(55)	(54-54.5)[32c]
Ph-CO-CHN_2	I	Ph-COCHIF	62	(70-72)	(67-8)[32c]
c-C_6H_{11}-CO-CHN_2		c-C_6H_{11}-$COCH_2F$	50	27 [0.4]	
c-C_6H_{11}-CO-CHN_2	Cl	c-C_6H_{11}-COCHClF	95	70 [1.2]	
c-C_6H_{11}-CO-CHN_2	Br	c-C_6H_{11}-COCHBrF	38	30 [0.1]	
c-C_6H_{11}-CO-CHN_2	I	c-C_6H_{11}-COCHIF	80	45 [0.9]	
C_2H_5-CO-CHN_2		C_2H_5-CO-CH_2F	40	50 [5]	111-112[32d]
C_2H_5-CO-CHN_2	Cl	C_2H_5-CO-CHClF	50	40 [15]	
C_2H_5-CO-CHN_2	Br	C_2H_5-CO-CHBrF	32	49 [2.4]	
C_2H_5-CO-CHN_2	I	C_2H_5-CO-CHIF	80	170 [4]	
C_2H_5O-CO-CHN_2		C_2H_5O-CO-CH_2F	40	117-118	116-120[32e]
C_2H_5O-CO-CHN_2	Cl	C_2H_5O-CO-CHClF	30	100	95.5[32f]
C_2H_5O-CO-CHN_2	Br	C_2H_5O-CO-CHBrF	50	68 [34]	68 [32][32f]
C_2H_5O-CO-CHN_2	I	C_2H_5O-CO-CHIF	50	68-72 [14]	68-72 [14][32f]
Ph-CHN_2		Ph-CH_2F	70	145 dec	140[32a]

Table XIV. Halogen Exchange Reactions with Mercuric Oxide-Pyridinium Poly(hydrogen fluoride)

halide	product	yield, %	bp, °C [mm], or (mp, °C)	lit. bp, °C [mm], or (mp, °C)
1,1-dichloropropane	1,1-difluoropropane	50	7-8	7-8[35a]
α-bromoacetophenone	α-fluoroacetophenone	68	45-47 [0.03]	65-70 [1][35b]
2-bromo-3-pentanone	2-fluoro-3-pentanone	45	58-63 [80]	60-61 [80][35c]
α-bromopropionic acid	α-fluoropropionic acid	50	66	65-66[35d]
α-chloropropiophenone	α-fluoropropiophenone	71	96 [12]	95-6 [12][35e]

considered to involve initial electrophilic halogen attack on the diazoalkane followed by concomitant loss of nitrogen and nucleophilic displacement of the incipient carbocation by fluoride ion.



The reaction of diazo compounds under these convenient conditions allows the ready preparation of related geminally dihalogenated compounds. The reported conversion of aliphatic amino acids into α-diazo esters by Yamada[35] provides a systematic methodology, which, when coupled with the above described procedure, provides a convenient conversion into α-amino-α-fluoro acids.

It was also found that when α-halo ketones or geminal dihalides were added to a suspension of yellow mercuric oxide in pyridinium polyhydrogen fluoride and heated at 50 °C at atmospheric pressure for approximately 15 h, the halides were exchanged for fluorides in good to moderate yield (see Table XIV[35]). The exchange was slowed down but not halted by the presence of a carbonyl group. Bromides were more readily exchanged than chlorides. No special precautions were required to exclude moisture.

$$RC(O)CH_2Y \xrightarrow[(HF)_x\text{-}C_5H_5N]{HgO} RC(O)CH_2F$$

$$RCY_2R_1 \xrightarrow[(HF)_x\text{-}C_5H_5N]{HgO} RCF_2R_1$$

Y = Cl, Br

Pyridinium poly(hydrogen fluoride) used in conjunction with mercuric oxide offers, in comparison with previous uses of mercuric ion assisted exchanges, the convenience of atmospheric pressure, relatively short reaction times at lower temperatures, and more general applicability in the presence of other functionalities.

Preparation of Acid Fluorides from Acid Chlorides and Acid Anhydrides

A general route to acid fluorides from acid chlorides and acid anhydrides, using anhydrous hydrogen fluoride, was described by Olah and Kuhn[37a] in 1961. We have now

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Table XV. Conversion of Acid Chlorides and Acid Anhydrides into Acid Fluorides

acid fluoride	% yield from acid chloride	% yield from acid anhydride	bp, °C [mm], or (mp, °C)	lit. bp, °C [mm], or (mp, °C)
acetyl fluoride	81	85	19-20	20[37a]
propionyl fluoride	90	89	43-44	43[37a]
butyric fluoride	*a*	87	69	69[37a]
undecanoyl fluoride	88	*a*	94-96 [10]	100-100.5 [12][37b]
cyclohexanoyl fluoride	91	*a*	144-145	146-148[37c]
benzoyl fluoride	92	92	75-77 [10]	157[37a]
phenylacetyl fluoride	89	*a*	85-86 [14]	85 [15][37a]

[a] Not studied.

found that the same conversion could also be brought about by using pyridinium poly(hydrogen fluoride). Generally, the reaction was completed within 15 min, and the yields of the products were comparable to those reported by using anhydrous hydrogen fluoride. Results of the present investigation are summarized in Table XV.

Experimental Section

General. Melting points were determined on a Mettler FP-1 melting point apparatus and are uncorrected. Proton (^{1}H NMR) and fluorine (F NMR) magnetic resonance spectra were recorded on Varian A60-A or A56/60 spectrometers. Infrared (IR) spectra were recorded on a Beckman IR-10 spectrometer, either as thin films or as solutions in CCl_4.

Analytical gas chromatography was performed with a Perkin-Elmer Model 226 chromatograph equipped with flame ionization detector and Infotronic Model CRS-100 digital printing integrator. The following stainless steel open tubular columns were used throughout this work: (a) 150 ft × 0.01 in. wall coated with butanediol succinate; (b) 150 ft × 0.01 in. wall coated with poly(propylene glycol); (c) 150 ft × 0.01 in. wall coated with *m*-bis(*m*-phenoxyphenoxyl)benzene modified with Apiezon L; and (d) 150 ft × 0.01 in. wall coated with squalene.

Optical activities were measured in pentane solution at 19.6 °C in a 2-d tube, using a Rudolph polarimeter with oscillating polarizer, Model 340, equipped with a photoelectric attachment.

Elemental microanalyses were performed by Galbraith Laboratories, Inc., Knoxville, Tenn. Throughout this work, reactions were conducted in polyolefin flasks and bottles. Plastic separatory funnels and beakers of Teflon FEP were used in the extraction procedures.

Pyridinium Poly(hydrogen fluoride) (CAUTION!)[38] (70% Hydrogen Fluoride by Weight). Into 42 g (0.53 mol) of reagent grade pyridine (dried over molecular sieves) at −78 °C in a polyethylene bottle was condensed 100 g (5 mol) of anhydrous hydrogen fluoride (Harshaw). The mixture was allowed to warm gradually to room temperature, the resulting solution being 70% by weight hydrogen fluoride. The concentration of the solution can be readily decreased by decreasing the amount of HF added. When pyridinium poly(hydrogen fluoride) was already available, it could be used as a convenient solvent medium to react additional pyridine and anhydrous HF at low temperatures.

Preparation of Alkyl Fluorides from Alkenes. Into a 70% hydrogen fluoride/pyridine solution (100 mL), alkene (0.1 mol) dissolved in tetrahydrofuran (25 mL) was added over 10 min at 0 °C. The reaction mixture was then allowed to stand at this temperature for 50 min. Alkyl fluoride was isolated either by quenching with ice–water or by adding chloroform or carbon tetrachloride and extracting the fluoride into the organic layer, from which, after distilling the solvent, it could be obtained easily in pure form.

Alkenes were, in general, reacted in the above described procedure. However, due to their low boiling points, propene, 2-butene, and 2-methylpropene were reacted in a pressure bottle. After completion of the reaction, the reaction mixture was cooled to dry ice–acetone temperature, the pressure bomb was opened, and the fluorides were extracted by cooled chloroform and isolated in the usual manner by distillation into a dry ice–acetone cooled trap.

Preparation of 1-Fluoro-2-iodocyclohexane. Into a mixture of 50 mL of pyridinium poly(hydrogen fluoride) (70%) and 30 mL of tetramethylene sulfone, iodine (7.2 g, 0.03 mol) was dissolved. Cyclohexene (2.6 g, 0.03 mol) dissolved in 30 mL of tetramethylene sulfone was then added to the above solution over 10 min at room temperature. The reaction mixture was stirred for 20 min and then poured into ice water and extracted with ether. The ether layer was washed with water, aqueous sodium hydrogen carbonate, and water and dried over anhydrous sodium sulfate. After evaporation of ether and unreacted cyclohexene and the usual purification, 1-fluoro-2-iodocyclohexane was obtained: yield, 4.9 g (60%); bp 73–75 °C (10 torr).

Preparation of 2,3-Difluoro-2,3-dimethylbutane. Into a polyethylene flask containing 100 mL of pyridinium poly(hydrogen fluoride) (70%) and 100 mL of ether, *N*-bromosuccinimide (18 g, 0.01 mol) was added. To this mixture, cooled by an ice bath, 2,3-dimethylbut-2-ene (8.5 g, 0.01 mol) was introduced at 0 °C, and the reaction mixture was stirred at room temperature for 30 min. Thereafter, silver fluoride (19.0 g, 0.1 mol) was added and the reaction continued for 2 h at room temperature. The reaction mixture was poured into ice–water and extracted with ether. The ether layer was washed with water, aqueous potassium hydroxide, and water and then dried over anhydrous sodium sulfate. After evaporation of ether at atmospheric pressure, carefully using a 10 in. column, 2,3-dimethyl-2,3-difluorobutane was obtained. It was further purified by preparative GLC, yield 7.3 g (60%)).

Preparation of 1-Fluoro-2-nitrocyclohexane. Into 70 mL of pyridinium poly(hydrogen fluoride) (70%) maintained in a polyethylene flask at −70 °C, 14 g (0.1 mol) of nitronium tetrafluoroborate was dissolved. Then cyclohexene (4.2 g, 0.05 mol) was added to the solution as it was stirred in over 10 min at −70 °C. The reaction mixture was then warmed up to 0 °C over 10 min; it continued for 1 h at 0 °C. The reaction mixture was poured into ice water and extracted with ether. The ether layer was washed with water, aqueous $NaHCO_3$, and water and dried over anhydrous sodium sulfate. After evaporation of the solvent, the residue was distilled and 1-fluoro-2-nitrocyclohexane was obtained: yield, 5.1 g, 70%; bp 50 °C (30 torr).

Preparation of *sec*-Butyl Fluoride. Into 100 mL of pyridinium poly(hydrogen fluoride) (70%) in a polyethylene bottle, *sec*-butyl alcohol (7.4 g, 0.1 mol) dissolved in 50 mL of *n*-hexane was added over 10 min, and the reaction mixture was kept at room temperature with stirring for 1 h. The reaction mixture was then cooled to −50 °C, and the organic layer was separated in a polyethylene separating funnel. It was subsequently distilled, collecting the *sec*-butyl fluoride in a cold trap cooled in a dry ice–acetone bath; yield, 5.2 g, 70%; bp 25–26 °C.

Preparation of 1-Chloropentane. 1-Pentanol (1.76 g, 0.02

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(37) (a) G. A. Olah and S. J. Kuhn, *J. Org. Chem.*, **26**, 237 (1961); (b) F. Seel and J. Langer, *Chem. Ber.*, **91**, 2553 (1958); (c) Y. Yamase, *Bull. Chem. Soc., Jpn.*, **34**, 480 (1961).

(38) **Caution**! Proper precautions must be used when handling anhydrous hydrogen fluoride and pyridinium poly(hydrogen fluoride). Hydrogen fluoride is extremely corrosive to human tissue, contact resulting in painful, slow-healing burns. Laboratory work with HF should be conducted only in an efficient hood, with the operator wearing a full-face shield and protective clothing. See G. A. Olah and M. Watkins, *Org. Synth.*, **58**, 75 (1978); and C. M. Sharts and W. A. Sheppard, *Org. React.*, **21**, 192, 220–223 (1974).

mol) was added to a solution of pyridinium poly(hydrogen fluoride) (50 mL), containing 1.74 g (0.03 mol) of sodium chloride, in a polyethylene bottle. The reaction mixture was stirred for 1 h, quenched with ice–water, and extracted with ether. The ether layer was neutralized with 5% aqueous sodium hydrogen carbonate solution and dried over anhydrous magnesium sulfate. Workup of the ether solution gave 1-chloropentane: yield 0.96 g (89%); bp 107 °C.

Preparation of 2-Fluorobutanoic Acid. To 2.1 g (0.02 mol) of 2-aminobutanoic acid dissolved in 50 mL of pyridinium poly(hydrogen fluoride) was slowly added, with good stirring, 2.1 g (0.03 mol) of sodium nitrite. After being stirred at room temperature for 4 h, the reaction mixture was quenched and extracted with ether. The ether layer was again washed with ice–water and dried over anhydrous sodium sulfate. Ether evaporation gave a crude product, from which 2-fluorobutanoic acid (1.79 g, 80% yield) was obtained upon distillation, bp 90–91 °C (12 mm).

Preparation of 2-Fluoroglutaric Acid. To 6.6 g (0.05 mol) of glutamic acid dissolved in 100 mL of pyridinium poly(hydrogen fluoride) was slowly added 4.7 g (0.06 mol) of sodium nitrite with stirring. After the solution had stirred at room temperature for 4 h, ca. 75 g of anhydrous potassium fluoride, followed by 250 mL of water, was added to the reaction mixture and stirring continued overnight. Filtration yielded a solution of pH 7 (as determined by pH paper), which was acidified to pH 3–4. Continuous extraction of the solution with 75 mL of diethyl ether for 48 h yielded 1.9 g (28% yield) of 2-fluoroglutaric acid. The product was characterizeed by its ^{1}H NMR and F NMR spectra, mp 113–114 °C.

Preparation of Monofluorosuccinic Acid. Aspartic acid (1.33 g, 10 mmol) was dissolved in 50 mL of pyridinium poly(hydrogen fluoride) in a polyethylene bottle. To this solution, with continued stirring, was slowly added 1.03 g (0.15 mmol) of sodium nitrite (dried at 140 °C for 24 h). After being stirred at room temperature for 4 h, the reaction mixture was quenched with 100 mL of ice–water. It was then extracted with ether for 24 h (continuous liquid–liquid extraction). The ether layer was then treated with 50 g of anhydrous potassium fluoride to remove HF extracted into the ether layer. The solution was reacidified with HCl and then separated. The ether layer was dried over anhydrous magnesium sulfate. Evaporation of the solvent gave 0.5 g of the monofluorosuccinic acid (38%), mp 143–144 °C.

Preparation of Isobutyl Fluoroformate. To 2.34 g (0.03 mol) of isobutyl carbamate magnetically stirred in 50 mL of pyridinium poly(hydrogen fluoride) at 0 °C was slowly added 2.1 g (0.03 mol) of sodium nitrite. After being stirred at 0 °C for 1 h, the reaction mixture was extracted directly with 150 mL of diethyl ether in three portions. The combined ether extract was washed with 5% aqueous sodium bicarbonate and dried over anhydrous magnesium sulfate. Following rotary evaporation of the solvent, the product was distilled at reduced pressure to give 1.85 g of 2-methylpropyl fluoroformate (78% yield), bp 27 °C (0.1 mm).

Preparation of *tert*-Butyl Fluoroformate. To 2.34 g (0.03 mol) of *tert*-butyl carbamate (Aldrich) magnetically stirred in 50 mL of pyridinium poly(hydrogen fluoride) at 0 °C was slowly added 2.1 g (0.03 mol) of sodium nitrite. The temperature of the reaction mixture, as measured by a Teflon-jacketed thermometer, was not allowed to rise above 5 °C. After being stirred at 0 °C for 1 h, the reaction mixture was extracted as described previously. Following rotary evaporation of the solvent, the product was distilled at reduced pressure to give 1.2 g (50% yield) of *tert*-butyl fluoroformate, bp 30 °C (20 mm).

Preparation of Fluorobenzene. To 1.86 g (0.02 mol) of aniline (purified by distillation at reduced pressure of zinc dust) dissolved in 50 mL of pyridinium poly(hydrogen fluoride) was slowly added 2.1 g (0.03 mol) of sodium nitrite. After being stirred at room temperature for 1 h, the solution was transferred to a stainless steel pressure vessel and heated to 85 °C for an additional hour. The reaction mixture was quenched with ice water and extracted with 250 mL of diethyl ether in three portions. The combined extracts were neutralized with 5% aqueous sodium bicarbonate and dried over anhydrous magnesium sulfate. After evaporation of the solvent, the crude product was distilled to yield 1.33 g (70% yield) of fluorobenzene, bp 85 °C (lit. bp 84.6 °C). The product was characterized by gas chromatography, using column B at 60 °C and 20 psig of He by comparison with authentic material.

Preparation of *p*-Bromonitrobenzene. To a solution of 13.8 g (0.40 mol) of ammonium bromide and 28 g (0.2 mol) of *p*-nitroaniline in 150 mL of pyridinium poly(hydrogen fluoride) was slowly added 0.14 g (0.17 mol) of sodium nitrite with stirring. After 1 h, the reaction was quenched with 100 mL of ice and extracted with 400 mL of diethyl ether in three portions. The combined ether extracts were neutralized with 5% aqueous sodium bicarbonate and dried over anhydrous magnesium sulfate. Evaporation of the solvent, followed by recrystallization from hexane, yielded 14 g (69% yield) of *p*-bromonitrobenzene, mp 125 °C (lit. mp 126 °C). The product was 97% pure as determined by gas chromatography on column A at 180 °C and 30 psig He.

Preparation of α-Fluoroacetophenone. To 100 mL of pyridinium poly(hydrogen fluoride) solution at −15 °C was slowly added 7.0 g (0.05 mol) of diazoacetophenone in 250 mL of diethyl ether so that the temperature of the solution did not exceed 0 °C (as measured by a Teflon-jacketed thermometer). After being warmed to room temperature and then stirred for 2 h, the product was isolated by extraction with 350 mL of pentane in three portions. Hydrogen fluoride was removed by treatment of the extract with anhydrous KF. After drying the solution over sodium sulfate, evaporation of the solvent yielded 3.5 g (51% yield), bp 62 °C (0.5 mm). The product α-fluoroacetophenone must be carefully freed from acid as it self-condenses readily.

Preparation of α-Bromo-α-fluoroacetophenone. To 12 g (0.07 mol) of *N*-bromosuccinimide dissolved in 100 mL of pyridinium poly(hydrogen fluoride) at −15 °C was slowly added 7.0 g (0.05 mol) of α-diazoacetophenone as described. The product was isolated as above, yielding 6.2 g (63% yield) of α-bromo-α-fluoroacetophenone, after recrystallization from petroleum ether (bp 35–40 °C), mp 70–72 °C.

Preparation of Ethyl Bromofluoroacetate. To 5.31 g (0.03 mol) of *N*-bromosuccinimide dissolved in 20 mL of pyridinium poly(hydrogen fluoride) at 0 °C was added, over 10 min, 2.3 g (0.02 mol) of ethyl diazoacetate (Aldrich) in 15 mL of diethyl ether. After being stirred at 0 °C for 0.5 h, the mixture was quenched with 50 mL of ice and extracted with 150 mL of diethyl ether in three portions. The combined extracts were washed with water, 5% aqueous sodium bicarbonate, and water and dried over anhydrous sodium sulfate. After concentration of the solution, 1.9 g (50% yield) of ethyl bromofluoroacetate was isolated by distillation, bp 68 °C (34 mm).

Preparation of α-Fluoroacetophone Using Mercuric Oxide. To 4.32 g (0.02 mol) of yellow mercuric oxide stirred in 30 mL of pyridinium poly(hydrogen fluoride) at 55 °C was added 1.99 g (0.01 mol) of α-bromoacetophenone. After the reaction mixture was stirred at 55 °C for 15 h, it was quenched with 75 mL of ice and extracted with 200 mL of benzene in three portions. The combined benzene extracts were washed with 5% aqueous sodium bicarbonate and water and dried over anhydrous magnesium sulfate. Crude α-fluoroacetophenone (0.940 g, 68% yield) was isolated by evaporation of the solvent. The product was characterized by ^{1}H NMR and found free of any trace of α-bromoacetophenone.

Preparation of α-Fluoroisobutyrophenone Using Mercuric Oxide. To 2.14 g (0.01 mol) of yellow mercuric oxide stirred in 30 mL of pyridinium poly(hydrogen fluoride) at 55 °C was added 0.91 g (0.005 mol) of α-chloroisobutyrophenone. After the reaction mixture was stirred at 55 °C for 53 h, the reaction was quenched and extracted as previously described. Crude α-fluoroisobutyropheone (0.55 g, 70% yield) was isolated by evaporation of the solvent. The product was characterized by ^{1}H NMR spectroscopy (60 MHz, $CDCl_3$), δ 5.4 (d, J_{HF} = 22 Hz).

Preparation of Methylcarbamyl Fluoride. Methyl isocyanate (1.14 g) was dissolved in 20 mL of pyridinium poly(hydrogen fluoride) in a polyethylene bottle at 0 °C. It was then stirred at room temperature for 24 h and extracted with chloroform. Chloroform was then carefully removed by distillation on a rotary evaporator. The residue was distilled under reduced pressure to obtain methylcarbamyl fluoride: bp 48–50 °C (6 mm); yield (0.6 g) 40%. The product was characterized by ^{1}H NMR and IR spectroscopy.

Preparation of Phenylcarbamyl Fluoride. Phenyl iso-

cyanate (1.19 g) was dissolved in 20 mL of pyridinium poly(hydrogen fluoride) in a polyethylene bottle and stirred at room temperature for 24 h. A stream of dry nitrogen was passed through the solution at 40 °C until practically all of the HF was removed and a semisolid was obtained. This semisolid was then dissolved in carbon tetrachloride and filtered. The filtrate, on evaporation, gave the phenylcarbamyl fluoride (0.8 g, 58%, mp 30–31 °C).

Benzoyl Fluoride. (i) From Benzoyl Chloride. To 5 mL of pyridinium poly(hydrogen fluoride) in a polyethylene bottle was added 1.48 g of benzoyl chloride. Evolution of hydrogen chloride was visible. The solution was stirred for 10 min, cooled to 0 °C, and quenched with 5 mL of ice–water. It was then extracted with benzene, washed with 5 mL of ice cold water followed by a solution of brine, and dried over anhydrous sodium sulfate. Evaporation of the solvent gave almost pure benzoyl fluoride which was further purified by distillation: yield 1.25 g, 92%; bp 149–160 °C.

(ii) From Benzoic Anhydride. To 5 mL of pyridinium poly(hydrogen fluoride) in a polyethylene bottle was added a solution of 2.2 g of benzoic anhydride in 3 mL of chloroform. The mixture was stirred for 10 min at room temperature, cooled to 0 °C, and then quenched with 5 mL of ice–water. It was then extracted with an additional 5 mL of chloroform, washed with 5 mL of ice water followed by a solution of brine, and dried over anhydrous sodium sulfate. Evaporation of the solvent gave a mixture of benzoic acid and benzoyl fluoride. Fractional distillation under reduced pressure gave pure benzoyl fluoride: 1.15 g; yield 92%; bp 75–77 °C (10 mm).

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Registry No. Propene, 115-07-1; cyclopropane, 75-19-4; 2-butene, 107-01-7; 2-methylpropene, 115-11-7; cyclopentene, 142-29-0; cyclohexene, 110-83-8; norbornene, 498-66-8; cycloheptene, 628-92-2; 1-hexyne, 693-02-7; 3-hexyne, 928-49-4; isopropyl fluoride, 420-26-8; propyl fluoride, 460-13-9; *sec*-butyl fluoride, 359-01-3; *tert*-butyl fluoride, 353-61-7; cyclopentyl fluoride, 1481-36-3; cyclohexyl fluoride, 372-46-3; 2-norbornyl fluoride, 694-95-1; cycloheptyl fluoride, 51443-95-9; 2,2-difluorohexane, 371-91-5; 3,3-difluorohexane, 358-68-9; ethene, 74-85-1; diphenylacetylene, 501-65-5; 1-iodo-2-fluoroethane, 762-51-6; 1-iodo-2-fluoropropane, 20174-93-0; 1-iodo-2-fluoro-2-methylpropane, 19869-79-5; 1-iodo-2-fluorohexane, 1786-51-2; 3-iodo-4-fluorohexane, 51443-96-0; 1-iodo-2-fluorocyclohexane, 656-59-7; 7-*anti*-iodo-2-*exo*-fluoronorbornane, 51443-97-1; 7-*syn*-iodo-2-*exo*-fluoronorbornane, 51443-98-2; 3-iodo-4-fluorohex-3-ene, 51443-99-3; 1-iodo-2-fluoro-1,2-diphenylethene, 51444-00-9; 2-butyne, 503-17-3; 1-bromo-2-fluoroethane, 762-49-2; 1-bromo-2-fluoropropane, 1871-72-3; 1-bromo-2-fluoro-2-methylpropane, 19869-78-4; 1-bromo-2-fluorohexane, 1871-74-5; 3-bromo-4-fluorohexane, 51444-01-0; 1-bromo-2-fluorocyclohexane, 656-57-5; 7-*anti*-bromo-2-*exo*-fluoronorbornane, 51444-02-1; 7-*syn*-bromo-2-*exo*-fluoronorbornane, 51444-03-2; 2-bromo-3-fluorobut-2-ene, 51444-04-3; 3-bromo-4-fluorohex-3-ene, 51444-05-4; 1-bromo-2-fluoro-1,2-diphenylethene, 720-41-2; 1-hexene, 592-41-6; 3-hexene, 592-47-2; 1-chloro-2-fluoropropane, 430-46-6; 1-chloro-2-fluoro-2-methylpropane, 19752-20-6; 1-chloro-2-fluorohexane, 51444-06-5; 3-chloro-4-fluorohexane, 51444-07-6; 1-chloro-2-fluorocyclohexane, 4536-11-2; 7-*anti*-chloro-2-*exo*-fluoronorbornane, 51444-08-7; 7-*syn*-chloro-2-*exo*-fluoronorbornane, 51444-09-8; 3-chloro-4-fluorohex-3-ene, 51444-10-1; 1-chloro-2 fluoro-1,2-diphenylethane, 71370-23-5; 2,3-dimethylbut-2-ene, 563-79-1; stilbene, 588-59-0; 2,3-difluoro-2,3-dimethylbutane, 17603-29-1; 3,4-difluorohexane, 51444-11-2; 1,2-difluorocyclohexane, 51444-12-3; 1,2-difluoro-1,2-diphenylethane, 345-82-4; chloroethene, 75-01-4; 1,1-dichloroethene, 75-35-4; 1-fluoro-2-nitroethane, 4528-33-0; 2-fluoro-1-nitropropane, 674-86-2; 2-fluoro-3-nitrobutane, 50998-14-6; 2-fluoro-1-nitrohexane, 50998-15-7; 1-chloro-1-fluoro-2-nitroethane, 461-70-1; 1,1-dichloro-1-fluoro-2-nitroethane, 1649-05-4; 1-fluoro-2-nitrocyclohexane, 50998-16-8; methyl isocyanate, 624-83-9; phenyl isocyanate, 103-71-9; *o*-tolyl isocyanate, 614-68-6; *p*-tolyl isocyanate, 622-58-2; methylcarbamyl fluoride, 51229-17-5; phenylcarbamyl fluoride, 458-91-8; *o*-tolylcarbamyl fluoride, 71370-24-6; *p*-tolylcarbamyl fluoride, 370-88-7; isopropyl alcohol, 67-63-0; *sec*-butyl alcohol, 78-92-2; *tert*-butyl alcohol, 75-65-0; 3-ethyl-3-pentyl alcohol, 597-49-9; 3-methyl-3-heptyl alcohol, 5582-82-1; 3-methyl-4-heptyl alcohol, 1838-73-9; cyclohexyl alcohol, 108-93-0; 2-norbornyl alcohol, 1632-68-4; 1-adamantyl alcohol, 768-95-6; 2-adamantyl alcohol, 700-57-2; α-phenylethyl alcohol, 98-85-1; triphenylmethyl alcohol, 76-84-6; 3-ethyl-3-pentyl fluoride, 649-80-9; 3-methyl-3-heptyl fluoride, 51010-71-0; 3-methyl-4-heptyl fluoride, 51010-72-1; 1-adamantyl fluoride, 768-92-3; 2-adamantyl fluoride, 16668-83-0; α-phenylethyl fluoride, 7100-97-2; triphenylmethyl fluoride, 427-36-1; *n*-hexyl alcohol, 111-27-3; *n*-octyl alcohol, 111-87-5; 2,2-dimethylpropyl alcohol, 75-84-3; cyclopentyl alcohol, 96-41-3; *n*-pentyl alcohol, 71-41-0; 2-methyl-1-butyl alcohol, 137-32-6; 2-octyl alcohol, 123-96-6; benzyl alcohol, 100-51-6; *n*-hexyl fluoride, 373-14-8; *n*-octyl fluoride, 463-11-6; 2,2-dimethylpropyl chloride, 753-89-9; 2,2-dimethylpropyl bromide, 630-17-1; 2,2-dimethylpropyl iodide, 15501-33-4; cyclohexyl chloride, 542-18-7; cyclohexyl bromide, 108-85-0; cyclohexyl iodide, 626-62-0; cyclopentyl chloride, 930-28-9; cyclopentyl bromide, 137-43-9; cyclopentyl iodide, 1556-18-9; 1-adamantyl chloride, 935-56-8; 1-adamantyl bromide, 768-90-1; 1-adamantyl iodide, 768-93-4; 2-adamantyl chloride, 7346-41-0; 2-adamantyl bromide, 7314-85-4; 2-adamantyl iodide, 18971-91-0; *n*-pentyl chloride, 543-59-9; *n*-pentyl bromide, 110-53-2; *n*-pentyl iodide, 628-17-1; 2-methyl-1-butyl chloride, 616-13-7; 2-methyl-1-butyl bromide, 10422-35-2; 2-methyl-1-butyl iodide, 616-14-8; 2-octyl chloride, 628-61-5; 2-octyl bromide, 557-35-7; 2-octyl iodide, 557-36-8; *exo*-2-norbornyl chloride, 765-91-3; *exo*-2-norbornyl bromide, 2534-77-2; *exo*-2-norbornyl iodide, 30983-85-8; benzyl chloride, 100-44-7; benzyl bromide, 100-39-0; benzyl iodide, 620-05-3; *tert*-butyl chloride, 507-20-0; *tert*-butyl iodide, 558-17-8; glycine, 56-40-6; alanine, 6898-94-8; 2-aminobutanoic acid, 80-60-4; valine, 72-18-4; leucine, 61-90-5; isoleucine, 73-32-5; phenylalanine, 63-91-2; tyrosine, 60-18-4; serine, 56-45-1; threonine, 72-19-5; aspartic acid, 56-84-8; glutamic acid, 56-86-0; fluoroacetic acid, 144-49-0; 2-fluoropropionic acid, 6087-13-4; 2-fluorobutanoic acid, 433-44-3; 2-fluoro-3-methylbutanoic acid, 1578-62-7; 2-fluoro-4-methylpentanoic acid, 6087-17-8; 2-fluoro-3-methylpentanoic acid, 6087-16-7; 2-fluoro-3-phenylpropanoic acid, 457-45-4; 2-fluoro-3-(*p*-hydroxyphenyl)propanoic acid, 53786-98-4; 2-fluoro-3-hydroxypropanoic acid, 359-27-3; 2-fluoro-3-hydroxybutanoic acid, 53786-99-5; fluorobutanedioic acid, 687-50-3; 2-fluoropentanedioic acid, 1578-67-2; methyl carbamate, 598-55-0; ethyl carbamate, 51-79-6; propyl carbamate, 627-12-3; isopropyl carbamate, 1746-77-6; butyl carbamate, 592-35-8; *sec*-butyl carbamate, 2114-15-0; isobutyl carbamate, 543-28-2; *tert*-butyl carbamate, 4248-19-5; methyl fluoroformate, 1538-06-3; ethyl fluoroformate, 461-64-3; propyl fluoroformate, 2105-91-1; isopropyl fluoroformate, 461-71-2; butyl fluoroformate, 2253-35-2; *sec*-butyl fluoroformate, 352-22-7; isobutyl fluoroformate, 53813-78-8; *tert*-butyl fluoroformate, 18595-34-1; aniline, 62-53-3; *o*-methylaniline, 95-53-4; *m*-methylaniline, 108-44-1; *p*-methylaniline, 106-49-0; *o*-nitroaniline, 88-74-4; *m*-nitroaniline, 99-09-2; *p*-nitroaniline, 100-01-6; *o*-(trifluoromethyl)aniline, 88-17-5; *m*-(trifluoromethyl)aniline, 98-16-8; fluorobenzene, 462-06-6; *o*-methylfluorobenzene, 95-52-3; *m*-methylfluorobenzene, 352-70-5; *p*-methylfluorobenzene, 352-32-9; *o*-nitrofluorobenzene, 1493-27-2; *m*-nitrofluorobenzene, 402-67-5; *p*-nitrofluorobenzene, 350-46-9; *o*-(trifluoromethyl)fluorobenzene, 392-85-8; *m*-(trifluoromethyl)fluorobenzene, 401-80-9; benzoyldiazomethane, 3282-32-4; (cyclohexylcarbonyl)diazomethane, 31151-40-3; propionyldiazomethane, 6831-84-1; 1-phenyl-2-fluoroethanone, 450-95-3; 1-phenyl-2-chloro-2-fluoroethanone, 447-15-4; 1-phenyl-2-bromo-2-fluoroethanone, 321-75-5; 1-phenyl-2-fluoro-2-iodoethanone, 447-16-5; 1-cyclohexyl-2-fluoroethanone, 768-04-7; 1-cyclohexyl-2-chloro-2-fluoroethanone, 54867-84-4; 1-cyclohexyl-2-bromo-2-fluoroethanone, 54867-85-5; 1-cyclohexyl-2-fluoro-2-iodoethanone, 54867-86-6; 1-fluoro-2-butanone, 453-10-1; 1-chloro-1-fluoro-2-butanone, 54867-87-7; 1-bromo-1-fluoro-2-butanone, 54867-88-8; 1-fluoro-1-iodo-2-butanone, 54867-89-9; (ethoxycarbonyl)diazomethane, 623-73-4; ethyl fluoroacetate, 459-72-3; ethyl chlorofluoroacetate, 401-56-9; ethnyl bromofluoroacetate, 401-55-8; ethyl fluoroiodoacetate, 401-58-1; benzyl fluoride, 350-50-5; 1,1-dichloropropane, 78-99-9; α-bromoacetophenone, 70-11-1; 2-bromo-3-pentanone, 815-52-1; α-bromopropionic acid, 598-72-1; α-chloropropiophenone, 6084-17-9; 1,1-difluoropropane, 430-61-5; α-fluoroacetophenone, 450-95-3; 2-fluoro-3-pentanone, 17042-20-5; α-fluoropropionic acid, 6087-13-4; α-fluoropropiophenone, 21120-36-5; acetyl fluoride, 557-99-3; propionyl fluoride, 430-71-7; butanoyl fluoride, 461-53-0; undecanoyl fluoride, 1599-06-0; cyclohexanoyl fluoride, 1977-87-3; benzoyl fluoride, 455-32-3; phenylacetyl fluoride, 370-84-3; acetyl chloride, 75-36-5; propionyl chloride, 79-03-8; undecanoyl chloride, 17746-05-3; cyclohexanoyl chloride, 2719-27-9; benzoyl chloride, 98-88-4; phenylacetyl chloride, 103-80-0; acetic acid anhydride, 108-24-7; propanoic acid anhydride, 123-62-6; butanoic acid anhydride, 106-31-0; benzoic acid anhydride, 93-97-0; pyridinium polyhydrogen fluoride, 62778-11-4; *p*-(trifluoromethyl)aniline, 455-14-1; (diazomethyl)benzene, 766-91-6; *p*-bromonitrobenzene, 586-78-7; α-fluoroisobutyrophenone, 71057-10-8; α-chloroisobutyrophenone, 7473-99-6.