Notes

Stereochemical Assignment by Mass Spectrometry. Metastable Ion Characteristics for Dehydrohalogenation

Kym C. Kim and R. Graham Cooks*

Department of Chemistry, Purdue University, West Lafayette, Indiana 47907

Received August 7, 1974

Mass spectrometry has not found wide application to problems in stereochemistry although some elegant demonstrations of its potential exist.[1] The usual but not the only approach[1c] is to measure fragment ion abundances for an elimination reaction; the spacial relationship between the groups involved in the elimination determines the activation energy for the reaction and hence the product ion abundance. We now show that the translational energy release associated with the fragmentation of metastable ions can serve to characterize the mechanism of a particular elementary reaction and so to distinguish stereoisomers. Thus, instead of relying only on a comparison of the relative extents to which different stereoisomers undergo a specific reaction, the reaction is further characterized in terms of its thermochemistry which might be unique to each stereoisomer. We also show that by employing two successive fragmentations it is sometimes possible to amplify stereochemical differences and so to facilitate the analysis. In particular, diastereometic ions can yield structurally isomeric fragment ions in the first step of the reaction. These products fragment as metastable ions and the relative abundances of the further products, in conjunction with the kinetic energies released, serve to characterize the primary product ions and so the neutral molecules.

Experimental Section

Measurements were made using a modified Hitachi RMH-2 mass spectrometer operated at an accelerating voltage of 8 KV, an ionizing electron energy of 70 eV, and an electron emission current of 1 mA. In some experiments a mass-analyzed ion kinetic energy spectrometer (MIKES) was also used under similar conditions. Reactions were followed in the first field-free region of the RMH-2 by the accelerating-voltage scan technique and in the preelectric sector region of the MIKES by electric sector scans. Kinetic energy releases were determined from the width of the metastable peak measured at half-maximum. A kinetic energy resolution of approximately 4000 (full width at half-maximum) was employed. Full details regarding instrumentation and methodology have been presented elsewhere.[2]

2,3-Difluorobutane was prepared by reaction of the *p*-toluenesulfonyl ester of the diol with KF in diethylene glycol.[3] The meso and *d,l* isomers were formed in approximately equal amounts and separated by preparative gas chromatography on an SF-96 column. The meso isomer is eluted first on a boiling point column.[4] **1-Fluoro-3-butene** was prepared from 1-hydroxy-3-butene by the same method. **2-Chloro-2-butene** was obtained commercially and the cis and trans isomers were separated by gc and their structures confirmed by nmr. The lower boiling isomer (trans, bp 63°) was eluted before the cis (bp 67°). **2-Chloro-1-butene** was obtained commercially and purified by gc. **2,3-Dichlorobutane** was obtained commercially and the meso and *d,l* isomers were separated by gc (SF-96).

Results

The 70-eV mass spectra of *d,l*- and *meso*-2,3-difluorobutane are identical. Both isomers show metastable peaks for the elimination of HF from both the molecular ion and the $(M - HF)\cdot^+$ fragment ion. The primary HF elimination is associated with a kinetic energy release of 15 ± 3 meV in both cases. However, the abundance of the metastable peak is about 15 times greater for the *d,l* than for the meso isomer. (The more intense peak height was 0.25% relative to that of the corresponding molecular ion.) The secondary HF elimination is associated with similar metastable ion abundances in the *d,l* and meso isomers; however, detailed analysis of the metastable peak at high kinetic energy resolution revealed a striking difference. Thus both isomers give composite metastable peaks[5] for this reaction, indicating that two processes occur for each isomer. The kinetic energy release for the broad component was 854 ± 30 meV for both isomers and approximately 32 meV for the narrow component in both cases. However (Figure 1), in one of the isomers the ratio of narrow to broad components was 3 times greater than in the other.

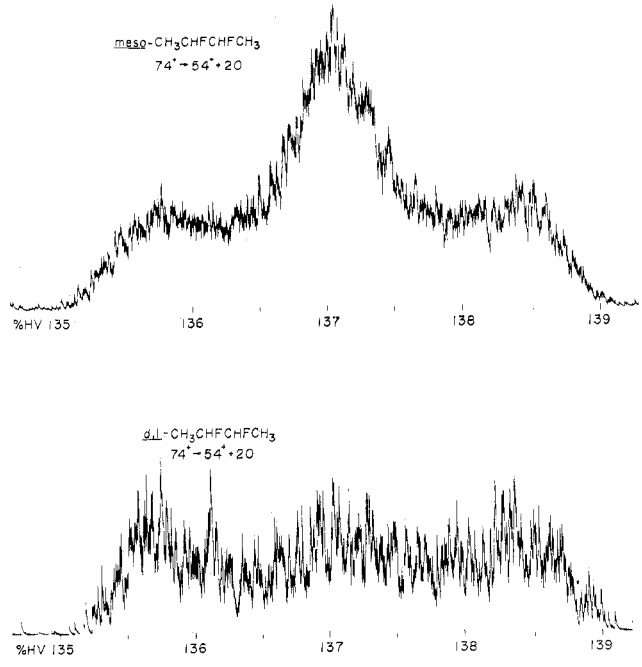


Figure 1. Overlapping broad and narrow metastable peaks for HF loss from the $(M - HF)\cdot^+$ fragment ion in *d,l*- and *meso*-2,3-difluorobutane. The spectra were obtained by scanning the accelerating voltage (HV) on the RMH-2 mass spectrometer.

The 2,3-dichlorobutanes could also be distinguished by ion kinetic energy spectrometry. Dehydrohalogenation of the molecular ions gave composite metastable peaks for both isomers with the relative contribution of the narrow peak being some 50% more intense in the meso compound.[6] Composite peaks were also observed for the secondary dehydrochlorination from the $C_4H_7Cl\cdot^+$ ion, the meso compound giving slightly more of the narrower component than the *d,l* isomer.

2-Chloro-1-butene and *cis*- and *trans*-2-chloro-2-butene all gave identical mass spectra. Moreover, the metastable peaks for HCl elimination from the respective molecular ions ($C_4H_7Cl\cdot^+$) were in each case similar to those observed for the further reaction of the primary products of dehydrochlorination of the 2,3-dichlorobutanes. The cis and trans isomers were indistinguishable in this regard but

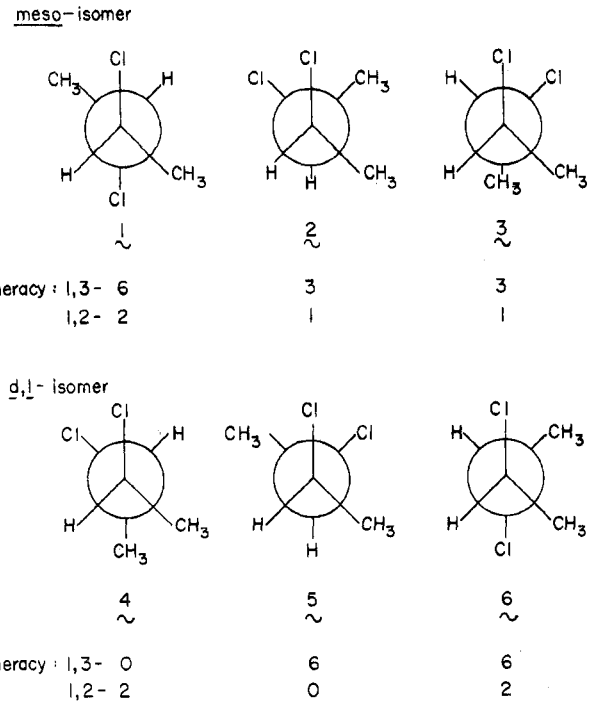
2-chloro-1-butene gave relatively more of the narrow component in this metastable ion reaction.

Discussion

The results presented show that it is possible to distinguish the stereoisomers under consideration by ion kinetic energy spectrometry. They also show that the fluoro and chloro compounds do not behave analogously.

In accounting for these observations note must be made of the fact that the kinetic energy release accompanying a metastable ion fragmentation can serve as a characteristic of ion structure and reaction mechanism.[7] This is facilitated by the results of previous studies on dehydrohalogenation by ion kinetic energy spectrometry.[6,8] A general conclusion possible from these studies is that dehydrohalogenation of haloalkanes will be associated with a large kinetic energy release when it occurs by 1,2 elimination and by a small release when it occurs by 1,3 elimination. Dependence of the relative abundances of metastable peaks associated with large and small energy releases upon the stereo isomer involved is the basic observation made in this study. Association of reaction mechanism with stereochemistry can hence be made.

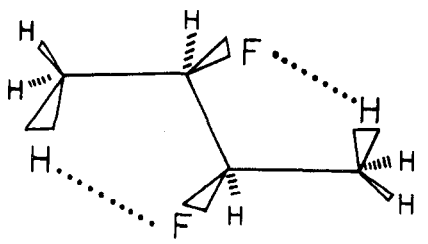
Consider, first, the primary dehydrochlorination of 2,3-dichlorobutane. Both isomers give both the broad and the narrow peaks which is interpreted as a result of competitive 1,2 and 1,3 eliminations.[5] The fact that 1,3 elimination is more favored relative to 1,2 elimination in the meso than in the *d,l* isomer follows from a consideration of literature data on rotamer stabilities.[9] In using these data it is assumed that the conformational preferences of the molecular ion will parallel those of the corresponding neutral molecules and that the potential energy minima reflect associated rotational barrier heights. Thus, *meso*-2,3-dichlorobutane can exist in three low-energy rotamers: one trans form (1) and two gauche forms (2 and 3) which are enantiomers.



The enthalpy of the trans configuration in the vapor phase is approximately 1.3 kcal/mol lower than that of the two gauche forms.[10] For the *d,l* isomer there are three separate rotamers of which one (4) is 1.5–1.6 kcal/mol more stable than the others.[10] The degeneracies for 1,2 and 1,3 eliminations are shown below the structures. Secondary hydrogen abstraction is assumed[6] to be favored over primary where competition is possible, *viz.* for the 1,2 elimination mechanism. It is apparent that in each isomer two of the total of four modes of 1,2 elimination are associated with the stable rotamer. Hence little, if any, difference in the abundance of the broad metastable peak is expected when the isomers are compared. However, for 1,3 elimination the reaction path degeneracy associated with the most stable *d,l* configuration is zero and hence its contribution to the metastable ion abundance should be negligible. Hence, the greater metastable ion abundance for the narrow peak is predicted to be associated with the meso isomer since for this isomer the population distribution of rotational isomers and the reaction path degeneracies favor the 1,3 elimination. The observed behavior confirms this prediction.

Since a conformational analysis of 2,3-difluorobutane has apparently not been reported, the experimental results cannot be compared with literature data in this case. Moreover, differences in steric size and electronegativity distinguish the fluoro and chloro compounds.

To account for the observed behavior we suggest that, at least in the molecular ion, rotamer **5** is specially stabilized in the fluorine case. Models show that in this species *two* H–F interactions involving quasi-five-membered rings (**7**)



7

could form such that one H–F bond locks the molecule into a configuration from which 1,3 elimination will occur from the other bond. This proposal is based upon the fact that electrostatic attractive forces between the polarizable methyl group and a halogen atom have significant effects upon conformational enthalpies.[11] The result, in terms of conformation preferences, is analogous to that when the halogen group is suitably oriented relative to a hydroxyl group—*viz.*, to that when the halogen hydrogen bonds to this group.[12] In the case of the strongly electronegative fluorine atom it seems to us appropriate to refer to the interaction as hydrogen bonding. It may be noted that the importance of strong hydrogen bonding in bimolecular mass spectrometry has recently been emphasized.[13]

The postulate of stronger hydrogen bonding in the fluoro than in the chloro compounds accounts for the suppression of the 1,2-elimination channel in both the meso and the *d,l* isomers. Moreover, since the *double* hydrogen bonding suggested above is applicable to only one of the six rotamers, hydrogen bonding also accounts for the much greater metastable ion abundance in the *d,l* as compared to the meso isomer. Another factor which probably contributes to the difference between the behavior of the fluorine and chlorine compounds is the steric size of halogen; it has been shown[1a] that HF elimination tends to occur *via* a cyclic activated complex of larger ring size than that for HCl elimination.

Turning to the secondary dehydrohalogenation, we again consider first the chloro compounds. The ion of interest is $C_4H_7Cl\cdot^+$ and the apposite observation concerns a difference of some 20% in relative peak heights for the broad and narrow components of the composite metastable peak in

the two isomers. A previous study[6] suggested that while the broad peak must be associated with 1,2 elimination across a saturated bond, the narrow peak could here be due either to 1,3 elimination or vinylic 1,2 elimination. It was also shown explicitly that the ratio of the broad and narrow components varied with the origin and, hence, the initial structure and internal energy distribution of the $C_4H_7Cl \cdot^+$ ion. These observations are supported by the new results obtained here on 2-chloro-2-butene and 2-chloro-1-butene. The conclusion must be that isomerization between the various $C_4H_7Cl \cdot^+$ structures is largely complete prior to metastable ion fragmentation, the small abundance differences associated with different methods of preparation reflecting differences in internal energy distributions.[14] Stereochemical distinctions can, therefore, not be made on the basis of the secondary dehydrochlorination.

In striking contrast, the secondary HF elimination gives the disparate metastable peaks illustrated in Figure 1. These differences must be due to *structural* differences in the reacting $(M - HF) \cdot^+$ ions since differences in the internal energy distributions, which for stereoisomers are expected to be very small in the molecular ions, should be even further reduced when the $(M - HF) \cdot^+$ product ions are compared.[15] (Compare also the preceding chlorine results.) Hence, we are apparently observing the amplification of stereochemical differences in the molecular ions into structural isomerism in the $(M - HF) \cdot^+$ fragment ions.

In accounting for this remarkable behavior the broad and narrow components are assigned, by analogy with dehydrochlorination,[6,8] as 1,2 elimination from saturated carbons on the one hand and 1,3 and/or vinylic 1,2 elimination on the other. The available data on HF loss also fit this picture, including that for 1-fluoro-3-butene which only shows a broad component (T = 0.80 eV) in the metastable peak for HF loss. Further evidence comes from the thermochemistry of the typical reactions 1 and 2. The heats of for-

$$CH_3CH{=}CFCH_3^{\cdot+} \longrightarrow CH_3C{\equiv}CCH_3^{\cdot+} + HF \quad (1)$$

$$CH_2{=}CHCHFCH_3^{\cdot+} \longrightarrow CH_2{=}CHCH{=}CH_2^{\cdot+} + HF \quad (2)$$

mation of the neutral C_4H_7F isomers are not well-known but it was sufficient for the comparison involved here to compare the analogous methyl-substituted butenes to account for the difference in the double-bond position. From the measured appearance potential[16] of the $(C_4H_7F - HF) \cdot^+$ ion, 11.9 ± 0.2 eV (AP − IP = 2.4eV), $\Delta H_f°(CH_3C{\equiv}CCH_3 \cdot^+)$ = 263 kcal/mol, $\Delta H_f°(CH_2{=}CHCH{=}CH_2 \cdot^+)$ = 236 kcal/mol, and $\Delta H_f°$ (HF) = −64.9 kcal/mol, it is estimated that the difference in the total energy available for partitioning in reactions 1 and 2 is ~41 kcal/mol. Hence the broad metastable peak is associated with reaction 2, which has a much greater energy available for partitioning.

The stereochemical differences between the meso and *d,l* molecular ions translate into geometrical isomerism in the dehydrohalogenation products, whether formed by 1,2 or by 1,3 elimination. Thus, 1,2 elimination from the meso molecular ion yields exclusively the trans olefin, while the *d,l* isomer yields exclusively the cis olefin. A corresponding stereospecificity exists in formation of the ionized cyclopropane which is the intial product of 1,3 elimination from the molecular ion. The presence of the broad component in Figure 1 requires that the intially formed butene isomerize in part to a structure such as the reactant shown in (2) from which 1,2 elimination can occur from saturated carbons. The *trans*-2-fluoro-2-butene, perhaps because of hydrogen bonding,[17] may undergo 1,3 elimination of HF more readily than the cis isomer undergoes either 1,3 or 1,2 elimination. Hence, given a primary 1,2 elimination, the narrow component is expected to be more pronounced for the meso compound as is indeed observed. It is not possible to tell whether the metastable $(M - HF) \cdot^+$ ions are formed from the molecular ion by the 1,2 or the 1,3 elimination mechanism. However, both reactions are stereospecific and the observed behavior is accounted for in either event if the isomerization of the intital $(M - HF) \cdot^+$ product ion is stereochemically controlled.

Thus the overall effect is that optical isomerism in the molecular ions is translated into geometrical isomerism in the $(M - HF) \cdot^+$ ions and, hence, into differences in the relative proportions of structural isomers for those $(M - HF) \cdot^+$ ions which react further.

Conclusion

The marked differences observed in this study between metastable peaks for stereoisomers, even when a secondary ion fragmentation is considered, emphasize the delicacy of mass spectrometry as a stereochemical probe. The unique contribution of kinetic energy measurements is that they make it possible to dissect individual reaction mechanisms on the basis of their dynamics and so to assign stereochemistry. Both the effect seen in the primary fragmentation, which is due to conformation preferences in the molecular ion, and that seen in the secondary fragmentation, which depends on the translation of optical isomerism into geometrical isomerism in the initial step, can be expected to occur in other classes of compound.

Acknowledgment. We thank the National Science Foundation for support of this work and Dr. J. B. Grutzner and Dr. M. M. Green for helpful discussions.

Registry No.—KF, 7789-23-3; 2,3-butanediol-*p*-toluenesulfonyl ester, 49662-27-3; *meso*-2,3-difluorobutane, 53586-61-1; *d,l*-2,3-difluorobutane, 53586-62-2; 1-fluoro-3-butane, 675-56-9; 1-hydroxy-3-butene, 627-27-0; *cis*-2-chloro-2-butene, 2211-69-0; *trans*-2-chloro-2-butene, 2211-68-9; 2-chloro-1-butene, 2211-70-3; *meso*-2,3-dichlorobutane, 4028-56-2; *d,l*-2,3-dichlorobutane, 2211-67-8.

References and Notes

(1) See for example (a) M. M. Green, R. J. Cook, J. M. Schwab, and R. B. Roy, *J. Amer. Chem. Soc.*, **92**, 3076 (1970), and other papers in this series; (b) S. Meyerson and A. W. Weitkamp, *Org. Mass Spectrom.*, **1**, 659 (1968); (c) K. Pihlaja and J. Jalonen, *ibid.*, **5**, 1363 (1971), and other references therein; (d) J. K. MacLeod and R. J. Wells, *J. Amer. Chem. Soc.*, **95**, 2387 (1973).
(2) R. G. Cooks, J. H. Beynon, R. M. Caprioli, and G. R. Lester, "Metastable Ions," Elsevier, Amsterdam, 1973.
(3) Compare W. F. Edgell and L. Parts, *J. Amer. Chem. Soc.*, **77**, 4899 (1955).
(4) P. S. Fredericks and J. M. Tedder, *J. Chem. Soc.*, 3520 (1961).
(5) R. G. Cooks, M. Bertrand, J. H. Beynon, M. E. Rennekamp, and D. W. Setser, *J. Amer. Chem. Soc.*, **95**, 1732 (1973).
(6) K. C. Kim, J. H. Beynon, and R. G. Cooks, *J. Chem. Phys.*, **61**, 1305 (1974).
(7) (a) E. G. Jones, L. E. Bauman, R. G. Cooks, and J. H. Beynon, *Org. Mass Spectrom.*, **7**, 185 (1973); (b) J. H. Beynon and R. G. Cooks, *Advan. Mass Spectrom.*, **6**, 835 (1974).
(8) R. G. Cooks, K. C. Kim, and J. H. Beynon, *Int. J. Mass Spectrom. Ion Phys.*, in press.
(9) For previous observations on rotational isomers and their effects on mass spectra see M. E. Munk, C. C. Kulkarni, C. L. Lee, and P. Brown, *Tetrahedron Lett.*, 1377 (1970).
(10) P. J. D. Park and E. Wyn-Jones, *J. Chem. Soc. A*, 422 (1969).
(11) (a) G. Szasz, *J. Chem. Phys.*, **23**, 2449 (1955); (b) N. Sheppard, *Advan. Spectrosc.*, **1**, 288 (1959).
(12) Reference 1b, p 300.
(13) D. P. Ridge and J. L. Beauchamp, *J. Amer. Chem. Soc.*, **96**, 637 (1974).
(14) Compare M. L. Gross and P.-H. Lin, *Org. Mass Spectrom.*, **7**, 795 (1973), and references therein.
(15) D. J. McAdoo, P. F. Bente III, M. L. Gross, and F. W. McLafferty, *Org. Mass Spectrom.*, **9**, 525 (1974).
(16) The broad and narrow components must have very similar appearance potentials for both to give metastable peaks.
(17) *Chem. Eng. News*, 39 (Oct. 7, 1963).