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Role of the Spectator Ring in the Gas-Phase Alkylation of 1,2-Diphenylethane by $(CH_3)_2X^+$ (X = F, Cl) and CF_3^+ ions

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The gas-phase alkylation of $C_6D_5CH_2CH_2C_6H_5$ by Me_2F^+, Me_2Cl^+, and CF_3^+ ions has been studied at 720 Torr, in the temperature range 47–120 °C with the radiolytic technique. An interannular hydron-exchange process between the two aromatic rings of (β-phenylethyl)arenium ions has been observed to occur on the nanosecond time scale and to obey thermal kinetics, with the normal positive dependence on temperature. When the efficiency of collisional deactivation is decreased (at 200 torr) or a highly exothermic reaction (alkylation by CF_3^+ ion) is carried out, an "anomalously" large extent of interannular hydron exchange takes place. The higher methylation rate (6.0:1) of 1,2-diphenylethane than of toluene and the marked positional selectivity (2 para/ortho ratio of 5.0) shown by Me_2X^+ ions have pointed out the fundamental role of persistent ion–neutral complexes between reactant pairs, as already suggested in previous radiolytic and mass spectrometric studies.

Introduction

Arenium ions have been found to be key intermediates in electrophilic aromatic substitution in condensed and in gas phases. They undergo fast proton shifts that have been investigated by computational methods.[1] NMR,[2] and mass spectrometric techniques.[3] It is of great interest to extend the study of the properties of protonated arenes to the gas phase, in order to obtain simple models of species unperturbed by the effects of solvation and ion pairing. At the low pressure typical of mass spectrometry, under conditions of unefficient collisional thermalization of excited intermediates, extensive rearrangement processes are known to occur, and extensive proton shifts in such excited gaseous arenium ions have been observed. Recently, the application of the radiolytic technique,[4] characterized by a much higher pressure domain, has allowed demonstration of the occurrence and the kinetic role of *thermal* H^+ (D^+) shifts in protonated, selectively deuterated toluenes[5] and 1,2-diphenylethane (DPE).[6] Rapid sampling of the gaseous species, which prevents unwanted structural changes before detection, and fast thermalization of the ionic intermediates by collisional deactivation with a dense bath gas[7] have provided valuable information about the structure and the reactivity of charged species in thermal equilibrium with the environment and have allowed the evaluation of the Arrhenius parameters for the intra[5]- and interannular[6] proton-transfer processes and the measurements of the relative H/D kinetic isotope effect (KIE). The aim of this work is to extend the study to a different class of gaseous electrophiles, namely, the $(CH_3)_2X^+$ (X = F, Cl) and CF_3^+ ions, which differ from the *tert*-butyl cation previously examined both in the thermochemistry of their alkylation reaction to the aromatic ring and in the fact that this process is pratically irreversible. The interannular proton migration process occurring in alkylated DPE may hopefully act as a probe of the kinetic effects of the energy content of the arenium intermediate, which may span from highly vibrationally excited states typical of the low-pressure mass spectrometric regime to the complete thermal equilibration achieved in the *tert*-butylation of DPE at atmospheric pressure.

Experimental Section

Materials. The gases were research-grade samples (Matheson Gas Products Inc.) having a stated purity of 99.9 mol %. MeF (99 mol %) contained small amounts of impurities, including Me_2O and $(Me)_2CO$. The chemicals used as reactants or reference standards were obtained from commercial sources. $C_6H_5CH_2CH_2C_6D_5$ (DPE) was prepared as described in ref 8, its identity and purity being established by GC MS analysis.

Radiolytic Reactions. The gaseous systems were prepared using a greaseless vacuum line according to a well-established procedure. Appropriate amounts of the bulk components (CH_3F, CH_3Cl, CF_4) together with the additives (O_2, C_2H_4) and with a few milligrams of the aromatic substrate were introduced into carefully outgassed Pyrex vessels (125 mL), equipped with break-seal tips. After cooling to the temperature of liquid nitrogen the bulbs were sealed off and then allowed to equilibrate at the irradiation temperature. The irradiations were carried out in a 220 Gammacell (Nuclear Canada Ltd.) at total doses of 1×10^4 Gy at a dose rate of ca. 2×10^4 Gy·h^{-1}. The reaction mixtures of radiolytic experiments were extracted with ethyl acetate by repeated freeze–thaw cycles, and the products were analyzed by GC MS using a Hewlett-Packard 5890 gas chromatograph connected to a Model 5970B mass-selective detector or to a FID unit. The separations of the isomeric products, whose identity was established by comparison of their retention volumes with those of authentic samples and from their mass spectra, were performed by the following capillary columns: (i) a 60-m-long, 0.25-mm-i.d. fused silica column coated with a 0.25-μm film of 20% diphenyl/80% dimethylpolysiloxane (SPB-20 column from Supelco Co.); (ii) a 30-m-long, 0.25-mm-i.d. poly(ethylene glycol) (Supelcowax 10) bonded-phase column (0.25-μm film thickness) from Supelco Co.; and (iii) a 50-m-long, 0.2-mm-i.d. fused-silica capillary column, coated with a 0.5-μm cross-linked methylsilicone film (Pona column from Hewlett-Packard).

Results

Table I summarizes the results concerning the isomeric composition and the deuterium distribution of the products formed from the gas-phase reaction of $C_6H_5CH_2CH_2C_6D_5$ (DPE-d_5) with charged electrophile (Me_2F^+, Me_2Cl^+, CF_3^+). A large excess (10 torr) of O_2 was present in each system as a radical scavenger to ensure the ionic origin of the products. Moreover, the observation that the yields of the methylated or the trifluoromethylated products decrease with increasing amounts of an added gaseous base (Et_3N, cyclohexanone) confirms the ionic character of the reactions, since these species are capable of efficiently intercepting charged reactants and intermediates. Conversion of the starting substrate is kept below 1% in order to minimize interference by undesired processes, such as direct radiolysis of

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TABLE I: Gas-Phase Reaction of Me_2X^+ (X = F, Cl) and CF_3^+ with $C_6H_5(CH_2)_2C_6D_5$

system composition, Torr[a]				isomeric composition[b]			isotopic composition[e]																	
							$MeC_{14}H_8D_5$/ $MeC_{14}H_9D_4$			$MeC_6H_4CH_2^+$/ $MeC_6H_3DCH_2^+$			$MeC_6D_4CH_2^+$/ $MeC_6HD_3CH_2^+$			$C_6H_5CH_2^+$/ $C_6H_4DCH_2^+$			$C_6D_5CH_2^+$/ $C_6HD_4CH_2^+$		
1,2-diphenylethane	base	bulk gas	temp, °C	*o*	*m*	*p*	*o*[d]	*m*	*p*	*o*	*m*	*p*	*o*	*m*	*p*	*o*	*m*	*p*	*o*	*m*	*p*
0.35	NEt_3 –	MeF 690	47	24	16	59	0.50	0.90	1.1	12.3	45.7	3.8	13.7	12.6	4.4	6.0	5.1	1.7	3.4	4.9	2.0
0.35	NEt_3 0.45	MeF 700	47	19	29	52	0.40	0.90	0.90	4.3	8.7	4.3	12.8	6.7	5.9	10.2	10.1	2.5	3.7	8.2	2.1
0.54	–	MeF 690	90	21	26	53	0.80	1.0	1.4	3.0	9.1	2.2	5.0	5.7	2.2	4.1	5.2	1.2	2.5	4.9	1.5
0.51	–	MeF 670	120	21	29	50	1.1	1.1	1.4	1.3	5.3	1.5	2.4	3.9	1.6	1.8	3.1	0.87	1.3	3.5	1.1
0.75	NEt_3 0.90	MeF 690	120	20	29	51	0.80	0.90	1.2	2.0	7.7	2.3	4.0	5.3	2.1	3.2	5.1	1.3	2.2	4.8	1.4
1.09	NEt_3 2.72	MeF 680	120	19	30	51	0.20	0.90	0.80	1.9	8.6	2.5	9.6	6.7	3.6	7.6	4.3	2.7	2.6	4.3	1.5
0.40	–	MeF 200	120	17	35	48	0.25	1.0	0.84	0.60	1.9	0.82	5.5	1.6	1.7	5.3	2.2	1.7	1.8	1.7	1.0
0.91	–	MeCl 680	120	19	26	55	1.0	1.1	1.3	1.1	2.5	1.1	1.7	1.5	1.1	1.6	1.8	0.69	1.1	1.7	0.80
0.59[c]	NEt_3 0.27	MeCl 690	120	18	26	56	0.85	1.1	1.3	1.5	3.9	1.4	2.3	2.9	1.2	1.8	2.1	0.82	1.0	2.4	0.83
0.81	c-$C_6H_{10}O$ 0.52	MeCl 670	120	20	30	50	0.40	1.0	0.93	1.8	5.9	1.9	7.7	4.3	2.6	4.5	3.0	1.9	2.3	3.5	1.1
0.55	c-$C_6H_{10}O$ 2.53	MeCl 670	120	34	23	43	0.25	1.0	0.70	3.0	3.4	2.1	8.2	4.6	3.4	5.3	2.5	2.0	2.8	3.0	1.6
1.08	c-$C_6H_{10}O$ 0.61	MeCl 680	90	21	28	51	0.12	0.80	0.51	1.7	4.8	2.5	13.3	5.9	5.6	6.3	3.1	3.2	3.9	4.1	1.9
0.35	–	CF_4 675	47	27	37	36	1.1	1.3	1.3	–	–	–	–	–	–	0.73	0.34	0.49	0.42	0.33	0.42
0.61	–	CF_4 700	120	31	34	35	1.2	1.2	1.2	–	–	–	–	–	–	0.31	0.21	0.32	0.29	0.34	0.33
0.78	c-$C_6H_{10}O$ 0.62	CF_4 670	120	38	29	33	1.1	1.2	1.1	–	–	–	–	–	–	0.23	0.26	0.28	0.24	0.25	0.28

[a] All gaseous systems contained O_2 (10 Torr) as a radical scavenger. [b] Standard deviation of ±10%. [c] The system contained 0.64 Torr of toluene; the competition gave a $k_{(DPE)}/k_{(toluene)}$ ratio of 6.0 ± 0.3. The isomeric distribution of the xylenes is *o* (60%), *m* (20%), *p* (20%). [d] At low temperature and/or at high base concentration, when the yields of products are poor, a very small impurity present in the substrate emerges, corresponding to the ortho-methylated isomer, with a mass spectrum characterized by m/z = 109, interfering with the quantitation of m/z = 109 ions from *o*-methyldiphenylethane. [e] Products: *o*-, *m*-, *p*-methyldiphenylethane.

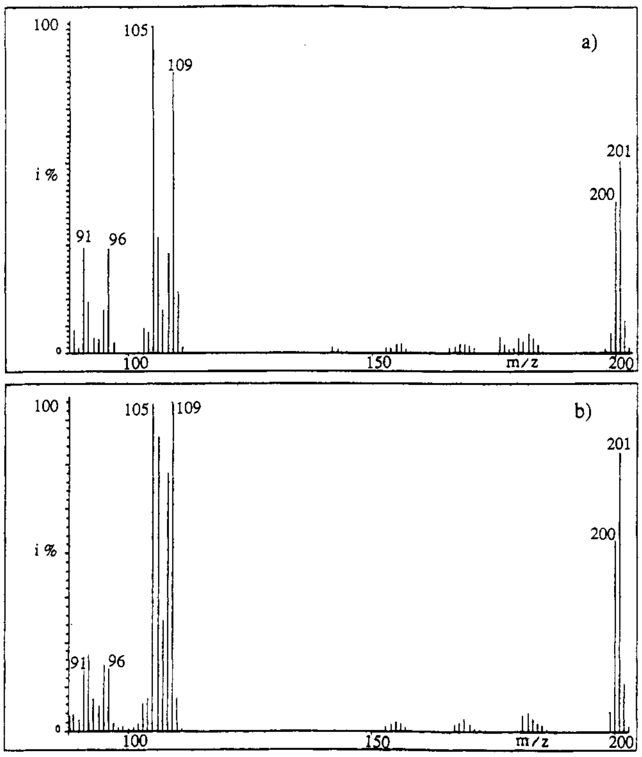


Figure 1. The 70-eV mass spectra of (a) *m*- and (b) *p*-methyldiphenylethane formed from DPE-d_5 (0.59 torr) in the $MeCl/O_2/NEt_3$ (1000:14:0.4) gaseous mixture at 720 torr, 120 °C.

the aromatics, which could complicate the mechanistic pattern of the reaction under study. The absolute yields of the products, expressed by their G_{+M}, i.e., the number of moles formed per joule absorbed, are affected by uncertainties due to dosimetric problems, as large as ±30%. In any case, the measured overall G_{+M} values are close to the known G_{+M} value of the ionic reactants, which indicates that aromatic substitution is a major reaction pathway of the gaseous electrophiles investigated.

Mass Spectrometric Analysis. The 70-eV mass spectrum of $C_6H_5CH_2CH_2C_6D_5$ is characterized by the neat cleavage of the aliphatic C–C bond, displaying equal abundancies of $C_6H_5CH_2^+$ and $C_6D_5CH_2^+$ fragment ions, without any appreciable interannular H/D scrambling prior to fragmentation of the molecular ion. This allows GC MS to be used to estimate not only the total D content but also the D distribution in the aryl rings of the products formed. As shown in Figure 1, the 70-eV fragmentation of the isomeric methyldiphenylethanes formed in the radiolytic system shows as the base peaks the ions $C_8H_9^+$ and $C_8H_5D_4^+$, at m/z = 105 and 109, respectively, formally corresponding to the ions $MeC_6H_4CH_2^+$ and $MeC_6D_4CH_2^+$, together with the ions $C_7H_7^+$ and $C_7H_2D_5^+$ (20%) at m/z = 91 and 96, respectively, corresponding to the ions $C_6H_5CH_2^+$ and $C_6D_5CH_2^+$ and the molecular ions at m/z = 200 and 201 (60%). Thus, three families of ions are present, each comprising "unmixed" ions, e.g., $MeC_6H_4CH_2^+$ and $MeC_6D_4CH_2^+$, together with ions showing some degree of a single H/D exchange between the two aryl rings, e.g., $MeC_6H_3DCH_2^+$ (m/z = 106) and $MeC_6HD_3CH_2$ + (m/z = 108).

Small amounts (<5%) of ions deriving from a more extensive H/D exchange, i.e., $MeC_6H_2D_2CH_2^+$ and $C_6H_3D_2CH_2^+$, are not significant, and their yields show no defined dependence on the experimental conditions. Considering the large predominance of the unexchanged ions with respect to the singly exchanged ones, the two isotopomers at m/z = 200 and 201 can be assumed to originate from the substitution reaction at the deuterated or at the unlabeled ring, respectively, followed by D^+ or H^+ loss. The intensity ratio of ions at m/z = 201 and 200 is characterized by a value close to unity, independent of environmental conditions,

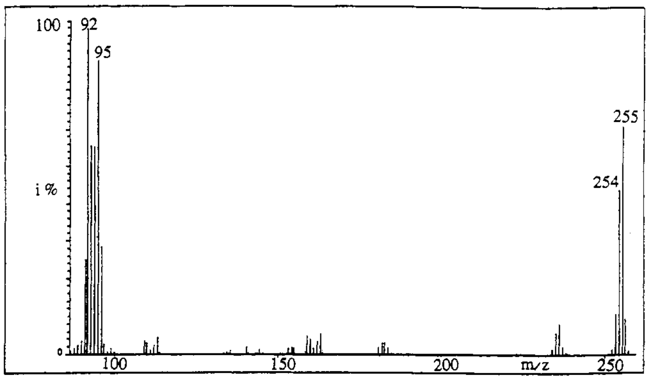


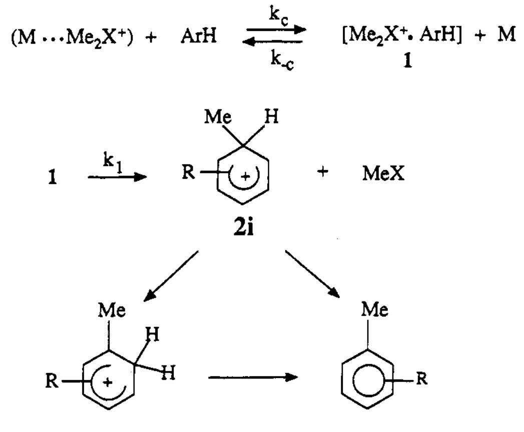
Figure 2. The 70-eV mass spectrum of *m*-(trifluoromethyl)diphenylethane formed from DPE-d_5 (0.81 torr) in the $CF_4/O_2/C_2H_4$ (1000:14:14) gaseous mixture at 720 torr, 120 °C.

suggesting an equal rate of alkylation of the two isotopically different rings of DPE. A typical EI mass spectrum of the trifluoromethylated products is reported in Figure 2, where the "singly exchanged" benzyl ions $C_6H_4DCH_2^+$ (m/z = 92) and $C_6HD_4CH_2^+$ (m/z = 95) are the base peaks, accompanied by significant "doubly exchanged" benzyl ions $C_6H_3D_2CH_2^+$ (m/z = 93) and $C_6H_2D_3CH_2^+$ (m/z = 94), with the molecular ions at m/z = 254 and 255.

Isotopic Distribution. The last columns of Table I give the ratios of the abundances of the unexchanged to the corresponding singly exchanged ions in the mass spectrum of the alkylated products, namely, the ratios $RC_6H_4CH_2^+/RC_6H_3DCH_2^+$, $RC_6D_4CH_2^+/RC_6HD_3CH_2^+$, $C_6H_5CH_2^+/C_6H_4DCH_2^+$, and $C_6D_5CH_2^+/C_6HD_4CH_2^+$. The ratios provide a direct measure of the extent of H^+ (D^+) transfer from the substituted to the spectator ring; i.e., the higher the extent of interannular proton exchange, the lower the ratios that will result. The extent of interannular H^+/D^+ exchange in the methylation products is shown from the ratios in Table I to be more pronounced in the ortho/para than in the meta isomer and to depend on several factors, increasing with (i) lower pressure, (ii) higher temperature, and (iii) a lower concentration of added base. A marked dependence of the extent of the H^+ (D^+) transfer emerges from the nature of the electrophile. The ratios $C_6H_5CH_2^+/C_6H_4DCH_2^+ = (i_{91})/(i_{92})$ and $C_6D_5CH_2^+/C_6HD_4CH_2^+ = (i_{96})/(i_{95})$ are much lower than unity in CF_4. This indicates that a much more extended H/D migration to the spectator ring occurs following the CF_3^+, rather than the Me_2X^+ (X = F, Cl), attack. This is immediately evident from the different "profile" of the families of $C_6X_5CH_2^+$ isotopomers (X = H, D) in the methylated and trifluoromethylated products, which becomes much less "concave" in the latter ones. The presence of singly exchanged ions in the alkylated benzyl group demonstrates that consecutive H^+ (D^+) transfer takes place from the alkylated ring to the unsubstituted one and back.

Isomeric Distribution. The reaction of $(CH_3)_2X^+$ (X = F, Cl) and CF_3^+ with DPE yields alkylated products whose isomeric distribution is given in Table I, together with the results of the competition experiments aimed at evaluating the relative reactivity of DPE toward toluene. The positional selectivity of the Me_2X^+ (X = F, Cl) attack is characterized by a predominant ortho–para orientation, with a considerably high extent of para substitution, measured by a 2 para/ortho (2p/o) ratio of 5.0 at 670–700 torr. The orientation found with the investigated electrophiles is that typical of an aromatic substrate PhR whose R group is a conjugatively electron-releasing group. Dimethylhalonium ions Me_2X^+ (X = F, Cl) show a pronounced electrophilic selectivity vs DPE, measured by a 2p/m ratio of ca. 3.0; when the electrophile is CF_3^+, the 2p/m ratio, in the presence of base, is ca. 1.8. When the reaction is carried out at the lowest pressure used (200 torr), a decrease of the positional selectivity, namely, a higher extent of meta substitution, is apparent. The noticeable predominance of para orientation is particular to DPE, while a comparable

SCHEME I



R= H, CH_2CH_2Ph

reactivity of the ortho and the para position (2p/o = 0.67, see footnote c in Table I) characterizes methylation of toluene by $(CH_3)_2Cl^+$. The substrate selectivity of Me_2Cl^+ at 120 °C, measured by the $k_{DPE}/k_{toluene}$ ratio of 6.0, shows a bias toward methylation of DPE, which is quite significant by gas-phase reactivity standards.

Discussion

Ionic Reactions. The primary charged reactants used in the present work are generated from the radiolysis of the bulk gas. MeF, MeCl, and CF_4 give respectively the Lewis acids Me_2F^+, Me_2Cl^+,[9] and CF_3^+,[10] which undergo many unreactive collisions with the parent molecules and can be regarded as fully thermalized before reacting with an aromatic substrate. As discussed in several previous mass spectrometric and radiolytic studies, dimethylhalonium ions are able to alkylate many aromatic molecules[9a–d,11,12] according to the general mechanistic sequence of the gas-phase aromatic substitution, exemplified in Scheme I. The primary step involves the association of the Me_2X^+ ion with the substrate, giving an electrostatic collision adduct **1** (π complex)[12] whose formation is less exothermic under the high-pressure conditions prevailing in the radiolytic experiments than in low-pressure systems such as conventional CI MS, since the cation is associated with a second MeX molecule in the dense bath gas.[11] The adduct can either back-dissociate or evolve into an ipso-alkylated arenium ion **2i** (σ complex), which can evolve by different competitive pathways, either reverting to **1** or undergoing other processes that remove the proton from the ipso carbon, i.e., via intramolecular isomerization by 1,2-proton shift or deprotonation by a base B. In the case of ArH = DPE (R = CH_2CH_2Ph), a unique feature will add to the general outline given for the monocyclic substrates, that is, the participation of the second (spectator) ring which may stabilize both the π[13] and the σ complexes by electrostatic interaction or even undergo protonation by the alkylated phenyl ring. As far as the early adduct **1** is concerned, the binding energy of the $[Me_2Cl^+\cdots C_6H_5CH_3]$ collision complex, reported to be ca. 12 kcal mol^{-1},[13] should be taken as a lower limit, considering that the electrophile can interact with both aromatic rings of DPE. Subsequent electrophilic attack at one ring to form a σ complex may be accompanied by reorientation of the second phenyl ring, leading to a more stable rotamer whereby the arenium moiety gains the most electrostatic stabilization. The 11 kcal mol^{-1} binding energy of the $[C_6H_7^+\cdot C_6H_6]$ complex[14] may represent an upper limit to this effect, which may be close to the difference in proton affinity (PA) between DPE and toluene.[15] In fact, the ΔPA = 5 kcal mol^{-1} value should be ascribed to the internal electrostatic stabilization by the unprotonated ring of $DPEH^+$ rather than to an intrinsic basicity difference due to a different electron-donating power of the Me vs $PhCH_2CH_2$

groups, in view of their very close σ values ($\sigma_p^+(\mathrm{Me}) = -0.31$, $\sigma_p^+(\mathrm{PhCH_2CH_2}) = -0.265$).[16]

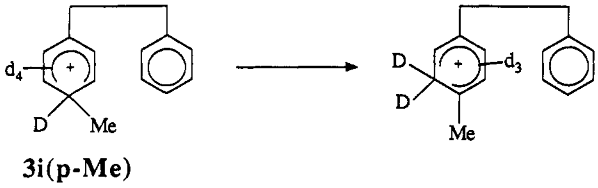
Because of the lack of specific thermochemical data on the energetics of the reactions and of the key ionic intermediates involved, it is useful to compare the alkylation of C_6H_6 by free dimethylhalonium and trifluoromethyl ions. Using the exothermicities of benzene as a rough estimate, one should consider that they do not take into account the binding energy of the electrophile to the bath gas and the proton affinity difference between benzene and DPE, which may be taken equal to the difference of the alkylation exothermicities of the isolated molecules (this latter factor alone would set the exothermicity of the alkylation of the DPE ca. 13 kcal mol^{-1} higher than that of benzene). The exothermicities of the alkylation processes from the free ions Me_2F^+, Me_2Cl^+, and CF_3^+ to C_6H_6 are estimated to be respectively 33.6, 28.2, and 59.1 kcal mol^{-1}.

The different methyl cation affinity between MeCl (64 kcal mol^{-1}) and MeF (59 kcal mol^{-1}),[15] reflected in the corresponding higher exothermicity of the Me_2F^+ alkylation process, points out Me_2Cl^+ as a milder electrophile than Me_2F^+. The CF_3^+ ion is known to be a rather indiscriminate reactant. It is generated from the radiolysis of CF_4, together with the $CF_3^\bullet$ radical, which can give rise to the same trifluoromethylated products. In order to intercept this radical pathway, C_2H_4 has been added (1 mol % with respect to CF_4) for its known reactivity toward $CF_3^\bullet$.

Ring-to-Ring Proton Exchange. The observation of H/D mixing in the methylated and trifluoromethylated products from DPE-d_5 proves that interannular proton transfer does occur. Following the attack of the electrophile E^+ on one of the rings of DPE-d_5, an arenium ion is formed, as illustrated in Scheme II, where species **3** derives from attack at the deuterated phenyl ring. Deuteron transfer from this alkylated ring leads to **4**, bearing a deuteron on an otherwise unsubstituted arenium moiety of DPE. This intermediate may in turn undergo a hydron transfer (a proton more likely than a deuteron, the latter transfer representing the reverse reaction of the previous step) to the deuterated alkylated ring to yield **5**. Such interannular hydron exchanges may in principle go on, leading ultimately to a statistical H/D distribution over the two aromatic rings, which is observed under the low-pressure, long-lifetime conditions prevailing in the mass spectrometric protonation of DPE-d_5 studied by Kuck *et al.*[3,18] The results of Table I indicate that the exchange rate observed in the radiolytic systems does not even approach such a limit. The extent of hydron exchange depends on several interdependent factors: (i) the arenium ion's lifetime, (ii) the kinetic barriers, (iii) the thermochemistry of the process, and (iv) the excess internal energy of the arenium ion undergoing exchange.

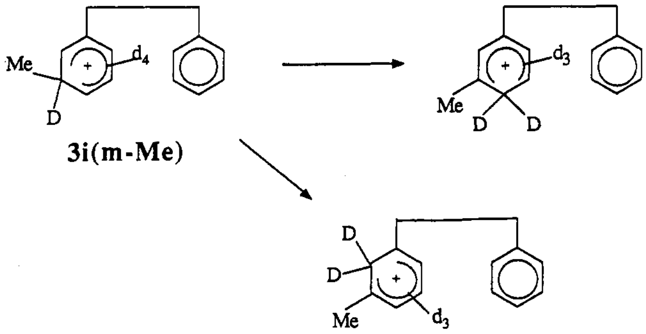
Concerning the first factor, the arenium ion's lifetime is limited in the radiolytic systems by collision with a base and hence depends on the concentration of the latter. If the base is sufficiently strong, one may reasonably assume that deprotonation of arenium intermediates such as **3**–**6** occurs with unit collision efficiency and without H/D isotopic discrimination at an absolute rate that may be estimated by the average dipole orientation (ADO) and related theories.[19] This means that at the highest base concentrations practicable to radiolytic experiments, at ca. 10 torr, ionic lifetimes can be reduced to a few nanoseconds. In general, the time available to unimolecular isomerization processes is orders of magnitude smaller than that in typical mass spectrometric experiments, where the time lag before structural analyses is in the microsecond range.

Very little is known about the intrinsic kinetic barriers (factor ii) of hydrogen-transfer reactions involving arenium ions. In this respect, the *tert*-butylation reaction of selectively deuterated toluenes and DPE-d_5 by Me_3C^+ ions[5,6] has led to quantitative kinetic data which may allow some generalizations to be drawn. Other factors held constant, there appears to exist a kinetic bias toward an intraannular 1,2-H shift with respect to interannular H^+ transfer. It seems reasonable to expect that methylated arenium ions will behave similarly to *tert*-butylated ones. In this case, the primary methylated "ipso" arenium ion **3i** will preferably undergo the intraannular shift shown in eq 1 before any ring-to-ring deuteron transfer will occur.



(1)

It is noteworthy that **3i(p-Me)** undergoes an almost thermoneutral 1,2-H shift while both 1,2-H shifts occurring after formation of **3i(m-Me)** lead to isomeric arenium ions highly stabilized by two electron-donating substituents in conjugatively effective ortho or para positions (eq 2).

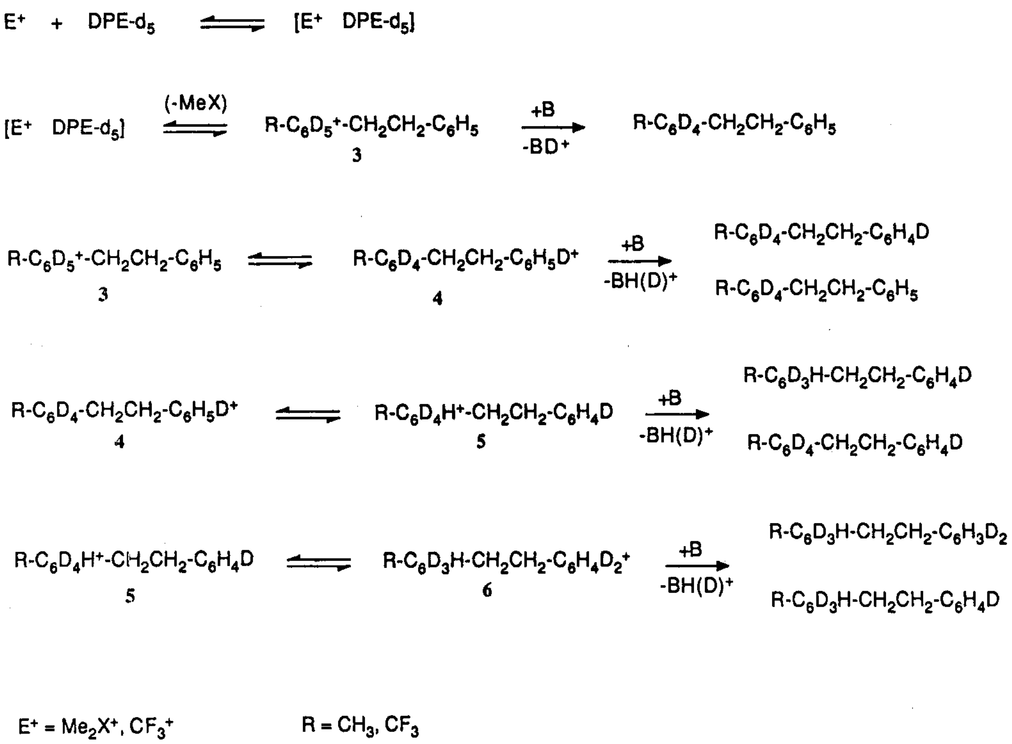


(2)

Next we consider factor iii. The spectator ring behaves as a base, accepting a hydron from the arenium moiety of **3**, and its efficiency will depend on its relative basicity. The presence of R = Me is expected to enhance the relative basicity of the alkylated ring and of R = CF_3 to lower it. Therefore, the first interannular transfer, **3** → **4**, will be highly favorable in the trifluoromethylation reaction, the opposite being true for the subsequent **4** → **5** transfer. The expectation of an easier interannular exchange in the trifluoromethylation than in the methylation reaction is experimentally verified. The results show a different behavior of the sterically comparable meta- and para-methylated isomers and a H/D exchange in the trifluoromethylation reaction extending much further than the first **3** → **4** step. The first interannular hydron transfer to the spectator ring is much more limited following methylation at the meta than at the para position of DPE. This is explained in light of the fast 1,2-H shift which leads to highly stabilized arenium ions from **3i(mMe)** but not from **3i(pMe)**.[5] Thus, in the meta-methylated isomer the first interannular shift has to surmount a thermodynamic gap close to the PA difference between *m*-xylene and toluene while this gap reduces to the PA difference between *p*-xylene and toluene in the case of the para-methylated isomer.[20]

The fourth important factor in determining the extent of ring-to-ring H/D exchange accounts for the relatively high extent of H/D scrambling characterizing all isomeric products of the trifluoromethylation reaction. In fact, ions **3** (R = CF_3) are generated via a very highly exothermic addition reaction, releasing an equally large amount of excess internal energy. Clearly the collisional deactivation of such "hot" arenium intermediates is not fast enough to prevent the occurrence of multiple, endothermic interannular hydron transfers. Collisional stabilization may also be incomplete in the methylation of DPE-d_5 by Me_2F^+, as shown by the much more pronounced H/D-exchange experiment run at the lowest MeF pressure (200 torr). Further lowering of the pressure makes thermal equilibration of the arenium intermediates

SCHEME II



$$E^+ + \text{DPE-}d_5 \rightleftharpoons [E^+\ \text{DPE-}d_5]$$

$$[E^+\ \text{DPE-}d_5] \xrightleftharpoons{(-\text{MeX})} \underset{3}{\text{R-C}_6\text{D}_5{}^{+}\text{-CH}_2\text{CH}_2\text{-C}_6\text{H}_5} \xrightarrow[-\text{BD}^+]{+\text{B}} \text{R-C}_6\text{D}_4\text{-CH}_2\text{CH}_2\text{-C}_6\text{H}_5$$

$$\underset{3}{\text{R-C}_6\text{D}_5{}^{+}\text{-CH}_2\text{CH}_2\text{-C}_6\text{H}_5} \rightleftharpoons \underset{4}{\text{R-C}_6\text{D}_4\text{-CH}_2\text{CH}_2\text{-C}_6\text{H}_5\text{D}^+} \xrightarrow[-\text{BH(D)}^+]{+\text{B}} \begin{matrix}\text{R-C}_6\text{D}_4\text{-CH}_2\text{CH}_2\text{-C}_6\text{H}_4\text{D}\\ \text{R-C}_6\text{D}_4\text{-CH}_2\text{CH}_2\text{-C}_6\text{H}_5\end{matrix}$$

$$\underset{4}{\text{R-C}_6\text{D}_4\text{-CH}_2\text{CH}_2\text{-C}_6\text{H}_5\text{D}^+} \rightleftharpoons \underset{5}{\text{R-C}_6\text{D}_4\text{H}^+\text{-CH}_2\text{CH}_2\text{-C}_6\text{H}_4\text{D}} \xrightarrow[-\text{BH(D)}^+]{+\text{B}} \begin{matrix}\text{R-C}_6\text{D}_3\text{H-CH}_2\text{CH}_2\text{-C}_6\text{H}_4\text{D}\\ \text{R-C}_6\text{D}_4\text{-CH}_2\text{CH}_2\text{-C}_6\text{H}_4\text{D}\end{matrix}$$

$$\underset{5}{\text{R-C}_6\text{D}_4\text{H}^+\text{-CH}_2\text{CH}_2\text{-C}_6\text{H}_4\text{D}} \rightleftharpoons \underset{6}{\text{R-C}_6\text{D}_3\text{H-CH}_2\text{CH}_2\text{-C}_6\text{H}_4\text{D}_2{}^+} \xrightarrow[-\text{BH(D)}^+]{+\text{B}} \begin{matrix}\text{R-C}_6\text{D}_3\text{H-CH}_2\text{CH}_2\text{-C}_6\text{H}_3\text{D}_2\\ \text{R-C}_6\text{D}_3\text{H-CH}_2\text{CH}_2\text{-C}_6\text{H}_4\text{D}\end{matrix}$$

$E^+ = \text{Me}_2\text{X}^+, \text{CF}_3{}^+$ $\quad$ $\text{R} = \text{CH}_3, \text{CF}_3$

still less effective, and this is a second factor concurring to induce complete randomization of all aromatic H/D atoms observed in protonated DPE under mass spectrometric conditions. At sufficiently high pressures, accessible only to the radiolytic technique, the high frequency of thermalizing ion–molecule collisions suppresses the "prompt" isomerization of hot ions, which allows ion–molecule reactions to obey ordinary thermal kinetics, with a positive dependence on the temperature. The observed increase with temperature of interannular H/D exchange in methylated (β-phenylethyl)arenium ions in gases at atmospheric pressure suggests, albeit it does not rigorously prove, that such processes do take place under thermal activation. This is allowed by the relatively slow kinetics of the process, which allows the collisions with the bath gas molecules, occurring at a rate of 10^{10}-10^{11} s^{-1} in the pressure range of interest, to thermalize the complex formed by the reactant *before* the alkylation can occur. An anomaly is represented by the failure to detect a more extensive, or at least comparable, interannular proton exchange in MeF than in MeCl, based on the lower exothermicity of the alkylation due to the higher methyl cation affinity of the latter in the experiments carried out at 120 °C in the absence of base. A set of data where the products of methylation by Me_2F^+ undergo a *less extensive* exchange than those from Me_2Cl^+ is not easy to justify, except by assuming the presence of some nucleophilic impurity in the MeF gas. This is actually the case, since the MeF gas contains traces of dimethyl ether $(CH_3)_2O$ ($\leq$1 mol %), a nucleophile able to intercept the $(CH_3)_2F^+$ ions, giving unreactive $(CH_3)_3O^+$ ions, which somewhat lowers the yields of the methylation products and, more importantly, inhibits the interannular hydron exchange by solvating the arenium ion or even deprotonating the arenium ion in view of the relatively high basicity of dimethyl ether.

Addition of relatively high amounts of strong bases in comparable MeF and MeCl systems brings about a more balanced extent of H/D exchange.

Methylation of DPE by Me_2X^+ (X = F, Cl). The isomeric composition of the products from the attack of the alkylating species Me_2X^+ and CF_3^+ demonstrates the electrophilic nature of the aromatic substitution favoring the position para with respect to the positions meta relative to the $PhCH_2CH_2$ group. At low pressure, under conditions favoring isomerization of the arenium ions to the most stable structure, larger amounts of the meta-substituted isomer are formed. The positional selectivity measured under prevailing kinetic control, i.e., in the presence of Et_3N, which ensures fast deprotonation of the primary intermediates, is characterized by a 2p/o ratio of 5.0. This is remarkably high when compared to the methylation of toluene, yielding a ratio close to unity in MeF[9b] and 0.67 in MeCl. Such an observation is difficult to explain with a differential activating effect of the Me and the $PhCH_2CH_2$ substituent on the ortho and para positions. It may be traced to a different stabilizing effect of the spectator ring of DPE on the intermediates involved in the ortho and para substitution, i.e., a sort of intramolecular differential solvation effect. Another hypothesis concerns the formation of a persistent $[Me_2X^+$–DPE] complex,[12] bound by purely electrostatic attraction: formation of "disolvated" ions, where the dimethylhalonium ion interacts simultaneously with the two rings, would increase the effective electrophile concentration at the para position, favoring substitution at this site.

The substrate selectivity, expressed by $k_{DPE}/k_{toluene}$ of 6.0 in MeCl, characterizes DPE as more reactive than toluene, despite the quite similar intrinsic activating power of the substituents. This result conforms to the kinetic role of the ion–neutral complex **1**, whose structure and stability differentiate DPE from toluene. In fact, referring to the general Scheme I, and considering that the kinetic pattern depends on the reactivity of the charged electrophile and on the activation of the substrate, one is led to conclude that the formation of the early complex **1** is not rate determining in the reaction of Me_2Cl^+ with toluene, i.e., $k_1 < k_{-c}$, while the stabilizing effect of the spectator ring of DPE makes $k_1 > k_{-c}$, accounting for the observed higher reactivity of DPE.

Conclusions

The gas-phase reactions of radiolytically formed Me_2X^+ with DPE have allowed study of the unimolecular reactivity of (β-phenylethyl)arenium ions, highlighting *thermal* interannular proton-exchange reactions between the two aromatic rings. At variance with mass spectrometric experiments, where a complete scrambling of the 11 aromatic protons of protonated DPE has been observed on the microsecond time scale,[3,18] the radiolytic results reveal the occurrence of a limited interannular proton transfer promoted by thermal methylation of DPE, occurring in the nanosecond time range. The striking difference between the mass spectrometric results and the radiolytic results stresses the requirement that the intermediate arenium ion be collisionally thermalized by a relatively dense bath gas. In the low-pressure domain typical of mass spectrometric techniques, fast reactions can occur *before* the excess energy released in the formation of an ionic intermediate is removed, during the relatively long lifetime of the ions, which explains the observed extensive isomerization processes.

The high-pressure radiolytic method used in this study has instead allowed study of interannular proton exchange in the thermal kinetics domain, with the normal positive dependence on temperature. Since in the radiolytic systems the extent of interannular hydron transfer is sensitive to the concentration of added base, an estimate can be made of the rate of interannular exchange, which is found to be on the order of 10^{-8}–10^{-9} s^{-1}. When the efficiency of collisional deactivation is decreased (e.g., at 200 torr) or a highly exothermic reaction (e.g., alkylation of CF_3^+ ions) is used, the ensuing excited arenium ions undergo an "anomalously" large extent of interannular hydron exchange.

The substrate and positional selectivity displayed by Me_2X^+ ions points to the fundamental role of persistent ion–neutral complexes formed between reactant pairs, as already observed in recent radiolytic[6] and mass spectrometric studies.[12]

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References and Notes

(1) (a) Hehre, W. J. In *Modern Theoretical Chemistry*; Schaefer, H. F. III, Ed.; Plenum Press: New York, **1977**; Chapter 7. (b) Sordo, T.; Bertrân, J.; Canadell, E. *J. Chem. Soc., Perkin Trans. 2* **1979**, 1486. (c) Mason, R.; Fernandez, M. T.; Jennings, K. R. *J. Chem. Soc., Faraday Trans. 2* **1987**, *83*, 89. (d) Dewar, M. J. S.; Dieter, K. M. *J. Am. Chem. Soc.* **1986**, *108*, 8075.

(2) (a) Brouwer, D. M.; Mackor, E. L.; Mac Lean, C. *Carbonium Ions*; Olah, G. A., Schleyer, P. v. R., Eds.; Wiley: New York, 1984; Vol. II, p 837. (b) Koptyug, V. A. *Contemporary Problems in Carbonium Ions Chemistry III*; Rees, Ch. Ed.; Springer-Verlag: Berlin, 1984; p 119.

(3) (a) Kuck, D. *Mass Spectrom. Rev.* **1990**, *9*, 583 and references therein.

(4) Cacace, F. *Acc. Chem. Res.* **1988**, *21*, 215.

(5) Cacace, F.; Crestoni, M. E.; Fornarini, S. *J. Am. Chem. Soc.* **1992**, *114*, 6776.

(6) Cacace, F.; Crestoni, M. E.; Fornarini, S.; Kuck, D. *J. Am. Chem. Soc.* **1993**, *115*, 1024.

(7) The collision frequency of an ion or ion–molecule complex in a dense gas at atmospheric pressure is of the order 10^{11} s^{-1}.

(8) Kuck, D.; Bäther, W.; Grützmacher, H. F. *Int. J. Mass Spectrom. Ion Processes* **1985**, *67*, 75.

(9) (a) Cipollini, R.; Pepe, N.; Speranza, M.; Lilla, G. *Gazz. Chim. Ital.* **1978**, *108*, 33. (b) Speranza, M.; Pepe, N.; Cipollini, R. *J. Chem. Soc. Perkin Trans. 2* **1979**, 1179. (c) Cacace, F.; De Petris, G.; Fornarini, S.; Giacomello, P. *J. Am. Chem. Soc.* **1986**, *108*, 7495. (d) Crestoni, M. E.; Fornarini, S. *J. Am. Chem. Soc.* **1989**, *111*, 6008. (e) Herod, A. A.; Harrison, A. G.; McAskill, N. A. *Can. J. Chem.* **1971**, *49*, 2217. (f) Beuchamp, J. L.; Holz, D.; Woodgate, S. D.; Patt, S. L. *J. Am. Chem. Soc.* **1972**, *94*, 2898. (g) Siek, L. W.; Gorden, R. Jr. *Int. J. Chem. Kinet.* **1973**, *5*, 445. (h) Pabst, M. J. K.; Tan, H. S.; Franklin, J. L. *Int. J. Mass Spectrom. Ion Phys.* **1976**, *20*, 191. (i) Hollis, J.; Tedder, J. M.; Walker, G. S. *J. Chem. Soc., Perkin Trans. 2* **1991**, 1187.

(10) (a) Cipollini, R.; Lilla, G.; Pepe, N.; Speranza, M. *J. Phys. Chem.* **1978**, *82*, 1207. (b) Blint, R. J.; McMahon, T. B. Beauchamp, J. L. *J. Am. Chem. Soc.* **1974**, *96*, 1269. (c) Morris, R. A.; Viggiano, A. A.; Van Doren, J. M.; Paulson, J. F. *J. Phys. Chem.* **1992**, *96*, 2597.

(11) Stone, J. A.; Lin, M. S.; Varah, J. *Can. J. Chem.* **1981**, *59*, 2412.

(12) (a) Kuck, D.; Matthias, C. *J. Am. Chem. Soc.* **1992**, *114*, 1901. (b) Audier, H. E.; Monteiro, C.; Mourgues, P.; Berthomieu, D. *Org. Mass Spectrom.* **1990**, *25*, 245.

(13) Sen Sharma, D. K.; Kebarle, P. *J. Am. Chem. Soc.* **1982**, *104*, 19.

(14) Mautner, M.; Hamlet, P.; Hunter, E. P.; Field, F. H. *J. Am. Chem. Soc.* **1978**, *100*, 5466.

(15) Unless otherwise specified, all thermochemical data are taken from: Lias, S. G.; Bartmess, J. E.; Liebmann, J. F.; Holmes, J. L.; Levin, R. D.; Mallard, N. G. *J. Phys. Chem. Ref. Data Suppl. 1* **1988**, 17. The PA of $PhCF_3$ is taken from: Karaman, R.; Huang, J. T. L.; Fry, J. L.. *J. Org. Chem.* **1991**, *56*, 188. The methyl cation affinity of MeF and MeCl is from: Mc Mahon, T. B.; Heinis, T.; Nicol, G.; Hovey, J. K.; Kebarle, P. *J. Am. Chem. Soc.* **1988**, *110*, 7591.

(16) Taylor, R. *Electrophilic Aromatic Substitution*; Wiley: New York, **1990**.

(17) Bucci, R.; Laguzzi, G.; Pompili, M. L.; Speranza, M. *J. Am. Chem. Soc.* **1991**, *113*, 4544.

(18) Kuck, D.; Bäther, W.; Grützmacher, H. F. *J. Am. Chem. Soc.* **1979**, *101*, 7154.

(19) Bowers, M. T.; Su, T. *Interactions between Ions and Molecules*; Ausloos, P., Ed.; Plenum Press: New York, 1975; p 163.

(20) The ΔPA of *m*-xylene/toluene pair is 6.1 kcal mol^{-1}; that of *p*-xylene/toluene pair is 2.2 kcal mol^{-1}; see ref 15.