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## Mechanistic studies

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A short description is given of some modern physical methods in mass spectrometry like field ionization kinetics, kinetic energy release measurements, collisional activation and ion cyclotron resonance. With these methods it is possible to study the mechanisms of fragmentation and the structures of ions in the gas phase over a time interval of  $10^{-11}$  to  $10^{-3}$  s. They are shown to full advantage in such studies if they are used in combination with isotopic labelling.

For example, on the basis of field ionization kinetics and deuterium labelling experiments, evidence is presented that the molecular ions of isobutyl alcohol generate, at  $10^{-11}$  s,  $\text{CH}_5\text{O}^+$  ions via a 1,4- shift of a hydrogen atom from one of the methyl groups to the oxygen atom, followed by a 1,2-elimination of protonated methanol with a hydrogen atom of the other methyl group.

At times longer than  $10^{-11}$  s two distinct interchange processes between hydrogen atoms appear to compete with this reaction, as shown from field ionization kinetic experiments in the time interval of  $10^{-11}$  to  $10^{-9}$  s and from decompositions of metastable ions in the time interval of  $10^{-6}$  to  $10^{-5}$  s.

Another example concerns the loss of formaldehyde from the  $[\text{M} - \text{methyl}]^+$  ions of methoxymethyl isopropyl ether. Combined labelling with  $^{18}\text{O}$  and deuterium has shown that these ions eliminate formaldehyde via two reaction channels, i.e. by methyl migration and by methoxyl migration. Both channels lead to the same products, but the methoxyl migration has the higher activation energy and the higher frequency factor.

An attempt has been made to prepare the  $[\text{M} - \text{methyl}]^+$  ions of methoxymethyl isopropyl ether as collision complexes in the ion-molecule reactions of methoxymethyl cations and acetaldehyde by using an ion cyclotron resonance spectrometer. On the basis of labelling experiments with  $^{18}\text{O}$  and deuterium it is shown that such collision complexes are not involved. A simple methyl cation transfer from the methoxymethyl cations to acetaldehyde molecules through a nucleophilic displacement is found instead. Furthermore, from this study, evidence is presented that the threshold energy required for 1,3-hydrogen shifts in long-lived (*ca.*  $10^{-3}$  s) methoxymethyl cations is 2.3 eV.

## INTRODUCTION AND METHODS

A detailed knowledge of the mechanisms of fragmentation and of the structures of ions in the gas phase is fundamental to mass spectrometry. Furthermore, it may provide a basis for theoretical studies and for a better understanding of chemical reactions in solution, where charged species frequently play an important role.

Many mechanistic studies have been performed with the use of mass spectrometers equipped with an electron impact ionization source. The energies of the bombarding electrons are usually of the order of 70 eV and these cause an extensive fragmentation of the ionized sample via a network of competitive and consecutive unimolecular reactions. This fragmentation is of great practical value, because it may serve as a fingerprint of the molecular structure of the sample, provided this is known. This prerequisite is often not attained for samples obtained

from reactions aimed at developing new methods in synthetic organic chemistry or isolated from natural sources. The molecular structure must then be derived from the information contained in the mass spectrum itself, which requires a detailed insight into the dissociation mechanisms and structures of the ionized species involved. However, the interpretation of such information from a mass spectrum, recorded at an electron energy of 70 eV, is complicated by the fact that the residence time of the ions in the ionization chamber is about  $10^{-6}$  s. This provides a time-integrated view of all the decompositions occurring in the first  $10^{-6}$  s after ionization, which is long in comparison with the vibrational period of a chemical bond ( $10^{-14}$  to  $10^{-13}$  s). Hence, a large proportion of the ions may have suffered structural changes by isomerization or rearrangement reactions before fragmentation within  $10^{-6}$  s. Therefore, in the past decade, various methods of studying the gas phase chemistry of ions in selected narrow time intervals have been developed and already successfully applied to mechanistic studies. They comprise, among others, field ionization kinetics and kinetic energy release measurements on decomposing ions as well as collisional activation and ion cyclotron resonance experiments on non-decomposing ions.

The underlying theories of these methods have been described elsewhere in detail and will be repeated here only in so far as they are required for the mechanistic studies discussed below.

#### *Field ionization kinetics*

For application of the field ionization kinetics method (Derrick & Burlingame 1974; Derrick 1975; Beckey 1977), gas phase molecules are ionized under the influence of extremely high electrical fields ( $10^9$ – $10^{10}$  V m $^{-1}$ ). These fields can be generated in various ways, of which the most widely used method nowadays is the positioning of a 10  $\mu$ m conditioned wire emitter (Schulten & Beckey 1972) at potential  $V_0$  (ca. 8 kV) at a distance of approximately 1.5 mm from a grounded and slotted cathode. Gas phase molecules may be ionized in the strong electrical field in a very narrow region close to the emitter. To a good approximation, the potential is equal to the emitter potential  $V_0$  at this point. Suppose that the ions, formed by either direct ionization or unimolecular decomposition close to the emitter, are stable for not less than  $10^{-5}$  s. They will acquire a kinetic energy  $zV_0$  during acceleration from the emitter to the cathode and will pass the electric sector of a double focusing mass spectrometer, set to transmit ions with a kinetic energy  $zV_0$ . Consequently, they will be mass analysed at their correct  $m/z$  values. In this way a field ionization spectrum may be obtained, containing peaks corresponding to the ions generated very near to the emitter, i.e. within approximately  $10^{-11}$  s.

Fragment ions  $m^+$ , generated by expulsion of  $(M-m)$  from  $M^+$  ions between the emitter and cathode at potential  $V_x$  are not transmitted through the electric sector, because they have insufficient kinetic energy ( $(zm/M)(V_0 - V_x) + zV_x$ ) to be focused by this sector. However, these ions can be transmitted through the electric sector by increasing the emitter potential  $V_0$  by an amount  $\Delta V$ , such that the kinetic energy of the fragment ions  $m^+$  is given by equation (1):

$$zV_0 = \frac{zm}{M} (V_0 + \Delta V - V_x) + zV_x. \quad (1)$$

Thus, it is possible to monitor at a fixed electric sector voltage the abundance of  $m^+$  ions as a function of the emitter potential  $V_0 + \Delta V$  (Falick *et al.* 1973). A scan of the emitter potential, achieved by increasing  $\Delta V$ , allows one to view the decompositions of ions  $M^+$  occurring at increasing distances from the emitter. Of course, these increased distances correspond to longer

lifetimes (Falick 1974) of the parent ion  $M^+$ . Expressing the abundance of  $m^+$  ions due to loss of  $(M - m)$  as a function of time following field ionization of  $M$ , the so-called field ionization kinetics curve of  $m^+$  is obtained. The time range, covered continuously by the field ionization kinetics method, is approximately  $10^{-11}$  to  $10^{-9}$  s. Additional points at longer times ( $10^{-6}$  to  $10^{-5}$  s) can be obtained from decompositions of  $M^+$  ions in the field-free regions of the double focusing mass spectrometer. These points are also accessible by the conventional electron impact ionization method.

#### *Kinetic energy release*

The metastable peaks resulting from decompositions of ions in the field-free regions of a double focusing mass spectrometer in the time interval of  $10^{-6}$  to  $10^{-5}$  s can be detected by scanning either one of the three possible variables:  $V$ , the accelerating voltage,  $E$ , the electric sector voltage and  $B$ , the magnetic field strength or a combination of these variables (Boyd & Beynon 1977; Jennings 1978; Bruins *et al.* 1978). Some of the scanning modes are capable of yielding information on peak shapes, which is valuable for mechanistic studies as it may give an insight into the potential energy surface over which a decomposition of interest occurs (Williams 1977). This follows from the origin of the shape of a metastable peak, which is the conversion of internal energy of an ion into kinetic energy of separation of its fragments (Cooks *et al.* 1973). Two separate sources may contribute to this kinetic energy release designated by  $T$ , namely (i) the excess energy  $\epsilon^\ddagger$  of the activated complex and (ii) the activation energy required to form the reactant ion from the products, the so-called reverse activation energy  $\epsilon_0^\ddagger$ . Both energies are available for partitioning between the internal energies of the products and kinetic energy of their separation. The kinetic energy release,  $T$ , may therefore be regarded as being the sum of  $T^\ddagger$ , the kinetic energy released from the excess energy of the activated complex, and of  $T^e$ , the kinetic energy released from the reverse activation energy. Although  $T^\ddagger$  and  $T^e$  cannot be separated rigorously, it is the term  $T^e$  that in most cases can be obtained to a good approximation from the width of a metastable peak (usually at half-height and designated by  $T_{\frac{1}{2}}$ ), because the corresponding metastable ions decompose within the narrow time interval of  $10^{-6}$  to  $10^{-5}$  s whose activated complexes are thus considered to have usually a relatively small excess energy,  $\epsilon^\ddagger$ . Hence,  $T^e$  depends upon the detailed energetics and dynamics of the reaction and is intrinsic to the particular process. This is the reason why kinetic energy release measurements on metastable ions are very valuable in mechanistic studies. The measured kinetic energy release  $T$  may, however, contain a significant contribution from  $T^\ddagger$ , if a rate-determining step is involved at some stage of the reaction and precedes the eventual fragmentation step of a metastable ion. A few examples have already been documented recently in some studies of unimolecular metastable decompositions of  $C_3H_7O^+$  (Bowen *et al.* 1977),  $C_4H_9O^+$  (Bowen & Williams 1977) and of phenol ions (Russell *et al.* 1978), where rate-determining isomerizations have been shown to occur before fragmentation.

#### *Collisional activation*

It will be clear that knowledge of the structures of the products generated in unimolecular fragmentations of ions is essential for achieving a picture of the reactions. A very powerful method of characterizing the structures of ions that do not decompose within  $10^{-5}$  s is the collision-induced dissociation (c.i.d.) or collisional activation (c.a.) method (Jennings 1968; McLafferty *et al.* 1973 *a, b*). A beam of mass selected  $m_1^+$  ions accelerated to 4–10 keV kinetic energy is passed through a collision chamber, which is located in one of the field free regions

of a double focusing mass spectrometer. Interaction of the accelerated  $m_1^+$  ions with the neutral gas molecules in the collision chamber results in conversion of a certain amount of translational energy into internal energy of the ions  $m_1^+$ , which subsequently fragment into ions having lower masses. These ions can be detected by an  $E$  scan, if a reverse geometry instrument is used with the collision chamber located between the magnetic and electric sector (Beynon *et al.* 1973) or by a linked  $B/E$  scan, if a conventional geometry instrument is used with the collision chamber located between the ion source and the electric sector (Bruins *et al.* 1978). The relative intensities of peaks given by fragment ions in the c.a. spectrum of ions  $m_1^+$  appear to be largely independent of the internal energies of ions  $m_1^+$ . Differences in relative intensities of peaks in the c.a. spectra given by ions from different sources can therefore be ascribed to differences in structure. Hence, c.a. spectra do provide a valuable fingerprint for ion structure especially when, in the near future, sufficient reference c.a. spectra of ions with known structure will have been collected.

#### *Ion cyclotron resonance*

Another method of obtaining structural information on non-decomposing ions that have a relatively long lifetime (*ca.*  $10^{-3}$  s) and a relatively low internal energy is based upon the use of ion-molecule reactions in an ion cyclotron resonance (i.c.r.) spectrometer (Baldeschwieler & Sample-Woodgate 1971; Lehman & Bursey 1976). In such an instrument ions are formed by electron impact in a uniform magnetic field,  $B$ . Their motion is constrained to an orbit of angular frequency  $\omega_c$  in a plane perpendicular to  $B$ . The cyclotron frequency,  $\omega_c$ , is independent of the velocity of the ions and is given by

$$\omega_c = Bz/m, \quad (2)$$

where  $m/z$  is the mass:charge ratio of the ion. If an alternating radio frequency field of frequency  $\omega_1$  is applied normal to  $B$ , ions will absorb energy from the r.f. field if  $\omega_1 = \omega_c$ . A spectrum linear in mass can be obtained by scanning the magnetic field at a fixed frequency  $\omega_1$ , so that ions of different  $m/z$  satisfy (2). The energy absorbed by the ions is detected by using a radio frequency marginal oscillator. As a consequence of energy absorption, the ions are continuously accelerated to larger orbital radii until the process is terminated by collision with either another particle or a wall. To avoid space charge effects, ions are removed from the source region by applying a small electrostatic field  $E$  normal to  $B$ . This causes the ions to drift in a direction perpendicular to both  $B$  and  $E$  with a velocity  $v_d = E/B$  from the source to the analyser region along a cycloidal trajectory. As a result of the cycloidal trajectory of the ions, the time spent by ions in the source and analyser regions is of the order of milliseconds. Therefore a large number of collisions with neutral molecules, giving a high secondary ion yield in the analyser region, will be achieved at low pressures (*ca.*  $10^{-3}$  Pa). Strong electric fields are not used in the i.c.r. instrument so that nearly thermal ion-molecule reactions can be studied. One of the most powerful features of i.c.r. spectrometry is the availability of the double resonance technique (Anders *et al.* 1966). This enables one to establish the relation between reactant ions  $P^+$  and their corresponding product ions  $S^+$ , generated via excited collision complexes  $(PN^+)^*$ :



In most cases the rate constant,  $k$ , of an ion-molecule reaction varies with the translational energy of the reactant ion  $P^+$  and this property is used in the double resonance technique. The intensity of the signal due to  $S^+$  is monitored by adjusting the magnetic field so that the

secondary ions  $S^+$  absorb energy from the marginal oscillator at a frequency  $\omega_1 = \omega_s$ . If a second r.f. field is applied either to the source or the analyser region and its r.f. oscillator frequency,  $\omega_2$ , equals the cyclotron resonance frequency of  $P^+$ , the primary ions will absorb energy so that their translational energy increases: the yield of  $S^+$  will change if  $P^+$  is a precursor of  $S^+$ , thereby establishing the relation between  $P^+$  and  $S^+$ .

At a fixed magnetic field the following relation holds:

$$m_p \omega_p = m_s \omega_s, \quad (4)$$

so that by scanning  $\omega_2$ , different precursors of  $S^+$  can be identified.

The assignment of the structure of non-decomposing ions in i.c.r. may be on the basis of their reactivity towards neutral molecules, though this method has to be used with caution because the reactivity may depend on the internal energy of the ions. This is one of the major reasons why it is so difficult to find suitable probe reactions for distinguishing ion structures by the i.c.r. method. Nevertheless, some clear-cut results have been obtained, e.g. the  $C_7H_7^+$  ions from 7-methoxycycloheptatriene are unreactive towards dimethylamine (Venema & Nibbering 1974), whereas the  $C_7H_7^+$  ions from benzyl methyl ether do react with dimethylamine (Bruins & Nibbering 1974). These observations suggest different ion structures: unreactive  $C_7H_7^+$  ions most probably have the tropylium structure and reactive  $C_7H_7^+$  ions the benzyl structure. Such a conclusion is indeed in agreement with results obtained from i.c.r. photodissociation (Dunbar 1976) and c.a. experiments (McLafferty & Winkler 1974) on  $C_7H_7^+$  ions.

Another use of i.c.r. is to study the mechanistic details of ion-molecule reactions, which may give an insight into the nature of the collision complexes involved. These complexes may be regarded as excited ions, which decompose unimolecularly into products similar to the ions generated upon electron impact in a sector instrument. Knowledge of the nature of the collision complexes may therefore be helpful for obtaining ideas about activated complexes of ions that fragment unimolecularly.

All of the methods described can be applied successfully in mechanistic studies and are shown to full advantage if they are used in combination with isotopic labelling as will be shown below.

## RESULTS AND DISCUSSION

### *Formation of $CH_5O^+$ ions from the molecular ions of isobutyl alcohol*

One of the most abundant ions generated by 70 eV electrons from the molecular ions of isobutyl alcohol is of  $m/z$  33 as shown in figure 1*a*. The corresponding peak even becomes the base peak at 15 eV as demonstrated in figure 1*b*.

The formation of ions of  $m/z$  33 from isobutyl alcohol is unusual; the peak is a minor one in the mass spectrum of *n*-butyl alcohol (McFadden *et al.* 1963) and absent in the mass spectra of *sec*- and *tert*-butyl alcohol. The elemental composition of these ions can only be  $CH_5O^+$ , which has been confirmed by high resolution mass measurements (Saunders & Williams 1963). They are generated from the molecular ions as is proved by the occurrence of the relevant metastable peak in the spectrum. Some deuterium labelling experiments performed two decades ago (McFadden *et al.* 1958; Eliel & Prosser 1956) suggest that two hydrogen atoms in the ions of  $m/z$  33 probably originate from either or both methyl groups.

The following specifically deuterium labelled isobutyl alcohols have been synthesized and measured by some of the methods described in the introduction to shed more light on the mechanism of formation of the ions of  $m/z$  33 (Tajima *et al.* 1978):

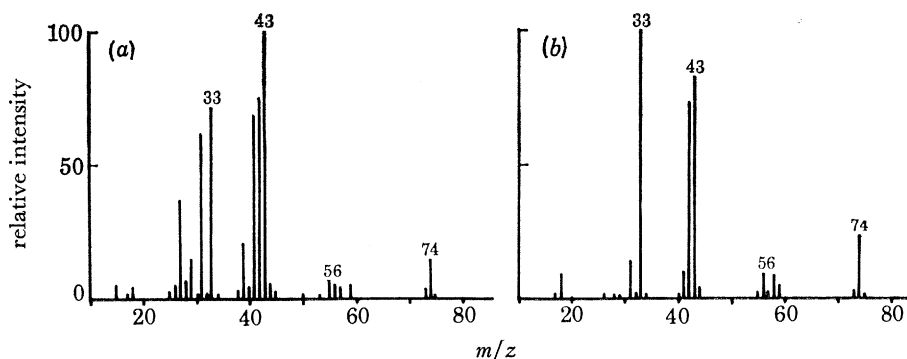
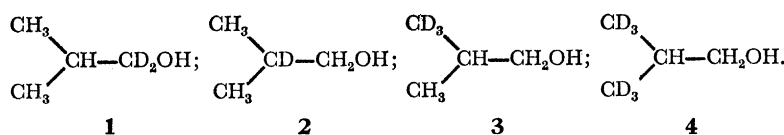


FIGURE 1. Electron impact spectra of isobutyl alcohol: (a) at 70 eV; (b) at 15 eV.



The 15 eV mass spectrum of **1** shows that the ions of  $m/z$  33 fully retain the original methylene hydrogen atoms, whereas that of **2** indicates that the methine hydrogen atom is not incorporated at all in these ions.

From the 15 eV spectrum of **3** it can be deduced that the ions under discussion may contain 0, 1, 2 or 3 deuterium atoms. The ratios of intensities of the corresponding peaks at  $m/z$  33, 34, 35 and 36 appear to be 10.0:63.8:25.7:0.5. This is close to the ratios (11.4:51.4:34.3:2.9) expected for a completely equilibrated interchange between the methyl hydrogen atoms and the hydroxyl hydrogen atom in the molecular ions before decomposition. Such interchange of hydrogen atoms is confirmed by the 15 eV spectrum of **4**, which shows incorporation of 2 or 3 deuterium atoms in the ions of  $m/z$  33, the ratio of intensities of the corresponding peaks at  $m/z$  35 and 36 being 52.5:47.5 (calculated ratio 42.9:57.1).

These results show therefore beyond doubt that the ions of  $m/z$  33 contain the original methylene group and that the other hydrogen atoms come from one or both methyl groups and the hydroxyl group. However, it is also clear that the equilibration of interchange between the methyl and hydroxyl hydrogen atoms in the molecular ions combined with their residence time of  $10^{-6}$  s in the ion source obscures the actual mechanism for formation of ions of  $m/z$  33.

Such hydrogen atom interchange processes are largely suppressed if decompositions are studied at shorter times by using the field ionization kinetics method as recently demonstrated for 3-phenylpropanal (Wolkoff *et al.* 1978). This method has therefore been applied to elucidating the process of formation of ions of  $m/z$  33. Figure 2 summarizes the data obtained for **4**.

It is seen that the predominant reaction is elimination of  $\text{C}_3\text{D}_4\text{H}^+$  at molecular ion lifetimes of *ca.*  $2 \times 10^{-11}$  s whereas the elimination of  $\text{C}_3\text{D}_3\text{H}_2^+$  becomes more important at increasing ion lifetimes. After *ca.*  $4 \times 10^{-10}$  s the relative probabilities of elimination of the two radicals is in a ratio which is expected for an almost completely equilibrated interchange of the six deuterium atoms and the oxygen bonded hydrogen atom. The observation that the interchange of hydrogen and deuterium atoms hardly takes place at very short ion lifetimes provides a suitable probe for determining the mechanism of  $\text{C}_3\text{H}_5^+$  elimination in generating ions of

$m/z$  33. The clearest insight into this is obtained from **3**: its molecular ions eliminate predominantly (more than 70%) a  $C_3H_3D_2^+$  radical at very short times. A straightforward interpretation is therefore that the mechanism involves a 1,4-shift of a hydrogen atom from one of the methyl groups to the oxygen atom followed by a 1,2-elimination of protonated methanol with a hydrogen atom of the other methyl group. At longer molecular ion lifetimes, the interchange of hydrogen atoms takes place because the reverse 1,4-hydrogen shift can then start to compete with the elimination of  $C_3H_5^+$ . This is shown in scheme 1.

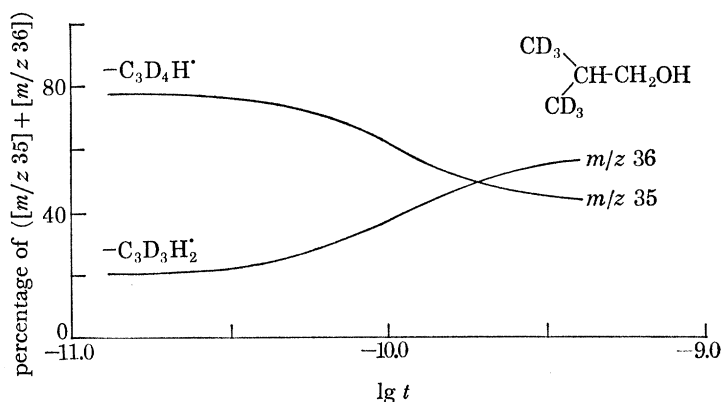
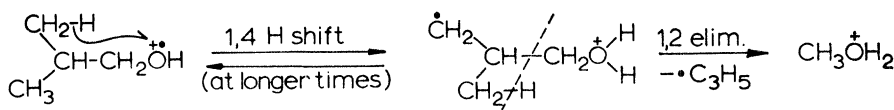
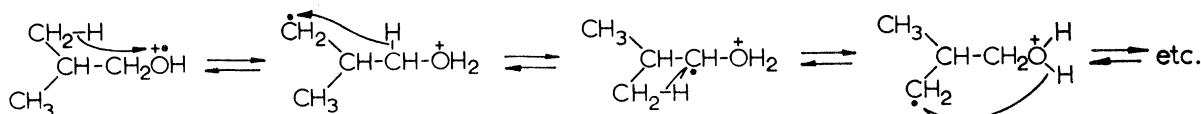


FIGURE 2. Loss of  $C_3H_nD_{5-n}^+$  as a function of the lifetime of the molecular ions from  $d_8$ -isobutyl alcohol.



SCHEME 1. Mechanism of the formation of  $CH_5O^+$  ions from the molecular ions of isobutyl alcohol, supported by results from deuterium labelling.

Turning now to the metastable decomposing molecular ions in the time interval of  $10^{-6}$  to  $10^{-5}$  s, it is found that **1** eliminates not only  $C_3H_5^+$  (89%), but also  $C_3H_4D^+$  (11%). Compound **2** still loses exclusively  $C_3H_4D^+$ . These observations reveal another interchange process of hydrogen atoms which apparently starts to compete with fragmentation at molecular ion lifetimes of  $10^{-6}$  to  $10^{-5}$  s and which takes place between the hydrogen atoms of the methylene and the methyl groups. The metastable decomposing molecular ions of **4** lose  $C_3D_2H_3^+$  (17%) in addition to  $C_3D_3H_2^+$  (62%) and  $C_3D_4H^+$  (21%). A mechanism for such an interchange reaction is shown in scheme 2.



SCHEME 2. Interchange reactions between the hydrogen atoms of the methylene and methyl groups in the molecular ions of isobutyl alcohol competing with the formation of  $CH_5O^+$  ions at molecular ion lifetimes of more than  $10^{-6}$  s.

Having established the mechanistic details for formation of ions of  $m/z$  33, let us now consider the underlying thermochemistry of this reaction. The activation energy,  $\epsilon_0$ , required to generate ions of  $m/z$  33 from the molecular ions, has been determined to be 0.4 eV. Assuming



that the corresponding activated complex does not contain any contribution from the excess energy,  $\epsilon^*$ , of the transition state, the potential energy–reaction coordinate diagram given in figure 3 can be constructed on the basis of known heats of formation of isobutyl alcohol, its molecular ion, protonated methanol and of the allyl radical.

It is seen that the reverse activation energy,  $\epsilon_0^*$ , has a small value of about 0.2 eV which is in agreement with the small kinetic energy release of 6.3 meV deduced from the width of the metastable peak at half height for the formation of ions of  $m/z$  33. This value roughly accounts for 50% of  $\epsilon_0^*$  if the formula  $\epsilon_0^* = 0.44 TS$  is used (Haney & Franklin 1968), where  $T$  is the kinetic energy released and  $S$  the number of oscillators in the activated complex.

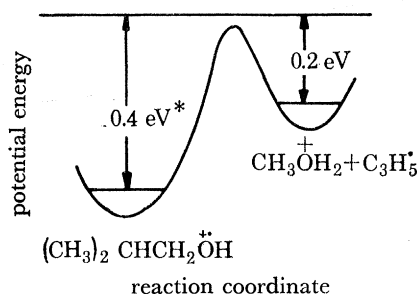
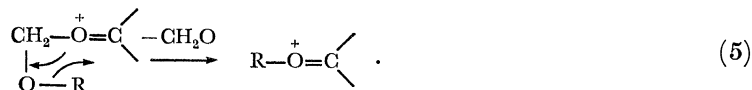


FIGURE 3. Thermochemistry pertaining to  $C_3H_5^+$  loss from the molecular ion of isobutyl alcohol. The value asterisked is the difference between the appearance energy for the reaction and the ionization energy of the reactant species.

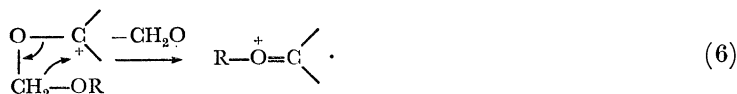
The low activation energy of 0.4 eV needed to generate ions of  $m/z$  33 implies that the hydrogen atom interchange processes given in schemes 1 and 2 occur at relatively low internal energies of the molecular ions, a phenomenon that is well documented in mass spectrometry.

*Elimination of formaldehyde from the (M–methyl)<sup>+</sup> ions of methoxymethyl isopropyl ether*

Ions generated via  $\alpha$ -cleavage from acetals eliminate formaldehyde, a reaction that has been proposed to proceed via alkyl migration as shown in (5) (Brown *et al.* 1965):



This reaction might, however, occur via alkoxy migration to a carbenium centre, a well known reaction type in gas phase ion chemistry (Cooks *et al.* 1967), as shown in (6):



Methoxymethyl isopropyl ether has been selected as a model compound to differentiate between mechanisms (5) and (6) which would both lead to precisely the same products, distinguishable only by isotopic labelling (Schoemaker *et al.* 1975). Its 70 eV mass spectrum indeed exhibits peaks at  $m/z$  89 =  $[M - \text{CH}_3]^+$  and at  $m/z$  59 =  $[M - \text{CH}_3 - \text{CH}_2\text{O}]^+$ .

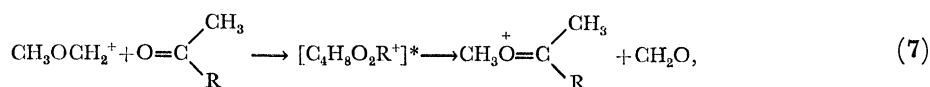
Upon simultaneous replacement of all isopropyl hydrogen atoms by deuterium and  $^{18}\text{O}$  substitution of the methoxy-oxygen atom, the peak at  $m/z$  = 89 in the 70 eV spectrum shifts completely to  $m/z$  95 =  $[M - \text{CD}_3]^+$ . Approximately 90% of the peak at  $m/z$  59 shifts to

$m/z$  65 and 10% to  $m/z$  63. High resolution mass measurements confirm that the peak at  $m/z$  65 contains the  $^{18}\text{O}$  atom and that at  $m/z$  63 the  $^{16}\text{O}$  atom. Furthermore, the hydrogen atoms of the expelled formaldehyde molecule originate exclusively from the original methylene group. This follows from the mass spectrum and high resolution mass measurements performed on the trideuteromethoxymethyl isopropyl ether which shows full retention of all deuterium atoms both in the  $[\text{M} - \text{methyl}]^+$  and in the  $[\text{M} - \text{methyl} - \text{formaldehyde}]^+$  ions. All data are therefore consistent with the expulsion of formaldehyde from the  $[\text{M} - \text{methyl}]^+$  ions via a mechanism involving approximately 90% methoxyl migration (equation 6) and 10% methyl migration (equation 5) at 70 eV in the ion source. The same ratio is found at 15 eV, but upon further lowering the electron energy the percentage of methyl migration gradually increases to 40% at 11 eV. In striking contrast, metastable  $[\text{M} - \text{methyl}]^+$  ions, decomposing in the time interval of  $10^{-6}$  to  $10^{-5}$  s, fragment virtually exclusively by methyl migration (equation 5) with a kinetic energy release of 15 meV (R. G. Cooks 1975, personal communication). Methoxyl migration is just detectable (less than 1%) in a mass spectrometer with reverse geometry (Beynon *et al.* 1973). The  $[\text{M} - \text{methyl}]^+$  ions, studied by collision-induced dissociation, show intermediate behaviour with methyl migration accounting for 90% of the total and methoxyl the remaining 10%. The metastable peak of the latter reaction was, however, too weak to allow the kinetic energy release to be determined (R. G. Cooks 1975, personal communication).

Recently, appearance energy measurements have been made for the reaction involving loss of formaldehyde from the  $[\text{M} - \text{methyl}]^+$  ions of methoxymethyl isopropyl ether (van Doorn & Nibbering 1978). In the ionization efficiency curve for this reaction, a break point is observed about 0.4 eV above the corresponding appearance energy, which itself appears to be 0.7 eV above the appearance energy of the  $[\text{M} - \text{methyl}]^+$  ions. This break point may be assumed to correspond with the onset of methoxyl migration in the  $[\text{M} - \text{methyl}]^+$  ions. The reaction studied is interesting and unusual in that two routes from the same reactants to the same products are involved. The experimental data indicate that methoxyl migration has the higher activation energy and the higher frequency factor. A higher activation energy is reasonable since the C–O bond to be cleaved has a considerable double bond character in this migration, but not in that involving the methyl migration. The higher frequency factor for methoxyl migration has been suggested (Schoemaker *et al.* 1975) to be a consequence of internal solvation of charge in the  $[\text{M} - \text{methyl}]^+$  ion by the nucleophilic methoxyl group. This will tend to lock the ion into a configuration favourable to this rearrangement.

#### *Ion–molecule reactions of methoxymethyl cations with acetaldehyde and acetone*

The behaviour of metastable  $[\text{M} - \text{methyl}]^+$  ions of methoxymethyl isopropyl ether described above prompted us to study the ion–molecule reactions of methoxymethyl cations with acetaldehyde and acetone in an ion cyclotron resonance spectrometer (van Doorn *et al.* 1978). The methoxymethyl cations were generated from dimethyl ether by electron impact. Double resonance experiments show that they indeed react both with acetaldehyde and with acetone to expel formaldehyde, as summarized in (7):



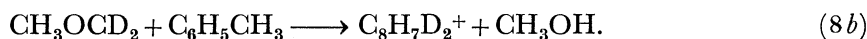
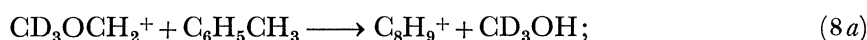
where R = H or CH<sub>3</sub>.

Before discussing this ion–molecule reaction in detail, it should be mentioned that methoxymethyl cations have been studied previously by deuterium labelling (Hvistendahl & Williams 1975). They can decompose by elimination of methane, a reaction which has been shown to require an activation energy of 3.6 eV accompanied by a complete randomization of all hydrogen atoms.

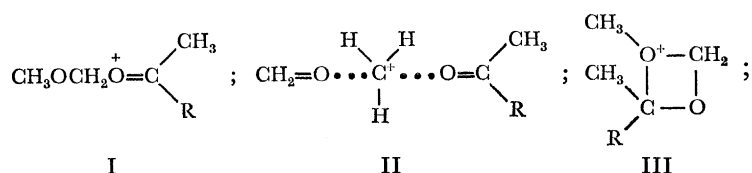
However, it should be realized that in (7) we are dealing with *non-decomposing* methoxymethyl cations as reactant ions. It was therefore essential from the outset to know whether or not the hydrogen atoms in these ions randomize.

Ion–molecule reactions of  $\text{CD}_3\text{OCH}_2^+$  and of  $\text{CH}_3\text{OCD}_2^+$  ions, generated from  $\text{CD}_3\text{OCH}_3$ , with a variety of organic substrates have been studied to obtain this knowledge.

Toluene appears to react with these ions in a highly specific way as noted earlier (Dunbar *et al.* 1973). In our experiments the collision complex decomposes to give  $\text{C}_8\text{H}_9^+$  and  $\text{CH}_3\text{OH}$ , while the  $\text{CH}_3\text{OH}$  molecule appears to contain the original methyl group for at least 96% at the reactions at 13 eV electron energy:



Hence it can be concluded that at least 96% of the time, the hydrogen atoms in non-decomposing methoxymethyl cations generated with 13 eV electrons retain their identity. This result should be borne in mind in the forthcoming discussions. Furthermore, (8a) and (8b) show that the methoxymethyl cations attack the aromatic ring with their terminal methylene group. If they attacked the lone pair electrons on the oxygen of acetaldehyde and acetone in precisely the same way, then the collision complexes in (7) should have the open-chain structure I, which is similar to the structure of the  $[\text{M} - \text{methyl}]^+$  ions of methoxymethyl isopropyl ether. However, *a priori*, other possible candidates for (7) such as a methyl cation bonded collision complex (II) or a four-membered ring collision complex (III) cannot be excluded:



where  $\text{R} = \text{H}$  or  $\text{CH}_3$ .

To discriminate between the possible collision complexes I–III, reactions of (un)labelled methoxymethyl cations with unlabelled acetaldehyde and acetone and  $[\text{^{18}O}]$ acetone were studied.

The results, obtained from the intensities of double resonance signals, are shown in table 1. They show that the formaldehyde molecule, eliminated from the collision complex, contains entirely the original methylene group and oxygen atom (based on the experiment with  $[\text{^{18}O}]$ -acetone) of the methoxymethyl cation. The intermediacy of collision complex III in (7) can therefore be excluded. The data of table 1 would also mean that only the methyl migration is operative if reaction (7) proceeds through collision complex I. That this might be true can be seen if the reaction coordinate diagram for the ion–molecule reaction of the methoxymethyl cation with acetaldehyde is considered. In this diagram (figure 4), the energies of the reactants,

collision complex I and products are shown. It can be seen that the reaction between the methoxymethyl cation and acetaldehyde is exothermic, but route B, corresponding to methoxyl migration in the collision complex, requires an activation energy as opposed to route A, corresponding to methyl migration in the collision complex. A similar diagram can be constructed for the reaction of the methoxymethyl cation with acetone.

TABLE 1. GENERATION OF (UN)LABELLED FORMALDEHYDE FROM THE ION-MOLECULE REACTIONS OF (UN)LABELLED METHOXYMETHYL CATIONS WITH UNLABELLED ACETALDEHYDE AND ACETONE AND [ $^{18}\text{O}$ ]ACETONE, AT 13 eV

reactant ion	substrate	formaldehyde lost		
		$\text{CH}_2\text{O}$	$\text{CD}_2\text{O}$	$\text{CH}_2^{18}\text{O}$
$\text{CH}_3\text{OCD}_2^+$	$\text{CH}_3\text{CHO}$	—	×	—
$\text{CD}_3\text{OCH}_2^+$	$\text{CH}_3\text{CHO}$	×	—	—
$\text{CD}_3\text{OCD}_2^+$	$\text{CH}_3\text{CHO}$	—	×	—
$\text{CH}_3\text{OCD}_2^+$	$(\text{CH}_3)_2\text{CO}$	—	×	—
$\text{CD}_3\text{OCH}_2^+$	$(\text{CH}_3)_2\text{CO}$	×	—	—
$\text{CD}_3\text{OCL}_2^+$	$(\text{CH}_3)_2\text{CO}$	—	×	—
$\text{CH}_3\text{OCH}_2^+$	$(\text{CH}_3)_2\text{C}^{18}\text{O}$	×†	—	—

† This remains unchanged over an electron energy range of 13–50 eV.

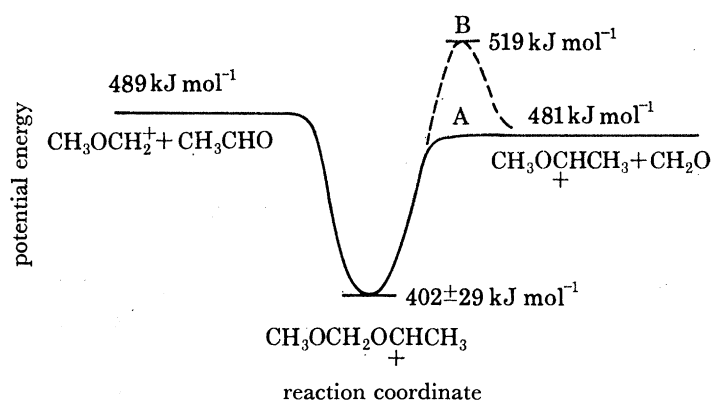


FIGURE 4. Reaction coordinate diagram illustrating the energetics of the possible reaction between the methoxymethyl cation and acetaldehyde. Route A corresponds to a methyl shift and route B to a methoxyl shift in the collision complex before formation of the products (see text).

Route B in figure 4 will not be accessible if the methoxymethyl cations are in their ground state. However, their internal energy may be 2.5 eV before scrambling of the hydrogen atoms starts and 3.6 eV before decomposition by loss of methane happens according to a gas phase study of some simple oxonium ions (Hvistendahl *et al.* 1975). The value of 2.5 eV is in excellent agreement with our value of about 2.3 eV for the onset of H–D scrambling (1,3-H shifts) in long-lived methoxymethyl cations from dimethyl ether, determined by i.c.r. in the following way: ion-molecule reactions of methoxymethyl cations, generated by 12–50 eV electrons, with acetone have shown that part of the collision complexes eliminate formaldehyde containing the original hydrogen atoms of the methoxymethyl cations at random, as indicated by the labelling results given in table 2.

Calibration of the appearance energy value for the formation of the product ions of the reaction of  $\text{CD}_3\text{OCH}_2^+$  ions with acetone by loss of  $\text{CHDO}$  (see table 2) against the appearance

energy value for the formation of  $\text{CD}_3\text{OCH}_2^+$  ions and the ionization energy of  $\text{CD}_3\text{OCH}_3^+$  taken to be identical with the known ionization energy of  $\text{CH}_3\text{OCH}_3^+$  ions (10.00 eV), then yields the above-mentioned 2.3 eV as threshold energy for H-D scrambling in long-lived methoxymethyl cations.

Reaction pathway B in figure 4 should therefore certainly become accessible when higher electron energies are used to generate methoxymethyl cations. The observation that the reaction between the methoxymethyl cation and  $[\text{^{18}O}]$ acetone does not result in any loss of  $\text{CH}_2^{18}\text{O}$  from the collision complex over an electron energy range of 13–50 eV (see table 1) may thus be taken as evidence against the occurrence of collision complex I in (7).

TABLE 2. LABEL DISTRIBUTIONS† (PERCENTAGES) IN THE NEUTRAL FORMALDEHYDE GENERATED FROM THE ION-MOLECULE REACTIONS OF (UN)LABELLED METHOXYMETHYL CATIONS WITH (UN)LABELLED ACETONE AS A FUNCTION OF THE ELECTRON ENERGY

reactant ion	substrate	formaldehyde lost	electron energy/eV					
			12	13	14	15	20	50
$\text{CH}_3\text{OCD}_2^+$	$(\text{CH}_3)_2\text{CO}$	$\text{CH}_2\text{O}$	0	4	7	9	16	13
		$\text{CHDO}$	0	1	10	12	18	19
		$\text{CD}_2\text{O}$	100	95	83	79	66	67
$\text{CD}_3\text{OCH}_2^+$	$(\text{CH}_3)_2\text{CO}$	$\text{CH}_2\text{O}$	100	97	90	83	71	74
		$\text{CHDO}$	0	2	7	11	19	18
		$\text{CD}_2\text{O}$	0	1	3	6	10	8
$\text{CH}_3\text{OCH}_2^+$	$(\text{CD}_3)_2\text{CO}$	$\text{CH}_2\text{O}$	—	—	100	—	—	> 99
		$\text{CHDO}$	—	—	0	—	—	< 1
		$\text{CD}_2\text{O}$	—	—	0	—	—	0

† The limits of error in the values are estimated to be 5%.

Apparently, (7) proceeds through collision complex II and may be regarded as a nucleophilic displacement reaction, a reaction type that has been observed earlier in the field of gas-phase ion-molecule chemistry (Olmstead & Brauman 1977).

An interesting implication of this i.c.r. study is that the activated complex for methyl migration in the  $[\text{M}-\text{methyl}]^+$  ion of methoxymethyl isopropyl ether, discussed above, possibly has the same structure as collision complex II.

## CONCLUSION

In this paper, evidence is presented that shows that the use of modern physical methods in mass spectrometry combined with isotopic labelling provides a detailed picture of the chemistry of ions in the gas phase. This might seem to be stating the obvious until it is recalled that only 25 years ago little if anything was known about the chemistry of isolated and charged species in the gas phase.

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