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Gas-Phase Reactivity of Ethyl Cations: Protonation and Alkylation of *N*-Methylpyrrole and Thiophene

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The gas-phase reactivity, in terms of deuteration versus alkylation, of radiolytically formed ethyl cations $C_2D_5^+$ toward *N*-methylpyrrole and thiophene has been studied in $CH_4-C_2D_6$ systems at 760 and 1520 Torr and in the presence of variable concentrations of triethylamine (TEA) with the aim of obtaining quantitative data on their competitive behavior. The substrate intramolecular selectivity has also been determined in both reaction channels. The gas-phase behavior of ethyl cations under high-pressure conditions demonstrates their predominant Bronsted versus Lewis acid reactivity toward the selected heteroaromatics, whose branching ratios, at a total pressure of 760 Torr, are 2.34 for *N*-methylpyrrole and 2.08 for thiophene. Intramolecular selectivity results indicate a substrate alkylation $\beta:\alpha = 58:42$ for N-methylpyrrole and $\beta:\alpha = 46:54$ for thiophene. The substrate deuteration, determined by ^2H NMR, is $\beta:\alpha = 50:50$ for N-methylpyrrole and $\beta:\alpha = 36:64$ for thiophene.

Introduction

The gas-phase reactivity of ionic electrophiles toward aromatic and heteroaromatic substrates has been extensively studied, both at low- and high-pressure conditions, using mass spectrometric and radiolytic techniques.[1] While a large body of data concerning the alkylating properties of different gaseous cations has been obtained in radiolytic experiments, only a limited number of studies have addressed the comparative evaluation of the Bronsted versus Lewis acid reactivity of these electrophilic species.[2] Determination of the dual behavior of ionic species containing both acidic hydrogens and a carbon-centered electrophilic site is fundamental to the understanding of their overall electrophilic reactivity.

Unlike the typical low-pressure conditions of mass spectrometric experiments, where protonated ion products can be formed both from the attack of alkyl cations and from the dissociation of the condensation ions, the radiolytic technique aids in the study of condensation and proton-transfer reactions at high pressure, where decomposition of the condensation ions is minimized because of the collisional quenching. Therefore, the radiolytic results provide a direct measurement of the attack of the reagent cations toward the selected substrates.

Deuterated ions with undeuterated substrates or, conversely, undeuterated ionic reagents with deuterated substrates are normally used in the determination of the complete reaction pathway. In fact, unless labeled reactants are used, the Bronsted acid reactivity of electrophilic species cannot be detected.

Recently, the competitive condensation and the proton-transfer reaction of $C_2H_5^+$ and *i*-$C_3H_7^+$ cations toward deuterated arenes and *i*-$C_3D_7^+$ cations toward *N*-methylpyrrole have been investigated, under kinetically controlled conditions and pressure values ranging between 700 and 1520 Torr.[2b]

Our present interest is to evaluate the Bronsted versus Lewis acid reactivity of d_5-ethyl cations, $C_2D_5^+$, toward *N*-methylpyrrole and thiophene**,** in order to relate the reactivity of different gaseous cations toward heteroaromatic substrates. The simple five-membered heteroaromatics were selected as substrates since their reactions with radiolytically formed electrophilic cations had been extensively investigated in previous studies,[1b,d,e] focusing attention on the alkylation reaction channels rather than on competitive reaction pathways.

Thermic ethyl cations are obtained from the dissociation of protonated ethonium ions, $C_2D_6H^+$, which are formed by the reaction of CH_5^+ and C_2D_6. Methonium ions CH_5^+ along with $C_2H_5^+$ are in turn generated from the γ-radiolysis of CH_4, used as a batch gas. Experiments have been carried out at high pressure (760−1520 Torr) and in the absence and presence of gaseous triethylamine (TEA). Owing to the collisional quenching of the bath gas, the fragmentation of the reaction adducts is minimized, while the presence of a strong base (PA = 232 kcal mol^{-1}) should ensure a fast neutralization of ionic intermediates. The selected experimental conditions therefore permit the determination of the direct attack of ethyl cations on heteroaromatic substrates, leading to D-incorporation and to d_5-ethylated products.

Experimental Section

Materials. Ethane-d_6, with a stated isotopic purity of 98%, was purchased from Cambridge Isotopes Laboratories. Methane and oxygen, research grade gases, were purchased from Matheson Co., each with a stated purity of 99.99 mol %, and were

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used without further purification. *N*-Methylpyrrole, thiophene, and triethylamine were research grade chemicals from Fluka AG. 2-Ethylthiophene, required as a GLC standard, was purchased from Aldrich Co. Isomeric ethyl-*N*-methylpyrroles and ethylthiophenes, used as mass spectrometric and gas chromatographic standards, were prepared according to established procedures and purified by GLC. Their purity was checked by GLC analysis on a Perkin-Elmer 8320 gas chromatograph equipped with a flame ionization detection (FID) unit, using the same column employed for the analysis of the irradiated mixture. Their identities were verified by conventional ^{1}H NMR spectroscopy.

Procedure. The general procedures for the preparation of the gaseous mixtures and their irradiation have been described elsewhere.[3] Typical experimental conditions were as follows: (a) methane, 730 Torr; ethane-d_6, 30 Torr; *N*-methylpyrrole and thiophene, 3 Torr; O_2, 4 Torr; TEA, 2−13 Torr; (b) methane, 1490 Torr; ethane-d_6, 30 Torr; *N*-methylpyrrole, 3 Torr; O_2, 4 Torr; TEA, 2−10 Torr.

The radiation dose, measured with a neopentane dosimeter,[4] was 3×10^4 Gy, delivered at the rate of 1.8×10^4 Gy h^{-1}, for all samples at 43 °C in a ^{60}Co γ-cell (Nordion Canada Ltd.).

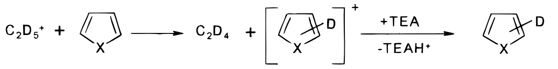
Product Analysis. The analysis of the products was carried out by injecting measured aliquots of the irradiated reaction mixture into a Hewlett-Packard 5988 GC−mass spectrometer, equipped with a flame ionization detection unit. The outlet of the gas chromatographic column was connected to a two-way splitter in order to simultaneously obtain a flame ionization and mass spectrometric detection of the injected samples. The yield of the deuterated *N*-methylpyrroles and deuterated thiophenes was measured by mass spectrometric analysis. The measurements were taken from the abundance of the M + 1 peak (m/z 82) of *N*-methylpyrrole and M + 1 peak (m/z 85) of thiophene, after subtracting the contribution of ^{13}C measured in several calibration experiments preceding and following the analysis of the irradiated sample. All of the mass spectrometric runs were performed in SIM conditions, selecting the m/z 81 and m/z 82 ions for *N*-methylpyrrole and the m/z 84 and m/z 85 for thiophene. The yields of deuterated *N*-methylpyrroles and deuterated thiophenes were then related to the yields of the alkylated derivatives calculated from the FID response in the same GC−MS analysis. The gas chromatographic separation of the α and β alkyl derivatives permits the determination of the substrate positional selectivity toward the reagent cations. The gas chromatographic column used in the products analysis was a 50 m. long CP-WAX 52, 0.32 mm i.d., with a 0.2 μm film of stationary phase (Chrompack). Qualitative mass spectrometric analyses of the reaction products were carried out by comparing their mass fragmentation spectra with those arising from the synthetic reference compounds.

To determine the substrate positional selectivity relevant to the Bronsted reactivity of the reagent cations, the position of deuteration in the heteroaromatic ring was detected by ^{2}H NMR. All NMR spectra were run on a Bruker AMX-600 operating at 600.13 MHz for proton and at 92.12 MHz for deuterium. All ^{2}H NMR spectra were run in 1,4 dioxane while ^{1}H spectra were run in 1,4-dioxane-d_8. The choice of the solvent was based on the fact that a large number of solvents were unsuitable either due to secondary reactions, difficulty in drying, or the risk of water inducing ^{1}H−^{2}H exchange. ^{2}H spectra were run without lock and to ensure the least amount of drift the NMR laboratory temperature was kept constant within 1 °C. The N_2 flux was thermostated within 1 °C before the Bruker variable-temperature unit (Eurotherm) was used. In this way, a regulation within ±0.1 °C was obtained. Stability and signal-to-noise ratio were checked as previously.[2c] The samples analyzed by ^{2}H NMR refer to radiolytic experiments carried out at a pressure of 760 Torr of bath gas and 10 Torr of TEA. To obtain a sufficient amount of product to match the ^{2}H NMR sensitivity, several reaction flasks were washed with dioxane, and the extracts were collected for the NMR analysis.

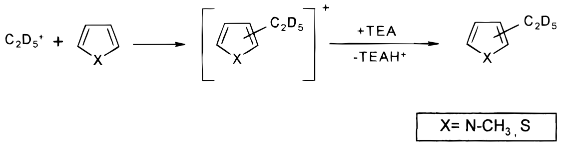
ICR Experiments. The experiments were performed by an Extrel FTMS, Millipore Corp., mass spectrometer. Typical experimental conditions were CH_4:C_2D_6:heteroaromatic substrate = 10:2:1 and total pressure 2×10^{-7} Torr. Once formed, the $C_2D_6H^+$ cations were isolated and allowed to react, in two separated runs, with *N*-methylpyrrole and thiophene. Before their dissociation to $C_2D_5^+$, the ethonium ions showed a very poor capability to deuterate the heteroaromatic substrates. The only significant ions observed in the spectra were m/z 82 and m/z 85, corresponding to protonated *N*-methylpyrrole and thiophene. For a delay of up to 200 ms, the m/z 83 and m/z 86 ions, corresponding to the deuterated substrates, were observed. Their formation strictly depended on $C_2D_5^+$ cations, since the sweeping out of the latter resulted in the disappearance of deuterated products.

Results

The gas-phase reaction of $C_2D_5^+$ cations with *N*-methylpyrrole and thiophene yields the corresponding deuterated and ethylated products (eqs 1 and 2).



(1)



(2)

Ethyl cations, $C_2D_5^+$, are formed by γ-irradiation of gaseous mixtures containing CH_4, C_2D_6, heteroaromatic substrates, O_2, and TEA. Oxygen (4 Torr), as radical scavenger, has been used to inhibit the formation of products from radical pathways, while TEA has been added to obtain a fast deprotonation of the ionic intermediates. The composition of the irradiated systems and the absolute and relative yields of the reaction products are indicated in Tables 1 and 2. The absolute yields of the products are expressed by their $G_{(M)}$values, defined as the number of molecules produced per 100 eV absorbed by the gaseous mixture.

The following main features arise from the inspection of Table 1: (a) The reaction products are deuterated *N*-methylpyrroles, C_5H_6DN, and d_5-ethyl-*N*-methylpyrroles, $C_7H_6D_5N$. (b) Their absolute yields decrease with the addition of TEA. (c) The $C_5H_6DN/C_7H_6D_5N$ ratio indicates a prevalent formation of the deuterated *N*-methylpyrroles over the d_5-ethyl-*N*-methylpyrroles. This ratio is not affected by the presence of TEA. (d) For all experimental conditions a prevalent formation of β-ethyl derivatives is observed. At 760 Torr, the II_α/II_β ratio increases along with the increasing concentration of TEA. (e) At 1520 Torr, the yields of the reaction products are lower than those observed at 760 Torr.

Data from Table 2 can be summarized as follows: (a) The obtained reaction products are deuterated thiophenes, C_4H_3DS, and d_5-ethyl-thiophenes, $C_6H_3D_5S$. (b) Their absolute yields

TABLE 1: Gas-Phase Reactions of Ethyl Cations with *N*-Methylpyrrole[a]

system composition (Torr)				product distribution							
				absolute yields (G_{+M})						relative yields	
substrate	bulk gas	additives		I		II		II_α	II_β	I/II	II_α/II_β
C_5H_7N (3)	$CH_4:C_2D_6$ (730:30)		O_2 (4)	C_5H_6DN	0.73	$C_7H_6D_5N$	0.35	0.12	0.23	2.08	0.52
C_5H_7N (3)	$CH_4:C_2D_6$ (730:30)	TEA (2)	O_2 (4)	C_5H_6DN	0.61	$C_7H_6D_5N$	0.30	0.12	0.18	2.03	0.67
C_5H_7N (3)	$CH_4:C_2D_6$ (730:30)	TEA (5)	O_2 (4)	C_5H_6DN	0.36	$C_7H_6D_5N$	0.18	0.07	0.11	2.00	0.64
C_5H_7N (3)	$CH_4:C_2D_6$ (730:30)	TEA (10)	O_2 (4)	C_5H_6DN	0.21	$C_7H_6D_5N$	0.12	0.05	0.07	1.76	0.71
C_5H_7N (3)	$CH_4:C_2D_6$ (1490:30)		O_2 (4)	C_5H_6DN	0.30	$C_7H_6D_5N$	0.15	0.05	0.10	2.00	0.50
C_5H_7N (3)	$CH_4:C_2D_6$ (1490:30)	TEA (5)	O_2 (4)	C_5H_6DN	0.12	$C_7H_6D_5N$	0.06	0.02	0.04	2.00	0.50
C_5H_7N (3)	$CH_4:C_2D_6$ (1490:30)	TEA (10)	O_2 (4)	C_5H_6DN	0.06	$C_7H_6D_5N$	0.03	0.01	0.02	2.00	0.50

[a] TEA = triethylamine, II_α = α-substituted ethyl derivatives, II_β = β-substituted ethyl derivatives.

TABLE 2: Gas-Phase Reactions of Ethyl Cations with Thiophene[a]

system composition (Torr)				product distribution							
				absolute yields (G_{+M})						relative yields	
substrate	bulk gas	additives		I		II		II_α	II_β	I/II	II_α/II_β
C_4H_4S (3)	$CH_4:C_2D_6$ (730:30)		O_2 (4)	C_4H_3DS	0.57	$C_4H_3D_5S$	0.39	0.21	0.18	1.47	1.17
C_4H_4S (3)	$CH_4:C_2D_6$ (730:30)	TEA (2)	O_2 (4)	C_4H_3DS	0.45	$C_4H_3D_5S$	0.34	0.18	0.16	1.34	1.12
C_4H_4S (3)	$CH_4:C_2D_6$ (730:30)	TEA (5)	O_2 (4)	C_4H_3DS	0.34	$C_4H_3D_5S$	0.26	0.14	0.12	1.30	1.17
C_4H_4S (3)	$CH_4:C_2D_6$ (730:30)	TEA (10)	O_2 (4)	C_4H_3DS	0.14	$C_4H_3D_5S$	0.13	0.07	0.06	1.07	1.17
C_4H_4S (3)	$CH_4:C_2D_6$ (730:30)	TEA (13)	O_2 (4)	C_4H_3DS	0.11	$C_4H_3D_5S$	0.11	0.06	0.05	1.04	1.25

[a] TEA = triethylamine, II_α = α-substituted ethyl derivatives, II_β = β-substituted ethyl derivatives.

decrease with increasing concentration of TEA. (c) The $C_4H_3DS/C_6H_3D_5S$ ratio tends toward the equivalence of the product yields at the highest concentration of TEA. (d) The isomeric distribution of the ethyl derivatives, which is not affected by the different base concentrations, corresponds to a ratio of $\beta:\alpha = 46:54$.

In addition to d_5-ethyl derivatives, undeuterated ethylated products have been obtained from the electrophilic attack of the radiolytically formed $C_2H_5^+$ cations on the selected substrates. Under GC–MS analytical conditions suitable for the discrimination and detection of partially deuterated ethylated products, only d_5-ethyl derivatives and undeuterated ethyl derivatives have been observed. A limited amount of d_9-butylated heteroaromatics, less than 4% with respect to d_5-ethyl heteroaromatics, has been detected.

While the presence of O_2 excludes the formation of the reaction products from radical pathways, their ionic origin is demonstrated by the depression of the reaction yields, caused by increasing concentrations of a base (TEA) which is capable of interacting with charged reactants.

The ^{2}H NMR results, related to the experiments carried out under kinetically controlled conditions, indicate a substrate deuterium incorporation corresponding to a ratio of $\beta:\alpha = 50:50$ for *N*-methylpyrrole and to a ratio of $\beta:\alpha = 36:64$ for thiophene.

Discussion

Reagent Ion. The reaction environment consisted of a gaseous mixture of CH_4, C_2D_6, a heteroaromatic substrate, O_2, and TEA. The experiments with *N*-methylpyrrole were carried out at the total pressure of 760 and 1520 Torr and the experiments with thiophene at the total pressure of 760 Torr. CH_4 was used as bath gas, i.e., present in a large excess over deuterated ethane and heteroaromatic substrates, to minimize their direct radiolysis. The molar ratios were $CH_4:C_2D_6:\text{substrate} = 243:10:1$ at 760 Torr and $CH_4:C_2D_6:\text{substrate} = 486:20:1$ at 1520 Torr.

The γ-radiolysis of the bath gas leads to the formation of CH_5^+ and $C_2H_5^+$ cations whose G_{+M} values were ca. 1.9 and 0.9, respectively.[5] Exothermic protonation of C_2D_6 by CH_5^+ ($\Delta H = -12$ kcal mol^{-1}) allows for the formation of ethonium ions, $C_2D_6H^+$ (eq 3), whose decomposition, in turn, lead to ethyl cations, $C_2D_5^+$ (eq 4).

$$CH_5^+ + C_2D_6 \rightarrow C_2D_6H^+ + CH_4 \tag{3}$$

$$C_2D_6H^+ \rightarrow C_2D_5^+ + HD \tag{4}$$

Under the selected experimental conditions a limited production of d_9-butyl cations occurred. This can be inferred from the relevant neutral products whose total yield is 4% with respect to that of the d_5-ethyl derivatives. The formation of d_9-butyl cations could be probably ascribed to coupling reactions of reactive species arising from the direct radiolysis of C_2D_6. In fact, in preliminary experiments performed to select the proper ratios in the gaseous reaction mixture, a direct dependence of the yield of d_9-butyl heteroaromatics on the concentration of C_2D_6 was observed.

Since the aim of our investigation was the study of the Bronsted vs Lewis acid reactivity of $C_2D_5^+$ cations toward the selected substrates, a preliminary evaluation of the reactivity of the other ionic species present in the reaction environment is necessary to verify the possible formation of interfering products. The ethyl cation $C_2H_5^+$ reacts with *N*-methylpyrrole and thiophene to form the relevant ethylated products that can be easily discriminated from the d_5-ethylated products, derived from the reaction of the $C_2D_5^+$ cations. All of the cationic species as CH_5^+, $C_2H_5^+$ and $C_2D_6H^+$ can exothermically protonate the heteroaromatic substrates providing neutral reaction products that are equivalent to the substrates. According to experimental evidence[6] and theoretical investigations,[7] two isomeric structures of the ethonium ions are conceivable: a C–C and a C–H protonated form. The H-bridged structure was indicated as the most stable, while the activation energy for its rearrangement into the C–H protonated form was calculated[7c] to be 7.2 kcal mol^{-1}. Since the activation energy for the decomposition of ethonium ions into H_2 and $C_2H_5^+$ is estimated for the C–C and a C–H protonated forms[7c] to be 13.6 and 9.1

kcal mol^{-1}, respectively, conversion should be favored over decomposition. After the rearrangement of the deuterated ethonium ion $C_2D_6H^+$ into the most stable form, H/D scrambling might occur. As a consequence, deuterated products could be formed in the reaction of the resulting ethonium ions with the substrates, in addition to those that arise from the direct attack of $C_2D_5^+$ cations. To clarify the role of $C_2D_6H^+$ cations as possible deuterating species toward the heteroaromatic substrates, preliminary ICR experiments have been performed. Once formed, the $C_2D_6H^+$ cations were isolated and allowed to react in two separate runs with *N*-methylpyrrole and thiophene. Before their dissociation to $C_2D_5^+$ (eq 4), the ethonium ions showed a very poor capability to deuterate the heteroaromatic substrates. In fact, the only significant ions observed in the spectra were those corresponding to the protonated *N*-methylpyrrole and thiophene, while the formation of deuterated products was found to depend on $C_2D_5^+$ cations.

Reaction Pathway. The gas-phase attack of $C_2D_5^+$ cations on the selected substrates is consistent with eqs 1 and 2 involving the formation of the relevant ionic intermediates which undergo collisional quenching with the bath CH_4 molecules, before neutralization by proton transfer to the added base (TEA). The ionic intermediates, in competition with collisional deactivation, may undergo isomerizations, by H, D, and $C_2D_5^+$ shifts, to more stable structures. However, these secondary processes are expected to be strongly reduced in gaseous systems at the highest total pressure and base concentration.

Reaction of $C_2D_5^+$ with *N*-Methylpyrrole. The C_5H_6DN/$C_7H_6D_5N$ ratio (Table 1) indicates a prevalent Bronsted acid over Lewis acid reactivity of the $C_2D_5^+$ cations, in all experimental conditions. A comparative examination of the data obtained at 760 and 1520 Torr shows that the absolute reaction yields of C_5H_6DN and $C_7H_6D_5N$ decrease as the pressure of the gaseous mixture increases, while the $C_5H_6DN/C_7H_6D_5N$ ratio is not affected by pressure variation. The reduction of the reaction yields, observed at 1520 Torr, can be reasonably ascribed to the more effective collisional quenching that ethonium ions undergo at this pressure value. Under these conditions, in fact, the dissociation of $C_2D_6H^+$ ions which leads to $C_2D_5^+$ cations should be reduced. On the other hand, a higher stabilization of the ethonium ions should favor isomerization processes whose activation barrier is lower than that for dissociations. Potential H/D scramblings occurring during isomerizations should enable ethonium ions to act as deuterating reagents toward *N*-methylpyrrole, increasing the yields of the C_5H_6DN products at the highest pressure conditions. However, since at 1520 Torr the $C_5H_6DN/C_7H_6D_5N$ ratio does not differ from that observed at 760 Torr, this hypothesis can be reasonably discarded. As further evidence for the absence of the H/D scrambling, only d_5-ethylated products were observed, even at 1520 Torr.

For a correct determination of the $C_5H_6DN/C_7H_6D_5N$ ratio, several features relevant to the calculation of the yields of the C_5H_6DN products have to be taken into account: (a) The attack of $C_2D_5^+$ cations on the substrate leads to the α and β ring deuterated adducts A and B which can either interconvert via deuteron shift or form the A_1 and B_1 adducts via proton shift (Figure 1). (b) Intramolecular selectivity data, obtained at 760 Torr and in the presence of 10 Torr of TEA, indicate a deuterium distribution β:α = 50:50 which supports the hypothesis of an indiscriminate deuteron vs proton shift, as expected on the grounds of the estimated exothermicity of the attack (ca. −52 kcal mol^{-1}). (c) Owing to the large proton affinity difference between *N*-methylpyrrole and TEA (ca. 17 kcal mol^{-1}), a selective deuteron vs proton abstraction by the added base can be excluded. Deprotonation of the A, B, A_1, and B_1 adducts by TEA (Figure 1) provides the neutral C_5H_6DN products, while deuteron abstraction from A and B adducts results in detection of products without D incorporation.

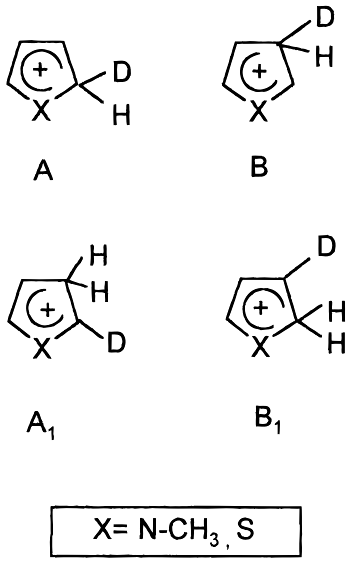


Figure 1.

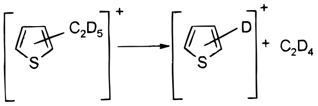
Therefore, the observed C_5H_6DN product yield (0.21) has to be corrected, taking into account the proton versus deuteron abstraction from the A and B adducts which is expected to occur in the ratio 1:1. In light of these considerations, the observed ratio $C_5H_6DN/C_7H_6D_5N$ (1.76) becomes 2.34. Inspection of Table 1 shows that β-ethyl derivatives (II_β) formed in reaction 2 predominate under all conditions. Moreover, while the II_α/II_β ratio increases at 760 Torr along with increasing concentrations of the added base, it is constant at 1520 Torr, irrespective of the different concentrations of TEA.

Probably due to its lower molar ratio in the gaseous mixtures at 1520 Torr with respect to that at 760 Torr, TEA is less effective in determining a fast deprotonation of the ionic adducts. At 1520 Torr, in fact, a similar distribution of isomeric ethylated products is observed in both the presence and absence of TEA.

The isomeric distribution of ethylated products at 760 Torr, which is affected by the base concentration, seems in particular to reflect the contribution of the primary *N*-ethylated adduct, which is expected to be formed according to the negative charge density of the ring positions of the substrate ($N > \beta > \alpha$). In fact, since *N*-ethylated products are not observed, the relevant adducts can undergo a back-dissociation or alternatively isomerize, forming α-ethylated intermediates whose deprotonation, when favored by TEA, results in the increased relative yield of II_α products. The prevalent formation of β-ethyl derivatives II_β confirms data of a previous paper,[1e] where the gas-phase intramolecular selectivity of *N*-methylpyrrole was investigated with $C_2H_5^+$ cations directly generated by γ-radiolysis of CH_4. The observed difference of the II_α/II_β ratios[8] can be ascribed to the different energy content of $C_2H_5^+$ and $C_2D_5^+$ cations. In particular, since the higher energy content of $C_2H_5^+$ cations should reasonably favor the back-dissociation of the *N*-ethylated adducts, the resulting isomeric distribution of the ethylated products is expected to reflect the direct attack on β and α carbons of the ring.

Reaction of $C_2D_5^+$ with Thiophene. The reaction of $C_2D_5^+$ cations with thiophene has been investigated in gaseous systems at a total pressure of 760 Torr. The low reaction yields of deuterated products C_4H_3DS, obtained under these conditions, exclude their determination at higher pressure (1520 Torr), where they are expected to decrease with reduced formation of $C_2D_5^+$ cations.

The values of the $C_4H_3DS/C_6H_3D_5S$ ratio (Table 2) indicate a slightly favored formation of C_4H_3DS products, which decreases with increasing concentrations of TEA. The influence of TEA on the products ratio can be related to the difference between the proton affinities of TEA (PA = 232 kcal mol^{-1}) and thiophene (PA = 196.6 kcal mol^{-1}) which allows a fast deprotonation of the d_5-ethylated adducts C precluding their evolution to deuteronated adducts D[9] (eq 5). The highest efficiency of deprotonation is reached at highest TEA concentration. The product distribution obtained in this condition reflects the attack of $C_2D_5^+$ cations.



C D

(5)

The same base effect was not observed in the experiments with *N*-methylpyrrole. Owing to the lower difference between the proton affinities of TEA and *N*-methylpyrrole (ca. 17 kcal mol^{-1}), the gaseous base could be less effective in precluding the formation of the relevant deuterated adducts. Consequently, any variation in the products ratio is observed in both the presence and absence of TEA.

The intramolecular selectivity of thiophene for deuterium incorporation that was investigated in the presence of 10 Torr of TEA corresponds to $\beta:\alpha = 36:64$. This deuterium distribution, differing from the statistical ratio ($\beta:\alpha = 50:50$), should reasonably exclude a complete H/D scrambling on the heteroaromatic ring, as in the case of *N*-methylpyrrole. This is probably attributable to the lower exothermicity of the relevant attack (estimated exothermicity ca. 21 kcal mol^{-1}) and to a more effective neutralization of the adduct D by TEA**.** Taking these considerations into account, the deuterated products C_4H_3DS should only arise from the neutralization of the A and B adducts, while the obtained yield represents the 50% of the actual one, as expected from an indiscriminate H/D abstraction by TEA. The large PA differences between thiophene and TEA should, in fact, exclude preferential proton vs deuteron abstraction due to kinetic isotope effects. As a consequence, evaluation of the experimental ratio of the reaction products, $C_4H_3DS/C_6H_3D_5S = 1.04$, has to consider in the yield of C_4H_3DS products, the contribution arising from deuteron abstraction of A and B adducts by TEA. Therefore, the resulting branching ratio of deuterated and ethylated products is equal to 2.08.

The isomeric distribution of d_5-ethylated products, $\beta:\alpha = 46:54$, which is in agreement with previous gas-phase radiolytic studies, is determined by the net charge position on the heteroaromatic ring, i.e., $\alpha > \beta > S$. Since sulfur is the less attractive site for an approaching charged electrophile, possible interactions between $C_2D_5^+$ cations and the heteroatom do not play a significant role in the $\alpha:\beta$ distribution of ethylated products. This is demonstrated by the constant ratio of II_α/II_β products obtained in both the presence and absence of TEA.

Conclusions

The gas-phase reactivity of $C_2D_5^+$ cations toward *N*-methylpyrrole and thiophene leads to the predominant formation of deuterated over alkylated products, under all experimental conditions.

Possible contributions to the production of deuterated heteroaromatic derivatives by ethonium ions $C_2D_6H^+$ can be reasonably excluded on the grounds of data obtained both in ICR and in radiolytic experiments at different pressure values.

In particular, the constant ratio of deuterated over alkylated products obtained at both 760 and 1520 Torr indicates that $C_2D_6H^+$ cations do not act as deuterating species toward the selected substrates even at the highest pressure, where the favored H/D scrambling could have resulted in an increased yield of deuterated products.

Substrate intramolecular selectivity results, related to the Lewis acid reactivity of $C_2D_5^+$ cations, show a prevalent β attack for *N*-methylpyrrole and a prevalent α attack for thiophene, confirming data obtained in previous radiolytic experiments. The distribution of the ethylated products reflects the position of the negative charge density of the heteroaromatic rings. In the case of *N*-methylpyrrole, where $N > \beta > \alpha$, the gas-phase attack of $C_2D_5^+$ cations on nitrogen does not result in a *N*-ethylated derivative. However, the attack on the heteroatom can be inferred from experimental conditions where a proper TEA concentration favors a fast deprotonation of the α-ethylated intermediate, the latter obtained by isomerization of the ethyl cations, after its primary attack on the heteroatom.

Concerning the Bronsted acid reactivity of $C_2D_5^+$ cations, the ^2H NMR results indicate a prevalent deuterium incorporation on the β position of the thiophene ring. The statistical distribution of deuterium, obtained in the case of *N*-methylpyrrole, supports the hypothesis of an indiscriminate deuteron vs proton shift, as expected on the grounds of the estimated exothermicity of the relevant attack.

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References and Notes

(1) (a) Speranza, M. *Adv. Heterocycl. Chem.* **1986**, *40*, 25. (b) Margonelli, A.; Speranza, M. *J. Chem. Soc., Perkin Trans. 2* **1983**, 1491. (c) Angelini, G.; Laguzzi, G.; Sparapani, C.; Speranza, M. *J. Am. Chem. Soc.* **1984**, *106*, 37. (d) Laguzzi, G.; Speranza, M. *J. Chem. Soc., Perkin Trans. 2* **1987**, 857. (e) Laguzzi, G.; Bucci, R.; Grandinetti, F.; Speranza, M. *J. Am. Chem. Soc.* **1990**, *112*, 3064. (f) Angelini, G.; Sparapani, C.; Speranza, M. *J. Am. Chem. Soc.* **1990**, *112*, 3060. (g) Bucci, R.; Laguzzi, G. *Rad. Acta* **1990**, *51*, 177. (h) Bucci, R.; Laguzzi, G.; Pompili, M. L.; Speranza, M. *J. Am. Chem. Soc.* **1991**, *113*, 4544. (i) Bucci, R.; Grandinetti, F.; Filippi, A.; Laguzzi, G.; Occhiucci, G.; Speranza, M. *J. Am. Chem. Soc.* **1991**, *113*, 4550. (l) Filippi, A.; Occhiucci, G.; Speranza, M. *Can. J. Chem.* **1991**, *69*, 732. (m) Filippi, A.; Occhiucci, G.; Sparapani, C.; Speranza, M. *Can. J. Chem.* **1991**, *69*, 740. (n) Giacomello, P.; Pepi, F. *J. Phys. Chem.* **1993**, *97*, 4421. (o) Cheung, M.; Harrison, A. G. *J. Mass Spectrom.* **1995**, *30*, 1272. (p) Tsuji, M.; Aizawa, M.; Nishimura, Y. *Bull. Chem. Soc. Jpn.* **1996**, *69*, 1055. (q) Nguyen, V. Q.; Turecek, F. *J. Mass Spectrom.* **1996**, *31*, 1173.

(2) (a) Kuck, D. *Mass Spectrom. Rev.* **1990**, *9*, 583. (b) Cerichelli, G.; Crestoni, M. E.; Fornarini, S. *J. Am. Chem. Soc.* **1992**, *114*, 2002. (c) Laguzzi, G.; Angelini, G.; Bucci, R.; Segre, A. L. *J. Phys. Chem.* **1994**, *98*, 6719.

(3) (a) Cacace, F.; Possagno, E. *J. Am. Chem. Soc.* **1973**, *95*, 3397. (b) Cacace, F. *Acc. Chem. Res.* **1988**, *21*, 215.

(4) (a) Lias, S. G.; Ausloos, P. *J. Chem. Phys.* **1965**, *43*, 2748. (b) Collin, G. J. *Can. J. Chem.* **1976**, *54*, 3050.

(5) Ausloos, P.; Lias, S. G.; Gorden, R. *J. Chem. Phys.* **1963**, *39*, 3341.

(6) (a) Olah, G. A.; Klopman, G.; Schlosberg, R. H. *J. Am. Chem. Soc.* **1969**, *91*, 3261. (b) Olah, G. A.; Halpern, Y.; Shen, J.; Mo, Y. K. *J. Am. Chem. Soc.* **1971**, *93*, 1251. (c) Weiner, J.; Smith, G. P. K.; Saunders, M.; Cross, R. J. *J. Am. Chem. Soc.* **1973**, *95*, 4115. (d) Hiraoka, K.; Kebarle, P. *Adv. Mass Spectrom.* **1978**, *7b*, 1408. (e) Yeh, L. I.; Price, J. M.; Lee, Y. T. *J. Am. Chem. Soc.* **1989**, *111*, 5597. (f) Heck, A. J. R.; deKoning, L. J.; Nibbering, N. M. M. *Int. J. Mass Spectrosc. Ion Processes* **1992**, *117*, 145.

(7) (a) Poirier, R. A.; Costantin, E.; Abbé, J. C.; Peterson, M. R.; Csizmadia, I. G. *J. Mol. Struct.* (*THEOCHEM*) **1982**, *88*, 343. (b) Hirao,

K.; Yamabe, S. *Chem. Phys.* **1984**, *89*, 237. (c) Carniero, J. W. de M.; Schleyer, P. v. R.; Saunders, M.; Remington, R.; Schaefer III, H. F.; Rauk, A.; Sorensen, T. S. *J. Am. Chem. Soc.* **1994**, *116*, 3483.

(8) The obtained II_{α}/II_{β} ratios were respectively 0.41 for ref 1e and 0.52 for the present work. Since in ref 1e and in the present work two different gaseous bases have been used, the comparison between the isomeric distribution of the ethylated products, in these works, is only possible in experimental conditions related to the absence of base.

(9) Since the PA value of the ethylated adduct of thiophene is unknown, the PA value of thiophene has been taken into account.