DO/3 study, later extended to methylcyclohexylium ion,[16] the energetically favored isomerization pathway corresponds to the protonated cyclopropane route, long suggested by Brouwer[17] and Saunders.[18] In this connection, our finding that rearrangement of gaseous $C_6H_{11}^+$ ions from the protonation of bicyclo[3.1.0]-hexane is much faster than that from the protonation of cyclo-hexene, despite the equal exothermicity of the two processes, provides fresh evidence for the mechanistic role of protonated cyclopropane in the **1** → **2** isomerization.

Conclusion

The present work points to the possibility of deriving the activation parameters for the *thermal*, unimolecular isomerization of a gaseous cation from a systematic temperature-dependence study, carried out with the now well-established radiolytic technique in different gases in a wide pressure range, and utilizing different reactions for the preparation of the ion of interest.

The usefulness of such an approach can be desumed from the contrast between the plethora of data on the kinetics of *bimolecular* ionic reactions from low-pressure mass spectrometric studies[19] and high-pressure β-decay[6] and radiolytic[5] investigations, and the preciously little which is known on the kinetics of *unimolecular* rearrangements of *thermal* gaseous ions. In this connection, it should be noted that only under conditions ensuring a thermal energy distribution do gas-phase processes lend themselves to standard kinetic treatments and to meaningful kinetic comparison with ionic reactions in solution.

Although the absolute accuracy of the results, in particular of the preexponential factor, depends to some extent on the accuracy of the current theories of ion-neutral collisions used to calculate the trapping time, to our knowledge this study provides the first estimate of the activation parameters for the unimolecular, thermal rearrangement of a gaseous ion, which, incidentally, marks a significant advance over previous radiolytic studies, where only activation-energy *differences* and *ratios* of preexponential factors of *bimolecular* reactions could be evaluated.[20,21]

As to the specific problem addressed, which represents a long-standing question of gas-phase ion chemistry, this work corroborates previous evidence for the existence of free cyclohexylium ion, providing a quantitative estimate of the barrier to its rearrangement and fresh mechanistic support to the protonated-cyclopropane route.

Acknowledgment. This work has financially been supported by the Italian National Research Council (C.N.R.) and the Ministry of Pubblica Istruzione.

Registry No. 1, 22499-63-4; **2**, 17106-22-8; C_1H_5, 15135-49-6; C_2H_5, 14936-94-8; s-C_3H_7, 19252-53-0; cyclohexene, 110-83-8; bicyclo[3.1.0]-hexane, 285-58-5; 1-methylcyclopentene, 693-89-0; methylenecyclopentane, 1528-30-9.

(16) Viruela-Martin, P. M.; Nebot-Gil, I.; Viruela-Martin, R.; Planelles, J. *J. Chem. Soc., Perkin Trans. 2* **1987**, 307.
(17) Brouwer, D. M.; Oelderick, J. M. *Recl. Trav. Chim. Pays-Bas* **1968**, *87*, 721.
(18) Saunders, M.; Hagen, E. L. *J. Am. Chem. Soc.* **1968**, *90*, 2436. See also *Acc. Chem. Res.* **1973**, *6*, 53.
(19) See, for instance, *Ionic Process in the Gas Phase*; Almoster-Ferreira, M. A., Ed.; D. Reidel: Dordrecht, The Netherlands, 1982, and references therein.
(20) Cacace, F.; Ciranni, G. *J. Am. Chem. Soc.* **1986**, *108*, 887.
(21) Speranza, M.; Laguzzi, G. *J. Am. Chem. Soc.* **1988**, *110*, 30.

Gas-Phase Reactions of Charged Electrophiles with Styrene and Phenylacetylene

Maria Elisa Crestoni and Simonetta Fornarini*

Contribution from the Dipartimento di Studi di Chimica e Tecnologia delle Sostanze Biologicamente Attive, Università di Roma "La Sapienza", I-00185, Rome, Italy.
Received November 16, 1988

Abstract: The reactions of styrene and phenylacetylene toward charged electrophiles have been studied in the gas phase by a radiolytic technique, supported by chemical ionization mass spectrometry. The two substrates undergo a methylation reaction by Me_2F^+ both at the ring and at the side chain, at variance with the side-chain electrophilic attack prevailing in condensed phase. The nitrating $(MeONO_2)H^+$ ion selectively nitrates the ortho position of styrene, an unprecedented ring nitration on this substrate. The formation of neutral isomeric products is determined by the efficiency of deprotonation of their ionic precursors and is sensitive inter alia to the presence of oxygen nucleophiles. The overall reactivity pattern is rationalized in terms of preferential electrostatic interactions between the reactants in a preliminary collision complex, whereby an incoming ROH molecule can simulate a "solvating" environment, shifting the reactivity in the direction observed in solution.

The reaction of styrenes with electrophilic reagents in solution occurs primarily at the double bond.[1] The phenyl ring thus behaves as "spectator" and, when systematically substituted, is exploited as a means to probe the development of charge on the α-carbon in the transition state.[2]

Acid catalysts promote well-known dimerization reactions and polymerization sequences involving the double bond.[1] Direct electrophilic attack on the aromatic nucleus occurs successfully only when the double bond is deactivated by the presence of electron-withdrawing groups.[3] In such way, it was found that the aromatic ring of styrene is actually *activated* toward electrophilic nitration by the vinyl substituent, although in general its reactivity is obscured by the overwhelming competition of side-chain attack.

The gas-phase protonation of styrene appears to display a close similarity to the behavior of this substrate in solution, in that the

(1) (a) *Friedel-Crafts and Related Reactions*; Olah, G. A., Ed. Interscience: New York, 1963-1965; Vol. I-IV. (b) Roberts, R. M.; Khalaf, A. A. *Friedel-Crafts Alkylation Chemistry*; M. Dekker: New York, 1984.
(2) For a recent example, see: Ruasse, M. R.; Argile, A.; Dubois, J. E. *J. Am. Chem. Soc.* **1984**, *106*, 4846.
(3) Reynolds, W. F.; Modro, T. A.; Mezey, P. G.; Skorupowa, E.; Maron, A. *Can. J. Chem.* **1980**, *58*, 412.

0002-7863/89/1511-6008$01.50/0

thermodynamically most favorable site is the side-chain β-position,[4] as in ring-substituted phenylacetylenes.[5] The question arises whether the thermodynamically favored site of electrophilic attack is also the kinetically favored site, and how the unsaturated ethenyl and ethynyl substituents compete with the directly bonded phenyl ring. With the aim of answering these questions we started a study on the gas-phase cationic methylation of styrene and phenylacetylene, reasoning that the covalently bound methyl group will mark the position of its kinetic attack in the products. This is based on the less pronounced ability of this group than of an "ipso" proton to undergo 1,2-migrations in arenium ions.[6] In this study, a combination of two techniques is exploited, namely, a mass spectrometric technique for the direct observation of ionic intermediates and a radiolytic technique for the characterization of their neutral end products. However, a caveat for the correct interpretation of radiolytic results, especially with regard to possible parasitic radical reactions, follows in the next paragraph.

The outcome of this work has revealed that, in the gas-phase, nuclear substitution by a cationic electrophile can readily occur on styrene, less so on phenylacetylene, showing that, on these substrates, the regioselectivity of electrophilic attack is markedly influenced by the reaction environment, in particular by solvent molecules.

Radiolytic Reactions. Ionic vs Radical Reactions. The radiolytic approach, whose principles and applications have been reviewed,[7] involves γ-irradiation of a bulk gas, yielding well-defined charged reagents, whose interaction with the substrate, present at low concentrations in the gas, gives ionic intermediates that are rapidly trapped by suitable nucleophiles. The neutral end products thus formed can be isolated and characterized, providing structural and stereochemical information on their charged precursors. An intrinsic problem associated with the radiolytic technique is the possible role of reactive neutral species, in particular of free radicals, formed in the irradiation together with the charged reactants, which can yield neutral products that superimpose on those from ionic reactions.

The problem is particularly serious in the present case, since styrene and phenylacetylene are highly reactive toward free radicals,[8] which makes it imperative to use utmost care in order to ascertain the ionic origin of the products of interest. The general criteria can be summarized as follows: (i) the ionic reaction of interest must be shown to occur efficiently in the system investigated by a preliminary study based on chemical ionization (CI) mass spectrometry; (ii) the yields of ionic products must be unaffected by the presence of radical scavengers, typically O_2; (iii) formation of the ionic products must be depressed by gaseous nucleophiles capable of intercepting the charged reactants and intermediates.

Frequently, the above criteria are insufficient to safely discriminate between ionic and radical pathways, and more specific tests must be adopted. We have applied the above criteria to the specific systems investigated, as illustrated by the following example. The ionic origin of the side-chain and ring-methylated products from styrene is consistent with the general criteria outlined above; e.g., their yield is drastically depressed by addition to the radiolytic system of a gaseous nucleophile, such as Me_2O, that intercepts Me_2F^+, the methylating cation.[9] On the other hand, another radiolytic product, propiophenone, is assigned a radical origin, owing to the insensitivity of its yields to the presence of bases or nucleophiles. A more specific test supports the assignment. In principle, propiophenone could be formed by an ionic reaction sequence[10]

$$PhC{\equiv}CH \xrightarrow[-MeF]{+Me_2F^+} PhC^+{=}CHCH_3 \xrightarrow{H_2O} PhC(^+OH_2){=}CHCH_3 \rightarrow \rightarrow PhCOEt$$

Specific tests, involving use of $H_2{}^{18}O$ as the oxygenated nucleophile, have shown that the ^{18}O label is *not* incorporated into the radiolytically formed propiophenone which rather derives its oxygen from the unlabeled O_2 radical scavenger. This finding contributes to disproving its ionic origin. In the ensuing presentation, radiolytic products whose origin was not positively identified as ionic by the above criteria will be ignored, focusing attention on assuredly ionic products.

Experimental Section

Materials. Research purity gases were obtained from Matheson Gas Products Inc. MeF was found by GLC analysis to be only 99 mol % pure and was freed from Me_2O and Me_2CO impurities by passage through molecular sieves, over dry ice vapors. Other chemicals used as substrates or reference gas chromatographic standards were commercially available from Aldrich Chimica Srl or Fluka AG. A few compounds were synthesized by unexceptional procedures: *o*- and *p*-nitrostyrenes were obtained by nitrating (β-chloroethyl)benzene in H_2SO_4/HNO_3 followed by dehydrochlorination over KOH; 1-methoxy-1-tolylethanes were prepared from the corresponding methylbenzaldehydes via addition of methyl Grignard reagent, hydrolysis, and Williamson etherification of the alcohol. Tolylacetylenes were prepared from methylacetophenones by treatment with PCl_5 and dehydrochlorination.[11] The products were purified by preparative GLC and identified by their MS and NMR spectra.

Chemical Ionization Mass Spectrometry. The CIMS experiments were run in a Hewlett-Packard Model 5982A quadrupole spectrometer operated in the chemical ionization mode, at a source temperature of 100 °C. The reactant gas was admitted into the source at ca. 1 Torr from a reservoir containing either purified MeF or a preformed 30:1 $CH_4/MeONO_2$ mixture.

Radiolytic Experiments. The gaseous samples were prepared by routine vacuum line procedures in sealed 135-mL glass vessels.[7] For the nitration experiments, possible acidic sites on the glass walls were deactivated with aqueous KOH. The irradiations were carried out at a dose rate of 4.5×10^3 Gy h^{-1} to a total dose of 13.5×10^3 Gy in a 220 Gammacell, Nuclear Canada Ltd., at 37 °C, unless otherwise stated.

Product Analysis. The reaction mixtures of radiolytic experiments were analyzed both as gaseous mixtures and as dissolved in methyl acetate solvent by freeze–thaw cycles. The identification of products was achieved by GLC–MS by comparison with reference compounds on the following capillary columns: (i) a 12 m long, 0.2 mm i.d. silica column with a 0.33-μm film of cross-linked methylsilicone gum phase, for the analysis of nitration experiments; (ii) a 50 m long, 0.2 mm i.d. silica column with a 0.5-μm film of cross-linked methylsilicone, for the analysis of methylation experiments.

The mass detector was a Hewlett-Packard Model 5970 mass selective detector. Radiochemical yields were evaluated by packed GLC using a Hewlett-Packard 5700 instrument. The FID response to the products, resolved through a 3.5 m long column, packed with SP2100 (20%) + Carbowax 1500 (0.1%) on 100–120 mesh Supelcoport, was normalized by individual calibration factors. The purity of the reactants and the results of blank experiments were checked by the same methods.

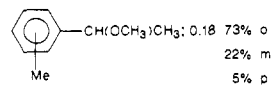
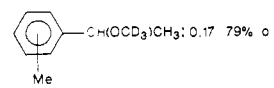
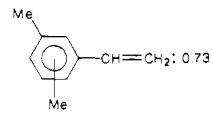
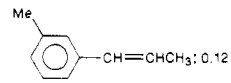
Results

Chemical Ionization Experiments. When styrene is allowed to react with Me_2F^+ under CI conditions, the most abundant adduct ion observed is the methylated substrate, i.e., $m/z = 119$. The same occurs on phenylacetylene ($m/z = 117$).

The nitration reaction carried out by protonated methyl nitrate is not as efficient as methylation by Me_2F^+. In a 3% $MeONO_2$/97% CH_4 gaseous mixture at ca. 1 Torr, $(MeONO_2)H^+$ is the major ion, NO_2^+ and $(MeONO_2)NO_2^+$ representing 13% and

(4) Harrison, A. G.; Houriet, R.; Tidwell, T. T. *J. Org. Chem.* **1984**, *49*, 1302.
(5) Marcuzzi, F.; Modena, G.; Paradisi, C.; Giancaspro, C.; Speranza, M. *J. Org. Chem.* **1985**, *50*, 4973.
(6) Koptyug, V. A. In *Contemporary Problems in Carbonium Ions Chemistry III*; Boschke, F. L., Ed.; Springer-Verlag: Berlin, 1984; p 146.
(7) For recent reviews on the radiolytic approach to gas-phase ion chemistry and description of the radiolytic technique, see: (a) Cacace, F. *Acc. Chem. Res.* **1988**, *21*, 215. (b) Cacace, F. In *Structure/Reactivity and Thermochemistry of Ions*; Ausloos, P., Lias, S. G., Eds.; Reidel: Dordrecht, 1987. (c) Speranza, M. *Gazz. Chim. Ital.* **1983**, *113*, 37. (d) Cacace, F. *Radiat Phys. Chem.* **1982**, *20*, 99.
(8) (a) Russel, G. A.; Tashtoush, H.; Ngoviwatchai, P. *J. Am. Chem. Soc.* **1984**, *106*, 4622. (b) Nagase, S.; Kern, C. W. *Ibid.* **1980**, *102*, 4513. (c) Amiel, Y. In *The Chemistry of Functional Groups, Supplement C: The Chemistry of Triple Bonded Functional Groups*; Patai, S., Rappoport, Z., Eds.; Wiley: New York, 1983; p 348.
(9) Sen Sharma, D. K.; Kebarle, P. *J. Am. Chem. Soc.* **1982**, *104*, 19.
(10) Fornarini, S.; Speranza, M. *J. Chem. Soc., Chem. Commun.* **1985**, 1692.
(11) Smith, L. I.; Hoehn, H. H. *J. Am. Chem. Soc.* **1941**, *63*, 1175.

Table I. Radiolytic Methylation of Styrene by Me_2F^+ Ions in the Gas Phase

entry	system composition,[a] Torr: substrate(s)	additive	MeF	methylated products,[b] G_{+M}				ratio[e]
1	styrene: 3.0		690	methylstyrenes: 0.73	77% o 21% m 2% p	*trans*-β-methylstyrene: 0.01		73
2	styrene: 4.0		165	methylstyrenes: 0.59	66% o 26% m 8% p	*trans*-β-methylstyrene: ≤0.005		
3	styrene: 3.5 mesitylene: 1.3		680	methylstyrenes: 0.77	77% o 16% m 7% p	*trans*-β-methylstyrene: ≤0.005	isodurene: 1.27	
4[c]	styrene: 4.1 mesitylene: 2.8		700	methylstyrenes: 2.12	75% o 18% m 7% p	*trans*-β-methylstyrene: ≤0.005	isodurene: 2.37	
5	styrene: 2.6	NEt_3: 0.84	710	methylstyrenes: 1.15	69% o 22% m 9% p	*trans*-β-methylstyrene: 0.05		23.0
6	styrene: 3.6	NEt_3: 0.80	150	methylstyrenes: 1.51	60% o 30% m 10% p	*trans*-β-methylstyrene: 0.06		25.0
7	styrene: 3.8	NEt_3: 1.50	690	methylstyrenes: 1.32	70% o 20% m 10% p	*trans*-β-methylstyrene: 0.12		11.0
8	styrene: 1.5	NEt_3: 5.05	700	methylstyrenes: 0.50	70% o 16% m 14% p	*trans*-β-methylstyrene: 0.12		4.2
9	styrene: 1.7	NEt_3: 10.9	700	methylstyrenes: 0.50	68% o 17% m 15% p	*trans*-β-methylstyrene: 0.14		3.6
10	styrene: 1.5	NEt_3: 17.1	700	methylstyrenes: 0.25	64% o 20% m 16% p	*trans*-β-methylstyrene: 0.06		4.2
11	styrene: 4.4 mesitylene: 0.9	NEt_3: 0.8	710	methylstyrenes: 1.16	66% o 19% m 15% p	*trans*-β-methylstyrene: 0.02	isodurene: 0.60	58.0
12	styrene: 4.2 mesitylene: 0.8	NEt_3: 1.60	695	methylstyrenes: 1.90	63% o 19% m 17% p	*trans*-β-methylstyrene: 0.20	isodurene: 0.55	9.5
13	styrene: 3.3	CH_3OH: 1.7	710	methylstyrenes: 0.60	78% o 20% m 2% p		$PhCH(OCH_3)CH_2CH_3$: 0.56	1.4
14	styrene: 2.2	CD_3OD: 2.1	700	methylstyrenes: 0.51	76% o 18% m 6% p		$PhCH(OCD_3)CH_2CH_3$: 0.53	1.3
15	styrene: 1.7	Me_2O: 10.0	700	methylstyrenes: 0.024		*trans*-β-methylstyrene: ≤0.005		
16[d]	styrene: 2.5		675	methylstyrenes: ≤0.005		*trans*-β-methylstyrene: ≤0.005		
17	*m*-methylstyrene: 2.6	NEt_3: 10.1	700					6.1

[a] All gaseous systems contain O_2 (10 Torr). [b] Standard deviation of data ca. 10%. [c] Experiment run at 100 °C. [d] Blank experiment without γ-irradiation. [e] Ratio of ring over side-chain attack.

20%, respectively, of the total ion intensity. However, when trace amounts of styrene or phenylacetylene, such as not to perturb the reactant ion composition, are admitted into the source, protonation competes effectively with formation of nitrated adducts, the ratio of nitrated versus protonated ions being 1:1 from styrene and 1:8 from phenylacetylene, which may be compared with the ratio 2:1 for benzene under the same conditions.

Radiolytic Methylation. The methylated products from the gas-phase reaction of Me_2F^+ with styrene under varying reaction conditions are reported in Table I.

The absolute yields of radiolytic reactions are expressed as G_{+M}, which indicates the number of product molecules formed per 100 eV energy absorbed by the system. The values of Table I compare well with the methylation yields of other arenes,[12] indicating a highly efficient overall reaction. In most cases, both products of nuclear substitution, methylstyrenes, and a product of side-chain attack, *trans*-β-methylstyrene, are formed. *trans*-β-Methylstyrene is invariably formed in lesser amount and its cis isomer is not formed at all. The ratio of the yields of *o*-, *m*-, and *p*-methylstyrene to that of *trans*-β-methylstyrene, which corresponds to the ratio of ring to side-chain attack, is dependent on the system composition. It shows a decreasing trend with increasing NEt_3 concentration, reaching a limiting value of ~4 (entries 8–10) while it drops to the lowest values, slightly above unity, in the presence of methanol. In the latter systems two major changes in the nature of the products are seen: first, *trans*-β-methylstyrene is not formed, but side-chain methyl attachment ends up into 1-methoxy-1-phenylpropane; second, ring attack also is partly followed by incorporation of a methoxyl group in the benzylic position, entries 13 and 14. The methyl group orientation in the 1-methoxy-1-tolylethanes is approximately the same as in the methylstyrenes. When perdeuterated methanol is used, the CD_3O moiety enters into the products. No additional deuterium atoms are incorporated, although mass analysis of the labeled MeOH recovered from

(12) (a) Cacace, F.; de Petris, G.; Fornarini, S.; Giacomello, P. *J. Am. Chem. Soc.* **1986**, *108*, 7495. (b) Speranza, M.; Pepe, N.; Cipollini, R. *J. Chem. Soc., Perkin Trans. 2* **1979**, 1179.

Table II. Radiolytic Methylation of Phenylacetylene by Me_2F^+ Ions in the Gas Phase

entry	system composition,[a] Torr substrate(s)	additive	MeF	methylated products,[b] G_{+M}				ratio[d]
1	phenylacetylene: 3.2		700	tolylacetylenes: 0.024	85% o 15% m ≤10% p	1-phenylpropyne: 0.26		0.092
2	phenylacetylene: 3.5		175	tolylacetylenes: 0.105	90% o 6% m 4% p	1-phenylpropyne: 0.65		0.16
3	phenylacetylene: 2.9 mesitylene: 1.1		720	tolylacetylenes: 0.063	63% o 27% m 10% p	1-phenylpropyne: 0.55	isodurene: 0.55	0.11
4	phenylacetylene: 4.0	NEt_3: 1.0	700	tolylacetylenes: 0.082	71% o 18% m 11% p	1-phenylpropyne: 0.40		0.21
5	phenylacetylene: 3.2	NEt_3: 0.7	170	tolylacetylenes: 0.145	75% o 15% m 10% p	1-phenylpropyne: 0.17		0.85
6	phenylacetylene: 1.6	NEt_3: 10.8	700	tolylacetylenes: 0.037	65% o 20% m 15% p	1-phenylpropyne: 0.15		0.25
7	phenylacetylene: 4.6 mesitylene: 1.6	NEt_3: 0.9	740	tolylacetylenes: 0.060		1-phenylpropyne: 0.15	isodurene: 0.64	0.40
8	phenylacetylene: 3.4	MeOH: 1.6	700	tolylacetylenes: 0.020	76% o 24% m ≤10% p	1-phenylpropyne: 0.53	*o*-methyl-acetophenone: 0.030	0.094
9	phenylacetylene: 5.9	$H_2{}^{18}O$: 1.9	700	tolylacetylenes: 0.012	85% o 15% m ≤10% p	1-phenylpropyne: 0.96	*o*-methylacetophenone: 0.003	0.016
10	phenylacetylene: 0.9	Me_2O: 15	700	tolylacetylenes: 0.003		1-phenylpropyne: 0.05		
11[c]	phenylacetylene: 2.7		690	tolylacetylenes: <0.002		1-phenylpropyne: <0.002		

[a] All gaseous systems contain O_2 (10 Torr). [b] Standard deviation of data ca. 10%. [c] Blank experiment without γ-irradiation. [d] Ratio of ring over side-chain attack.

the irradiated gas reveals complete H/D scrambling in the hydroxyl group.

Under otherwise equal conditions, the ratio of ring over side-chain attack is higher when a methyl group is present in the meta position of the substrate (entry 17).

No methylation occurs in the absence of γ-irradiation, cf. entry 16, while a powerful inhibiting effect is shown by Me_2O, an oxygen nucleophile (entry 15), and, to a much lesser extent, by NEt_3, a hindered base (entries 5–10).

Low concentrations of NEt_3 can actually *increase* the absolute yield of the methylation products of styrene, measured by their G_{+M} values, up to a maximum occurring at a NEt_3 pressure of 0.80–1.50 Torr, a behavior not shown by a competition substrate, mesitylene (entries 11 and 12).

The yield of the methylated product from mesitylene is proportional to its molar fraction with respect to styrene. As a result, the apparent reactivity ratio of styrene relative to mesitylene, measured by the yield of the methylated styrenes over the yield of isodurene, corrected by the ratio of the substrate concentration, varies from 0.23 (entry 3, no NEt_3 present) to 0.73 (entry 12, NEt_3, 1.6 Torr).

Table II shows the distribution of methylated products from the reaction of Me_2F^+ with phenylacetylene. On this substrate also, products from attack both to the ring, i.e., tolylacetylenes, and to the side chain, i.e., 1-phenylpropyne, are observed, the major difference with respect to styrene being the inverse proportion of ring over side-chain attack. A value of 0.2 is found in the presence of NEt_3 (entries 4 and 6) while the styrene ratio leveled to the value of 4. However, no definite correlation with the reaction conditions emerges. The reactivity of phenylacetylene relative to mesitylene yields a ratio of 0.11 when NEt_3 is present (entry 7).

In the presence of added oxygen nucleophiles, i.e., MeOH or water, ring attack yields an additional product that is *o*-methylacetophenone, which incorporates ^{18}O when $H_2{}^{18}O$ is used. As for styrene, the blank experiment without sample irradiation does not show any thermal component to product formation.

Radiolytic Nitration. Only a limited radiolytic study of the nitration reaction effected by the $(MeONO_2)H^+$ ion was possible and restricted to styrene. The general usefulness of this nitrating agent for the study of gas-phase ion–molecule reactions was hampered by the fact that its precursor, methyl nitrate, undergoes a slow thermal reaction with phenylacetylene and forms a β-nitro product with styrene under some conditions.[13] While this is not a drawback in the mass spectrometric study, where the neutral substrate is separately introduced into the ion source where it reacts with the already formed ionic reagent,[14] it definitely prevents a quantitative study by the radiolytic technique. Nevertheless, an interesting finding is the occurrence of ortho nitration to the styrene ring, falling off with the addition of increasing amounts of NEt_3. The G_{+M} value of *o*-nitrostyrene measured in CH_4 (700 Torr) containing $MeNO_3$ (20 Torr) is 1.2 with no added base, to become 0.97, 0.12, and undetectably low at 0.31, 1.21, and 7.78 Torr NEt_3, respectively. β-Nitrostyrene is not significant, being formed by a slow thermal reaction. It is to be noticed, however, that this product is not formed when the NEt_3 pressure is greater than 0.31 Torr; it appears that the base inhibits the thermal β-nitration.

Discussion

Ionic Reagents. Ionization of gaseous MeF and of the gaseous mixture $CH_4/MeONO_2$ (35:1) is known to yield Me_2F^+ and $(MeONO_2)H^+$ ions, via a well-established sequence of ion–molecule reactions. The one leading to Me_2F^+ involves protonation of methyl fluoride followed by nucleophilic displacement of HF by a second MeF molecule

$$MeF^{\bullet+} \xrightarrow[-CH_2F^{\bullet}]{+MeF} MeFH^+ \xrightarrow[-HF]{MeF} Me_2F^+$$

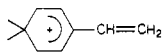
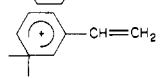
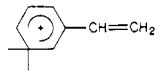
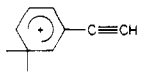
while $(MeONO_2)H^+$ is obtained by protonation of methyl nitrate by the stable $C_nH_5^+$ (n = 1, 2) ions formed in the bulk CH_4 plasma.

$$C_nH_5^+ + MeONO_2 \rightarrow C_nH_4 + (MeONO_2)H^+$$

(13) This problem was still more severe in the attempt to use $CF_3CH_2O-NO_2$ as precursor of the nitrating ion $(CF_3CH_2ONO_2)H^+$.

(14) For a caveat on reactions between substrate molecules and chemical ionization reagent, see: Budzikiewicz, H. *Org. Mass Spectrom.* **1988**, *23*, 561.

Table III. Estimated Thermochemical Data[a]

substrate	reactant ion	product ion	$\Delta H°$, kcal/mol
styrene	Me_2F^+	$PhC^+HCH_2CH_3$	−47
styrene	Me_2F^+	$PhC^+(CH_3)_2$	−55
styrene	Me_2F^+	p-Me-C_6H_4-C^+HCH_3	−55
styrene	Me_2F^+		−42
styrene	Me_2F^+		−29
styrene	$(MeONO_2)H^+$		−4
styrene	$(MeONO_2)H^+$	PhC^+HCH_3	−27
phenylacetylene	Me_2F^+	$PhC^+{=}CHCH_3$	−54
phenylacetylene	Me_2F^+	p-Me-C_6H_4-$C^+{=}CH_2$	−53
phenylacetylene	Me_2F^+		−30

[a] See: Reference 16.

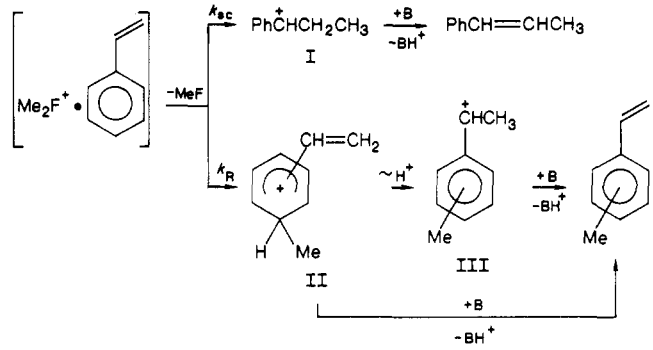
These ionic processes take place both in the CI ion source of a mass spectrometer, and in gaseous systems subjected to γ-irradiation, as discussed in several studies.[12,15] It is thus feasible to take advantage of the combination of the two techniques, which are complementary. In fact, by the mass spectrometric technique one can directly detect the ionic process of interest from the disappearance of the reactant ion and the formation of the charged product, as exemplified for a general methylation reaction

$$Me_2F^+ + ArH \rightarrow MeF + ArHMe^+$$

However, direct information on the structure of $ArHMe^+$ can be achieved only by the identification of the neutral products from its deprotonation, formed in parallel radiolytic experiments. As a probe for their ionic origin, these products are required to show lowering yields on addition of increasing amounts of nucleophiles and/or bases competing with the substrate. Such effect is positively observed for the products listed in Tables I and II on addition of Me_2O. Dimethyl ether is known to react efficiently with dialkylhalonium ions to give stable trialkyloxonium ions.[9] The effect of comparable amounts of NEt_3 is much less pronounced, probably on account of steric hindrance to nucleophilic attack to Me_2F^+ by the hindered NEt_3, making far an inefficient competitor with the substrate.

On the other hand, NEt_3 is a powerful base (PA = 232 kcal/mol)[16b] and the noticeable decrease in absolute yields caused by 10–20 Torr NEt_3 is due to the deprotonation of ions precursor to Me_2F^+, e.g., $MeFH^+$, where now NEt_3 faces competition with the most abundant MeF molecules. Minor amounts of NEt_3 can actually increase the yield of the methylation products, as explained in the following paragraph.

Scheme I



The yield of *o*-nitrostyrene is depressed by even small concentrations of NEt_3, in accord with the fact that all steps of the nitrating ions formation sequence is efficiently depressed by competitive deprotonation.

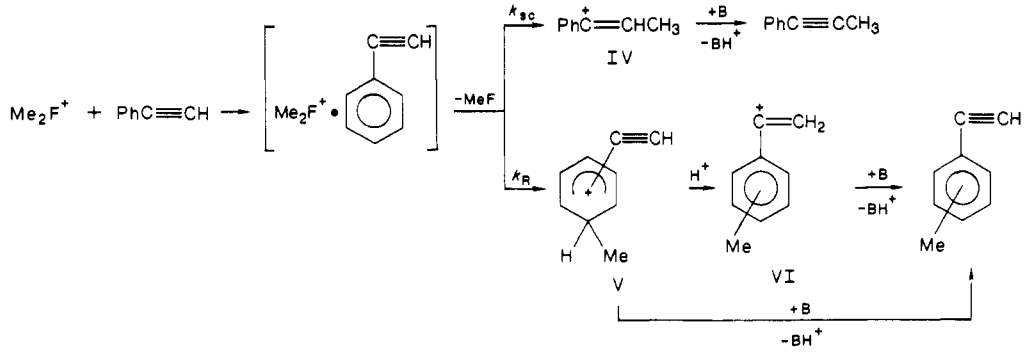
Methylation of Styrene. Methylation of styrene by Me_2F^+ is thermodynamically allowed both at the ring and at the side-chain β-position, as shown in Table III. Accordingly, methylated adduct ions are observed in CI experiments. Both reactions are strongly energetically favored owing to the low methyl cation affinity of MeF.[16a] On these grounds, the apparent regioselectivity of ring versus side-chain attack, corresponding to a ratio of ~70 for the methylation of styrene in 690 Torr MeF, is striking. This value is however misleading, as suggested by the increase of the methylation yield caused by traces of NEt_3 and by the leveling of the regioselectivity of ring attack to the ratio of 4 at higher base concentrations. A rationale for this behavior can be sought in the framework of Scheme I. The product of side-chain methylation is the fairly stable benzylic ion I. Ring methylation yields arenium ions, which may undergo ring to side-chain proton migration (vide infra), again forming substituted benzyl cations III. The high proton affinity (PA) of their conjugate bases, 201 kcal/mol for β-methylstyrene,[16b] 207.6 for *p*-methylstyrene,[4] together with the extensive charge delocalization of benzyl-type ions, makes these species hard to deprotonate. They may thus partly escape detection in the systems containing no specially added strong bases, being probably trapped by adventitious nucleophiles, by the glass walls of the vessels or by the unsaturated substrate. The arenium ions primarily formed by ring attack are expected to evolve more easily into products, as ring basicity is lower than side-chain basicity,[4] and moreover, arenium ions do not normally display a tendency for addition reactions. Such reasoning can account for the experimental findings, if one thinks that most of the ions formed by side-chain attack and those formed by ring attack followed by proton migration to the side chain may be lost in the absence of a powerful base. Within this framework, the ring over side-chain kinetic ratio reduces to 4, which is still remarkable in view of two factors: (i) the strongly negative reaction enthalpies for both types of attack, apparently favoring the side-chain β-carbon, (ii) the overwhelming side-chain electrophilic attack occurring in condensed phase. In agreement with the point (i) and with the ratio of 4 for unsubstituted styrene, the ring over side-chain ratio is increased only to 6 in the presence of a *m*-methyl substituent on the styrene ring. The electron-releasing effect of the methyl group only slightly influences the electrophile selectivity in the direction of ring attack.

The orientation measured under conditions of prevailing kinetic control, i.e., in the presence of NEt_3, ensuring fast deprotonation of the primary adduct intermediates (entries 8–10, Table I), is characterized by a meta/para ratio of 0.6. This value lends support to an ortho–para directing effect exerted by the vinyl group[3] toward electrophilic addition. Most of the ring methylation, however, appears to occur on the ortho position. This is not unusual for the attack of charged electrophiles to aromatic substrates substituted by groups containing heteroatoms, such as NR_2, OR, and halogen, both in the gas phase and in solution.[1,17] It

(15) (a) Attinà, M.; Cacace, F. *J. Am. Chem. Soc.* **1986**, *108*, 318. (b) Attinà, M.; Cacace, F.; Yañez, M. *J. Am. Chem. Soc.* **1987**, *109*, 5092. For a study of the protonation site in $(MeONO_2)H^+$, see: (c) Bernardi, F.; Cacace, F.; Grandinetti, F. *J. Chem. Soc., Perkin Trans. 2*, in press.

(16) Thermochemical data for neutral species: Cox, J. D.; Pilcher, G. *Thermochemistry of Organic and Organometallic Compounds*; Academic Press: London, 1970. The methyl cation affinity of MeF is from: (a) McMahon, T. B.; Heinis, T.; Nicol, G.; Hovey, J. K.; Kebarle, P. *J. Am. Chem. Soc.* **1988**, *110*, 7591. PA values are from: (b) Lias, S. G.; Liebman, J. F.; Levin, R. D. *J. Phys. Chem. Ref. Data* **1984**, *13*, 695. Values for styrene and *p*- and α-methylstyrene in: Reference 4. β-Methylstyrene in: (c) Galli, C.; Speranza, M. *Org. Mass Spectrom.* **1989**, *24*, 139. *p*-Tolylacetylene in: Reference 5. $MeONO_2$ in: Reference 15b,c. The PA of the Me or NO_2 ipso position in *m*-methylstyrene, *m*-tolylacetylene, and *m*-nitrostyrene is taken equal to the same position of toluene ((d) Devlin, J. L., III; Wolf, J. F.; Taft, R. W.; Here, W. J. *J. Am. Chem. Soc.* **1976**, *98*, 1990) or nitrobenzene (ref 15b), respectively. The PA of the Me ipso position of *p*-methylstyrene is taken equal to the *para-unsubstituted position of styrene: Cf.* ref d and 3. The $\Delta H°$ of ion $Ph\text{-}C^+{=}CHCH_3$ was estimated from the effect of methyl substitution on the PA value of propyne (ref b) and the known PA value of phenylacetylene (ref 5).

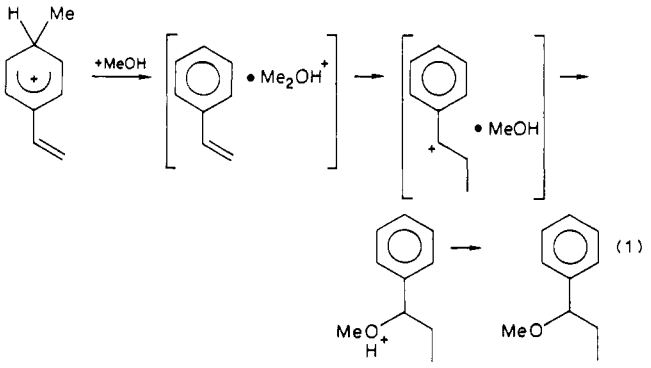
Scheme II



is less expected when the substituent is a phenyl[12a] or a vinyl group, as in this case. The origin of this effect may be traced to the dynamics of formation of the σ-complex, which is preceded by an ion–molecule collision complex. This complex, bound by electrostatic attraction, attains the highest stability when the two methyl groups of Me_2F^+, bearing most of the positive charge, interact simultaneously with two electron-donating centers, such as the vinyl and phenyl moieties of styrene.[18] In this way an oriented complex is formed where the local concentration of the electrophile is highest at the ortho positions.

The existence of a persistent Me_2F^+–styrene complex is also suggested by the noticeable increase of side-chain attack in the presence of MeOH, whose basicity is too low to promote deprotonation of I. Under these conditions, side-chain methylation does not yield *trans*-β-methylstyrene, but rather 1-methoxy-1-phenylpropane is formed by addition of MeOH. Thus it may be inferred that the Me_2F^+–styrene complex, upon collision with one or more MeOH molecules, sees a partial "solvating" environment, shifting the preferred site of attack exactly in the direction observed in solution. It is possible that a MeOH molecule in the complex may better solvate an incipient benzyl cation rather than an arenium-type one.

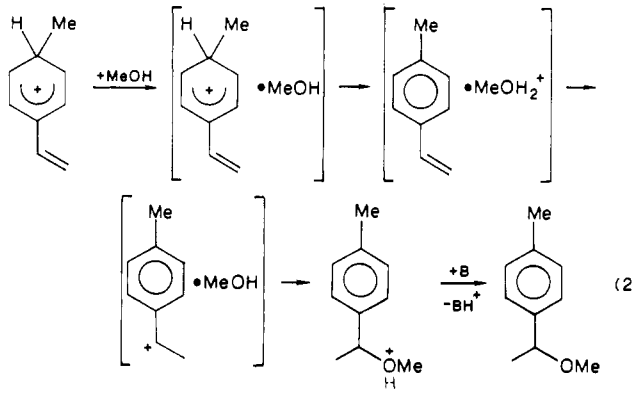
Two other pathways may conceivably account for the observed increase of side-chain methylation. A first reason may simply be that the electrophile has changed: Me_2F^+ partly alkylates methanol, yielding Me_2OH^+ which, in turn, can transfer a methyl to styrene, favoring the side-chain β-position. A second route may involve the reaction of MeOH with the preformed σ-complexed styrene, in a "catalyzed" ring to side-chain methyl transfer, according to reaction 1. However, both pathways involve methylation of styrene by an ion, Me_2OH^+, where one methyl group originates from the alcohol and the second one from MeF.



(1)

Consequently, when perdeuterated methanol is used, one should expect incorporation into the side-chain carbon, of both CH_3 and CD_3, if allowance is made for a secondary deuterium isotope effect. This is not the case, as the mass spectral fragmentation pattern of 1-methoxyl-1-phenylpropane is only consistent with the presence of a deuterated methoxyl group, thus discarding the proposed alternative mechanisms.

The use of MeOH as a trapping agent has allowed the detection of an otherwise elusive process. In fact, the formation of 1-methoxy-1-tolylethanes derives from ring methylation of styrene by Me_2F^+, followed by ring to side-chain proton migration to give substituted benzyl cations III (Scheme I), which eventually add to MeOH. In the absence of MeOH, ions III may be deprotonated by strong bases to yield methylstyrenes, indistinguishable from those arising from the deprotonation of arenium ions II. The migration of hydrogen to the side chain implies several 1,2-shifts on adjacent ring positions, a process that is reported to occur with great ease within certain gaseous arenium ions.[19] Eventually, a shift to the side chain will occur, probably from the ortho, or the ipso position to the vinyl group. The details of this process, which was previously observed in the cationic vinylation of benzene,[20] are not yet known. It seems, however, that the ring-walk implies lower barriers for the proton than migration to the side chain, since the ring methyl distribution is closely the same both in methylstyrenes and 1-methoxy-1-tolylethanes. Alternatively, a MeOH molecule may "catalyze" the proton migration as in reaction 2. Although thermodynamically unfavorable, proton transfer to MeOH may be energetically allowed within the ion–molecule complex by the electrostatic energy released by the interaction of the isolated reactants.[21]



(2)

Unfortunately, side-chain deuterium incorporation in the systems containing perdeuterated methanol provides no mechanistic insight because of fast isotopic scrambling of hydroxylic deuterium

(17) (a) Attinà, M.; Cacace, F. *J. Am. Chem. Soc.* **1983**, *105*, 1122. (b) Attinà, M.; Giacomello, P. *Ibid.* **1979**, *101*, 6040. (c) Pepe, N.; Speranza, M.; *J. Chem. Soc., Perkin Trans. 2* **1981**, 1430. (d) Angelini, G.; Lilla, G.; Speranza, M. *J. Am. Chem. Soc.* **1982**, *104*, 7091. (e) Chatfield, D. A.; Bursey, M. *Ibid.* **1976**, *98*, 6492, and references therein. (f) Aliprandi, B.; Cacace, F.; Fornarini, S. *Tetrahedron* **1987**, *43*, 2831.

(18) For the potential energy surfaces of gas-phase ion–molecule reactions, see, e.g.: Han, C.-C.; Dodd, J. A.; Brauman, J. I. *J. Phys. Chem.* **1986**, *90*, 471. For dimethylhalonium–arene complex binding energies, see: Reference 9. For the formation of adduct ions in gas-phase aromatic substitution, see: Cacace, F. *J. Chem. Soc., Perkin Trans. 2* **1982**, 1129.

(19) (a) Mason, R. S.; Fernandez, M. T.; Jennings, K. R. *J. Chem. Soc., Faraday Trans. 2* **1987**, *83*, 89. (b) Mason, R. S.; Fernandez, M. T.; Jennings, K. R. *Ibid.* **1987**, *83*, 159.

(20) Fornarini, S.; Speranza, M. *J. Am. Chem. Soc.* **1985**, *107*, 5358.

(21) (a) Lias, S. G. *J. Phys. Chem.* **1984**, *88*, 4401. (b) Grabowski, J. J.; De Puy, C. H.; Van Doren, J. M.; Bierbaum, V. M. *J. Am. Chem. Soc.* **1985**, *107*, 7384, and references cited therein.

and label loss in CD_3OD in the radiolytic experiments.

Methylation of Phenylacetylene. The overall reactivity displayed by phenylacetylene toward Me_2F^+ shares many features in common with styrene. The distinct increase in the yield of both products of attack to the ring, tolylacetylenes, and to the side-chain, 1-phenylpropyne, with increasing NEt_3 concentration (entries 1 and 4), is consistent with a product-limiting deprotonation step of phenylvinyl cations IV and VI, as shown in Scheme II.

The available thermochemical information does not allow estimation of the enthalpy change for attack at the para ring position. For other relevant processes the $\Delta H°$s are negative and similar for both substrates (Table III). However, a marked difference of regioselectivity of ring versus side-chain attack is found. In the presence of NEt_3, the leveling value is 0.2 for phenylacetylene, to be compared with 4 for styrene, meaning that the triple bond is favored by a factor of 5 over the aromatic ring of phenylacetylene. As was already observed in the methylation of styrene, the addition of oxygenated nucleophiles, ROH, (R = H, Me), enhances the side-chain attack, shifting the reactivity pattern toward a solution-like behavior.

Structural factors seem to control the reaction of ROH with α-phenylvinyl cations, IV and VI. In fact, *o*-methylacetophenone is formed from attack at the ortho position, followed by ring to side-chain proton migration to form VI, which adds to ROH and eventually ketonizes. Ion IV, from side-chain methyl attack, behaves differently, yielding exclusively 1-phenylpropyne. It appears that ROH, or more likely a cluster $(ROH)_n$, reacts with IV as a base rather than as a nucleophile to give an alkylene oxonium ion.

The ortho position is clearly a privileged site of attack in phenylacetylene as well, which stems from the possible coordination of the electrophile with the phenyl and ethynyl groups in the oriented complex, preliminary to formation of the σ-complex. Such behavior may then be thought of as a generalized feature in the interaction of bidentate electrophiles with arenes bearing π-substituents, despite their difference in geometry and electron-donor ability in biphenyl, styrene, and phenylacetylene.

The Nitration Process. The wealth of data and the fundamental issues concerning aromatic nitration make it the primary choice for a representative electrophilic aromatic substitution reaction.[22] Both phenylacetylene and styrene may add a nitronium ion from protonated methyl nitrate as shown by CI mass spectrometry. At the same time, a proton-transfer reaction competes efficiently with nitronium-ion transfer from the same reagent.

Whether the NO_2^+ adduct ion is π- or σ-bonded and, if σ-, which is the site of NO_2 attachment can not directly be answered by CIMS. Nor is the radiolytic technique much help in elucidating the problem, because of thermal nitration reactions effected by alkyl nitrates on phenylacetylene and at the side chain of styrene in the absence of NEt_3. What can be safely assessed is that nitration of styrene takes place exclusively at the ortho position under the conditions of radiolytic experiments that favor kinetic control of the reaction, i.e., in the presence of a strong base that rapidly deprotonates ionic intermediates. In the absence of fast quenching, a ring to side-chain nitro group shift may not be excluded. Thus, from our present viewpoint, we may regard the $(MeONO_2)H^+$/styrene complex as bound by coordination of the styrene double bond with the proton and the phenyl ring with the nitro group of $(MeONO_2)H^+$. Such interactions may account for the highly efficient protonation channel, driven by a most favorable $\Delta H°$ (Table III), as observed by CIMS, and for the practically exclusive ortho nitration, found in the radiolytic experiments. This dual interaction is feasible if the protonation site of $MeONO_2$ is the methoxyl, rather than the nitro, oxygen atom, as suggested by recent calculations.[15c]

Substrate Selectivity. The Me_2F^+ ion is known to be a relatively strong electrophile, reacting at every collision with activated aromatic substrates and with benzene itself. The relative reactivity of styrene and phenylacetylene with respect to mesitylene as a reference substrate, in the presence of NEt_3, ensuring fast deprotonation of primary adduct ions, shows an apparent trend: mesitylene ($\simeq$benzene)[12b] > styrene > phenylacetylene. From this, the following reactivity order would be set for electrophilic attack by Me_2F^+ ions in the gas phase: styrene, (ring) > styrene (vinyl group) > phenylacetylene (ethynyl group) > phenylacetylene (ring). We further know that the first inequality holds as well for nitration by $(MeONO_2)H^+$.

This gas-phase study has thus allowed the uncovering of intrinsic reactivity features displayed by styrene and phenylacetylene toward charged electrophiles in the absence of complicating environmental effects, such as solvent, counterions, or acidic catalysts. Ultimately, these features point to a major role played by electrostatic interactions between reactant pairs within the ion–molecule collision complex.

Direct comparison between the intrinsic reactivity of the double and triple carbon–carbon bond is beyond the scope of this study but still remains a challenging problem.[23]

Acknowledgment. We wish to thank Professors Fulvio Cacace and Maurizio Speranza for their active interest and helpful discussion. The work was supported by the Italian Ministero della Pubblica Istruzione.

Registry No. Me_2F^+, 64710-12-9; $(MeONO_2)H^+$, 99573-80-5; MeF, 593-53-3; $MeONO_2$, 598-58-3; styrene, 100-42-5; phenylacetylene, 536-74-3.

(22) Schofield, K. *Aromatic Nitration*; Cambridge Press: Cambridge, U.K., 1980.

(23) (a) Melloni, M.; Modena, G.; Tonellato, U. *Acc. Chem. Res.* **1981**, *14*, 227. (b) Legon, A. C.; Millen, D. J. *J. Chem. Soc., Chem. Commun.* **1987**, *986*, and references cited therein.