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Attempted hydrogen–deuterium exchange of the *protio*-trimethyloxonium dication $(CH_3)_3OH^{2+}$, study of methylating ability of $(CH_3)_3O^+$ in superacids and theoretical investigations

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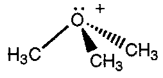
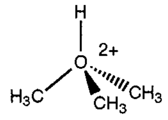
ABSTRACT **Attempted hydrogen–deuterium exchange of trimethyloxonium ion, $(CH_3)_3O^+$ with excess of 1:1 $^2HF/SbF_5$ superacid at −30°C over a period of 30 days showed no exchange. Theoretical calculations at the MP2/6–31G** level are in accord with the lack of hydrogen–deuterium exchange in the methyl group of the $(CH_3)_3O^+$ cation as protonation (protosolvation) prefers the oxygen lone pair of electrons, instead of a C—H bond. Methylation of aromatics with the $(CH_3)_3O^+CF_3SO_3^-$ in CF_3SO_3H and $2CF_3SO_3H{:}B(O_3SCF_3)_3$ was also studied. Whereas in triflic acid no alkylation was observed, in triflatoboric acid, a powerful superacid, alkylation takes place, indicating protolytic activation of the trimethyloxonium ion.**

Trialkyloxonium ions (Meerwein salts), R_3O^+, with various counterions such as SbF_6^-, BF_4^-, $SbCl_6^-$, and PF_6^- are excellent alkylating agents for nucleophiles containing heteroatoms such as N, O, or S. In general they are not capable of C-alkylation of aromatic or aliphatic compounds. In conjunction with protic superacid $FSO_3H{:}SbF_5$ (Magic Acid), however, they were found to alkylate aromatics (1). Benzene and toluene have been methylated with trimethyloxonium salts in the presence of Magic Acid (1). The methylation of toluene gave an isomer distribution of 60% *ortho*-, 11% *meta*-, and 21% *para*-xylene, indicative of a typical electrophilic aromatic substitution. To account for the enhanced reactivity of trimethyloxonium ion under superacid conditions, Olah (2) suggested that the *de facto* alkylating agent in these reactions is not the trimethyloxonium ion itself but, rather, its protonated (i.e., protosolvated) form, $(CH_3)_3OH^{2+}$. Protolytic activation of the $(CH_3)_3O^+$ ion leads to a highly electron-deficient superelectrophilic gitonic dication, which is substantially more reactive than its parent monocation.



trimethyloxonium ion



O-protonated trimethyloxonium dication

Whereas theoretical calculations (3) substantiated the activation of trimethyloxonium ion by O-protonation, possible C—H protonation of the ion is also possible and has not previously been studied. C—H protonation of trimethyloxonium ion would lead to dication $(CH_3)_2O^+CH_4^+$ involving a three-center two-electron (3c–2e) bond. Previously, we have been able to show by hydrogen–deuterium exchange experiments and theoretical calculations that long-lived stable alkyl cations, such as *tert*-butyl (4) and 2-propyl cations (5), can undergo C—H protonation to form highly electron-deficient *protio*-alkyl dications.

Hydrogen–deuterium exchange was also observed at the CH_3 groups of the long-lived acylium ions $CH_3CH_2CO^+$, $(CH_3)_2CHCO^+$, and $(CH_3)_3CCO^+$ when treated with excess $^2HF/SbF_5$ superacid (6). C—H bond protonation–deuteriation involving the intermediacy of the corresponding protio-(deuterio)acylium dications is suggested to account for the exchanges. The observed hydrogen–deuterium exchange in these acyl cations is consistent with theoretical calculations that showed that the C—H-protonated isomers are more stable than their corresponding O-protonated isomers. Under similar conditions, no exchange was observed in the acetyl ion CH_3CO^+ in $^2HF/SbF_5$. The lack of hydrogen–deuterium exchange in CH_3CO^+ is again consistent with theoretical calculations that showed that in this case the O-protonated isomer CH_3COH^{2+} is more stable than the C—H-protonated isomer CH_4CO^{2+} by 18.9 kcal/mol (1 cal = 4.184 J) (6).

We report now the study of possible hydrogen–deuterium exchange study of trimethyloxonium ion in $^2HF/SbF_5$ superacid solution. *Ab initio* calculations at the MP2/6–31G** level were also carried out to investigate the structures and energies of protonated trimethyloxonium dications. In addition we also report study of methylation of aromatics with trimethyl oxonium ion in CF_3SO_3H (triflic acid) and the much more acidic triflatoboric acid $2CF_3SO_3H{:}B(CF_3SO_3)_3$ system, the later leading to a highly reactive C-methylating system.[¶]

EXPERIMENTAL SECTION

$(CH_3)_3O^+BF_4^-$ (Aldrich), anhydrous HF (Setic Lab), H_2O (Acros), and benzoyl chloride (Lancaster Synthesis) are commercially available products and were used as received. Antimony pentafluoride (Allied Chemical) was doubly distilled prior to use. ^2HF was prepared from benzoyl fluoride and ^2H_2O (7). Benzoyl fluoride was prepared from benzoyl chloride and anhydrous HF as reported (8).

^1H and ^2H NMR spectra were obtained on a Bruker AM 400 spectrometer equipped with a variable temperature probe at 400 and 61.4 MHz, respectively. Five-millimeter quartz NMR tubes were used for samples containing ^2HF. NMR spectra were obtained with respect to TMS by using an acetone-d_6 capillary as the external standard.

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Abbreviation: ZPE, zero point vibrational energies.

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[¶]This is paper 36 in the series "Chemistry in Superacids"; paper 35 is ref. 14.

H/^{2}H Exchange Experiments with ^{2}HF/SbF$_5$. $(CH_3)_3O^+BF_4^-$ (about 150 mg) was placed in a Kel-F tube and cooled to −78°C in a dry ice/acetone bath. Approximately 2 ml of $^2HF/SbF_5$ (2.5:1 molar solution) was added at −78°C. The ensuing mixture was vigorously stirred (Vortex stirrer) was kept at −15°C and periodically monitored by ^1H and ^2H NMR spectroscopy.

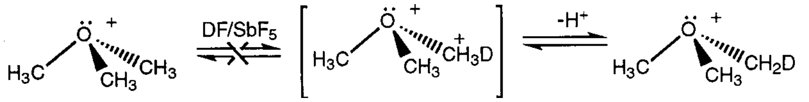
Methylation of Aromatics. Trimethyloxonium triflate $(CH_3)_3O^+CF_3SO_3^-$ was prepared by reacting dimethyl ether $(CH_3)_2O$ with methyl triflate $CH_3SO_3CF_3$ at −20°C. Triflatoboric acid $2CF_3SO_3H{:}B(CF_3SO_3)_3$ was prepared according to the reported method (9).

Approximately 0.1 g of $(CH_3)_3O^+CF_3SO_3^-$ was added to a 10-molar excess of the aromatic in 1.5 ml of the acid system as solvent at −30°C in a 5-ml round-bottom flask equipped with a magnetic stirrer under nitrogen atmosphere. The mixture was stirred vigorously, allowed to slowly warm up to 0°C, kept at this temperature for 30 min, and subsequently warmed to the temperature indicated in Table 2. After the completion of the reaction, a 0.25-ml portion of the mixture was quenched with saturated solution of sodium carbonate and extracted with ether. GLC analysis of the resulting ether solution was carried out by using cyclohexane as internal standard to give the isomer distribution as well as overall yield.

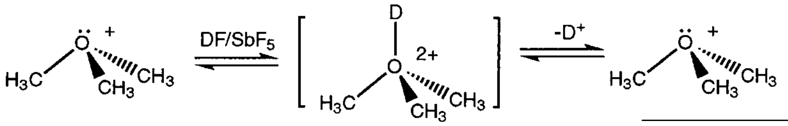
RESULTS AND DISCUSSION

Trimethyloxonium tetrafluoroborate, $(CH_3)_3O^+BF_4^-$, was allowed to react with excess of 1:1 $^2HF/SbF_5$ superacid at −30°C. The 1:1 $^2HF/SbF_5$ is one of the strongest superacid systems known (10). The resulting solution was periodically monitored by ^1H and ^2H NMR spectroscopy to observe any hydrogen–deuterium exchange at the CH_3 groups of $(CH_3)_3O^+$ ion. Under these conditions and over a period of 30 days, no exchange could be detected. Further no decomposition of the $(CH_3)_3O^+$ ion occurs. Even at room temperature, no exchange products or decomposition of the $(CH_3)_3O^+$ ion was detected over a period of 30 days.

To account for the absence of isotopic exchange, protonation (deuteration) of the $(CH_3)_3O^+$ ion at the methyl group can be excluded.



The enhanced reactivity of trimethyloxonium ion under superacid conditions as observed by Olah *et al.* (1), therefore, must be due to the formation of the superelectrophilic gitonic O-protonated trimethyloxonium dication $(CH_3)_3OH^{2+}$ as the *de facto* reactive intermediate and not the C—H-protonated $(CH_3)_2O^+CH_4^+$. Thus the observed lack of hydrogen–deuterium exchange in the present study is in accord with the favorable O-deuteurolytic activation of the $(CH_3)_3O^+$ ion.



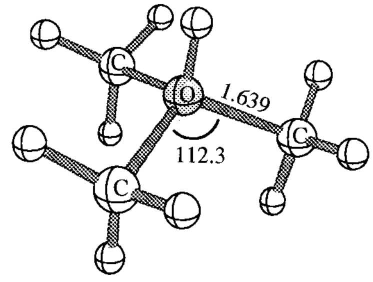
To further comprehend the nature of the protonated trimethyloxonium dication *ab initio* calculations were carried out. All structures were optimized at the correlated MP2/6–31G** level with GAUSSIAN 94 programs (11). Vibrational frequencies at the MP2/6–31G**//MP2/6–31G** level were used to characterize stationary points as minima and to evaluate zero point vibrational energies (ZPE), which are scaled by a factor of 0.93. Single point calculations were performed at the MP4SDTQ/6–311G**//MP2/6–31G** level. Geometries and energies are given in Fig. 1 and Table 1, respectively.

Both O-protonated $(CH_3)_3O^+$ (compound **1**) and C-protonated $(CH_3)_3O^+$ (compound **2**) are the energy minima on the potential energy surface. At the MP4SDTQ/6–311G**//MP2/6–31G** + ZPE level, compound **1** is the global minimum being, 31.2 kcal/mol more stable than compound **2**. This is again consistent with the lack of any observable hydrogen–deuterium exchange in trimethyloxonium ion with $^2HF/SbF_5$ because the substantial energy difference between dications **1** and **2** suggests the absence of C—H protonation (deuteriation). A previous theoretical study by Olah *et al.* (3) showed that the dication **1** exists as a thermodynamically and kinetically stable species and also that at the MP2/6–31G*//HF/6–31G* level the dication **1** is even 27.6 kcal/mol more stable than the trimethyloxonium ion in the idealized gas phase (3). Recently Olah *et al.* (12) have reported the structures and calculated ^{13}C and ^{17}O NMR chemical shifts of $(CH_3)_3O^+$ and its O-protonated compound **1**.

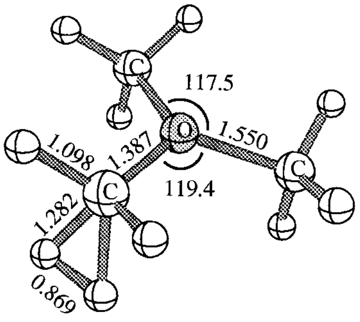
The dication **2**, a nonclassical ion, involves a pentacoordinate carbon center with a three-center two-electron (3c-2e) bond. Thus, the C_s symmetrical structure **2** is in fact a oxonium carbonium dication. In comparison, the global minimum structure of protio-*tert*-butyl dication was found to be a carbenium carbonium type structure $[(CH_3)_2C^+CH_4^+]$. The central oxygen atom in compound **2** is slightly pyramidal. The pyramidalization level is about 7 degrees, expressed as the out-of-plane bending angle of the central atom relative to the plane defined by its three bonding partners. For comparison, the corresponding value for the trimethyloxonium ion is about 16 degrees. The carbonium carbon–oxygen bond distance of compound **2** is 1.387 Å, significantly shorter than methyl carbon–oxygen bond distance of 1.550 Å. The shorter carbonium carbon–oxygen bond distance of compound **2** can be explained by the donor–acceptor interactions [in which $(CH_3)_2O$ and H_2 are donors and CH_2^{2+} is the acceptor] as shown by Koch *et al.* (13). However, both C—O bond distances of compound **2** (1.387 Å and 1.550 Å) are considerably shorter compared with the C—O bond distance (1.639 Å) of compound **1**.

Determining the protonation site of alkyloxonium ions is essential to understand the reactivity of these ions in superacids. Previous calculations have shown that in the gas phase the diprotonations of methyl alcohol and dimethyl ether give preferentially the O,C-protonated dication $^+CH_4OH_2^+$ and the O,O-protonated dication $(CH_3)_2OH_2^{2+}$, respectively (3). These results are in accord with their various reactions in superacid solutions (2, 3).

Alkylation of Aromatics with Protolytically Activated Trimethyloxonium Ion. Trimethyloxonium triflate $(CH_3)_3O^+CF_3SO_3^-$ was reacted with a 10-molar excess of different aromatics at room temperature in the presence of $2CF_3SO_3H{:}B(CF_3SO_3)_3$ as solvent. Results of methylation of arenes are summarized in Table 2.



1 (C_{3V})



2 (C_s)

FIG. 1. MP2/6–31G** optimized structures of compounds **1** and **2**.

Triflatoboric acid, $2CF_3SO_3H{:}B(CF_3SO_3)_3$ is known to be a very powerful ($H_o = -20.5$) (10) superacid. In contrast, when using only triflic acid CF_3SO_3H ($H_o = -14.1$) (7), no alkylation was observed. The stronger triflatoboric acid is, therefore, able to further protosolvate the $(CH_3)_3O^+$ ion to highly active methylating agent. With this reagent system, methylation of arenes was possible (see Table 2), although no attempt was made to optimize the reaction conditions. In a previous study (1), benzene and toluene was found to be methylated with trimethyloxonium salts in the presence of $FSO_3H{:}SbF_5$ (magic acid). Whereas aromatics themselves are protonated in superacids, at room temperature there is always a sufficient equilibrium with the nonprotonated aromatics present to allow alkylation.

Table 1. Energies, ZPE, and relative energies

Ion	MP2/6-31G**// MP2/6-31G**(ZPE)	MP4(SDTQ)/6-311G**// MP2/6-31G**	Relative energy, kcal/mol
1	194.10472 (78.0)	194.25351	0.0
2	194.04983 (75.4)	194.19967	31.2

Energies are in minus arbitrary units. ZPE is in kcal/mol at MP2/6-31G** level scaled by a factor of 0.93. Relative energies are based on MP4(SDTQ)/6-311G**//MP2/6-31G** + ZPE.

Table 2. Methylation of arenes in the $(CH_3)_3O^+CF_3SO_3^-/2\,CF_3SO_3H{:}B(CF_3SO_3)_3$

Arene	*T*, °C	Time, h	*ortho*, %	*meta*, %	*para*, %	Yield, %
Benzene	23	10				20
Toluene	23	10	64	12	24	21
Chlorobenzene	45	11	34	2	64	18
Fluorobenzene	45	11	14	0	86	17

In conclusion, hydrogen–deuterium exchange experiments were carried out on the $(CH_3)_3O^+$ ion by reacting $(CH_3)_3O^+BF_4^-$ with excess 1:1 ^{2}HF/SbF5 superacid at −30°C and at room temperature (observed by ^{2}H NMR spectroscopy). Under these conditions and over a period of 30 days, no exchange could be observed at the CH_3 groups, which would involve the intermediacy of the corresponding O,C-protio(deuterio)trimethyloxonium dications. The lack of hydrogen–deuterium exchange in $(CH_3)_3O^+$ is consistent with theoretical calculations at the MP2/6–31G** level that showed that the O-protonated isomer $(CH_3)_3OH^{2+}$ **1** is more stable than the C—H-protonated isomer $(CH_3)_2O^+CH_4^+$ **2** by 31.2 kcal/mol. The calculated C_s symmetrical structure **2** can be considered as a oxonium carbonium dication that involves a pentacoordinate carbon center with a three-center two-electron (3c-2e) bond. The $(CH_3)_3O^+SO_3CF_3^-/2CF_3SO_3H{:}B(CF_3SO_3)_3$ system was shown to be a powerful methylating agent for the methylation of aromatics and deactivated aromatics.

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