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The role of the lifetimes of ion–neutral complexes in gas-phase electrophilic aromatic substitution

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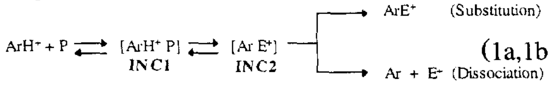
Abstract

The gas-phase aromatic substitution occurring in the ion–neutral complex (INC) formed upon addition of arenium ions to proelectrophiles has been investigated by triple quadrupole mass spectrometry (TQMS). From measured cross-sections in experiments involving different arenium ions at various kinetic energy with numerous proelectrophiles, it was possible to ascertain the central role of the lifetime of INCs in dictating the efficiency of the substitution process. © 1998 Elsevier Science B.V.

1. Introduction

We have recently demonstrated [1–5] an alternative path of electrophilic aromatic substitution in the gas phase according to the general scheme



(1a,1b)

where the neutral species P, denoted as *proelectrophile*, is converted into a charged Lewis acid upon protonation.

The peculiar features of the above sequence are the generation of the electrophile and the attack on the aromatic as consecutive events occurring in the same orbiting ion–neutral complex (INC1, INC2).

The ability of several classes of proelectrophiles as well as arenium ions to promote such an alternative mechanism were widely tested in order to identify the factors affecting the substitution efficiency.

The above investigations were carried out under very different pressure domains, ranging from 10^{-8} to 10^{-7} Torr in ICR experiments [4,5] to the atmospheric pressure of the radiolytic experiments [1]. As an extension of such a systematic study, we report here the results of experiments performed on a triple quadrupole instrument whose applications to the study of the structure, reactivity and thermochemistry of gaseous ions are widely documented [6–14].

In particular, the peculiar ability of the above technique to vary the relative kinetic energy of the colliding species has been exploited to demonstrate the role of the INCs in the intracomplex substitution processes.

2. Experimental

All the chemicals were research-grade products from Aldrich Chemical Company, Inc., used without

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Table 1
Phenomenological absolute cross-sections for the intracomplex substitution of the $CF_3C_6H_6^+$ ion with various proelectrophiles

E_{CM} (eV)	Proelectrophile	$\sigma_s(E_{CM})$ (cm^2)[a]		Other observed reactions	
0.4	C_2H_5OH	0		proton transfer,	loss of HF
0.4	CH_3ONO	6×10^{-15}	(nitrosation)	proton transfer,	loss of HF
0.4	C_3H_6	5×10^{-16}	(i-propylation)	proton transfer,	loss of HF
0.4	CH_3ONO_2	0		proton transfer,	loss of HF
0.4	C_2H_5Br	6×10^{-16}	(ethylation)	proton transfer,	loss of HF
0.4	C_2H_4	5×10^{-16}	(ethylation)		loss of HF
1.2	C_2H_5OH	0		proton transfer,	loss of HF
1.2	CH_3ONO	6×10^{-15}	(nitrosation)	proton transfer,	loss of HF
1.2	C_3H_6	3×10^{-16}	(i-propylation)	proton transfer,	loss of HF
1.2	CH_3ONO_2	0		proton transfer,	loss of HF
1.2	C_2H_5Br	3×10^{-16}	(ethylation)	proton transfer,	loss of HF
1.2	C_2H_4	3×10^{-16}	(ethylation)		loss of HF
1.2	C_2H_5OH	0		proton transfer,	loss of HF
2.4	CH_3ONO	5×10^{-15}	(nitrosation)	proton transfer,	loss of HF
2.4	C_3H_6	2×10^{-16}	(i-propylation)	proton transfer,	loss of HF
2.4	CH_3ONO_2	0		proton transfer,	loss of HF
2.4	C_2H_5Br	1×10^{-16}	(ethylation)	proton transfer,	loss of HF
2.4	C_2H_4	1×10^{-16}	(ethylation)		loss of HF

[a] Standard deviation ±20%.

further purification or were prepared following standard procedures. The experiments were performed on a triple quadrupole spectrometer model Quattro from VG Micromass. The arenium ions (benzenium, toluenium and α,α,α-trifluorotoluenium ions) generated in the CH_4/CI^+ source at an estimated pressure of 0.1 Torr were selected by the first quadrupole (Q1) and introduced into the grounded collision cell (actually a hexapolar RF-only cell) containing the proelectrophile at variable thickness not exceeding 10^{14} cm^{-2}. The ionic products were eventually analyzed by scanning the third quadrupole (Q3) at a frequency of 150 amu s^{-1} (60 scans accumulated for each experience).

An approximate estimate of the axial kinetic energy of the arenium ions was obtained by the following procedure that represents a simplified version of the method described in the literature [10], adapted to a triple sector spectrometer. Both the ion source and collision cell, actually a RF-only hexapolar cell, were grounded, the ions being accelerated by applying a positive potential, in the range from 1 to 10 V, to the repeller.

Of course, the kinetic energy of the ions from the CI source can appreciably differ from the nominal value based on the repeller voltage and is affected by a considerable scatter. In order to approximately estimate these quantities, the ion intensity was plotted versus the dc potential, with respect to ground of

Table 2
Phenomenological absolute cross-sections for the intracomplex substitution for the $CH_3C_6H_6^+$ ion with various proelectrophiles

E_{CM} (eV)	Proelectrophile	$\sigma_s(E_{CM})$ (cm^2)[a]		Other observed reactions
0.4	C_2H_5OH	3×10^{-15}	(ethylation)	proton transfer
0.4	CH_3ONO	2×10^{-13}	(nitrosation)	proton transfer
0.4	C_3H_6	1×10^{-14}	(i-propylation)	proton transfer
0.4	CH_3ONO_2	1×10^{-16}	(nitration)	proton transfer
0.4	C_2H_5Br	0		n.r.
0.4	C_2H_4	0		n.r.
1.2	C_2H_5OH	2×10^{-15}	(ethylation)	proton transfer
1.2	CH_3ONO	2×10^{-13}	(nitrosation)	proton transfer
1.2	C_3H_6	9×10^{-15}	(i-propylation)	proton transfer
1.2	CH_3ONO_2	1×10^{-16}	(nitration)	proton transfer
1.2	C_2H_5Br	0		n.r.
1.2	C_2H_4	0		n.r.
2.4	C_2H_5OH	2×10^{-15}	(ethylation)	proton transfer
2.4	CH_3ONO	2×10^{-13}	(nitrosation)	proton transfer
2.4	C_3H_6	9×10^{-15}	(i-propylation)	proton transfer
2.4	CH_3ONO_2	1×10^{-16}	(nitration)	proton transfer
2.4	C_2H_5Br	0		n.r.
2.4	C_2H_4	0		n.r.

[a] Standard deviation ±20%.

Table 3
Phenomenological absolute cross-sections for the intracomplex substitution for the $C_6H_7^+$ ion with various proelectrophiles

E_{CM} (eV)	Proelectrophile	$\sigma_s(E_{CM})$ (cm^2)[a]		Other observed reactions	
0.4	C_2H_5OH	8×10^{-14}	(ethylation)	proton transfer	
0.4	CH_3ONO	9×10^{-14}	(nitrosation)	proton transfer	
0.4	C_3H_6	7×10^{-14}	(i-propylation)	proton transfer,	second i-propylation
0.4	CH_3ONO_2	3×10^{-14}	(nitration)	proton transfer,	second nitration
0.4	C_2H_5Br	0		n.r.	
0.4	C_2H_4	0		n.r.	
1.2	C_2H_5OH	8×10^{-14}	(ethylation)	proton transfer	
1.2	CH_3ONO	9×10^{-14}	(nitrosation)	proton transfer	
1.2	C_3H_6	3×10^{-14}	(i-propylation)	proton transfer,	second i-propylation
1.2	CH_3ONO_2	3×10^{-14}	(nitration)	proton transfer,	second nitration
1.2	C_2H_5Br	0		n.r.	
1.2	C_2H_4	0		n.r.	
2.4	C_2H_5OH	7×10^{-14}	(ethylation)	proton transfer	
2.4	CH_3ONO	9×10^{-14}	(nitrosation)	proton transfer	
2.4	C_3H_6	1×10^{-14}	(i-propylation)	proton transfer,	second i-propylation
2.4	CH_3ONO_2	3×10^{-14}	(nitration)	proton transfer,	second nitration
2.4	C_2H_5Br	0		n.r.	
2.4	C_2H_4	0		n.r.	

[a] Standard deviation ±20%.

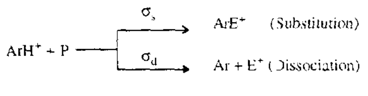
the third quadropole (Q3) which can be regarded as a blocking potential. In this way, one obtains a sigmoid curve, and the Q3 potential corresponding to the inflection point can be taken as an approximate indication of the axial translational energy of the ions in the laboratory reference frame.

The kinetic energies in the center of mass frame (E_{CM}) of the reacting species were evaluated according to the standard equation

$$E_{CM} = E_{LAB}\frac{m_P}{m_P + m_{ArH^+}}. \qquad (2)$$

All the experiments were performed at four different values (0.4, 1.2, 2.4 and 6 eV) of the nominal E_{CM}, the efficiency of reaction (1a) has been estimated by measuring the phenomenological absolute cross-sections of the substitution process (σ_s) at different E_{CM} for several classes of proelectrophiles and arenium ions.

To this end we considered the simplified overall reaction scheme



(3a,3b)

where σ_d is the phenomenological absolute cross-section for proton transfer (namely the INC2 dissociation channel in Scheme 1). The σ_s values were obtained by a numerical fitting of the measured intensity of the products ArE$^+$, $I_{(ArE^+)}$, at different

Table 4
Proton affinities (kcal/mol) of arenes and proelectrophiles

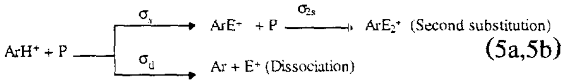
Base	PA (kcal/mol)
C_6H_6	181.3[b], 180.0[a]
$CH_3C_6H_5$	189.8[b], 187.7[a]
$CF_3C_6H_5$	167.7[c]
CH_3ONO	187[d]
CH_3ONO_2	178[e]
C_2H_5OH	188.3[b]
C_2H_5Br	163.9[f]
C_2H_4	162.6[a]
C_3H_6	178.4[a]

[a] From Ref. [15].
[b] From Ref. [16].
[c] Corresponding to the more basic anular position calculated at the MP2(full)/6-31G(d)//HF/6-31G(d) level of theory from Ref. [17].
[d] Calculated at the G2 level of theory from Ref. [18].
[e] From Ref. [19].
[f] Calculated at the G2 level of theory from an unpublished result by M. Aschi.

values of the nominal proelectrophile thickness (S) with the equation

$$\frac{I_{(\mathrm{ArE}^+)}}{I_{0(\mathrm{ArH}^+)}}=\left[\frac{\sigma_s}{\sigma_s+\sigma_d}\right]\left\{1-\exp\left[-(\sigma_s+\sigma_d)S\right]\right\}. \tag{4}$$

In several cases (see below) we observed the ArE$^+$ ion giving rise to a further intracomplex substitution according to the overall reaction scheme



(5a,5b)

In these cases the σ_s values were deduced by fitting the ArE$^+$ intensities at different target thickness of P with the equation

$$\frac{I_{(\mathrm{ArE}^+)}}{I_{0(\mathrm{ArH}^+)}}=\left[\frac{\sigma_s}{\sigma_{2s}-\sigma_s-\sigma_d}\right]$$
$$\times\left\{\exp-\left[(\sigma_s+\sigma_d)S\right]-\exp-\left[\sigma_{2s}S\right]\right\}, \tag{6}$$

where σ_{2s} is the phenomenological cross-section for the second substitution.

However, owing to the large uncertainty affecting in particular the E_{LAB} values and the internal energy content of the ArH$^+$ ions formed via exothermic processes in the source, the absolute phenomenological σ_s values must be considered highly approximate allowing just a qualitative discussion.

It should be noted that the above equations assume that the processes studied occur under single collision, whereas the observation of disubstituted ions shows that double collisions occur at some extent. However, beside on the intensity of disubstituted ions, the fraction of double collisions appears to be quite low and does not affect Eqs. (4) and (6) at the approximation level of this work.

3. Results and discussion

The estimated absolute cross-sections for the intracomplex substitution reaction at different E_{CM} values are collected in Tables 1–3. As discussed in details in the earlier papers [2–5], there is a direct correlation between the efficiency of the reaction and the difference (ΔPA) between the PA of the arene and the proelectrophile (Table 4). Accordingly, the $\sigma_s(E_{CM})$ values given in Table 2 are related to the ΔPA values and the corresponding graphs are depicted in Figs. 1–3 for the $C_6H_7^+$, $CH_3C_6H_6^+$ and the $CF_3C_6H_6^+$ ions, respectively.

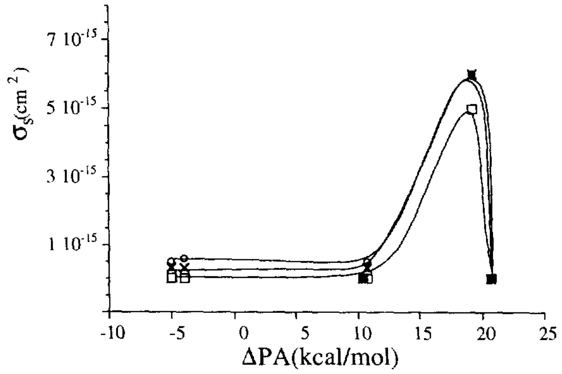


Fig. 1. Phenomenal absolute cross-section for the substitution reaction of $CF_3C_6H_6^+$ ion with selected proelectrophiles vs. the difference between the proton affinities of proelectrophile and arene. Each set corresponds to E_{CM} of 0.4 eV (○), 1.2 eV (×) and 2.4 eV (□).

In all the three sets of experiments, no reaction occurs at $E_{CM}=6$ eV. In general the substitution reaction was found to show an optimal efficiency range falling in a relatively narrow domain of E_{CM} and ΔPA. The observed trends suggest the following

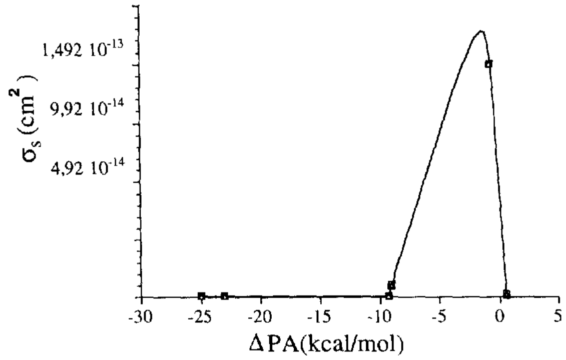


Fig. 2. Phenomenal absolute cross-section for the substitution reaction of $CH_3C_6H_6^+$ ion with selected proelectrophiles vs. the difference between the proton affinities of proelectrophile and arene. Each set corresponds to E_{CM} of 0.4 eV (○), 1.2 eV (□) and 2.4 eV (△).

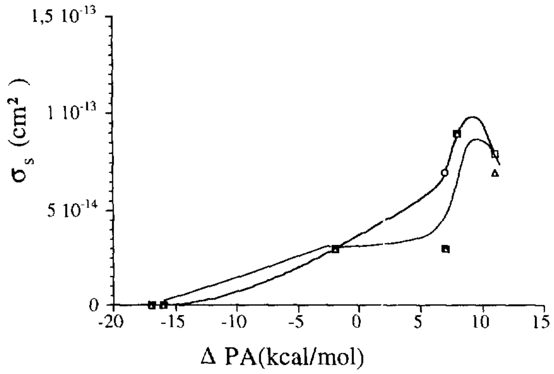


Fig. 3. Phenomenal absolute cross-section for the substitution reaction of $C_6H_7^+$ ion with selected proelectrophiles vs. the difference between the proton affinities of proelectrophile and arene. Each set corresponds to E_{CM} of 0.4 eV (○), 1.2 eV (□), 2.4 eV (△).

qualitative considerations on the intracomplex substitution efficiency.

3.1. Early entropy barrier

In the TQMS experiments, a high E_{CM} value can be expected to largely increase the internal energy content of the first orbiting ion–neutral complex (INC1) based on total energy and angular momentum conservation requirement of the colliding species. Consequently the back dissociation, owing to its looser TS (see Fig. 4) will be by far the more efficient process, owing to its looser TS (see Fig. 2) suppressing other reactions characterized by a tighter TS [20–22].

3.2. Early energy barrier for INC1 → INC2 conversion

A necessary condition for the occurrence of the overall substitution reaction is the ability of the INC1 → INC2 conversion to efficiently compete with the INC1 back dissociation. Based on the Hammond postulate, we can qualitatively relate (Fig. 4a,b) the rate of the above intracomplex proton transfer process with its thermochemistry according to the equation

$$-\Delta H(\text{INC1} \rightarrow \text{INC2}) = -(\Delta\text{PA} + \Delta\text{BE}), \qquad (7)$$

where ΔBE is the binding energy difference of the ligands in the INC2 and INC1 species the value of which is not supposed to exceed 5–10 kcal/mol [23,24]; therefore the low efficiency of substitution (in some cases no substitution was observed) shown in particular by the reactions of $C_6H_7^+$ and $CH_3C_6H_6^+$ at negative or slightly positive ΔPA values can be rationalized by invoking an early energy barrier [2] which prevents (if no reaction is

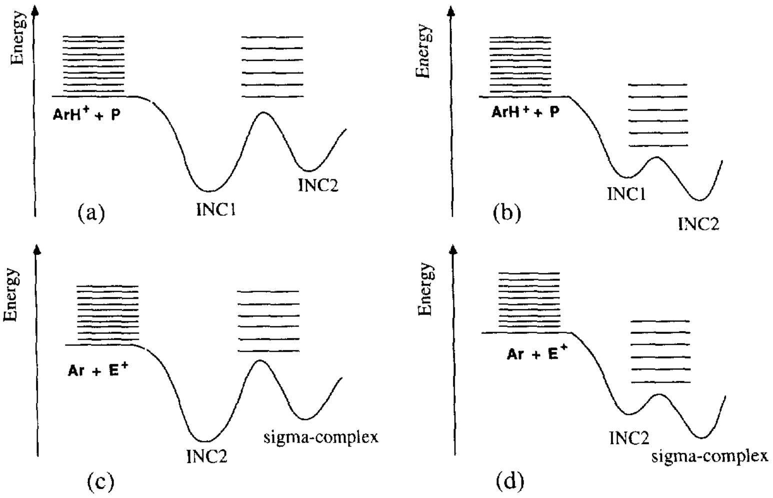


Fig. 4. Schematic potential energy diagrams (see text).

observed) or slows down the overall substitution reaction.

3.3. Late energy barrier for INC2 → σ-complex conversion

Also in the case of relatively fast intracomplex proton transfer reaction, the increase of the substitution reaction efficiency can be prevented by another energy barrier [2] (see Fig. 4c,d) concerning the *INC2 → σ-complex* transformation due to the low reactivity of the partners within the ion–neutral complex.

3.4. Late entropy barrier for INC2 → σ-complex conversion

From Tables 1–3 and Figs. 1–3 in all the three sets of experiments, the efficiency of substitution systematically decreases with the ΔPA increase. This seemingly paradoxical trend can be rationalized by invoking a late entropy barrier. In fact, the exothermicity associated with the conversion of INC1 into INC2, completely stored as internal energy content in the latter orbiting ion–neutral complex, will strongly raise the efficiency of the INC2 dissociation with respect to other entropically less favoured competing processes (INC2 → INC1 or INC2 → σ-complex as shown in Fig. 4) [20–22].

Thus, the maxima of the curves can qualitatively be viewed as the best compromise of intrinsic features of the reagents (ΔPA, nucleophilicity/electrophilicity, etc.) and extrinsic features, such as E_{CM}, that make the lifetime of INC1 and INC2 established by the microcanonical dissociation rate constants comparable with the reaction time of proton transfer and substitution.

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