circumstances, it is desirable to have the organic phase somewhat volatile to facilitate the separation of the ether produced. The methyl propyl ether is very volatile (bp < 40 °C) and a high boiling solvent seemed preferable. Propyl alcohol is very soluble in water and a polar solvent was chosen to help keep the alcohol partitioned in the organic phase. The organic solvent chosen was chlorobenzene.

0.0625 mol of propanol	6 mL
tetrabutylammonium iodide (TBAI)	0.125 g
chlorobenzene	25 mL
0.1625 mol 50% NaOH solution	9 mL
0.075 mol dimethyl sulfate	7 mL
concentrated NH_4OH	1.5 mL
total volume =	49 mL

Propanol, chlorobenzene, and TBAI are mixed and allowed to equilibrate with the NaOH solution for 15–30 min. During this step, the mixture is cooled in an ice bath to absorb the heat evolved. The dimethyl sulfate is added dropwise over a period of 45–60 min. The ice bath is continued during this step. Considerable foaming and thickening of the mixture occurs. The reaction must be carefully monitored to ensure that vigorous stirring is maintained. The ice bath is removed and replaced with a water bath. The mixture is allowed to stir for 2 h. At this point, the reaction should be complete. Concentrated NH_4OH is added and stirred for an additional 30 min to destroy any unreacted dimethyl sulfate. The mixture is washed over water and the organic phase is retained. Care must be taken to be sure that the organic phase is retained. The first washing produces an organic phase that is less dense than the basic aqueous phase. The next washing produces an aqueous phase that is less dense than the organic phase. Presence of the ether was confirmed by EI mass spectrometry using the HP 5993B GC/MS and a published EI mass spectrum.[76] Reaction efficiency was not investigated and the sample was not further purified. Determination of the retention time was completed with use of the ether dissolved in chlorobenzene. This synthesis was also used to make 2-methoxypropane (isopropyl methyl ether) from isopropyl alcohol.

Registry No. $CH_3CH_2CH_2Br$, 106-94-5; CH_3O^-, 3315-60-4.

---

[76] Heller, S. R.; Milne, G. W. A. *EPA/NIH Mass Spectral Data Base*, National Standard Reference Data Series: NSRDS-NBS63; U.S. Dept. of Commerce, U.S. Government Printing Office: Washington, D.C., 1978.

Experimental Study of the Potential Energy Surface of the Protonated Cyclohexene Oxide/Cyclohexanone System. Isomerization, Dissociation, and Ion–Molecule Reactions of the Isolated Ions in the Gas Phase

Hilkka I. Kenttämaa,* Robin R. Pachuta,† Arlene P. Rothwell, and R. Graham Cooks

Contribution from the Department of Chemistry, Purdue University, West Lafayette, Indiana 47907. Received May 25, 1988

Abstract: The structures and properties of gaseous protonated cyclohexene oxide and cyclohexanone are studied by employing dissociation and ion–molecule reactions occurring in a triple quadrupole mass spectrometer, a quadrupole ion trap, and a hybrid BQ tandem mass spectrometer. Upon activation by collisions with either a gas-phase target or a surface, isomerization occurs and results in identical dissociation products with similar abundances for the two ions. This is explained by the small barrier of isomerization (ca. 12 kcal/mol) estimated for the epoxide ion. The product arising from the lowest energy dissociation reaction (H_2O loss) is the cyclohexenyl cation and not a methylcyclopentenyl cation as suggested earlier. In contrast to its behavior in superacid media, cyclohexenyl cation does *not* undergo facile ring contraction in the gas phase. Protonated cyclohexene oxide and protonated cyclohexanone do have distinct structures at low internal energies, as indicated by their different product distributions from gas-phase reactions with various organic reagents, including 1,3-pentadiene, dimethoxymethane, crotonaldehyde, and methyl formate. Reactivity with ethyl vinyl ether is particularly noteworthy since this reagent forms, in great abundance, a stable adduct with the epoxide ion but not with ions incorporating other oxygen-containing functionalities, e.g. protonated ketones, esters, ethers, and alcohols. The mechanism of the adduct formation reaction is discussed. The proton affinity of cyclohexene oxide was determined by energy-resolved bracketing experiments, a technique in which a proton-transfer reaction is judged as endo- or exothermic on the basis of its dependence on the reactant ion kinetic energy. The value for cyclohexene oxide was found to be 202 ± 5 kcal/mol, which yields a heat of formation for protonated cyclohexene oxide of 135 ± 5 kcal/mol. Results obtained by examination of the dissociation and ion–molecule reaction products of parent ions with differing amounts of internal energy, and determination of kinetic energy thresholds for collision-activated dissociation reactions of stable parent ions, indicate that about 10 kcal/mol is required for isomerization as well as for water loss from protonated cycylohexene oxide. The potential energy surface obtained for the protonated cyclohexene oxide/cyclohexanone system is compared with those calculated or estimated earlier for other epoxides.

Acid-catalyzed reactions involving opening of an epoxide ring are of wide interest.[1-6] Aside from their synthetic importance, acid-catalyzed nucleophilic addition reactions of epoxides play an important role in metabolic activation of carcinogens.[1,6-9] Accordingly, many experimental studies have focused on the mechanisms and energetics of reactions of protonated epoxides in condensed phases.[1-5,8] Several groups have employed theoretical calculations to gain a better understanding of the parameters

---

[†] Current address: General Mills, Inc., James Ford Bell Technical Center, 9000 Plymouth Ave., Minneapolis, MN 55427.

[1] Parker, R. E.; Isaacs, S. *Chem. Rev.* **1959**, *59*, 737.

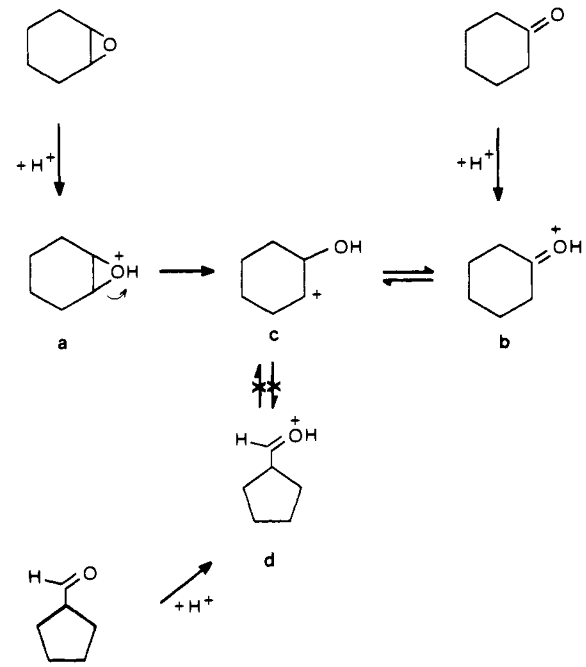
[2] Hulbert, P. B. *Nature (London)* **1975**, *256*, 146.

[3] Yang, S. K.; McCourt, D. W.; Gelboin, H. V. *J. Am. Chem. Soc.* **1977**, *99*, 5130.

[4] (a) Berti, G.; Canedoli, S ; Crotti, P.; Macchia, F. *J. Chem. Soc., Perkin Trans. 1* **1984**, 1184. (b) Crotti, P.; Ferretti, M.; Macchia, F.; Stoppioni, A. *J. Org. Chem.* **1984**, *49*, 4706, and references therein.

0002-7863/89/1511-1654$01.50/0

Scheme I



controlling the intrinsic reactivity of epoxides in the absence of solvents.[8,10-13] Unfortunately, hardly any experimental results exist to complement these studies. In fact, ethylene oxide and propylene oxide are still the only simple protonated epoxides for which gas-phase experimental data other than product distributions of dissociation reactions are available.[14-17] It follows that many fundamental questions remain unanswered, such as whether protonated epoxides other than ethylene oxide are intrinsically stable species.

Extensive studies utilizing various mass spectrometric methods have demonstrated that protonated ethylene oxide is thermodynamically as well as kinetically stable in the gas phase.[14,18] The epoxide ion and its more stable isomer, protonated acetaldehyde, are separated by a high-energy intermediate, a *primary carbocation*, which represents the highest energy point on the potential energy surface between the protonated epoxide and protonated acetaldehyde.[13] In contrast, the dissociation products of protonated 1- and 2-phenylpropylene oxides generated by methane chemical ionization of the corresponding neutral molecules suggest that these ions rapidly interconvert with various isomeric structures.[19] These protonated epoxides produce a *delocalized* carbocation upon ring opening.

The results currently available for protonated epoxides producing a *secondary* carbocation upon ring opening are inconsistent. Isomerization of protonated propylene oxide[16,17,24,25] and protonated butylene oxide[26] has been estimated to require only 3-5 kcal/mol. If the barrier for ring opening of protonated epoxides to generate a second carbocation were indeed very low, isomerization of the epoxides should, upon activation, be very fast. However, while the data obtained from collision-activated dissociation[20] studies suggest that protonation of cyclohexene oxide and cyclohexanone in the gas phase yields ions with the same structure(s),[21] protonated 2-pentene oxide[22] has been found to be a stable, noninterconverting species. Protonated propylene oxide apparently interconverts with protonated propanal when generated by methane or isobutane chemical ionization[16,17] but not when generated by ion–molecule reactions occurring in pure propylene oxide after electron impact (self-chemical ionization).[23]

A well-known possible complication in isomer differentiation by dissociation reactions arises from the fact that some isomeric ions produce *identical fragmenting structures* or *fragment via the same intermediates*. Many hydrocarbon ions present examples of this kind.[27,28] If protonated cyclohexene oxide (a, Scheme I) and protonated cyclohexanone (b, Scheme I) both rearrange to a secondary carbocation structure (c, Scheme I) in the course of fragmentation, as their similar dissociation products suggest,[21] it may not be possible to differentiate the ions a and b on the basis of their dissociation reactions. The ion c is not expected to be a stable species.[21,29] However, it does not undergo a fast ring-contraction reaction to form the ion d (Scheme I), as indicated by the finding that protonated cyclopentane carboxaldehyde (d) produces different fragmentation products from those found for a and b.[21]

We report here a gas-phase experimental study of the structures, thermochemistry, and reactions of protonated cyclohexene oxide and its isomer, protonated cyclohexanone. Tandem mass spectrometry with collision-activated[20] and surface-induced dissociation,[30,31] as well as low-energy ion–molecule reactions,[27] were employed to examine the properties of the ions. The results show that protonated cyclohexene oxide is a stable species in the gas phase. The same conclusion probably applies to many other simple protonated epoxides that generate a secondary carbocation upon ring opening. However, special care must be taken in order to avoid isomerization of these species in the gas phase due to excess energy deposited in the ions upon generation or during analysis of their structures.

Experimental Section

Collision-activated dissociation experiments using a gas-phase target, and most of the ion–molecule reaction experiments, were carried out with a Finnigan 4500 triple quadrupole mass spectrometer.[32] Unless otherwise specified, ions were generated by chemical ionization using isobutane as the reagent gas at a nominal pressure of about 0.4 Torr, as read by a Pirani gauge. The ion source temperature was 100–150 °C. To measure ionic products from dissociation or ion–molecule reactions of mass-selected ions, the instrument was set to perform daughter scans; i.e.,

---

(5) Crotti, P.; Dell'Omodarme, G.; Ferretti, M.; Macchia, F. *J. Am. Chem. Soc.* **1987**, *109*, 1463, and references therein.

(6) Sims, P.; Grover, P. L. *Adv. Cancer Res.* **1974**, *20*, 165.

(7) Jerina, D. M.; Daly, J. W. *Science* **1974**, *185*, 573.

(8) Ferrell, J. E., Jr.; Loew, G. H. *J. Am. Chem. Soc.* **1979**, *101*, 1385, and references therein.

(9) Agarwal, S. K.; Sayer, J. M.; Yeh, H. J. C.; Pannell, L. K.; Hilton, B. D.; Pigott, M. A.; Dipple, A.; Yagi, A.; Jerina, D. M. *J. Am. Chem. Soc.* **1987**, *109*, 2497.

(10) Hopkinson, A. C.; Lien, M. H.; Csizmadia, I. G.; Yates, K. *Theor. Chim. Acta* **1978**, *47*, 97.

(11) Lischka, H.; Kohler, H. *J. Chem. Phys. Lett.* **1979**, *63*, 326.

(12) Nobes, R. H.; Rodwell, W. R.; Bouma, W. J.; Radom, L. *J. Am. Chem. Soc.* **1981**, *103*, 1913.

(13) Ford, G. P.; Smith, C. T. *J. Am. Chem. Soc.* **1987**, *109*, 1325.

(14) Staley, R. H.; Corderman, R. R.; Foster, M. S.; Beauchamp, J. L. *J. Am. Chem. Soc.* **1974**, *96*, 1260.

(15) Bowen, R. D.; Kalman, J. R.; Williams, D. H. *J. Am. Chem. Soc.* **1977**, *99*, 5481.

(16) Bowen, R. D.; Harrison, A. G. *Org. Mass Spectrom.* **1981**, *20*, 159.

(17) Harrison, A. G.; Gäumann, T.; Stahl, D. *Org. Mass Spectrom.* **1983**, *18*, 517.

(18) Van de Graaf, B.; Dymerski, P. P.; McLafferty, F. W. *J. Chem. Soc., Chem. Commun.* **1975**, 978.

(19) Audier, H.-E.; Bouchoux, G.; Milliet, A.; Denhez, J.-P.; Maquestiau, A.; Flammang, R. *J. Chem. Res., Miniprint* **1982**, 943.

(20) McLafferty, F. W., Ed. *Tandem Mass Spectrometry*; Wiley: New York, 1983.

(21) Wolfschütz, R.; Schwarz, H.; Blum, W.; Richter, W. J. *Org. Mass Spectrom.* **1979**, *14*, 462.

(22) Headley, J. V.; Harrison, A. G. *Can. J. Chem.* **1985**, *63*, 609.

(23) Bowers, M. T.; Morgan, R. P.; Beynon, J. H. Unpublished results quoted in ref 16.

(24) Bowen, R. D.; Kalman, J. R.; Williams, D. H. *J. Am. Chem. Soc.* **1977**, *99*, 5481.

(25) Bowen, R. D.; Williams, D. H.; Hvistendahl, G.; Kalman, J. R. *Org. Mass Spectrom.* **1978**, *13*, 721.

(26) Audier, H. E.; Milliet, A.; Perret, C.; Vareene, P. *Org. Mass Spectrom.* **1979**, *14*, 129.

(27) See, for example: Levsen, K. *Fundamental Aspects of Organic Mass Spectrometry*; Verlag Chemie: New York, 1978.

(28) Bowen, R. D.; Williams, D. H.; Schwarz, H. *Angew. Chem., Int. Ed. Engl.* **1979**, *18*, 451.

(29) Gäumann, T.; Houriet, R.; Stahl, D.; Tabet, J.-C.; Heinrich, N.; Schwarz, H. *Org. Mass Spectrom.* **1983**, *18*, 215.

(30) Mabud, Md. A.; DeKrey, M. J.; Cooks, R. G. *Int. J. Mass Spectrom. Ion Processes* **1985**, *67*, 285.

(31) DeKrey, M. J.; Mabud, Md. A.; Cooks, R. G.; Syka, J. E. P. *Int. J. Mass Spectrom. Ion Processes* **1985**, *67*, 295.

(32) Slayback, J. R. B.; Story, M. S. *Ind. Res. Dev.* **1981**, 129.

the first quadrupole was fixed at the mass value of the ion of interest, and the third quadrupole was scanned for the products. For collision-activated dissociation experiments, argon was introduced into the center quadrupole at a nominal pressure of about 2 mTorr (as read by a Hastings thermocouple gauge directly connected to the quadrupole collision chamber) for multiple-collision conditions and less than 0.1 mTorr for single-collision conditions (indicated pressure ca. 5 × 10^{-7} Torr read on a Bayard–Albert ionization gauge situated outside the collision chamber).[33] For ion–molecule reaction experiments,[34-42] neutral organic reagents were introduced into the center quadrupole at a nominal pressure of about 4 mTorr (multiple-collision conditions), unless otherwise specified. The voltages on the various focusing lenses before and after the center quadrupole, as well as the potential difference between the second and the third quadrupole, were adjusted to maximize the abundances of dissociation or ion–molecule reaction products,[43] as required.

The potential difference between the ion source (ground potential) and the center quadrupole determines the axial kinetic energy, or collision energy, of the reactant ions arriving in the collision region. For most ion–molecule reaction experiments, the collision energy was 0.5–1 eV (laboratory frame, E_{lab}), unless otherwise specified. In the energy-resolved experiments, successive daughter spectra were recorded as the collision energy was increased in small increments up to ca. 30 eV (E_{lab}). Energy-resolved data for the dissociation reactions were constructed on the basis of peak intensities normalized at each energy to total fragment ion current or to the most intense peak.

All kinetic energy threshold determinations[39,42,44] were carried out under single-collision conditions. Retarding potential experiments[44] (the center quadrupole retarding) were used to locate the zero of the energy axis. The results indicated a kinetic energy spread for the parent ions of about 3.5 eV (fwhm) (1.0 eV in the center-of-mass frame, E_{cm}, for argon target), which is comparable to that reported for other triple quadrupole instruments.[44,45] The reproducibility of our threshold values was ±0.2 eV (E_{cm}) or better. The threshold energies obtained with this methodology for certain dissociation reactions of protonated acetaldehyde were somewhat larger than the values presented[39] in an earlier study utilizing a similar instrument but a somewhat different procedure to deduce the threshold values from experimental data. By assuming a linear dependence of the cross sections on collision energy and correcting for the thermal motion of the target,[46] we obtained thresholds of 4.9 eV (E_{cm}) and 6.7 eV (precision ±0.2 eV) for formation of the fragment ions 27^+ and 30^+, respectively, while the corresponding values presented[39] earlier are 4.0 ± 0.2 eV for 27^+ and 6.2 ± 0.2 eV for 30^+. However, in the earlier study,[39] the parent ion (protonated acetaldehyde) was generated by dissociative electron ionization of 2-propanol by using 11.0–11.5 eV electrons. These protonated acetaldehyde ions may contain up to 1.3 eV excess internal energy when they leave the ion source.[39] This possible excess energy may lead to lower threshold values than is obtained in our experiments where the parent ions were generated by isobutane chemical ionization of the corresponding neutral molecules. The parent ions may contain up to 0.4-eV excitation energy from the protonation reaction in these experiments.

A custom-built hybrid instrument[30] equipped with a magnetic analyzer for mass selection of the parent ions and a quadrupole mass filter for analysis of the products was used to examine dissociation reactions induced by collisions with a stainless steel surface (surface-induced dissociation, SID).[30,31] Ions were generated by isobutane chemical ionization in a source held at a potential in the range of 25–100 V with respect to ground. The ion beam was accelerated to 6 keV prior to mass selection by the magnetic sector and decelerated to ground potential prior to collision with the stainless steel surface. All data were taken with an incident angle of 25° (estimated uncertainty 3°) with respect to the surface normal. The angle of deviation was 121° from the original beam direction. Energy-resolved data were recorded as discussed for the triple quadrupole instrument.

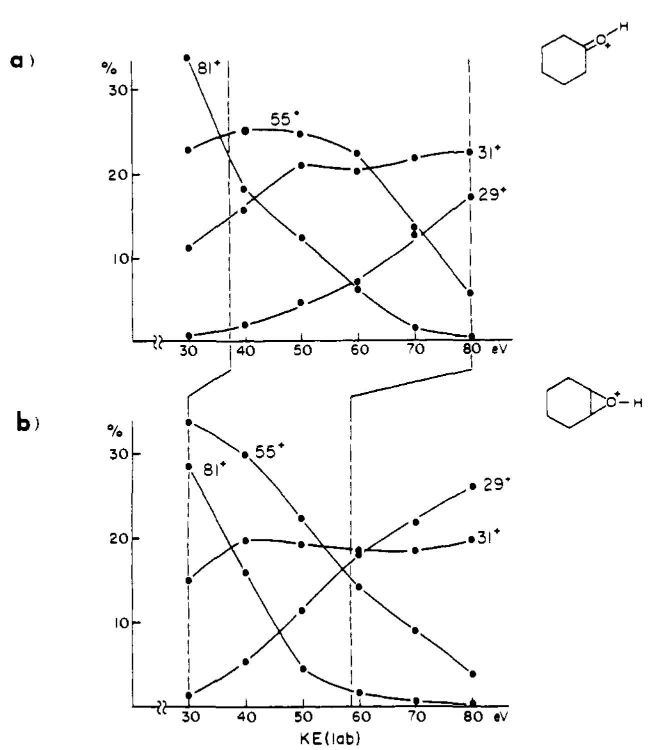


Figure 1. Energy-resolved data obtained by surface-induced dissociation for (a) protonated cyclohexanone and (b) protonated cyclohexene oxide (the most abundant fragment ions are shown). The data are normalized to total fragment ion current at each energy. The energy range where fragmentation of the ketone resembles that obtained for the epoxide is indicated by dotted lines.

Some ion–molecule reaction experiments were carried out with a Finnigan 700 quadrupole ion trap detector,[47,48] which had been slightly modified, as described earlier.[47] The ion trap was not heated for these experiments. Helium buffer gas was introduced at an uncorrected ion gauge pressure of about 2.6 × 10^{-5} Torr (corresponding approximately to 10^{-3} Torr in the trap), and the indicated pressures of cyclohexene oxide, cyclohexanone, and ethyl vinyl ether were each ca. 1 × 10^{-7} Torr. After an ionization time (electron beam gated on) of about 8–12 ms and an additional reaction time (electron beam gated off) of about 2.3 ms, a radio frequency pulse (0.02–0.2 ms) was used to eject all ions with mass values below the mass values of the ions of interest. After this, the radio-frequency voltage level was reduced in order to trap all product ions formed during the ensuing reaction period, which was varied from 0.1 to 3000 ms. The products were detected in ca. 1 s by a final scan of the radio-frequency voltage. Ten scans were accumulated to produce the spectra presented here. All the experiments were performed at a frequency of 1.1 MHz with grounded end-cap electrodes.

All the compounds used were high-purity commercial samples, and they were used without further purification.

Results and Discussion

The structures of protonated cyclohexene oxide and protonated cyclohexanone were examined by activating them by one or more collisions with a gas-phase target[20] and determining the collision-activated dissociation (CAD) product distributions as a function of collision energy (energy-resolved mass spectrometry, ERMS).[20] This method allows one to examine the effects of ion internal energy on fragmentation patterns and enables differen-

---

(33) Kenttämaa, H. I.; Cooks, R. G. *J. Am. Chem. Soc.* **1985**, *107*, 1881.

(34) Batey, J. H.; Tedder, J. M. *J. Chem. Soc., Perkin Trans. 2* **1983**, 1263.

(35) See, for example: (a) Fetterolf, D. D.; Yost, R. A. *Int. J. Mass Spectrom. Ion Processes* **1984**, *62*, 33. (b) Fetterolf, D. D.; Yost, R. A.; Eyler, J. R. *Org. Mass Spectrom.* **1984**, *19*, 104. (c) Tabet, J. C.; Guenat, C. *Adv. Mass Spectrosc., Part B* **1985**, 831.

(36) Jalonen, J. *J. Chem. Soc., Chem. Commun.* **1985**, 872.

(37) Glish, G. L.; Hemberger, P. H.; Cooks, R. G. *Anal. Chim. Acta* **1980**, *119*, 137.

(38) (a) Schmit, J. P.; Dawson, P. H.; Beaulieu, N. *Org. Mass Spectrom.* **1985**, *20*, 269. (b) Schmit, J. P.; Beaudet, S.; Brisson, A. *Org. Mass Spectrom.* **1986**, *21*, 493.

(39) Kinter, M. T.; Bursey, M. M. *J. Am. Chem. Soc.* **1986**, *108*, 1797.

(40) White, E. L.; Tabet, J.-C.; Bursey, M. M. *Org. Mass Spectrom.* **1987**, *22*, 132.

(41) Kinter, M. T.; Bursey, M. M. *Org. Mass Spectrom.* **1987**, *22*, 775.

(42) Graul, S. T.; Squires, R. R. *Int. J. Mass Spectrom. Ion Processes* **1987**, *81*, 183.

(43) Pachuta, R. R.; Kenttämaa, H. I.; Cooks, R. G.; Zennie, T. M.; Ping, C.; Chang, C.-j.; Cassady, J. M. *Org. Mass Spectrom.* **1988**, *23*, 10.

(44) Douglas, D. J. *J. Phys. Chem.* **1982**, *86*, 185.

(45) Dawson, P. H.; French, J. B.; Buckley, J. A.; Douglas, D. J.; Simmons, D. *Org. Mass Spectrom.* **1982**, *17*, 205.

(46) Chantry, P. J. *J. Chem. Phys.* **1971**, *55*, 2746.

(47) Brodbelt, J. S.; Louris, J. N.; Cooks, R. G. *Anal. Chem.* **1987**, *59*, 1278.

(48) Stafford, G. C., Jr.; Kelley, P. E.; Syka, J. E. P.; Reynolds, W. E.; Todd, J. F. J. *Int. J. Mass Spectrom. Ion Processes* **1984**, *60*, 85.

Table I. Energy-Resolved Collision-Activated Dissociation Spectra of Protonated Cyclohexene Oxide and Protonated Cyclohexanone (Multiple-Collision Conditions, Triple Quadrupole Mass Spectrometer)

	laboratory ion kinetic energy, eV	relative abundance,[a] %, at *m*/*z* = 41	55	77	79	81
protonated cyclohexene oxide	5	1	14	1	18	65
	10	8	20	5	18	50
	15	15	27	7	18	33
	20	32	27	7	11	22
	25	42	23	9	12	15
protonated cyclohexanone	5	<1	7	2	16	76
	10	3	15	4	22	56
	15	10	22	7	22	39
	20	23	25	9	19	24
	25	37	24	15	9	15

[a] Normalized at each energy to the sum of the abundances of the fragment ions shown.

tiation of many isomeric ions even when they produce identical dissociation products at a given energy.[33,49-52] Further, a new mass spectrometric technique was also employed where dissociation is induced by collisions with a surface (surface-induced dissociation, SID).[30,31] This approach has proven to be very sensitive to structural differences in isomeric ions,[28,53,54] especially when applied in the energy-resolved fashion.

Because it is occasionally very difficult to differentiate isomeric ions on the basis of their dissociation reactions for the reasons presented above, ion–molecule reactions were also used to examine the structures of protonated cyclohexene oxide and protonated cyclohexanone. Since the method is based on specific chemical reactivity of the ions toward a selected reagent, rather than on the way in which the ions break apart after excitation, complementary information[14,27,35,52] to dissociation reactions can be obtained. A triple quadrupole mass spectrometer was employed to study the pressure and kinetic energy dependence of interesting reactions, while their time dependence was examined by using a quadrupole ion trap.

Dissociation Reactions. 1. Isomer Differentiation. Protonated cyclohexene oxide and protonated cyclohexanone were found to produce similar dissociation product distributions (Table I; Figures 1 and 2). Variation of collision energy does not facilitate differentiation of the parent ions. This is true for collision-activated as well as surface-induced dissociation. Some of the results are discussed below in detail.

Some minor differences are seen in the dissociation product distributions obtained for protonated cyclohexene oxide and protonated cyclohexanone but these differences are more likely due to different amounts of internal energy present in the fragmenting ions than due to different ion structures. For example, when activated by *a single* collision with argon, the protonated epoxide undergoes dehydration (to produce a fragment 81^+) somewhat more readily than the protonated ketone (data not shown). The protonated epoxide is a higher energy species than the keto form (the proton affinities of the epoxide and the ketone are comparable, but the neutral epoxide has a higher heat of formation; for thermochemical data, see below). Thus, if the same ion structure or mixture of structures is generated from protonated cyclohexene oxide and protonated cyclohexanone during the experiment, those generated from the epoxide will at least initially have a higher internal energy content. These ions can therefore be expected to fragment more readily than those generated from the ketone, as is observed.

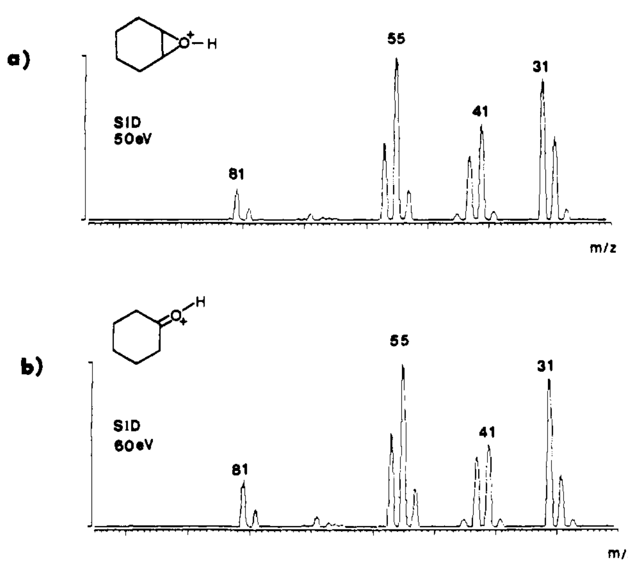


Figure 2. Surface-induced dissociation spectrum of (a) protonated cyclohexene oxide (99^+) at 50 eV collision energy (laboratory frame) and (b) protonated cyclohexanone (99^+) at 60 eV collision energy (lab).

When ion activation was accomplished by *multiple* collisions with argon, the ions generated from the epoxide again gave a larger relative amount of high-energy products at a given collision energy than those generated from the ketone (Table I). For example, the abundances of the fragments 79^+ and 55^+ are equal at about 10 eV collision energy (lab) for cyclohexene oxide, but 15 eV is required for this to be true for cyclohexanone (Table I). The same applies to surface-induced dissociation where the energy-resolved data obtained for the ketone are reproduced by the epoxide ion but shifted to a lower energy range (Figure 1). These differences are again readily explained on the basis of different amounts of internal energy present in the fragmenting ions. This internal energy effect is clearly demonstrated by the spectra shown in Figure 2; practically identical product distributions are obtained for the epoxide and the ketone by using a laboratory collision energy of 50 eV for the former and 60 eV for the latter. Thus, the ions generated from the epoxide require *less* activation than those obtained from the ketone to yield the same product distribution, in agreement with the discussion presented above.

In conclusion, the differences seen in the dissociation product distributions of the ions generated by protonating cyclohexene oxide and cyclohexanone cannot be used to decide whether the low-energy parent ions are distinct, noninterconverting species. However, the fragmentation patterns strongly suggest that at some stage during the experiment, the parent ions isomerize to or fragment via a common structure, probably c (Scheme I).

2. Structure of the Major Fragment Ion. At low internal energies, protonated cyclohexene oxide and protonated cyclohexanone mainly dissociate by loss of H_2O to yield an ion 81^+. The mechanism of dehydration of protonated cyclohexanone has received attention recently.[21,29,55,56] On the basis of high-energy (keV) collisional activation experiments with protonated 1,3- and 1,4-cyclohexadiene as reference ions, the dehydration product of protonated cyclohexanone, as well as that of protonated cyclohexene oxide, was concluded[29] to have the 1-methylcyclopentenyl structure and not the expected cyclohexenyl structure. These cations were estimated to be nearly equally stable, with a high energy barrier (about 47 kcal/mol) separating them.[29] Since authentic methylcyclopentenyl cations were not examined in the

---

(49) Fetterolf, D. D.; Yost, R. A. *Int. J. Mass Spectrom. Ion Phys.* **1982**, *44*, 37.

(50) Verma, S.; Ciupek, J. D.; Cooks, R. G. *Int. J. Mass Spectrom. Ion Processes* **1984**, *62*, 219.

(51) Zwinselman, J. J.; Nacson, S.; Harrison, A. G. *Int. J. Mass Spectrom. Ion Processes* **1985**, *67*, 93.

(52) Holmes, J. L. *Org. Mass Spectrom.* **1985**, *20*, 169, and references therein.

(53) Mabud, Md. A.; Ast, T.; Verma, S.; Jiang, Y.-X.; Cooks, R. G. *J. Am. Chem. Soc.* **1987**, *109*, 7597.

(54) Hayward, M. J.; Mabud, Md. A.; Cooks, R. G. *J. Am. Chem. Soc.* **1988**, *110*, 1343.

(55) Diakiw, V.; Goldsack, R. J.; Shannon, J. S.; Lacey, M. J. *Org. Mass Spectrom.* **1978**, *13*, 462.

(56) Heinrich, N.; Wolfschütz, R.; Frenking, G.; Schwarz, H. *Int. J. Mass Spectrom. Ion Phys.* **1982**, *44*, 81.

(57) Farcasiu, D.; Craine, L. *J. Chem. Soc., Chem. Commun.* **1976**, 687.

Table II. Energy-Resolved Collision-Activated Dissociation Spectra Obtained by Using Single-Collision Conditions for the Dehydration Product (81^+) of Protonated Cyclohexene Oxide and Protonated Cyclohexanone and for Protonated Cyclohexadiene (81^+) and Protonated Methylcyclopentadiene (81^+)

precursor molecule	laboratory ion kinetic energy, eV	relative abundance, %, at m/z = 29	39	41	53	55
cyclohexene oxide	15	<1	<1	100	27	3
cyclohexanone		<1	<1	100	24	2
cyclohexadiene		<1	<1	100	28	3
methylcyclopentadiene		<1	<1	100	14	1
cyclohexene oxide	23	4	3	100	22	3
cyclohexanone		4	3	100	20	3
cyclohexadiene		3	3	100	21	3
methylcyclopentadiene		1	1	100	12	1
cyclohexene oxide	28	7	7	100	21	3
cyclohexanone		7	7	100	19	3
cyclohexadiene		6	6	100	20	3
methylcyclopentadiene		4	3	100	13	2

study mentioned above and since the ions were generated by methane chemical ionization, a method that usually produces highly energized cations, we decided to reexamine the structures of the dehydration products of protonated cyclohexene oxide and protonated cyclohexanone. A more gentle chemical ionization method[16] (isobutane reagent) was employed to generate the dehydration products and the reference ions, and energy-resolved collision-activated dissociation was used to examine their structures. Protonated 1,3-cyclohexadiene and protonated methylcyclopentadiene were chosen as reference ions. Protonation of these two compounds by *tert*-butyl cation generated from isobutane will yield cyclohexenyl reference ions (probably mainly the 2-cyclohexenyl structure) and methylcyclopentenyl reference ions (probably a mixture of 1-, 2-, and 4-methylcyclopentenyl structures). The exothermicity of the protonation reaction is too small (about 4 kcal/mol) to induce isomerization between the cyclohexenyl and methylcyclopentenyl structures prior to collisional activation (about 47 kcal/mol required,[29] see above).

Table II shows the energy-resolved collision-activated dissociation spectra of the ions 81^+ generated by loss of H_2O from protonated cyclohexene oxide and protonated cyclohexanone and by protonation of 1,3-cyclohexadiene and methylcyclopentadiene. Reproducible differences are seen in the product distributions obtained for the reference ions, protonated methylcyclopentadiene, and protonated 1,3-cyclohexadiene. Moreover, the product ion distributions obtained for protonated 1,3-cyclohexadiene and those obtained for the dehydration products 81^+ generated from both cyclohexanone and cyclohexene oxide are practically identical. The differences seen in the data of the reference ions are not expected to be due to differences in internal energies of the fragmenting ions since the internal energies of protonated 1,3-cyclohexadiene and protonated methylcyclopentadiene must be comparable (the heats of formation and proton affinities of the neutral precursors are comparable).[29] Accordingly, the differences in the fragmentation products of the reference ions were found *not* to be internal energy dependent. For example, the ratio of the abundances of the two major products, 41^+ due to loss of C_3H_4 and 53^+ due to loss of C_2H_4, remains constant over the collision energy range 20–30 eV (lab), being 100:13 for the ions generated from methylcyclopentadiene and 100:22, 100:20, and 10:21 for the ions generated from cyclohexene oxide, cyclohexanone, and 1,3-cyclohexadiene, respectively.

We conclude that most of the ions 81^+ generated by dehydration of protonated cyclohexene oxide and protonated cyclohexanone must have the cyclohexenyl structure and not the methylcyclopentenyl structure. Apparently, the cyclohexenyl cation does not readily undergo a ring-contraction reaction in the gas phase, in contrast to the results obtained with superacid solutions.[58,59]

Scheme II

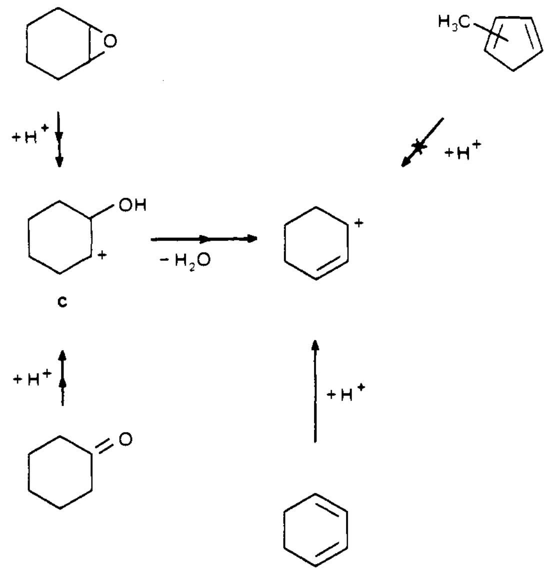
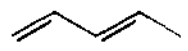
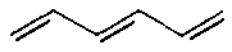
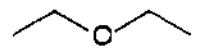
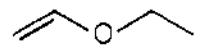
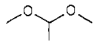
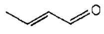
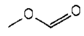


Table III. Differentiation of Protonated Cyclohexanone and Protonated Cyclohexadiene on the Basis of Their Ion–Molecule Reaction Products Formed in the Center Quadrupole of the Triple Quadrupole Mass Spectrometer

reagent in Q2	isomer differentiation	comments
	+	*a*
	–	
	–	
	+	*b*
	+	*c*
	+	*d*
	+	*e*
	+	*b*
CH_3OH	–	
$(CH_3O)_3P$	+	*a*
Ar (CAD)	–	

[a] For example, the protonated epoxide forms a more abundant adduct. [b] See text. [c] Only the protonated ketone forms a major ion formally due to loss of methanol from an adduct with the reagent. [d] The ketone and the epoxide give different amounts of the dehydration product (81^+) and an ion due to loss of methanol from an adduct with the reagent. [e] The protonated ketone forms a more abundant adduct.

Several pathways for formation of a cyclohexenyl cation from protonated cyclohexanone and protonated cyclohexene oxide are conceivable. Recent MNDO calculations[56] suggest that dehydration of protonated cyclohexanone involves initial formation of the carbocation c, as presented in Scheme II.

Ion–Molecule Reactions. 1. Isomer Differentiation. Protonated cyclohexene oxide and protonated cyclohexanone yield different product distributions when allowed to react with various organic reagents in the center quadrupole of the triple quadrupole instrument (Table III). However, in most cases the differences are confined to the relative abundances of common product ions. For example, upon collision with methyl formate, the protonated epoxide gives the dehydration product 81^+ as the most abundant product ion while the products 61^+ and 159^+ (from endothermic proton transfer to methyl formate and formation of a stable complex or adduct with methyl formate, respectively) have relative

---

(58) Seybold, G.; Vogel, P.; Saunders, M.; Wiberg, K. B. *J. Am. Chem. Soc.* **1973**, *95*, 2045.

(59) Beauchamp, J. L.; Dunbar, R. C. *J. Am. Chem. Soc.* **1970**, *92*, 1477.

(60) (a) Lias, S. G.; Liebman, J. F.; Levin, R. D. *J. Phys. Chem. Ref. Data* **1984**, *13*, 695. (b) Lias, S. G.; Bartmess, J. E.; Liebman, J. F.; Holmes, J. L.; Levin, R. D.; Mallard, W. G. *J. Phys. Chem. Ref. Data, Suppl. 1* **1988**, *17*.

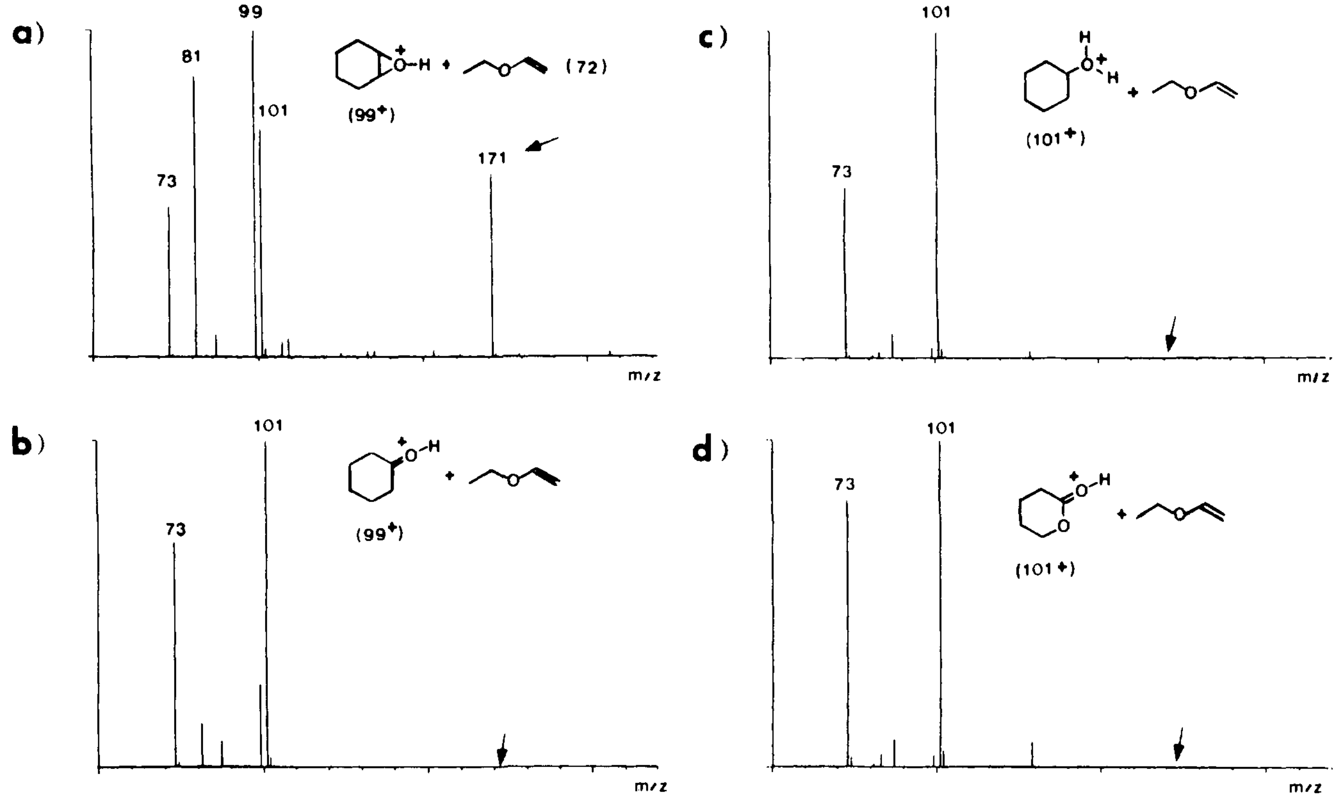


Figure 3. Product ion distributions (MS/MS daughter spectra) obtained for various reactant ions upon collisions with ethyl vinyl ether (ca. 2 mTorr) in the center quadrupole of the triple quadrupole mass spectrometer at ca. 0.5 eV translational energy. The mass value corresponding to the adduct of each reactant ion with ethyl vinyl ether is indicated by an arrow. (a) Protonated cyclohexene oxide (generated by electron impact on a mixture of isobutane and cyclohexene oxide at relatively high sample pressure; see text for discussion), (b) protonated cyclohexanone, (c) protonated cyclohexanol, and (d) protonated δ-valerolactone.

abundances equal to or less than 20% of that of 81^+. In contrast, the keto ion gives the adduct 159^+ and the ion 81^+ as the main products. Proton transfer to methyl formate again results in a minor product ion (61^+).

The case of ethyl vinyl ether will be discussed in detail since this reagent produces *qualitatively* different product distributions for the isomeric parent ions. Ethyl vinyl ether forms an abundant stable complex or adduct (171^+) with the protonated epoxide but not with the protonated ketone (parts a and b of Figure 3). While the observation of a different ion–molecule reaction product for protonated cyclohexene oxide and cyclohexanone suggests that the parent ions have different structures, the finding could also be due to differing amounts of internal energy present in the reacting ions.[59] Therefore, we examined the dependence of the product distributions of these ion–molecule reactions on the internal energy with which the ions are formed in the ion source.

The internal energy of the ions in the ion source was varied by (i) varying the pressure in the ion source and thereby the number of thermalizing collisions that the possibly vibrationally excited ions undergo prior to leaving the ion source[61] and (ii) varying the exothermicity of the protonation reaction by using different protonating reagents,[16] i.e., *tert*-butyl cation from isobutane (proton affinity (PA) of 2-butylene is 196 kcal/mol[60]), protonated diethyl ether (generated by electron impact on diethyl ether at 0.05–0.17 Torr; PA of diethyl ether is 200 kcal/mol[60]), and cyclohexenyl cation from cyclohexene oxide (PA of cyclohexadiene is 200 kcal/mol[29]). Cyclohexenyl cation is the major product formed from cyclohexene oxide upon isobutane chemical ionization. At high sample pressures, it protonates neutral cyclohexene oxide, and is likely to be the major species producing stable protonated cyclohexene oxide in the ion source.

The product distributions obtained for protonated cyclohexene oxide reacting with ethyl vinyl ether were found to depend strongly on the amount of internal energy *initially deposited*, i.e. the nature of the protonating agent, rather than the total pressure in the ion source. When the initial internal energy of the ions was *reduced*, they yielded significantly *more* adduct (171^+) in the center quadrupole (Figure 4). This behavior found for the epoxide at low internal energies is increasingly different from that found for the ketone and thus provides evidence against the possibility that the epoxide and the keto ions isomerize to a common structure prior to or during reaction with ethyl vinyl ether. The protonated epoxide is a higher energy species than the ketone, as noted above. It follows that if the same structure or mixture of structures is generated from these ions, that generated from the epoxide must have a higher internal energy content and *decreasing* the amount of energy of the reacting ions generated from the epoxide should result in behavior *more similar* to that observed for the ions generated from the ketone. The results of Figure 4 suggest a further conclusion; namely, that while the epoxide ions generated with a small amount of internal energy largely retain their structure, many of the ions generated with larger amounts of energy do isomerize and as a result do not form an adduct with ethyl vinyl ether.

2. Mechanism of Adduct Formation between Protonated Cyclohexene Oxide and Ethyl Vinyl Ether. The reaction leading to formation of a stable adduct for the epoxide ion shows characteristics expected[62] for an associative ion–molecule reaction. The product yield has a negative dependence on parent ion kinetic energy (see Figure 6c), which is typical for an exothermic reaction. A second-order dependence of the relative product ion abundance on the pressure of ethyl vinyl ether below 2 mTorr (Figure 5) indicates that a three-body collision is necessary for collisional stabilization of the product. The mechanism probably involves opening of the epoxide ring (route b, Scheme III). The back-reaction is slow, which results in a long enough lifetime for the

---

(61) Illies, A. J.; Liu, S.; Bowers, M. T. *J. Am. Chem. Soc.* **1981**, *103*, 5674.

(62) Bowers, M. T., Ed. *Gas Phase Ion Chemistry*; Academic Press: New York, 1979; Vol. 1.

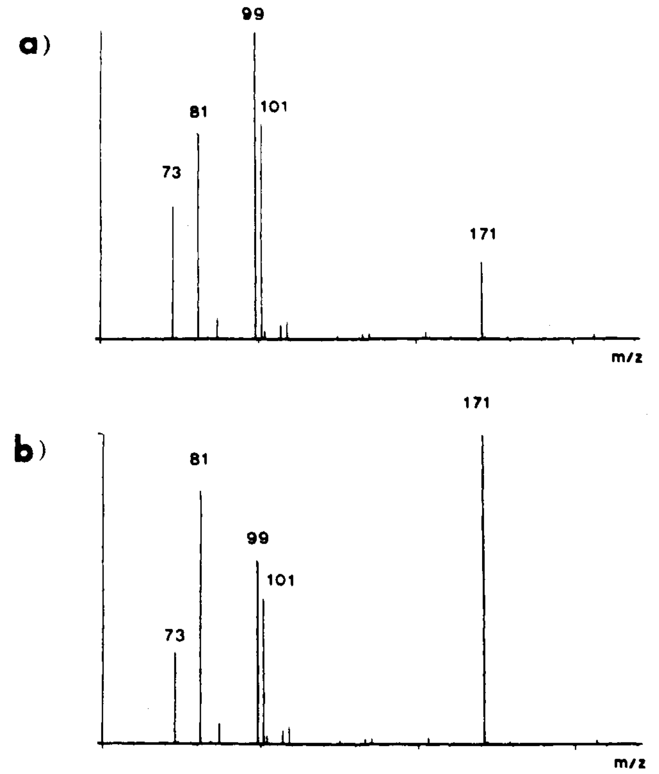


Figure 4. Product ion distributions obtained for protonated cyclohexene oxide upon collisions with ethyl vinyl ether (ca. 2 mTorr) in the center quadrupole of the triple quadrupole mass spectrometer. The ion translational energy was ca. 0.5 eV. A less abundant ionic adduct (171^+) was formed when protonated cyclohexene oxide was generated by (a) isobutane chemical ionization (low sample pressure) instead of (b) a more gentle method (protonation by cyclohexenyl cation under high sample pressure; see text for discussion).

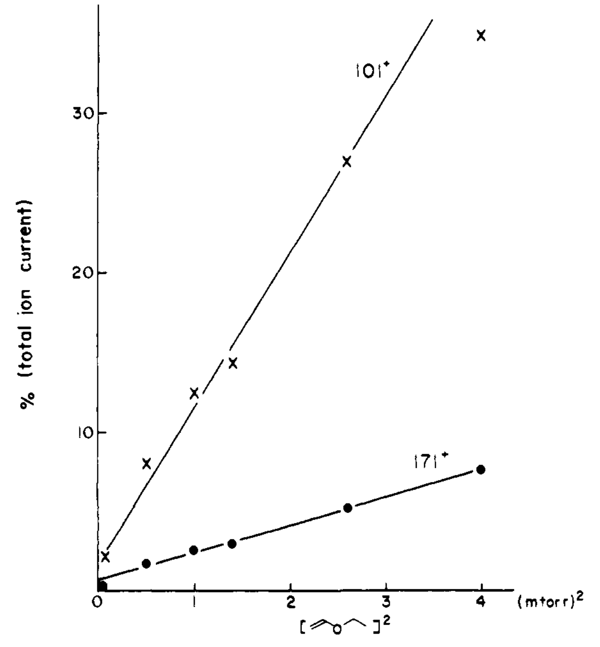
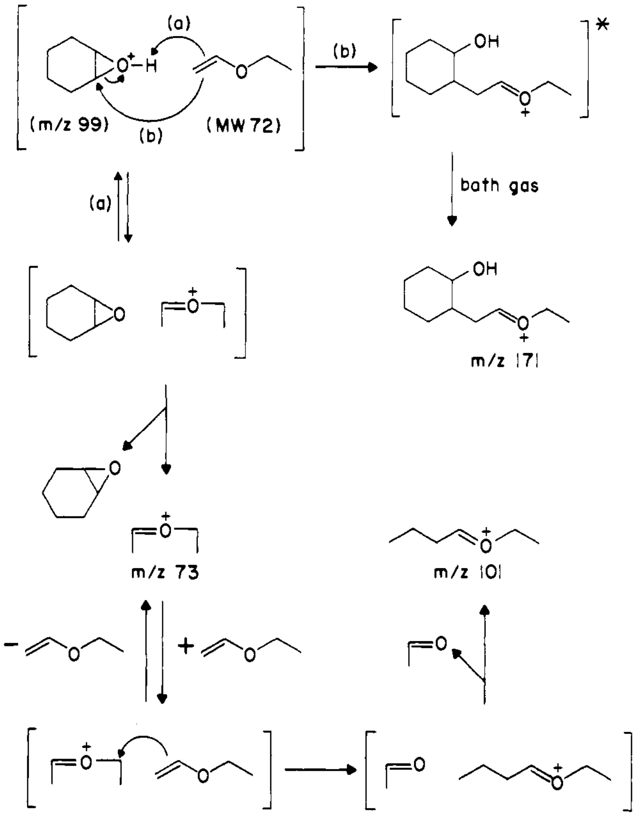


Figure 5. Relative abundances of ethylated ethyl vinyl ether (101^+) and the adduct of protonated cyclohexene oxide and ethyl vinyl ether (171^+) as a function of ethyl vinyl ether pressure. The ions were formed in reactions of protonated cyclohexene oxide (generated by isobutane chemical ionization) and ethyl vinyl ether in the center quadrupole of the triple quadrupole mass spectrometer at 0.6 eV laboratory ion kinetic energy.

Scheme III



high-energy adduct to survive before collisions with additional ethyl vinyl ether molecules (bath gas) remove some of the excess internal energy. The attack of ethyl vinyl ether at the epoxide carbon most probably occurs through a carbon and not the oxygen atom of the neutral reagent. This proposal is supported by the result that diethyl ether, which does not have a nucleophilic carbon atom, does not show a similar selectivity in its reactions. This latter molecule yields an abundant adduct (a proton-bound dimer) with the protonated epoxide as well as the protonated ketone.

Further support for the mechanism in route b of Scheme III is provided by the observation that a stable adduct was not formed when *protonated* ethyl vinyl ether was allowed to react with neutral cyclohexene oxide (see also results presented in ref 63). If the adduct were just a collisionally stabilized proton-bound dimer, it should be formed here as well as upon collision between the protonated epoxide and neutral ether. Apparently, the epoxide (proton affinity estimated to be about 202 kcal/mol; see below) is not basic enough to deprotonate protonated ethyl vinyl ether (proton affinity 208 kcal/mol[60]) and thus to generate, within the collision complex, the nucleophile necessary for adduct formation.

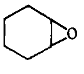
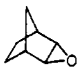
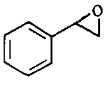
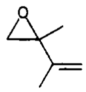
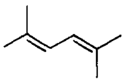
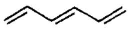
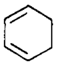
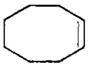
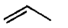
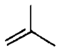
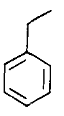
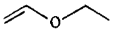
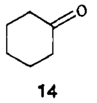
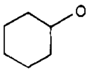
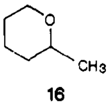
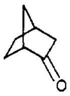
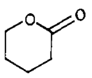
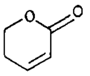
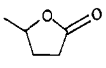
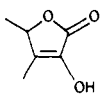
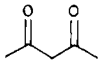
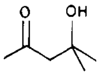
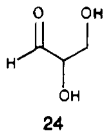
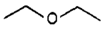
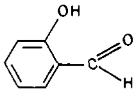
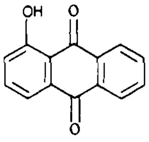
3. Generality of Adduct Formation with Ethyl Vinyl Ether. The generality of formation of a stable adduct with ethyl vinyl ether in the center quadrupole of the triple quadrupole instrument was examined by using different model ions with oxygen-containing functional groups (Table IV). It was found that while protonated cyclohexene oxide (**1**) and protonated *exo*-2,3-epoxynorbornane (**2**) produce stable adducts, many closely related ions do not (e.g., cyclohexanone (**14**), cyclohexanol (**15**), 2-methyltetrahydropyran (**16**), and simple valerolactones (**18**–**20**) (Table IV; see also Figure 3)). Thus, adduct formation can be used to differentiate protonated *exo*-2,3-epoxynorbornane (**2**) from its isomer, protonated norbornanone (**17**), which does not give an adduct with ethyl vinyl ether. Note that these isomeric ions are difficult to distinguish by collisional activation because they yield similar dissociation product distributions on the triple quadrupole mass spectrometer.

Not all protonated epoxides studied form stable adducts with ethyl vinyl ether. While protonated cyclohexene oxide (**1**), protonated *exo*-2,3-epoxynorbornane (**2**), and protonated styrene oxide (**3**) produce stable adducts, protonated 2,4,4-trimethylpentene oxide (**4**) and protonated 3-epoxy-2,3-dimethylbutene (**5**) do not.

---

(63) Keough, T. *Anal. Chem.* **1982**, *54*, 2540.

Table IV. Formation of a Stable Adduct between Some Protonated Molecules and Ethyl Vinyl Ether in the Center Quadrupole of the Triple Quadrupole Mass Spectrometer

adduct obsd	adduct *not* obsd
Epoxides	
 **1**  **2**  **3**	 **4**  **5**
Hydrocarbons	
 **6**  **7**  **8**  **12**	 **9**  **10**  **11**
Others	
 **13**	 **14**  **15**  **16**  **17**  **18**  **19**  **20**  **21**  **22**  **23**  **24**  **25**  **26**  **27**

The former ion (**4**) rapidly decomposes by loss of water upon gas-phase collisions with either argon or ethyl vinyl ether. The reason why protonated 3-epoxy-2,3-dimethylbutene (**5**) does not produce a stable adduct is not as clear. However, the ion formed by protonation of 3-epoxy-2,3-dimethylbutene may not be an oxygen-protonated epoxide since protonation of this molecule may occur on either oxygen or an sp^2 carbon. Adduct formation is not expected for the carbon-protonated form (see Table IV). In fact, the site of protonation of styrene oxide (**3**) is not known either. In this case, however, protonation of the aromatic ring would give a delocalized carbocation, and many protonated conjugated dienes produce stable adducts with ethyl vinyl ether under the experimental conditions used (**6**–**8**, Table IV). Thus, the adduct formation seen for styrene oxide could be due to addition of ethyl vinyl ether to the protonated aromatic ring,[63-65] if carbon protonation dominates, or addition to the epoxide ring, if oxygen protonation dominates, or both.

Several protonated bi- and trifunctional, aliphatic and aromatic molecules were examined and found not to produce stable adducts with ethyl vinyl ether (**21**–**24**, **26**, **27**; Table IV). Protonated diethyl ether (**25**) does not give an adduct, but ethyl vinyl ether (**13**) does. This adduct probably has the structure of a proton-bound dimer. Larger ions (MW > 300) are likely[43] to give stable proton-bound or electrostatically bound adducts with ethyl vinyl ether independent of the structure of these ions because of the longer lifetime possible for a larger ion–molecule complex prior to relaxing third-body collisions.

4. Products Obtained with Ethyl Vinyl Ether under Different Experimental Conditions. The relative abundances of the products obtained upon collisions of reactant ions with ethyl vinyl ether in the center quadrupole of the triple quadrupole mass spectrometer, as well as in the quadrupole ion trap, were found to be strongly dependent on the pressure of the reagents, reaction time (in the ion trap), and parent ion kinetic energy (in the triple quadrupole instrument). For protonated cyclohexene oxide, the method used to generate the parent ion was also an important factor. The product ion distributions obtained for protonated cyclohexene oxide under experimental conditions are presented in Figure 6.

The main primary product of protonated cyclohexene oxide at *high* collision energies (81^+) arises from collision-activated dehydration of the reactant ion, as discussed above. When both the collision energy as well as ethyl vinyl ether pressure are low in the triple quadrupole instrument or when short reaction times are used in the ion trap, the most abundant *primary* product is protonated ethyl vinyl ether (73^+; Figure 6; see also Figure 3) formed by proton abstraction from either protonated cyclohexene oxide (99^+) or its dehydration product (81^+).

For protonated cyclohexene oxide, as well as for all the model ions studied, the main secondary product predominating when a low ion kinetic energy *and* high ethyl vinyl ether pressure is used in the triple quadrupole instrument, or when long reaction times

---

(64) Drewery, C. J.; Jennings, K. R. *Int. Phys.* **1976**, *19*, 287.

(65) Ferrer-Correia, A. J. V.; Jennings, K. R.; Sen Sharma, D. K. *Org. Mass Spectrom.* **1976**, *11*, 867.

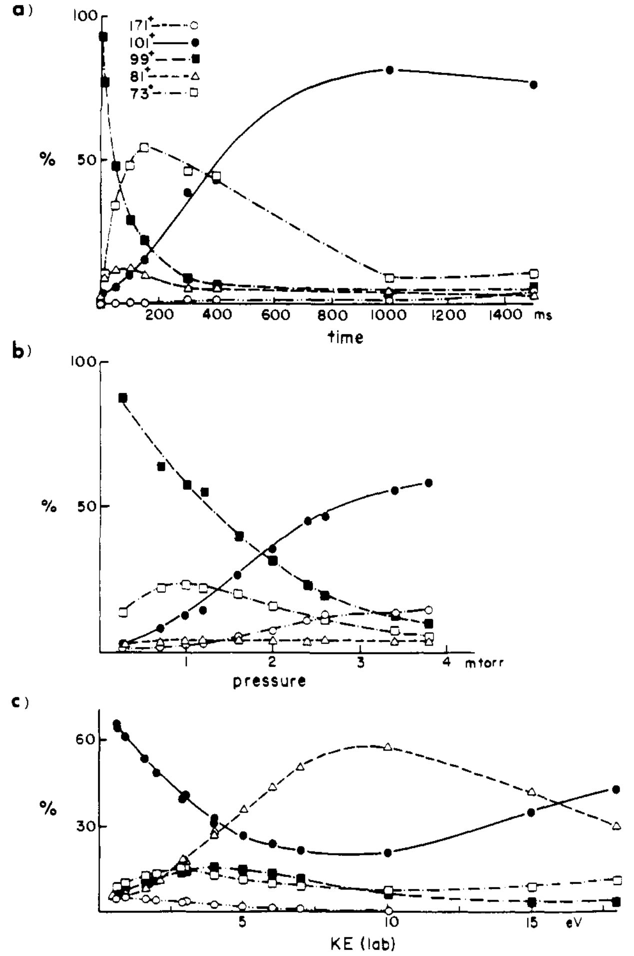


Figure 6. Product ion distributions (a) as a function of *time* for protonated cyclohexene oxide (99^+) in a mixture of cyclohexene oxide and ethyl vinyl ether in the quadrupole ion trap (1 mTorr of He), (b) as a function of ethyl vinyl ether *pressure* (0.6 eV laboratory ion kinetic energy), and (c) as a function of parent ion *kinetic energy* (4 mTorr of ethyl vinyl ether in the center quadrupole), for protonated cyclohexene oxide and ethyl vinyl ether in the center quadrupole of the triple quadrupole mass spectrometer. Protonated cyclohexene oxide was generated by isobutane chemical ionization. Note that the experimental conditions are different from those used for the data in Figures 3 and 4. The relative abundances of the ions obtained in each experiment are normalized to the corresponding total ion current.

Table V. Energy-Resolved Proton Affinity Bracketing Experiments ($MH^+ + N \rightarrow M + NH^+$) for Model Systems

reactant (M)	reagent (N)	ΔH_{prot},[a] kcal/mol	expt indicates an exo- or endothermic reaction
ethylene	methanol	−19.3	exothermic[b]
furan	ethyl acetate	−8.5	exothermic[c]
cyclohexanone	ethyl vinyl ether	−6.0	exothermic[d,e]
isobutene	ethyl acetate	−4.8	exothermic[c]
acetyl acetone	ethyl vinyl ether	+0.4	endothermic
cyclohexanone	ethyl acetate	+0.7	exothermic[c]
dimethyl sulfoxide	ethyl vinyl ether	+3.9	mildly exothermic[d]
acetophenone	ethyl acetate	+4.7	endothermic[f]
2-methylfuran	ethyl acetate	+5.5	mildly endothermic[c]
pyrrole	ethyl acetate	+6.9	endothermic[c]
ethyl acetate	methanol	+18.8	endothermic[b]
cyclohexanone	methanol	+19.5	endothermic[b]
1,5-diaminopentane	ethyl acetate	+37.4	endothermic[c]

[a] Proton affinities from ref 60. [b] On the basis of the sum of the abundances of the ions $CH_3OH_2^+$ and $(CH_3)_2OH^+$. [c] On the basis of the sum of the abundances of the ions $CH_3C(O)OCH_2CH_3{\cdot}H^+$, $[CH_3C(O)OCH_2CH_3]_2{\cdot}H^+$, and CH_3CO^+. [d] On the basis of the sum of the abundances of the ions $CH_3CH{=}O^+CH_2CH_3$ and $CH_3(CH_2)_2CH{=}O^+CH_2CH_3$. [e] The same result was obtained by using single-collision conditions. [f] On the basis of the sum of the abundances of the ions $CH_3C(O)OCH_2CH_3{\cdot}H^+$ and $[CH_3C(O)OCH_2CH_3]_2{\cdot}H^+$, formed under multiple-collision conditions. The ion CH_3CO^+ could not be used since it is a dissociation product of the reactant ion as well as the protonated target (N). However, this ion has a small abundance in comparison with the other two products.

Table VI. Energy-Resolved Proton Affinity Bracketing Experiments ($MH^+ + N \rightarrow M + NH^+$) for Cyclohexene Oxide (N)

reactant (M)	reagent (N)	proton affinity of M,[a] kcal/mol	expt indicates an exo- or endothermic reaction[b]
isobutene	cyclohexene oxide	195.9	exothermic
diethyl ketone		201.4	exothermic
pinacolone		202.3	exothermic
diisopropyl ketone		204.9	thermoneutral or slightly endothermic[c]
cyclopropyl methyl ketone		205.1	endothermic
ethyl vinyl ether		207.4	endothermic[d]
dimethyl sulfoxide		211.3	endothermic

[a] Proton affinities from ref 60. [b] On the basis of the sum of the abundances of protonated cyclohexene oxide and its dissociation product, m/z 81. [c] The reaction appears to be thermoneutral under single-collision conditions. [d] When protonated cyclohexene oxide is allowed to collide with neutral ethyl vinyl ether, the proton-transfer reaction appears to be exothermic, as expected.

are used in the ion trap, is ethylated ethyl vinyl ether (101^+) formed in an exothermic reaction ($\Delta H = -22$ kcal/mol[66-68]) between a neutral ethyl vinyl ether molecule and protonated ethyl vinyl ether (73^+) (see route a, Scheme III; the dehydration product 81^+ is another source for 73^+).[43] The identity of the reactant ion was confirmed by selecting protonated ethyl vinyl ether as the reactant for reactions occurring with neutral ethyl vinyl ether in the center quadrupole of the triple quadrupole mass spectrometer and by examining reactions occurring in pure ethyl vinyl ether after electron ionization in the ion trap while selectively ejecting reactant ions from the trap during the reaction period. Further confirmation comes from time and pressure dependence of the product distributions (Figures 6a and 6b). For example, at low pressures (below 2 mTorr), formation of 101^+ follows second-order kinetics with respect to ethyl vinyl ether pressure (Figure 5), as expected[62] if protonated ethyl vinyl ether were the precursor for 101^+.

Other secondary products formed in reactions of protonated ethyl vinyl ether with neutral vinyl ether include the dimer (145^+) noted above, a product which corresponds to methylated ethyl vinyl ether (87^+), and the interesting ions 129^+ and 157^+, which formally correspond to addition of one and two ethylenes, respectively, to the 101^+ ion.

Thermochemistry. 1. Heat of Formation for Protonated Cyclohexene Oxide. The proton affinity of cyclohexene oxide was estimated by energy-resolved bracketing experiments[41] using the triple quadrupole instrument. In these experiments, the kinetic energy of a reactant ion was varied in order to determine whether proton transfer to the target molecule in the center quadrupole of the triple quadrupole mass spectrometer is exothermic (negative kinetic energy dependence) or not. This approach[50] is based on the assumption that the proton-transfer reaction has no significant energy or entropy barriers. Reactions involving protonation of *neutral* cyclohexene oxide by various reference ions (as opposed

---

(66) Estimated by using the following values: $\Delta H_f = -34$ kcal/mol for ethyl vinyl ether,[60] $\Delta H_f = 124$ kcal/mol for protonated ethyl vinyl ether,[60] $\Delta H_f = -40$ kcal/mol for acetaldehyde,[60] and $\Delta H_f = +104.4$ kcal/mol for protonated 1-butenyl ethyl ether. The last value was approximated by assuming that the proton affinities (PA) of 1-butenyl ethyl ether and 1-propenyl ethyl ether (PA = 211 kcal/mol, see ref 67) are equal and by using the group increment method of Benson[68] to calculate ΔH_f for 1-butenyl ethyl ether ($\Delta H_f = -47.6$ kcal/mol).

(67) Bouchoux, G.; Djazi, F.; Hoppilliard, Y.; Houriet, R.; Rolli, E. *Org. Mass Spectrom.* **1986**, *21*, 209.

(68) Benson, S. W. *Thermochemical Kinetcs*; Wiley: New York, 1976.

(69) Houriet, R.; Schwarz, H.; Zummack, W.; Andrade, J. G.; Schleyer, P. v. R. *Nouv. J. Chim.* **1981**, *5*, 505.

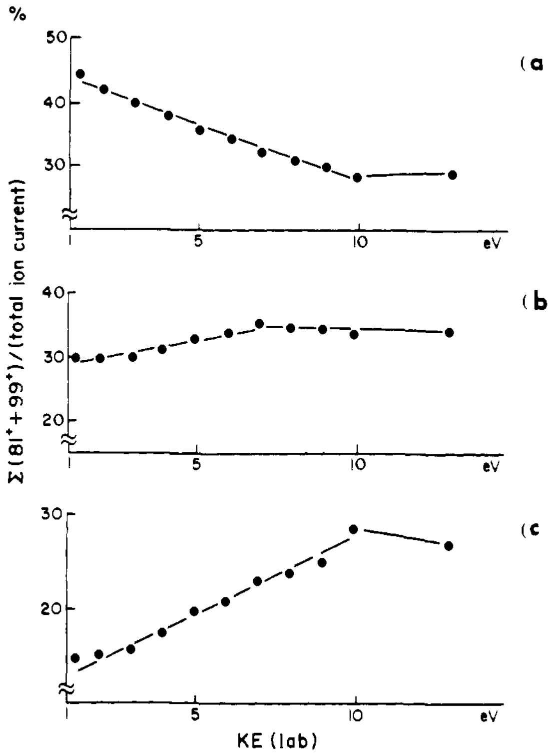


Figure 7. Sum of the relative abundances of protonated cyclohexene oxide (99^+) and its dehydration product (81^+) as a function of parent ion kinetic energy (lab). The ions were formed upon collisions of (a) protonated pinacolone (proton affinity (PA) = 202.3 kcal/mol), (b) protonated diisopropyl ketone (PA = 204.9 kcal/mol), and (c) protonated cyclopropyl methyl ketone (PA = 205.1 kcal/mol) with neutral cyclohexene oxide (ca. 1.4 mTorr) in the center quadrupole of the triple quadrupole mass spectrometer.

to reactions of protonated epoxide with neutral reference bases) were used to ensure that the epoxide and not the keto structure was being examined.

Table V summarizes the data for various model systems, and Table VI and Figure 7 show data for cyclohexene oxide. All the data were obtained by using multiple-collision conditions. Endo- and exothermic reactions, which have a heat of reaction within 5 kcal/mol from thermoneutral, cannot be differentiated by this approach since some slightly endothermic reactions show a negative kinetic energy dependence in our experiments. For example, if the data in Table V were used to estimate the proton affinity of ethyl acetate, the value obtained would be about 3 kcal/mol higher than that reported[60] earlier (between the proton affinities of cyclohexanone and acetophenone). Related problems have been addressed earlier;[70] e.g., slightly endothermic reactions may have a negative temperature dependence. Other conceivable complications associated with our experiments include dissociation of the protonated target molecule and ion–molecule reactions of the protonated target molecule with neutral target molecules. These reactions were taken into account when necessary (see Table V). While experiments employing single-collision conditions[41] would be free of some of these complications, the use of multiple-collision conditions has the advantage of producing much larger ion currents. A few experiments were performed by using single-collision conditions (Tables V and VI) to verify that the interpretation of the results obtained at high target pressures was correct.

On the basis of the data shown in Table V and Figure 7, we conclude that the proton affinity of cyclohexene oxide is close to that of pinacolone (202 kcal/mol), the reference base with the highest proton affinity showing exothermic behavior (see Table VI). This result is in agreement with the finding that ammonium ion (proton affinity of NH_3 is 205 kcal/mol[60,71]) does not protonate cyclohexene oxide in the ion source under chemical ionization conditions: only an ammonium adduct was observed in this experiment. The heat of formation of neutral cyclohexene oxide is −30 kcal/mol.[60b,68] This value, together with the proton affinity of cyclohexene oxide (202 ± 5 kcal/mol), gives a heat of formation of 135 ± 5 kcal/mol for protonated cyclohexene oxide.

2. Activation Energy for Isomerization. Experiments yielding information concerning the isomerization barrier(s) of protonated cyclohexene oxide involve generation of protonated cyclohexene oxide with differing amounts of internal energy in the ion source of the triple quadrupole instrument and observation of the products formed for these ions in reactions with ethyl vinyl ether in the center quadrupole. Variation of the total pressure in the ion source did not have significant effects on the product distribution as long as this did not lead to changes in the nature of the protonating agent in the ion source. This result suggests that the energy deposited upon *protonation* mainly determines whether ring opening of the epoxide ion occurs or not; i.e. ring opening is so fast that collisional relaxation of the nascent, hot epoxide ions does not play an important role in the ion source.

We estimate the energy barrier(s) for isomerization of protonated cyclohexene oxide to the isomeric structures b and/or c (Scheme I) to be close to 12 kcal/mol on the basis of the experiments described above where different reagents (*tert*-butyl cation, protonated diethyl ether, and cyclohexenyl cation from cyclohexene oxide) were used to protonate cyclohexene oxide in the ion source. For example, when *tert*-butyl cation was used as the protonating agent ($\Delta H_{\mathrm{prot}} = -6 \pm 5$ kcal/mol) and the sample pressure was kept low to avoid protonation by cyclohexenyl cation, only a very weak signal was obtained for formation of an adduct of protonated cyclohexene oxide and ethyl vinyl ether in the center quadrupole. The maximum amount of energy that the epoxide ions may have from the protonation reaction in the ion source is about 6 kcal/mol. In addition, they have an unknown amount of thermal energy, which on average will be less than 10 kcal/mol.[72,73] Thus, about 16 kcal/mol is an *upper limit* to the amount of energy needed to cause isomerization of protonated cyclohexene oxide. When the sample pressure was increased but the total pressure kept constant, a significantly larger number of stable, unisomerized epoxide ions was formed in the ion source, as indicated by a remarkably more abundant ionic adduct generated in reactions of these ions with ethyl vinyl ether in the center quadrupole (Figure 4). The higher sample pressure in the ion source enhances the possibility of protonation of cyclohexene oxide by the abundant dehydration product 81^+, which is a more gentle protonating agent ($\Delta H_{\mathrm{prot}} = -2 \pm 5$ kcal/mol) than *tert*-butyl cation. This result suggests that the average energy needed for isomerization of protonated cyclohexene oxide is close to 12 kcal/mol and may be somewhat below this value (the maximum amount of energy that the epoxide ions may have from the protonation reaction in the ion source). The use of protonated diethyl ether as the protonating agent ($\Delta H_{\mathrm{prot}} = -2 \pm 5$ kcal/mol) also results in an abundant adduct in the center quadrupole, thus providing further support for this estimate.

3. Energy Required for Fragmentation. Protonation of cyclohexene oxide molecules by *tert*-butyl cations in the ion source gives the nascent epoxide ions enough energy to cause almost complete fragmentation to 81^+. Thus, the activation energy needed for this fragmentation reaction must be less than 16 kcal/mol (see above); that is, the barriers for isomerization and the threshold energy for fragmentation of the protonated epoxide must be comparable. Rearrangement of the epoxide ion to the keto structure may actually be faster than dehydration since the isomerization only requires opening of the epoxide ring (a direct bond cleavage) and a 1,2-hydride shift that can be very facile in gas-phase cations.[27]

Determination of ion kinetic energy thresholds for dissociation reactions has been successfully used in various cases to estimate

---

(70) See, for example: Ausloos, P., Lias, S. G., Eds. *Structures, Reactivity and Thermochemistry of Ions*; NATO ISI Series; D. Reidel: Boston, 1987.

(71) Westmore, J. B.; Alauddin, M. M. *Mass Spectrom. Rev.* **1986**, *5*, 381.

(72) Griffiths, I. W.; Mukhtar, E. S.; Harris, F. M.; Beynon, J. H. *Int. J. Mass Spectrom. Ion Phys.* **1982**, *43*, 283.

(73) Brand, W. A.; Baer, T. *Int. J. Mass Spectrom. Ion Phys.* **1983**, *49*, 103.

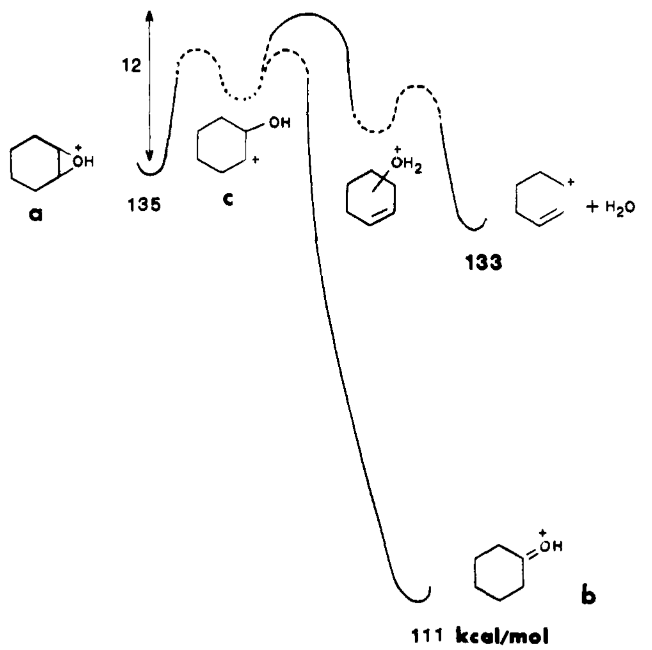


Figure 8. Potential energy surface estimated for the protonated cyclohexene oxide/cyclohexanone system.

an upper limit for reaction enthalpy with a triple quadrupole mass spectrometer.[39,41,42,44] This approach cannot be used to estimate the activation energy of a reaction with so low an activation energy as found for water loss from protonated cyclohexene oxide. Therefore, we estimated this energy in an indirect way by approximating the energy necessary for water loss from the isomeric keto ion. This approach is based on the assumption that water loss from the epoxide and the keto ions occurs via the same intermediate structure (c, Scheme II). The threshold experiments gave a value of 37 ± 5 kcal/mol for activation energy of loss of water from protonated cyclohexanone, which in turn gives an activation energy of 13 ± 7 kcal/mol for water loss from protonated cyclohexene oxide, in good agreement with the estimate made above (<16 kcal/mol).

4. Potential Energy Surfaces of Protonated Epoxides. A limited amount of information is available on isomerization of protonated epoxides in the gas phase. While calculations based on semiempirical methods, as well as lower level ab initio calculations, suggest that a barrier may exist between some protonated epoxides and the isomeric hydroxycarbocations formed by opening of the epoxide ring,[12,13] higher level ab initio calculations indicate a small or no barrier for protonated ethylene oxide, the only case examined thus far.[13] Experimental results indicate that ring opening of protonated ethylene oxide to generate a *primary* carbocation is 24 kcal/mol endothermic.[74] Protonated benzene oxide generates an *allylic* carbocation upon ring opening, and this reaction has been calculated[8] (MNDO method) to be essentially thermoneutral ($\Delta H = +1$ kcal/mol) but to have a 12 kcal/mol energy barrier, while ring opening of protonated 1- and 2-phenylpropylene oxides to delocalized carbocations has been estimated[19] to be 23–25 kcal/mol exothermic. In contrast, the activation energies needed to open protonated propylene and butylene oxides to generate *secondary* carbocations have been estimated to be only 3–5 kcal/mol,[16,17,24-26] as mentioned above.

Our estimate of the potential energy surface for protonated cyclohexene oxide and protonated cyclohexanone is presented in Figure 8. The intermediate carbocation c, although not expected to be stable,[21,29] may nevertheless exist in a shallow potential energy well (Figure 8) in contrast to the primary carbocation generated from protonated ethylene oxide.[13] We do not have direct evidence concerning the stability of the carbocation c or the possible barriers between the cation and the epoxide and keto forms. On the basis of MNDO calculations, the carbocation c has been estimated[56] to be 36 kcal/mol higher in energy than protonated cyclohexanone. This value would give an activation energy of at least 12 kcal/mol for the ring-opening reaction of protonated cyclohexene oxide, which is in good agreement with our estimate for the activation energy of isomerization (close to 12 kcal/mol). The nature of the possible stable intermediates formed after structure c and before the dehydration takes place is not known, but two different structures with a cyclohexene skeleton have been proposed earlier.[56]

The activation energy needed for isomerization of protonated cyclohexene oxide (Figure 8) is somewhat higher than those approximated[16,17,24-26] for other epoxides generating a secondary carbocation upon ring opening (3–5 kcal/mol). However, experimental evidence exists that indicates distinct structures for protonated propylene oxide and protonated propanal,[23] as well as for protonated 2-pentene oxide and its isomeric forms.[22] Moreover, our results indicate that protonated *exo*-2,3-epoxynorbornane and protonated norbornanone have stable structures. All these findings suggest that, in general, protonated epoxides generating a secondary carbocation intermediate are stable species. Thus, the activation energy of isomerization for these protonated epoxides must be higher than 3–5 kcal/mol.

Conclusions

(i) Protonated cyclohexene oxide and cyclohexanone can be generated as stable, distinct species in the gas phase, in spite of the small amount of energy (estimated to be close to 12 kcal/mol) required to isomerize the epoxide ion. Moreover, protonated cyclohexene oxide remains unisomerized in an ion–molecule complex for long enough to undergo structurally characteristic reactions with various organic reagents. The same applies to protonated *exo*-2,3-epoxynorbornane, which can be differentiated from its isomer, protonated norbornanone, on the basis of its reactivity toward ethyl vinyl ether. These results, together with some earlier experimental results[22,23] obtained for protonated propylene oxide and protonated 2-pentene oxide, suggest that isomerization of simple protonated epoxides via secondary carbocations may often be sufficiently endothermic to allow observation of the parent cations as stable species, provided care is taken to generate the ions with only small amounts of internal energy. However, since the barriers for isomerization of protonated simple epoxides appear to be lower than or comparable to the barriers for the lowest energy dissociation reactions, fragmentation of these cations probably occurs via initial opening of the epoxide ring. This is especially likely for those epoxides that do not have fast, energetically favorable direct-bond cleavages available to them, since opening of a protonated epoxide ring can be expected to be a relatively fast reaction. Fragmentation of protonated epoxides via a structure that is readily accessible to the isomeric carbonyl form can complicate the characterization of these ions by dissociation reactions, as has been demonstrated in several cases.

(ii) This study presents an especially dramatic example of the complex interplay of the various parameters that determine the product distributions obtained in mass spectrometry. A single set of dissociation products obtained for ions generated with a significant amount of internal energy, and later activated by depositing an unknown distribution of internal energies, can give misleading results. Our results underscore the fact[20,52] that one should carefully consider internal energy effects when interpreting the data obtained for similar ion structures. Generation of the ions with as little internal energy as possible, and the use of several complementary methods (e.g. energy-resolved dissociation reactions, low-energy ion–molecule reactions) to examine the ion structures, is desirable. The combined use of a triple quadrupole mass spectrometer and a quadrupole ion trap can be a useful approach in solving ion structural problems because a variety of complementary data can be obtained.

(iii) It was demonstrated that, in contrast to an earlier view,[49] a triple quadrupole mass spectrometer operating under multiple-collision conditions can be used to bracket proton affinities (to ±5 kcal/mol) by observing the kinetic energy dependence for

---

[74] Bowen, R. D.; Williams, D. H.; Hvistendahl, G. *J. Am. Chem. Soc.* **1977**, *99*, 7509.

proton transfer with reagents of known proton affinity.

(iv) Adduct formation with ethyl vinyl ether has promise as an analytically useful reaction for screening of epoxide functionalities in small molecules. Further studies on the analytical applications of ion-molecule reactions occurring in the center quadrupole of a triple quadrupole mass spectrometer and a quadrupole ion trap are clearly warranted.

Acknowledgment. Dr. M. A. Mabud is thanked for recording the surface-induced dissociation spectra, and Professor R. R. Squires, for the use of his computer program for calculation of experimental collision-activated dissociation threshold energies. Financial support provided by the National Science Foundation (H.I.K.; Grant CHE-8717380) and National Institutes of Health (R.G.C.; Grant CA-33326) is gratefully acknowleged.

Solid-State Polymerization of Molecular Metal Oxide Clusters: Aluminum 12-Tungstophosphate

A. R. Siedle,*[†] Thomas E. Wood,[‡] Myles L. Brostrom,[†] David C. Koskenmaki,[§] Bernard Montez,[⊥] and Eric Oldfield[⊥]

Contribution from 3M Corporate Research Laboratories, 3M Ceramics Technology Center, and 3M Industrial and Electronics Sector Research Laboratory, St. Paul, Minnesota 55144, and School of Chemical Sciences, University of Illinois, Urbana, Illinois 61801.

Received March 4, 1988

Abstract: The molecular metal oxide cluster compound $[Al(H_2O)_6]PW_{12}O_{40}{\cdot}4H_2O$ reversibly dehydrates at 375 °C. Upon heating to ≥550 °C, irreversible conversion to $AlPO_4$ and cubic WO_3 ($a = 7.521$ (5) Å) occurs in a solid-state process likened to polymerization. The reaction has been studied by thermogravimetric analysis, differential scanning calorimetry, X-ray and electron diffraction as well as ^{27}Al and ^{31}P solid-state NMR. It is proposed as a model for synthesis of ceramics by sol-gel methods.

Chemical ceramics is a generic technology relating to the formation of condensed phase materials, such as metal oxides, from monomeric precursors such as metal alkoxides or aquated metal ions. Embedded in this technology is an underlying chemical question: how can bulk, infinite-lattice materials evolve from molecule-sized species? In one depiction of sol-gel ceramics synthesis, hydrolysis of $M(H_2O)_n{}^{m+}$ or $M(OR)_m$ (M and R are generalized metal and alkyl groups, respectively) yields M-O-M or M-OH-M species that, as the hydrolysis proceeds, increase in molecular weight and crosslink density until, ultimately, a recognizable polymer or colloid separates as a new, discrete phase.[1-6] We consider here an alternative scenario, applicable to some metals, in which hydrolysis produces ionic molecular metal oxide clusters that, on heating, condense or polymerize to form bulk oxides.

It has long been known that H_3O^+ and group I metal salts of heteropolyanions are thermally unstable and form metal oxides on heating[7-11] by processes that we view not as mere decomposition but as polymerization reactions. Oxide cluster polymerization is taxonomically and logically related to the more familiar polymerization of organic monomers, such as styrene, in the sense that very high molecular weight materials are formed by the combination of a large number of low molecular weight precursors. Polymerization of molecular metal oxide clusters could potentially play an important role in chemical ceramics. In addition, because cluster polymerization occurs at relatively low temperatures (500-600 °C) compared with those usually employed in synthesis of both ceramics and complex oxides, there exists the potential of preparing by this route new, kinetically stable but thermodynamically unstable materials. This paper describes in detail one such exemplary reaction, the solid-state conversion of hydrated aluminum 12-tungstophosphate to $AlPO_4$ and the previously unreported cubic form of tungsten trioxide.

Results and Discussion

Crystalline hydrated aluminum 12-tungstophosphate, $[Al(H_2O)_6]PW_{12}O_{40}{\cdot}4H_2O$, may be prepared in high purity by reaction of aluminum metal with aqueous $(H_3O)_3PW_{12}O_{40}$ in air.[12,13] The process differs from many dissolving metal reactions in that hydrogen is not evolved. Instead, aluminum reduces $PW_{12}O_{40}{}^{3-}$ to a blue heteropolyanion that is subsequently reoxidized by atmospheric oxygen, eq 1. The product separates, after concen-

$$4Al + 4(H_3O)_3PW_{12}O_{40} + 3O_2 + 22H_2O \rightarrow 4[Al(H_2O)_6]PW_{12}O_{40}{\cdot}4H_2O \quad (1)$$

[†] 3M Corporate Research Laboratories.
[‡] 3M Ceramics Technology Center.
[§] 3M Industrial and Electronics Sector Research Laboratory.
[⊥] University of Illinois.

(1) Dislich, H. *J. Non-Cryst. Solids* **1983**, *57*, 371.

(2) *Better Ceramics through Chemistry*; Brinker, C. J., ed. Materials Research Society Symposium Proceedings, Elsevier: New York, NY, 1984; Vol. 32.

(3) Livage, J.; Lemerle, J. *Ann. Rev. Mater. Sci.* **1982**, *12*, 103.

(4) Ramsay, J. D. F. *Chem. Soc. Rev.* **1986**, *15*, 335.

(5) Artaki, I.; Bradley, M.; Zerda, T. W.; Jonas, J. *J. Phys. Chem.* **1985**, *89*, 4299.

(6) Orgaz, F.; Rawson, H. *J. Non-Cryst. Solids* **1986**, *82*, 57.

(7) Tsigdinos, G. A. *Ind. Eng. Chem. Prod. Res. Dev.* **1974**, *13*, 267.

(8) Brown, D. H. *J. Chem. Soc.* **1962**, 3189.

(9) Rashkin, J. A.; Pierron, E. D.; Parker, D. L. *J. Phys. Chem.* **1967**, *71*, 2165.

(10) Basu, A. K.; Sale, F. R. *J. Mater. Sci.* **1977**, *12*, 1115.

(11) West, S. F.; Audreith, L. F. *J. Phys. Chem.* **1955**, *59*, 1069. These workers were among the first to actually examine by X-ray powder diffraction the products of decomposition of H_3O^+ Keggin ion salts.

(12) Preparation of $AlPW_{12}O_{40}$ (degree of hydration not stated) by evaporation "over a water bath" of aqueous $Al(NO_3)_3$ and $(H_3O)_3PW_{12}O_{40}$ has been reported: Baba, T.; Wanatabe, H.; Ono, Y. *J. Phys. Chem.* **1983**, *87*, 2406. Presumably, a hot water bath was used. No characterization data were given. We find that if the reaction shown in eq 1 is carried out at 50 °C, the product contains impurities demonstrable by additional ^{31}P NMR peaks.

(13) A compound described as $AlPW_{12}O_{40}{\cdot}13H_2O$ has been prepared from $(H_3O)_3PW_{12}O_{40}$ and $Al(i\text{-}OC_3H_7)_3$, but no characterization data were given: Hayashi, H.; Moffat, J. B. *J. Catal.* **1983**, *81*, 61. Subsequently, analytical data indicated the composition to be $Al_{0.58}H_{1.26}PW_{12}O_{40}$; the X-ray powder pattern was analyzed in terms of a cubic unit cell having $a = 12.135$ Å.[29] On the basis of diffraction data alone, this material differs from the $[Al(H_2O)_6]PW_{12}O_{40}{\cdot}4H_2O$ that we report.

0002-7863/89/1511-1665$01.50/0