

active theoretical and experimental interest in gas-phase ion chemistry.⁶⁻¹¹ Among the different classes of electrophilic substitution investigated, the one to be discussed here is aromatic alkylation *via* sequence 2, where alkenes and cycloalkenes are used as proelectrophiles.

Experimental Section

Materials. The gases were research products obtained from Matheson Gas Products Inc. or Sigma-Aldrich srl with a stated purity exceeding 99.95 mol % (Ar, O₂, CH₄, CF₄) and 99 mol % (C₃H₆, iC₄H₈, (CH₃)₂O). CH₃F, purchased from Fluorochem Ltd. with a stated purity of 99 mol %, contained (CH₃)₂O, ca. 0.15 mol %, and traces of acetone, as shown by analyses performed by GC and GC/MS. C₆D₆, with a stated isotopic purity in excess of 99.96 atom %, was obtained from Sigma-Aldrich srl. All other chemicals were research grade products from commercial sources or were prepared according to standard procedures, e.g., in the case of isomeric cymenes, isopropyltrifluorotoluenes, *tert*-butyltoluenes, and cyclopentyltoluenes.

Instruments. The FT-ICR mass spectra were recorded using a Bruker Spectrospin Apex TM 47e instrument, equipped with an external ion source, two computer-controlled pulsed valves, and a XMass data system. The radiolytic products were analyzed by GC/MS using a HP 5890 GC coupled to a HP 5970 B mass-selective detector, from Hewlett-Packard Co., and a VG Micromass TRIO 1 benchtop GC/MS. In addition, a HP 5890 GC, equipped with a FID, was used for the quantitative analysis of the products.

Radiolytic Experiments. The gaseous samples were prepared according to standard procedures, using a greaseless vacuum line, in sealed 135-mL Pyrex vessels. The irradiations were performed in a 220 Gammacell from Nuclear Canada Ltd. equipped with a thermostatic device designed to maintain the sample to within ± 1 °C from any desired temperature in the range from 40° to 150 °C. The irradiation time was 2 h, the total dose 1×10^4 Gy. Following the irradiation, the vessel was cooled to 77 K, and its contents dissolved into CH₃OH, carefully washing the inner walls, and performing repeated freeze-thaw cycles. The nature, the yields, the D content, and its intramolecular distribution in the aromatic products were determined by GC, using the internal-standard method, and by GC/MS, making use, when required, of specifically labeled reference standards. The column used was a 50-m long, 0.2-mm i.d. fused-silica capillary column, coated with a 0.5 μ m layer of cross-linked methylsilicone phase (PONA column from HP) operated in the temperature range from 70° to 220 °C.

Results

Mass Spectrometric Results. The CH₄/CI spectra of gaseous mixtures containing C₆H₆ and olefins, recorded at 150 °C at pressures from 0.1 to 0.5 Torr, display peaks whose *m/z* ratios are those expected for the corresponding arenium ions, e.g., the C₆H₆iC₃H₇⁺ ion in the CH₄/CI of benzene/propene mixtures. Whereas these experiments demonstrate the occurrence of gas-phase isopropylation, they give no information as to whether, and to what an extent, alkylation occurs *via* sequence 2. ICR spectrometry, with its unique ability to establish parent-daughter relationships in consecutive ion-molecule reactions, is the technique of choice to discriminate among channels 1 and 2. Unfortunately, the charged products from exothermic addition reactions, such as the final step of sequence 2, are bound to undergo back dissociation in the low-pressure range (10^{-8} – 10^{-7} Torr) typical of FT-ICR experiments, which generally prevents detection of the alkylated aromatic adducts. E.g., preliminary FT-ICR experiments were performed, where C₆H₆D⁺

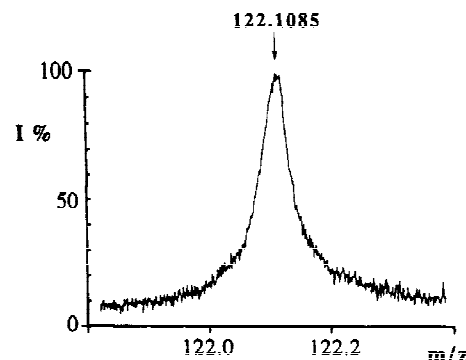


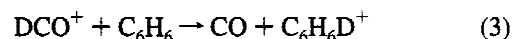
Figure 1. The C₉H₁₂D⁺ peak, calculated *m/z* = 122.10800, from the addition of C₆H₆D⁺ to C₃H₆.

Table 1. Relevant Thermochemical Data

reaction	ΔH° , kcal mol ⁻¹
(3) COH ⁺ + C ₆ H ₆ = CO + (C ₆ H ₇) ⁺	-39.4, ^a -38.1 ^b
(4) (CH ₃) ₂ F ⁺ + C ₃ H ₆ = CH ₃ F + sC ₄ H ₉ ⁺	-33.0 ^c
(5) (CH ₃) ₂ F ⁺ + C ₆ H ₆ = CH ₃ F + (CH ₃ C ₆ H ₆) ⁺	-43.0, ^{a,d} -40.5 ^{b,d}
(7) sC ₄ H ₉ ⁺ + C ₆ H ₆ = (sC ₄ H ₉ C ₆ H ₆) ⁺	-33.3 ^{d,e}
(9) (CH ₃ C ₆ H ₆) ⁺ + (CH ₃) ₂ O = CH ₃ C ₆ H ₅ + (CH ₃) ₂ OH ⁺	-2.3 ^a
(10) (CH ₃ C ₆ H ₆) ⁺ + C ₃ H ₆ = (CH ₃ C ₆ H ₅ iC ₃ H ₇) ⁺	-28.3 ^f
(12) CH ₃ ⁺ + C ₃ H ₆ = CH ₄ + iC ₃ H ₇ ⁺	-47.9, ^a -48.2 ^b
(13) CH ₃ ⁺ + C ₆ H ₆ = CH ₄ + C ₆ H ₇ ⁺	-49.7, ^a -50.0 ^b
(15,25) iC ₃ H ₇ ⁺ + C ₆ H ₆ = (iC ₃ H ₇ C ₆ H ₆) ⁺	-35.7 ^{u,i}
(18) C ₆ H ₇ ⁺ + C ₃ H ₆ = (iC ₃ H ₇ C ₆ H ₆) ⁺	-33.9, ^{a,d} -34.1 ^{b,d}
(20) CF ₃ ⁺ + C ₆ H ₆ = (CF ₃ C ₆ H ₆) ⁺	58.7 ^{d,g}
(22) (CF ₃ C ₆ H ₆) ⁺ + C ₃ H ₆ = (CF ₃ C ₆ H ₅ iC ₃ H ₇) ⁺	ca. -85 ^h
(27) (CH ₃ C ₆ H ₆) ⁺ + iC ₄ H ₈ = (CH ₃ C ₆ H ₅ tC ₄ H ₉) ⁺	-24.3 ^{u,i}

^a According to the NIST database, ref 12. ^b According to the revised PA scale of ref 13. ^c From the heat of formation of (CH₃)₂F⁺, ref 14 and 15, and of sC₄H₉⁺, ref 12. ^d Referred to formation of the most stable protomer. ^e Estimated from the data of ref 12. ^f Referred to formation of protonated *p*-cymene, taking the PA of the latter equal to that of cumene, ref 12. ^g From the theoretically calculated PA of CF₃C₆H₅ see ref 16. ^h From the heat of formation of *p*-CF₃C₆H₄iC₃H₇, and its PA, estimated by the group method. ⁱ Referred to formation of protonated *p*-*tert*-butyltoluene, taking the PA of the latter equal to that of *tert*-butylbenzene, ref 12.

ions, *m/z* = 80, obtained in the external source of the spectrometer by CO-D₂/CI of ¹²C₆-C₆H₆ according to the highly exothermic (Table 1) process, were driven into the resonance



cell, isolated by selective-ejection techniques, and allowed to react with C₃H₆ contained in the cell at a low stationary pressure $(1-5) \times 10^{-8}$ Torr. As anticipated, no C₉H₁₂D⁺ ions from sequence 2 were detected, owing to their complete back dissociation. However, by using a pulsed valve, one can obtain, albeit for a short time (<5 ms), C₃H₆ pressures up to 5×10^{-5} Torr, which allows collisional stabilization of a fraction of the excited C₉H₁₂D⁺ ions, and hence their positive identification by accurate mass measurement (Figure 1). Despite their low relative intensity (<5%), detection of the alkylated adducts is significant, since they can only arise *via* intracomplex alkylation, according to the sequence

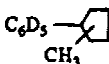


In fact, no C₆H₆ was introduced into the reaction cell,¹⁷ which excludes the role of any free isopropyl ion in the formation of the observed C₉H₁₂D⁺ ions.

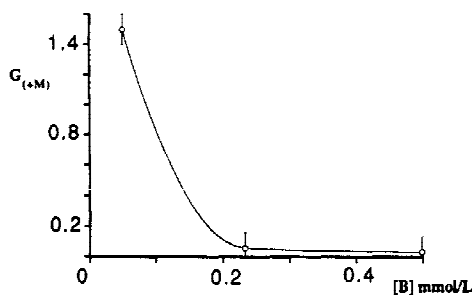
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Table 2. Radiolytic Alkylation

T (K)	system composition (Torr) ^a		products yields ^b $G(+M) \times 100$				products ratios
			Isopropylation				
	$C_3H_6^c$	$(CH_3)_2O$	$C_6D_5CH_3$	$C_6D_5iC_3H_7$	$C_6D_5sC_4H_9$	$CH_3C_6D_4iC_3H_6D$	$CH_3C_6D_4iC_3H_6D:C_6D_5CH_3$
315	5.0	1.0	14.0	6.4	6.7	0.018 ^d	0.001
353	5.0	1.0	24.9	1.0	6.6	0.17	0.007
353	9.0	1.0	38.1	0.4	7.2	0.50	0.013
353	20.0	1.0	12.4	9.8	6.8	0.26	0.021
393	5.0	1.0	31.8	1.3	9.8	1.0	0.031
408	5.0	1.0	19.3	0.8	10.8	0.7	0.036
	$C_3H_6^e$	$(C_2H_5)_3N$	$C_6D_5iC_3H_7$	$C_6HD_4iC_3H_6D$	$C_6Y_4(iC_3Y_7)_2^f$	$C_6Y_3(iC_3Y_7)_3$	
315	10.0	0.2	11.5	24.4	2.5 ^f	n.d.	
353	10.0	0.2	13.9	21.8	3.2	0.03	
393	10.0	0.2	15.0	19.8	4.2	n.d.	
	$C_3H_6^g$	$(CH_3)_2O$	$C_6D_5CF_3$	$C_6D_5iC_3H_6Y^h$	$CF_3C_6D_4iC_3H_6D^i$		$CF_3C_6D_4iC_3H_6D:C_6D_5CF_3$
315	10.0	1.1	9.0	11.0	1.2		0.13
315	10.0	1.1	1.1	8.0	6.3	0.9	0.11
			<i>tert</i> -Butylation				
	$iC_4H_8^j$	$(CH_3)_2O$	$C_6D_5CH_3$	$[CH_3C_6D_4iC_4H_8D]$			$CH_3C_6D_4iC_4H_8D:C_6D_5CH_3$
315	10.0	1.0	12.8	0.26 (m = 27%, p = 73%)			0.026
353	10.0	1.0	29.8	0.15 (m = 28%, p = 72%)			0.014
393	10.0	1.0	29.8	0.16 (m = 40%, p = 60%)			0.005
			Cyclopentylation				
	$c-C_5H_{10}^k$	$(CH_3)_2O$	$C_6D_5CH_3$	$C_6D_5cC_5H_9$		$CH_3C_6D_4cC_5H_8D$	$CH_3C_3D_4cC_5H_8D:C_6D_5CH_3$
315	10.0	1.0	11.7	1.2	0.88	0.67 ^l	0.06
353	10.0	1.0	17.3	1.0	0.50	1.5	0.09
353	10.0	5.1	12.5	0.40	0.15	0.059	0.05
353	10.0	10.1	12.3	0.17	0.10	0.033	0.03
393	10.0	1.0	13.2	0.40	0.16	0.014	0.11

^a All systems contained 720 Torr of the bulk gas and O₂, 10 Torr. ^b Standard deviation of the yields ±10%, increasing to ±20% for G_(+M) values <10⁻³. ^c Bulk gas CH₃F, C₆D₆ 1.5 Torr. ^d Isomeric composition of cymenes, o = 50%, m = p = 25%. ^e Bulk gas CH₄, C₆D₆ 3 Torr. ^f Isomeric composition of diisopropylbenzenes, o = 47%, m = 22%, p = 31%; Y = H, D. ^g Bulk gas CF₄, C₆D₆ 2.4 Torr. ^h Y = H, D in the approximate 4:1 ratio. ⁱ m = 75%, p = 25%, also formed CF₃C₆D₃ (iC₃H₆D)₂ and CF₃C₆D₂ (iC₃H₆D)₃. ^j Bulk gas CH₃F, C₆D₆ 3.0 Torr. ^k Bulk gas CH₃F, C₆D₆ 1.2 Torr. ^l Isomeric composition of cyclopentyltoluenes o = 40%, m = 29%, p = 31%.

**Figure 2.** Depression of the radiolytic yields of aromatic products from gas-phase cyclopentylation upon addition of increasing amounts of (C₂H₅)₃N.

In summary, the results show that charged products whose *m/z* ratio corresponds to that expected for alkylated arenium ions are formed upon addition of benzenium ions to propene, in a process that occurs without separation of the reactants after their encounter. The results are consistent with, but fall short of proving, operation of sequence 2, in that the lack of structural discrimination of FT-ICR spectrometry does not allow for the exclusion of the possibility that the C₉H₁₂D⁺ ions observed are noncovalent complexes, rather than protonated cumene.

Radiolytic Alkylation. Methodology. This technique, whose principles, experimental details, and applications have been reviewed,⁴ is based on the γ irradiation of a gaseous system whose bulk component gives upon ionization the charged reagent of interest, *via* a well-defined sequence of reactions. Following complete collisional thermalization, the ion interacts with the aromatic substrate(s), giving charged intermediates whose deprotonation yields neutral end products, analyzed by

GC, GC/MS, or NMR. The radicals cogenerated in the radiolysis together with the charged species are trapped by an efficient scavenger (O₂) present at a relatively high concentration in the gas. In any case, the ionic origin of the products of interest is independently confirmed by the depression, and eventually the suppression, of their yields caused by increasing concentrations of interceptors, e.g., bases, that trap the charged species (Figure 2). Furthermore, independent evidence for the postulated ionic reagents and intermediates is obtained from the mass spectrometric study of the same system, and, finally, the very nature of the products, e.g., the alkylated arenes relevant to this work, often indicates their ionic origin.

The results from the study of the reactions investigated are summarized in Table 2, where the yields of the products are expressed by their G_(+M) values, namely the number of molecules formed per 100 eV absorbed.

Isopropylation. Three primary charged reagents have been used, namely (CH₃)₂F⁺, C_nH₅⁺ (*n* = 1, 2), and CF₃⁺, obtained from the irradiation of CH₃F, CH₄, and CF₄, respectively. (CH₃)₂F⁺ is the major stable ion formed, together with traces of CH₃FH⁺, upon ionization of gaseous CH₃F, according to fast, consecutive ion-molecule reactions firmly established by mass spectrometric and radiolytic studies.^{18–22} The (CH₃)₂F⁺ ions react with C₃H₆ and C₆D₆ according to the sequence of ion-molecule reactions illustrated by the simplified scheme A of Chart 1. The paramount result is the formation of CH₃C₆D₄-

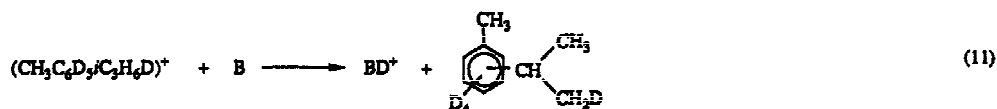
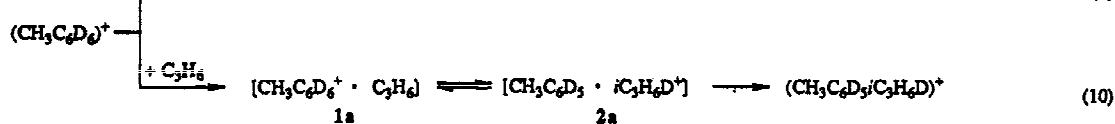
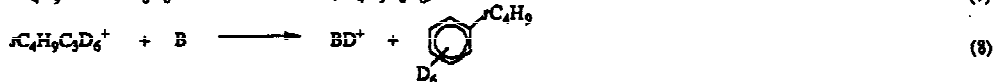
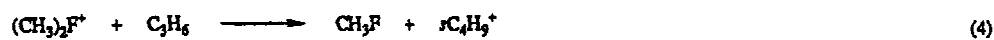
(12) Lias, S. G.; Bartmess, J. E.; Liebman, J. F.; Holmes, J. L.; Levin, R. D.; Mallard, W. G. *J. Phys. Chem. Ref. Data* **1988**, 17 suppl. No. 1.

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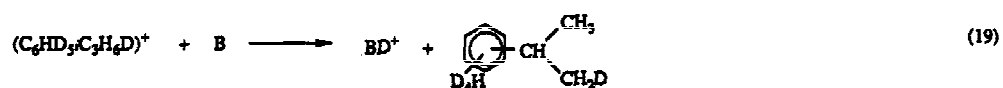
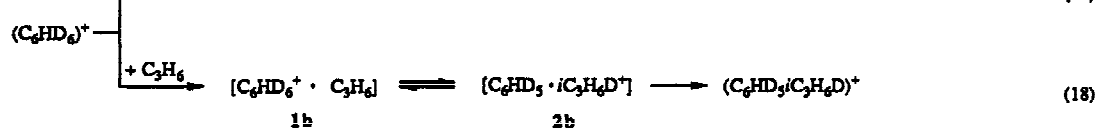
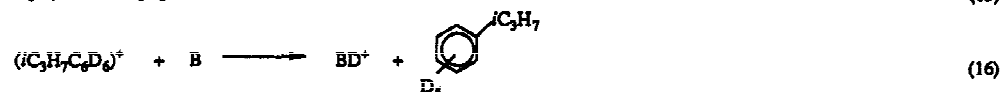
(14) McMahon, T. B.; Heinis, T.; Nicol, G.; Hovey, J. K.; Kebarle, P. *J. Am. Chem. Soc.* **1988**, 110, 7591.

Chart 1

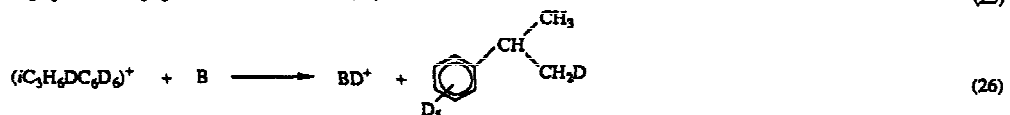
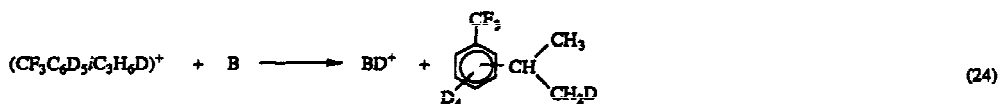
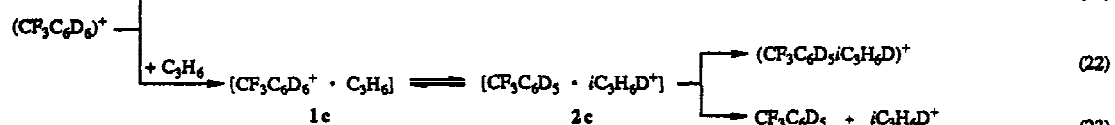
A



B



C



CH(CH₃)CH₂D isomeric cymenes, whose nature, isotopic distribution, and yields have been established by GC and GC/MS. Their formation can only occur *via* reactions 10 and 11, since alkylation of toluene by free *i*C₃H₆D⁺ ions is ruled out, under the experimental conditions chosen, by the fact that no toluene is present in the gas, except for the very small amounts formed during the radiolysis e.g., *via* reactions 5 and 9. Given the enormous excess of C₃H₆ and C₆D₆ as well as the indiscriminate reactivity of free isopropyl cation,²³ any deuterated cymenes formed from free *i*C₃H₆D⁺ ions would be orders of magnitude below the detection limit. Accordingly, formation of CH₃C₆D₄iC₃H₆D isomers provides compelling evidence for the operation of intracomplex alkylation 2. According to scheme A of Chart 1, the efficiency of the process depends on the competition between deprotonation 9 and the alkylation sequence 10, and hence the ratio *R* between the yield of CH₃C₆D₄iC₃H₆D and of CH₃C₆D₅ obeys the relation $R = k_{10}/[C_3H_6]/k_9[B]$. For a fixed value of [B], *R* should linearly increase with [C₃H₆], an expectation borne out by the results of competition experiments (Figure 3).

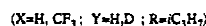
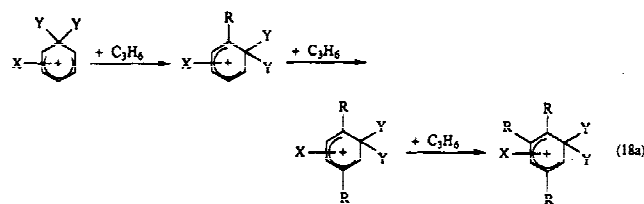
Remarkably, *R* undergoes a sharp increase with the temperature, reflecting the corresponding increase of the *k*₁₀/*k*₉ ratio illustrated in Figure 4. Since the exothermic proton transfer 9 to an unhindered *n*-type base is expected to be a fast, weakly temperature-dependent process,²⁴ the trend is most likely traced to the increase of *k*₁₀ with the temperature. Interestingly, the isomeric composition of the cymenes from reactions 10 and 11 corresponds, within experimental errors, to that observed in the direct alkylation of toluene by free *i*C₃H₇⁺ ions²³ (*vide infra*).

The results show that the *i*C₃H₆D⁺ ions quantitatively react with CH₃C₆D₅ within complex 2a without escaping into the gaseous medium, where they would be trapped by C₆D₆ yielding *i*C₃H₆DC₆D₅, which has not been detected among the products.

Formation of *sec*-C₄H₉C₆D₅ is readily accommodated by the consecutive reactions 4, 7, and 8 of scheme A, whereas *i*C₃H₇C₆D₅ is produced from the alkylation of C₆D₆ by free, unlabeled isopropyl ions from the protonation of propene by radiolytically formed Brønsted acids such as CH₃FH⁺, H₃O⁺, etc.

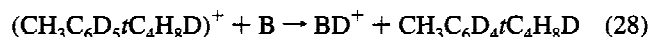
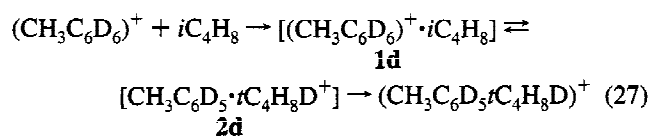
A different approach has been based on the use of CH₅⁺ and C₂H₅⁺, the major ions formed with a combined *G*_(+M) value of ca. 3 in neat irradiated CH₄.²⁵ Their interaction with C₃H₆ and

C₆D₆ promotes the ionic reaction pattern illustrated, in a simplified form, in scheme B of Chart 1. The salient result is the formation of cumene of the isotopic composition C₆HD₄-CH(CH₃)CH₂D, demonstrated by its EI mass spectrum that displays equally intense (*M* - 15) and (*M* - 16) peaks, arising from the loss of CH₂Y (Y = H,D), according to a fragmentation pattern typical of isopropylated arenes. Formation of C₆HD₄-CH(CH₃)CH₂D can only be traced to deprotonation of an arenium ion formed within the complex 2b, since any free *i*C₃H₆D⁺ ions would be trapped by C₆D₆, yielding instead C₆D₅-CH(CH₃)CH₂D as the final product. The failure to detect the latter indicates that no *i*C₃H₆D⁺ ions escape from 2b. The *i*C₃H₇C₆D₅ cumene, formed in significant yields, arises from the attack on C₆D₆ of the *i*C₃H₇⁺ ions formed upon protonation of C₃H₆ by C_nH₅⁺. The efficiency of the alkylation 18 is appreciably higher than of the corresponding process 10, and, in addition, it is nearly independent of the temperature. Another interesting feature is the formation of di-, and even triisopropylbenzenes, pointing to operation of consecutive alkylation steps in the complexes formed upon addition of increasingly substituted arenium ions to propene.



The third reagent used, CF₃⁺, is the major cation formed upon ionization of CF₄ and is unreactive toward the parent molecule.⁴ Irradiation of C₃H₆ and C₆D₆ highly diluted in CF₄ gas promotes the ionic reactions illustrated in the simplified scheme C of Chart 1. Occurrence of the alkylation within complex 2c is demonstrated by formation of CF₃C₆D₄iC₃H₆D isomers, a process which can only occur *via* sequence 22. However, at variance with the alkylation reactions previously discussed, there is evidence that a fraction of the *i*C₃H₆D⁺ ions formed within complex 2c fails to react with CF₃C₆D₅, a strongly deactivated substrate, and escapes into the gaseous medium, where the ions are trapped by C₆D₆, giving C₆D₅*i*C₃H₆D, detected in significant yields among the products.

***tert*-Butylation.** Irradiation of gaseous systems containing *i*C₄H₈ and C₆D₆ highly diluted in CH₃F promotes a sequence of ionic reactions analogous to those illustrated in the scheme A of Chart 1. Isolation of isomeric CH₃C₆D₄*i*C₄H₈D *tert*-butyltoluenes among the products indicates operation of the alkylation pathway



As in isopropylation, the isotopic composition of *tert*-butyltoluenes, in particular the presence of a D atom in a methyl group of the *tert*-butyl substituent, is only consistent with intracomplex alkylation. The efficiency of the process, expressed by the *k*₂₇/*k*₉ ratio deduced from the product ratio *R*, decreases at higher temperatures (Figure 5), whereas the extent

(15) The data of ref 14 have been adjusted to the scale revised by the following: Glukhovtsev, M. N.; Szulejko, J. E.; McMahon, T. B.; Gauld, J. W.; Scott, A. P.; Smith, B. J.; Pross, A.; Radom, L. *J. Phys. Chem.* **1994**, *98*, 13099.

(16) No published values of the PA of C₆H₅CF₃ are available. We have used the PA = 166.4 kcal mol⁻¹ obtained from a MINDO study: Karaman, R.; Huang, J.-T. L.; Fry, J. L. *J. Org. Chem.* **1991**, *56*, 188.

(17) Despite efficient differential pumping of the transfer system, traces of C₆H₆ actually leak from the external ion source into the cell, but its concentration is far too low to account for the C₆H₁₂D⁺ ions observed, especially in view of the large (more than 50 000-fold) excess of C₃H₆.

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(22) Speranza, M.; Pepe, N.; Cipollini, R. *J. Chem. Soc., Perkin Trans. 2* **1979**, 1179.

(23) The lack of selectivity of free *i*C₃H₇⁺ is reflected by a *k*_{toluene}:*k*_{benzene} ratio of 1.0 ± 0.1 in C₃H₈ at 720 Torr at 37.5 °C, and by the isomeric composition of the cymenes formed: *o* = 48%, *m* = 28%, *p* = 24%, according to the following: Attinà, M.; Cacace, F.; Ciranni, G.; Giacomello, P. *J. Chem. Soc., Perkin Trans. 2* **1979**, 891.

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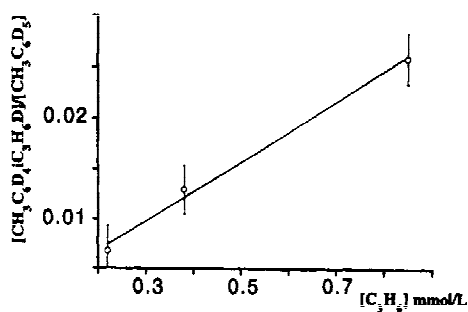


Figure 3. Increase of the relative efficiency of isopropylation with the concentrations of propene, see text.

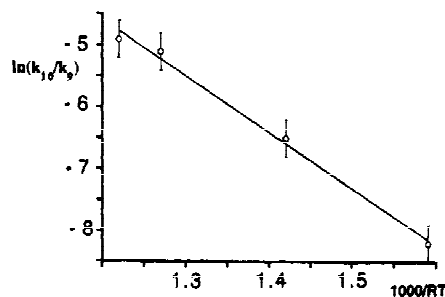


Figure 4. Temperature dependence of the k_{10}/k_9 ratio, see text.

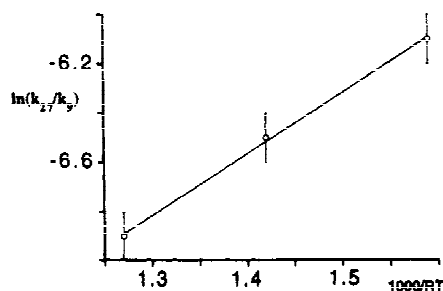


Figure 5. Temperature dependence of the k_{27}/k_9 ratio, see text.

of meta substitution increases, consistent with the trend prevailing in gas-phase *tert*-butylation of toluene by free $tC_4H_9^+$ ions.^{26,27}

Cyclopentylation. Irradiation of $c\text{-C}_5\text{H}_8$ and C_6D_6 in excess CH_3F promotes aromatic cyclopentylation according to a reaction sequence analogous to that illustrated in scheme A of Chart 1, whose key steps are the competitive processes

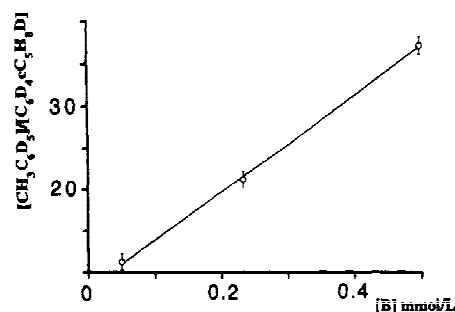
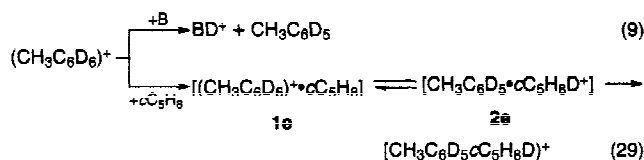


Figure 6. Dependence of the relative efficiency of cyclopentylation on the concentration of added $(\text{CH}_3)_2\text{O}$.

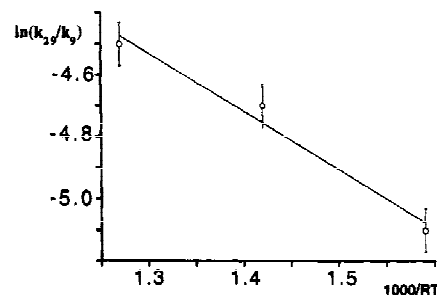
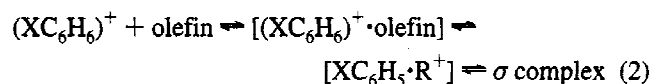


Figure 7. Temperature dependence of the k_{29}/k_9 ratio, see text.

protonation of C_6D_6 by radiolytically formed Brønsted acids, such as CH_3FH^+ , H_3O^+ , etc. The other product identified, methylcyclopentylbenzene, arises from the alkylation of C_6D_6 by methylcyclopentyl cations formed upon methylation of C_6H_6 by $(\text{CH}_3)_2\text{F}^+$ ions.

Discussion

The results reported in the previous section demonstrate operation of intracomplex aromatic alkylation according to the sequence



Such contrasting, and in some respects seemingly paradoxical, features can be rationalized taking into account the relative stability of complexes **1** and **2**, and the barrier for their interconversion, that depends on the balance between the basicities of the arene and of the olefin involved, whose proton affinities (PA) are reported for convenience in Table 3.

Let us consider first the pairs where $\Delta PA = PA(\text{arene}) - PA(\text{olefin})$ is large, say $>20 \text{ kcal mol}^{-1}$, e.g., in the case of toluene *vs* ethylene or *idurene vs* propene. Despite the larger ion-molecule interaction energy and hence the higher stabilization expected for complexes **2** with respect to the corresponding

(26) Cacace, F.; Ciranni, G. *J. Am. Chem. Soc.* **1986**, *108*, 887.

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

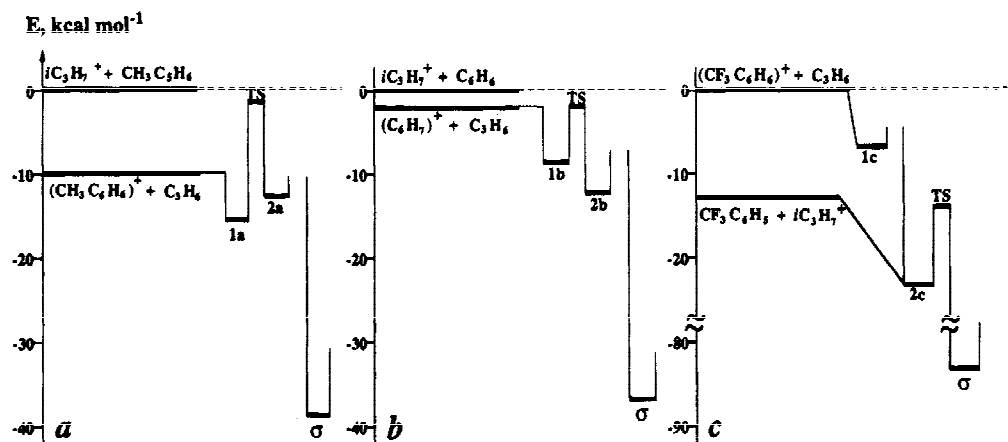


Figure 8. Schematic potential energy-reaction coordinate diagram for the reactions with propene of (a) toluenium ion, (b) benzenium ion, and (c) trifluoromethylbenzenium ion.

Table 3. Proton Affinity of Arenes and Olefins

base	PA, kcal mol ⁻¹
C ₆ H ₆	181.3, ^a 180.0 ^b
CH ₃ C ₆ H ₅	189.8, ^a 187.7 ^b
CF ₃ C ₆ H ₅	≥ 166.4 ^c
C ₂ H ₄	162.6 ^{a,b}
C ₃ H ₆	179.5, ^a 178.4 ^b
iC ₃ H ₇ ⁺	195.9, ^a 191.7 ^b
cC ₅ H ₈	ca. 189 ^d

^a From ref 12. ^b From ref 13. ^c From ref 16. ^d Estimated value, taken equal to the PA of c-C₅H₁₀, ref 12.

complexes 1,²⁸ the latter ones are much more stable in the case considered, which introduces a large endothermicity component into the barrier for 1 → 2 conversion, thus blocking the whole alkylation sequence 2.

Next we turn to pairs whose ΔPA is smaller, say 10 kcal mol⁻¹, as in the case of toluene *vs* propene, illustrated in the schematic energy diagram of Figure 8a. Apart from the heats of formation of the free reactants and of the σ complex, deduced from literature values,^{12,13} the diagram should be regarded as qualitative, since the reported energies of complexes 1a and 2a are educated guesses that however are not inconsistent with theoretical estimates for related systems.¹¹ The stability gap due to the higher PA of toluene than of propene is assumed to be considerably reduced by the higher interaction energy in 2a than in 1a, making the 1a → 2a conversion only moderately endothermic. Under the additional assumption that the activation energy for the alkylation sequence 2 is associated to the 1a → 2a conversion step, the experimental value of 9.1 ± 1.0 kcal mol⁻¹ from the Arrhenius plot of Figure 4 represents the ΔE_a difference between the barrier for the back dissociation of 1a and for its conversion into 2a, leading to a E_a value of ca. 14 kcal mol⁻¹ for the latter process. Upon subtraction of the endothermicity term, the intrinsic barrier for D⁺ transfer from the toluenium ion to propene in complex 1a can be estimated of the order of 10 kcal mol⁻¹. Albeit largely approximate, this value is reasonably close to those derived from experimental and theoretical methods for related processes. The only available experimental E_a value for *thermal*, gas-phase H⁺(D⁺) transfer between π-type centers, that refers to interannular exchange in protonated diphenylethane, amounts to 6.3 (8.0) kcal mol⁻¹.²⁹ Furthermore, according to AM 1 semiempirical calculations, the intrinsic barrier for the slightly *exothermic* 1b → 2b conversion *via* H⁺ transfer amounts to 6 kcal mol⁻¹.³⁰

(28) According to semiempirical calculations, ref 11, the interaction energy of complex 2 exceeds that of complex 1 by ca. 8 kcal mol⁻¹ for the *p*-xylene/propene pair.

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

The case where ΔPA ≈ 0 is aptly illustrated by the benzene/propene pair (Figure 8b). Owing to its larger interaction energy, complex 2b is appreciably more stable than 1b, and according to the Hammond postulate the intrinsic barrier for 1b → 2b conversion is expected to be somewhat lower than in the previously discussed case. This expectation is borne out, since the observed weakly *negative* temperature dependence points to a barrier height not exceeding that for dissociation of 1b, estimated on the order of 6 kcal mol⁻¹ according to the results of semiempirical and *ab initio* calculations.¹¹ The estimated E_a value agrees as well with the height of the barrier from the above mentioned AM 1 study.³⁰ Analogous considerations apply to the toluene/cpene and toluene/ibutene pairs, whose ΔPA is also small.

Finally, an example where the PA of the olefin considerably exceeds that of the aromatic molecule, namely ΔPA < 0, is offered by the CF₃C₆H₅/C₃H₆ pair (Figure 8c). Here complex 1c can evolve into complex 2c *via* an exothermic process, presumably characterized by a barrier whose height is expected to be very small, according to the Hammond postulate. The efficiency of the alkylation sequence 2 depends on the *k*₂₂/*k*₂₃ ratio, affected in turn by the relative height of the barriers for the formation of the Wheland intermediate from 2c and for dissociation of the complex. The observation of a weakly negative temperature dependence suggests that the two barriers are comparable, pointing to an appreciable activation energy for the formation of the σ complex. Such a finding, that sets CF₃C₆H₅ apart from C₆H₆ and CH₃C₆H₅, befits the strong deactivation of the substrate, whose low reactivity toward gaseous cations was previously reported.³¹ The special features outlined in the energy diagram of Figure 8c provide a reasonable explanation for the observed loss of iC₃H₇D⁺ ions from complex 2c.

The above discussion is based on the implicit assumption that the alkylation occurs *via* a stepwise mechanism where proton transfer to the olefin and formation of the σ complex are two distinct, consecutive processes. However, a concerted mechanism is also conceivable, and actually it has been considered in a mass spectrometric study of the fragmentation of protonated arenes.³² It is difficult to devise a crucial mechanistic test capable of rigorously discriminating between the stepwise and the concerted mechanism. The best argument we can offer is based on a comparative study of the isomeric

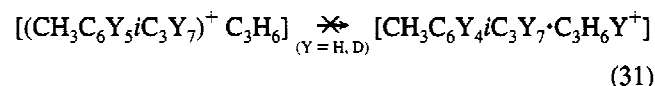
(30) Berthomieu, D.; Audier, H.; Denhez, J. P.; Monteiro, C.; Mourgues, P. *Org. Mass Spectrom.* **1991**, *26*, 271.

(31) Attina, M.; Cacace, F.; Yañez, M. *J. Am. Chem. Soc.* **1987**, *109*, 5092.

(32) Denhez, J. P.; Audier, H. E.; Berthomieu, D. *Org. Mass Spectrom.* **1993**, *28*, 704.

composition of the cymenes from the reaction of toluenium ions with propene (Table 2) and from the alkylation of toluene by bona fide isopropyl ions from the radiolysis of C_3H_8 at 720 Torr, in a series of specifically designed control experiments performed as described in earlier reports.³³ Significantly, the positional selectivity of the two processes is the same, within experimental errors, over the temperature range from 42 to 80 °C. This observation speaks against the operation of a concerted mechanism, unless one is willing to assume that the latter is characterized by the same activation parameters of the stepwise mechanism, a position that would strongly detract from the relevance of a discrimination between the two pathways.

Polyalkylation. A distinctive feature of the intracomplex alkylation is the formation of polysubstituted derivatives, particularly of the less activated aromatic substrates. E.g., as reported in a previous section, di- and triisopropylated products of $CF_3C_6H_5$ are formed, whereas no polyisopropylated toluenes have been detected. Such a peculiar trend finds a reasonable explanation if one takes into account the relative basicity of the arenes and the olefins involved in the consecutive alkylation steps. In the case of toluene, the first alkylation step yields protonated cymenes, whose conjugate bases are stronger than toluene. This increases the ΔPA basicity gap between the arene and propene, making the reaction



more endothermic than reaction 10, and hence the second alkylation step much slower than the first one. The situation is different in the case of $CF_3C_6H_5$. The first alkylation step gives protonated isopropyltrifluoromethylbenzenes, whose conjugate bases are still weaker than propene. As a consequence, conversion of the complexes **1** formed upon addition to propene into the corresponding complexes **2** is still not endothermic, and the second alkylation step is likely to be as efficient as the first one, or even more efficient, owing to the higher activation of certain $CF_3C_6H_4iC_3H_7$ isomers than of $CF_3C_6H_5$, which favors conversion of the corresponding complexes **2** into Wheland intermediates.

Conclusion

By exploiting the unique features of the gaseous reaction environment we have demonstrated the operation and outlined the special mechanistic features of an alternative route to

electrophilic aromatic substitution occurring within the complexes formed upon addition of arenium ions to olefins. The results of a systematic survey currently under way in this laboratory show that reaction (2) is quite general. Far from being restricted to the use of olefins as the proelectrophiles, nor, for that matter, to aromatic alkylation, the process has been found to encompass many classes of substitution reactions, including nitrosation, nitration, amination, silylation, germylation, etc. that will be examined in forthcoming papers.

The intracomplex reaction (2) provides a new entry into the manifold of electrophilic substitution, of considerable potential interest in view of the very short lifetime, well below 10^{-9} s, of the charged electrophile prior to its capture by the aromatic molecule contained in the *same* ion–molecule complex, and hence having a very high local concentration. This might widen the scope of aromatic substitution to unstable electrophiles that in conventional bimolecular reactions undergo rearrangement or dissociation well before interacting with the aromatic substrate.

Finally, the present results are relevant to gas-phase ion chemistry, as a direct demonstration of a reaction occurring within a bona fide ion–neutral complex. The mechanistic role of INCs has long been postulated in mass spectrometry,^{6–11} based however on indirect evidence related to the fragmentation pattern of excited species from the ionization of a parent molecule where the putative components of the complex were covalently bound. In a specific case of alkylarenium ions, the lack of irrefutable experimental evidence has forced recourse to theoretical approaches,^{11,30} whose results, incidentally, despite the severe limitations imposed by the complexity of the system, do not appear inconsistent with the experimental evidence from this work.

By contrast, the approach outlined in this report provides positive evidence for the occurrence of electrophilic aromatic substitution within ion–molecule complexes *prepared by assembling their initially separate components*, exactly as in condensed-phase coordination chemistry. Furthermore, the complexes are thermally equilibrated with the dense gaseous environment, which allows meaningful definition of the reaction temperature, and confers generality to the results, making them amenable to the standard kinetic treatment universally used in solution chemistry.

Acknowledgment. The financial support from Università “La Sapienza” and the Italian National Research Council (CNR) is acknowledged. The authors are grateful to F. Angelelli for his skillful assistance in the FT-ICR experiments.

(33) Attinà, M.; Giacomello, P. *J. Am. Chem. Soc.* **1979**, *101*, 6040.