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GAS PHASE AROMATIC NITRATION BY PROTONATED FLUOROALKYL NITRATES

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Abstract: The study of gas-phase aromatic nitration by protonated alkyl nitrates has been extended from $[CH_3NO_3]H^+$ (1) to $[CF_3CH_2NO_3]H^+$ (2) and $[(CF_3)_2CHNO_3]H^+$ (3). Radiolytically generated 2 and 3 efficiently promote aromatic nitration in CH_4 at 760 torr, 37°C, according to an ionic mechanism whose charged reactants and intermediates have directly been detected by chemical ionization mass spectrometry. The selectivity of 2 and 3, measured by ρ values of -2.6 and -2.4 respectively, as compared to -3.87 of 1, characterizes the fluorinated cations as highly reactive and unselective gaseous electrophiles.

Recent studies based on a combination of mass spectrometric, radiolytic and computational techniques have identified protonated methyl nitrate (1), in practice a NO_2^+ ion "solvated" by one methanol molecule, as the first example of a well-behaved nitrating cation whose reactivity toward aromatic substrates conforms in the gas phase to the classical pattern prevailing in solution.[1-4]

The present study is aimed at supporting and extending the above results, and their mechanistic interpretation, by using more activated nitrating cations. To this end, two electron-deficient nitrate esters, $CF_3CH_2NO_3$ and $(CF_3)_2CHNO_3$, have been protonated in the gas phase by radiolytically generated CH_5^+ and $C_2H_5^+$ ions, and the nitration of representative aromatic substrates by the corresponding cations, $\left[CF_3CH_2NO_3\right]H^+$ (2) and $\left[(CF_3)_2CHNO_3\right]H^+$ (3), has been studied in CH_4 at 37°C, 760 torr. Coordinated experiments based on chemical ionization mass spectrometry (CIMS) have been carried out in CH_4 at pressures up to 0.5 torr in order to achieve direct detection of the charged reactants and intermediates involved in the gas-phase aromatic nitration.

RESULTS

Irradiation with γ photons (37°C, 5×10^3 Gy) of gaseous systems containing CH_4 as the bulk component (746 torr), together with the fluoroalkyl nitrate (ca.10 torr), the aromatic substrate(s) (0.2 to 0.5 torr) in the presence of a radical scavenger (O_2, 10 torr) and of a thermal-electron interceptor (SF_6, 5 torr), gives the expected nitrated aromatics with typical G_{+M} values from 1.9 to 3.3,[5] corresponding to percentual yields from 60 to 100%.

The following considerations argue for the ionic character of the nitration. First, the irradiated systems contain an effective radical scavenger. Second, the presence of a gaseous base, capable of intercepting the CH_5^+ and $C_2H_5^+$ ions from CH_4, as well as the $\left[RNO_3\right]H^+$ ions, causes a strong depression of the yields, that gradually decline as the base concentration is increased. Typically, the nitrotoluenes yield drops to ca.20% in the presence of NEt_3 (2.3 torr) and to less than 10% in the presence of isopropanol (3.2 torr). Finally, no nitration occurs in irradiated systems where CH_4 is replaced by i-C_4H_{10}. This is particularly significant in view of the inability of the t-$C_4H_9^+$ ions from i-C_4H_{10} to accomplish protonation of the fluoroalkyl nitrates.[6] As a consequence, the i-C_4H_{10} experiments provide strong evidence for the role of protonated esters **2** and **3** as the nitrating reactants.

Table 1 summarizes the results of the competition experiments aimed at measuring the substrate and the positional selectivity of **2** and **3**. Pertinent data from previous studies[2] of aromatic nitration by protonated methyl nitrate **1** are included for comparison purposes. The results outlined in Table 1 characterize the fluorinated cations as typically electrophilic reagents, displaying the expected decrease of both substrate and positional selectivity with respect to **1**.

DISCUSSION

The nitrating reactant is formed in the radiolytic systems by proton transfer from the $C_nH_5^+$ ions, the major Brønsted acids in irradiated methane, to the fluoroalkyl nitrates

$$C_nH_5^+ + RNO_3 \longrightarrow C_nH_4 + \left[RNO_3\right]H^+ \qquad (1)$$

The process has been shown to be exothermic by 44 (n=1) and 13 (n=2) kcal mol^{-1} when R=Me.[2] While the proton affinity (PA) of the fluoroalkyl nitrates is unknown, their protonation by CH_5^+ is undoubtedly exothermic, which seems most likely by $C_2H_5^+$ as well.[7]

The cations **2** and **3** from process (1), thermalized by many unreactive collisions with CH_4 molecules, react with the aromatic substrate according to a process that can be regarded as the nucleophilic displacement of the corresponding alcohol

$$\left[RNO_3\right]H^+ + C_6H_5X \longrightarrow ROH + \left[XC_6H_5NO_2\right]^+ \qquad (2)$$

Nitration of benzene by protonated methyl nitrate *via* (2) has been shown to be energetically allowed,[2] and the process can be expected to be appreciably more exothermic when the fluorinated cations **2** and **3** are involved, in view of the lower binding energy of NO_2^+ to their electron-deficient ROH moieties. Eventually, the arenium ions from (2) undergo deprotonation by any gaseous base of adequate strenght, including the aromatic substrate itself, yielding the observed neutral nitrobenzenes

$$\left[XC_6H_5NO_2\right]^+ + B \longrightarrow XC_6H_4NO_2 + BH^+ \qquad (3)$$

Application of CIMS to the problem has allowed direct observation of processes (1) and (2). In fact, the CI mass spectra of $CF_3CH_2NO_3$ and of $(CF_3)_2CHNO_3$, recorded in CH_4 at 0.5 torr at a source temperature of 100°C, display the corresponding protonated adducts at m/e=146 and respectively 214 as the most abundant peaks, with considerably smaller abundances of NO_2^+, m/e=46, and of other fragment ions. When a trace of C_6D_6 is introduced into the $CH_4/CF_3CH_2NO_3$ plasma,[8] one can detect the appearence of a mass peak at m/e=130, corresponding to that of the $C_6D_6NO_2^+$ adduct, and a comparable peak at m/e 129, assigned to the $C_6D_5HNO_2^+$ adduct. Analogous results are obtained in CIMS experiments involving $CH_4/(CF_3)_2CHNO_3/C_6H_6$ mixtures, where formation of the $C_6H_6NO_2^+$ adduct, m/e=124, is detectable. The nitrated adducts are far from abundant, accounting in general for less than 1% of the total ionic current, which is hardly surprising under the conditions prevailing in the CI ion source, whose low pressure and the high temperature conspire with the relative inefficiency of collisional stabilization to favour dissociation of the products from exothermic ion-molecule reactions. Despite the qualitative character of their correlation with the radiolytic results, that pertain to a profoundly different reaction environment, the CIMS measurements provide a useful support to the suggested reaction sequence.

Gas-phase nitration of ten monosubstituted benzenes by **1** has been found to obey a linear Hammett's type plot, characterized by a ρ value of -3.87 and a correlation coefficient of 0.96.[2]

Table 1. Gas Phase Aromatic Nitration by $[RNO_3]H^+$ Ions in CH_4 at 760 torr, 37°C.

Substrate	Reactant[a]	k_S	Orientation[c]		
(S)		k_B	o%	m%	p%
PhMe	**1**	5.1	59	7	34
	2	2.1	52	14	34
	3	1.4	46	9	45
PhF	**1**	0.15	14	13	73
	2	0.52	25	7	68
	3	0.67	26	7	67
PhCl	**1**	0.19	36	10	54
	2	0.44	52	9	39
	3	0.43	56	5	39
Ph-n-Pr	**1**	7.0	50	4	46
	2	2.4	46	11	43
	3	1.6	40	14	46
Ph-i-Pr	**1**	6.0	31	5	64
	2	2.8	33	11	56
	3	1.9	32	10	58
Ph-c-Pr	**1**	10.6	72	6	22
	2	1.9	57	6	37
	3	1.1	60	10	30
Ph-t-Bu	**1**	8.4	17	8	75
	2	2.0	19	9	72
	3	1.5	18	12	70
$PhCF_3$	**1**	0.0037		100	
	2	0.018		100	
	3	0.017		100	
Isodurene	**1**	5.7[e]			
	2	2.2[e]			
	3	2.0			

(a) Data concerning 1, taken from ref.1, measured in CH_4 at 720 torr, 37.5°C. (b) Standard deviation ca. 10%. (d) Small amounts of products other than nitrocyclopropylbenzenes are formed, probably from side-chain attack. (e) Data from ref.3.

Analogous plots

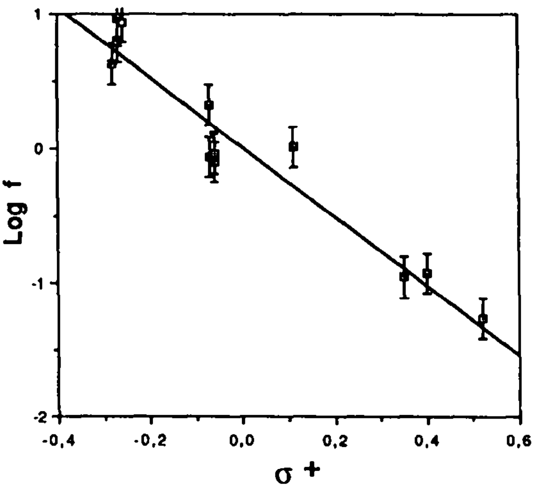


Figure 1. Hammett's type plot for aromatic nitration by 2.

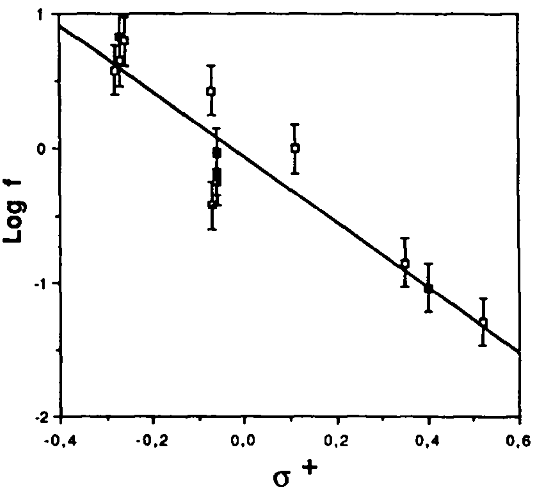
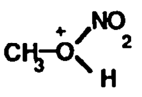


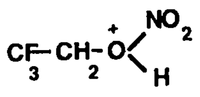
Figure 2. Hammett's type plot for aromatic nitration by 3.

have been constructed from the data of Table 1, despite the complication arising from the inherently low selectivity of 2 and 3, which makes it difficult to discern the onset of a limiting rate in the nitration of the most activated substrates,[9] a feature observed in the case of cation 1. Taking into account all available data except those concerning cyclopropylbenzene that clearly fall below the alignment of the other points denoting occurrence of encounter-rate nitration, one obtains least square fitted correlations characterized by a ρ value of -2.6 ± 0.2 for 2 and -2.4 ± 0.2 for 3, with correlation coefficients of 0.96 and 0.93 respectively. Since other substrates could conceivably undergo encounter-rate nitration, reservation is in order as to the absolute accuracy of the ρ values reported. Nevertheless, neither such problems nor the relatively large scatter of the data can obscure the feature most significant to the present discussion, i.e. that nitration by the electron-deficient species 2 and 3 is indisputably much more indiscriminate than by protonated methyl nitrate 1, as shown by their less negative ρ values.

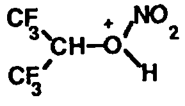
The observed trend fits into the reaction scheme suggested for gas-phase aromatic nitration by protonated alkyl nitrates. In fact, the binding energy of NO_2^+ to the ROH moiety, 24 kcal mol^{-1} in



1



2



3

the case of 1, is expected to decrease in passing to 2 and 3, owing to the electron deficiency of the corresponding alcohols, which reflects on the charge density on the N atom, as well as on the O-N-O angle of the nitro group, conferring the fluorinated reactants with nitrating properties gradually approaching those of free NO_2^+.

The closely similar behaviour of 2 and 3, despite the presence of an additional electron-withdrawing CF_3 group in the latter, suggests that a limit has been reached beyond which no further significant increase of the reactivity can be reached by enhancing the electron deficient character of the R group in the $\left[RNO_3\right]H^+$ cation. This conclusion is reinforced by the practical consideration that even the stability of the neutral RNO_3 molecules is adversely affected by the presence of electron-withdrawing groups. Thus, while $CF_3CH_2NO_3$ and $(CF_3)_2CHNO_3$ can be obtained by nitration of the corresponding alcohols,[10] and have been used, albeit with limited success, as reactants for the N-nitration of amines, preparation of perfluoro-t-butyl nitrate and of hexafluoro-t-butyl nitrate failed, owing to the instability of the esters.[11]

EXPERIMENTAL

Materials. The gases where research-grade samples with a purity exceeding 99.9 mol% from Matheson Gas Products Inc. The chemicals used as substrates or as analytical standards were obtained from commercial sources, or prepared according to unexceptional procedures. Trifluoroethyl nitrate and hexafluoroisopropyl nitrate were obtained essentially as described by Bottaro, Schmitt and Bedford.[11]

Radiolytic Experiments. The technique used for the preparation of the samples and their γ radiolysis has previously been described.[2] The irradiations were performed in 250-mL pyrex bulbs in a 220 Gammacell (Nuclear Canada Ltd.). Analysis of the products was carried out by GC and GC/MS using the following columns: (i) a 3.3-m long, 3-mm i.d. glass column, packed with SP-2100 (20% w/w) and Carbowax 1500 (1% w/w) on 100-120 mesh Supelcoport, operated at 150-170°C, (ii) a 25-m long, 0.25-mm i.d. fused-silica capillary column, coated with methylsilicone fluid, operated from 80 to 150°C, (iii) a 10-m long, 0.53-mm i.d. fused-silica column, coated with polymethylphenylsiloxane, operated at 120°C, (iv) a 10-m long, 0.53-mm i.d. column, coated with Superox, operated from 45 to 140°, (v) a 12-m long, 0.2-mm i.d. fused-silica column, coated with crosslinked methylsilicone polymer, operated from 70 to 160°C. The analyses were performed using a Dani 3800 gas chromatograph, equipped with a programmated-temperature injector, as well as a 5890 A Hewlett-Packard and a Sigma 1 instrument from Perkin-Elmer. The GC/MS analyses were carried out on a MSD HP 5970 instrument, equipped with a HP Chemstation 59970 from Hewlett-Packard.

Chemical Ionization Spectra. The spectra were recorded using a Hewlett-Packard 5892 A quadrupole spectrometer and a magnetic ZAB-2F spectrometer (VG Micromass Ltd.), both operated in the CI mode.

Warning. Alkyl nitrates are liable to explode if overheated. No such accident has been observed during this study using fluoroalkyl nitrates, that however should be regarded as potentially dangerous compounds, since *inter alia* inhalation of their vapors can cause adverse physiological effects.

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5. The G_{+M} values express the number of molecules formed per 100 eV absorbed by the gas. Owing to dosimetric problems, the *absolute* values, and therefore the *absolute* yields, are affected by overall uncertainties of ca.30%.
6. In fact, the proton affinity of i-C_4H_8 exceeds that of $MeNO_3$ and, *a fortiori* those of $CF_3CH_2NO_3$ and of $(CF_3)_2CHNO_3$, cfr. Lias, S.G.; Liebman, J.F.; Levin, R.D., *J.Phys.Chem.Ref.Data* **1984**, *13*, 695, and ref.2.
7. The endothermic character of proton transfer from $C_2H_5^+$ to $CF_3CH_2NO_3$ would require that the PA of the latter is <162.6 kcal mol^{-1}.
8. C_6D_6 has been used instead of C_6H_6 since ions having the same m/e ratio as the $C_6H_6NO_2^+$ adduct are present in low abundances in the CI spectra of $CH_4/CF_3CH_2NO_3$ mixtures.
9. Attainment of a limiting rate in the nitration of the most activated substrates by **2** is suggested, inter alia, by the low value (1.5) of the $k_{isodurene}/k_{toluene}$ ratio, cfr.Table 1 and ref.3.
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