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Structures and Mechanisms of Reactions of Isomeric $C_2H_3O^+$ and $C_2H_3S^+$ Ions Revealed through Ion/Molecule Reactions in Conjunction with 2D and 3D Mass Spectrometry

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Abstract: Ion/molecule reactions are used to demonstrate that mass-selected $C_2H_3O^+$ and $C_2H_3S^+$ ions have distinctive reactivities which depend on the precursor molecule from which they are generated. Several isomers of both ions are distinguished, and the mechanisms of their reactions are elucidated. Structural characterization of the ion/molecule products is achieved in multistage (MS^3) experiments. In reactions with isoprene, the acetyl cation (**a**) is unique in that it displays a $[4 + 2^+]$ Diels–Alder cycloaddition product while other $C_2H_3O^+$ isomers, O-protonated ketene (**b**) and the oxiranyl cation (**c**), as well as the isobar $C_3H_7^+$, undergo proton-transfer reactions. The proportion of the acetyl ion in *m/z* 43 ion mixtures is estimated by comparing the extent to which cycloaddition and proton transfer take place. On this basis, compounds with various functionalities are ordered in terms of the degree to which their *m/z* 43 fragments comprise the acetyl cation. Correlations are developed with the degree of enolization in the molecular ions of the precursors. Further distinction of $C_2H_3O^+$ isomers **a**–**c** is achieved in reactions with methylanisoles. Ion **a** preferentially forms the intact adduct with these reagents while ions **b** and **c** fail to do so, their spectra being dominated by characteristic charge-exchange, proton-transfer, and adduct-fragmentation products. Ion **c** reacts with *m*- and *o*-methylanisole by a process which formally corresponds to CH^+ addition to the neutral molecule. Reaction with *p*-methylanisole shows predominant formation of the $CH_2^{\cdot+}$ addition product. Sequential product MS^3 spectra show that methyne addition yields *m*- and *o*-methylmethoxytropylium ions, while methylene addition yields ionized 2,4-dimethylanisole. The $C_2H_3S^+$ ions formed from a variety of precursors show similar product spectra upon reaction with isoprene, all displaying abundant cycloaddition products. Sequential product spectra are identical, a result that indicates formation of a common adduct. Reaction with *m*-methylanisole, however, allows distinction of the isomeric $C_2H_3S^+$ ions and shows that the failure to distinguish these isomers by reaction with isoprene is the result of isomerization of the different cycloaddition products to a common structure. Similarly, failure to distinguish the $C_2H_3S^+$ ions by previous collision-induced-dissociation experiments is interpreted to be a result of isomerization after collision, not of the existence of a single ionic population. These results provide an illustration of the detailed information on ions which is possible using ion/molecule reactions and the degree to which the structures of ion/molecule reaction products can be elucidated using multistage (pentaquadrupole) mass spectrometry.

Introduction

The potential value of gas-phase ion/molecule reactions in elucidating the structures of gaseous ions, or of the neutral molecules from which they are derived, has long been recognized.[1] On the other hand, ion/molecule reactivity has been shown to be strongly dependent upon experimental conditions and on the internal energy of the reactants,[2] and this accounts for the fact that methods based on dissociation, especially the technique of collision-induced dissociation (CID), have become the standard methods for distinction of ionic isomers.[3] CID has its own limitations, and rapid isomerization following excitation is a common reason for failure to achieve structural distinction. In a few cases, including the $C_2H_3S^+$ system, fragmentation can occur apparently via an excited electronic state, and this greatly complicates interpretation of the CID data. The lower collision energy normally used in ion/molecule reactions helps to minimize interconversion between isomers, although energy is released on formation of the ion/molecule reaction complex, and isomerization may not be precluded.

Access to a variety of neutral reagents provides a ready means to vary the types of ion/molecule reactions occurring and so increases the potential utility of this method of characterizing gaseous ions and their neutral counterparts. Ion/molecule reactions have been successfully used for isomer distinction[1] and even for identification of particular functional groups in complex organic molecules.[4] Recent examples[5] of the effective use of ion/molecule reactions for ion structure characterization in cases where CID fails include the distinction of protonated cyclohexene from protonated cyclohexene oxide achieved on reaction with ethyl vinyl ether.[5a] In this case, CID spectra are very similar, suggesting that these ions isomerize to or fragment via a common activated structure. Similarly, ion/molecule reactions with various neutral reagents can be used to distinguish between several $C_4H_4^{\cdot+}$ isomers[5b,c] while high- and low-energy CID experiments are less successful.

The $C_2H_3O^+$ and $C_2H_3S^+$ systems have been investigated extensively by several dissociation techniques,[6-9] but many issues remain unresolved, and the quality of the chemical information

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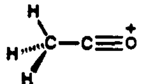
obtained on these systems is not completely satisfactory. These systems therefore represent excellent models in which to test further the value of ion/molecule reactions, especially when they are used in conjunction with the variety of MS^3 experiments[10] made available in the pentaquadrupole instrument.[11]

It has been demonstrated, by means of ab initio molecular orbital calculations,[12] that the $C_2H_3O^+$ isomers **a–c** exist in deep potential energy wells, while isomers **d** and **e** are also stable and offer some prospect for experimental observation. Results of high-energy CID experiments[9] on $C_2H_3O^+$ ions show that none of the isomers **a–c** display unique fragments and that no structural correlations could be based on the abundance of the CH_3^+ ion, the ion expected to be diagnostic of the acetyl cation (**a**). Lacking this parameter, the abundance ratio $[CHO^+]:[CO^+]$ of ~0.67[9c] and later 0.50[9e] was suggested to be a criterion to detect the pure acetyl cation (**a**). Structures **b** (2.5,[9c] 4.3[9e]) and **c** (2.9,[9c] 5.0,[9d] 10.6[9g]) were assigned on the basis of higher values of this ratio. The only other information available on this system is that ion **d** has been reported to be formed from dimethyl squarate and to display a low-abundance yet unique high-energy CID fragment at m/z 30.[9f] Clearly it is desirable to have additional procedures for establishing these structures. The situation is even less satisfactory with low-energy CID, where isomer distinction has not been achieved[13] and where the methyl cation is always the predominant fragment.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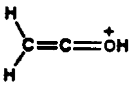
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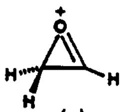
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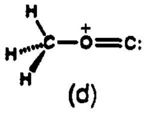
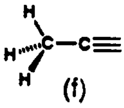
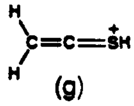
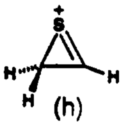

(d)


(e)

Theoretical calculations on the $C_2H_3S^+$ system[14] have shown ions **f–h** to be the most stable isomers, in analogy with ions **a–c** for the $C_2H_3O^+$ system. High-energy CID of $C_2H_3S^+$ ions yields very little of the methyl fragment, suggestive of the absence of the thioacetyl cation.[6] However, Caserio and Kim,[1c] by employing ion/molecule reactions, showed that $C_2H_3S^+$ ions generated from precursors containing the thioacetyl structure are composed mainly of the thioacetyl cation (**f**). An explanation for the high-energy CID results is that fragmentation occurs from an excited electronic state accessed in high-energy collisions.[7,8] Experiments in the low-energy CID regime[7] also failed to identify $C_2H_3S^+$ ions other than **f**, a result which was accounted for by isomerization prior to fragmentation. The thioacetyl cation is also the only species observed in experiments in which inelastic energy loss is measured in translational-energy spectroscopy.[8] Charge-stripping experiments on the $C_2H_3S^+$ system produced similar product abundances for a variety of precursors, leading to the conclusion that a common structure was involved.[6] However, there are small differences in abundances, suggesting that isomerization of the ions sampled in the experiment was incomplete. Recent high-energy CID results,[9f] which suggest that ion **h** is formed from dithiolane, have reopened the question of the identification of other $C_2H_3S^+$ isomers,


(f)


(g)


(h)

The aim of this study is to examine the ion/molecule reactions of the $C_2H_3O(S)^+$ ions to address such questions as the following: (i) Does isomerization of $C_2H_3S^+$ ions occur before or as a result of the activating collision? (ii) If the latter case applies, can ion/molecule reactions be used to avoid isomerization and hence to distinguish the isomers? (iii) Do ion/molecule reactions lead to different assignments of $C_2H_3O^+$ structures than those obtained in the high-energy CID experiments. (iv) Do ion/molecule reactions allow compositional analyses in cases wherein mixtures of isomers are formed? MS^3 experiments are particularly valuable in answering these questions. Certain types of MS^3 experiments have become an essential feature of the studies of ion/molecule reactions in the ion cyclotron resonance (ICR) mass spectrometer[15] and more recently in studies of thermal ion/molecule reactions in the flowing afterglow instrument.[16] A pentaquadrupole instrument is particularly useful[11] in allowing the full range[10] of MS^3 experiments to be accessed and in allowing ion/molecule reactions or collision-induced dissociation to be studied in either of two reaction regions. In the experiment named the sequential product (formerly daughter) scan, a mass-selected reaction product ion is subjected to a further stage of reaction and its products are displayed. These experiments[1h,5b,11c,17] permit structural identification of ion/molecule reaction products, and of ions formed by dissociation of specific parents, so enabling one to explore both the different reactivities of isomeric ions and the mechanisms of their reactions.

Experimental Section

The experiments were performed using a custom-built pentaquadrupole mass spectrometer[11c] consisting of three mass-analyzing (Q1, Q3, Q5) and two collision quadrupoles (Q2, Q4). The instrument was operated at a radio frequency (rf) which gave a nominal mass range of 1000 Da/charge for each mass analyzer. Ion/molecule reactions were performed using Q1 to mass select the ion of interest. After reaction in Q2 with a neutral gas, Q3 was used to record the ion/molecule product spectrum, while Q5 was operated in the nonanalyzing rf-only mode. The nominal sample and neutral gas pressures were typically 5×10^{-6} and 5×10^{-5} Torr, respectively. Instrument parameters and gas pressures were adjusted to maximize the abundance of ion/molecule products and held constant while the complete set of precursors was studied, except for the reaction of m/z 43 ions with isoprene, in which the experimental conditions were adjusted to reproduce the ratio m/z 111:m/z 81 of 5.6 for acetone before acquisition of spectra at different times.

For the MS^3 experiments, either CID with argon or ion/molecule reactions were performed in Q2 and Q4, depending on the experiment at hand. The sequential product scans were acquired by selecting a

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Table I. Selected Ion/Molecule Product Spectral Data[a] of Some $C_2H_3O^+$ Ions[b] with Isoprene

		product[c] (*m/z*)				high-energy CID results[d]	
	precursor	81	111	[111:81]	% **a**	[29:28]	major isomer
1[e]	$H_3CCO_2CH_3$	12	100	8.3	98	0.56[f]	**a**
2	$(H_3CCO)_2CH_2$	10	100	10	100	0.65	**a**
3	H_3CCOCH_3	18	100	5.6	93	0.68	**a**
4	H_3CCOH	27	100	3.7	85	0.72	**a**
5	H_3CCOCl	16	100	6.7	95	0.68	**a**
6	H_3CCO_2H	11	100	9.1	99	0.56[f]	**a**
7	$(H_3CCO)_2O$	13	100	7.7	97	0.63	**a**
8	$H_3CCONHCH_3$	13	100	7.7	97		
9	propylene oxide	21	100	4.8	90	1.25	**a**/**c**[g]
10	$H_5C_2OCH{=}CH_2$	11	100	8.3	98	0.76	**a**
11	cyclopentanone	22	100	4.5	90		
12	$H_5C_2OC_2H_5$	30	100	3.3	83		
13	H_5C_2OD (*m/z* 44)	100[h]	1		none	2.5[f,i]	**b**′[j]
	H_5C_2OD (*m/z* 43)	17	100	5.9	94	0.63[f]	**a**
14	H_5C_2OH	61	100	1.6	66	1.4[f]	**b**/**a**
15	$(ClCH_2)_2CHOH$	100	27	0.27	20	2.9	**c**[g]
16	$(HOCH_2)_2CHOH$	64	100	1.6	65	2.0	**c**[g]/**a**
17	$ClCH_2COH$	100	27	0.27	20		
18	tetrahydrofuran	100	28	0.28	22		
19	1,3-dioxolane	77	100	1.3	60	10.6[k]	**c**
20	2-methyl-1,3-dioxolane	16	100	6.3	95	0.88[k]	**a**
21	2-octanone	32	100	3.1	82		
22	3-octanone	100	61	0.61	40		
23	4-octanone	100	10	0.10	9		

[a] The reagent ion *m/z* 43 and proton-transfer products except *m/z* 81 are not reported; see text. [b] Also $C_2H_2DO^+$ for deuterated ethanol. [c] Abundances relative to the major ion excluding *m/z* 43. [d] Reference 9c unless otherwise noted. In cases of mixtures, the first ion mentioned was most prominent. [e] Complete spectrum presented in Figure 1. [f] Reference 9d. [g] The oxiranyl cation or ion $^+CH_2CH{=}O$. [h] Additional peaks displayed in this spectrum are *m/z* 136 (3), 96 (5), 82 (16), 70 (38), 46 (16), and 42 (12). [i] Value is for $[(CHO^+) + (CDO^+):(CO^+)]$. [j] **b**′ is deuterated **b**. [k] Reference 9g.

Table II. Selected Sequential Parent Spectral Data[a] Represented as Parent Ion → 43 → Products

		products[b] (*m/z*)			
precursor	parent ion	81	111	[111:81]	% **a**
10	72	14	100	7.1	96
	44	11	100	8.3	98
19	73	100			none
	45	100			none
	44	14	100	7.1	96
20	87	9	100	9.1	99
	73	100			none
	58	11	100	9.1	99
	45	100			none
21	85	100	71	0.71	43
	71	15	100	6.7	95
	58	17	100	5.9	94
23	71	100	1.5		none
	58	12	100	8.3	98

[a] The reagent ion *m/z* 43 and proton-transfer products except *m/z* 81 are not reported. [b] Abundances relative to the major ion excluding *m/z* 43.

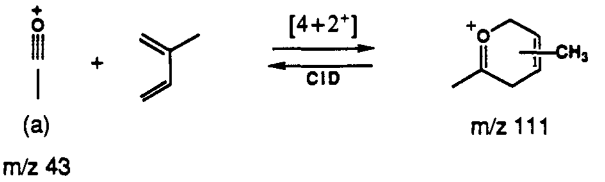
parent ion in Q1, setting Q3 to select a specific fragment ion or ion/molecule product of interest generated in Q2, and then scanning Q5 to record the spectrum of products generated from this ion in Q4. To record a familial scan, Q3 was set to select *m/z* 43 while both Q1 and Q5 were scanned to produce a three-dimensional output. Ionization was accomplished by 70-eV electron impact. The collision energy, calculated as the voltage difference between the ion source (grounded) and the collision quadrupole, was typically near 0 eV (nominal quadrupole offset +1 V) for ion/molecule reactions and 10 eV for CID, in both MS^2 and MS^3 experiments.

1,3-Dithiolane (**24**) was prepared according to a reported method.[18] All other compounds were commercially available and used without further purification.

Results and Discussion

The $C_2H_3O^+$ Case. A. Reaction with Isoprene. Considering the unsaturated character of isomers **a**–**c**, cycloaddition would seem to be a good choice of a structurally diagnostic reaction, and isoprene was selected as the neutral reagent. A variety of precursor compounds (**1**–**23**, see Table I) were used to generate ions of *m/z* 43. The product spectral data obtained by subjecting these ions to ion/molecule reactions with isoprene are given in Table I. For comparison, the ratio *m/z* 29:*m/z* 28 obtained in previous high-energy CID experiments and the predominant $C_2H_3O^+$ isomers suggested from these ratios are also listed. While there is an approximate correlation between the CID and ion/molecule results, the latter appear to provide more precise data, as is now discussed.

Scheme I



Since ab initio calculations show the *acetyl cation* (**a**) to be by far the most stable $C_2H_3O^+$ ion,[12] the CID results therefore led to the assignment of **a** as the predominant *m/z* 43 ion generated by simple α-cleavage processes from compounds containing the acetyl group.[9] Ion *m/z* 43 generated by 70-eV EI from methyl acetate (**1**), and therefore expected to have structure **a**, was mass selected and reacted with isoprene at near 0-eV collision energy. The product spectrum (Figure 1a) displays an abundant adduct at *m/z* 111, as well as the proton-transfer product, protonated isoprene, which occurs at *m/z* 69, and several other product ions of low abundance mainly at *m/z* 67, 81, 95, 135, 137, and 149. The origin of these ions was established by recording the product spectrum for the isobaric *m/z* 43 ion, $C_3H_7^+$ (supplementary material, Figure S-1), generated from *n*-nonane. This spectrum displays no adduct at *m/z* 111 but shows the expected protonated isoprene ion at *m/z* 69, as well as all the additional ions observed in the spectrum for precursor **1** in similar abundance ratios. It is therefore concluded that this set of ions arises after proton transfer and is due to reactions between protonated and neutral isoprene. The same set of product ions was observed in the ion/molecule reaction of the isoprene molecular ion with neutral isoprene.[1j,5c] For the data presented in Table I (and also Table II), only the relative abundance of *m/z* 81 is reported, the other

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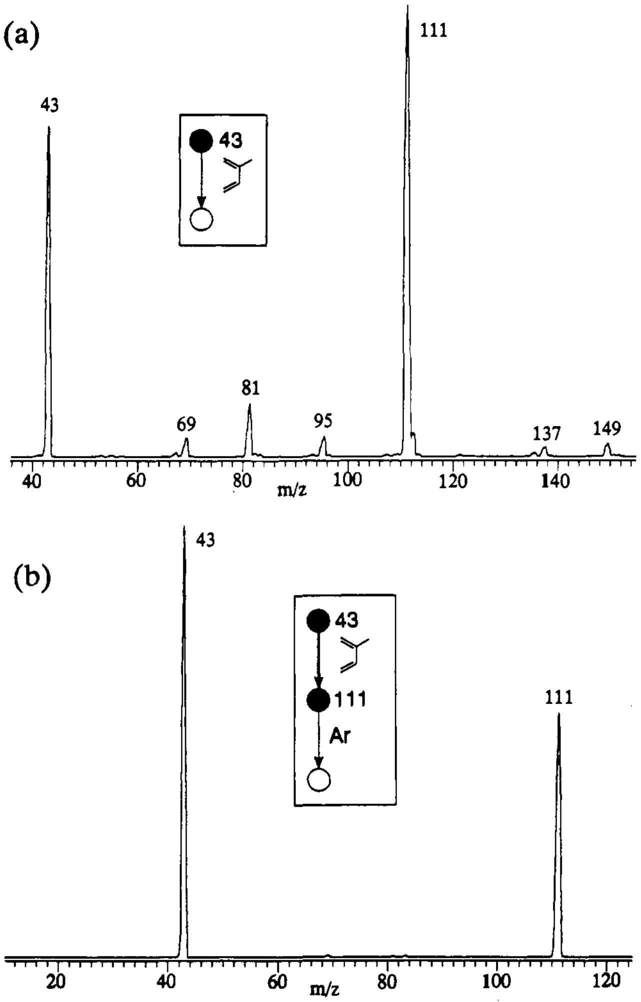


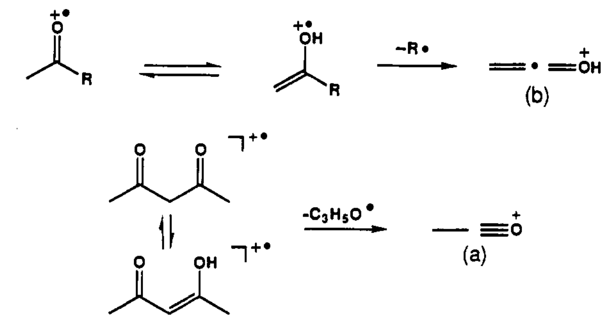
Figure 1. (a) Ion/molecule reaction product spectrum (isoprene reagent) for *m/z* 43 ions generated from methyl acetate (**1**), showing the [4 + 2$^+$] cycloadduct at *m/z* 111 and proton-transfer products and (b) MS^3 sequential product spectrum for the reaction *m/z* 43 → *m/z* 111, showing its retro Diels–Alder CID fragmentation.

proton-transfer products being omitted since little variation in their relative abundance was observed throughout this study.

Clearly the acetyl cation (**a**) reacts with isoprene by two competitive channels: formation of the adduct of *m/z* 111 and proton transfer[19] to generate the other ions observed. The first reaction dominates the product spectrum, and it is ascribed to [4 + 2$^+$] Diels–Alder cycloaddition (Scheme I). Evidence for this mechanism is found by recording the sequential product spectrum for the reaction sequence *m/z* 43 → *m/z* 111 → products (Figure 1b). This MS^3 spectrum is remarkably simple, showing *m/z* 43 as the almost exclusive fragment of the *m/z* 111 adduct ions generated from *m/z* 43. The reaction sequence displayed in this spectrum is a Diels–Alder cycloaddition followed by the collision-induced retro Diels–Alder process. A detailed study of the cycloaddition reactions of acylium ions is reported elsewhere.[20]

O-Protonated ketene (**b**) was studied by generating *m/z* 44 from the molecular ion of ethanol-OD (**13**) in the expectation that this would yield the O-dueterated version of **b** (viz., **b′**) generated by a sequential fragmentation process involving loss of an unlabeled hydrogen atom and unlabeled molecular hydrogen. CID in the kiloelectronvolt regime has been interpreted in these terms[9d] because of a high *m/z* 28:*m/z* 29 ratio for this ion. The ion/molecule product spectrum of **b′** in reaction with isoprene (Table I) fails to display any cycloadduct at *m/z* 112. Instead, proton- and deuterium-transfer reactions predominate, as established by comparison with Figure 1. On the other hand, fragmentation of the O-deuterated ethanol molecular ion by loss of a hydrogen atom and HD is expected to generate the acetyl cation, and this is confirmed by the fact that the product spectrum of *m/z* 43 displays an abundant *m/z* 111 adduct (Table I).

Scheme II



The *oxiranyl cation* (**c**) is the predominant *m/z* 43 ion proposed in CID experiments and metastable peak shape analysis[9d] to be formed from 1,3-dichloro-2-propanol (**15**). In agreement with this, the isoprene ion/molecule results show formation in low abundance of the adduct at *m/z* 111, which indicates predominant formation of ions other than the acetyl cation (Table I). Reaction with methylanisoles (see below) clearly shows predominant formation of ion **c** from this precursor. Reaction of the oxiranyl cation (**c**) with isoprene is therefore dominated by proton transfer, and the small amount of adduct observed could either be a result of a limited degree of reaction of ion **c** with isoprene or, alternatively, be due to reaction of a small amount of acetyl ion present in a mixture. The acetyl cation could be generated in the ion source or by the isomerization **c** → **a** upon collision with the neutral reagent. Using data taken from sequential product spectra (see below), we concluded that ion **c** does not react with isoprene to any measurable extent nor does it isomerize to **a** upon collision. These facts indicate that the *m/z* 111 adduct displayed here is due to reaction of approximately 20% of source-generated acetyl cations, the presence of which was not recognizable in the high-energy CID experiments,[9c] but is indicated by metastable peak shape analysis.[9d] The lack of cycloaddition reactivity of the oxiranyl cation (**c**) is supported by the observation that the oxonium ion $H_5C_2O^+{=}CH_2$, which is structurally related to **c**, does not display any cycloaddition adduct in its product spectrum with isoprene. The spectrum is dominated by the proton-transfer products.[20]

These results of ion/molecule reactions with isoprene show that the acetyl cation (**a**) can be differentiated easily from its isomers **b** and **c** on the basis of adduct formation at *m/z* 111, which is attributed exclusively to reaction of the acetyl cation. No such simple differentiation is possible between **b** and **c**, both ions apparently undergoing mainly proton-transfer reactions with isoprene. Ion *m/z* 81 is the most abundant product of the proton-transfer reactions, and precursor **2** displays the highest ratio *m/z* 111:*m/z* 81 of 10. If a ratio (r) of 10 is attributed to the pure acetyl ion, its composition in mixtures can be estimated using the equation $\%\ a = 100r/[r + (1 - 0.1r)]$, the results for which are listed in Table I. These results show systematic trends with differences in structure and functionality in the precursor molecule affecting the *m/z* 43 isomeric composition as discussed below.

B. Correlations with Precursor Structure. Precursors **1**–**8** contain the acetyl group and are therefore expected to generate mainly the acetyl cation. Each displays a *m/z* 111:*m/z* 81 ratio between 3.7 and 10, which corresponds to 85–100% of isomer **a** by the above relationship. These small variations can be explained in terms of the extent of enolization of the molecular ion[9d] of the precursor, fragmentation of the ionized enolic form yielding O-protonated ketene (**b**), as shown in Scheme II. This explanation might appear to be complicated by the observation that enolic ions usually fragment to acylium ions, by a process that involves prior

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[19] Reactive collisions between 1,3-butadiene and $C_2H_3O^+$ ions generated from acetone and methanol have been reported. Apparently, a combination of fragmentation and proton-transfer reactions occurred: Jalonen, J. *J. Chem. Soc., Chem. Commun.* **1985**, 872.

[20] Eberlin, M. N.; Cooks, R. G. Submitted for publication.

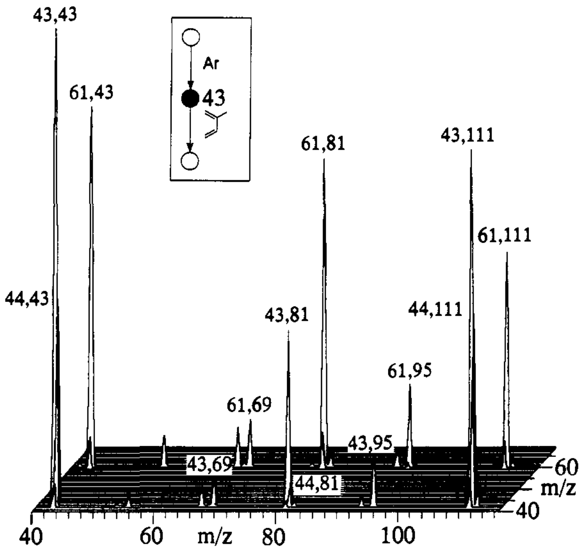
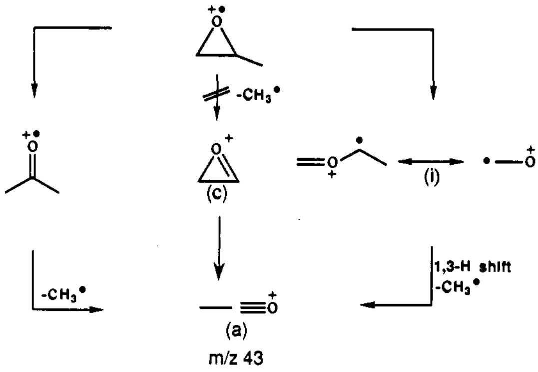


Figure 2. Three-dimensional MS^3 familial spectrum for glycerol acquired by selecting ions m/z 43 as the intermediate. The angled axis displays the parents of m/z 43 ions while the horizontal axis displays the ion/molecule products of these CID-generated m/z 43 ions upon reaction with isoprene. Mass assignments refer to the initial and final product ions.

Scheme III



ketonization.[21,22] However, considering that enolic ions are more stable than the keto forms, and that the barrier to interconversion is high,[21] the enolic ions formed by enolization must contain high internal energies. It is therefore likely that at least some of these high internal energy enolic ions will fragment to form **b**. This can explain the fragmentation behavior different from that observed for enolic ions obtained with lower internal energies by other methods,[22] or by fragmentation,[21] as is the case for enolic ions formed from ionized octanones (see below).

Among compounds **1–8**, acetaldehyde (**4**) yields m/z 43 ions which display the smallest amount of isomer **a** and hence, by inference, the greatest proportion of **b** (15%). This is followed by acetone (**3**, 7%), acetyl chloride (**5**, 5%), acetic anhydride (**7**, 3%), *N*-methylacetamide (**8**, 3%), methyl acetate (**1**, 2%), and acetic acid (**6**, 1%). Acetylacetone (**2**) gives the purest acetyl ion, which is consistent with the fact that both the keto and the enolic forms fragment by simple α-cleavage to give acetyl cations (Scheme II). High-energy CID results have shown approximately 5% of ion **b** cogenerated with ion **a** for several acetyl precursors.[9e] The present results are in general agreement with the earlier data, but they provide more precise information. Measurements on metastable ions indicate 1% of **b** for acetone and 2.7% for acetaldehyde,[9d] which is consistent with the expectation that enolization will be reduced in the ions of low-internal energy sampled in these experiments.

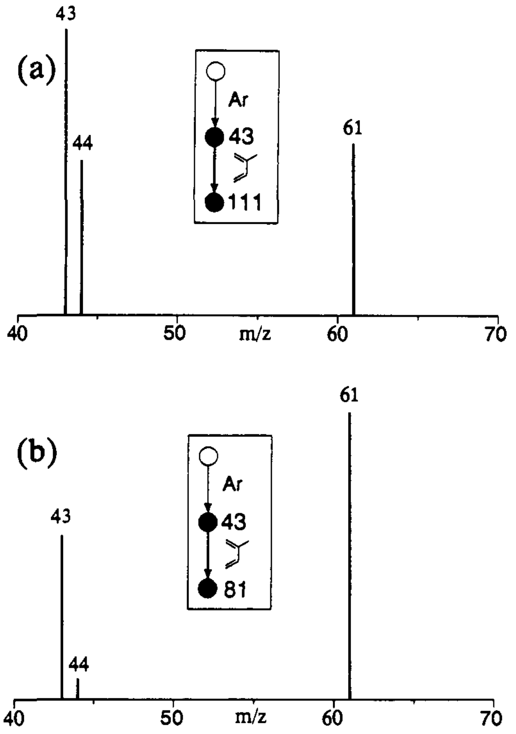


Figure 3. MS^3 sequential parent spectra extracted from the familial spectrum displayed in Figure 2, showing the precursors which react via m/z 43 to form (a) m/z 111 and (b) m/z 81.

Propylene oxide (**9**) could generate the oxiranyl cation (**c**) by loss of a methyl radical in a simple α-cleavage process, but its ion/molecule product spectrum shows the presence of acetyl cation (**a**) in approximately 90% abundance. This result can be interpreted (Scheme III) as a consequence of isomerization to the acetone molecule ion prior to fragmentation or isomerization to ion **i**, in a ring-opening process similar to that proposed for ionized oxirane.[23] Isomerization **c** → **a** prior to or during collision was eliminated by acquiring MS^3 spectra described below. The minor (10%) isomer was not identified.

Ethyl vinyl ether (**10**), cyclopentanone (**11**), diethyl ether (**12**), ethanol (**14**), and glycerol (**16**) are precursors which do not contain acetyl groups and so cannot form the acetyl cation by α-cleavage processes. Nevertheless, the m/z 111:m/z 81 ratios obtained indicate moderate to high percentages of acetyl cations. On the basis of the results for ethanol-OD (**13**), it is clear that unlabeled ethanol (**14**) should generate a mixture of acetyl and protonated ketene ions. The ion/molecule data for the m/z 43 ions generated from ethanol (Table I) suggest a ratio of approximately 65% of the acetyl ion (**a**) and 35% of protonated ketene ion (**b**). It is interesting to note that this estimate is very close to the ratio m/z 43:m/z 44 (approximately 2:1) displayed in the mass spectrum of ethanol-OD.[24]

Sequential product spectra for ethyl vinyl ether (**10**) show that both the molecular ion (m/z 72) and the ethylene elimination fragment (m/z 44) form the acetyl cation in high abundances (Table II). The molecular ion can fragment to the acetyl ion by a mechanism involving a 1,2-hydrogen shift in the vinyl group followed by ethyl radical loss.[25] Metastable ion[26] and CID[27]

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[21] Schwarz, H. *Adv. Mass Spectrom.* **1985**, *10A*, 13.

[22] Turecek, F. *J. Chem. Soc., Chem. Commun.* **1984**, 1374.

[23] Bouma, W. J.; MacLeod, J. K.; Radom, L. *J. Chem. Soc., Chem. Commun.* **1978**, 724.

[24] The 70-eV EI mass spectrum of ethanol-OD shows the following ions in the molecular ion region, m/z (relative abundance): 48(3), 47(30), 46(100), 45(54), 44(14), 43(27), 42(6), and 41(2).

[25] Budzikiewicz, H.; Djerassi, C.; Williams, D. H. *Mass Spectrometry of Organic Compounds*; Holden-Day: San Francisco, 1967; p 234.

[26] Holmes, J. L.; Terlouw, J. K. *Can. J. Chem.* **1975**, *53*, 2676.

[27] Van de Sande, C. C.; McLafferty, F. W. *J. Am. Chem. Soc.* **1975**, *97*, 4613.

[28] Hass, J. R.; Cooks, R. G.; Elder, J. F., Jr.; Bursey, M. M.; Kingston, D. G. *Org. Mass Spectrom.* **1976**, *11*, 697.

experiments show the fragment ion *m/z* 44 to be ionized vinyl alcohol, and its mechanism of fragmentation to yield *m/z* 43 has been established to occur by a 1,2-hydrogen shift to yield the distonic ion, ionized hydroxy methyl carbene, followed by loss of a hydrogen atom to form the acetyl cation.[21]

Glycerol (**16**) forms *m/z* 43 ions of which 65% are acetyl cations. Two independent fragmentation processes, occurring via ions *m/z* 61 and *m/z* 44, lead to formation of *m/z* 43 ions, as demonstrated by recording the CID product spectra of these precursors. It has been proposed that the ion *m/z* 44, vinyl alcohol, fragments to the acetyl cation (**a**) while *m/z* 61 ($C_2H_5O_2^+$) fragments to the oxiranyl cation (**c**) by loss of water.[9c] The three-dimensional familial spectrum (Figure 2) was recorded for glycerol to check the mechanism of *m/z* 43 formation. In this spectrum, the angled axis displays the parents which give *m/z* 43 by CID, and it confirms that they are principally ions *m/z* 44 and *m/z* 61, while the horizontal axis displays the ion/molecule products arising upon reaction between isoprene and the variously generated *m/z* 43 ions. It is evident from the 3D plot that the acetyl ion is a predominant contributor to *m/z* 43 formed from all precursors. For instance, *m/z* 44 gives rise to *m/z* 43 ions which display little tendency to generate products of *m/z* 81 compared to their tendency to generate *m/z* 111. Because of the large abundance of *m/z* 43, this is more easily seen by extracting sequential parent spectra from the familial scan. The sequential parent spectra,[10] showing firstly those precursors which react via *m/z* 43 to form *m/z* 111 and also those which react via *m/z* 43 to form *m/z* 81, are presented in Figure 3. These spectra record subsets of the *m/z* 43 ion population selected on the basis of chemical reactivity; Figure 3a records the acetyl cation population as recognized through the cycloaddition reaction with isoprene, while Figure 3b records those *m/z* 43 ions which undergo proton transfer. As we have seen, this population includes ions **b** and **c** as well as the $C_3H_7^+$ isobar. Both spectra identify the parents of these specific forms of *m/z* 43.

The glycerol-derived ion, *m/z* 44, produces a *m/z* 43 ion which reacts with isoprene to give a very abundant *m/z* 111 adduct and little of the proton-transfer product at *m/z* 81 (10:1); this shows that it indeed fragments to form the acetyl cation exclusively, as proposed above. However, *m/z* 61 generated from glycerol by CID shows a relatively high abundance of both *m/z* 111 and *m/z* 81 (1.5:1), demonstrating that this ion fragments to form a mixture of *m/z* 43 isomers constituted of approximately 40% of acetyl cations. Together, the two precursor ions yield 65% acetyl cations. The remaining 35% of the *m/z* 43 ions cannot be assigned using isoprene, but the use of methylanisoles (see below) shows them to be oxiranyl cations (**c**).

High-energy CID results for α-bromoacetaldehyde[9e] have led to the attribution of a mixture of 85% acetyl and 15% oxiranyl cations to the *m/z* 43 fragment. However, the product spectrum of the ion *m/z* 43 generated from the chlorine analogue, α-chloracetaldehyde (**17**), displays a low-abundance adduct (Table I), which indicates only an approximately 20% contribution of the acetyl cation. Apparently, cyclization to **c** occurs much more readily for the chloro compound.

Tetrahydrofuran (**18**) also shows a low percentage of the acetyl cation. High-resolution measurements[29] on its *m/z* 43 fragment show 26% of $C_2H_3O^+$, 57% of the isobaric ion $C_3H_7^+$, and 17% of $^{13}CC_2H_6^{\bullet+}$. The fact that ion/molecule reactions with isoprene give 22% of acetyl cation indicates that this ion is the main constituent of the $C_2H_3O^+$ ion subpopulation of *m/z* 43 formed from **18**.

The results for the two 1,3-dioxolanes (**19**, **20**) are consistent with the known unimolecular dissociations of these compounds,[30] the presence of the 2-methyl substituent allowing formation of **a** from the molecular ion of **20** (95%) by a favorable route, loss of a hydrogen atom and ethylene oxide. Less favorable processes can be expected to be involved for the formation of **a** from **19** (65%). It is interesting to note that high-energy CID experiments on *m/z* 43 formed from **19** show a very high *m/z* 29:*m/z* 28 ratio (10.6), a result which led to the conclusion that the oxiranyl cation (**c**) is the major *m/z* 43 constitutent.[9g] Although the formation of other isomers was considered, this high ratio suggested a very low abundance of the acetyl cation, but this is not the case, at least under the conditions used in the present experiments.

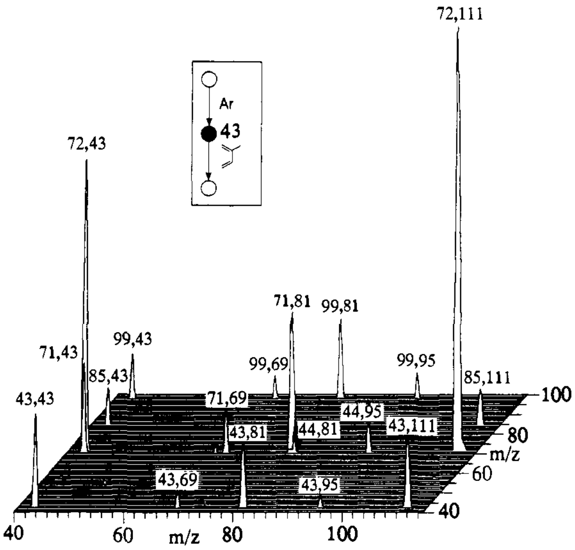

Figure 4. Three-dimensional MS^3 familial spectrum for 3-octanone (**22**) acquired by selecting ions *m/z* 43 as the intermediate. The angled axis displays the parents of *m/z* 43 ions while the horizontal axis displays the ion/molecule products of these CID-generated *m/z* 43 ions upon reaction with isoprene. Mass assignments refer to the initial and final product ions.

Sequential product spectra were applied to further characterize the ion chemistry of the two 1,3-dioxolanes. They showed that *m/z* 43 has three main parents in the case of compound **19**, viz., ions *m/z* 44, 45, and 73, and four main parents for **20**, the ions *m/z* 45, 58, 73, and 87. They also show that *m/z* 45 and 73 for both precursors fragment by CID to give *m/z* 43 which forms no cycloadduct at *m/z* 111 with isoprene (Table II). The other parent ions fragment to give *m/z* 43 ions composed mainly of the acetyl cation. The fact that the ion *m/z* 43 formed from *m/z* 73 and 45 shows no adduct formation at all is significant because it confirms that the oxiranyl isomer (**c**), the most likely isomer formed from these precursors,[9g] does not react detectably with isoprene by cycloaddition. It is therefore concluded that the adduct formed from *m/z* 43 ions generated from 1,3-dichloro-2-propanol (**15**) is not a result of reaction to a small extent of isomer **c** with isoprene (see previous discussion on this precursor).

We now turn to a dissociation of the three isomeric octanones, **21**, **22**, and **23**. Both $C_2H_3O^+$ as well as the isobar $C_3H_7^+$ may comprise the *m/z* 43 fragments for these ketones. 2-Octanone (**21**), as expected, displays acetyl cation formation to the greatest extent, and the contribution decreases as one moves to 3-octanone (**22**) and 4-octanone (**23**). The presence of a significant fraction (40%) of the acetyl cation in the *m/z* 43 population generated from 3-octanone is interesting, considering the position of the carbonyl group. In order to establish the nature of the *m/z* 43 mixture generated from each of its several parent ions produced from ionized **23**, a familial spectrum (Figure 4) was recorded. As was the case for glycerol (Figure 2), the angled axis displays the parents of *m/z* 43 while the horizontal axis displays the ion/molecule products resulting from reaction with isoprene of *m/z* 43 ions derived by CID from the indicated precursor. The sequential parent spectrum showing those precursors which react via *m/z* 43 to form *m/z* 111 and *m/z* 81 were again extracted from the familial spectrum and are presented in Figure 5, in order to represent in compact form the precursors of the acetyl cation (Figure 5a) and other *m/z* 43 ions (Figure 5b).

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[29] Smakman, R.; de Boer, Th. J. *Org. Mass Spectrom.* **1968**, *1*, 403.

[30] (a) Audier, H.; Fêtizon, M.; Gramain, J.-C.; Schalbar, J.; Waegel, B. *Bull. Soc. Chim. Fr.* **1964**, 1880. (b) Marshall, J. T. B.; Williams, D. H. *Tetrahedron* **1967**, *23*, 321.

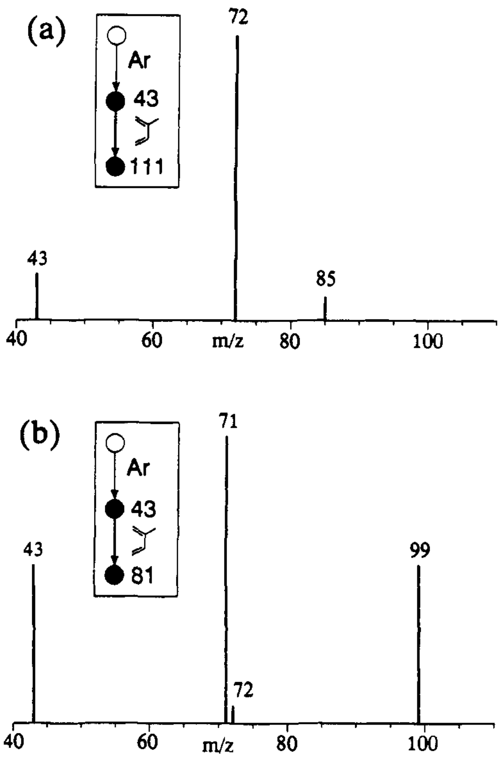
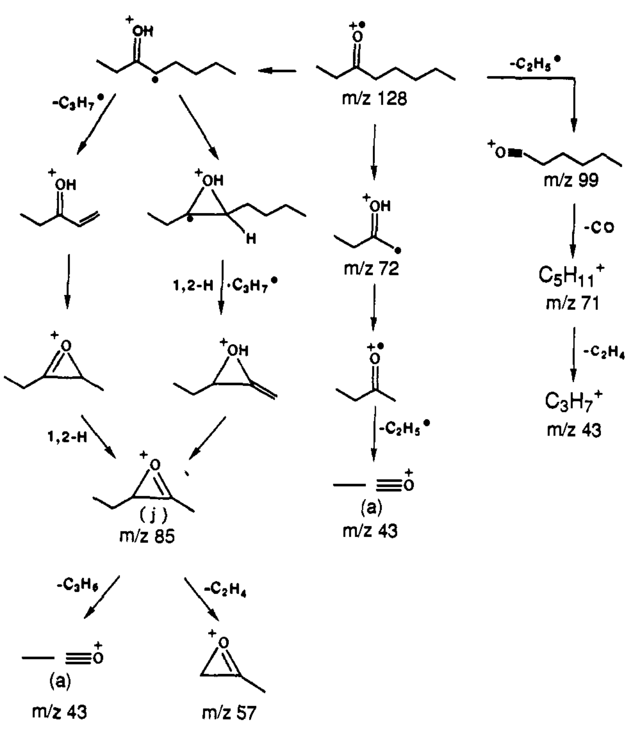


Figure 5. MS^3 sequential parent spectra extracted from the familial spectrum displayed in Figure 4, showing the precursors which react via m/z 43 to form (a) m/z 111 and (b) m/z 81.

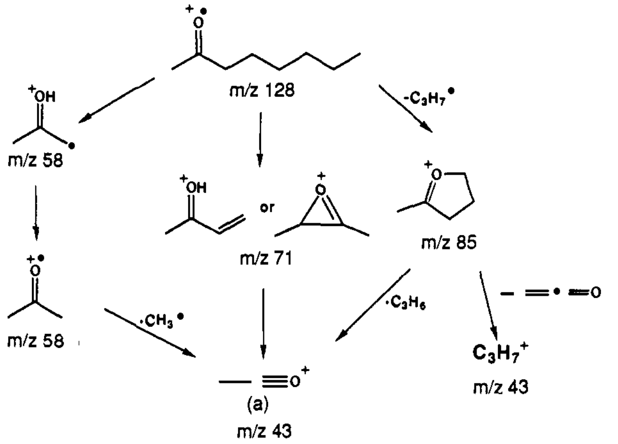
We now consider each of the precursors of m/z 43 for 3-octanone in turn. Ion m/z 43 formed by CID from m/z 99 reacts with isoprene to form an abundant m/z 81 but fails to yield a cycloadduct at m/z 111, which proves that the population does not include acetyl cations and suggests that the $C_3H_7^+$ isobar is the only m/z 43 ion formed from this parent. This result is expected, considering that m/z 99 is the n-$C_5H_{11}C{\equiv}O^+$ acylium ion and that it fragments by the mechanism shown in Scheme IV. Scheme IV also shows the other mechanisms discussed below. The analogous result for m/z 71 also indicates predominant formation of $C_3H_7^+$, confirming its alkyl composition. Direct loss of ethyl from the enolic ion at m/z 72, generated by the McLafferty rearrangement, is expected to form the O-protonated ketene ion (**b**). However, its product spectrum shows an abundant m/z 111 adduct, which implies that the McLafferty product undergoes ketonization to the 2-butanone molecular ion before fragmenting to the acetyl cation (Scheme IV). Analogous behavior has been shown to occur for the enol of acetone.[31] Even the small contribution of m/z 72 to Figure 5b is consistent with the acetyl structure since, as shown in Figure 1, some proton transfer is expected to occur for this isomer.

The fragment ion m/z 85 is an unexpected intermediate known to connect the 3-octanone molecular ion and m/z 43.[32] The m/z 43 ion produced by this fragmentation route reacts with isoprene to yield the m/z 111 adduct, indicating it to be the acetyl ion. This information allows one to address the problem of the intriguing mechanism of m/z 43 formation from m/z 85,[32] which has itself been postulated to be the product of reciprocal hydrogen transfer, i.e., O-protonated ethyl vinyl ketone (Scheme IV). Fragmentation of the authentic protonated ketone to yield m/z 43 has been reported,[33] and this corroborates the assignment. The CID product spectrum of m/z 85 (not shown) displays m/z 57 and m/z 43 as the two major fragments in a 4:1 proportion, respectively. The MS^3 data show that the fragmentation of m/z 85 to yield m/z 43 leads to the acetyl cation rather than the other $C_2H_3O^+$ isomers or the isobar $C_3H_7^+$. Therefore, the cyclic structure **j** (Scheme IV) is proposed for those ions of m/z 85 which fragment to m/z 57 and the acetyl cation (m/z 43) by neutral losses of C_2H_4 and C_3H_6, respectively. Two processes (Scheme IV) are visualized for formation of ion **j**: (i) reciprocal hydrogen transfer in the molecular ion leading to cyclization before fragmentation by loss of the propyl radical with subsequent intramolecular proton transfer or (ii) isomerization of O-protonated vinyl ethyl ketone via intramolecular proton transfer and cyclization, followed by a 1,2-hydrogen shift.

Scheme IV



Scheme V



Sequential product scans were also recorded for several precursors of m/z 43 in 2- and 4-octanone, and the resulting spectral data are included in Table II. The fragment ion m/z 58 for 2-octanone displays in its spectrum a high m/z 111:m/z 81 ratio, which again indicates generation of the acetyl cation via prior ketonization (Scheme V). The reciprocal hydrogen transfer fragment (m/z 71) also yields a m/z 43 fragment which is mostly the acetyl cation. In analogy to the behavior the homologous ion m/z 85 for 3-octane, a cyclic structure (Scheme V) is likely for m/z 71, which would then fragment to the acetyl cation by C_2H_4 loss. The final and simplest fragmentation route proceeds by

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(31) Turecek, F.; McLafferty, F. W. J. Am. Chem. Soc. **1984**, 106, 2525.

(32) O'Lear, J. R.; Wright, L. G.; Louris, J. N.; Cooks, R. G. Org. Mass Spectrom. **1987**, 22, 348.

(33) Griffin, L. L.; Holden, K.; Hudson, C. E.; MacAdoo, D. J. Org. Mass Spectrom. **1986**, 21, 175.

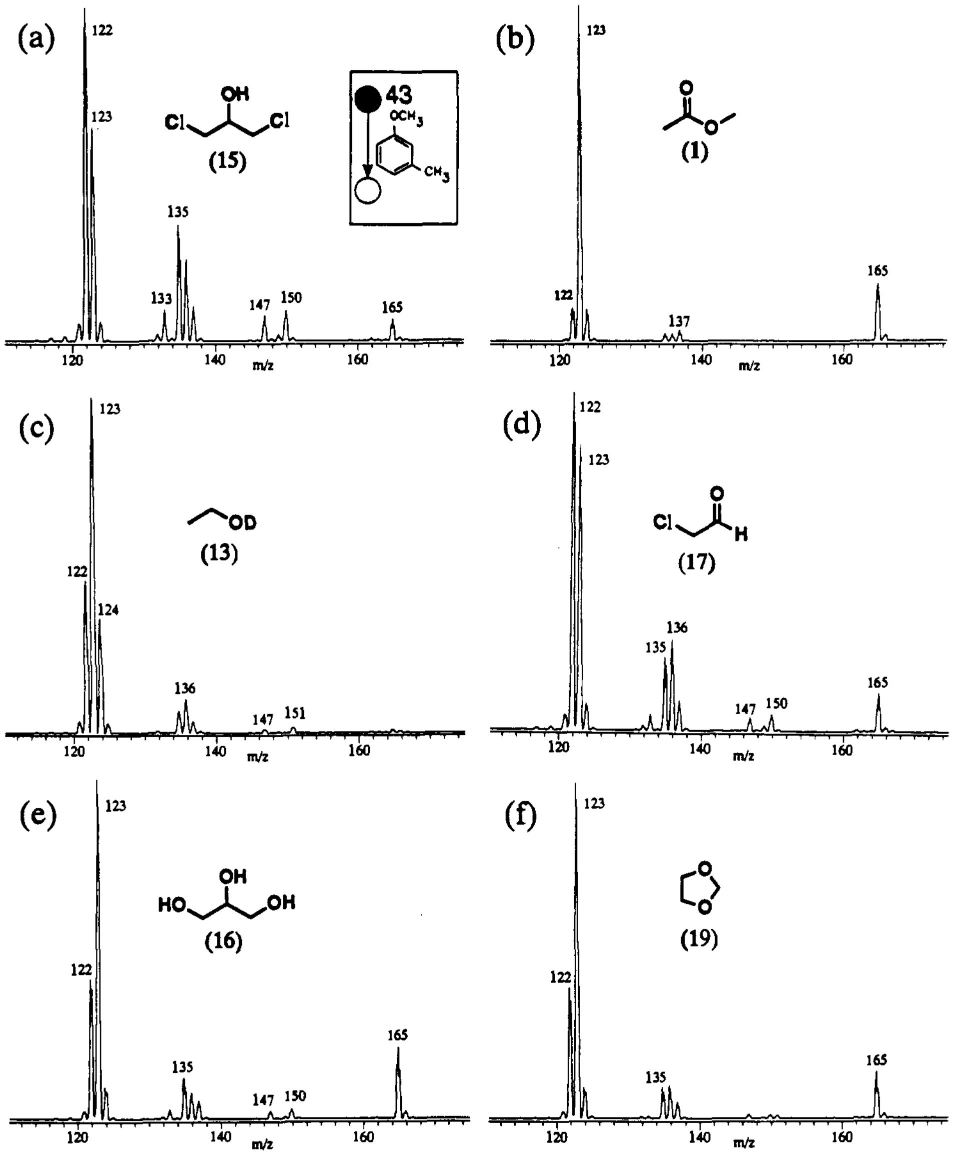
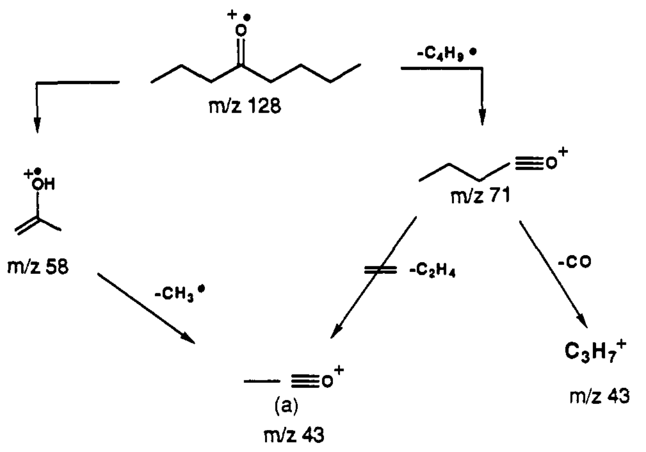


Figure 6. Ion/molecule reaction product spectrum (*m*-methylanisole reagent) for m/z 43 generated from (a) 1,3-dichloro-2-propanol (**15**), (b) methyl acetate (**1**), (c) ion m/z 44 generated from ethanol-OD (**13**), (d) α-chloroacetaldehyde (**17**), (e) glycerol (**16**), and (f) 1,3-dioxolane (**19**).

Scheme VI

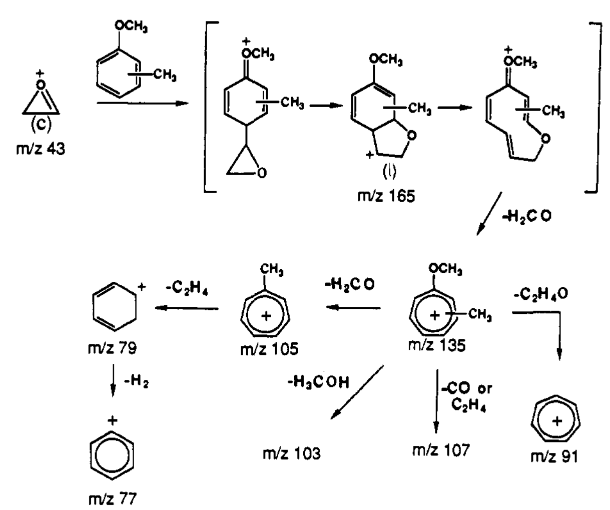


propyl radical loss to give the cyclic oxonium ion m/z 85, the most abundant intermediate ion that connects the 2-octanone molecular ion and the m/z 43 fragment.[32] This precursor gives a mixture of ions at m/z 43 of which the acetyl cation constitutes approximately 45%. The other ions comprise the isobar $C_3H_7^+$, formed by loss of neutral ketene.

Turning to 4-octanone, the double McLafferty rearrangement product, m/z 58, also gives mostly the acetyl cation, which indicates that ketonization also occurs for this ion (Scheme VI). Ion m/z 71 could fragment to m/z 43 by loss of either CO or ethene to give $C_3H_7^+$ or the acetyl cation, respectively (Scheme VI). The sequential product spectrum for this ion clearly indicates that the CO loss process occurs exclusively.

C. Ion Interconversion and Internal Energy Effects. The relevance of these effects to the above results was checked by performing the following MS^3 experiments: Ion source generated m/z 43 ions from precursors **1**, **14**, **15**, and **22** were selected in Q1, collided with argon in Q2 at several collision energies varying from 2 to 100 eV, mass selected again in Q3, and further reacted with isoprene in Q4, while Q5 was scanned to acquire the ion/molecule product spectra. In the second quadrupole, the m/z 43 ions were subjected to collision with argon at such a pressure as to cause an approximately 70% reduction in the ion beam intensity. In principle, these conditions could result in activation or deactivation of the surviving m/z 43 ions. No significant variation in the relative ratio of ion/molecule reaction products was observed, from which one can conclude that ion internal energy effects on the relative extent of the proton transfer and cycloaddition reactions of the m/z 43 ions are negligible. These results show also that no significant isomer interconversion occurs without being followed by rapid fragmentation, and hence isomerization

Scheme VII



is not expected to occur under the much milder conditions used to perform the ion/molecule reactions.

D. Reaction with Methylanisoles. Since reaction with isoprene does not allow distinction between isomers **b** and **c**, several other reagent gases (ethylene oxide, allene, 1,3-dioxolane, ethyl vinyl ether, benzene, thiophene, anisole, and methylanisoles) were tested as candidates for achieving such a distinction. The best structural distinction was achieved by reactions of the *m/z* 43 ions with methylanisoles, and therefore these results are presented below in detail.

***m*-Methylanisole.** 1,3-Dichloro-2-propanol (**15**) is believed from earlier work to yield the oxiranyl cation (**c**), and the ion/molecule reactions with isoprene show predominance of an isomer (or isomers) other than acetyl. The spectrum of the ion/molecule products arising from reaction between *m*-methylanisole and *m/z* 43 derived from this compound (Figure 6a) shows the intact adduct in low abundance at *m/z* 165 and a relatively abundant *m/z* 135 product. The latter formally corresponds to CH^+ addition to the neutral reagent, a type of reaction which has been observed to occur between aromatic compounds and several ionic species.[17a,33] Formation of *m/z* 135 can be rationalized as a result of fragmentation of the adduct by loss of formaldehyde. A mechanism can be proposed for this process (Scheme VII) in which a favorable fused-ring intermediate (l) is involved only for the *oxiranyl cation* (**c**) leading to formation of the stable *m*-methylmethoxytropylium ion. Such a stable intermediate (l) cannot be postulated for **a** or **b**, for which four-membered cyclic intermediates would be involved in similar processes. The sequential product spectrum for the reaction *m/z* 43 → *m/z* 135 (Figure 7a) displays fragmentation behavior that is in agreement with the proposed ion structure, as shown in Scheme VII. Note also the similarity of this spectrum to that of α-methoxy-*p*-xylene,[34] the molecular ion of which is expected to fragment by hydrogen atom loss to form the isomeric *p*-methylmethoxytropylium ion. This result leads to the conclusion that the *m/z* 43 ions formed from 1,3-dichloro-2-propanol (**15**) are composed of 80% of the oxiranyl cation (**c**) while the results of ion/molecule reaction with isoprene (Table I) shows that the acetyl cation constitutes approximately 20% of the *m/z* 43 composition.

The *acetyl cation* (**a**), generated from methyl acetate, shows a very different spectrum upon reaction with *m*-methylanisole (Figure 6). Ion *m/z* 135 is generated in very low abundance while the intact adduct (*m/z* 165) is quite abundant. Another very distinctive feature is the predominance of the proton-transfer reaction product (*m/z* 123) over the charge-exchange product (*m/z* 122), indicated by the respective abundance ratio of 10:1. On the basis of these results, the small amount of adduct at *m/z* 165 displayed in the product spectrum of precursor **15** (Figure 6a) can be attributed mainly to reaction of acetyl cations (**a**) cogenerated with ion **c** (20%). Taking this into account, approximately 45% of *m/z* 123 in Figure 6a derives from **a**, giving a ratio *m/z* 123:*m/z* 122 of 1:3.5 for ion **c**.

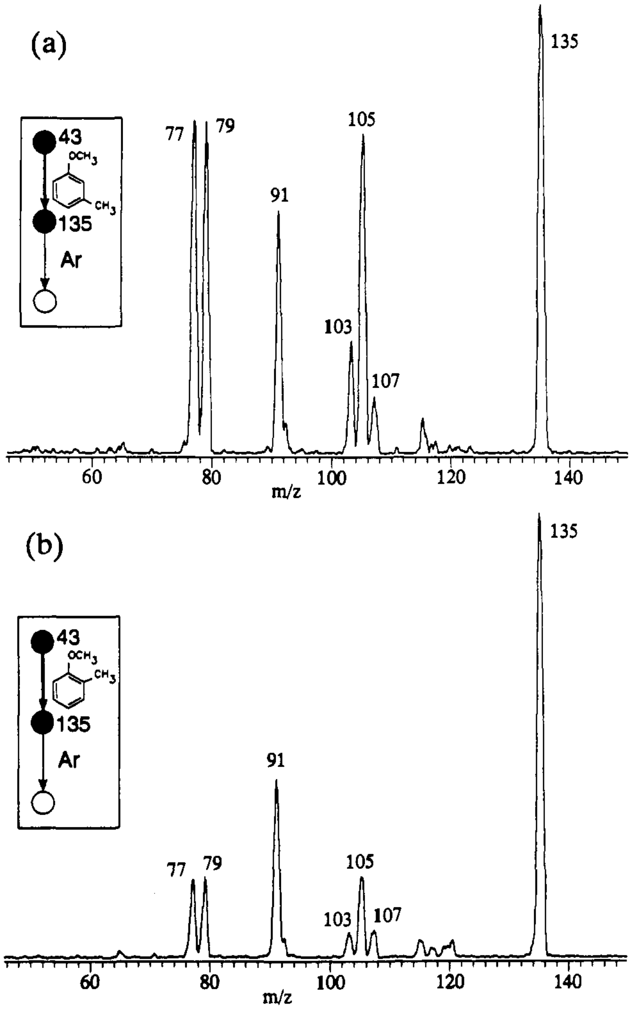


Figure 7. MS^3 sequential product spectra on ion *m/z* 135 generated by reaction of ion *m/z* 43 from 1,3-dichloro-2-propanol (**15**) with (a) *m*-methylanisole and (b) *o*-methylanisole showing CID fragmentation indicative of methylmethoxytropylium ions.

The product spectrum for *O-protonated ketene*, represented by the *m/z* 44 ion (**b'**) formed from ethanol-OD (Figure 6c), includes an ion of low abundance at *m/z* 135 as well as a ratio of *m/z* 123 (plus *m/z* 124):*m/z* 122 of 3:1, which is intermediate compared to the values for **a** (10:1) and **c** (1:3.5). The adduct at *m/z* 166 is practically absent. These features, especially the ratio *m/z* 123:*m/z* 122, allow clear distinction of isomers **a**, **b**, and **c**, and the results in Figure 6a–c can be used to assign structures to *m/z* 43 ions generated from other precursors. The cases of α-chloroacetaldehyde, glycerol, and dioxolane are considered next.

α-Chloroacetaldehyde (**17**) and 1,3-dichloro-2-propanol (**15**) show similar percentages of acetyl cation formation (20%) in the reaction with isoprene (Table I). The fact that **17** displays a *m/z* 123:*m/z* 122 ratio in the reaction with *m*-methylanisole (Figure 6d) quite similar to that of **15** (Figure 6a) indicates that **c** is also the major *m/z* 43 ion generated from **17**. The slightly higher *m/z* 123:*m/z* 122 ratio and less abundant *m/z* 135 for **17** indicate a small contribution of ion **b**. The *m/z* 123:*m/z* 122 ratio and also the relative abundance of *m/z* 165 and *m/z* 135 for glycerol (**16**, Figure 6e) and 1,3-dioxolane (**19**, Figure 6f) clearly indicate that a mixture of approximately $^2/_3$ ion **a** and $^1/_3$ ion **c** is generated from these precursors, as also indicated in the reactions with

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[34] McLafferty, F. W.; Stauffer, D. B. *The Wiley/NBS Registry of Mass Spectral Data*; Wiley: New York, Vol. 1, 1989.

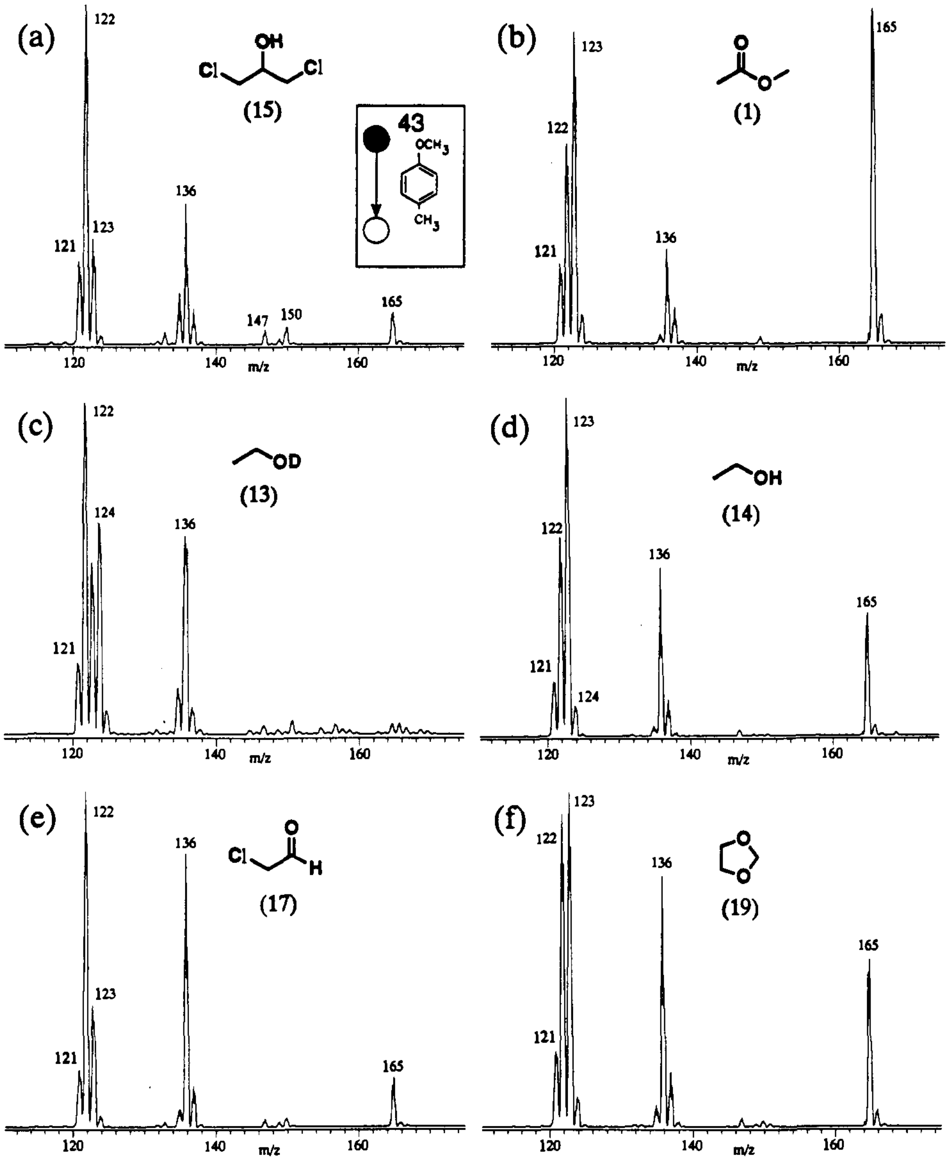
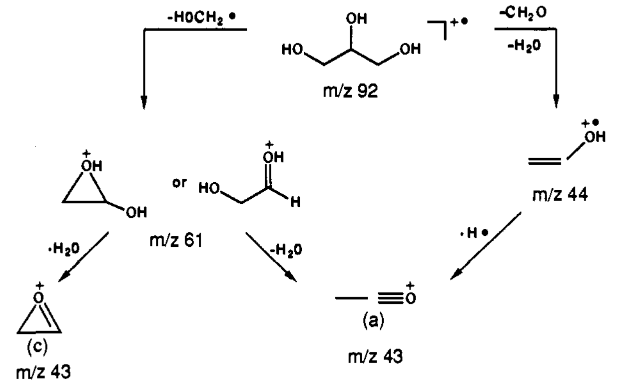


Figure 8. Products of ion/molecule reactions with *p*-methylanisole of ions *m/z* 43 generated from (a) 1,3-dichloro-2-propanol (**15**), (b) methyl acetate (**1**), (c) ion *m/z* 44 generated from ethanol-OD (**13**), (d) ethanol (**15**), (e) α-chloroacetaldehyde (**17**), and (f) 1,3-dioxolane (**19**).

isoprene (Table I). The presence of ion **b** to a small extent cannot of course be dismissed. This is especially true for 1,3-dioxolane, for which the higher *m/z* 123:*m/z* 122 ratio (when corrected for the contribution of *m/z* 123 arising from a, using the *m/z* 123:*m/z* 165 ratio of 6 in Figure 6b) and the less abundant *m/z* 135 product both point to some contribution of **b** to the mixture.

A study of glycerol-$(OD)_3$ showed that the major fraction of *m/z* 43 does not bear a hydroxy group.[9b] Weber and Levsen[9a] proposed on the basis of CID results that O-protonated ketene (**b**) is the major *m/z* 43 ion formed from glycerol, while Terlouw, Heerma, and Dijkstra[9b,d] proposed a mixture consisting largely of oxiranyl cation (**c**) or $^+CH_2CHO$, with some contribution of acetyl cation (**a**). The ion/molecule results with isoprene (Table I) and *m*-methylanisole (Figure 6e) are in approximate agreement with the findings of Terlouw et al., clearly showing that the *m/z* 43 mixture is made up of ions **a** (65%) and **c** (35%), with **a** predominant. Even more detailed information is provided by the MS^3 scans (Figures 2 and 3), which, as already discussed, show that ion **c** is generated from the *m/z* 61 parent together with **a** in approximately a 3:2 proportion, while the *m/z* 44 parent ion forms predominantly **a**. The fragmentation pathway proposed for ionized glycerol to *m/z* ions is shown in Scheme VIII. Note that the acetyl cation (**a**) can be formed from $HOCH_2CH{=}O^+H \rightleftharpoons H_2O^+CH_2CH{=}O$ (*m/z* 61) through the intermediate $^+CH_2CH{=}O$ (*m/z* 43) ion, which was shown by ab initio calculations[12] not to exist in a potential well but to collapse to **a**.

Scheme VIII



o-Methylanisole. Reactions with *o*-methylanisole produce spectra for these precursors similar to those obtained for *m*-methylanisole. The sequential product spectrum for the reaction *m/z* 43 → *m/z* 135 (Figure 7b) is also in agreement with the formation of a *o*-methylmethoxytropylium ion. In this spectrum, the higher relative abundance of ion *m/z* 91, compared to that observed for the *m*-methyl isomer, can be rationalized as a result

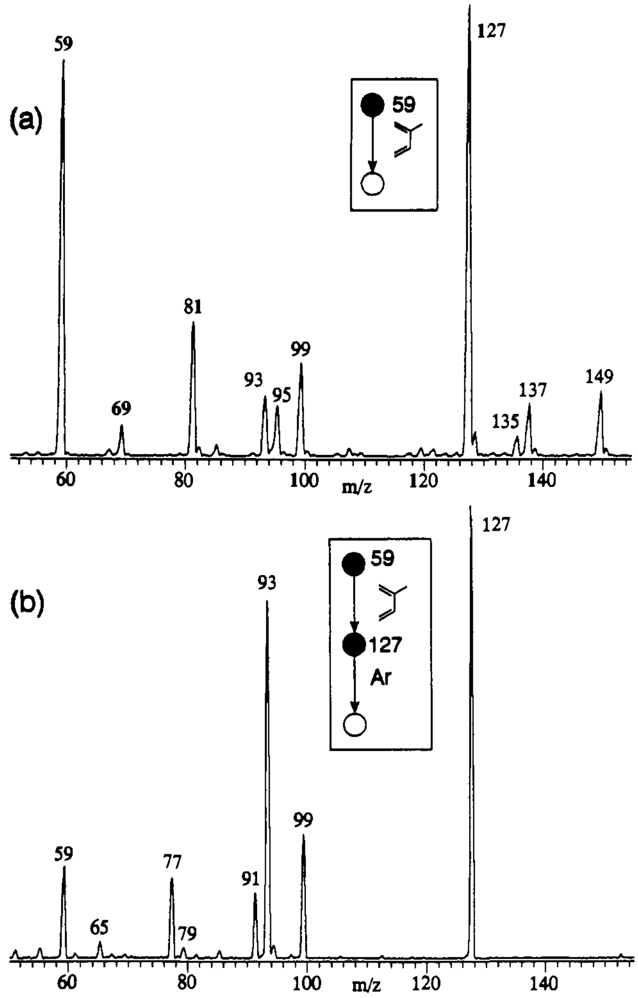


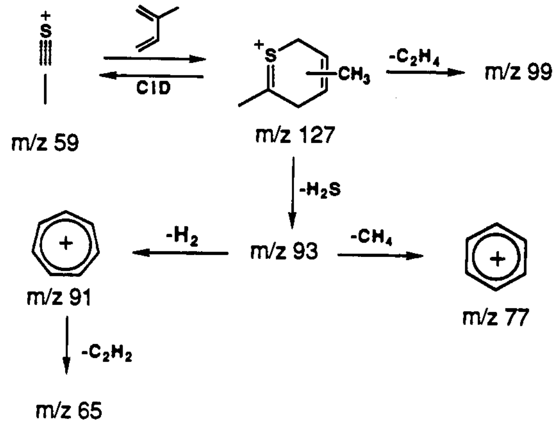
Figure 9. (a) Products of ion/molecule reactions with isoprene of *m/z* 59 ions generated from propylene sulfoxide (**25**) showing the [4 + 2^+] cycloadduct at *m/z* 127, the proton-transfer products, and two additional ions at *m/z* 99 and *m/z* 93. (b) MS^3 sequential product spectrum for the reaction *m/z* 59 → *m/z* 127, showing its CID fragments.

of an ortho effect, which favors fragmentation by loss of a C_2H_4O neutral, as shown in Scheme VII.

p-Methylanisole. Reactions with *p*-methylanisole also produce spectra (Figure 8) which allow unequivocal distinction between all three $C_2H_3O^+$ isomers **a**–**c**. The *oxiranyl cation* (**c**) from precursor **15** gives a low proton transfer (*m/z* 123) to charge exchange (*m/z* 122) ratio (1:3) and a small amount of adduct formation at *m/z* 165 (Figure 8a), the latter again being attributed to 20% of **a** (Table I) cogenerated with this ion. The *acetyl cation* (**a**) shows a *m/z* 122:*m/z* 123 ratio of 1:1.7, less formation of *m/z* 136, and also a remarkably abundant adduct at *m/z* 165 (Figure 8b). *O-Protonated ketene* (ion **b′** at *m/z* 44 from precursor **13**) shows a higher *m/z* 122:(*m/z* 123 plus *m/z* 124) ratio (1.2:1), a higher abundance of *m/z* 136, and almost complete absence of the adduct at *m/z* 166 (Figure 8c). Considering these trends, the presence of a mixture of approximately $^2/_3$ **a** and $^1/_3$ **b** for ethanol (Figure 8d) and $^2/_3$ **a** and $^1/_3$ **c** for α-chloroacetaldehyde (Figure 8e) is clearly indicated by their *m/z* 43 product spectra. For 1,3-dioxolane (Figure 8f) the high relative abundance of *m/z* 123 and *m/z* 136 indicates the presence of **b** to a small extent together with **a** and **c**, as also indicated by reaction with *m*-methylanisole.

Each of these spectra shows greater formation of the product *m/z* 136 over *m/z* 135 for all isomers (Figure 8) compared to the product spectra resulting from reaction with *o*- and *m*-methylanisole (Figure 6). Sequential product spectra which display the CID fragments formed from *m/z* 136 itself generated from *m/z* 43 ions from precursors **1** (Figure S-2), **14**, and **15** are very similar, indicating formation of a common ion/molecule product for isomers **a**–**c**. These spectra are also very similar to the mass spectra reported for ionized 2,4-dimethylanisole.[35] This molecule ion is therefore proposed to be formed from **a** by acetylation at the oxygen atom to generate initially O-methylated phenyl acetate. The aromatic ring is strongly deactivated in the ionic adduct, allowing ortho methylation with concomitant CO elimination to occur. The driving force for the final hydrogen atom loss in which a closed-shell ion yields two open-shell products is the restoration of the aromatic ring.

Scheme IX



The $C_2H_3S^+$ Case. A. Reaction with Isoprene. Reactions with isoprene of *m/z* 59 ions generated from a variety of precursors (**24**–**31**, see Figure 10) yield very similar spectra, as typified for the case of precursor **25** in Figure 9a. The spectra are dominated by *m/z* 127, which again can be assigned as the [4 + 2^+] Diels–Alder cycloadduct; also seen are the products of reaction of protonated isoprene with neutral isoprene, already familiar from the corresponding $C_2H_3O^+$ spectra, as well as two additional ions at *m/z* 99 and *m/z* 93. The similarity of these spectra could mean that (i) each of the precursors generates the same *m/z* 59 ion structure, (ii) isomerization takes place due to collision with the reagent gas, or (iii) all the isomers react with isoprene to generate the same adduct.

Although similar product spectra are obtained, structural differences in the adducts themselves could allow distinction of the isomers if they were to display different fragmentation behavior. However, the sequential product spectra for *m/z* 127 generated from all the precursors, exemplified in Figure 9b for precursor **25**, are also very similar, which indicates that the *m/z* 127 adduct formed is identical. If different CH_3S^+ isomers are involved, this result could be postulated to be a consequence of isomerization of the different adducts promoted by energy released in the course of the ion/molecule reaction. Like its oxygen analogue (Figure S-1), the cyclic adduct *m/z* 127 fragments by a retro Diels–Alder process as evidenced by the presence of the *m/z* 59 fragment, but other processes, which must involve ring opening, occur to a greater extent (Figure 9b). This is not surprising, considering the known capability of sulfur ions to fragment via complex dissociation patterns.[36] This spectrum also shows that ions *m/z* 99 and *m/z* 93, observed in the ion/molecule product spectra (Figure 9a), are fragments of the adduct. Scheme IX summarizes the fragmentation pathways proposed for ion *m/z* 127.

B. Reaction with *m*-Methylanisole. Despite the fact that reaction with isoprene does not allow distinction of the $C_2H_3S^+$ isomers, product spectra showing the reactions of *m/z* 59 ions generated from precursors **24**–**31** with *m*-methylanisole (Figure

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[35] Harrison, A. G.; Camilleri, H.; McMahon, A. W. *Int. J. Mass Spectrom. Ion Processes* **1988**, *86*, 303.

[36] Johnstone, R. A. W., Ed. *Mass Spectrometry*; The Chemical Society: London, 1979; Vol. 5, p 277.

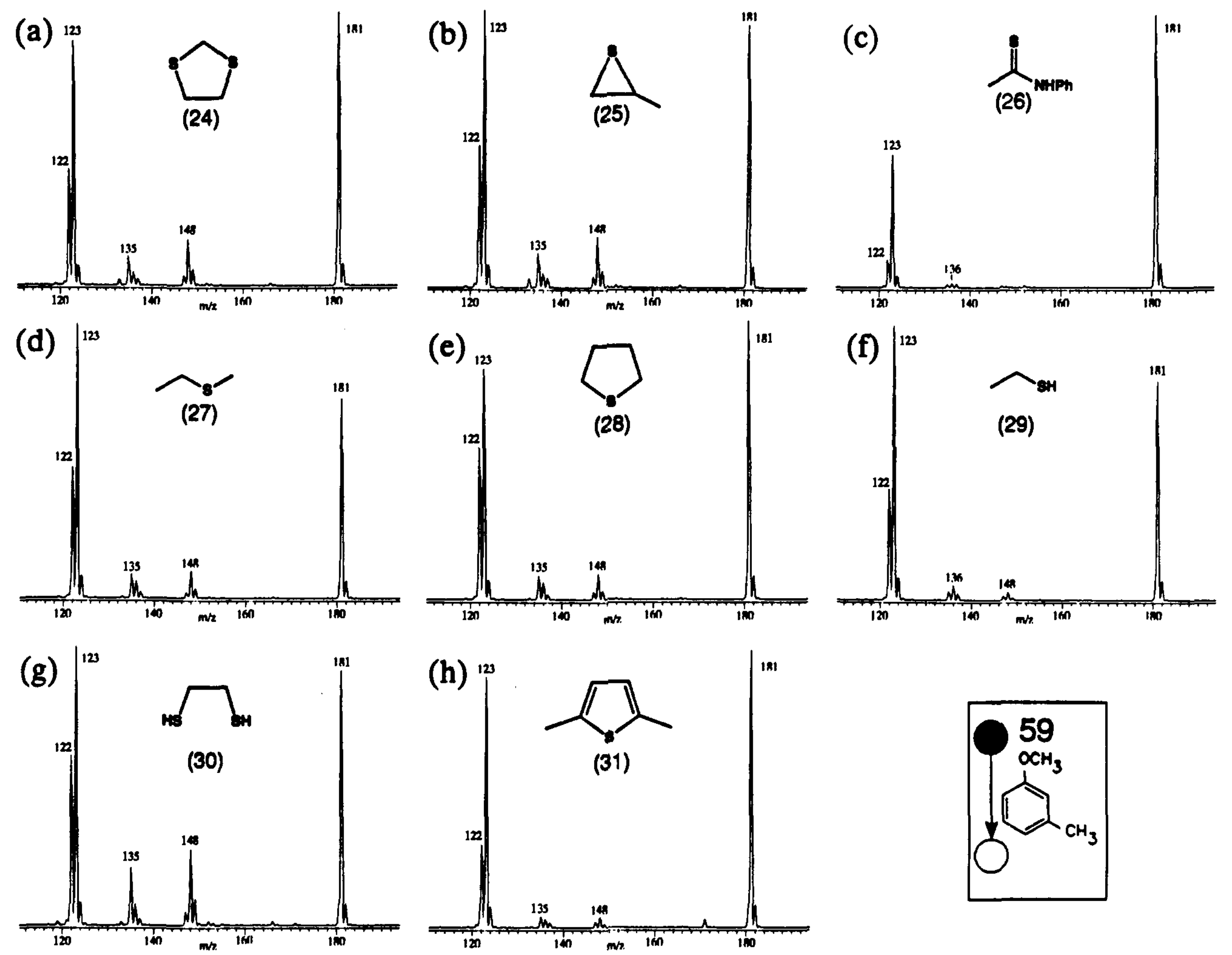

Figure 10. Products of ion/molecule reactions with *m*-methylanisole of *m/z* 59 ions for the reaction *m/z* 43 → *m/z* 127 generated from (a) dithiolane, (b) propylene sulfide, (c) *N*-phenylthioacetamide, (d) ethyl methyl sulfide, (e) tetrahydrothiophene, (f) ethanethiol, (g) 1,2-ethenedithiol, and (h) 2,5-dimethylthiophene.

10) do show differences that can be tentatively related to contributions of different $C_2H_3S^+$ isomers.

The spectra for dithiolane (**24**, Figure 10a) and propylene sulfoxide (**25**, Figure 10b) are very similar but show distinctive differences in ion abundances from all the other spectra. These spectra display, as the major products, ions which can be assigned as the charge-exchange product at *m/z* 122, the proton-exchange product at *m/z* 123, the *m*-methylmethoxytropylium ion at *m/z* 135, and an ion at *m/z* 148, the latter two formed by neutral losses of thioformaldehyde and HS• radical from the adduct at *m/z* 181, respectively. The *thioxiranyl ion* (**h**) can be formed from the molecular ion of **25** by a simple α-cleavage process and from the molecular ion of **24** by a process similar to that occurring for 1,3-dioxolane[9f] which leads to formation of mainly the oxiranyl ion (**c**). This suggests that **h** is the predominant *m/z* 59 ion generated from these two precursors, **24** and **25**. Note also that formation of *m/z* 135 can be generated from ion **h** by a process similar to that proposed for the oxiranyl cation (Scheme VII). The sequential product spectrum taken on ion *m/z* 135 is analogous to that of the oxygen analogue shown in Figure 7a. The product spectrum of *m/z* 59 generated from *N*-phenylthioacetamide (**26**), which is expected to generate mainly the *thioacetyl cation* (**f**) by a simple α-cleavage process, is unique in several respects (Figure 10c). Ions *m/z* 135 and *m/z* 148 are displayed here at very low abundance, the predominant product ion being the adduct at *m/z* 181. Another distinctive feature is the greater abundance of *m/z* 123 compared to *m/z* 122. The reactivity of **f** with *m*-methylanisole is analogous to that observed for the oxygen analogue a (Figure 6b).

The product spectra for ethyl methyl sulfide (**27**), thiofuran (**28**), and ethanethiol (**29**), Figure 10d–f, respectively, are intermediate between the spectra displayed for precursors **25** and **26**, and therefore formation of a mixture of *m/z* 59 isomers is postulated. In analogy with the behavior of ethanol (**14**), a mixture of the thioacetyl (**f**) and *S-protonated thioketene* (**g**) cations is expected to be formed from ethanethiol (**29**). Note, for this precursor, the very low abundance of *m/z* 135 and also 148, indicative of the absence of ion **h**, and the lower relative abundance of the adduct at *m/z* 181, which appears to be due to contributions of ion **g**. The spectrum for 1,2-ethanedithiol (**30**, Figure 10g) displays the most abundant formation of the ions *m/z* 135 and *m/z* 148, which indicates that the $C_2H_3S^+$ mixture formed from this precursor has the highest percentage of the thioxiranyl cation (**h**) among the sulfur compounds investigated. This is consistent with the fact that this isomer can be easily visualized to be formed from the molecular ion of **30** by a cyclization process involving loss of HS• radical to form protonated ethylene sulfoxide, which can lose H_2 to yield ion **h**.

The thioacetyl cation (**f**) is expected to be formed in great abundance from 2,5-dimethylthiophene (**31**) due to the fact that it bears a methyl group in both the 2- and 5-positions.[37] The similarity of its product spectrum (Figure 10h) with that for *N*-phenylthioacetamide (Figure 10c) confirms this view. The slightly higher abundance of the *m/z* 135 and 148 products and

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(37) (a) Dunbar, R. C.; Shen, J.; Melby, E.; Olah, G. A. *J. Am. Chem. Soc.* **1973**, *95*, 7200. (b) Brodbelt, J. S.; Lion, J.; Donovan, T. *Anal. Chem.*, in press.

of *m*/*z* 122 compared to *m*/*z* 123, in combination with the lower relative abundance of *m*/*z* 181, indicates a moderate contribution from another isomer, likely **h**.

These results shows that different $C_2H_3S^+$ ions indeed are formed from the precursors studied here and that their structures can be identified on the basis of their chemical reactivity, which parallels that of their oxygen analogues. This indicates also that the similar spectra displayed in reactions with isoprene (Figure 9a) are a result of reaction of these ions to give different cycloaddition products which undergo isomerization to a common structure, as indicated by the sequential product spectra (Figure 9b). In addition, failure to distinguish the isomers by previous low- and high-energy CID experiments can be attributed to the fact that these ions, due to activation by collision, fragment via a common structure yielding the thioacetyl cation.

Conclusion

The principal conclusion of this study is that by judicious choice of reagents it is possible to obtain high-quality structural information on gaseous ions by recording ion/molecule reaction products. In the case of the $C_2H_3O(S)^+$ ions this extends and enhances the structural information provided by previous studies using low- and high-energy collisional-dissociation methods. The ion/molecule reactions allow estimates of the compositions of mixtures of ions, and even minor components can be detected. The present results agree well with high-energy CID experiments on $C_2H_3O^+$ ions for precursors which form acetyl cations in high abundance. However, for precursors generating a mixture of isomers, modified conclusions are drawn, particularly for glycerol and dioxolane. Also, the ion/molecule results give a more precise estimation of **b** cogenerated with **a** due to enolization of the molecular ions of precursors containing the acetyl group. In the sulfur system, CID causes isomerization which is decreased under the much milder collision conditions used for ion/molecule reactions. Several isomers are distinguished and their structures identified on the basis of their chemical reactivity, which is related to that of the oxygen analogues.

The effects of differences in ion internal energy, often considered a weakness in ion characterization by ion/molecule reactions, are minimal under the conditions chosen here. These findings are encouraging for future studies in which the aim is the characterization of ions or of neutral molecules by examination of the gaseous ions generated from them.

A second major conclusion of the study is that the ability to examine the structures of the ion/molecule reaction products by a subsequent collision-induced dissociation step in MS^3 experiments is invaluable in elucidating the ion/molecule chemistry, and so helpful in assigning the identity of the reagent and adduct ions. When groups of compounds which generate an ion of interest are being compared, the three-dimensional familial scan is a useful approach to capturing all the data pertaining to the ion of interest. Other MS^3 experiments, including the sequential product and the sequential parent spectra, also are valuable in recognizing the isomeric ions generated as fragmentation products of a particular precursor and in recognizing the parent ions which react to yield a particular isomeric species.

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Supplementary Material Available: An ion/molecule reaction product spectrum (isoprene reagent) for *m*/*z* 43 ions ($C_3H_7^+$) generated from *n*-nonane and an MS^3 sequential product spectrum for ion *m*/*z* 136 generated by ion/molecule reaction with *p*-methylanisole of *m*/*z* 43 ions from methyl acetate (2 pages). Ordering information is given on any current masthead page.