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Stable Dialkyl Ether/Poly(Hydrogen Fluoride) Complexes: Dimethyl Ether/Poly(Hydrogen Fluoride), A New, Convenient, and Effective Fluorinating Agent[1a]

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Abstract: The preparation, ^{1}H, ^{13}C, and ^{19}F NMR structural characterization as well as with DFT-based theoretical calculations of stable dialkyl ether/poly(hydrogen fluoride) complexes are reported. Dimethyl ether/poly(hydrogen fluoride) (DMEPHF), are stable complexes of particular interest and use. The DFT calculations, that are in agreement with NMR data, suggest a cyclic poly(hydrogen fluoride) bridged structure for DMEPHF. The complex, DME-5 HF was found to be a convenient and effective new fluorinating agent with the ease of workup and applied to several fluorination reactions, such as the hydrofluorination and bromofluorination of alkenes, and fluorination of alcohols giving good to excellent yield with high selectivity. Homologous dialkyl ether/poly(hydrogen fluoride) ($R_2O/[HF]_n$, R = Et, nPr) systems are also stable and suitable for fluorination reactions.

Introduction

The rapidly growing number of organofluorine compounds, especially in materials and pharmaceutical sciences, justifies the further search for convenient and safe fluorinating reagents.[1b] Anhydrous hydrogen fluoride (AHF) is the cheapest and most widely used fluorinating agent. However, due to its volatility, high reactivity, corrosiveness and toxic nature, the use of AHF requires special experimental setup and handling. Extensive efforts have been made to render AHF less toxic, safe and convenient in handling by developing modified HF reagents.[1−3] As a result, effective alternatives were developed, such as our pyridinium/poly(hydrogen fluoride) (PPHF, Olah's reagent),[4] and poly(vinylpyridinium)/poly(hydrogen fluoride) (PVPHF)[5,6] complexes and a series of HF/amine complexes.[7] The pyridinium/poly(hydrogen fluoride) (30/70) system was found to be a versatile fluorinating agent and is used in a wide variety of fluorination reactions.[4] On the basis of the successful stabilization of HF with pyridine other amines were also employed. As a result, amine-stabilized HF reagents became widely used in organofluorine chemistry.[1−3] The preparation of the solid poly(vinylpyridine)/poly(hydrogen fluoride) (PVPHF)[5,6] complex resulted in substantial improvements due to easy workup, compared to the liquid amine/HF reagents.[1−3,7] Although, these reagents function as suitable forms of HF, some difficulties of separation, handling and stability still remain.

Stable alkyl ether/poly(hydrogen fluoride) complexes, have not yet been reported. Despite the fact that HF forms complex with several O-containing compounds,[8,9] these adducts were not isolated nor characterized or explored as fluorinating reagents. The only relevant report is the use of HF/tetrahydrofuran (THF) mixtures and its utilization in polymerization of THF.[10]

We now report the preparation of stable dialkyl ether/poly(hydrogen fluoride) complexes ($R_2O/[HF]_n$, R = Me, Et, nPr). The dimethyl ether/poly(hydrogen fluoride) systems, as representatives of the broad class of dialkyl ether/poly(hydrogen fluoride) complexes, were studied in detail. The structural characterization of the complexes was carried out by ^{1}H, ^{13}C, and ^{19}F NMR spectroscopy. The spectroscopic data and density functional theory (DFT) calculations indicate preferred cyclic structure for these complexes. The complexes were found to be generally applicable, new fluorinating reagents. Their advantageous use has been illustrated through applications, such as hydrofluorination and bromofluorination of alkenes and fluorination of alcohols.

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Table 1. Preparation of and Characterization of DMEPHF Complexes of Various Molar Ratios

starting mol ratio DME:HF	measured mol ratio of the complex DME:HF	NMR mol ratio of the complex DME:HF	density g cm^{-3}
2:1	2:1.20	1:1.29	0.87
1:1	1:1.20	1:1.26	0.87
1:2	1:2.30	1:2.28	0.90
1:3	1:3.26	1:3.54	0.93
1:4	1:4.26	1:4.38	0.96
1:5	1:5.21	1:5.44	0.98
1:10	1:10.12	−	0.99

Table 2. ^{1}H, ^{13}C, and ^{19}F NMR Characterization of DMEHF Complexes of Various Molar Ratios at 20 °C

HF:DME ratio	δ ^{1}H(CH$_3$) ppm	δ ^{1}H(HF) ppm	δ ^{13}C ppm	δ ^{19}F ppm
neat DME	3.13	−	59.9	−
neat HF	−	9.02	−	−191.0
1.26	3.28	9.06	59.9	−194.5
1.74	3.36	9.25	60.0	−192.8
2.28	3.40	9.30	60.1	−191.9
3.54	3.47	9.22	60.3	−191.1
5.44	3.50	9.09	60.5	−191.0

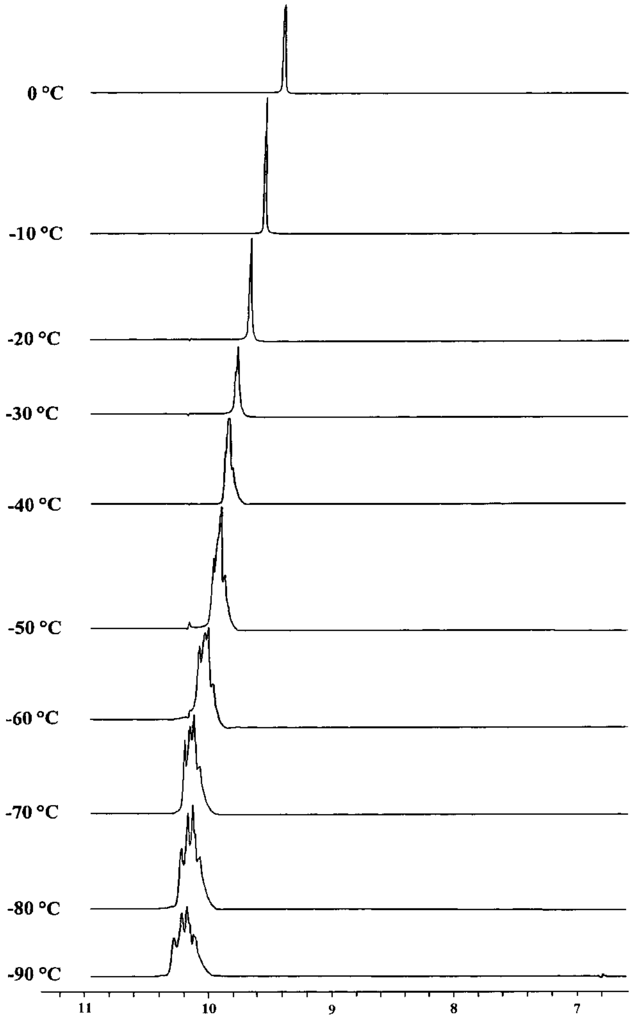

Figure 1. ^{1}H NMR signals of H(F) in DMEHF complex (HF:DME = 3:1) as a function of temperature.

Results and Discussion

Preparation of DMEPHF Complexes. The preparation of the dimethyl ether/HF complexes is carried out through the careful addition of liquid hydrogen fluoride (HF) to the ether at −78 °C. The complex formation is somewhat exothermic, and initially HF should be added very carefully. The preparation of the DMEPHF complexes independent of the relative ratio of the components can be carried out by mixing dimethyl ether (DME) and hydrogen fluoride (HF) in their condensed forms. Although no vigorous heat generation is observed, initially HF should be added in small portions. After reaching the 1:1 molar ratio no further exothermic reaction ensues. Complexes of higher HF/DME ratios can be prepared by addition of further calculated amounts of HF (Table 1).

As shown in Table 1, it is not possible to prepare stable complexes with excess DME. When preparation of a DME/HF = 2:1 complex was attempted, it showed extensive and rapid initial weight loss that gradually decreased and finally stabilized with a composition of the stable mixture (^{1}H NMR) with the ratio of DME to HF of 1:1.29. This ratio is identical to that obtained while attempting to prepare 1:1 complex ratio (1:1.26). According to earlier studies, amine/Lewis base/HF systems form hydrogen-bonded poly(hydrogen fluoride) complexes with no indication of “naked” F^{-} ions.[11] This accounts for the increased higher amount of HF in the stable composition. The DME/HF complex with 1:1.3 ratio can be considered as the stable reagent system with the lowest ratio of HF.

The DME/HF (1:1.3) mixture does not fume. However, with increase in HF concentration a slight fuming is observed upon exposure to air. The HF concentration can be increased up to HF/DME ratio of 10 without significant decrease in stability. After preparation, the mixture can be stored at room temperature for months without any loss of weight or activity. Samples stored in a desiccator or under dry air showed the same activity in applications indicating the stability of the reagent system. Physicochemical characteristics, such as density and NMR data were determined. As shown (Table 1), the densities of the mixtures gradually increase and the densities of the 1:5 to 1:10 reagents are close to that of pure liquid HF as expected. The DME/HF complexes exhibit high thermal stability and can be distilled under atmospheric pressure. It should be noted, that some weight loss was observed upon heating at atmospheric pressure and due to this the ratios slightly changed during distillation. The distillation of DME/HF (1:1.3) mixture at 80 °C, resulted in a 1:1.8 mixture. However, about 80% of the original amount was recovered, and no extensive decomposition took place. In contrast, the fractional distillation of DME/HF(1:5) resulted in mixtures with varying molar ratios, the ratio in first fraction was ∼1:7. Subsequently, the ratio gradually decreased and the last (fourth) fraction corresponded to 1:4 molar ratio. Earlier studies on dimethyl ether/hydrogen chloride complexes[12] and a recent gas phase study of dimethyl ether/HF complex by cell and supersonic jet/FTIR experiments[13] have demonstrated the stability of such complexes even in the gas phase.

Similarly, homologous higher dialkyl ether/HF (1:5) complexes, which were expected to be effective reagents, were also

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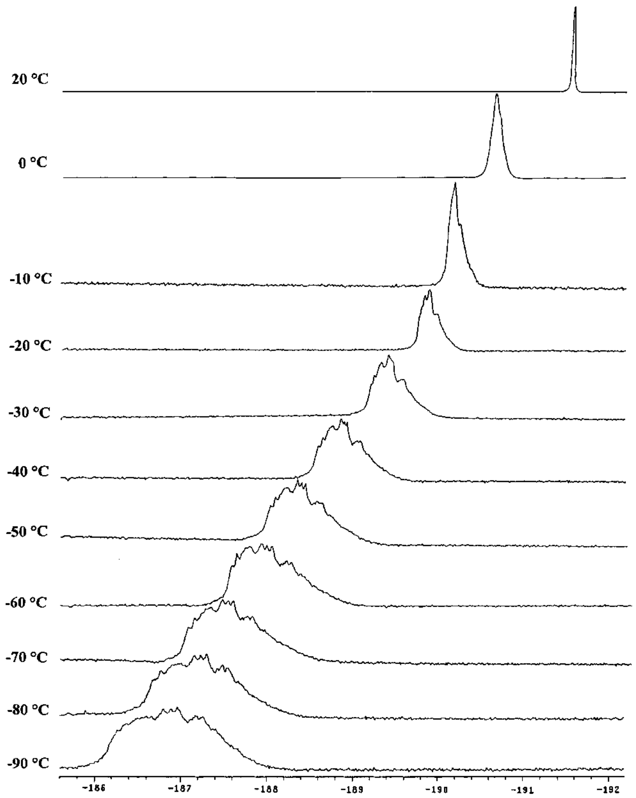
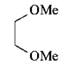
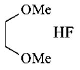


Figure 2. ^{19}F NMR signals of DMEHF complex (HF:DME = 3:1) as a function of temperature.

prepared and studied. The complexes are stable and only a slight fuming is observed on exposure to air. The diethyl ether (DEE) and dipropyl ether (DPE) complexes were found to be stable and can be stored at room temperature for a considerable time without significant loss of weight or activity. Unlike DEE and DPE, hydrogen fluoride complexes of higher dialkyl ethers can also be prepared. However, they show limited or no stability at room temperature. The freshly prepared colorless complexes became dark, reddish-brown solutions indicating the formation of decomposition products. In the case of methyl-*tert*-butyl ether (MTBE), after 1h the formation of a two-layer system was observed. The hydrocarbon phase is a multicomponent mixture of C_8 and higher hydrocarbons (mostly alkenes) and higher molecular weight ethers. The other phase was found to be CH_3OH/HF complex. This indicates the cleavage of MTBE and the subsequent formation of *tert*-butyl cation, which can initiate oligomerization reactions.

Characterization of $R_2O/[HF]_n$ complexes by ^1H, ^{13}C, and ^{19}F NMR Spectroscopy. To learn more about the structural properties of the R_2O-$[HF]_n$ complexes extended NMR studies were carried out, particularly on the dimethyl ether/poly-(hydrogen fluoride complexes. In the ^1H NMR studies, chemical shifts of both methyl group in the DME and HF were determined for each complex prepared. Although DME and HF are both gases at room temperature, they are quite soluble in $CDCl_3$, allowing the determination of chemical shifts for the parent compounds. These values are δ 3.13 (s, CH_3) and $\sim\delta$ 7.5 (b, HF). When studying HF in a more dilute solution (5-fold dilution) a sharp peak appeared at δ 9.1, indicating the presence of close to monomeric HF-like species. The ^1H NMR chemical shifts for the varied complex ratios are shown in Table 2.

Table 3. ^1H, ^{13}C, and ^{19}F NMR Characterization of Higher Dialkyl Ether/HF Complexes

Ether complex	δ $^1H(CH_3)$ ppm	δ $^1H(HF)$ ppm	δ ^{13}C ppm	δ ^{19}F ppm
HF	-	9.02	-	-191.0
Et_2O	3.23(q), 0.96(t)	-	65.7, 14.5	-
Et_2O-HF	3.86(q), 1.29(t)	9.56	67.4, 14.1	-187.1
nPr_2O	3.35(t), 1.59(m), 0.91(t)	-	72.7, 23.1, 10.7	-
nPr_2O-HF	3.71(t), 1.69(m), 0.92(t)	9.41	74.7, 21.3, 9.4	-187.2
nBu_2O	3.33(t), 1.49(m) 1.30(m), 0.85(t)	-	70.7, 32.0, 19.5 13.9	-
nBu_2O-HF	3.76(t), 1.64(m) 1.33(m), 0.90(t)	9.36	73.1, 30.0, 18.6 13.2	-187.1
*t*BuOMe	2.92(s), 0.90(s)	-	72.3, 49.0, 26.7	-
*t*BuOMe-HF[a]	3.66 (s)	6.61	-[b]	-188.9
	3.28, 3.13(s)	-	71.7, 58.8	-
	3.83, 3.35(s)	8.33	-[b]	-190.3

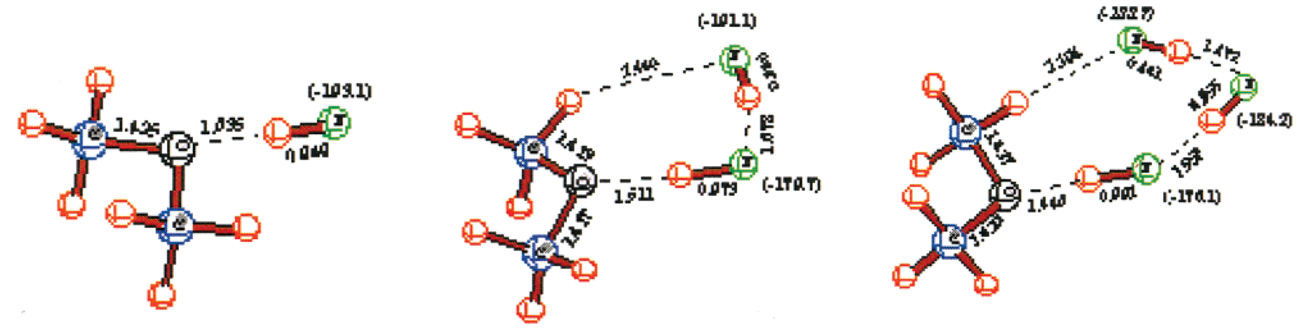
[a] According to the analysis this complex is in fact CH_3OH/HF due to the cleavage of MTBE. [b] Due to solubility problems these data could not be obtained.

In the DMEPHF samples only the sharp peak at $\sim\delta$ 9.1−9.3 appeared, indicating a low level of self-association of HF in these mixtures. As expected, the CH_3 signal of DME shows increased deshielding as the HF ratio increases. To distinguish between hydrogen-bonded and protonated oxonium ion nature of the complexes, low-temperature NMR measurements (down to −90 °C) were also carried out. The NMR spectrum of dimethyloxonium ion (prepared in $FSO_3H/SbF_5/SO_2$) is known, and shows a broad multiplet at $\sim\delta$ 9.2 (OH^+) and a sharp doublet at δ 4.5 (CH_3) at −60 °C.[9] In the DMEPHF complexes none of these peaks were found. The slight downfield shift of the CH_3 signal indicates a more electronegative environment, however, no significant O-protonation can be considered. On the basis of these data, DMEPHF complexes are most likely hydrogen-bonded complexes and are not Meerwein-type acidic oxonium ions.[8] However, an interesting observation was made concerning the absorption of the HF proton signals as a function of temperature, which is shown in Figure 1. Analyzing the spectra, no evidence for the disproportionation of the complex to trimethyloxonium ion was obtained.

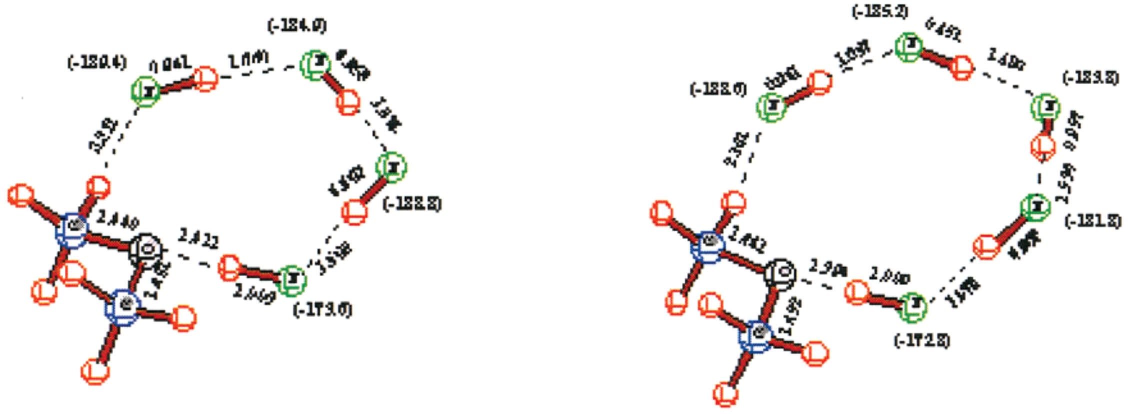
The $^1H(F)$ absorption changed, and was shifted gradually to a lower field by lowering the temperature. The deshielding of the ^1H NMR shifts is as large as $\sim$1 ppm. As an additional effect of decreasing temperature, the signal broadened and a splitting was observed. The appearance of the ^1H absorption at varied chemical shifts indicates the presence of different acidic protons.

Similar to ^1H NMR measurements ^{13}C NMR chemical shifts were also determined with increasing HF concentration. The results are summarized in Table 2.

The trend in the changes of ^{13}C NMR chemical shifts of DME also follows that observed in the ^1H NMR investigations, namely, slight downfield shift of the CH_3 signal.



1, C_S [E = -255.57702 Hartrees] **2**, C_1 [E = -356.07466 Hartrees] **3**, C_1 [E = -456.57351 Hartrees]



4, C_S [E = -557.07125 Hartrees] **5**, C_1 [E = -657.56821 Hartrees]

Figure 3. B3LYP/6-311+G** calculated structures, energies [in brackets] and IGLO chemical shifts (in parentheses) of **1**−**5**.

The ^{19}F NMR chemical shifts gradually move to higher field with increasing HF concentration and finally reach the chemical shift of pure HF (Table 2).

A relatively large difference in ^{19}F NMR chemical shift values (∼4.5 ppm) can be found between DME/HF (1:1.3) and pure HF (recorded in $CDCl_3$). It can be explained by the inductive effect of DME in the hydrogen-bonded network. As the HF concentration increases, this difference gradually decreases. The difference of the ^{19}F NMR chemical shift of DME/HF(1/5) complex compared to pure HF is negligible. Variable-temperature ^{19}F NMR measurements (Figure 2) are similar to that of variable temperature ^{1}H NMR studies (Figure 1). The ^{19}F NMR signal showed a deshielding with gradual splitting and broadening, indicating again the presence of different F-species.

Similar ^{1}H, ^{13}C, and ^{19}F NMR spectroscopic characterization of the higher homologous dialkyl ether/poly(hydrogen fluoride) complexes was also carried out and data are summarized in Table 3.

Theoretical Calculations. As the NMR data suggested a hydrogen-bonded structure for the DMEPHF complexes, theoretical calculations were carried out to obtain more insight into its molecular structure. Structures of DMEPHF complexes with different compositions were computed using the density functional theory method (DFT)[14] at the B3LYP[15]/6-311+G** level[16] using the Gaussian-98[17] package of programs. Recently, Rankin and Boyd have calculated[18] the structure of hydrogen-bonded dimer of HF at the B3LYP/6-311+ (2df,p) level and found results that matched experimental values very closely, supporting the reliability of the DFT method. The minimum energy structure for 1:1 complex of DME and HF was found to be of C_s symmetry **1**. Selected optimized parameters are shown in Figure 3.

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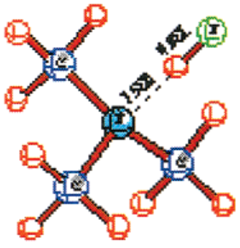
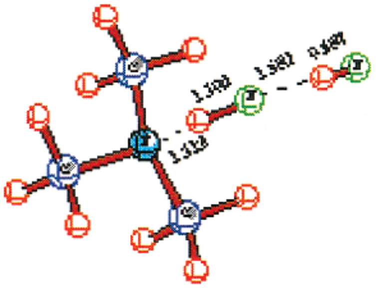
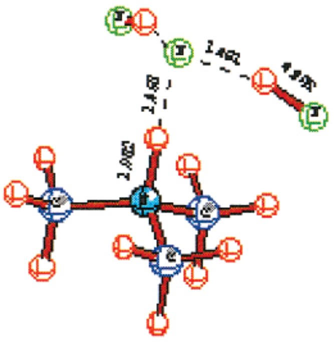


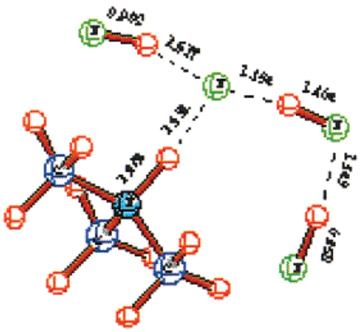
6, C_{3v} [E = -275.03433 Hartrees]



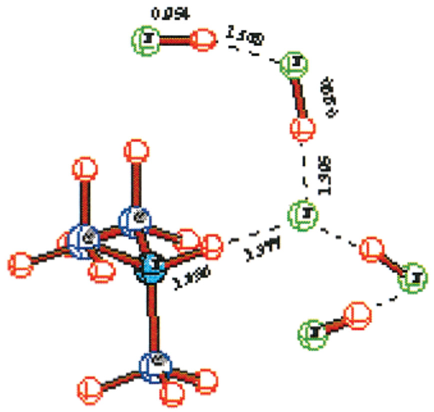
7, C_s [E = -375.53630 Hartrees]



8, C_s [E = -476.04360 Hartrees]



9, C_1 [E = -576.54926 Hartrees]



10, C_s [E = -677.05256 Hartrees]

Figure 4. B3LYP/6-311+G** calculated structures, energies [in brackets] of **6**−**10**.

The critical H−O bond distance of **1** is 1.635 Å. This indicates that the structure **1** is a moderately strong hydrogen-bonded complex. Dissociation of **1** into DMF and HF was calculated to be endothermic by 8.8 kcal/mol.

The minimum-energy structure for 1:2 complex of Me_2O and HF was found to be of C_1 symmetry **2** (Figure 3). The H−O bond distance of **2** is 1.511 Å. This is 0.124 Å shorter than that of **1**. This shows that the HF is more strongly hydrogen-bonded to the oxygen in **2** than in **1**. Similarly, structures of 1:3, 1:4, and 1:5 complexes of DMF and HF, **3**, **4**, and **5**, respectively, were also calculated and depicted in Figure 3. With the increase in the number of HF molecules, the H−O bond length becomes increasingly shorter reaching 1.394 Å for 1:5 complex **5**. However, structure **5** is still may not be considered as an oxonium ion. It is significant to note that as shown in Figure 3, the complexes have a tendency to form cyclic structures. Such cyclic structures start to form at DME/HF ratio of 1:2 and remain favored with increasing HF amounts. With the increase in the number of HF molecules the CH···F bond lengths become increasingly shorter due to an increase in the oxonium ion character. Such an increase in the oxonium ion character in turn enhances the acidic nature of the C−H bond, resulting in better C−H···F hydrogen bonding. Dissociation of **2** into **1** and HF was calculated to be also endothermic by 7.5 kcal/mol. The ^{19}F NMR chemical shifts of the complexes (**1**−**5**) using B3LYP/6-311+G** geometries were calculated by the IGLO[19] (individual gauge for localized orbital) method and are shown in Figure 3. According to the calculations, the different F and H species can be observed in the corresponding NMR spectra at lower temperatures (Figures 1 and 2). Although the experimental and the calculated chemical shifts slightly vary, it can be explained on the basis of strong solvent dependence of ^{19}F NMR chemical shifts[20] compared to the calculated theoretical shifts in the idealized gas phase.

Our data are in agreement with the previous gas-phase study of the DME/HF (1:1) complex,[13] and its calculated structure. They provide interesting new insights into the structural arrangement of higher HF-containing complexes. As shown, our calculations suggest a cyclic structure for the HF/DME (ratio 2 and higher) complexes. It should be also noted that a similar arrangement was suggested for the diethyl ether/HF (1:1)

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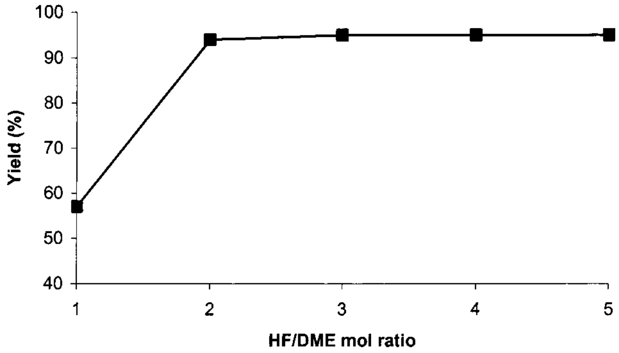


Figure 5. Effect of HF/DME mol ratio on the yield of hydrofluorination of 2,3-dimethyl-2-butene.

complex based on the FT-IR measurements, where the C_2 alkyl chain make the formation of the cyclic structure facile.[21]

For comparison we have also calculated the complexes of Me_3N and HF at the B3LYP/6-311+G** level (Figure 4).

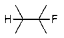
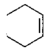
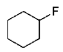
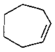
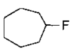
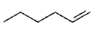
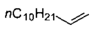
The minimum-energy structure for 1:1 complex of Me_3N and HF was found to be of C_{3v} symmetry **6**. The H−N bond distance in **6** is 1.588 Å. The minimum energy structure for 1:2 complex of Me_3N and HF was computed to be of C_s symmetry **7** (Figure 4). The H−N bond distance of **7** is 1.313 Å. Structures of 1:3, 1:4, and 1:5 complexes of Me_3N and HF, **8**, **9**, and **10**, respectively, were also calculated and depicted in Figure 4. The calculations show good correlation with crystal structures determined by X-ray diffraction.[22] However, unlike DMEHF, structures **8**, **9**, and **10** can be considered as ammonium ions solvated by F^- $(HF)_n$ ($n = 2$, 3, and 4) with H−N bond lengths of 1.082, 1.064, and 1.056 Å, respectively.

As the data indicate, the complexes of DME and HF are remarkably stable liquids with cyclic, hydrogen-bonded poly(hydrogen fluoride)-type structures.

Application of Dialkyl Ether/Poly(hydrogen fluoride) Complexes in Fluorination Reactions. Dimethyl Ether/Poly(hydrogen fluoride) (DMEPHF). The DMEPHF reagents with various DME/HF ratios were probed to select the most suitable ratio for fluorination reactions. Hydrofluorination of 2,3-dimethyl-2-butene was selected as the test reaction for this purpose. 2-Fluoro-2,3-dimethylbutane was isolated in all reactions as the only product with high purity. The variation of yields as a function of reagent composition is shown in Figure 5.

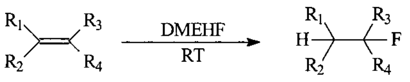
As shown on Figure 5 the 1/1.3 (close to 1/1) mixture gave only a moderate 57% yield, while the other complexes with higher HF ratios resulted in excellent (94−95%) yields under similar experimental conditions. Regarding activity, it can be concluded, that the ~1/1.3 mixture is not preferable for hydrofluorination. However, all the other complexes gave excellent results, when HF is at least in 1 molar excess compared to DME. We selected DMEPHF with a 1:5 ratio for a comprehensive study of fluorination reactions. This complex contains the least amount of DME, necessary for the stabilization of poly(hydrogen fluoride).

Table 4. Hydrofluorination of Alkenes with DMEHF (1/5) Reagent

Subsrate	Temperature C	Reaction time H	Product	Yield %	Selectivity %
	RT	1		94	100
	RT	3		92	100
	RT	3		77	100
	RT	1	$C_6H_{11}F$	73	2 isomers[a]
	RT	1	$C_{12}H_{25}F$	90	3 isomers[b]
	RT	3		83	<1% *endo*

[a] 2-Fluorohexane (68%) and 3-fluoro-hexane (32%). [b] 2-Fluoro-dodecane (46%), 3-fluoro-dodecane (30%) and 4-fluoro-dodecane (24%).

DMEPHF(1:5) was used in hydrofluorination of various alkenes. The reactions were carried out at room temperature under atmospheric pressure.



R_1, R_2, R_3, R_4 = H or alkyl

Since most alkenes used were liquids, the reactions were carried out without solvent except in the case of norbornylene, where CH_2Cl_2 was used as the solvent. In most cases the reaction mixtures turn homogeneous after an induction period (5−30 min), with the exception of 1-dodecene, where the hydrofluorination took place in a two-phase system. The results are listed in Table 4.

As can be seen from Table 4 hydrofluorinations resulted in good-to-excellent yields of the monofluoro products with high selectivity, with the exception of straight-chain alkenes because of their ease of isomerization, giving isomeric secondary alkyl fluorides. No tertiary fluorides, however, were formed.

The DMEPHF reagent system is quite reactive and cannot be used for the hydrofluorination of alkynes and highly active alkenes such as styrene derivatives due to their ability to initiate extensive polymerization (even with DMEHF (1:1.3) at −20 °C).

The fluorination of tertiary and secondary alcohols also takes place in good-to-excellent preparative yields (Table 5).

R_1, R_2, R_3 = H or alkyl

Liquid alcohols were used without solvent since the DMEHF complex can also serve as a solvent. Solid substrates were generally treated in CH_2Cl_2 solution. Secondary alcohols react sluggishly with DMEHF (1:5) reagent system at room temperature. However, at more elevated temperatures (50 °C), a 2-fold increase in reaction rates was observed, although the yields are

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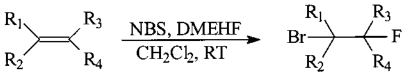
(21) Andrews, L.; Johnson, G. L.; Davis, S. R. *J. Phys Chem.* **1985**, *89*, 1710.
(22) Wiechert, D.; Mootz, D.; Franz, R.; Siegemund, G. *Chem. Eur. J.* **1998**, *4*, 1043.

still very low (10%, 36 h). Therefore, a reagent with higher (1/10) DMEHF ratio was used. It should be noted that there is no significant difference in the stability between the 1:5 and 1:10 reagent systems. Due to the higher HF concentration, the 1/10 reagent has higher reactivity and gave 80% conversion of cyclohexanol after a 1-h reaction time. The isolated yield for fluorocyclohexane (49%) is, however, significantly lower than the overall conversion due to the concomitant formation of dicyclohexyl ether (9% yield) and bicyclohexyl (16% yield). Further increase in HF concentration does not result in higher yield of fluorocyclohexane. Using neat HF, only the formation of higher hydrocarbons (bicyclohexyl and isomeric dimethyl decalins) but no fluorocyclohexane was observed.

It is also worth noting, that the high yield of fluorinated product (85%) in the reaction of 2,5-dimethyl-2-hexanol was surprising, since with other reagents, such as PVPHF, rapid dehydration occurs. In the present case, most likely, due to the larger amount of available "free" fluoride, the desired fluorination took place instead. In the case of 2,5-dimethyl-2,5-hexanediol, however, the corresponding tetramethyltetrahydrofuran was the only observed product.

The dehydration reaction of 1,4-diols catalyzed by liquid or solid acids usually results in the formation of tetrahydrofuran derivatives, but only at elevated temperatures (e.g., Nafion-H (180 °C), HY-zeolite (250 °C), heteropoly acids (160 °C)).[23]

Bromofluorination of alkenes can also be carried out with DMEPHF in good yields (Table 6).

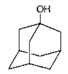
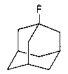
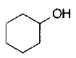
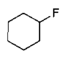
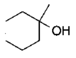
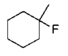
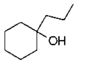
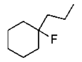
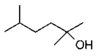
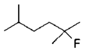


R_1, R_2, R_3, R_4 = H or alkyl

The products were usually formed with very high stereo (*trans*) and regio selectivity, except for open-chain alkenes, wherein varied regioisomers were formed according to the NMR spectra of the products. No bromofluorinated products were isolated in the case of highly activated olefins due to extensive and rapid polymerization.

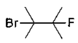
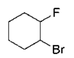
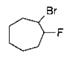
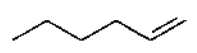
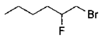
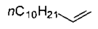
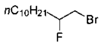
The activity of DMEPHF reagent system, compared to earlier developed PPHF[4] and PVPHF[5,6] is higher due to the significantly lower basicity of dimethyl ether. While in the former cases the onium ionic character of the reagents is clear, DMEPHF is a hydrogen-bonded and not an onium ionic system. Thus, HF is more accessible for the fluorination reactions. The activity differences are most pronounced in the case of OH-to-F substitutions and bromofluorinations. This higher activity results in certain limitations in the use of DMEPHF use with highly reactive olefins due to their extensive polymerization. The high stability and easy handling of he DMEPHF systems make their use safe and convenient. A further significant advantage is that during the workup, volatile gaseous DME is readily removed from the product mixture.

Table 5. Fluorination of Alcohols with DMEHF (1/5) Reagent

Subsrate	Temperature °C	Reaction time h	Product	Yield %
	RT	3		95
	RT	72		10
	50	36		10
	RT	2		49*
	RT	3		83
	RT	3		88
	RT	2		85
Ph3C-OH	RT	3	Ph3C-F	97
	RT	3		85

*DMEHF (1/10) reagent was used.

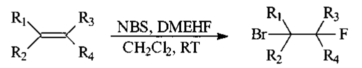
Table 6. Bromofluorination of Alkenes with NBS/DMEHF(1/5) Reagent

Subsrate	Temperature °C	Reaction time h	Product	Yield %	Selectivity %
	RT	1		65	100
	RT	3		71	100
	RT	3		80	100
	RT	3		72	80
	RT	3		87	90

Similarly, the stable 1:5 $Et_2O/[HF]_n$ and $nPr_2O/[HF]_n$ complexes (DEEPHF and DPEPHF) were studied in their applicability as fluorinating agents. Hydrofluorination and bromofluorination of olefins and fluorination of alcohols were used as test reactions. All reactions were carried out at room temperature under atmospheric pressure.

R_1, R_2, R_3, R_4 = H or alkyl

R_1, R_2, R_3 = H or alkyl



R_1, R_2, R_3, R_4 = H or alkyl

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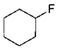
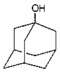
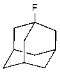
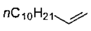
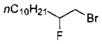
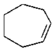
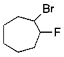
(23) Bucsi, I.; Molnár, A.; Bartók, M.; Olah, G. A. *Tetrahedron* **1995**, *51*, 3319. Török, B.; Bucsi, I.; Beregszászi, T.; Kapocsi, I.; Molnár, Á. *J. Mol. Catal. A* **1996**, *107*, 305.

Table 7. Application of Diethyl Ether(DEEHF)/ and Di-*n*-propyl Ether/HF (DPEHF) (1/5) Reagents in Hydrofluorination and Bromofluorination of Alkenes and Fluorination of Alcohols[a]

Substrate	Product	Reagent	Reaction time	Yield[b]	Selectivity
			h	%	%
		DEEHF	3	86	Less than 1% *endo*
		DPEHF	3	82	
		DEEHF	3	91	100
		DPEHF	3	89	100
		DEEHF	3	96	100
		DPEHF	3	93	100
Ph_3C-OH	Ph_3C-F	DEEHF	3	95	100
		DPEHF	3	94	100
		DEEHF	3	86	92
		DPEHF	3	84	93
		DEEHF	3	80	100
		DPEHF	3	81	100

[a] Each reaction was carried out at room temperature. [b] Isolated yields.

The results obtained are summarized in Table 7.

The products were usually formed in high yields and selectivity with the exception of highly reactive olefins and alkynes; these underwent rapid polymerization.

Conclusions

The preparation and NMR structural characterization together with DFT-based theoretical calculations of dialkyl ether/poly(hydrogen fluoride) particularly dimethyl ether/poly(hydrogen fluoride) (DMEPHF) complexes were carried out. The DFT-based structural and NMR chemical shift calculations are in agreement with the experimental NMR data suggesting a cyclic poly(hydrogen fluoride)-bridged structure for the complexes. The complex of these two volatile components were found to be surprisingly stable. This allows their use as new and effective fluorinating agents. The most conventional (1:5) reagent systems were used in a number of fluorination reactions, such as hydrofluorination and bromofluorination of alkenes, fluorination of alcohols giving the corresponding fluorinated products in good-to-excellent yields. The high stability allows easy handling of the reagent; simple and easy workup together with their high reactivity make the $R_2O/[HF]_5$ complexes novel and convenient reagents for fluorination reactions.

Experimental Section and Calculational Methods

General Methods. The chemicals used in this study were commercially available. Dimethyl ether and hydrogen fluoride, purity >99.5%, were purchased from Matheson, while the organic reactants (alkenes, alcohols) were Aldrich products. The ^1H, ^{13}C, and ^{19}F NMR measurements were carried out using a 300 MHz superconducting NMR spectrometer, in $CDCl_3$ as solvent. TMS (^1H, ^{13}C) and CCl_3F (^{19}F) were used as internal standards. The spectra were recorded in a 5-mm glass NMR tube using an inner Teflon liner.

Caution: Anhydrous HF is an extremely corrosive and low-boiling gas (19.5 °C) and should be handled in a well-ventilated hood with protective gloves, face mask, and clothing.

Typical Preparation of Dialkyl Ether/Poly(hydrogen fluoride) Complexes: Dimethyl Ether/Poly(hydrogen fluoride) (DMEHF). Forty grams of condensed dimethyl ether (DME) was placed into a 250-mL polyethylene (Nalgene brand) bottle at −78 °C under a dry argon atmosphere. Anhydrous, condensed hydrogen fluoride (HF) was then added in small portions with continuous shaking. The first 5−10 mL of HF should be added very carefully, although no vigorous reaction was detected. The amount of HF depends on the desired reagent composition, for example, 40 g of HF should be added to reach DME:HF = 1:2 molar ratio. A nonviscous, colorless, liquid was obtained, that was stable at room temperature. The reagent system kept in a closed Nalgene bottle does not lose HF and can be stored in a fume hood, although for long-time storage a refrigerator is recommended. Its activity did not change during 3 months storage at room temperature.

General Procedure for Hydrofluorination of Alkenes with Dialkyl Ether/Poly(hydrogen fluoride) Complexes: Preparation of Fluorocyclohexane with DMEPHF (1:5). Cyclohexene (8.2 g, 0.1 mol) was placed into a 30-mL polyethylene bottle and cooled to −20 to −30 °C in dry ice/acetone bath, and then 7.5 mL of DMEHF (1/5) was added dropwise during continuous cooling and shaking. The bottle was then closed, and the reaction mixture was stirred at room temperature for 3 h and then quenched with ice-cold water. The product was extracted with CH_2Cl_2 in a plastic separatory funnel and washed with water and aqueous $NaHCO_3$. After careful solvent removal and distillation 8.9 g of fluorocyclohexane was isolated as colorless liquid (92% yield). **Warning**: Working with highly active reactants may cause the reaction may to turn exothermic, resulting in extensive gas evolution. The pressure inside the flask should be checked frequently to avoid a blow-up. Use of a pressure relief valve is recommended.

Typical Fluorination of Alcohols with Dialkyl Ether/Poly(hydrogen fluoride) Complexes: Preparation of *exo* 2-Norbornyl Fluoride with DMEPHF (1:5). Nine grams of *exo*-norborneol was placed into a 30-mL polyethylene bottle and dissolved in 5 mL of dichloromethane. The solution was cooled to −20 to −30 °C, and 10.5 mL of DMEHF was added dropwise during continuous shaking and cooling. After the addition of the reagent the mixture was stirred for 1 h at ambient temperature. The reaction was quenched with ice-cold water, the organic phase was separated and washed three times with H_2O and then neutralized with aqueous $NaHCO_3$, and the solvent was evaporated. After distillation 7.8 g of *exo*-2-norbornyl fluoride was isolated as colorless liquid that crystallized slowly (85% yield).

General Procedure for Bromofluorination of Alkenes with NBS/Dialkyl Ether/Poly(hydrogen fluoride) Complexes: Preparation of 2-Bromo-3-fluoro-2,3-dimethyl-butane with NBS/DMEHF

Two grams of 2,3-dimethyl-2-butene was dissolved in 5 mL of CH_2Cl_2 in a 30-mL polyethylene bottle. A premixed CH_2Cl_2 (10 mL) solution of 3 g of *N*-bromosuccinimide (NBS) and DMEHF(1/5)was then added dropwise at −20 to −30 °C. The reaction mixture was then stirred at room temperature for 2 h. The quenching and workup were carried out as described above. The resulting organic solution was subjected to column chromatography (silica gel, eluent: hexane). After solvent evaporation 2.8 g (65%) 2-bromo-3-fluoro-2,3-dimethyl-butane was obtained.

Theoretical Calculations, Basis Set and Geometry. Density functional theory (DFT)[14] calculations were performed with the GAUSSIAN-98[17] package of programs. Optimized geometries were obtained at the B3LYP[15]/6-311+G** level.[16] Energies were obtained at the B3LYP/6-311+G**//B3LYP/6-311+G** + ZPE (zero-point vibrational energy scaled by a factor of 0.98) level. NMR calculations were performed according to the reported method using IGLO programs[19] at the IGLO II levels using B3LYP/6-311+G** geometries. Huzinaga[24] Gaussian orbitals were used as follows; Basis II: C, O, N

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(24) Huzinaga, S. *Approximate Atomic Wave Function*; University of Alberta, Edmonton, Alberta, Canada, 1971.

or F: 9s 5p 1d contracted to [51111, 2111, 1], d exponent: 1.0; H: 5s 1p contracted to [311, 1], p exponent: 0.70. ^{19}F NMR chemical shifts were referenced to $CFCl_3$ (calculated absolute shift, i.e, δ (^{19}F) = 207.8)

Acknowledgment. Support of our work by the Loker Hydrocarbon Research Institute and National Science Foundation is gratefully acknowledged. This paper is dedicated to Professor Arpad Molnar of the University of Szeged, Hungary, on the occasion of his 60th birthday.

Supporting Information Available: Spectroscopic data on fluorinated products (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

JA0124109