PREFACE

The use of information, derived from mass spectral investigations, in the determination of structural features in organic molecules is hampered by the lack of understanding of the mechanisms by which electron impact induced fragmentations occur. It will only be after the dissociation mechanisms in relatively small molecules have been thoroughly investigated using isotopic labeling and high resolution techniques, that fragmentation sequences can be rationalized and/or predicted with any degree of accuracy. These results may then, hopefully, be applied to larger, more complex molecules.

Our interest in the "ortho effect" stems from the fact that while such an effect has been widely observed, little is known about the relationship between its occurrence and the geometrical arrangement of the participating groups. Also, the behaviour of each functional group in a certain stereochemical environment may be characteristic of both the particular group and its environment. If such were the case, the presence and position of functional groups within organic molecules may become more easily detectable from mass spectral data.

It is with this purpose in mind that this work was undertaken. It is hoped that the results obtained will prove useful to the organic chemist, whose chief interest in mass spectrometry is the identification of reaction products.

Most of the work described in this thesis has been or is in course of publication as indicated by the following list of papers.

1. The Mass Spectra of Carboxylic Acids-I: Fragmentation Mechanisms in Maleic and Fumaric Acids and Related compounds.
   F. Benoit, J.L. Holmes and N.S. Isaacs, Org. Mass Spectrom. 2, 591 (1969)
2. Mass Spectra and Fragmentation Mechanisms of some Nitrophenylhydrazines and Nitrophenylhydrazones.
   F. Benoit and J.L. Holmes, Can. J. Chem, 47, 3611 (1969)
3. Ortho Effects-I: Fragmentation Mechanisms in some ortho-Substituted Nitroarenes
   F. Benoit and J.L. Holmes, Org. Mass Spectrom. 3, 993(1970)
4. The Mechanism of NO loss from the Molecular Ion of Nitrobenzene and the Fragmentation Behaviour of the Phenoxy and p-Aminophenoxy Cations
   F. Benoit and J.L. Holmes, Chem. Comm. 1031 (1970)
5. The Mass Spectra of Carboxylic Acids-III: The Structures of Molecular and Fragment Ions in Benzoic Acid and Related Molecules
   J.L. Holmes and F. Benoit, Org. Mass Spectrom. 4, 97(1970)
6. Metastable Peak Analysis; a Method for Elucidating Fragmentation Mechanisms and Ion Structures in Mass Spectrometry. Part II. Water Loss from the Molecular Ion of 1,2-cyclohexanediol.
   F. Benoit and J.L. Holmes, Can. J. Chem. 49, 1161 (1971)
7. The Mass Spectra of Benzamide and Thiobenzamide.
   J.L. Holmes and F. Benoit, Org. Mass Spectrom, 5, 525 (1971)

It should be noted that the numbering of the schemes and figures begins at 1 and the lettering of ions at (a) in each chapter.

Acknowledgements

I wish to express my greatest appreciation to Dr. J.L. Holmes for his guidance throughout the preparation of this work. His patience, understanding and confidence were extremely valuable to me throughout the time required to perform this work. I also thank Mr. A. Philpot, R. Larose and P. Coulombe whose technical assistance greatly aided in the experimental work. Financial support from the Province of Ontario in the form of Province of Ontario Graduate Fellowships (1968-71) is gratefully acknowledged.

To my wife and parents

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Abstract

The presence of an "ortho effect" in the electron impact induced fragmentations of some o-nitroarenes, of some 1,2-dicarboxylic acids and of benzoic acid (and related compounds) has been investigated. Three different ortho effects are noted ; these are 1) transfer of a hydrogen atom between ortho substituents 2) migration of a part of a substituent to the ortho (unsubstituted or vacant) site and 3) mixing of the ortho hydrogen atoms with those of the substituent group. The nitro to nitrite conversion in the dissociation of nitrobenzene was shown not to involve participation of the ortho site although it was aided by the ortho substituent in some ortho substituted nitroarenes.

The geometric requirements for an "ortho effect" in 1,2-dicarboxylic acids was examined. Results have shown that the "ortho effect" is prominent where the rigid geometry of the acid holds the carboxyl groups in close proximity. In other instances, where the carbon skeleton is flexible, interaction of the carboxyl group with a skeletal methylene position predominates.

The mechanism for water loss from the molecular ion of 1,2-cyclohexanediols was shown to involve hydrogen scrambling as well as an "ortho effect". However the direct interaction between the hydroxyl groups was only minor.

CHAPTER 1

INTRODUCTION

General Theory of Mass Spectrometry

The use of mass spectrometry for the identification of organic compounds is becoming increasingly attractive to the organic chemist. However, the identification of structural features solely from mass spectral data is no simple task. Although a sample molecule yields a characteristic mass spectrum, the exact behaviour of most organic compounds within the mass spectrometer is still largely unpredictable. While analysis is based on the assumption that the ground state geometry will somehow be reflected in the fragmentation sequence, many examples are known wherein extensive, unpredictable rearrangements have occurred[1a]. Hydrogen and even skeletal atoms have participated in these little understood reactions. e.g. the production of $C_2H_5^{+\cdot}$ in neo-pentane,[1b] the loss of $^{13}C_2H_2$ from 1,3,5 - $^{13}C_3$ - benzene[2], and the generation of the tropylium ion from numerous isomeric C_7H_8 compounds[3,4].

Such observations discourage one from the unequivocal assignment of definite structures to fragment, and perhaps

even to molecular ions. Usually, many isomeric forms of a species can conceivably fragment according to the sequence registered in the mass spectrum. For molecular ions one generally assumes that the ground state geometry is retained, unless there is strong evidence to the contrary. This assumption will be made throughout this work. In fragmentation schemes, structures are shown merely to illustrate a possible dissociation sequence and are justified only by their ability to undergo the metastable or otherwise supported dissociations. This difficulty in structural assignments need not necessarily impair analysis of a mass spectrum because knowledge of the exact structure of a fragment ion, while important, may not be essential. Indeed, whether the benzene molecular ion is linear or cyclic is of relatively little consequence; the important feature is the behaviour of the ion e.g. the fact that it fragments mainly by loss of the elements of acetylene[2] contributes more to the structural identification of this ion than the question of its exact shape.

It is possible, in some instances, to eliminate certain structural representations on the basis of the behaviour of the ion. A model compound may sometimes be used to generate an ion of the same chemical constitution as that under investigation; comparison of their behaviours may indicate whether the ions are structurally similar or not. For example, the observation that p-nitrophenol

exibits a "flat-top metastable" for the loss of NO while the meta isomer shows a gaussian metastable for the same dissociation has been used as evidence that these ions have different structures.[5] The para isomer yields a quinoid structure which the meta isomer cannot. In the study of benzoic acid, we have used phthalaldehydic acid as a model for the production of the ion $C_7H_5O^+$ (the details are outlined below in Chap 3).

At present, many compounds apparently fragment in a fashion peculiar to themselves and it is difficult to extract general rules from the mass spectra of a series of related compounds. For this reason, the prediction of fragmentation sequences is at best hazardous. The description of adequate fragmentation mechanisms for compounds of known structure requires extensive investigation. It is hoped that when the behaviour of each functional group in a variety of environments has been described, its presence within a molecule will be more easily detected, and the identification of structural features in unknown molecules will become more feasible.

The Mass Spectrum

The production of a mass spectrum will now be reviewed.[6] It should be noted that the instrument is operated at low ambient pressure in order to avoid collision induced reactions between the various species present. Sample pressures in the range of 10^{-7} to 10^{-6}mm mercury, in the ion source, are sufficient to produce a spectrum.

Two inlet systems (a) (scheme 1)are available for sample insertion; the direct inlet system may be used for relatively involatile samples, whereas the all-glass heated inlet system is used for sample of high volatility. In the ion source, the sample molecules interact with a beam of high energy electrons (b) (the electrons suffer a potential drop of ~70 volts), become energised, and produce molecular ions by ejection of an electron. These ions may then dissociate in a variety of ways.

Upon formation, the ions experience an acceleration due to the potential difference between the walls of the ion source (~2,000 V) and the exit slit (0 V). This acceleration directs the ions from the source towards the analyzer tube (d) via the field free region (e). Under the influence of the magnetic field in the analyzer tube, the ions will suffer a deflection through an angle that is proportional to their mass.

The motion of the ions thus far described may be represented by the following equations. If the accelerating potential is V, the kinetic energy imparted to the ions will be

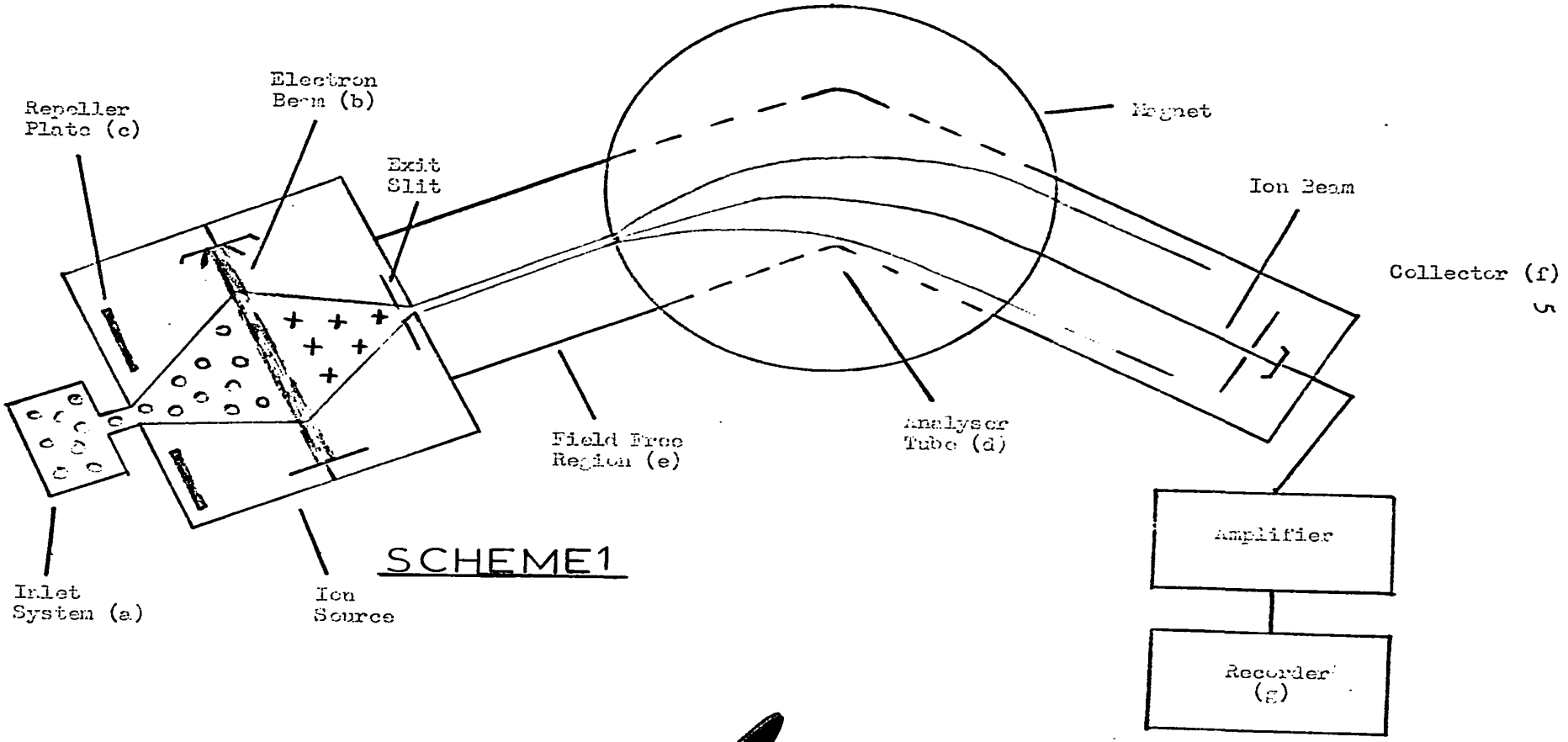
$$eV = \tfrac{1}{2} mv^2 \qquad \text{.....(1)}$$

where e = electronic charge

m = mass of the ion

v = velocity of the ion

In the analyzer tube, the centripetal force, Hev, due to the magnetic field is balanced by the centrifugal force, mv^2/r.


Repeller Plate (c)
Electron Beam (b)
Exit Slit
Magnet
Ion Beam
Collector (f)
Field Free Region (e)
Analyser Tube (d)
Amplifier
Recorder (g)
Inlet System (a)
Ion Source

SCHEME1

$$Hev = \frac{mv^2}{r} \qquad \ldots\ldots\ldots(2)$$

where H = magnetic field

r = radius of curvature of ion path

Eliminating v between (1) and (2) yields that

$$\frac{m}{e} = \frac{H^2 r^2}{2V} \qquad \ldots\ldots\ldots(3)$$

It is possible to control the motion of the ion throughout its flight by varying any of three parameters H, V, and r. It is convenient to retain r constant. Two modes of scanning are then available in order to allow an ion of mass to charge ratio m/e to describe a path whose radius of curvature is r. Most instruments use magnetic scanning devices in conjunction with a fixed but variable accelerating potential. Ions of successive m/e values may then be focussed to strike the collector plate (f). The induced current flowing from the collector may then be amplified and recorded (g) in a number of ways. Most instruments use a visicorder i.e. recording on ultra violet sensitive paper. For simple presentation the intensity of the strongest peak (base peak) in the spectrum is arbitrarily equated to 100 units. Other peaks may then be measured relative to the base peak and plotted as a bar graph. This process yields the mass spectra shown throughout this work.

Metastable Ions

Equation (3), above, is only valid for those ions that are formed within the ion source, and thus possess kinetic

energy eV. If, however, an ion (m_1) fragments in the field free region (e), between the ion source and the analyzer tube it will produce an ion (m^*) that has a mass (m_2) characteristic of its own chemical composition, but a velocity (v_1) characteristic of its precursor ion (m_1). Such ions (m^*) are energetically different from those ions of similar mass (m_2) that are formed in the ion source. The latter ions (m_2) will appear in the spectrum at m_2/e whereas the former (m^*) appear as a broad diffuse peak,[7] centered at $(m_2)^2/m_1$. These ions (m^*) are called metastable ions owing to the instability of their precursor ions. The presence of a metastable in a mass spectrum may be taken as conclusive evidence for the transition that gives rise to it. Caution must, however, be exercised, as more than one transition may yield a specific metastable. An example of this is found in the mass spectrum of o-nitrobenzaldehyde. A metastable is observed at 71.5 ± 0.2. Two possible transitions (m/e 151→m/e 104, m^* - 71.6 and m/e 121→m/e 93, m^* - 71.5) could yield such a metastable and it is not immediately obvious which transition does so (Chap 2). In the fragmentation schemes, where a dissociation is supported by a metastable, the transition is labeled by an asterisk.

High Resolution: Double focusing Mass Spectrometer

In the above treatment, only the effect of a magnetic field on the motion of the ions was considered. Under such conditions, it is possible to distinguish, quite easily, between

ions whose mass differential is of the order of one atomic mass unit. If, however, one wishes to determine the exact mass of a species, or to differentiate between ions whose mass differential is in the order of tenths (or less) of an a.m.u., the resolution of the instrument must be increased. This may be achieved by placing a curved electrostatic field between the ion source and the analyzer tube.

When the sample molecules enter the ion source they move with random velocity due to thermal kinetic energy. This random velocity, when summed with that due to the accelerating potential, produces an energy distribution amongst the ions. Thus, the peaks have a finite width, which is of the order of 0.01 a.m.u. at room temperature for an ion of mass 100. This would correspond to an ideal resolution of 1 part in 10,000. However, many samples are inserted at higher temperatures (200^{o}C is common for liquids, and 100 - 200^{o}C for solids). There are also limitations inherent in the geometry of the instruments e.g. finite ion source exit slit width, finite collector slit width and response time of the recorder. For these reasons, one usually obtains a resolving power of 1 part in 5,000 (10% valley) for a single focusing mass spectrometer. The resolution may be increased considerably by placing an electrostatic sector before the analyzer tube. The potential across the electrostatic sector is such that only ions in very narrow energy range are allowed to exit the sector. The resulting reduction in

the energy spread is sufficient to raise the resolution to 1 in 100,000 or greater depending on the instrument.

Metastable Defocusing[8]

Due to the energy focusing effect of the electrostatic field, it will not be possible for both the main ion beam and the metastable ions (formed in the first field free region, between the ion source and the electrostatic sector) to be focused through the electrostatic unit at the same applied potential. This is because the metastable ions are energetically different from the main ion beam. One can adjust the sector voltage such that one "sees" only the metastable ion peaks. This potential (Vm^*) can be shown to be related to that of the main beam (Vm.b.) by the following

$$Vm^* = \frac{M_2}{M_1} Vm.b. \qquad \text{.....(4)}$$

for the metastable transition $m_1^+ \rightarrow m_2^+$. Due to the selection of only a narrow energy range of the metastable ion by the electrostatic sector, only a small portion of the metastable peak is observed at any one potential across the sector. In order to obtain the whole metastable profile, the peak heights at potentials about the value Vm^* must be summed. Such results may be obtained in two ways. If one inserts an ion monitor at the electrostatic sector exit slit and then allows the sector potential to vary from 0 to Vm.b. one obtains the metastables as gaussian curves and the main beam as a sharp peak. Such spectra are called IKES (Ion Kinetic - Energy Spectra)[9]. If one suspects the presence of

metastable ions due to transitions involving doubly charged species, the region between Vm.b. and 2 Vm.b. may be investigated. The other method involves scanning magnetically at various, fixed potentials about Vm.b. Only a portion of the metastable is observed in each scan; summation over the potential range investigated yields the total metastable profile.

Such procedures are reasonable, provided that the energy distribution amongst the metastable ions is homogeneous and is due to their thermal kinetic energy. In the case of a flat-top metastable the energy distribution amongst the ions is also due to the conversion of internal to translational energy[10,11].

The maximum for m^* should occur at Vm^*, thus equation (4) may be used in determining the transition that gives rise to the metastable. The above procedure enables one to isolate the metastable peak and to measure its height and/or area. In a normal spectrum, these measurements are made difficult by the presence of neighbouring ion peaks. The use of the areas of such "defocused" metastable ion peaks will be further discussed in the analysis of water loss from cyclohexane diols (Chap 6).

Analysis of a Mass Spectrum

Having obtained the mass spectrum of the compound under investigation, various approaches are possible. The simplest is to record the relative intensities of the peaks; such compilations exist as the "Dow Uncertified Mass Spectral

Data, 1963" and "Compilation of Mass Spectral Data" A. Cornu and R. Massot (Heyden and Son Ltd, 1966) (only the ten most intense peaks are presented). This information, with the molecular weight, then allows the organic chemist to identify his material by comparing its spectrum with those in the compilations. This process is greatly aided by computer methods. However useful this approach may be to the organic chemist, it requires little or no understanding of the fragmentation mechanism and if one is to identify "original compounds" that do not appear in such compilation, it will be necessary to determine a suitable fragmentation mechanism. For this purpose knowledge of the identity of the major peaks is needed. Of greater importance, perhaps, is the origin of each peak. Many transitions may be identified by metastable peaks; others, simply by the mass differential between itself and its obvious precursor e.g. the peak at m/e 93 in the mass spectrum of nitrobenzene[1c] can only arise from the molecular ion , by loss of 30 mass units (NO). In other cases, the origin of a peak is ambiguous. For example, is the M-30 peak (m/e 123) in o-nitroanisole (Chap 2) due to loss of NO or CH_2O? Both these losses, from the molecular ions, are formally possible. With a high resolution instrument it would be easy to distinguish between the two resulting ions ($C_7H_7O_2^+$ from NO loss and $C_6H_5NO_2^{+\cdot}$ from CH_2O loss) on the basis of their mass difference ($C_7H_7O_2^+$ = 123.0548 a.m.u. and $C_6H_5NO_2^{+\cdot}$ = 123.0455 a.m.u.) of 0.0093 a.m.u. An instrument with a resolving power of 1 part in 13,000 would be capable

of distinguishing between these two species.

The problem could also be solved by substituting deuterium in the methyl function. This would result in a shift of the m/e 123 peak to either m/e 124 (M-CD_2O) or m/e 126 (M-NO) depending on the fragmentation mechanism. In this way it has been established that 80% of the m/e 123 species is $C_6H_5NO_2^+$ and 20% is $C_7H_7O_2^+$ (Chap 2). Isotopic labeling, such as this, constitutes an important technique in mass spectral investigations. In addition to allowing one to distinguish between various species of the same nominal mass, deuterium labeling also enables one to determine the origin of the hydrogen atoms involved in the dissociation process. Mechanistically, such information is valuable. Other isotopes that may also be easily incorporated into organic molecules are carbon-13 and oxygen-18.

In the above instance (o-nitroanisole), the ejected formaldehyde entity was shown to contain two of the hydrogen atoms originally located in the methyl function. Thus, it was possible to determine the initial fragmentation steps in this compound (Chap 2).

Hydrogen Scrambling

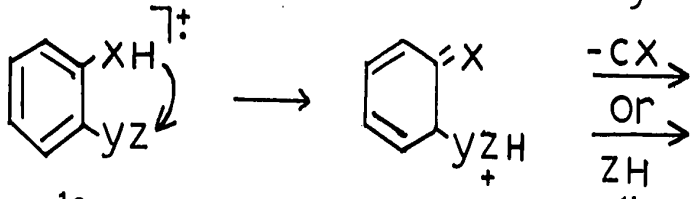
In some instances, incorporation of a deuterium label leads to complex and, at first glance, uninterpretable results. This arises when the hydrogen and deuterium atoms participate in a little understood "scrambling" or "mixing" process. Intramolecular hydrogen migrations are known to occur in certain species in solution[12] and they appear to

have low activation energies. It is not totally unexpected then, for the highly energised species present in the mass spectrometer to undergo such reactions, although, I am sure, most mass spectrometrists would prefer that they did not.

When "scrambling" occurs in an ion, the use of the relative peak heights of the daughter ions may by themselves, allow one to interpret the results. But this is not always so; (for example the problem of the mechanism of hydroxyl loss from benzoic acid could not be solved on the basis of peak heights alone[13]). Use can then be made of the metastable ion peaks. Under the assumption that the relative areas of metastable ion peaks are proportional to the abundance of their precursor ions, these areas may be used to determine the ratio of hydrogen and deuterium atoms involved in the loss under investigation. In practice, it is found that such groupings of metastable peaks have similar widths at half height and, thus their ratio may be measured directly from the peak heights. In carboxyl deuterated benzoic acid, the metastable ion peaks for OH and OD losses from the molecular ion are observed in a ratio of 2:1[13], indicating that two hydrogen and one deuterium atoms participate in the equilibration process. The mechanism of such equilibrations will be discussed further when the fragmentation of benzoic acid (Chap 3) and 1, 2-cyclohexanediols (Chap 6) are described.

Ortho Effects

There are few general rules that could be used to predict fragmentation sequences; one widely observed phenomenon is the "ortho effect"[1d-h]. This effect is defined as any interaction between a functional group and the ortho substituent or position. Dissociations by this mechanism are characterised by the transfer of a hydrogen atom between two adjacent groups followed by ejection of a small species. Thus, the loss of CH_3OH from methyl



salicylate[1e], the loss of OH from o-nitroaniline[1h], and the loss of H_2O from salicylic acid[1f] have been explained. These losses are not observed in the corresponding meta and para isomers. In these examples the intermediacy of a six membered transition state has been proposed. In some molecules, seven membered intermediates are necessary to explain the fragmentation sequence (e.g. the loss of H_2CO from o-nitroanisole (Chap.3), CO_2 from o-nitrobenzoic acid (Chap.3), and H_2O from phthalic acid (Chap.4)).

The "ortho" ring site may participate in the fragmentation sequence in yet other fashions. The hydrogen atom involved in the loss of OH from the molecular ion of carboxyl deuterated benzoic acid partly originates from the ortho positions[14]. The identity of the intermediate will be commented on in Chap.3. Further, migration of portions of a functional

group to an ortho ring site has been postulated to explain the loss of CO from the benzoic acid molecular ion (Chap 3), from the ($M-NO_2$) species in o-nitrobenzoic acid (Chap 2) and from the molecular ion in fumaric acid (Chap 4).

Thus far, the "ortho effect" has been only invoked to rationalize fragmentation mechanisms in ortho disubstituted arenes and 1, 2 - disubstituted ethylenes. In such systems the rigid geometrical arrangement facilitates such interactions. However,it is of interest to determine whether or not this geometrical arrangement is necessary for the operation of an "ortho effect". In order to test this idea, the carboxyl - carboxyl interaction observed in 1, 2 - dicarboxylic acids (Chap 5) was used as a probe. A variety of unsaturated six membered cyclic 1, 2 - dicarboxylic acids were investigated. The presence of an ortho interaction is then characterized by the losses of CO_2 and/or H_2O (D_2O in the carboxyl deuterated analogues) from the molecular ion.

Further, it is of interest to know which common functional groups participate in an "ortho effect". In this respect, the behaviour of many functional groups vis à vis the nitro group has been examined (Chap 2). The nitro group was chosen since it is an "acceptor" only , i.e. it participates in ortho transfers by receiving a transferred hydrogen atom.

The fragmentation schemes shown throughout this thesis are speculative except insofar as (i) the appropriate metastable peaks were observed, and (ii) the structures are compatible with the labeling experiments. Masses shown in

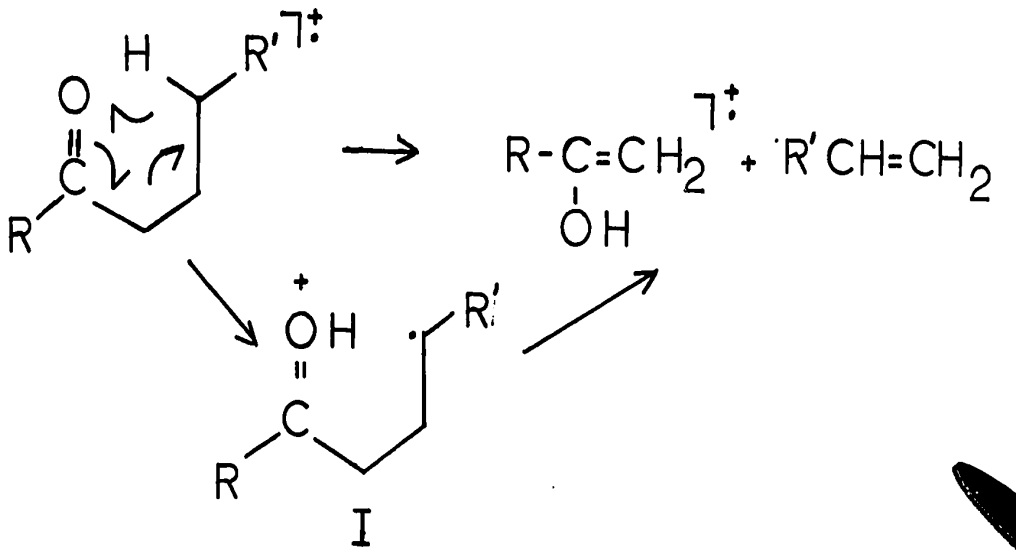
parentheses are for deuterium labeling experiments unless otherwise stipulated.

CHAPTER 2

"Ortho effects" in the fragmentation of some ortho substituted nitroarenes

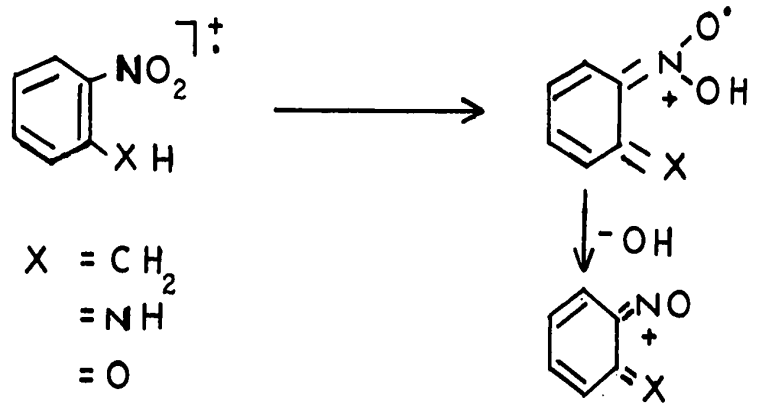
The fragmentations of some ortho substituted nitroarenes (such as o-nitrotoluene[1h] and o-nitroaniline[1h]) are characterized by an "ortho effect" particularly when the substituent group contains an α- hydrogen atom. The term "ortho effect" is, at present, ill defined; it is usually invoked to explain the participation of the hydrogen atom(s) of an ortho substituent or position in the dissociation sequence of ortho substituted arenes. In its simplest form, an "ortho effect" consists of the transfer of a hydrogen atom from a "donor" group to an ortho "acceptor" function. The mechanism of this transfer is similar to that of the McLafferty rearrangement which operates in the electron impact induced fragmentation of some ketones, esters and acids[1j]. This process has been shown to involve

migration of a hydrogen atom exclusively from the γ carbon position to the carbonyl oxygen with the concomitant ejection of an alkene. The rearrangement necessitates bond migration within a six membered ring as shown below.



It is not certain whether the mechanism is concerted or stepwise,i.e. whether the intermediate I can exist as a stable entity.

In o-nitrophenol, o-nitrotoluene and o-nitroaniline the transfer of a hydrogen atom to the nitro function does indeed involve a six membered transition state. However, if one applies the mechanism of the McLafferty rearrangement to these molecules the ejection of an alkene is not possible due to the second double bond in the system. Instead, one obtains a stable intermediate (similar to I above) which fragments by the loss of an OH radical.



Another difference between these two hydrogen atom migrations is the position of origin of the hydrogen atom. Whereas the McLafferty rearrangement can only operate via a six membered transition state, in the "ortho effect" five, six and seven membered transition states have been observed e.g. the loss of OH from 2-methylpyridine N-oxide[1j] (5-membered) and NH_3 from o-ethoxybenzamide[1k] (7-membered). The reason for these other possible transition states may be the presence of the aromatic ring within the intermediate ; the aromatic nucleus may hold the substituents in close enough proximity to allow the five and seven membered rings to be operative also.

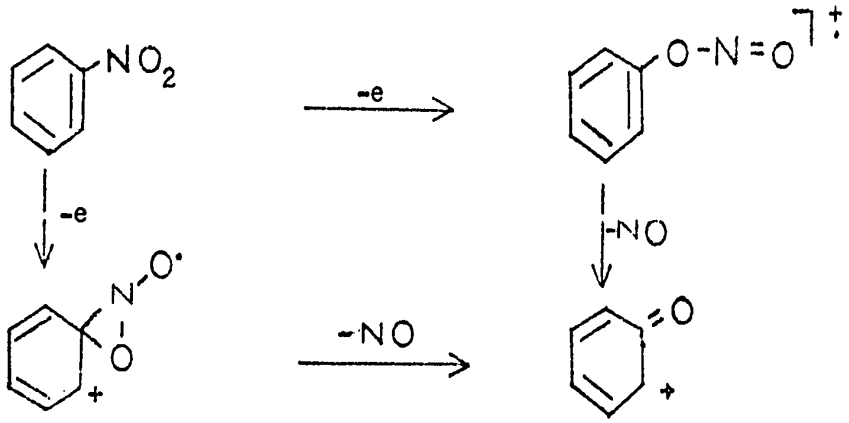
The requirements then for the operation of an "ortho effect" are the presence of suitable "donor" and "acceptor" groups in sufficiently close proximity. A suitable "donor" must contain at least one hydrogen atom positioned such that a five, six or seven membered ring intermediate is possible with the ortho substituent. A suitable "acceptor" must be able to form a bond with the transferred hydrogen atom.

Thus, the oxygen atoms of the nitro group can act as hydrogen atom acceptors whenever the ortho substituent has an α-or β-hydrogen atom.

Williams et al.have studied "ortho effects" in some nitroarenes where the substituents contained oxygen[15]. All their fragmentation schemes involved interaction between the ortho groups but there were some unexpected and puzzling features in some of their spectra, particularly those of o-nitrobenzoic acid and o-nitrobenzamide; the difficulties probably arose from contaminants resulting from the thermolysis of these compounds within the mass spectrometer's ion source and/or inlet system. The authors realized that this was the case in o-nitrobenzamide. Unfortunately, there was an error in the quoted mass of a peak in their mass spectrum of o-nitroanisole. Furthermore, their interpretation of the mass spectrum of o-nitrobenzaldehyde was equivocal and that of o-nitrobenzylalcohol incomplete. The mass spectra of these and related molecules have been reinvestigated and the results of experiments described in this thesis allow a more complete and consistent interpretation of the ortho effects involved.

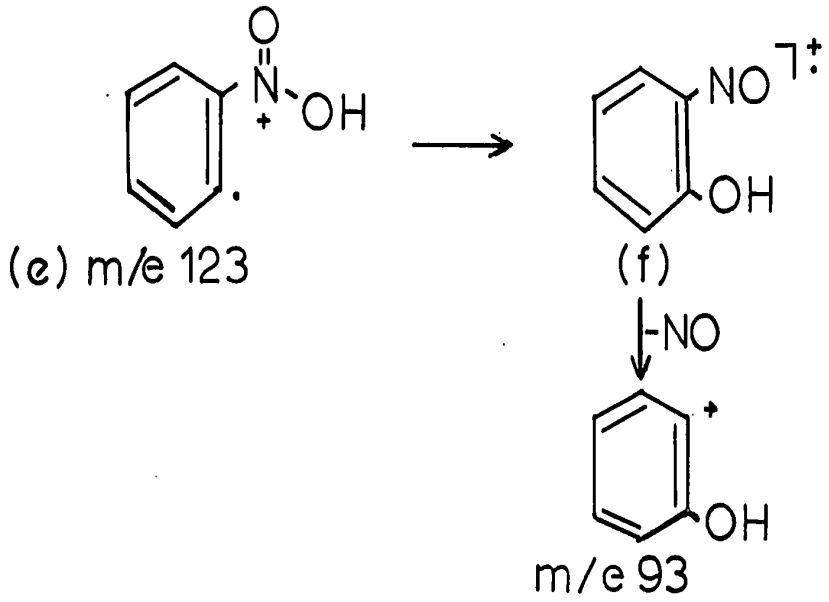
Before discussing the fragmentation of ortho substituted nitroarenes it will be useful to review the dissociation sequence in the parent compound, nitrobenzene. This compound

fragments via the successive losses of NO_2 and C_2H_2 to generate ions at m/e 77 and m/e 51 respectively[1c]. An intriguing minor dissociation sequence is the successive losses of NO and CO from the molecular ion. For the molecular ion to be able to lose NO, rearrangement of the nitro group is necessary. Two mechanisms seem reasonable and these have been discussed in a review article by Bursey[16]; they are "in situ" nitro-nitrite isomerization and rearrangement via a three-membered ring intermediate. Participation of the ortho hydrogen



was considered unlikely because 2,3,5,6-tetrafluoro-nitrobenzene[17] still showed NO loss from the molecular ions. Further, the presence of a "flat-top" metastable accompanying NO loss in o- and p-nitrophenol but not in the meta isomer supports the suggestion[5] that the remaining oxygen is attached to the original ring position. In order to explain the relatively large energy release required for a flat top metastable the authors proposed that the (M-NO) ion in the para and ortho

isomers must have a quinoid structure which is absent in the meta isomer. However, in our analysis of nitroarenes we have found that NO loss was aided by participation of the ortho positions. This is the case in o-nitroanisole where the M-CH_2O species, which we represent as ion(e) (Scheme 4), showed an appreciable loss of NO.



Ion(e) can only lose NO after migration of hydroxyl to the vacant ortho site. A similar proposal has been used to explain CO loss from the molecular ion of benzoic acid (Chap 3). It was felt that ion(e) might be an intermediate in the fragmentation of nitrobenzene.

In order to test this proposal we have studied the mass spectrum of 1-^{13}C-nitrobenzene. Complete retention of the label in the $C_5H_5^+$ ion would give support to our proposed mechanism while complete loss would rule it out. Partial

loss of the label would suggest the occurrence of oxygen migration or "scrambling" and such behaviour has been reported as occurring in the ion $C_6H_6NO^+$ produced by NO loss from the molecular ion of p-nitroaniline[18]. Davis and Williams find this result difficult to reconcile with their metastable-ion studies which indicate retention of positional identity.[19] In order to clarify this point we have investigated the mass spectrum of 1-^{13}C-4-nitroaniline.

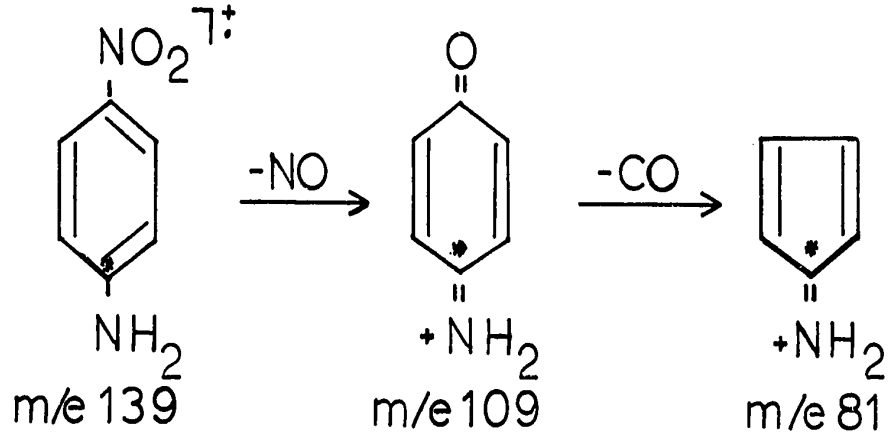
(1) 1-^{13}C -Nitrobenzene and 1-^{13}C -4-Nitroaniline

The 70ev mass spectrum of 1-^{13}C -Nitrobenzene showed that the M-NO-CO species does not preferentially retain the ^{13}C label ; indeed, m/e 66, ($^{13}CC_4H_5^+$) is 9.1 ± 0.9% of m/e 65, ($C_5H_5^+$) (in the unlabeled material m/e 66 was 6.5% of m/e 65). At low eV, (17 - 20V) the m/e 66 peak is 7.1 ± 0.8% of m/e 65 peak. Thus retention of the ^{13}C label is no greater than 3%. We conclude, from this result, that the positional identity of the remaining oxygen atom is retained in the "nitro-nitrite" isomerization and that ion(e) does not participate in the fragmentation of nitrobenzene. These results, however, do not allow us to distinguish between the two mechanisms discussed by Bursey[16].

The phenyl ion m/e 78 ($^{13}CC_5H_5^+$) produced by loss of NO_2 from the molecular ion is observed to lose the label randomly upon further fragmentation. The loss of acetylene from the phenyl species produces peaks at m/e 52 and m/e 51 whose ratio is 2:1. This ratio corresponds to the random

selection of any two carbon atoms from the six present. A similar result has been obtained in the fragmentation of benzene[2] itself.

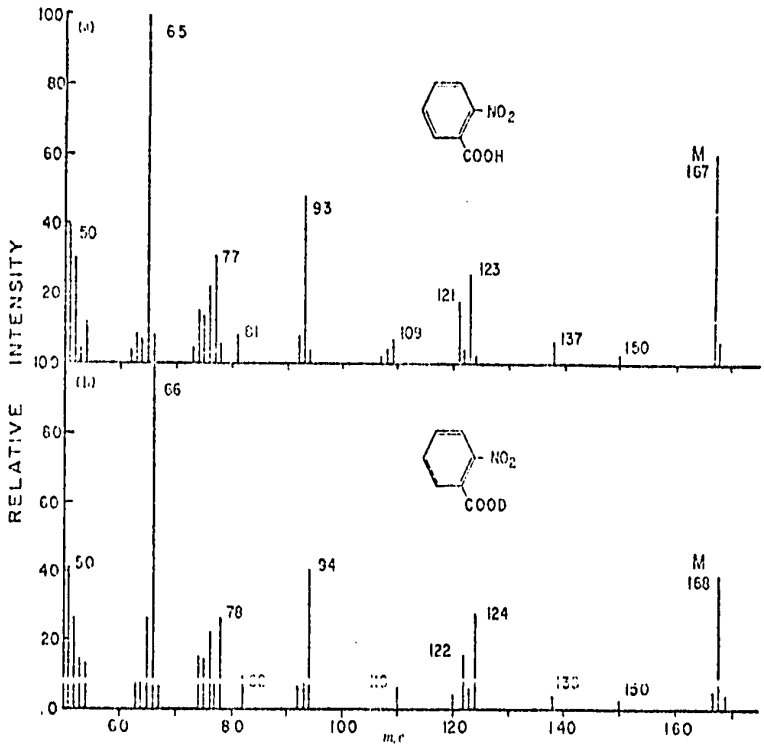
In the mass spectrum of 1-^{13}C -4-nitroaniline the M-NO-CO species m/e 81 is found to retain the label ; in the 70ev mass spectrum the peak corresponding to loss of label, m/e 80 is no more than 3% of the peak corresponding to label retention. At ~15 eV a similar result is obtained.



This result, therefore, removes the recently quoted inconsistency[19]; both the phenoxy and p-aminophenoxy cations generated from the corresponding nitro compounds retain the positional identity of the oxygen atom in the nitro-nitrite isomerization. No migration of the oxygen atom, either before or after NO loss is observed.

(2) o-Nitrobenzoic acid

The mass spectrum of this compound (Fig. 1a) differs in several respects from that reported by Williams et al[15].



FIGS. 1a and 1b. Mass spectra of *o*-nitrobenzoic acid and *o*-nitrobenzoic acid-carboxyl-d_1.

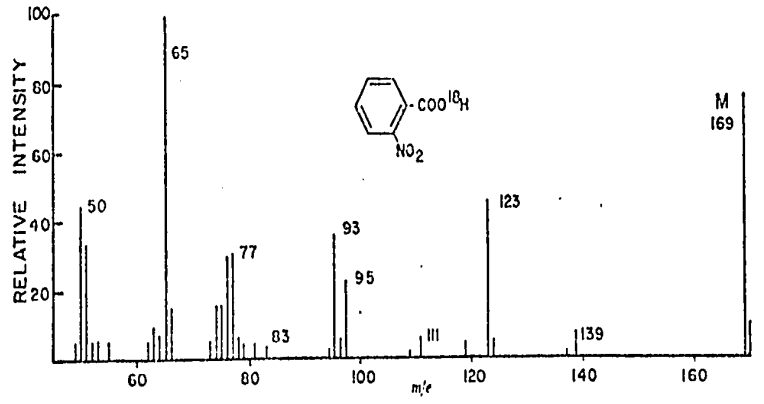
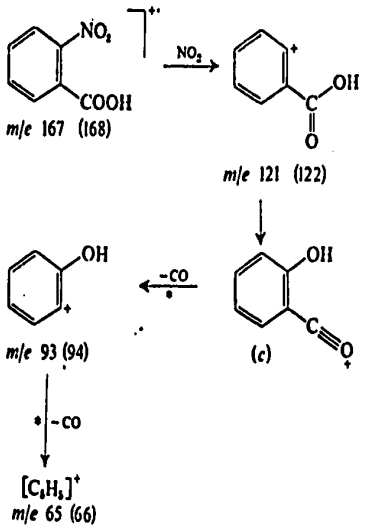


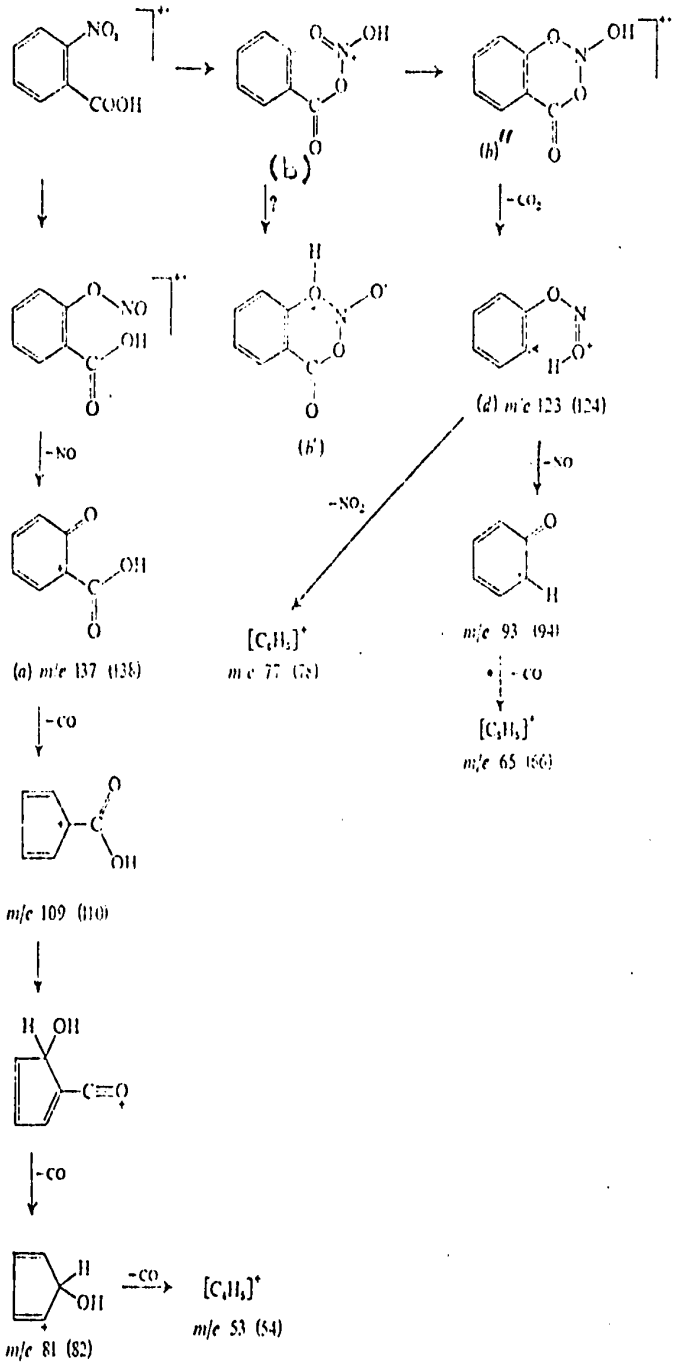
FIG. 1c. Mass spectrum of *o*-nitrobenzoic acid-carboxyl O^{18}.

Their spectrum showed fragments characteristic of nitrobenzene and a large m/e 44 peak. We found this compound to be thermally labile and it readily decarboxylated in a heated ion source (~150°) to yield a mass spectrum similar to that of nitrobenzene and with a very prominent m/e 44 (CO_2) peak. With source temperature 35°, however, there was no evidence for thermal decarboxylation, the m/e 44 peak remaining close to background intensity. We conclude therefore that the prominent m/e 123 peak in our mass spectrum indeed arises from electron-impact induced elimination of CO_2; we propose that this elimination occurs via an "ortho effect" and follows transfer of carboxyl hydrogen to nitro oxygen. Williams et al.[15] proposed that the carboxyl hydrogen migrated to the nitrogen atom on the grounds that the fragment ion m/e 106 (i.e. m/e 123 - OH) was absent whereas in the mass spectrum of o-nitroanisole the same species, m/e 123 ($C_6H_5NO_2^{+\cdot}$), lost OH. We discuss this point further under o-nitroanisole. The mass spectra of the d_1 (carboxyl) acid and the ^{18}O (carboxyl) acid are shown as Figs. 1b and 1c respectively.

The proposed fragmentation routes for o-nitrobenzoic acid are shown as Schemes 1 and 2. Scheme 1 shows a simple fragmentation involving loss of the nitro group followed by migration of hydroxyl to the vacant ortho site followed by two successive CO losses. Scheme 2 is more complicated, involving "nitro to nitrite" isomerization assisted by the carboxyl group and will be further discussed under o-nitroanisole.



SCHEME 1. Fragmentation mechanism for *o*-nitrobenzoic acid.



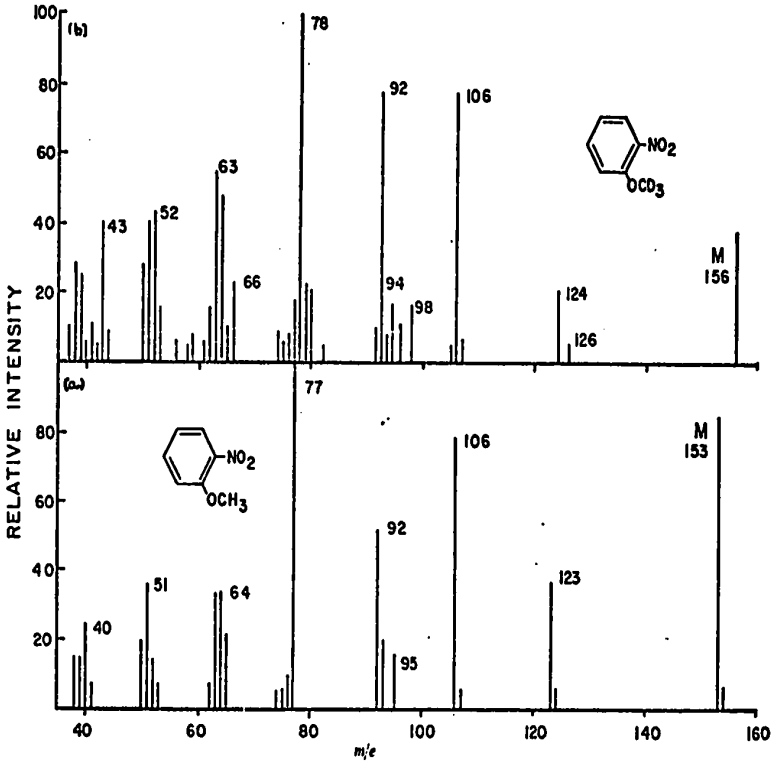
SCHEME 2. Fragmentation mechanism for *o*-nitrobenzoic acid.

site. Indeed an analogous migration and double CO loss is observed as a minor route in the benzoic acid fragmentation. (Chap 3)

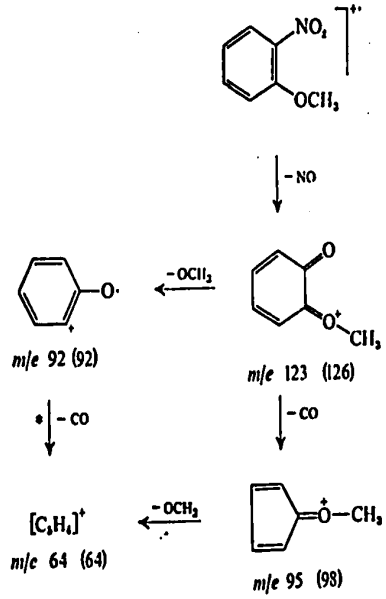
(3) o-nitroanisole

The mass spectrum of o-nitroanisole is shown as Fig. 2a. Our spectrum is closely similar to that of Williams et al.[15] except that the fragment m/e 92 in our spectrum was reported at m/e 91 in the earlier study. We believe that the discrepancy lies in a mass counting error; the authors were unable to explain the origin of their m/e 91 fragment. They also stated that the m/e 123 species arose by the loss of CH_2O from the molecular ion following migration of a methyl hydrogen atom to the nitro oxygen. The mass spectrum of α-d_3 o-nitroanisole is shown as Fig. 2b. Comparison of Figs. 2a and 2b shows that only 80% of the (M - 30) fragment ion in the unlabeled compound arises from CH_2O loss and the remaining 20% from NO loss. Here, "in situ" nitro to nitrite isomerization is most probable because the M-NO species fragments by loss of CH_3O, i.e. it is the (M-NO) species which yields the ion m/e 92 by loss of CH_3O (Scheme 3).

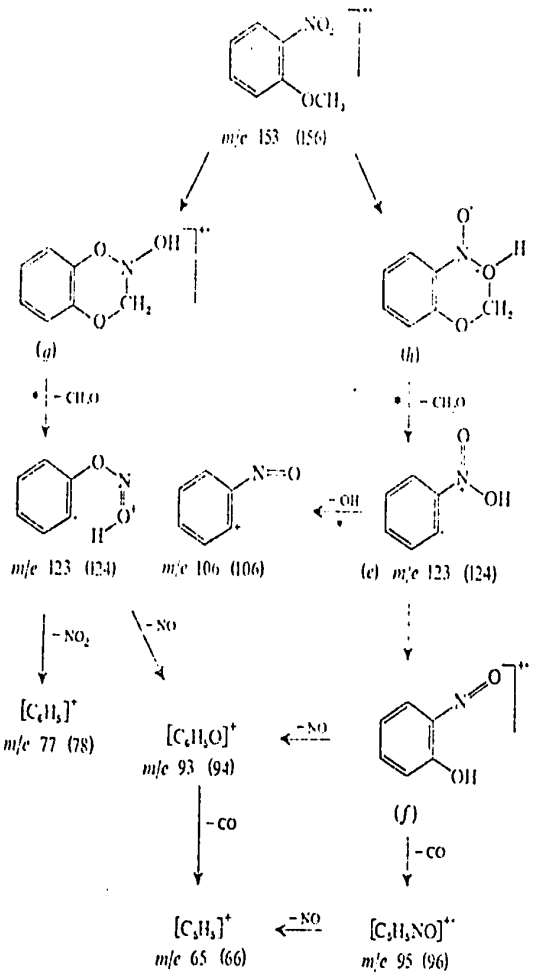
It was considered significant[15] that the ion ($C_6H_5NO_2^{+\cdot}$), m/e 123, fragments differently from the same species observed in o-nitrobenzoic acid. In o-nitroanisole this ion loses OH, CO, NO or NO_2 in parallel fragmentations whereas in the acid it loses only NO or NO_2. We explain this behaviour by proposing that in the acid, "nitro to nitrite" isomerization



FIGS. 2a and 2b. Mass spectra of *o*-nitroanisole and *o*-nitroanisole-α-d_3.



SCHEME 3. Fragmentation mechanism for *o*-nitroanisole.



SCHEME 4. Fragmentation mechanism for *o*-nitroanisole.

is complete (Scheme 2) but in the anisole both nitro and nitrite forms participate in the fragmentation and that the OH lost comes from the protonated nitro group shown in Scheme 4 (ion e). The latter process was indeed proposed earlier[15]. Migration of OH to the vacant ortho site in ion(e) yields ion(f), which loses CO or NO. An explanation for the presence of both nitro and nitrite forms in the anisole fragmentation may lie in the formation of two possible six-membered cyclic ions(g) and (h) involving the ortho groups, whereas in the acid the similar six-membered cyclic ion(b") can only involve the nitrite form. In the latter case, this would necessitate the expansion of a five-membered ring (ion b).

(4) o-Nitrobenzaldehyde

The mass spectrum of this compound (Fig. 3) agrees with that previously reported by Williams et al.[15] whose fragmentation sequence involved conversion of the aldehyde to o-nitrosobenzoic acid (this by analogy with the photochemical transformation). The authors presented two fragmentation sequences, both involving the rearranged molecular ion. These are the successive losses of NO, CO and CO as one sequence and of NO, OH and CO as the other.

They thus explained the peak at m/e 104 as arising by OH loss from m/e 121 (M - NO). This was later[11] deemed unlikely because whereas the mass spectrum of o-nitrosobenzoic acid also showed peaks corresponding to successive losses of NO, CO and CO, the peak of m/e 104 was only small. We present

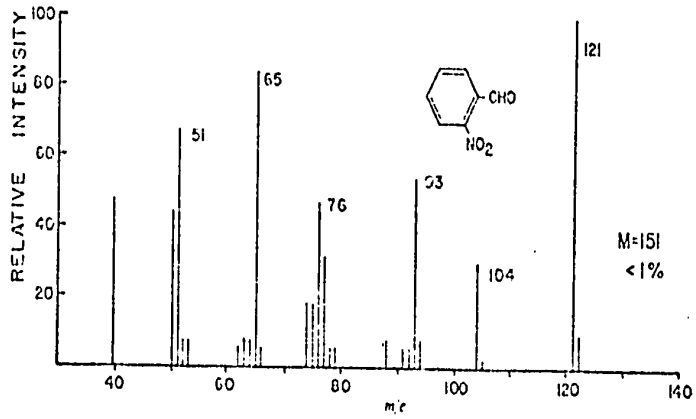


FIG. 3. Mass spectrum of *o*-nitrobenzaldehyde.

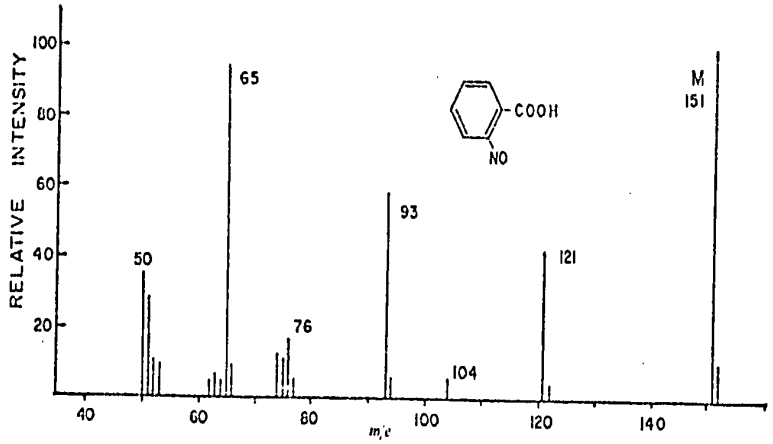
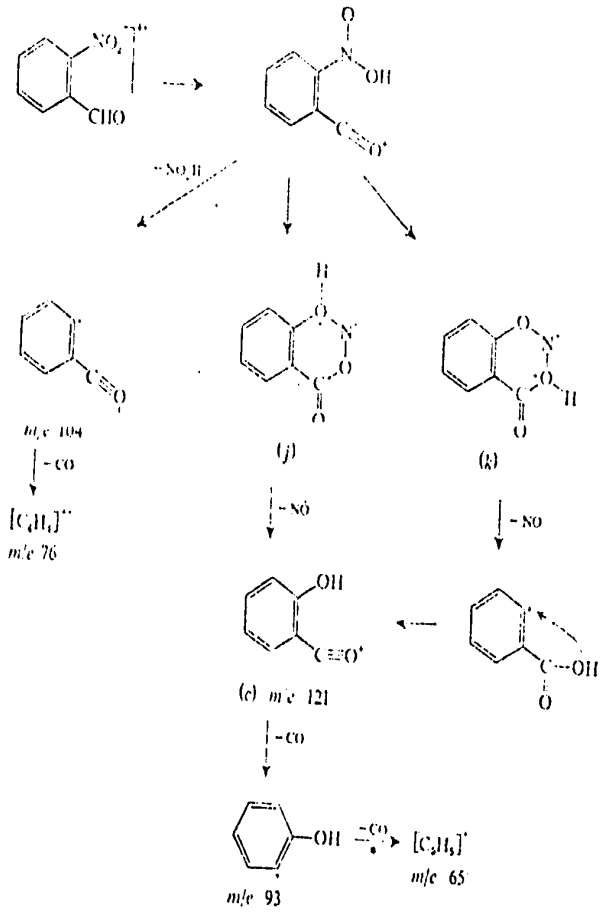


FIG. 4. Mass spectrum of *o*-nitrosobenzoic acid.

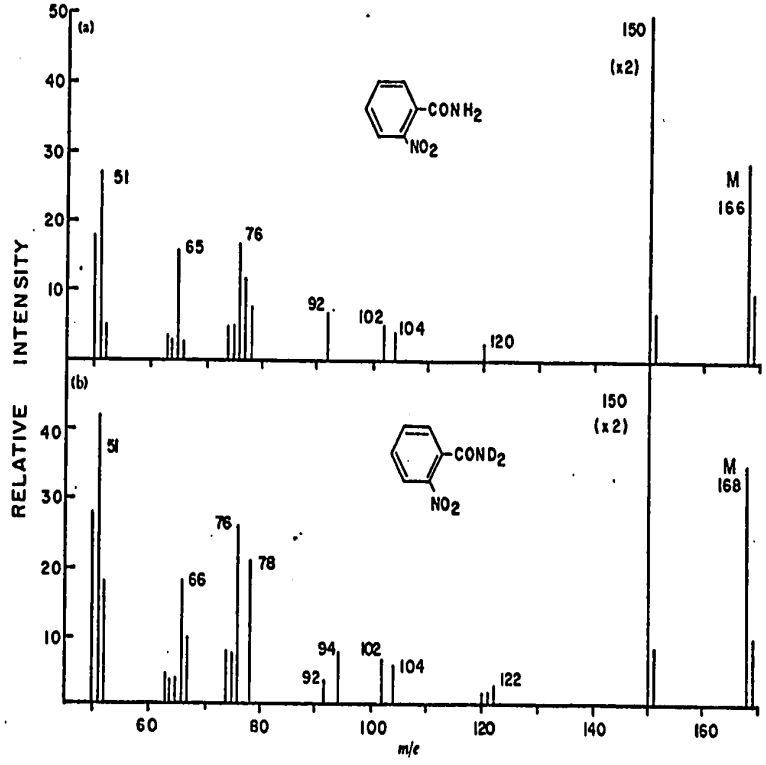


SCHEME 5. Fragmentation mechanism for *o*-nitrobenzaldehyde.

the hitherto unpublished mass spectrum of o-nitrosobenzoic acid as Fig. 4 and therein m/e 104=5%. It should also be noted that this compound (the acid) exhibits an intense molecular ion (base peak) whereas for the aldehyde the molecular ion has a relative abundance of less than 1%; this also makes unlikely the intermediacy of the nitroso acid in the aldehyde fragmentation. It is therefore more likely that m/e 104 in the aldehyde arises directly by NO_2H loss from the rearranged molecular ion in which the aldehydic hydrogen atom has migrated to the nitro oxygen atom (Scheme 5). The m/e 121 ion ($C_7H_5O_2^+$) is of interest since it appears in the mass spectra of o-nitrobenzoic acid, o-nitrobenzaldehyde and o-nitrosobenzoic acid. In each case the ion fragments by two successive CO losses and we propose this common ion has the structure(c) in Scheme 1 and arises in the aldehyde via intermediates of nitrite form, (j) and (k) (Scheme 5). These are necessary to explain the generation of ion(c) via an intermediate other than o-nitrosobenzoic acid.

(5) <u>o-Nitrobenzamide</u>

The mass spectrum of o-nitrobenzamide (Fig. 5a) shows little resemblance to that reported earlier[15] and this difference lies in thermal decomposition in the ion source, a complication that was indeed realised by the previous workers . We find extensive dehydration in a heated source but no evidence of decomposition in a source maintained at 35°; it was necessary to raise the temperature of the sample probe heater to 200° to volatilize sufficient material to

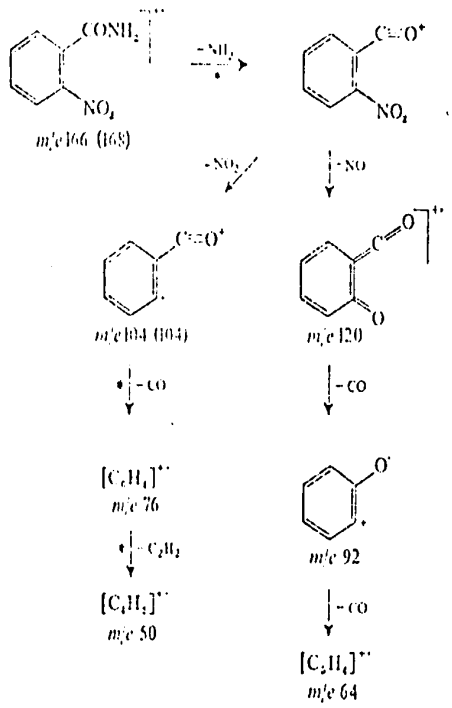


FIGS. 5a and 5b. Mass spectra of *o*-nitrobenzamide and *o*-nitrobenzamide-N-d_2.

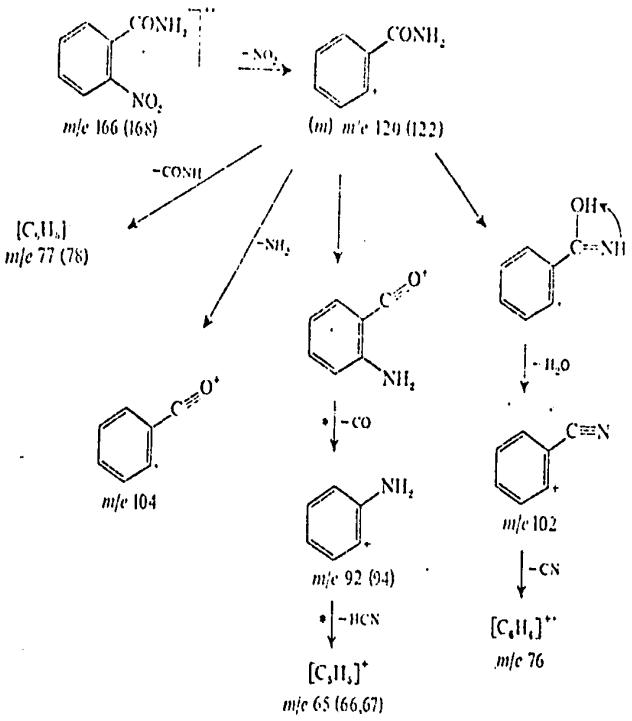
obtain a spectrum but "background" H_2O remained unaffected and m/e 148 (M - 18) was~1%. The mass spectrum of the N-dideutero compound is shown as Fig. 5b. We propose the fragmentation mechanism shown in Schemes 6 and 7. This compound displays no primary "ortho-effect" insofar as it is not necessary to invoke either atom or group transfer between the ortho substituents in the first steps of the fragmentation; indeed the ortho groups appear to act independently. This conclusion was also drawn by Williams et al[15]. In Scheme 6, events following the loss of NH_2 from the molecular ion are shown as simple cleavages. However, the loss of NO_2 from the molecular ion yields ion m whose complex fragmentation is shown in Scheme 7; this ion(i) loses H_2O (D_2O) possibly via the imide form, (ii) loses CO probably after migration of NH_2 to the vacant ortho-site (we postulate a similar migration to occur in benzamide, see chap 3), (iii) loses CONH perhaps following migration of H to the vacant ortho site. It seems reasonable that the important feature governing such migrations is the charge density at the ortho position. In this compound, nitro-nitrite conversion is incomplete as indicated by the loss of only NO_2 from the molecular ion whereas NO_2 and NO loss appear in the fragmentation of ion m/e 150.

(6) <u>o-Nitrobenzyl alcohol</u>

The mass spectrum of this compound (Fig. 6a) was also reported by Williams et al[15]. who proposed that loss of H_2O from the molecular ion proceeded by a mechanism analogous to



SCHEME 6. Fragmentation mechanism for *o*-nitrobenzamide.



SCHEME 7. Fragmentation mechanism for *o*-nitrobenzamide.

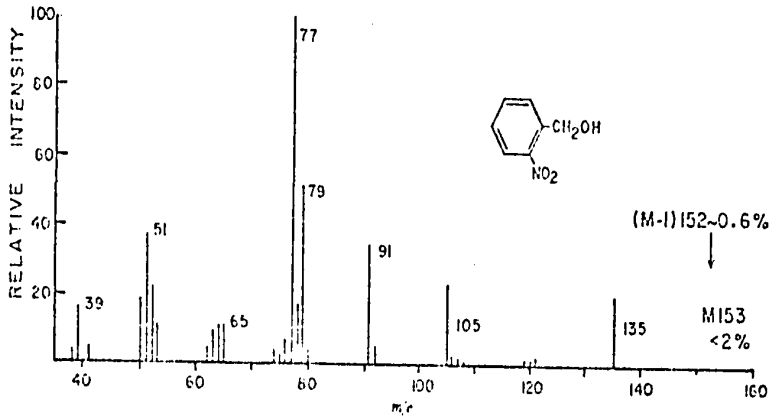


FIG. 6a. Mass spectra of *o*-nitrobenzyl alcohol.

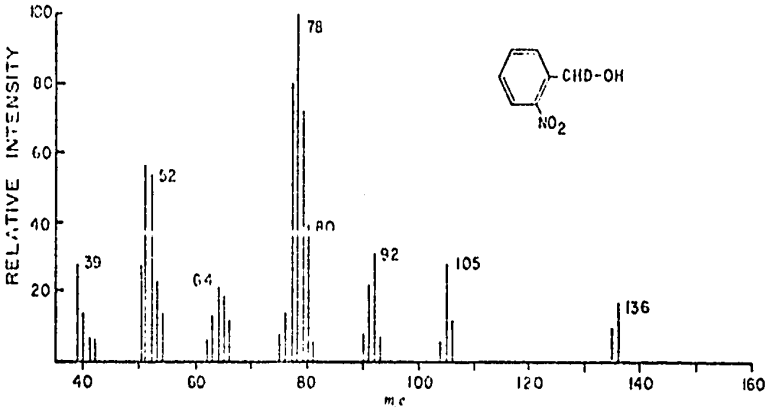


FIG. 6b. Mass spectra of *o*-nitrobenzyl alcohol-α-d_1.

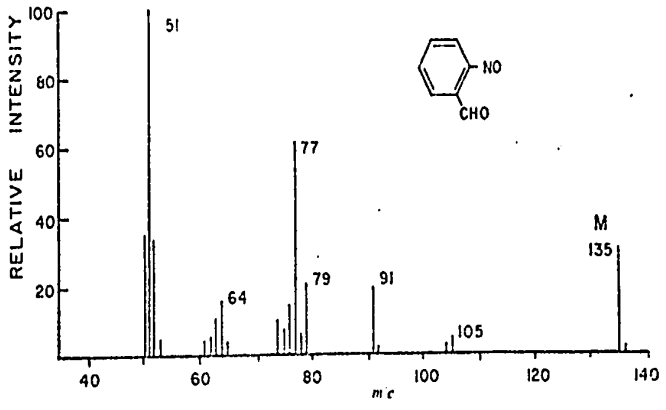
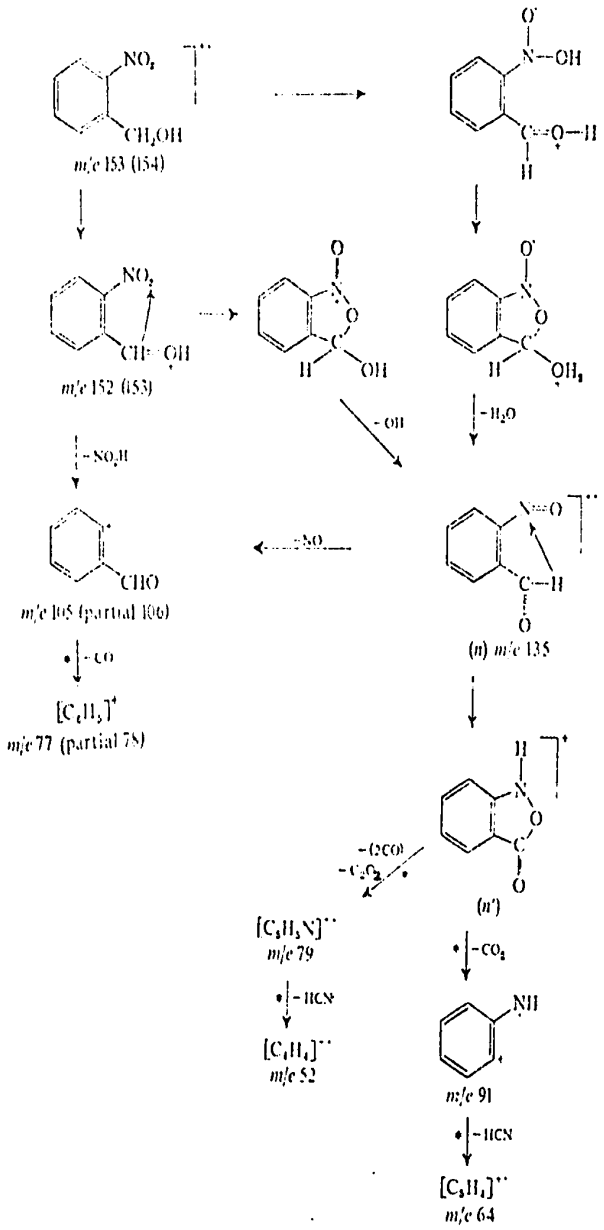


FIG. 7. Mass spectrum of *o*-nitrosobenzaldehyde.

that of the photochemical dehydration which yields o-nitroso-benzaldehyde. They reported a prominent (10%) (M - 3) ion (m/e 150); we do not observe this feature (m/e 150=0.05%) but otherwise the spectra are similar. We confirm that in O-d_1 o-nitrobenzyl alcohol, water elimination from the molecular ion involves complete loss of the label. In the case of the α-d_1 compound (Fig. 6b) there is an isotope effect, the loss of H_2O being about 1.6 times that of HDO. In Fig. 6a a small (M - 1) peak is shown (0.6%); in the α-d_1 compound (M -1) (0.4%), (M - 2) 0.2%. The (M - H_2O) ion could arise from either direct elimination from the molecular ion or by OH loss from the (M - H) species; the ratio of ~2 for H/D loss from the molecular ion lends support to the latter hypothesis since the apparent isotope effect associated with (M - H_2O) (the observed (M - H_2O):(M - HDO) ratio is ~1.6) is large for the direct loss of water. Both routes are shown in Scheme 8 (masses in parentheses refer to O-d_1 compound). In the compound labeled with ^{18}O in the alcohol group, only one fragment was observed to retain the label; m/e 105 was partially shifted to m/e 107 showing that either the molecular ion loses NO_2H or (M - 1) loses NO_2. This result also indicates that the m/e 105 species results from NO loss from m/e 135 ($C_7H_5NO_2$). The fragment ion m/e 91 arises from m/e 135 by CO_2 loss (m^*61.3; 62.2 -d_1) and then eliminates HCN (m^*45.0) to yield m/e 64.

The ion m/e 135 also fragments by loss of C_2O_2 (probably



SCHEME 8. Fragmentation mechanism for *o*-nitrobenzyl alcohol.

as two successive CO losses but nevertheless yielding a metastable m* 46.2; such processes have been reported[20]) to yield the ion m/e 79. Considerable rearrangment must have taken place before such an elimination. A valid structure, compatible with the results of the labeling experiments, is that of o-nitrosobenzaldehyde (n). This compound was prepared and its mass spectrum is shown as Fig. 7. This spectrum is remarkably similar to that of o-nitrobenzyl alcohol; we thus confirm that these two compounds fragment via a common intermediate ion (n) or (n').

(7) 2,4 - Dinitrophenylhydrazine (2,4-DNP)

The mass spectrum of 2,4-dinitrophenylhydrazine (Fig. 8a) may also be interpreted by involving an "ortho effect". The mass spectrum of this compound has not been previously investigated. In Scheme 9, two H atoms are shown as migrating from the hydrazine function to the o-nitro group and the subsequent loss of water produces fragment ion(o) m/e 180 which further dissociates via the successive losses of N_2, NO and NO to produce fragment ions (p) (q), and (r). The fragment ion r, m/e 92 then dissociates further to produce the peaks m/e 64 and 63 by loss of CO or CHO, as is found in the case of aryl oxygen compounds[1m]. A fragment ion of some interest in the above sequence is (p), m/e 152. Upon deuteration of the hydrazine function (Fig. 8b) m/e 152 is shifted to m/e 153 (2% b.p.) and m/e 155, (s), (1% b.p.); the former arising by loss of D_2ON_2 (either as D_2O and N_2

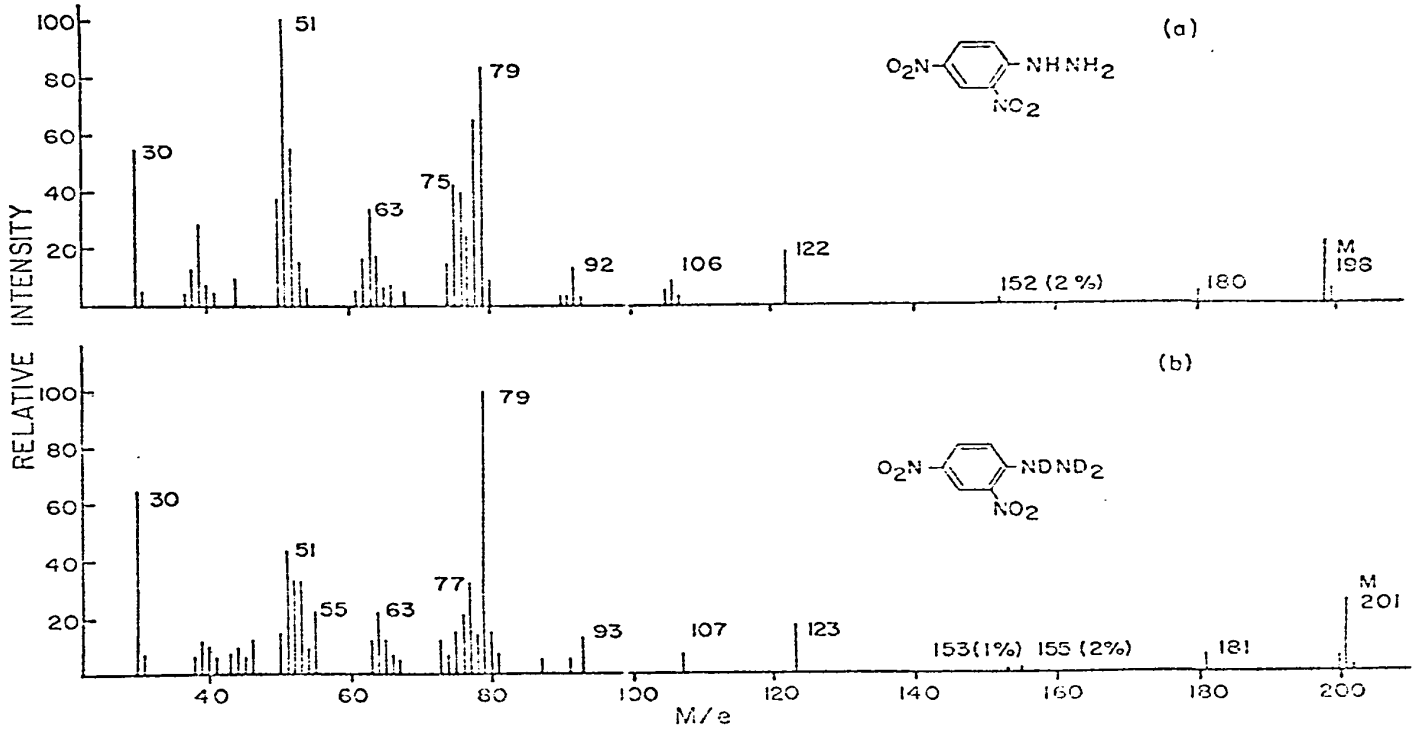
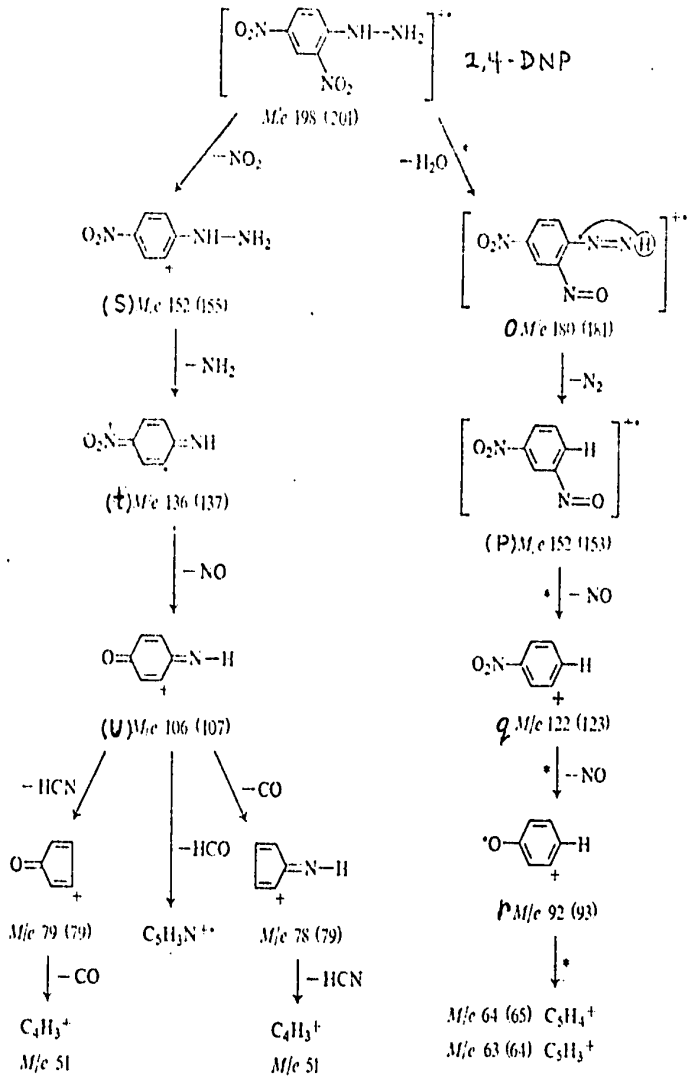


FIG. 8. Mass spectra of (*a*) 2,4-dinitrophenylhydrazine and (*b*) its *N,N'*-d_2-analogue.



SCHEME 9

Fragmentation mechanism of 2,4-dinitrophenylhydrazine.

successively or as (D_2ON_2) from the molecular ion while the latter arises by loss of NO_2 from the molecular ion. The nitro group lost is believed to be from the ortho position because (s) does not show the loss of H_2O or OH that could be expected from interaction of an ortho-nitro group with the hydrazine function. Fragment ion (s) then successively loses NH_2 and NO to yield fragment ions (t) and (u). Fragment (u) can then undergo the loss of HCN, CO or HCO to produce fragments of m/e 79, m/e 78 and m/e 77 respectively. It should be noted that m/e 79 is not shifted upon deuteration while m/e 78 is shifted to m/e 79. Thus the intensity of the latter peak is increased sufficiently for it to become base peak while in the undeuterated compound, m/e 51 is base peak.

(8) <u>para- and ortho-nitrophenylhydrazine</u> (p and o-NP)

The mass spectra of 2,4-DNP and p-nitrophenylhydrazine (p-NP) are superficially similar, except that in the latter many fragment ions appear at one mass unit higher. For example, peaks at m/e 152, m/e 122, m/e 106, and m/e 79 in 2,4-DNP are observed at m/e 153, m/e 123, m/e 107 and m/e 80 in the mass spectrum of p-NP which is shown as Fig. 9a. One peak prominent in Fig. 9 which does not appear strongly in the mass spectrum of 2,4-DNP is that at m/e 90. In the N,N' - trideuterated analogue of p-NP, the peaks at m/e 107 and m/e 90 are shifted to m/e 110 and m/e 91 respectively. These can be explained if the loss of NO_2 from the molecular ion is followed by ring opening together with migration of

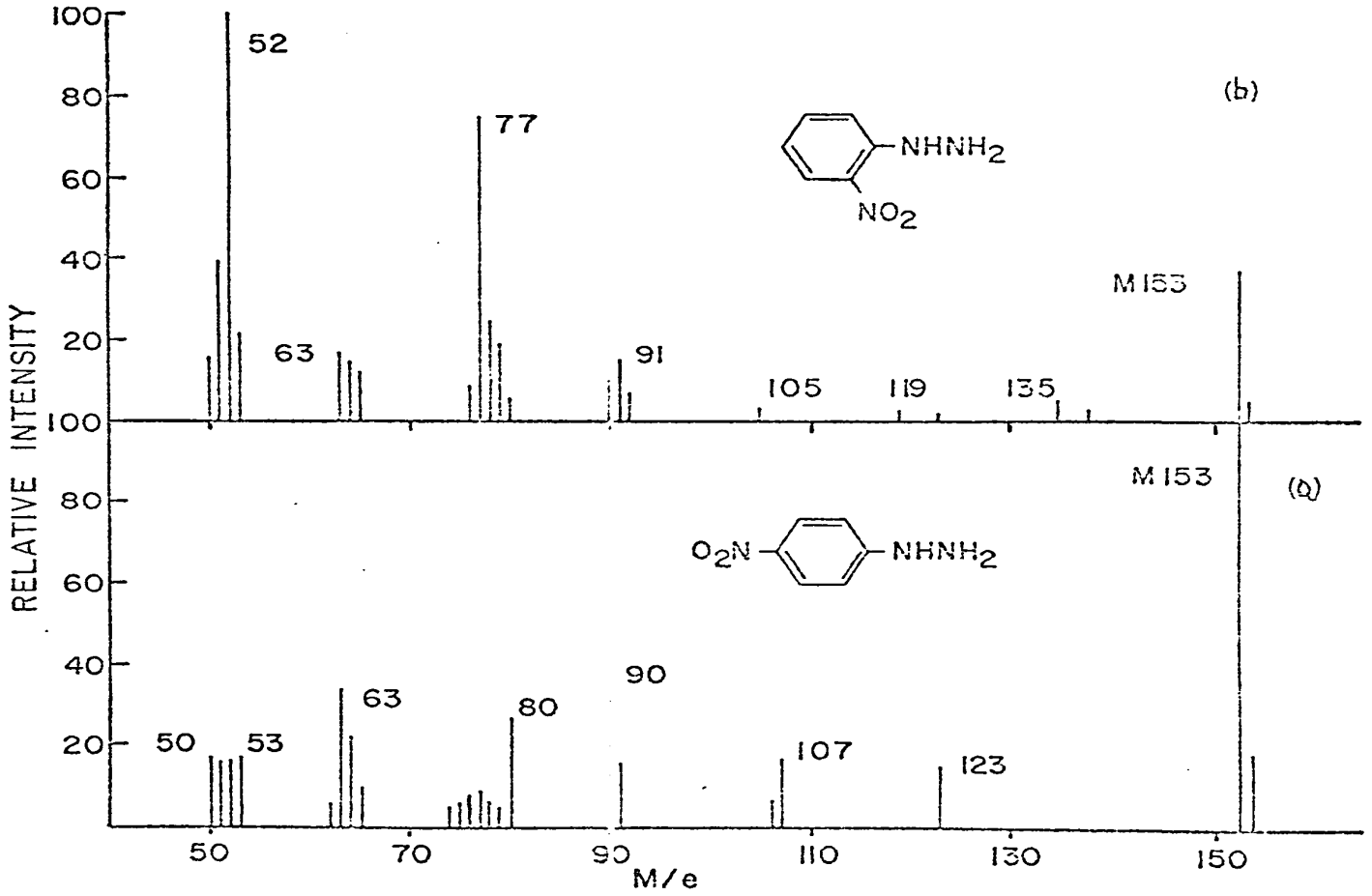
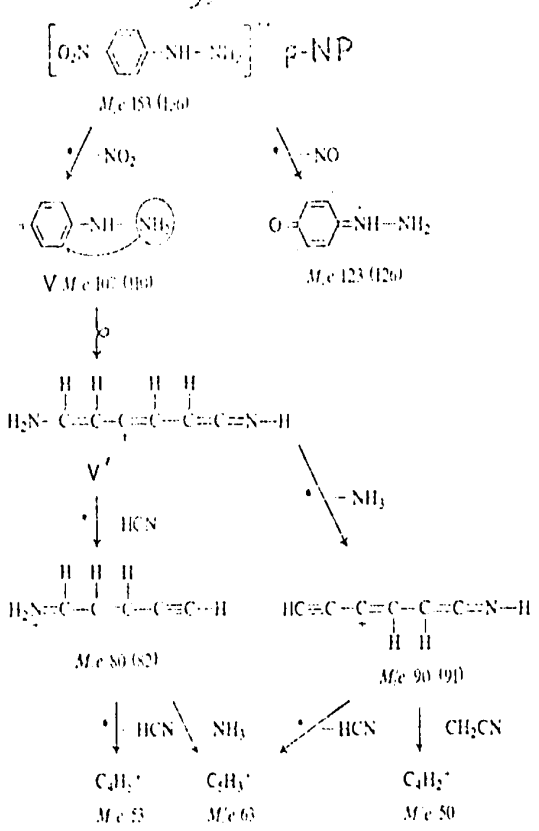


FIG. 9. Mass spectra of (*a*) *p*- and (*b*) *o*-nitrophenylhydrazine.

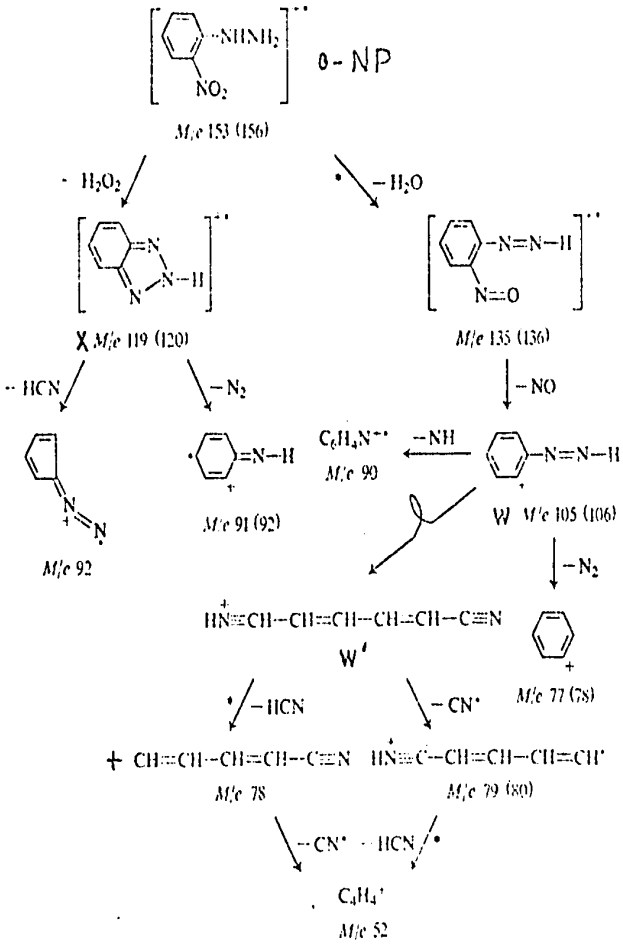
$NH_2^{\cdot}$ to the ortho-position yielding the fragment ions (y) and (y') shown in Scheme 10. The linear structure (y') would be better able to carry two positive charges than the cyclic form and indeed a small peak (0.1%) is found at m/e 53.5. Fragment (y') can lose either HCN or NH_3 to give ions m/e 80 and m/e 90 respectively; the latter pair can undergo conjugate losses as shown, to produce the ion m/e 63. It is noteworthy that the ion m/e 107 is <u>not</u> the analogue of m/e 106, (u) (which contained oxygen) in the mass spectrum of 2,4-DNP. This explains the lower intensities of peaks at m/e 78 and m/e 79 in p-NP; these were found to arise by loss of HCO$^{\cdot}$ or CO from (u) in 2,4-DNP.

The mass spectrum of o-nitrophenylhydrazine (o-NP) (Fig. 9b) is appreciably different from that of the para isomer. This is due to the "ortho-effect" described in the fragmentation of 2,4-DNP. The ortho isomer sequentially loses H_2O and NO from the molecular ion to give fragment ion (w) as shown in Scheme 11. The loss of N_2 or NH$^{\cdot}$ from (w) to produce ions m/e 77 and m/e 90 respectively could occur readily from a cyclic entity. To explain the loss of HCN or CN$^{\cdot}$ from (w) we again propose ring opening following migration of NH$^{\cdot}$ to the ortho position to produce (w'). The latter can sequentially lose CN$^{\cdot}$ and HCN (or <u>vice versa</u>) yielding m/e 79, m/e 78 and m/e 52. Thus the ortho isomer, whose mass spectrum is superficially different from that of p-NP fragments by a closely similar mechanism.



Scheme 10

Fragmentation mechanism of *p*-nitrophenylhydrazine.



Scheme 11

The loss of H_2O_2 from the molecular ion is not widely encountered and deserves mention; the transfer of two H atoms to different oxygen atoms on the nitro group with subsequent loss of H_2O_2 could yield the stable entity (x) which can further lose either N_2 or HCN to produce m/e 91 and 92 respectively as shown in Scheme 11.

Conclusions

The study of 1-^{13}C -nitrobenzene and 1-^{13}C -4-nitro-aniline has confirmed that "nitro-nitrite" isomerization occurs "in situ" and that migration of an oxygen atom to the other ring positions does not occur either before or after loss of NO from the respective molecular ions.

In this study of o-nitroarenes we have proposed the operation of two types of "ortho effect". The first is the already familiar transfer of a H atom, in the molecular ion, from one substituent to the other. In the above compounds transfer of H from the substituent to the nitro group is usually followed by the elimination of a small radical or molecule.

In some of the compounds discussed above we have found it necessary, however, to invoke a greater participation of the ortho substituent. Indeed, in many of the schemes, bicyclic intermediates have been proposed; in the case of o-nitrobenzoic acid they seem necessary to explain the behaviour of ion (d) (Scheme 2) in the case of o-nitrobenzaldehyde they

are used to account for the presence of ion (c) (Scheme 5), and in the case of o-nitrobenzyl alcohol they are invoked to explain the losses of CO_2 and C_2O_2 from ions (n) and (n'), m/e 135 (Scheme 8).

In o-nitrobenzoic acid, o-nitroanisole and o-nitrobenzaldehyde the proposed cyclic intermediates assist the "nitro to nitrite" isomerization; we show this conversion as involving the expansion of a five-membered to a six-membered ring. In o-nitroanisole two six-membered cyclic structures appear possible for the molecular ion, one involving the nitro form and the other the nitrite form; in o-nitrobenzoic acid only the nitrite form may be represented as a six-membered cyclic species and this dissimilarity was invoked to explain the different behaviour of the ions m/e 123 in these two compounds.

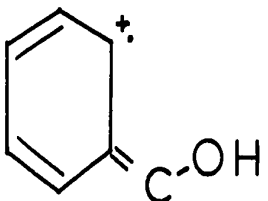
The second "ortho effect" concerns the migration of an atom or group of atoms from a substituent to the vacated (probably charge-carrying) ortho site. That such migrations have occurred is inferred from the loss of CO from ions (c), (f) and (m) and HCN from ion (w). This second "ortho effect" is illustrated in the fragmentation schemes of o-nitrobenzoic acid (Scheme 1), o-nitroanisole (Scheme 4), o-nitrobenzaldehyde (Scheme 5), o-nitrobenzamide (Scheme 6) and o-nitrophenylhydrazine; in these compounds the migrating groups are OH (from COOH, NO_2H and COOH respectively) for the first three and NH_2 (from $CONH_2$ and $NHNH_2$) for the last two.

CHAPTER 3

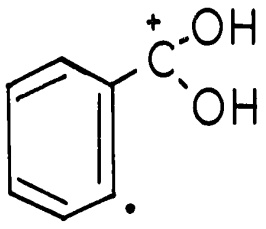
Benzoic acid and related molecules

The main features of the fragmentation mechanism of benzoic acid have been elucidated by Beynon et al[13] and by Meyerson and Corbin[14]. They both observed the molecular ion of this compound to fragment via the successive losses of OH, CO and C_2H_2 ; metastable ions were present for all three processes. Two minor fragmentation routes were also noted ; one involves the loss of CO_2[14] and the other the loss of CO[13,14], each occurring from the molecular ion. However, what appeared at first glance to be a simple fragmentation, involving ions whose identity and structure were obvious, proved to be quite complex when the mass spectrum of the carboxyl deuterated derivative was investigated. The puzzling feature in the mass spectrum of carboxyl deuterated benzoic acid

was the presence of an appreciable M - OH peak at m/e 106[13] ; the peak due to OD loss m/e 105 was more intense. Metastable ions were observed for both the losses of OH and OD and were found to be in a ratio of 2 to 1 in favour of OH loss. Deuterium labeling of the 2,3, and 4 ring positions[14] revealed that the ortho hydrogen atoms were involved ; only the ortho labeled material showing OD loss. It was concluded that the molecular ion has at least two structures from which hydroxyl loss can occur; one being the unrearranged ion ($C_6H_5COOH^{+\cdot}$) whose decomposition is rapid and thus does not contribute to a metastable transition, the other being a rearranged species such as (a) or (b) whose fragmentation is sufficiently slow to yield a metastable ion in addition to the normal fragment ion. Two forms (a) and (b) were proposed.



(a)



(b)

Meyerson's experiments indicated that 18% of the $C_7H_5O^+$ (m/e 105) fragment ions from (unlabeled) benzoic acid had lost hydrogen from an ortho ring position. The fate of the resulting species was not described. However, it was pointed out that it was unlikely to be a precursor of the phenyl ion ($C_6H_5^+$) since the latter species was observed to retain its relative abundance

in the mass spectrum of the 2,3-d_2 acid[14], i.e. the relative intensity of the ($C_6H_3D_2^+$) ion was very close to that of ($C_6H_5^+$) in the unlabeled acid. In a more recent study[21], performed by McLafferty, considerable interest lay in the fate of the $C_7H_5O^+$ ion. This ion is prominent in the mass spectra of many oxy-aromatic compounds and is commonly represented as $C_6H_5CO^+$ (the benzoyl cation). It was evident from the earlier experiments[13,14] that this ion was not unique viz. the ion of m/e 106, $C_7H_4DO^+$, arising from carboxyl deuterated benzoic acid by OH loss does not fragment by CO loss to the same extent as does the ion m/e 105 in the same mass spectrum. McLafferty considered the energy of the ions to interpret this feature; he declared that the equilibrated species that had lost an ortho hydrogen atom possessed insufficient energy to fragment further (by CO loss) whereas the m/e 105 species that arose by direct cleavage had sufficient energy to fragment further. These conclusions were reached as a result of low electron energy studies, i.e. he measured the appearence potential for each process. Furthermore, he was able to observe a shift in the metastable ion ratio (from 2:1 to 1.5:1 at low pressures and to 1:1 at high pressures ($2X10^{-4}$ Torr)) at lower electron energies.

A further study of the equilibrating species of the benzoic acid molecular ion has been performed by Shapiro et al[22]. In these experiments the benzoic acid molecular ion is generated in the mass spectrum of ethyl benzoate by a McLafferty rearrangement. By incorporating deuterium in the ethyl group and ^{18}O in the ester function they were able to

produce carboxyl-d, carboxyl-d-^{18}O, and ^{18}O labeled benzoic acid derivatives. They conclude from their results that the carboxyl oxygen atoms are non equivalent and they thus ruled out any possibility of hydrogen atom exchange between the oxygen atoms. They postulated that the equilibration process involves a series of rotomeric forms of the benzoic acid molecular ion. The conversion of one rotomer to the other occurs via ion (a) (p.54) . Through a series of such interconversions a collection of rotomers is generated, each one differing by the position of the deuterium atom. The ratio of metastable ion peak heights would then simply reflect the relative abundance of these rotomers. However the authors failed to mention the fate of the resulting equilibrated species. It has been pointed out[1n] that the equilibrating species is unlikely to regenerate the unrearranged molecular ion. This point will be dealt with later in light of our results.

In order to aid our investigation of the benzoic acid problem we have also studied compounds, such as phthalaldehydic and phthalic acids, which also generate $C_7H_5O^{+\cdot}$ ions whose behaviour is analogous to that observed in benzoic acid. The results obtained from the mass spectra of these compounds have allowed us to propose a reasonable alternative explanation for the behaviour of the benzoic acid molecular ion.

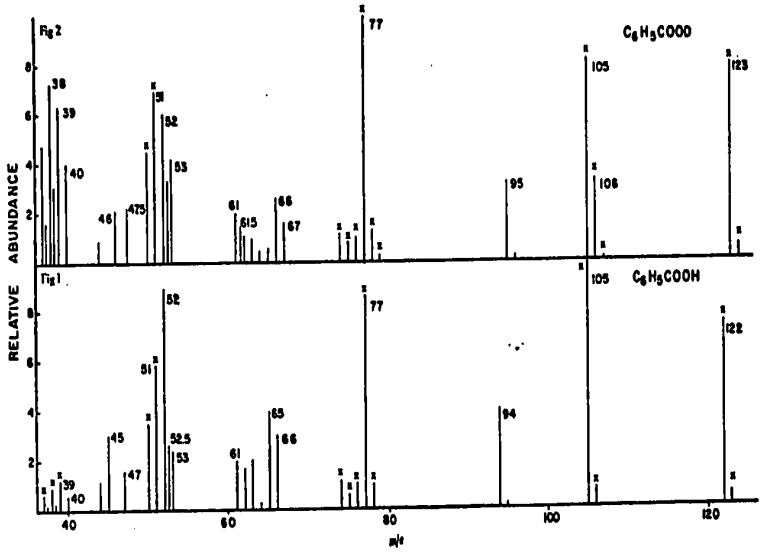
The mass spectra of thio-benzoic acid, benzamide and thiobenzamide were also investigated to see if the ortho hydrogen atoms also participate in their fragmentation sequences.

Equilibration of the functional hydrogen atoms with the ortho hydrogen atoms could yield some unexpected fragmentation sequences due to the presence of two different heteroatoms in the functional group. The mass spectra of thiobenzoic acid and thiobenzamide have not been previously reported while that of benzamide[24] was marred by thermal dehydration in the heated glass inlet system.

(1) **Benzoic acid**

The mass spectra of benzoic acid and the d_1 (carboxyl) acid are shown in Figures 1 and 2 respectively, plotted on an enlarged scale to accentuate ions of low abundance. The deuterated acid contained less than 5% unlabeled material. There is some loss of CO_2 from the molecular ion ; we observe that the fragment m/e 78 is more abundant than that resulting from the normal isotopic contribution of ^{13}C from m/e 77 and the presence of the small peak at m/e 79 in the d_1 acid confirms this result. Furthermore at a nominal electron energy of ~15eV where the m/e 77 ion (d_1 acid) is absent, the ion at m/e 79 remains. At 17.5eV, the ions m/e 77 and m/e 46 are present and a broad metastable centred at approximately m/e 48.0 provides proof for the proposal[14] that m/e 77 arises, at least partially, from the molecular ion by COOD loss (calc. $123 \rightarrow 77m^* = 48.2$). The small peak at m/e 52 ($C_4H_4^{+\cdot}$) arises partially by loss of C_2H_2 from m/e 78 (m^* obs 34.7, calc. 34.7).

The major difficulty in the d_1 acid is to deduce the



FIGS. 1 and 2. The mass spectra of benzoic acid and benzoic acid, carboxyl-d_1. Peaks labelled x are drawn at *one-tenth* their true relative abundances.

fate of the species m/e 106 and m/e 105. Beynon[13] stated that the metastable peaks in the carboxyl-d_1 acid spectrum at m/e 57.4 and 56.5 (produced by the fragmentations m/e 106 → 78, m/e 105 → 77 respectively) were in the "same approximate ratio as the ions of masses 106 and 105 from which they arise". Without numerical values this statement is ambiguous. Our results at 70eV show that in the undeuterated acid the metastable m/e 57.4 (106→78) is 9 ± 2% of that at m/e 56.5 (105→77) and thus the former corresponds to the natural ^{13}C content of $C_7H_5O^+$. For the carboxyl deuterated acid the corresponding figure is 15 ± 3%. We conclude therefore that very few of the ions of m/e 106 in the d_1 acid dissociate by CO loss and moreover the metastable peak intensities (m/e 57.4, 56.5) closely reflect those of the daughter ions at m/e 78 and 77 (Figure 2). Neither do these ions dissociate by loss of DCO (or HCO) since the ion m/e 76 shows the same relative abundance in both the labeled and unlabeled acids. Indeed, no <u>intense</u> fragment ion, other than m/e 106, displays retention of deuterium. Among the relatively minor fragments m/e 52, $C_4H_4^+$ (d_0) is partially shifted to m/e 53, $C_4H_3D^+$(d_1) and m/e 39, C_3H_3(d_0) is partially displaced to m/e 40, $C_3H_2D^+$(d_1); it is formally possible that these ions do originate from the m/e 105 (106) species. At 70eV the relative abundances of the peaks m/e 105 and 106 are 82% and 33% of base peak respectively. Correcting the latter for ^{13}C contribution from m/e 105, taking the observed ratio of 2:1 for the intensities of metastable

peaks m/e 91.4 (123→106) and m/e 89.6 (123→105), we can estimate that in the unlabeled acid 24% of the $C_7H_5O^+$ ions have lost hydrogen from the ortho position, and that some 36% of the $C_7H_5O^{+\cdot}$ ions at 70eV arise from a rearranged molecular ion in excellent agreement with Meyerson's value[14]. At reduced electron energies, down to 12.5eV, the above ratio of the metastable intensities in the d_1 acid remains unchanged.

This is contrary to the results obtained by McLafferty[21]; he observed a ratio of 0.67±0.07 for the metastable peaks (M-OD : M-OH) (our ratio is 0.52±0.03). However, when our instrument was operated at a nominal pressure of $\sim 10^{-5}$ torr we observed variations in the metastable ratio at all electron energies. The ratio was found to be highly pressure dependent. The high pressure was achieved by increasing the abundance of D_2O within the instrument (see Technique 1 appendix I). An interpretation consistent with the above results is that the pressure induced shift in the metastable ratio is due to collisional interactions between ions and neutral molecules. The increased OD loss would be expected if unscrambled molecular ions were to dissociate after collision with D_2O in the field free region.

The ratio of the relative abundances of m/e 106 and m/e 105, on the other hand, increases from 0.4 at 70eV to 0.7 at 12.5eV. (Fig 2a). We interpret this latter shift as an

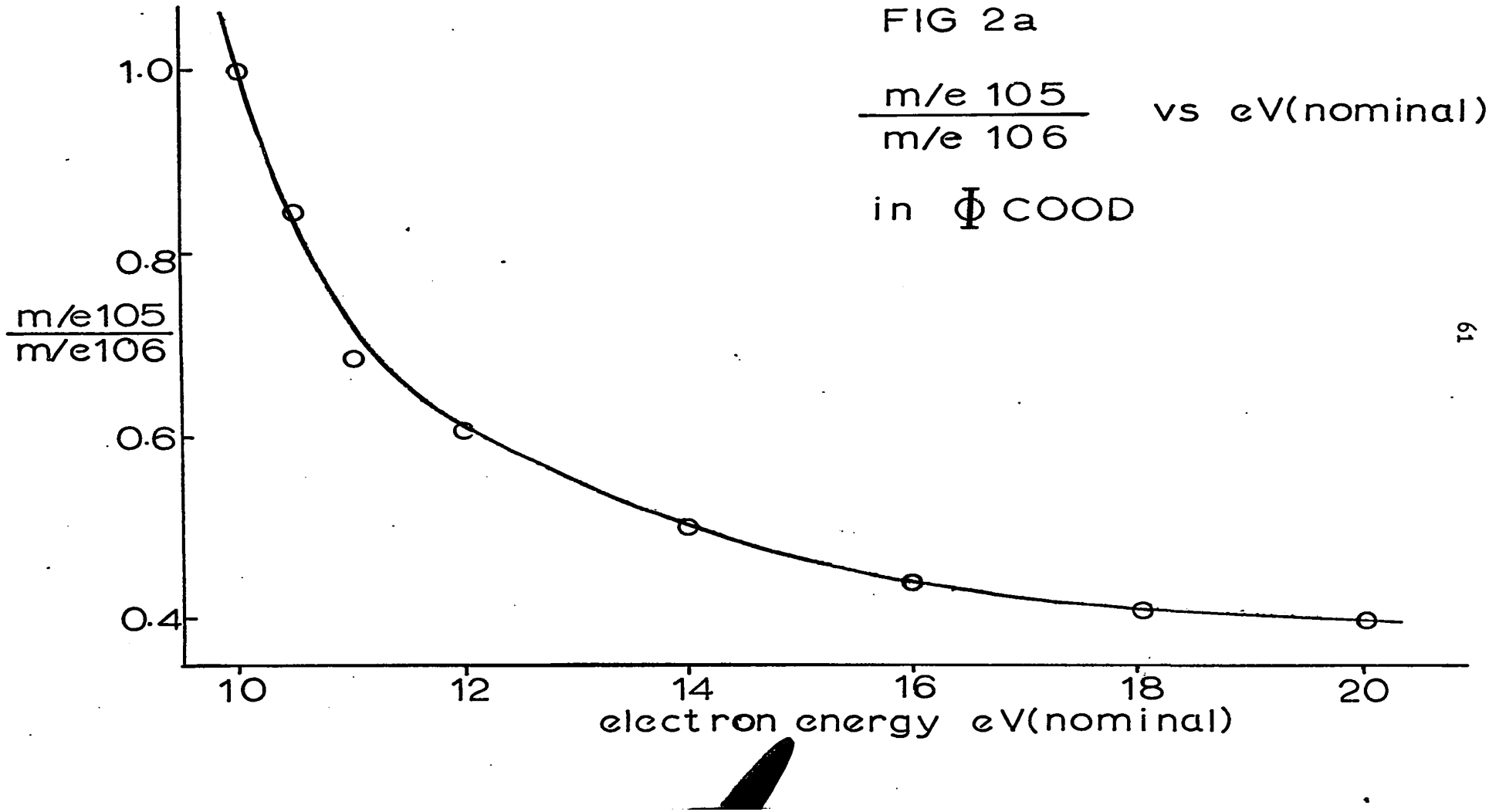
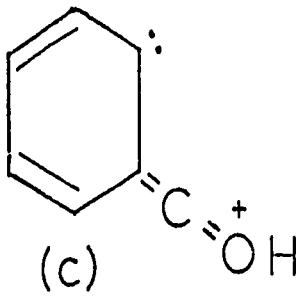


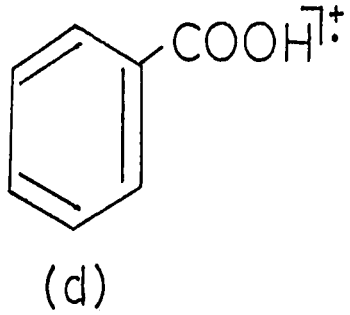
FIG 2a
m/e 105 / m/e 106 vs eV(nominal)
in Φ COOD
1.0
0.8
0.6
0.4
m/e105 / m/e106
10
12
14
16
18
20
electron energy eV(nominal)

increase in dissociation from the scrambled mode of the molecular ion at lower eV. All the above results indicate that the ions of m/e 105 and 106 arising from hydroxyl loss from the rearranged molecular ion are unusually stable (compared with $C_6H_5CO^+$, the benzoyl ion) and contribute negligibly to the major features in the mass spectrum. Two interpretations of these observations have been postulated.

One is that the m/e 105 species which arises from the rearranged molecular ion is structurally different from that which arises by direct cleavage, the other is that the two species at m/e 105 are energetically different. Meyerson[14] proposed the former and presented structure (c) for the rearranged m/e 105 species. McLafferty postulated the latter[21].



(c)



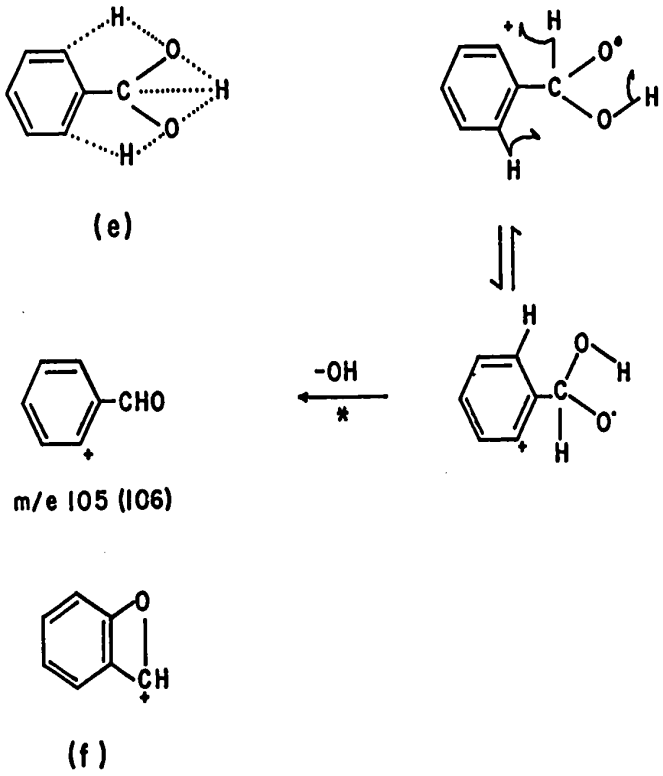
(d)

It has been pointed out[1n] that equilibration of the benzoic acid molecular ion must occur via an intermediate other than the unrearranged molecular ion (d). The proposed structure, (a) (p.54) ,could accommodate this observation only if the equilibration occurs via a concerted mechanism. However, according to McLafferty's interpretation it is sufficient to require that the molecular ions that equilibrate <u>not</u> be able

to generate a species m/e 105 with sufficient energy to fragment further. This is reasonable if, as McLafferty has postulated, only the molecular ions of low internal energy equilibrate.

We propose that the equilibrated species of m/e 105 is structurally and possibly energetically different from the benzoyl cation that arises by direct cleavage. A structural representation of the molecular ion that could equilibrate via an intermediate other than (d) (p.62) is ion (e) where hydrogen migration is envisaged as occurring to the carbonyl carbon atom as well as the carbonyl oxygen atom.

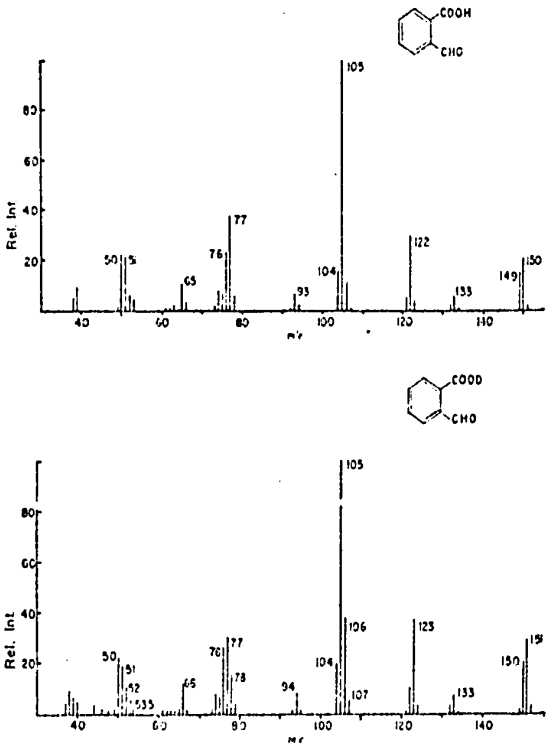
The general structure of ion (e) is shown in Scheme 1 where the dotted lines represent possible bonding and not partial bonding. In this symmetrical form each hydrogen atom has lost its original positional identity. Rotation of either of the C-O bonds or the C-C bond will change the environment of the hydrogen atoms. The essential feature of this species is that one hydrogen be bonded to the carbonyl carbon, thus preventing regeneration of (d). In the dissociation of ion (e) (Scheme 1) the hydrogen shifts are not necessarily concerted but can equally be regarded as sequential. Such an equilibrating species can then lose OH and OD in a ratio of 2:1 in the (carboxyl) monodeuterated acid. We propose that the species represented by Meyerson[14] as the diradical ion (c) can be better shown as structure (f), involving the interaction of the "aldehydic function" with the vacant ortho site.



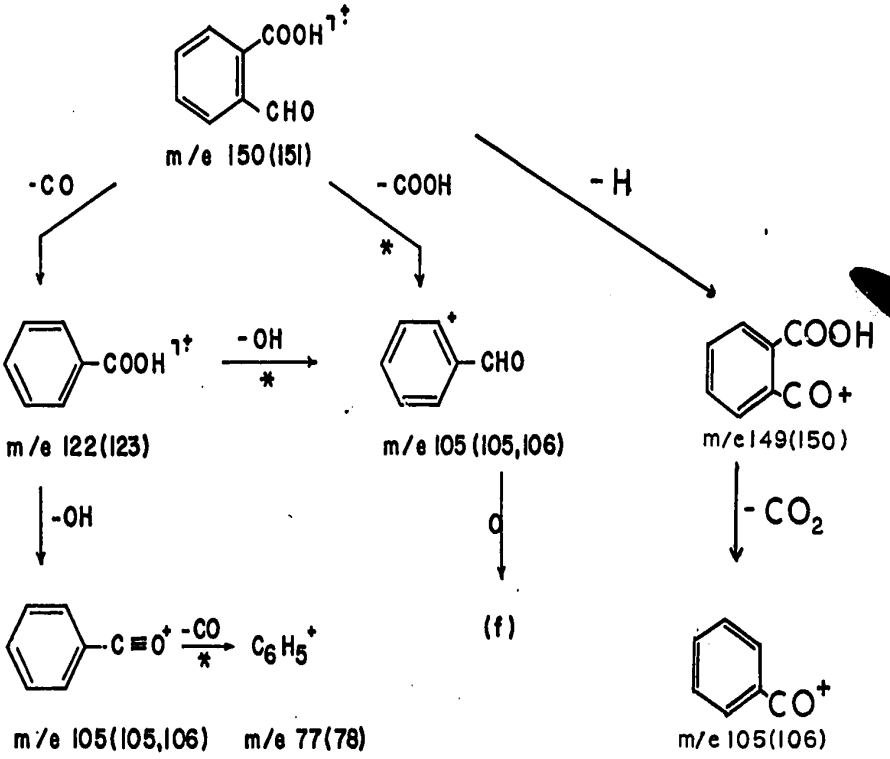
SCHEME 1. Fragmentation mechanism of benzoic acid. Generation of ions *e* and *f*.

(2) m/e $C_7H_5O^{+\cdot}$ in phthalaldehydic acid

In order to test our structural assignment we have examined the mass spectrum of phthalaldehydic acid (fig. 3). This compound generates a species at m/e 105 by loss of the carboxyl function from the molecular ion (Scheme 2). This transition is supported by a metastable at m/e 73.5. The resulting ion is similar to that which we propose to be generated from the equilibrated molecular ion of benzoic acid and is better represented as ion (f) because it does not behave as an aromatic aldehyde, i.e. it does not yield an intense m/e 104 by loss of a hydrogen atom as is observed in the mass spectrum of benzaldehyde [1p] . The origin of m/e 105 in phthalaldehydic acid is, however, not unique ; in addition to the above source, m/e 105 can also arise by hydroxyl loss from m/e 122 or by CO_2 loss from m/e 149 (M-1). The m/e 122 species arises by loss of CO from the molecular ion and behaves similarly to the benzoic acid molecular ion. Indeed, in the carboxyl deuterated analogue of phthalaldehydic acid (Fig. 4) metastable ions for OH and OD losses from m/e 123 are in the ratio of 2:1 ; the same ratio as that observed in carboxyl deuterated benzoic acid. In the labeled phthalaldehydic acid there is an appreciable m/e 106 peak which could arise <u>either</u> by equilibration of the m/e 123 species as in benzoic acid <u>or</u> by loss of CO_2 from the M-1 ion. In the first process, the resulting m/e 106 ion should be the same as that generated from benzoic acid, i. e. it should not dissociate appreciably to m/e 78 by loss of CO by



FIGS. 3 and 4. The mass spectrum of phthalaldehydic acid and phthalaldehydic acid-d_1.



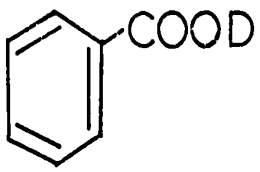
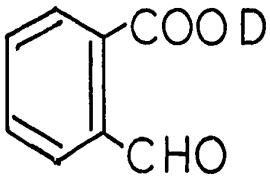
SCHEME 2. Fragmentation mechanism of phthalaldehydic acid.

virtue of structure and/or energy content.

The m/e 105 species that arises from an equilibrated molecular ion is characterized by its inability to fragment further to the same extent as the benzoyl cation that arises by direct cleavage. McLafferty[21] compared the ratios of the metastable peaks for hydroxyl loss (A), the fragment peaks for hydroxyl loss (B), the metastable peaks for CO loss from the M - hydroxyl entity (C) and the m/e 78 and m/e 77 peaks (D) in the mass spectrum of carboxyl deuterated benzoic acid (Table 1). The energy required in the molecular ion for the transitions represented by A to D to occur increases from A to D. This is true because the molecular ion requires more energy if it is to generate a fragment ion that has sufficient energy to further dissociate. Also, metastable ion transitions occur from species whose lifetime is sufficiently long to allow them to exit the ion source before dissociation and thus these species have a lower internal energy than those that dissociate in the source. McLafferty postulated that the ratio increases from A to D because the molecular ions that undergo equilibration have less energy than those that fragment directly. Thus, those ions that arise from an equilibrated molecular ion contribute less to the mass spectrum than those that arise from a non-equilibrating species.

We have measured ratios B, C and D from the mass spectrum of carboxyl deuterated phthalaldehydic acid and these are presented in Table 1. That B is the same in both instances is

TABLE 1

	 a	
(A) $m^* \frac{123 \rightarrow 105}{123 \rightarrow 106}$	0.67	0.52
(B) $\frac{m/e\,105}{m/e\,106}$	2.9	2.9
(C) $m^* \frac{105 \rightarrow 77}{106 \rightarrow 78}$	12	2.0
(D) $\frac{m/e\ 77}{m/e\ 78}$	>20	2.0

a - from reference 21

fortuitous because in phthaldehydic acid m/e 105 arises from three precursor ions. In this instance there is a decrease in going from B to C and C and D are the same. This would indicate that the energy content of ions m/e 106 and m/e 105 that dissociate to m/e 78 and m/e 77 is the same.

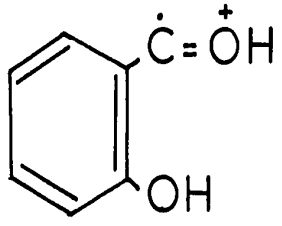
The important feature, however, is that B>C. In benzoic acid carboxyl-d_1 the reverse was true and the reason given there was that there exists a species of m/e 106 that does not dissociate further (as do some of the ions m/e 105). By a similar argument, the reason why B>C in phthalaldehydic acid carboxyl-d_1 could be that there is a species of m/e 105 that behaves like the m/e 106 in benzoic acid carboxyl-d_1. The ion m/e 105 in phthalaldehydic acid carboxyl-d_1 arises from m/e 123 by OD loss and from the molecular ion by COOD loss. In the former instance, by analogy with benzoic acid, the m/e 105 species is mainly the benzoyl cation and should dissociate further whereas in the latter case, the m/e 105 species may be represented as ion (f) (scheme 1).

An alternate proposal is that the ratios C and D are lower than B because either there exists a species of m/e 105 that behaves as the m/e 106 ion in benzoic acid carboxyl-d , or if there were a m/e 106 species in phthalaldehydic acid carboxyl-d_1 that readily undergoes further dissociation. In the latter case the process m/e 106→m/e 78 would be more prominent. Such a species m/e 106 is present ; it arises from the M-1 ion by CO_2 loss and formally corresponds to the ortho-d_1-benzoyl cation which could dissociate further.

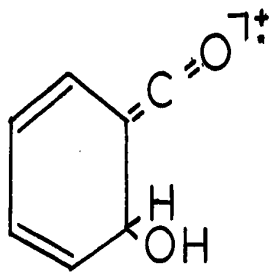
We conclude therefrom that both the above proposals are valid. The existence of a stable m/e 105 species in phthalaldehydic acid carboxyl-d_1 is further supported by the ratio of m/e 105 : m/e 77. In phthaldehydic acid carboxyl-d_1 this ratio is 3.4 whereas in benzoic acid carboxyl-d_1 it is 0.8. We further conclude that ion (f) is the stable species that arises from the equilibrating molecular ion of benzoic acid. Ion (f) most likely has a different internal energy than its isomer, the benzoyl cation.

(3) Minor fragmentation routes in benzoic acid

A prominent minor fragment in the benzoic acid spectrum which fully retains the deuterium label is that at m/e 94 (95), M-CO (m* obs 72.4 (73.4) calc 72.4 (73.4)). The molecular ion of fumaric acid (Chap 4) was observed to lose CO as a major fragmentation process; the mechanism proposed involved hydroxyl migration. The loss of CO from benzoic acid can be visualised as originating via hydroxyl migration to the vacated ortho site in the molecular ion (e) yielding an ion such as (g). If migration was to a filled ortho position ion (h) would result; this could lose CO directly whereas (g) must rearrange (possibly to (h)).



(g)

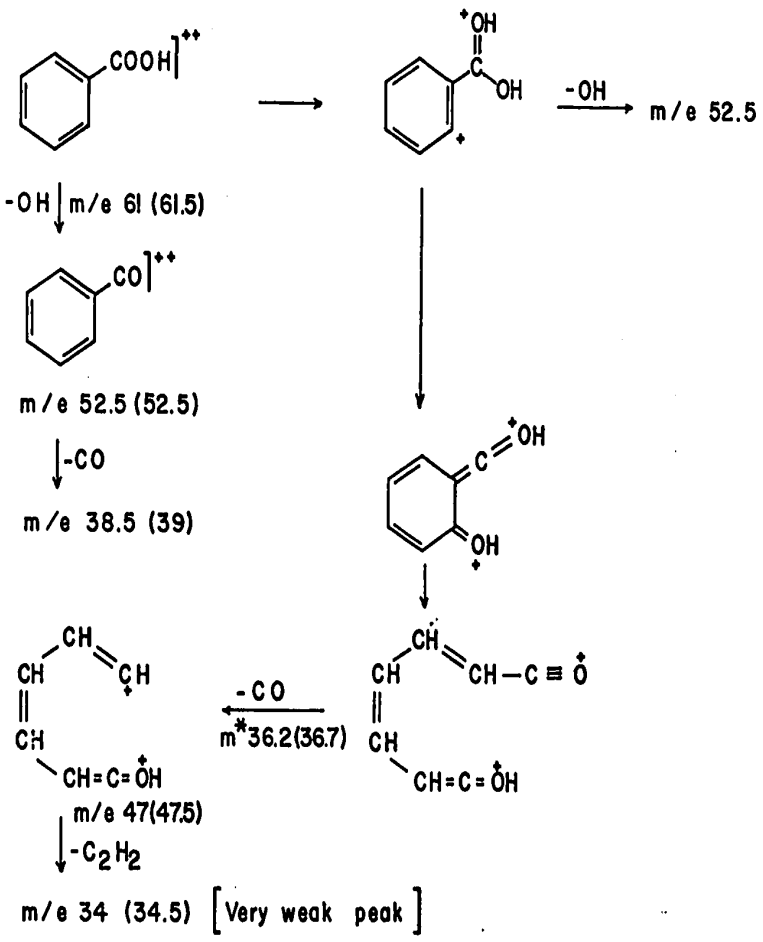


(h)

The CO lost from these ions may contain either the carboxyl or an ortho ring carbon atom. The mass spectrum of the carboxyl C^{13} acid was examined and it was found that approximately 10% of the label was retained in the ion $C_6H_6O^{+\cdot}$ at 70eV; (at lower electron energies the label retention was greater; at 15eV it was 20%). This parallels the increase in abundance of rearranged molecular ions inferred earlier and supports the hydroxyl migration hypothesis. The structure of the ion m/e 94 (95) is indeed a matter for conjecture but it behaves similarly to the molecular ion in phenol in so far as it is the precursor of ions m/e 66 and 65 (CO, H loss from m/e 94). These peaks are of relative intensity 1.0:1.3 and in the d_1 acid they are shifted to m/e 67, 66 and 65 with approximate relative intensities 1.0:1.5:0.4 respectively, indicating preferential retention of deuterium either as a result of a large isotope effect or, more probably, owing to almost random loss of H and D from $C_5H_5D^{+\cdot}$.

(4) Doubly Charged Ions in Benzoic acid

The "simple" fragmentation route (M→105→77) has corresponding doubly charged ions. Meyerson[14] declared that the labeled $C_7H_5O^+$ ion which has lost an ortho hydrogen atom does not display its doubly charged counterpart. This is so; the doubly charged ion m/e 52.5 is not displaced to m/e 53 in the d_1 acid. The latter is made up of C_3HO^+ and $C_4H_3D^+$. Another prominent doubly-charged fragmentation route involves CO loss from the molecular ion and we propose that for this



SCHEME 3. Fragmentation mechanism scheme for doubly charged ions in the benzoic acid mass spectrum.

pathway the molecular ion is non-cyclic and has undergone hydroxyl migration as in the singly charged species. This is shown as Scheme 3. It is improbable that the ion m/e 34 ($C_4H_4O^{++}$) fragments further to yield another doubly charged ion owing to the large repulsion energy which would reside in a small ion bearing two charges.

(5) Phthalic acid: Mass spectra of phthalic acid recorded earlier[13,23] were marred by thermal decarboxylation in heated inlet systems and ion sources; this resulted in thermal production of benzoic acid. A corrected mass spectrum (Chap 4) was later reported in which m/e 122 arose only from electron impact. Carboxyl to carboxyl hydrogen atom transfer followed by loss of CO_2 yielded two species of m/e 122, one fragmenting by OH loss and the other by loss of H_2O. The former behaviour is analogous to that of benzoic acid; indeed if hydrogen atom tranfer occurs to the carbonyl oxygen, subsequent CO_2 loss yields ion (a) proposed by Meyerson as the rearranged benzoic acid molecular ion. Analysis of the mass spectrum of dideutero phthalic acid (Figure 5, Scheme 4), reveals that ion (a) is able to generate both ion (f) and $C_6H_5CO^+$ upon loss of hydroxyl. We conclude that equilibration of ion (a) must occur via the unrearranged benzoic acid molecular ion (otherwise $C_6H_5CO^+$ would be unexpected). If the hydrogen atom transfer occurs to the hydroxyl oxygen, CO_2 loss produces a species of m/e 122 that could readily lose H_2O. In the deuterated analogue this

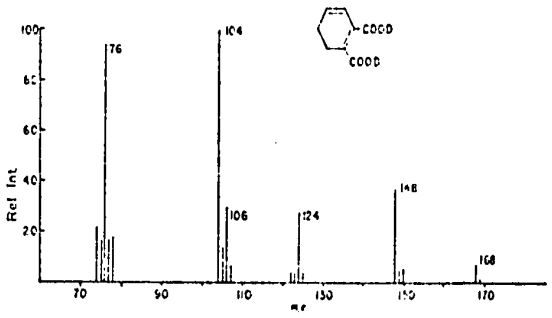


FIG. 5. The mass spectrum of phthalic acid-d_4.

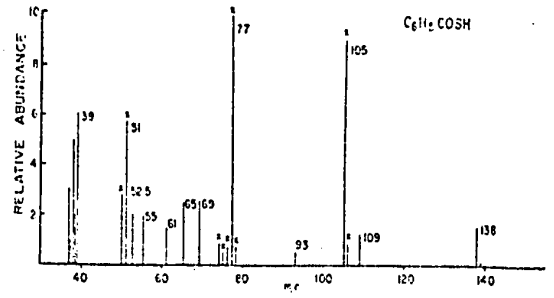
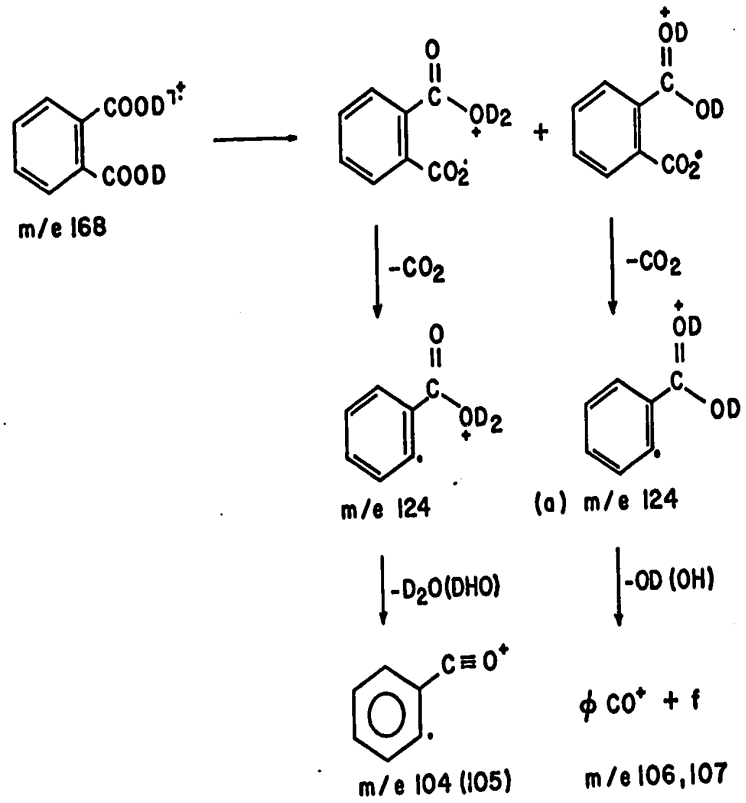


FIG. 6. The mass spectrum of thiobenzoic acid. Peaks labelled x are drawn at one-tenth their true relative abundances.

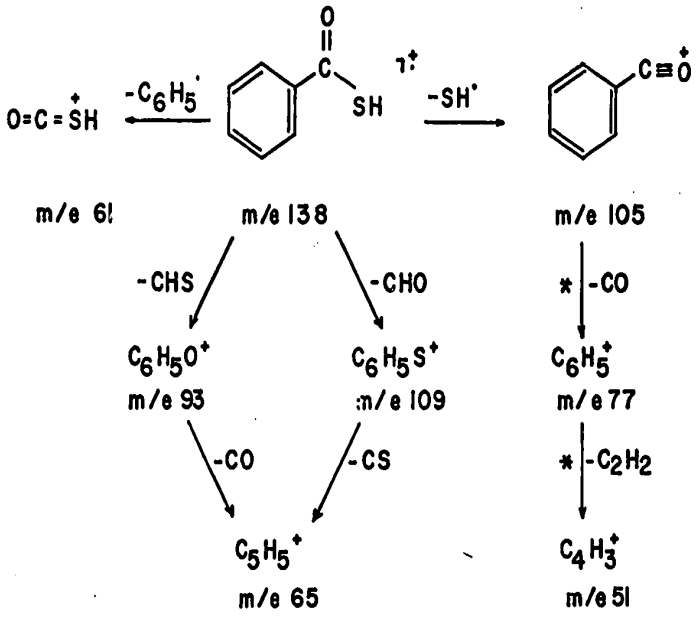


SCHEME 4. Fragmentation mechanism of phthalic acid-d_2.

loss is observed as D_2O. Loss of HDO is a minor process, certainly not more than 6% of total water loss. Thus, little equilibration occurs in this entity.

Furthermore, we do not observe D-H exchange in the phthalic acid molecular ion, there being neither OH nor HDO loss therefrom. We interpret this as showing that the carboxyl hydrogens are strongly intramolecularly associated with their carboxyl neighbours.

(6) Thiobenzoic acid: The hitherto unreported mass spectrum of this compound is shown as Figure 6, again enlarged to display minor peaks. There are only four prominent peaks in the spectrum (m/e 105, 77, 51 and 50) and their identities are not problematic. The main fragmentation route is shown in Scheme 5. The mass spectrum of the d_1 (thiocarboxyl) acid is not presented because it was almost identical with that of the unlabeled compound; the only exceptions were the shift of $M^{+\cdot}$ to m/e 139 and the minor doubly charged fragments m/e 55, 69 were displaced wholly to m/e 55.5, 69.5. The molecular ion of the d_1 acid does therefore not lose either OH, OD or SH indicating that it should be represented as unrearranged and that there is little contribution from ions of type (e). There are, however, minor features which suggest that some group migration does occur in the molecular ion to a small extent; these are the fragment ions m/e 93 (M - CSH; M - CSD) and m/e 109 (M - COH; M - COD). In each case fragmentation is accompanied by complete loss of the label in the d_1 acid again indicating



SCHEME 5. Fragmentation mechanism of thiobenzoic acid.

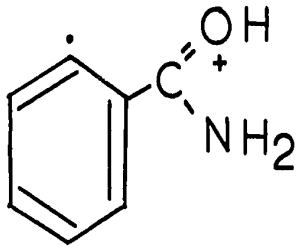
that there is no appreciable ortho-hydrogen equilibration; each of these ions is probably a precursor of ion m/e 65, arising from further loss of CO and CS respectively. Until the appropriate ^{13}C labeling experiments have been performed the mechanism of CSH and COH losses could only be speculative.

The major fragmentation (shown in Scheme 5) is accompanied by the corresponding doubly charged ions m/e 69, 52.5 and 38.5. Another doubly charged ion is that observed at m/e 55 (d_1 55.5) and this corresponds to the doubly charged molecular ion losing CO a process also observed in benzoic acid, except that in this case the doubly charged species is the more abundant. It is curious that whereas the molecular ion of benzoic acid loses CO the thio analogue loses HCO (DCO). There is some subtle distinction here between the various forms of the molecular ions; possibly in the thio compound ions of type (g) or (h) dissociate rapidly, i.e. have too short a lifetime to rearrange as does the corresponding species in benzoic acid. There are no peaks corresponding to either (M - CS) or (M - CS)

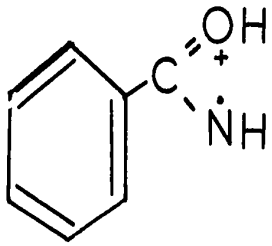
(7) Benzamide

The mass spectrum of this compound is shown as Fig. 7. The main fragmentation sequence can be described by simple cleavages from the unrearranged molecule (Scheme 6). There is no loss of NHD (or NH_2) from the N-d_2 amide, whose mass spectrum is shown as Fig. 8. Therefore, in contrast to the behaviour of the benzoic acid molecular ion, there is no exchange of amide deuterium with ring hydrogen atoms. However,

the presence of minor fragments (Fig. 7) m/e 104 (M - OH) and m/e 103 (M - H_2O) indicates that the molecular ion may not be a unique species but could be represented as being partially in its "ortho-hydrogen-migrated" or imide forms (i) and (j) respectively. The H_2O loss is not due to

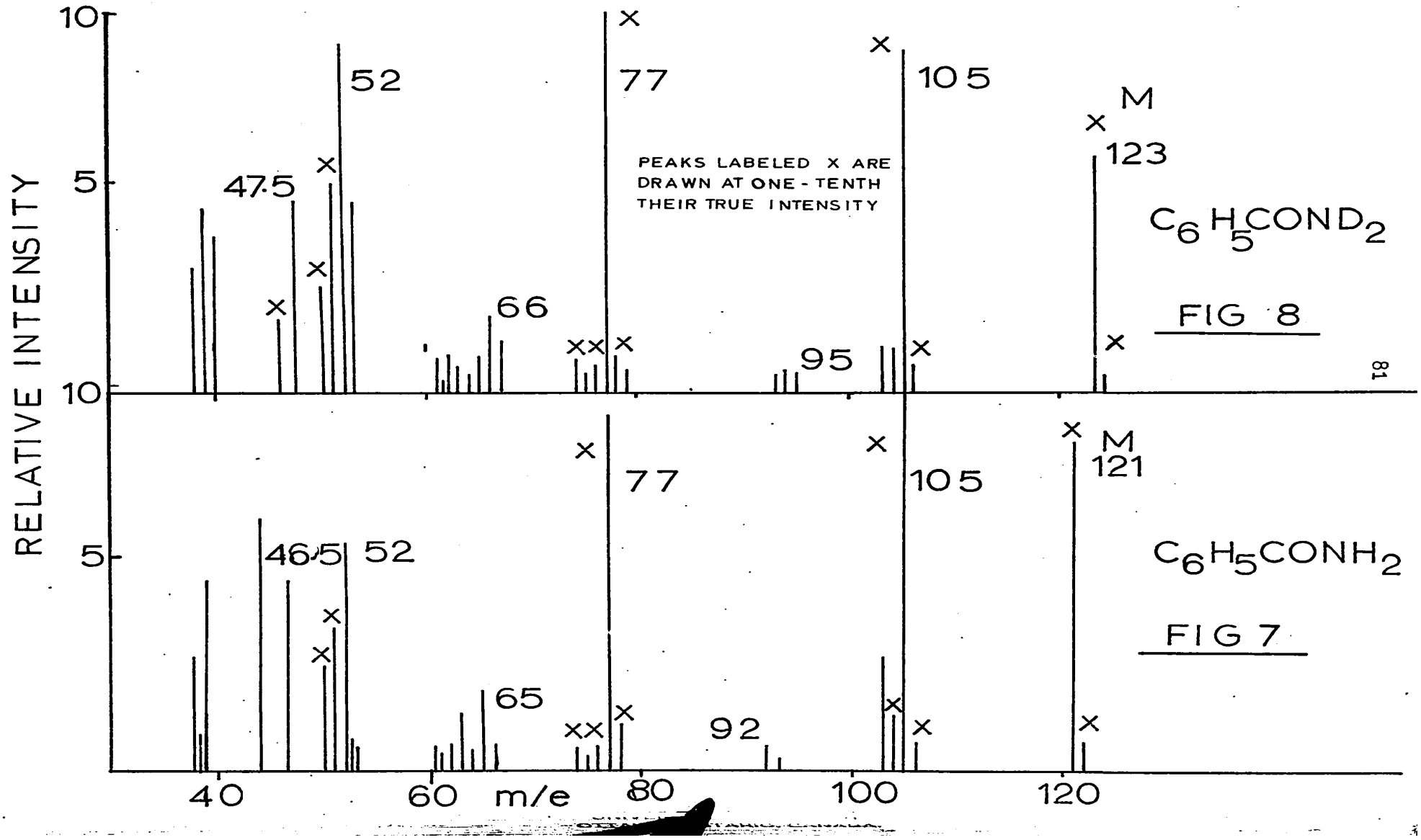


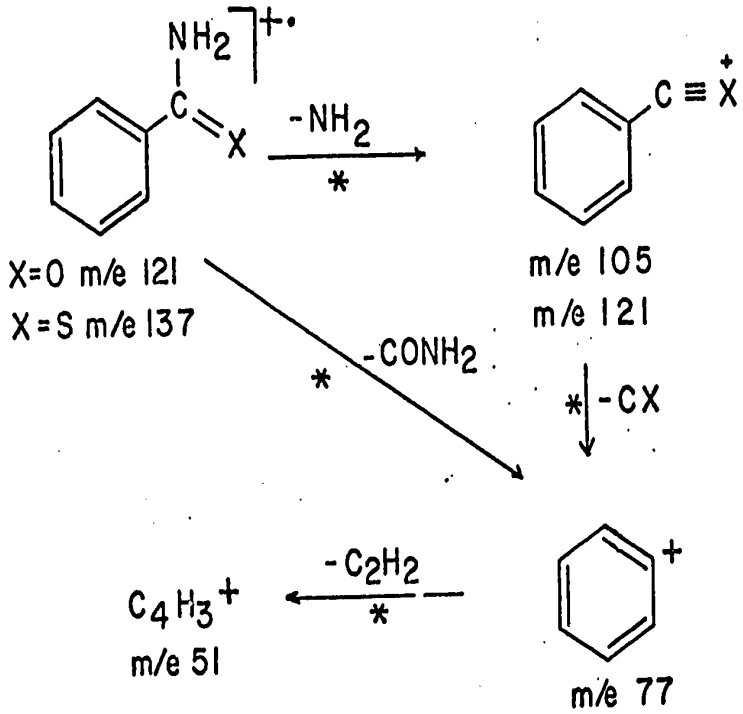
(i)



(j)

thermal dehydration because the intensity of the m/e 103 peak was not a function of source temperature from 35 - 80°C. In the N-d_2 amide (Fig. 8) the peaks m/e 104, 103 remained, indicating loss of HDO and D_2O from the molecular ion; by analogy with benzoic acid, we propose that the hydrogen atom originates from the ortho ring position. The N-d_2 molecular ion does not lose OH (the peak m/e 106 corresponds only to the normal ^{13}C content of m/e 105) and so must only lose OD (yielding part of the m/e 105 peak), very probably from the imide form (j). The losses of HDO and D_2O are together of similar magnitude (relative to the molecular ions) to the H_2O lost from the unlabeled amide. We infer therefore, that the labeled amide does not lose H_2O from its molecular ion. If structure (i) is present it can lose ND_2 but must not


RELATIVE INTENSITY
10
5
10
5
52
77
105
M
123
47.5
66
95
PEAKS LABELED X ARE
DRAWN AT ONE-TENTH
THEIR TRUE INTENSITY
C6H5COND2
FIG 8
81
77
105
M
121
46.5
52
65
92
C6H5CONH2
FIG 7
40
60
m/e
80
100
120

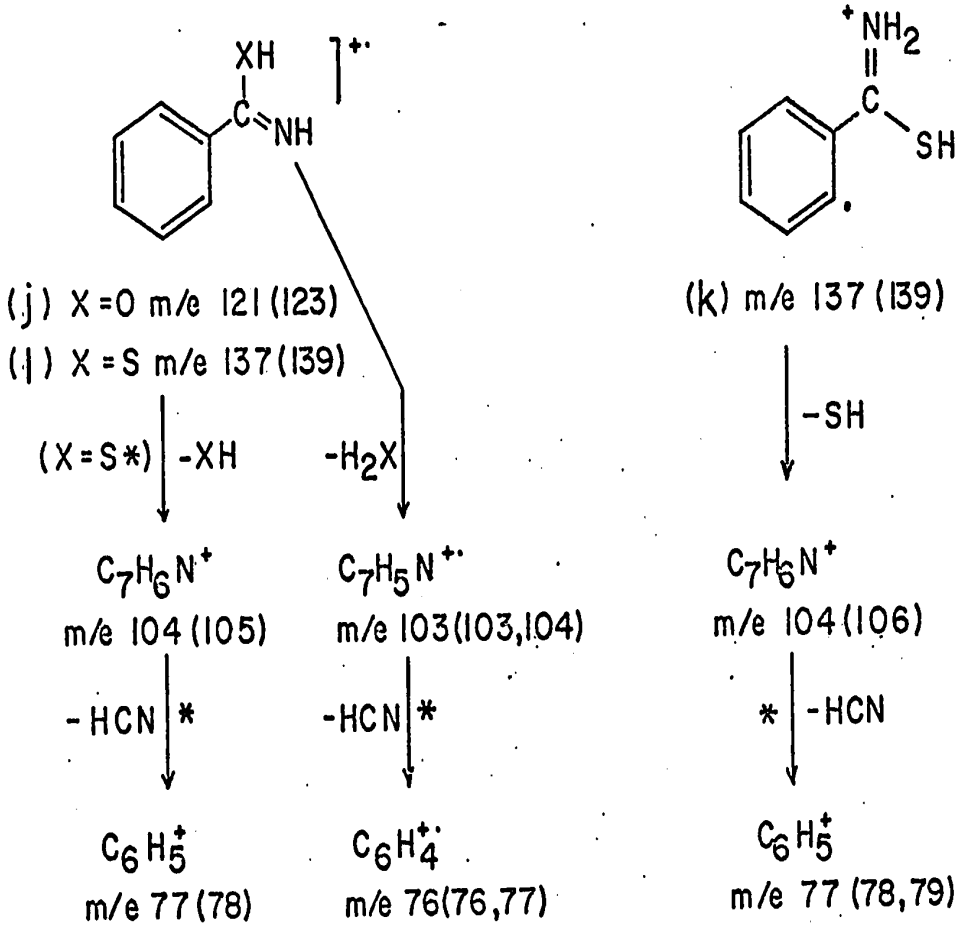

NH2
+·
C
X
-NH2
*
C ≡ X
+
X=O m/e 121
X=S m/e 137
m/e 105
m/e 121
-CONH2
*
*
-CX
-C2H2
*
C4H3+
m/e 51
+
m/e 77

SCHEME 6

exchange N-deuterium with O-hydrogen (no loss of NHD from N-d_2 molecular ion observed); it could formally lose HDO but must not lose OH (see above). On the other hand, structure (j) can readily lose OD and D_2O. To lose HDO, interaction with a ring hydrogen must be invoked. However, (i) cannot exchange O-deuterium with ring hydrogen if the amide form of the molecular ion were in equilibrium with the imide form. If (i) does exchange O-deuterium with ring hydrogen it must not dissociate by OH loss (not observed). Circumstantially therefore, we conclude that the imide form (j) best fits the observations and there is no need to invoke an equilibration involving ortho ring hydrogens as in the case of benzoic acid. The fragmentations discussed above are shown in Scheme 7.

The molecular ion also loses CO and HCO (m/e 93 and 92, abundance ratio 1:2) as a minor process, somewhat analogous to the behaviour of benzoic acid (above). In the d_2 amide these fragments appear at m/e 95, 94 and 93 (abundance ratio approximately 1:1:1) indicating similar probabilities for CDO and CHO losses and also that ring hydrogen atoms are again involved. These latter ions are the probable precursors of peaks m/e 64-66. The observation that m/e 78 is larger than its normal ^{13}C isotopic abundance from m/e 77 may indicate that the molecular ion can eliminate (CONH) in a manner analogous to CO_2 loss from benzoic acid (above); this is substantiated by the small m/e 79 peak in the d_2 amide.

This molecule exhibits in its mass spectrum a doubly

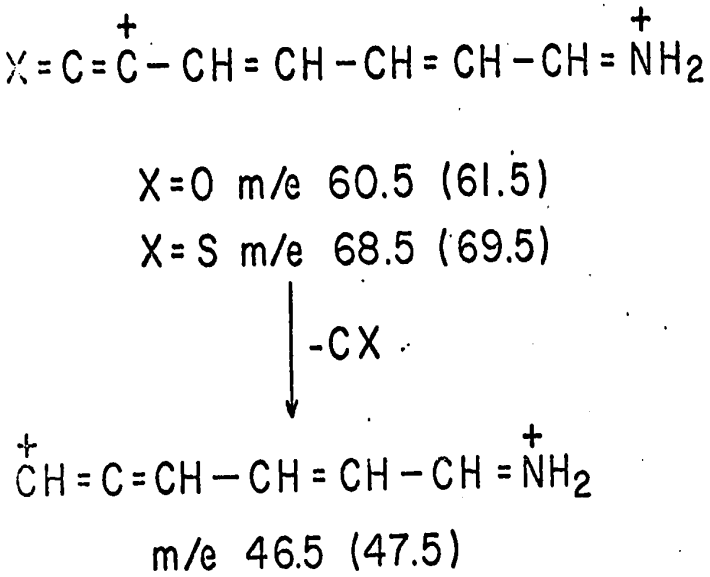

XH
C
NH
+·
(j) X = O m/e 121 (123)
(l) X = S m/e 137 (139)
(X = S*)
-XH
-H2X
C7H6N+
m/e 104 (105)
-HCN
*
C6H5+
m/e 77 (78)
C7H5N+·
m/e 103 (103,104)
-HCN
*
C6H4+·
m/e 76 (76,77)
+NH2
C
SH
(k) m/e 137 (139)
-SH
C7H6N+
m/e 104 (106)
*
-HCN
C6H5+
m/e 77 (78,79)

SCHEME 7

charged fragment ion appearing at m/e 46.5 (47.5 d_2) which is remarkable for being some twenty times more intense (5% b.p.) than its singly charged counterpart (0.25% b.p.). There is also a metastable peak at m/e 35.8 (calc 35.8) for its genesis from the doubly charged molecular ion. This we interpret as shown in Scheme 8; the doubly charged molecular ion is represented as a non-cyclic species in which the amino group has migrated to the ortho ring position before ring opening. The ions m/e 33.5 (34.5) are of very low abundance and it is not possible to identify partial deuterium loss from the ion m/e 47.5 $(C_6H_5D_2N)^{++}$.

(8) Thiobenzamide

The mass spectrum of this compound (Fig 9) has not been reported previously. It is clearly much more complex than that of benzamide. The molecular ion fragments mainly via three parallel processes of similar importance; loss of NH_2, SH and H_2S (Schemes 7 and 8). In addition the molecular ion eliminates H, CS and HCN in relatively minor processes. As with benzamide, only loss of ND_2 takes place from the molecular ion of the labeled thioamide (see Fig. 10) indicating that exchange between amide deuterium and ring hydrogens is negligible. Examination of Fig. 10 indicates that the N-d_2 molecular ion loses both SH and SD and thus ring hydrogen atoms must here be involved. The loss of H (H,D) from the molecular ion (see Fig. 10) may be hydrogen attached to S in species of appropriate structure; an analogy may be drawn with the behaviour of thiophenol[lq]. It


X=C=C⁺-CH=CH-CH=CH-CH=N⁺H2
X=O m/e 60.5 (61.5)
X=S m/e 68.5 (69.5)
-CX
CH⁺=C=CH-CH=CH-CH=N⁺H2
m/e 46.5 (47.5)

SCHEME 8

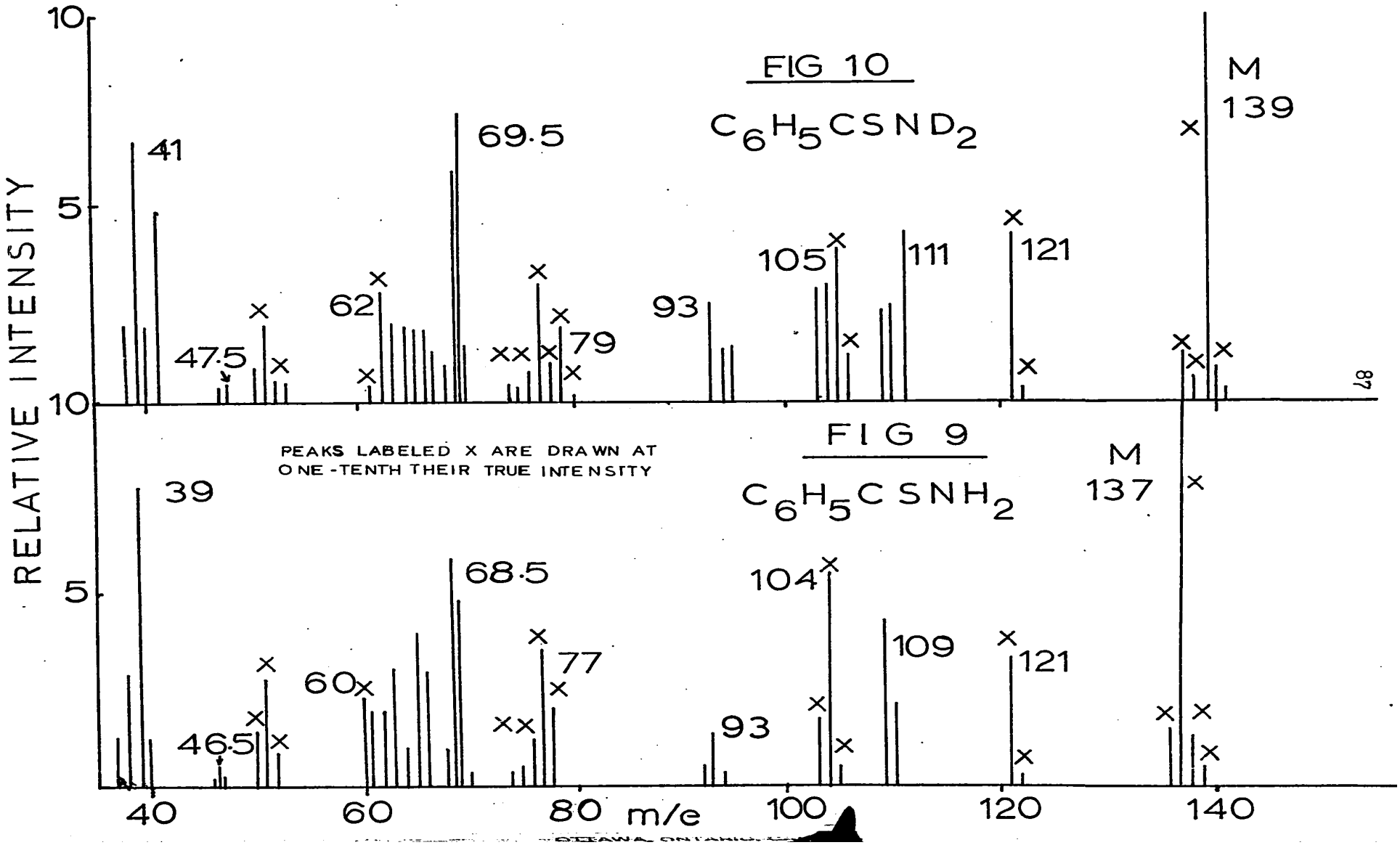


FIG 10
$C_6H_5CSND_2$
M
139
41
69.5
105
111
121
62
93
47.5
79
87
PEAKS LABELED X ARE DRAWN AT
ONE-TENTH THEIR TRUE INTENSITY
FIG 9
$C_6H_5CSNH_2$
M
137
39
68.5
104
109
121
77
60
93
46.5
RELATIVE INTENSITY
10
5
10
5
40
60
80
m/e
100
120
140

is uncertain as to whether the unlabeled molecular ion loses H_2S to yield m/e 103 or whether this ion arises from SH loss from (M - H). Likewise in the labeled amide, with respect to the origins of peaks m/e 104 and 103, (M - HDS) and (M - D_2S). We were unable to examine the m/e 105 peak in the d_2 amide at sufficiently high resolution to show whether it contained $C_7H_3D_2N^+$ (i.e. M - H_2S). Considerable rearrangement and/or equilibration of H and D would be necessary before the labeled molecular ion could eliminate H_2S. However, the abundance of m/e 103 (loss of H_2S) in the unlabeled compound was 17% b.p. and the combined peaks for losses of HDS and D_2S in the d_2 amide amount to only 6%; this apparent deficit may lie in the m/e 105 peak as M - H_2S. On the other hand, the sum of the relative abundances for the above peaks is appreciably less in the d_2 amide (57%) than the unlabeled amide (77%) perhaps indicating an isotope effect. The losses of HS, DS, H_2S, HDS and D_2S can be envisaged as taking place though the intermediacy of ions (k) and (l) analogous to (i) and (j) in Scheme 7. The minor fragments (Fig. 9) at m/e 109 ($C_6H_5S^+$), 110 ($C_6H_6S^{+\cdot}$) arising from loss of HCN from (M-1) (m* obs 87.3; calc 87.3) and M, and those at m/e 92 ($C_6H_6N^+$), 93 ($C_6H_7N^{+\cdot}$) arising from CS loss from M and (M-1) (or HCS from M) can be attributed respectively to processes following migration of SH and NH_2 to the ortho ring position. These ions are probable precursors of m/e 65 ($C_5H_5^+$) and 66 ($C_5H_6^{+\cdot}$), the former pair by CS loss (m/e 109 → 65 m* obs 38.8; calc 38.8) and the latter by

loss of HCN. The origin of m/e 78, $C_6H_6^{+\cdot}$, is uncertain; its genesis certainly involves rearrangements since this peak is displaced to m/e 79 and 80 in the dideuterated compound.

Few doubly charged ions were observed; the only one of magnitude being M^{++} at m/e 68.5 (69.5). An unusual fragment is that at m/e 69 ($CH \equiv C\text{-}C \equiv \overset{+}{S}$) which retains no label and whose origin is also uncertain. It could arise from a non-cyclic species derived from ring fission following NH_2 migration to the ring in ion (k).

Conclusions

The chief observation that should be made concerns the $C_7H_5O^+$ (m/e 105) ion, ubiquitous in the mass spectra of aromatic oxy-compounds. This ion is not necessarily simply the benzoyl cation $C_6H_5CO^+$, which readily dissociates to the phenyl ion. The presence in a mass spectrum of $C_7H_5O^+$ accompanied by a relatively less abundant m/e 77 ($C_6H_5^+$) may be indicative of ions of structure other than benzoyl , for example that which is shown as (f). This was the case in phthalaldehydic acid.[21] Arguments, based on the energy of the ion, have also been postulated to account for the inability of ion (f) to dissociate further. We feel that these alone are insufficient to account adequately for the behaviour of this species. The similarity in behaviour of the m/e 105 species generated by COOH loss in phthalaldehydic acid and that generated in benzoic acid after equilibration strongly indicates that these two species are structurally the same.

Shapiro et al[22] have proposed that the equilibration of

the benzoic acid molecular ion occurs via ion (a). The evidence from phthalic acid above, that ion (a) produces both ion (f) and the benzoyl cation indicates that ion (a) regenerates the unrearranged benzoic acid molecular ion. Equilibration cannot occur in this fashion because such a process could generate benzoyl cations containing an ortho-d which could then dissociate by loss of CO to yield m/e 78 and this is not observed.

We therefore conclude that ion (f) is structurally as well as energetically different from the benzoyl cation and that its inability to dissociate further is due to both these features. Equilibration of the benzoic acid molecular ion occurs via an intermediate such as (e) rather than ion (a) as suggested by Meyerson and Shapiro et al.

No equilibration process was detected in the fragmentation of thiobenzoic acid. On the other hand the mass spectra of deuterium labeled benzamide and thiobenzamide indicate that these molecular ions undergo rearrangement prior to dissociation. For benzamide it was sufficient to postulate participation of the imide form of the molecular ion to rationatize its fragmentation behaviour and no ortho participation could be detected. For the thio-compound a similar proposal was insufficient to account for the greater complexity of its mass spectrum. In this amide the ring hydrogen atoms are certainly exchanged with amide hydrogen leading to a diverse set of fragmentation routes involving loss of sulphur. It should be noted, however, that the extent of rearrangement in the molecular ions of the amides is relatively minor compared to that observed in benzoic acid.

CHAPTER 4

"Ortho Effects" in the Fragmentation of Dicarboxylic Acids

Reports on the mass spectra of carboxylic acids have been relatively few ; the reason for this neglect is their low volatility and/or thermal instability. It has been considered more convenient to study the more volatile methyl esters but with the advent of heated direct source inlet probes the original objection to their study has been removed. Those acids, that have been studied previously, fragment in a variety of ways, the simplest of which is a direct cleavage wherein the molecular ions fragment by the successive losses of OH and CO ; this, for example, is observed in aromatic acids such as benzoic[13] and terephthalic acids[13]. In other instances rearrangement of the molecular ion prior to fragmentation gives rise to an m/e 60 species

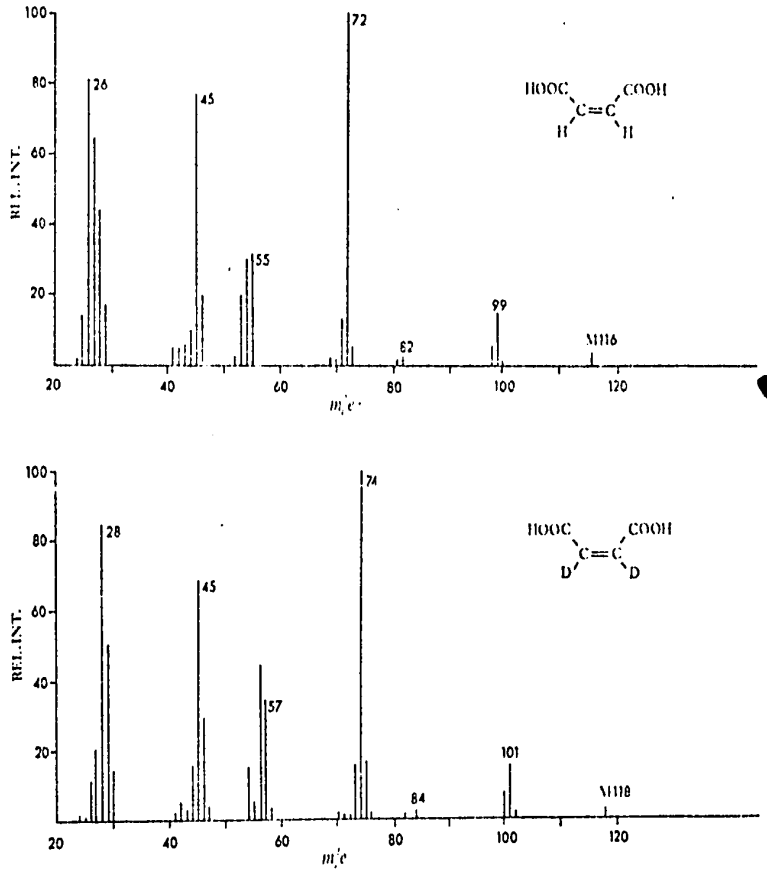
or water loss.

Indeed, in aliphatic acids (C>4) the major fragmentation mode is the generation of $C_2H_4O_2^{+\cdot}$ (m/e 60)[1r] by a McLafferty rearrangement (see p. 17 Chap 2). In this case the loss is preceded by transfer of a γ hydrogen atom to the carbonyl oxygen. In some ω-phenylalkanoic acids[1s] (C>3), water loss from the molecular ion has been observed. Here, transfer of a γ hydrogen atom occurs to the hydroxyl group. However, in monocarboxylic acids, the loss of CO_2 from the molecular ion is not observed as a major fragmentation.

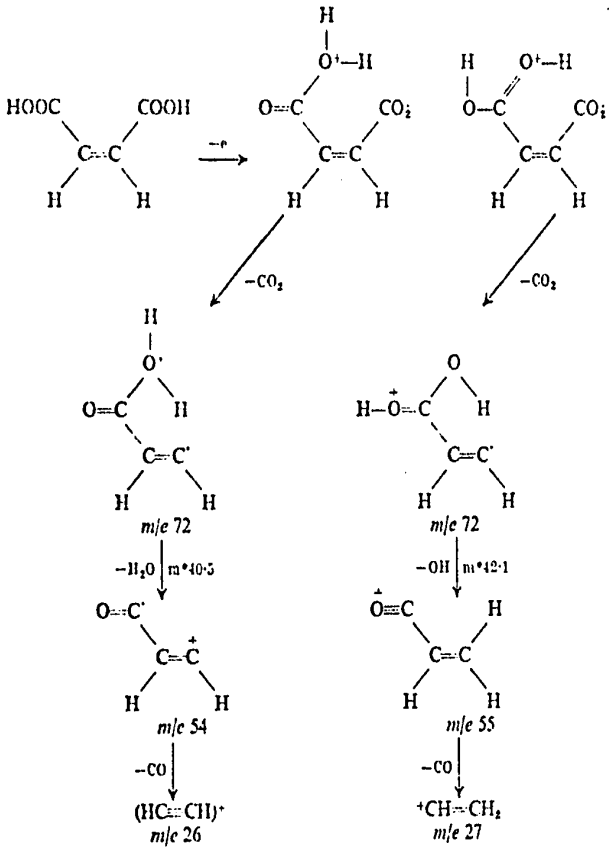
Studies of dicarboxylic acids are very few and some were marred by thermal degradation within the heated inlet systems. Indeed in the previous work maleic[25] and phthalic acids[13] were respectively thermally dehydrated and decarboxylated upon insertion into the instrument. This chapter deals with the electron impact induced fragmentation of some dicarboxylic acids. The operation of an "ortho effect" in some of these compounds gives rise to a unique fragmentation that may be useful in characterising some dicarboxylic acids. Indeed, it is possible to distinguish between some cis and trans isomeric dicarboxylic acids on the basis of an interaction between carboxyl groups that is present in the cis acid but absent in the trans.

Maleic acid

The mass spectra of maleic acid, maleic acid-2,3-d_2 fumaric acid and fumaric acid-2,3-d_2 are shown as Fig. 1, 2, 5 and 6 respectively. Comparison of Figs. 1 and 5 shows



FIGS. 1 and 2. Mass spectra of maleic acid and maleic acid-2,3-d_2.



SCHEME 1. Fragmentation scheme for maleic acid.

that the fragmentations of maleic and fumaric acids are strikingly different. The 2,3-dideutero acids were prepared to permit unequivocal identification of the fragmentation pathways.

The molecular ion of maleic acid is of weak intensity and there are weak fragments corresponding to the loss of H_2O and OH (m/e 98,99). The reference spectrum for this compound[25] is identical with that of maleic anhydride and bears little resemblance to our spectrum; however, by admitting maleic acid to our ion source by the indirect inlet system, i.e. through several feet of glass tubing at 200°, we obtained spectra closely similar to that reported earlier. Clearly, in the earlier work extensive thermal dehydration was taking place in the mass spectrometer inlet system. In order to eliminate such a possibility in our apparatus the source block was maintained at room temperature (25 to 30°) and the direct sample insertion probe only was gently heated. It was found that the relative abundance of the m/e 44, 72, 98 and 99 ions did not change with variation of probe heater temperature from 80 to 250° indicating that neither thermal dehydration nor decarboxylation products were contributing to the mass spectrum. It should be emphasised that the recorded temperature is that of the probe heater and not that of the sample which receives heat by radiation rather than by direct-contact conduction.

The base peak, m/e 72, corresponds to loss of CO_2 from

the molecular ion (m/e 74 in the d_2 acid); appropriate metastable peaks show that this fragment ion loses OH and H_2O to yield ions m/e 55 and 54 respectively (the latter are displaced to m/e 57 and 56 in the 2,3-d_2 acid). We interpret these observations as arising from H atom transfer from carboxyl to carboxyl and this part of the fragmentation mechanism can therefore be represented by Scheme 1.

In this instance the "ortho effect" occurs via a seven membered ring intermediate. The ions m/e 99, 98 and 82, correspond to losses of OH, H_2O and 2OH respectively from the carboxyl groups only, since they are displaced to 101, 100 and 84 in the 2,3-d_2 acid. The absence of m/e 99 in the 2,3-dideutero acid indicates that H - D scrambling does not occur. The m/e 81 ion is displaced to m/e 82 in the d_2 acid spectrum indicating sequential loss of OH and HDO or vice versa from the molecular ion.

The molecular ion also fragments by loss of CO_2H, there being appropriate metastable peaks at m/e 17.5 and 43.5 corresponding to the charge residing on the m/e 45 and m/e 71 species respectively. The latter presumably loses H_2O to yield the ion m/e 53, which is shifted to m/e 54 in the dideuterated acid (HDO loss). The H atom transfer from carboxyl to carboxyl shown in Scheme 1 may well be an important process in the fragmentation of cis-1,2 dicarboxylic acids and so the mass spectra of citraconic and phthalic acids were recorded and are shown as Figs. 3 and 4.

Citraconic acid (cis propene-1,2-dicarboxylic acid) (Fig. 3)

The similarity between the fragmentation mechanism of this

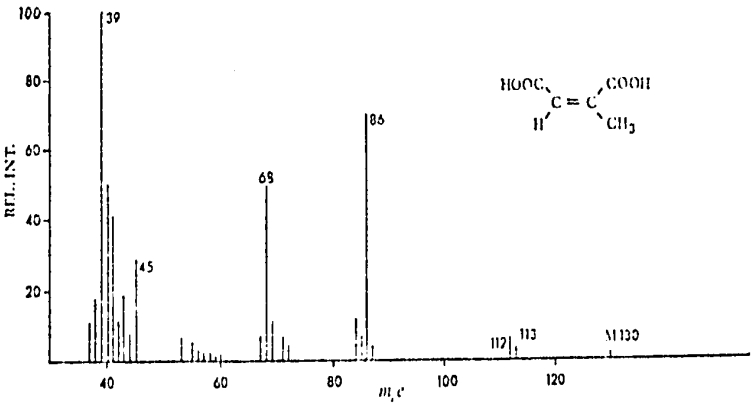


FIG. 3. Mass spectrum of citraconic acid.

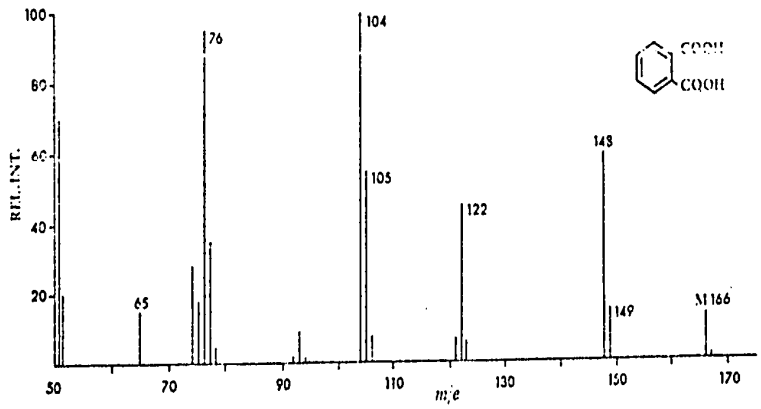
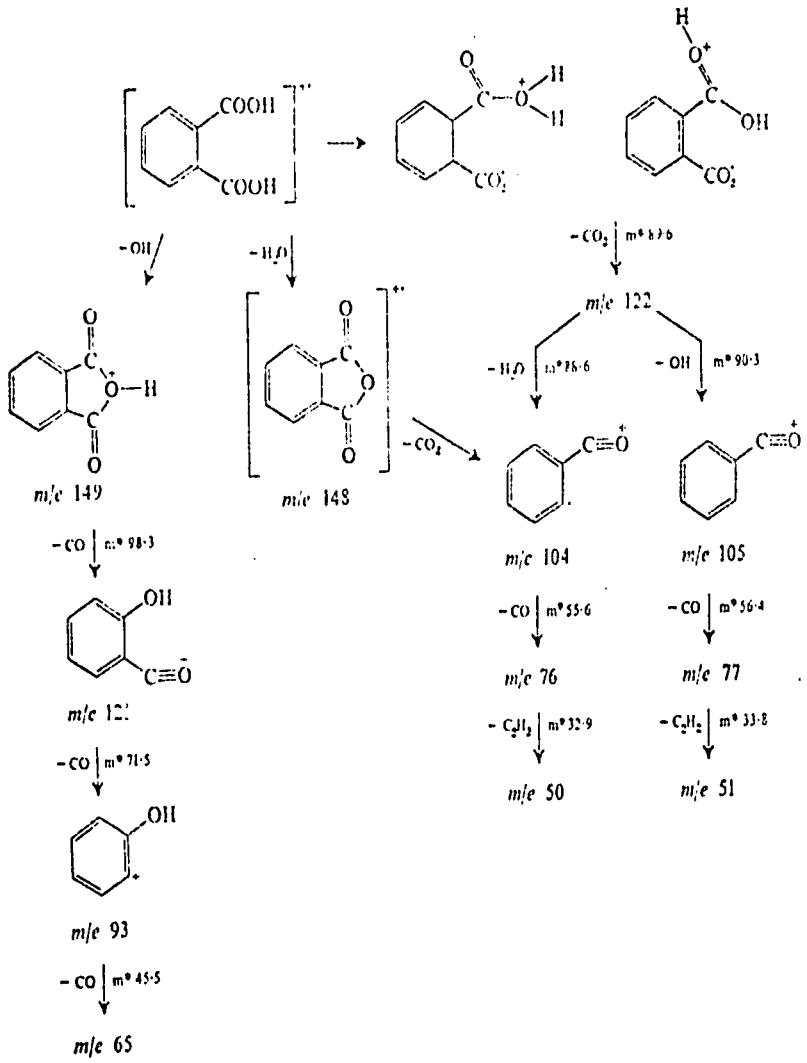


FIG. 4. Mass spectrum of phthalic acid.

compound and that of maleic acid is very striking. Again the major initial fragmentation involves loss of CO_2 via an "ortho effect" yielding the ion m/e 86, followed almost exclusively by loss of H_2O to yield the ion m/e 68 (metastables observed for these processes at m/e 65 and 53.9 respectively). It is not possible to determine whether the -1 and/or -2 carboxyl groups are acting as H atom acceptor in this acid. The origin of the base peak m/e 39 ($C_3H_3^+$) is uncertain.

Phthalic acid (Fig. 4)

The mass spectrum of this compound has been reported previously[13,23] and the problem of dehydration in a heated inlet system was recognised by Beynon et al[13]. We have remeasured the mass spectrum of phthalic acid, taking precautions as described above for maleic acid. Our mass spectrum is shown as Fig. 4 and differs in several important respects from that obtained by Beynon et al., who observed m/e 149 > m/e 148, m/e 122 = 85%, m/e 105 = 100%, m/e 104 = 20%, m/e 77 = m/e 76 = m/e 65 = 35%. The discrepancies cannot in either case be dismissed lightly as due to a predictable thermal dehydration; Beynon et al. were quite satisfied that at 100° to 125° (their source and direct inlet temperature) no dehydration was taking place. Their fragmentation scheme proposes CO_2 loss from the molecular ion to yield an ion m/e 122 which behaves similarly to the molecular ion of benzoic acid; indeed their spectrum below m/e 122 closely resembles that of benzoic acid except for the presence of m/e 65 and 76. In order to discover the reason for the different spectra described



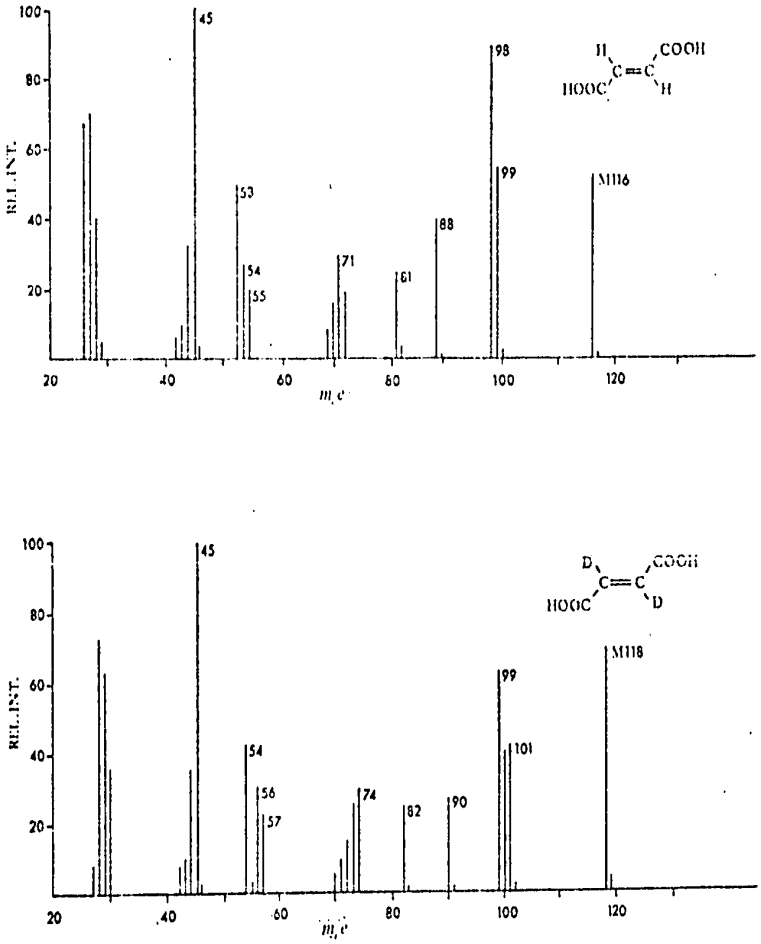
SCHEME 2. Fragmentation scheme for phthalic acid.

above, we have carried out the following experiments. The mass spectra of two samples of phthalic acid were measured under identical experimental conditions (source temperature 35°, probe heater 60°, electron energy 70eV). One was the reagent grade acid (Eastman) and the other was prepared by acid hydrolysis of the mono potassium salt (Eastman, 99.95%) and recrystallized twice from water; the latter product was dried in vacuo in the mass spectrometer inlet system prior to being admitted to the ion source. The two spectra were identical, showing that our results cannot be due to traces of the anhydride as an impurity in the acid. A series of spectra were then obtained, raising the probe heater temperature by 20° between each run; the source block was not heated and its temperature never exceeded 50°. Up to 100° the spectra remained essentially unchanged. Above 100° the relative intensities of the m/e 122, 105, 77 and 44 peaks increased with rise of temperature while the intensities of the background m/e 32 (O_2) and m/e 18 (H_2O) remained constant. Above 150° the m/e 18 peak began to increase relative to m/e 32. At 170° the most prominent fragment ions were m/e 105 (100%), m/e 122 (95%), m/e 76 (56%), m/e 50 (51%), m/e 104 (47%), m/e 77 (40%). We interpret these results as follows; above 100° thermal decarboxylation to yield benzoic acid begins, probably catalysed by the copper block which constitutes the sample probe heater. This accounts for the increased relative intensities of the benzoic acid type fragments and the concomitant increase of m/e 44. Above 150° dehydration appears to commence and the mass spectrum

is then much closer to that obtained by Beynon. Metastable peaks were measured from a spectrum obtained at 80° and these are indicated in Scheme 2 which we propose as the fragmentation mechanism for phthalic acid. That the minor fragments m/e 149, 121, 93, 65 are interrelated is indicated by the observation of the appropriate metastable peaks. Part of this mechanism is the same as that proposed for maleic acid (Scheme 1); again the major fragmentation route is envisaged as beginning by H atom transfer from carboxyl to carboxyl in the molecular ion. This "ortho effect" mechanism accounts satisfactorily for the marked difference between the mass spectrum of phthalic acid and those of iso- and terephthalic acids whose mass spectra are almost identical; the latter pair fragment by successive loss of OH and CO with no elimination of CO_2. Beynon's fragmentation mechanism for phthalic acid is discussed by Budizikiewicz et al.[11] They propose loss of CO_2 from the molecular ion, with the H atom returning to the ring, thus yielding the benzoic acid molecular ion; such a mechanism is unattractive because it should also hold for the isomeric acids since it involves no specific interaction between the ortho carboxyl groups.

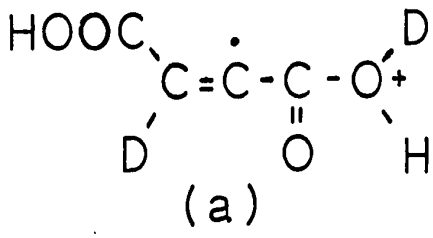
Fumaric acid (Figs. 5 and 6)

No evidence could be obtained for thermal degradation of this acid ; the mass spectrum of this compound obtained by direct inlet insertion into the cold ion source was closely similar to that obtained using the heated, glass, indirect inlet system and heated ion source (150°).

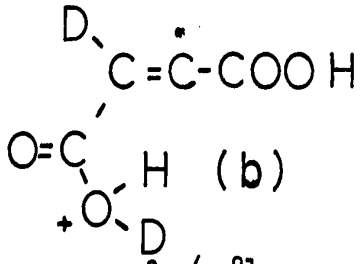


FIGS. 5 and 6. Mass spectra of fumaric acid and fumaric acid-2,3-d_2.

The molecular ion of this compound is seen to be more stable than that of maleic acid. In both fumaric acid and fumaric acid 2,3-d_2 the base peak is at m/e 45. In the undeuterated acid there is a prominent peak at m/e 98 (M - H_2O), in the dideuterated acid this peak is only partially shifted to m/e 99 (M - HDO); the m/e 100 fragment corresponds to $C_4D_2O_3^{+\cdot}$ (by high resolution m/e 100 = 100.0128, $C_4D_2O_3$= 100.0129, $C_4DH_2O_3$ = 100.0145, no broadening of m/e 100 observed) indicating loss of H_2O only (and therefore absence of H - D mixing) from the molecular ion. These losses of H_2O and HDO are confirmed also by metastable peaks at m/e 84.7 and 83.1 respectively (m/e 82.7 in the undeuterated acid). It should be emphasised that there is no metastable corresponding to (M - OH) and so we assume therefore that the metastable in the d_2 acid corresponding to (M - 18) is not from (M - OD). The (M - HDO) fragmentation can be envisaged as arising from a structure of the type (a) or (b):

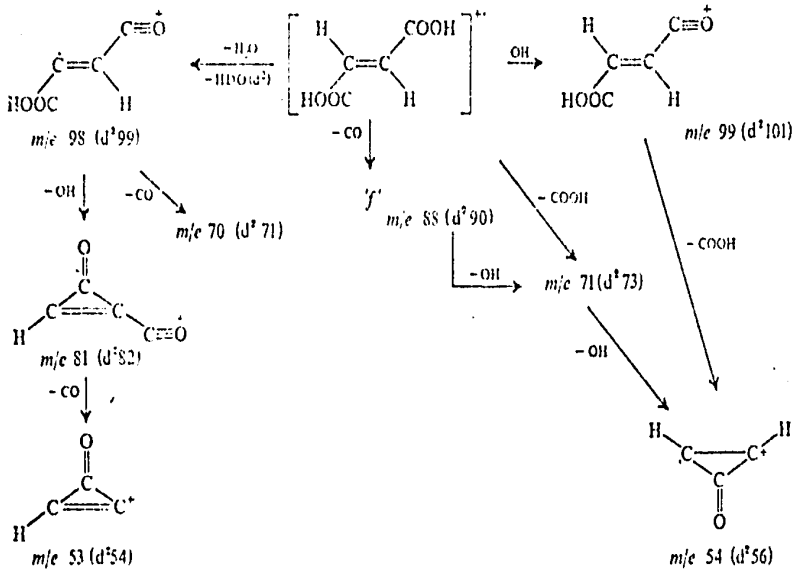


(a)

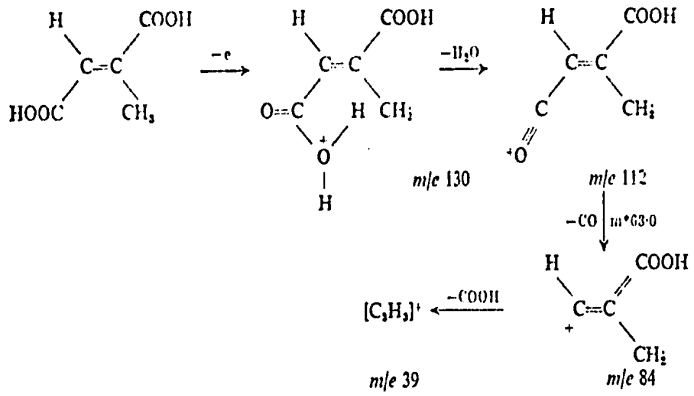


(b)

Further support for (a) and (b) lies in the presence of m/e 81 (Fig. 5) which is shifted only to m/e 82 in fumaric acid-d_2 (Fig. 6), indicating that H - D mixing is not taking place.

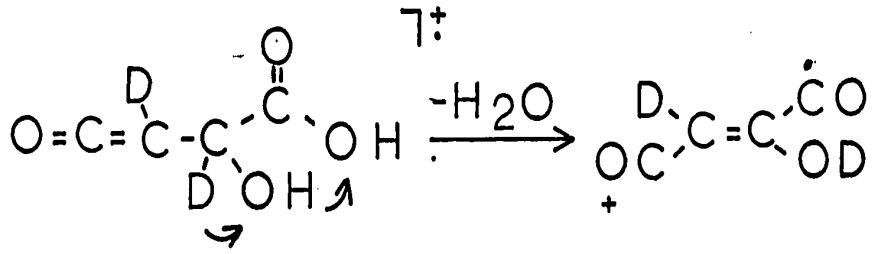


SCHEME 3. Fragmentation scheme for fumaric acid.

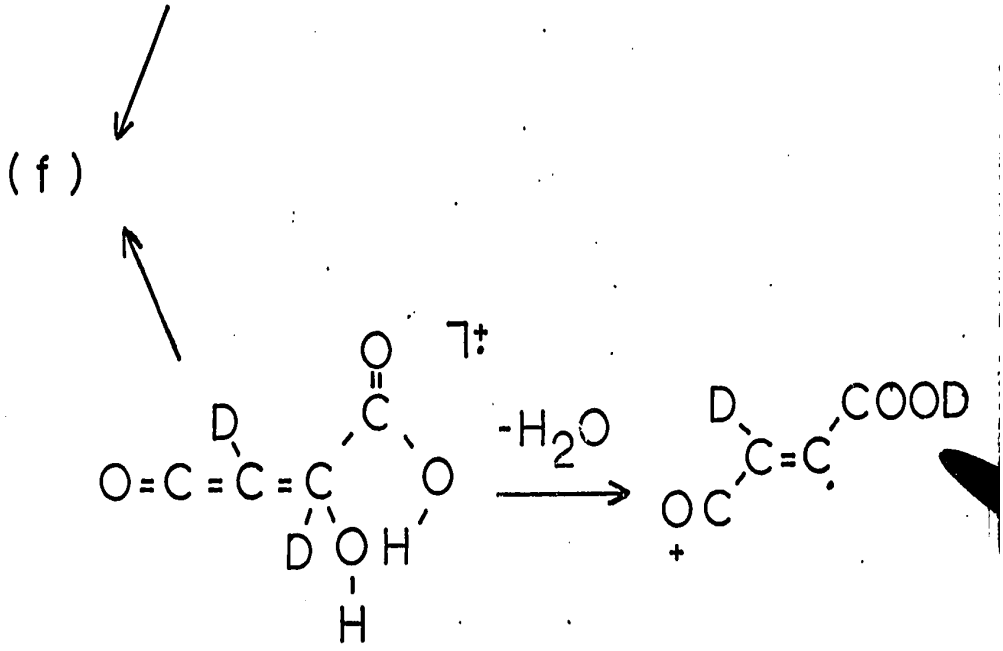


SCHEME 4. Partial fragmentation scheme for mesaconic acid.

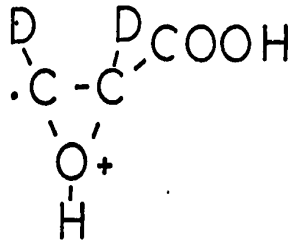
SCHEME 3a



(d) (e) m/e 100



(f)



(f) m/e 88

The structure of the molecular ion from which H_2O is lost from the d_2 acid is problematical. If rotation about the carbon-carbon double bond is proposed then maleic acid behaviour might be observed instead. Also difficult to envisage is the origin of the (M - CO) fragment ion m/e 88, ($d_2$90). It is possible to explain both these observations if hydroxyl migration is involved, to yield a molecular ion such as (d) which could lose either CO or H_2O as indicated. The fragmentation pathway proposed for fumaric acid is shown as Scheme 3; the structures of the ions are only tentative but the scheme satisfactorily accounts for the observations in both the nondeuterated and dideuterated acids. The m/e 72 fragment ion probably results from some isomerisation of the fumaric molecular ion to that of maleic acid.

Mesaconic acid (trans propene-1,2-dicarboxylic acid)

Since citraconic acid displayed similar fragmentation behaviour to maleic acid then mesaconic acid might be expected to show similarities with fumaric acid. The mesaconic acid mass spectrum is shown as Fig. 7. It is, however, much simpler than that of fumaric acid, having only two important fragment ions at high mass, m/e 112 (M - H_2O) and m/e 84 (M - CH_2O_2). A strong metastable peak at m/e 63 indicates that the latter fragment arises by loss of CO from the former. Fragment ions prominent in the fumaric acid spectrum, corresponding to (M - OH), (M - CO), are completely absent in Fig. 7; we conclude that mesaconic acid is not behaving like fumaric acid but that its fragmentation involves

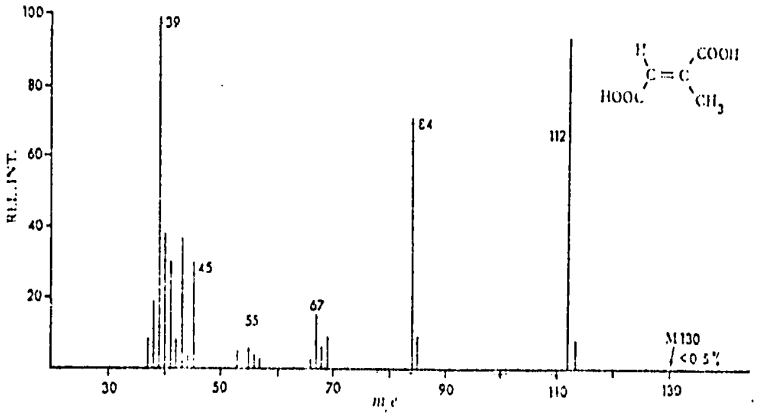


FIG. 7. Mass spectrum of mesaconic acid.

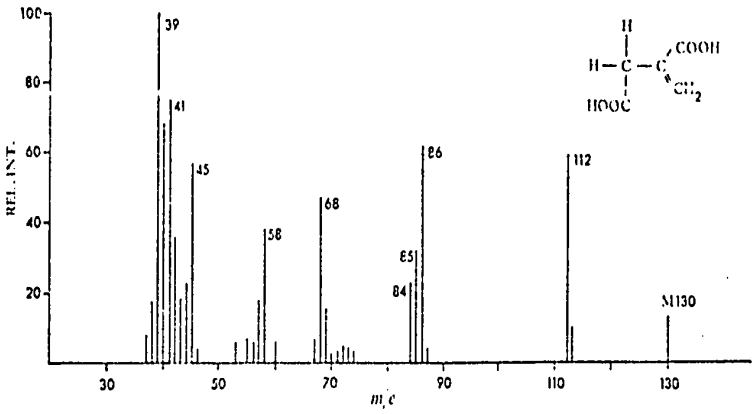


FIG. 8. Mass spectrum of itaconic acid.

participation of the methyl H atoms as shown in Scheme 4. This is similar to the fragmentation observed in the mass spectra of dicarboxylic acids having hydrogen atoms γ- to a carboxyl group[26].

Itaconic acid

Fig. 8 shows the mass spectrum of itaconic acid (propene-2,3-dicarboxylic acid). This compound shows characteristics of both 1,2 isomers indicating that both mesaconic and citraconic type fragmentations are taking place. The only prominent fragment ion absent in the 1,2 acids is that at m/e 58; this species can only reasonably be $(CH_2COO)^+$ which can arise from fission of the 2,3 carbon-carbon bond after H atom transfer from the 3-carboxyl group to the 2-carboxyl group.

Conclusion

From the point of view of structure assignments from mass spectra, the experimental results described above indicate that when a pair of 1,2 carboxyl groups are either held in the same plane by virtue of molecular geometry or can achieve approximate coplanarity by rotation of the 1,2 carbon-carbon bond, loss of CO_2 or H_2O from the molecular ion is observed. These losses result from the migration of a hydrogen atom from one carboxyl group to another, i.e. via the operation of a seven centered "ortho effect".

CHAPTER 5

The Fragmentation of some Cyclic Dicarboxylic Acids

In the previous chapter (Chap 4) the operation of an "ortho effect" in the fragmentation of some unsaturated dicarboxylic acids was discussed. Migration of a hydrogen atom from one carboxyl group to the other yielded a molecular ion that could fragment by loss of CO_2 or H_2O. This rearrangement process operated only in those acids whose geometry permitted easy interaction between the carboxyl functions. This was the case in maleic, citraconic and phthalic acids in which the rigid geometry holds the carboxyl functions in close proximity to one another. However, fragmentation initiated by an "ortho effect" was absent in those acids (fumaric and mesaconic acids) wherein the carboxyl functions are not in close proximity. In the case where the acid functions were not rigidly held by doubly

bonded carbons (itaconic acid), fragmentations characteristic of both citraconic and mesaconic acids were observed, presumably resulting from the ability of the carboxyl groups to take up either a "cis" (citraconic type) or "trans" (mesaconic type) orientation.

This chapter deals with the fragmentation of some cyclic dicarboxylic acids ; in these acids the carboxyl functions are relatively rigidly held in a particular stereochemical arrangement. The dihedral angle between carboxyl groups ranges from 0° in the Δ^{1} unsaturated acids to 180° in <u>trans</u> 3,5-cyclohexadiene-1,2-dicarboxylic acid. It is hoped that a study of such a group of compounds will reveal whether it is possible to correlate the "ortho effect" in 1,2-dicarboxylic acids to the geometrical arrangement of the carboxyl groups.

The molecular ions of the dicarboxylic acids discussed below, fragment by one or more of the following three losses: 1) the loss of H_2O, 2) the loss of CO_2, and 3) the loss of COOH. Two mechanisms are involved in the water elimination; in one, both carboxyl hydrogen atoms are lost, while in the other, a ring hydrogen atom and a carboxyl hydrogen atom are involved. Only the former mode of water loss is due to an "ortho effect". The molecular ions of most of the acids studied were either absent or of low intensity.

(1) <u>Cis and trans cyclohexane-1,2-dicarboxylic acids</u>
<u>cis cyclohexane-1,2-dicarboxylic acid</u>

The mass spectra and dissociation sequence of this compound are shown as figs 1a and b and scheme 1 respectively (in

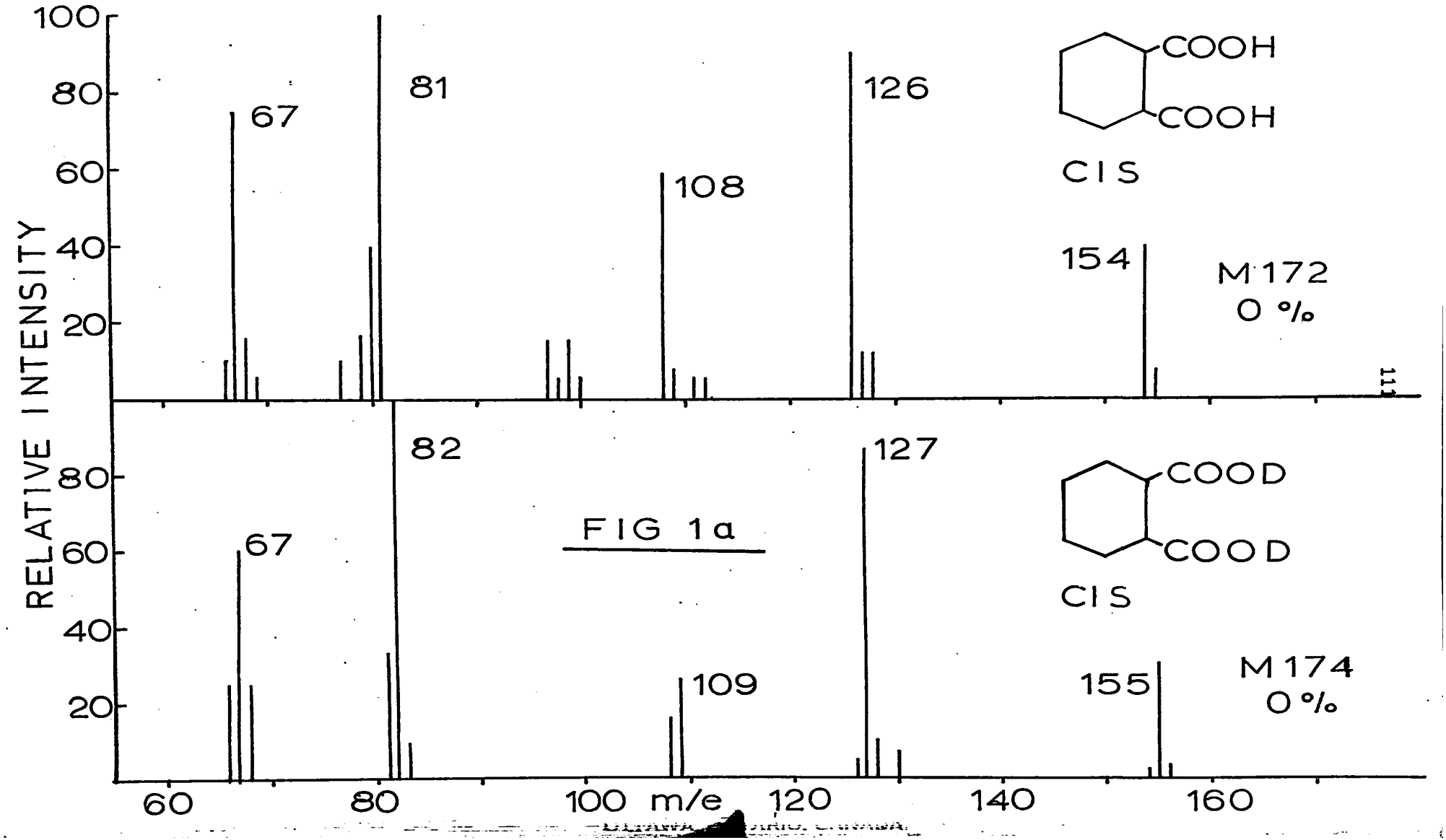

100
80
60
40
20
RELATIVE INTENSITY
67
81
108
126
154
M 172
0 %
COOH
COOH
CIS
82
127
109
155
M 174
0 %
COOD
COOD
CIS
60
80
100 m/e
120
140
160

FIG 1a

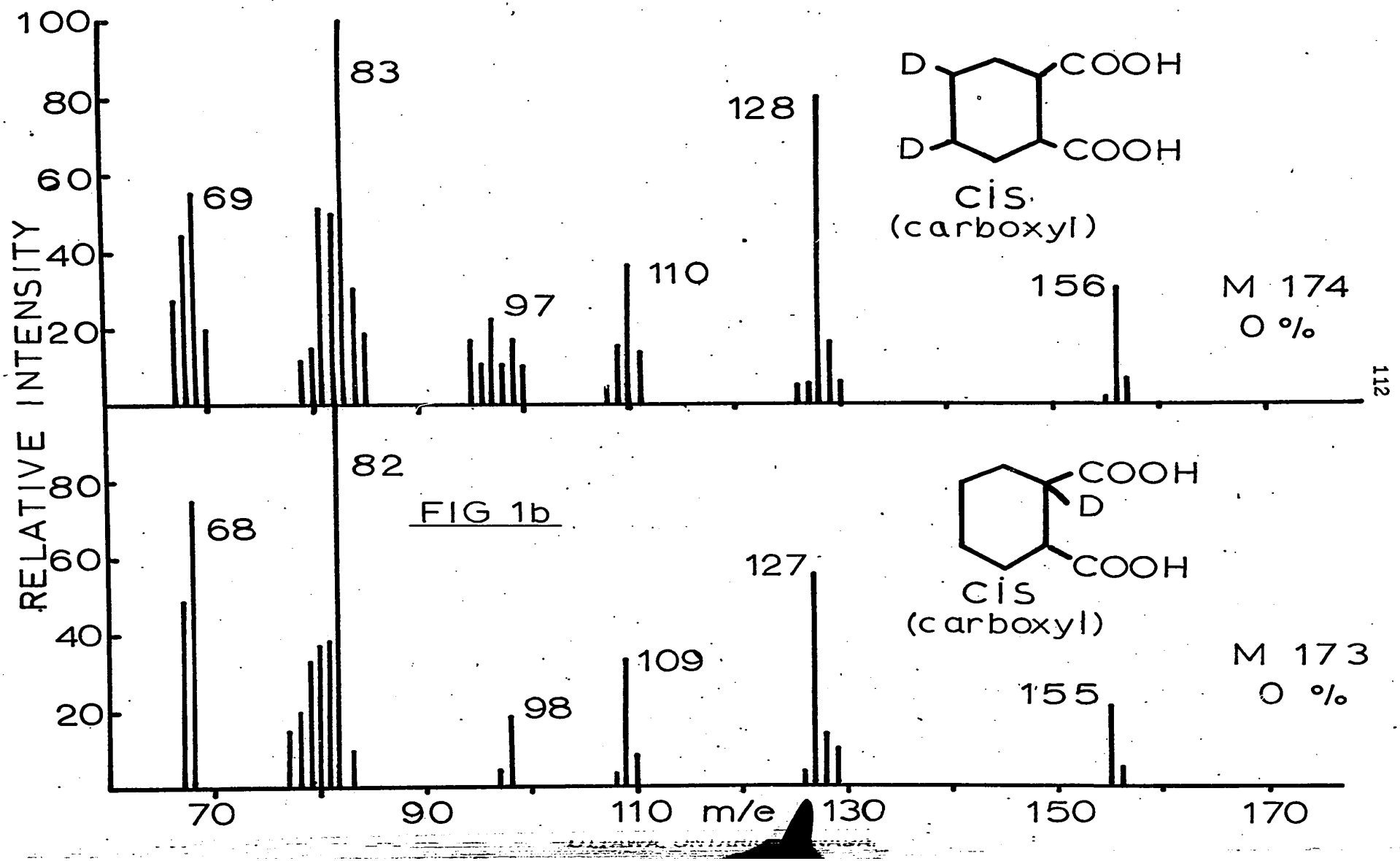
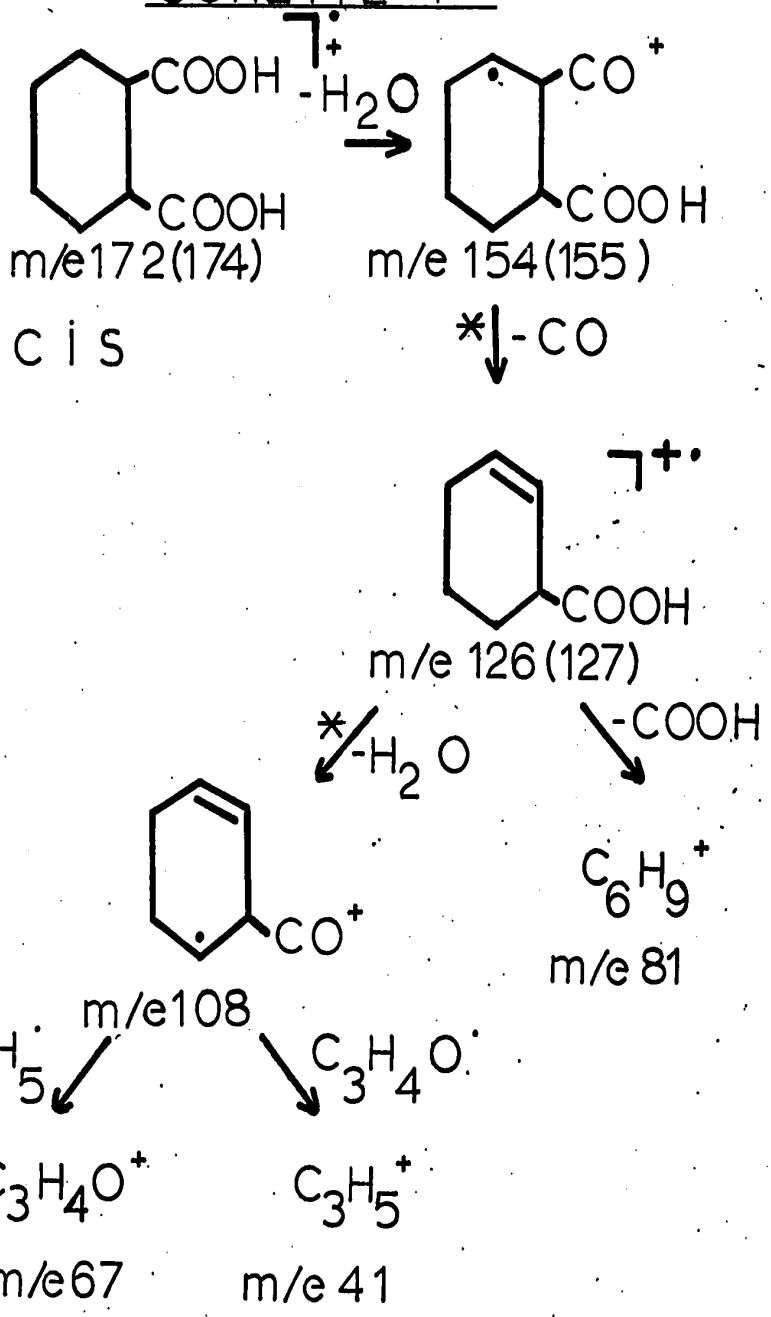

RELATIVE INTENSITY
100
80
60
40
20
83
69
97
110
128
156
M 174
0 %
D
COOH
D
COOH
CIS
(carboxyl)
112
82
68
98
109
127
155
M 173
0 %
COOH
D
COOH
CIS
(carboxyl)
70
90
110
m/e
130
150
170

FIG 1b

SCHEME 1


COOH
COOH
-H2O
CO+
COOH
m/e172(174)
m/e 154(155)
cis
*
-CO
COOH
m/e 126(127)
*
-H2O
-COOH
C6H9+
m/e 81
CO+
m/e108
C3H5·
C3H4O·
C3H4O+
C3H5+
m/e67
m/e 41

the schemes the numbers in parentheses refer to the carboxyl labeled materials unless otherwise stated). This acid exhibits little fragmentation via an "ortho effect". Indeed there is little loss of CO_2 from the molecular ion and only 15% of the water loss involves both carboxyl hydrogen atoms (fig. 1a). Dissociation proceeds mainly by interaction of the carboxyl groups with the cyclohexane ring. This leads to the successive losses of H_2O, CO, and COOH from the molecular ion to yield the major peaks in the mass spectrum at m/e 154, m/e 126 and base peak m/e 81 respectively. Minor fragmentation routes which generate the other peaks in the spectrum are shown in the scheme. The major source of ring hydrogen atom in the water loss is either the 3 or 6 position.

Analysis of the mass spectrum of the 3,3,6,6-d_4 analogue revealed that 55% of the water loss involved HDO and 45%, H_2O. The other ring positions are not greatly involved because very little or no loss of DHO is observed from the 1-d_1 and 4,5-d_2 analogues (fig.1b). It is most likely that a carboxyl group abstracts an adjacent ring hydrogen atom because the resulting species can, after CO loss, yield what is formally the molecular ion of 3-cyclohexene-1-carboxylic acid. If the interaction were between the carboxyl function in the 1 position and the hydrogen atom in the 3 position a less stable bicyclic entity might result from the subsequent CO loss.

<u>trans cyclohexane-1,2-dicarboxylic acid</u>

The mass spectrum and dissociation sequence for this acid

are shown as figs 2a and b and Scheme 2 respectively. Two modes of fragmentation of the molecular ion are observed. These are the losses of CO_2 and H_2O. About 33% of the water loss is due to interaction of the carboxyl groups (from the COOD analogue fig. 2a). Thus the "ortho effect" greatly influences the fragmentation of this compound.

Part of the dissociation sequence is similar to that of the cis acid. Here, however, the water loss involves abstraction of a hydrogen atom from either the 1,2,3 or 6 ring positions. By subsequent CO loss the $(M-H_2O)$ ion can generate either 1-cyclohexene-1-carboxylic acid or 3-cyclohexene-1-carboxylic acid depending on the site from which the hydrogen atom is abstracted (Scheme 2).

The $(M-CO_2)$ species, m/e 128, yields peaks at m/e 110 and m/e 82 by successive losses of H_2O and CO. These peaks were relatively minor in the cis isomer. The presence of these peaks in the trans isomer allows one to distinguish between these two stereo isomers on the basis of their mass spectra alone.

In general, appreciable differences between configurational isomers such as these are unexpected. Indeed in a recent review[16] on stereochemical isomers it was noted that frequently, stereoisomers produce identical or closely similar mass spectra. Small differences in peak heights, which are often more pronounced at low electron energies have been observed. In other systems, the marked difference between stereoisomers (such as maleic and fumaric acids (Chap 4) is easily explained on the basis that an interaction present in one isomer is impossible in the other.

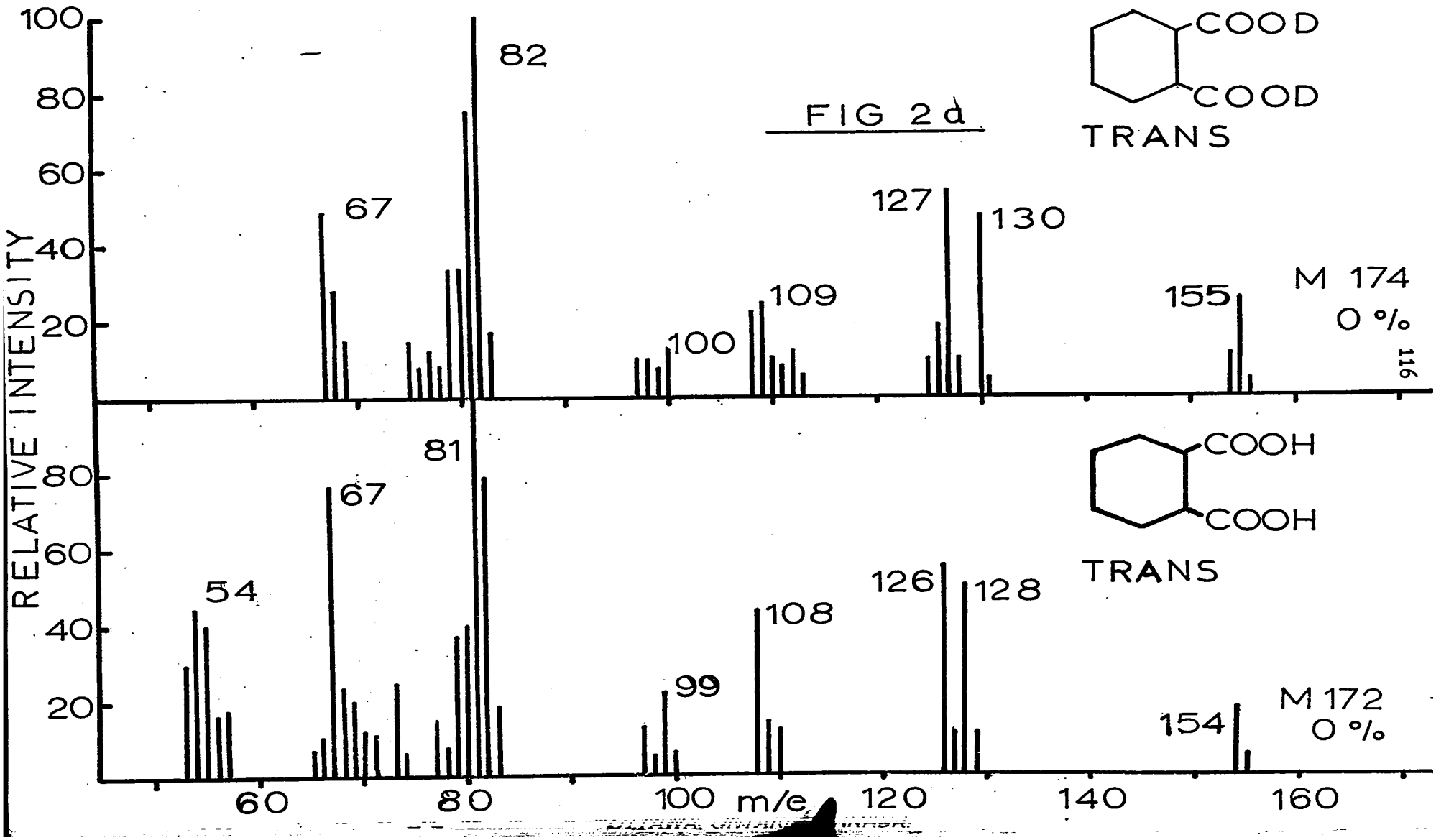


FIG 2d
COOD
COOD
TRANS
M 174
0 %
116
82
67
127
130
109
100
155
COOH
COOH
TRANS
M 172
0 %
81
67
54
126
128
108
99
154
RELATIVE INTENSITY
100
80
60
40
20
60
80
100 m/e
120
140
160

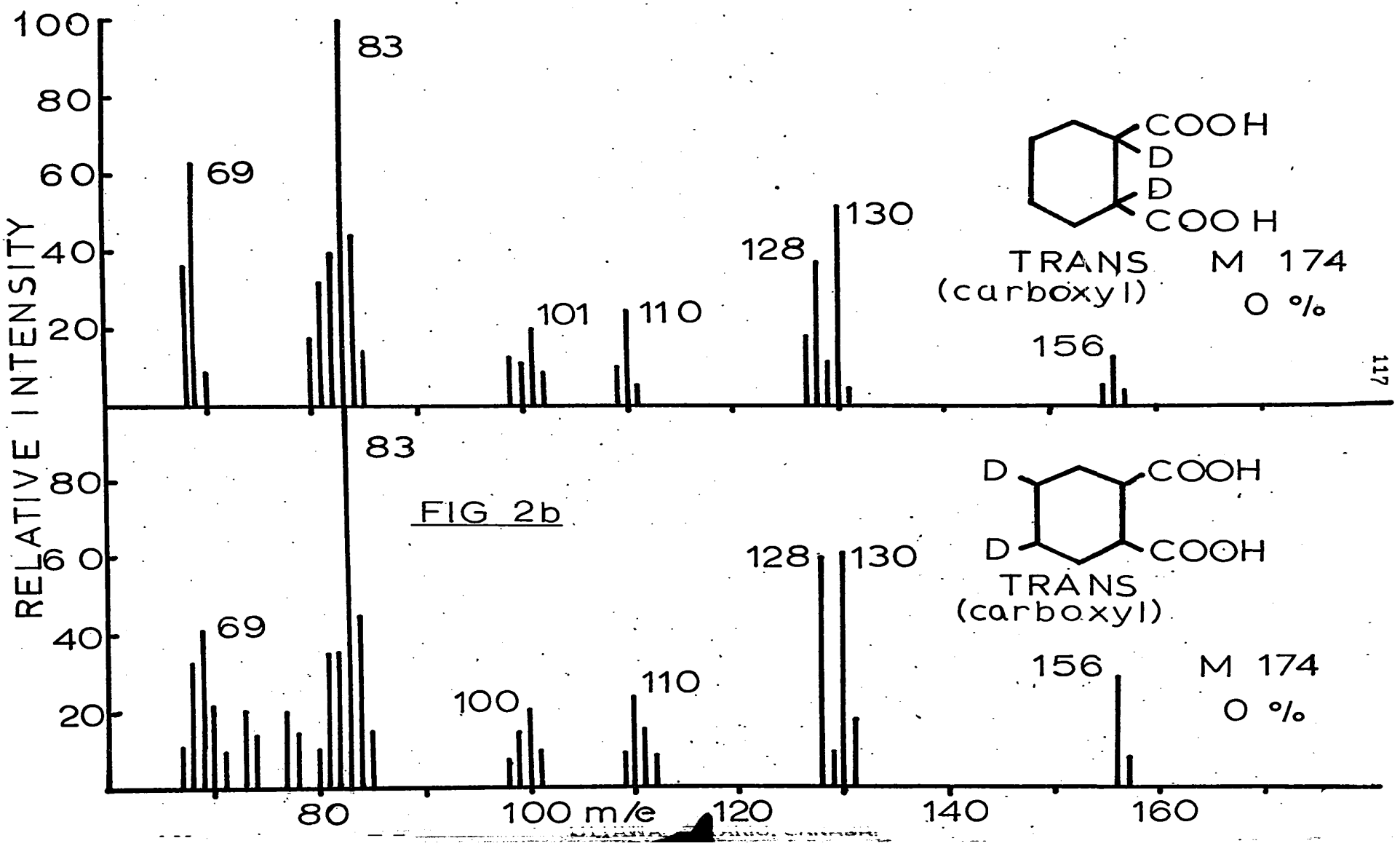
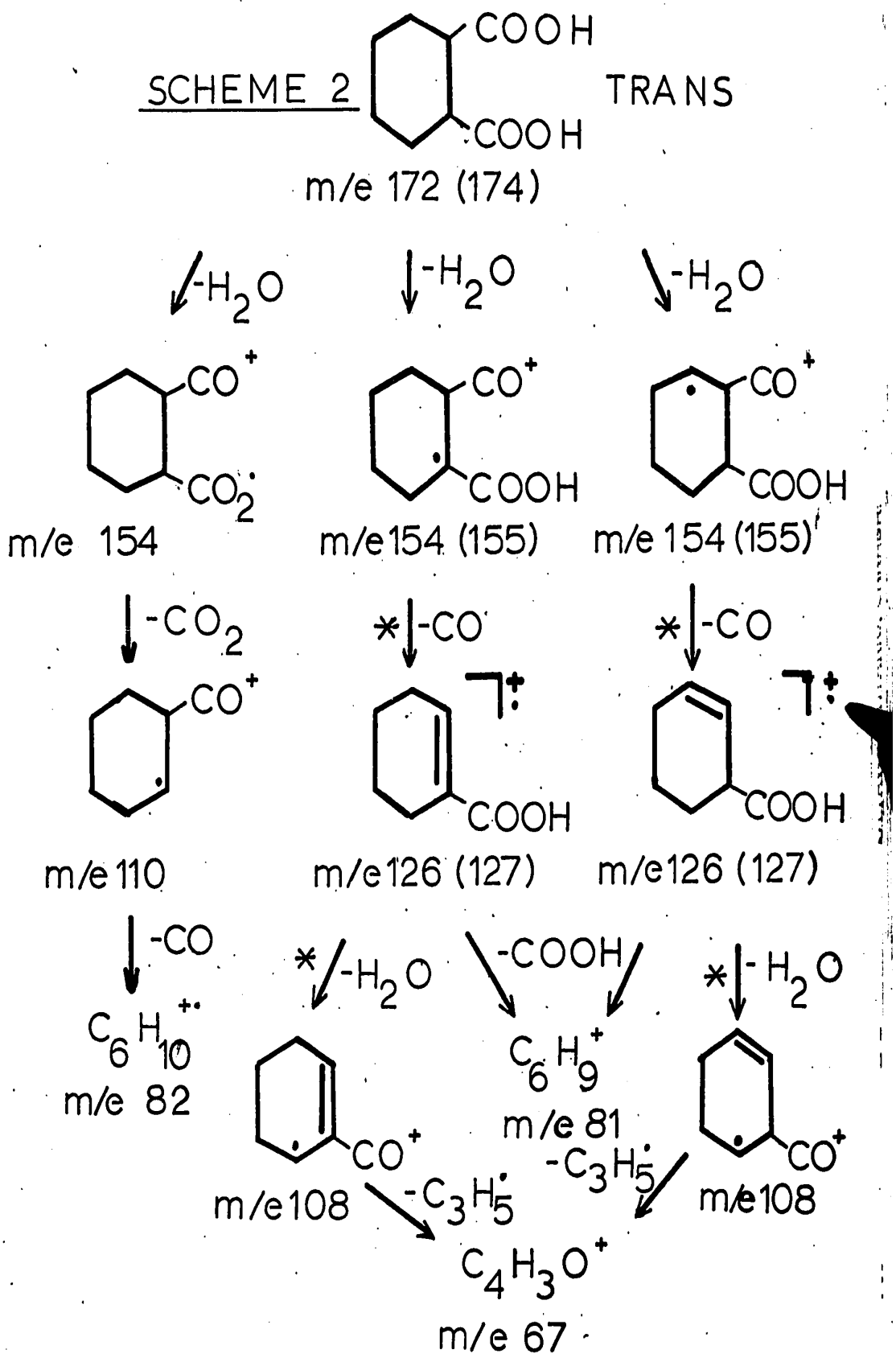
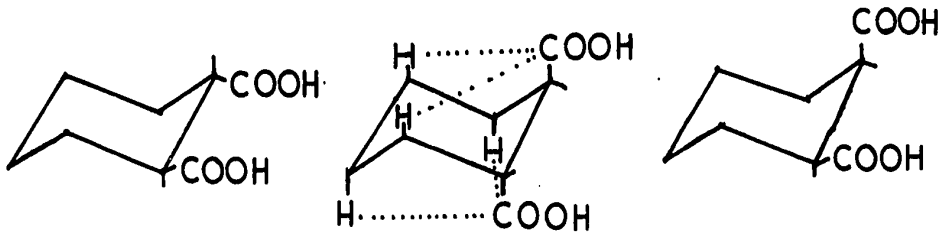

RELATIVE INTENSITY
100
80
60
40
20
83
69
101
110
128
130
156
COOH
D
D
COOH
TRANS
(carboxyl)
M 174
0 %
117
83
69
100
110
128
130
156
D
COOH
D
COOH
TRANS
(carboxyl)
M 174
0 %
80
100 m/e
120
140
160

FIG 2b


SCHEME 2
COOH
COOH
TRANS
m/e 172 (174)
-H2O
-H2O
-H2O
CO+
CO2·
m/e 154
CO+
COOH
m/e 154 (155)
CO+
COOH
m/e 154 (155)
-CO2
CO+
m/e 110
*-CO
COOH
m/e 126 (127)
*-CO
COOH
m/e 126 (127)
-CO
C6H10+·
m/e 82
*-H2O
CO+
m/e 108
-COOH
C6H9+
m/e 81
*-H2O
CO+
m/e 108
-C3H5·
-C3H5·
C4H3O+
m/e 67

In more flexible systems such as *cis* and *trans* cyclohexanediols[28] *cis* and *trans* decalins[1u], and *cis* and *trans* dimethycyclohexane[1u.] the mass spectra of the respective isomers are very similar. The cyclohexane 1,2-dicarboxylic acids resemble these latter systems and yet their dissociation sequences are markedly different.

The differences in the mass spectra of these two compounds are due to the carboxyl - carboxyl interaction that is present only in the *trans* isomer. However, the geometrical relationship between the carboxyl groups is *identical* in both isomers, i.e. the distance and dihedral angle between the acid functions are the same.



trans diequatorial | trans diaxial | cis ax.-equat.

The only apparent difference between these two isomers is the orientation of the carboxyl functions with respect to the cyclohexane ring. In their more stable conformations, the *cis* acid will have an axially and an equatorially oriented carboxyl group whereas the *trans* acid will have two equatorially oriented carboxyl functions. The other possible conformation in the *trans* acid would have both carboxyl groups axially oriented. However,

this conformation is not as stable as that in which the carboxyl groups are equatorially oriented because of the unfavourable interaction with the axial hydrogen atoms in the 3 positions (the carboxyl group being in the 1 position).

There are four such interactions in the diaxial conformation and none in the diequatorial. The inability of the carboxyl groups to interact with one another in the cis acid could be due to a preferred interaction between an axial carboxyl group and the ring hydrogen atoms. Thus the axial carboxyl group would be "unavailable" for participation in an "ortho effect" with its neighbouring acid function.

(2) cis and trans cyclobutane-1,2-dicarboxylic acids

These two acids, similarly exhibit different mass spectra (fig. 3). The operation of an "ortho effect" in the cis compound yields an intense ($M-CO_2$) ion (50% b.p.) whereas in the trans isomer this peak is only 14% b.p. The main dissociation sequences are shown as schemes 3 and 4. In the trans isomer water loss involves abstraction of a ring hydrogen atom, most likely from the 1 or 2 position (because interaction of the carboxyl groups with the other ring positions would be difficult). Base peak arises by the successive losses of $C_2H_3^{\bullet}$, CO_2 and H_2O from the molecular ion. This sequence involves the operation of an "ortho effect" in the $M - C_2H_3^{\bullet}$ species. Indeed, loss of $C_2H_3^{\bullet}$ from the ring yields ion (a) (m/e 117, Scheme 3) in which the carboxyl groups can interact. In the molecular ion, this interaction is impossible because of the rigid geometry. Ion (a) behaves similarly to the molecular ion of succinic acid[26] which

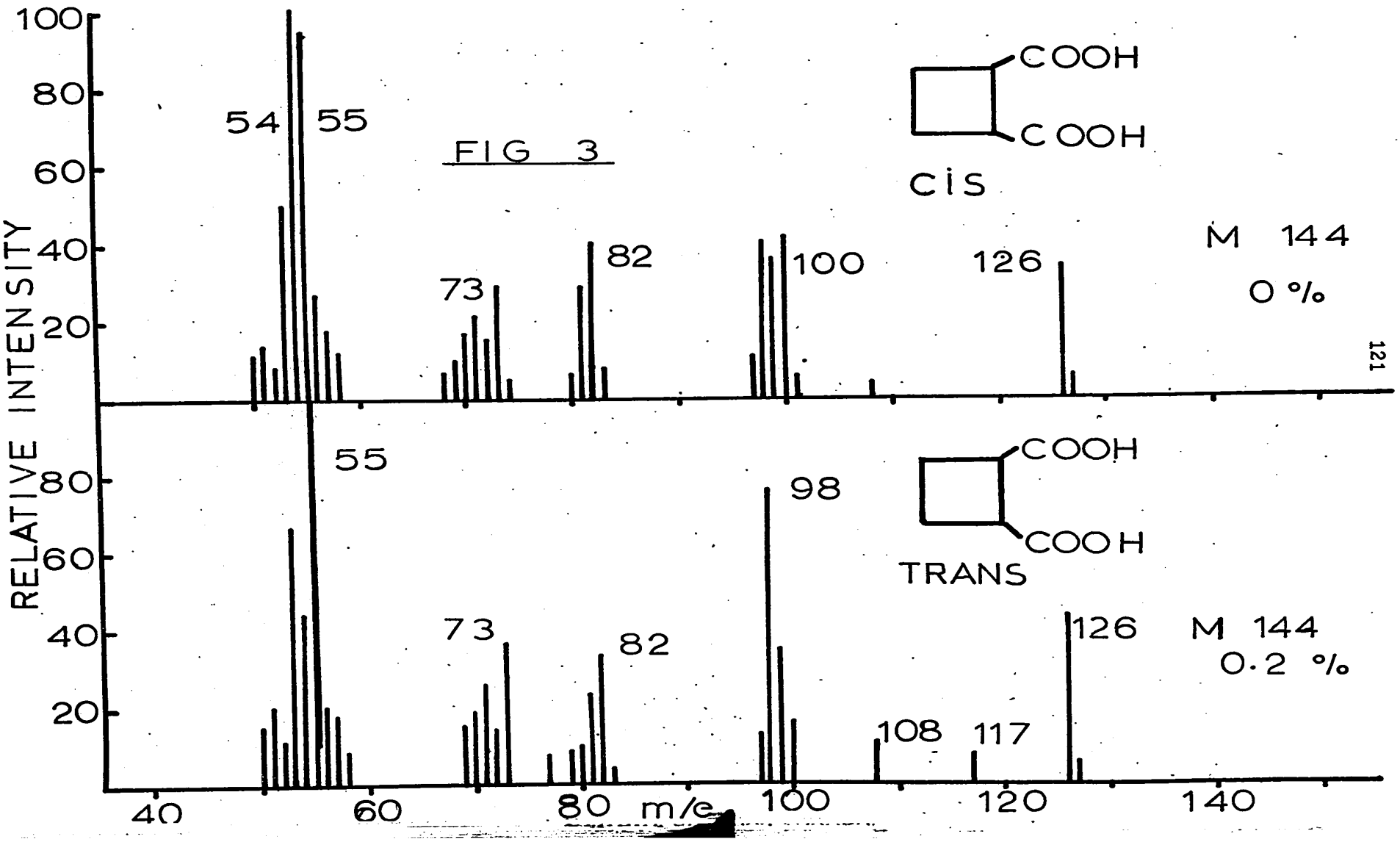
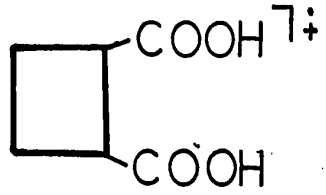


FIG 3
RELATIVE INTENSITY
100
80
60
40
20
54
55
73
82
100
126
121
COOH
COOH
CIS
M 144
0 %
55
98
73
82
126
108
117
COOH
COOH
TRANS
M 144
0.2 %
40
60
80
m/e
100
120
140

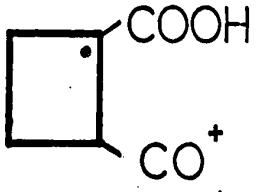
SCHEME 3

TRANS



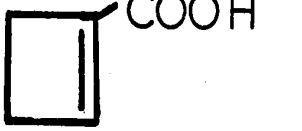
m/e 144 (146)

$-H_2O$



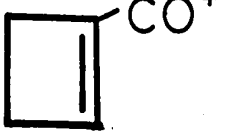
m/e 126 (127)

$-CO$



m/e 98 (99)

$-OH$



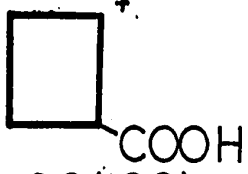
m/e 81

$-CO$

$C_4H_5^+$

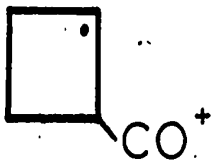
m/e 53

$-COOH$



m/e 99 (100)

$-OH$



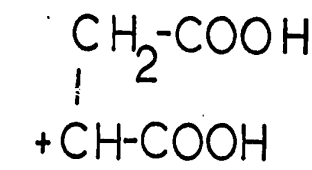
m/e 82

$-CO$

$C_4H_6^{+\cdot}$

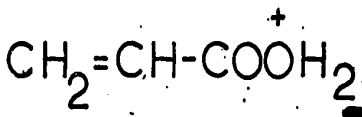
m/e 54

$-C_2H_3^{\cdot}$



(a) m/e 117 (119)

$-CO_2$



m/e 73 (75)

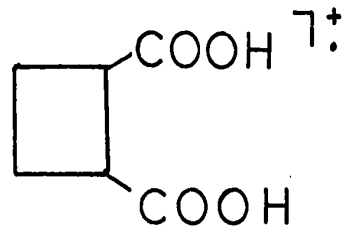
$-H_2O$

$CH_2=CH-CO^+$

m/e 55

SCHEME 4

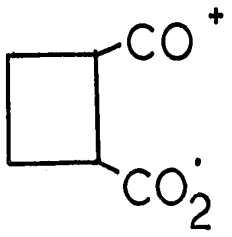
CIS



m/e 144

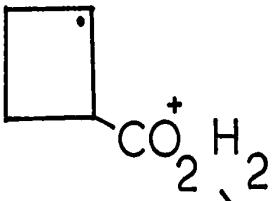
-COOH → as in scheme 3

-H_2O



m/e 126

-CO_2

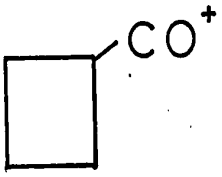


m/e 100

-C_2H_3·

-CO_2

-H_2O



m/e 82

-CO

$C_4H_6^{+\cdot}$

m/e 54

$CH_2=CH-CO_2^+H_2$

m/e 73

-H_2O

$CH_2=CH-CO^+$

m/e 55

also fragments by the successive losses of H_2O and CO_2 (or vice-versa).

In the molecular ion of the cis isomer, interaction of the carboxyl groups is possible and this results in the successive losses of CO_2 and H_2O (or vice-versa). The resulting ion at m/e 82 generates base peak at m/e 54 by CO loss (Scheme 4). The remaining dissociation sequences are similar to those in the trans isomer.

The marked difference in fragmentation mechanisms of this pair of isomeric acids is not unexpected, because, with the rigid geometry of the cyclobutane ring, a situation similar to that in maleic and fumaric acids is obtained. In the cis acid the carboxyl groups are held in close proximity to one another whereas in the trans isomer they are remote. The above results indicate that in both the cyclohexane-1,2-dicarboxylic acids and the cyclobutane-1,2-dicarboxylic acids ring opening does not occur. If ring opening preceded fragmentation, the mass spectra of the cis and trans isomers would be expected to be the same.

(3) Cis and trans 4-cyclohexene-1,2-dicarboxylic acids

The mass spectra of these two acids are shown as figs 4 and 5. The marked differences observed in the mass spectra of the isomeric cis and trans acids above is absent here. Indeed both acids yield very similar spectra. Their fragmentations involve the successive losses of H_2O, CO and COOH from the

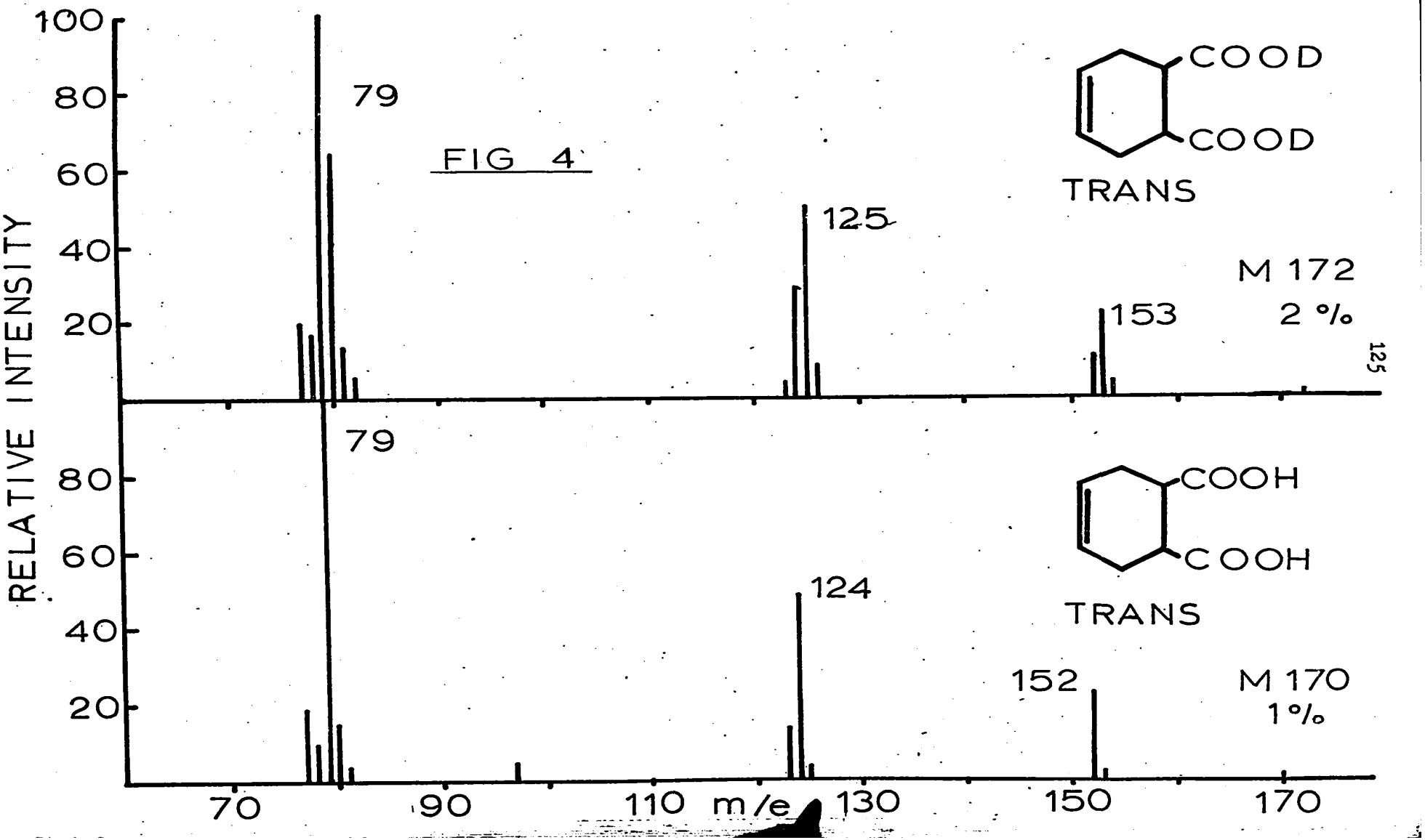


FIG 4
RELATIVE INTENSITY
100
80
60
40
20
79
125
153
M 172
2 %
125
COOD
COOD
TRANS
79
124
152
M 170
1%
COOH
COOH
TRANS
70
90
110
m/e
130
150
170

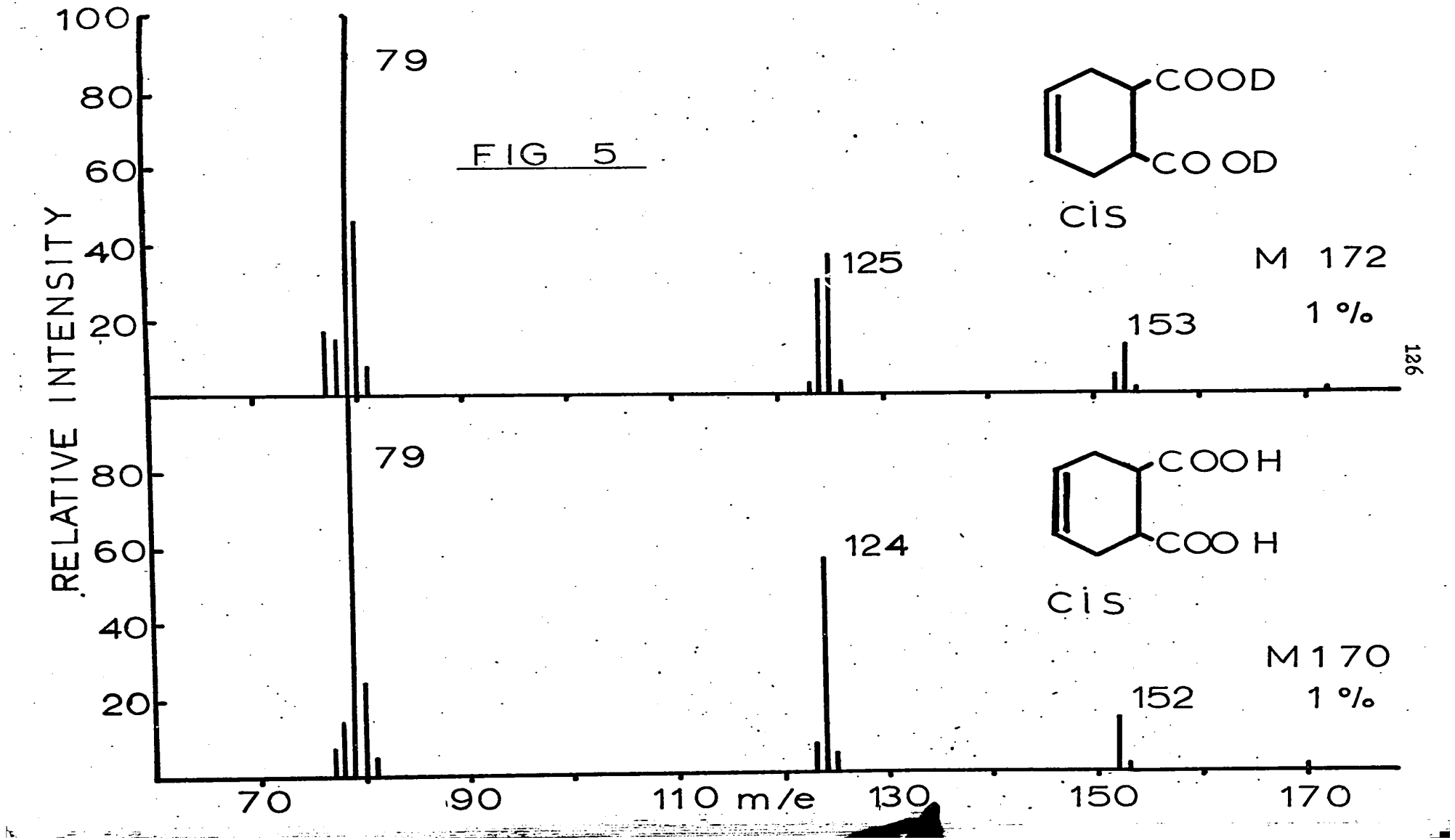

100
80
60
40
20
RELATIVE INTENSITY
79
125
153
M 172
1 %
126
COOD
COOD
CIS
79
124
152
M 170
1 %
COOH
COOH
CIS
70
90
110 m/e
130
150
170

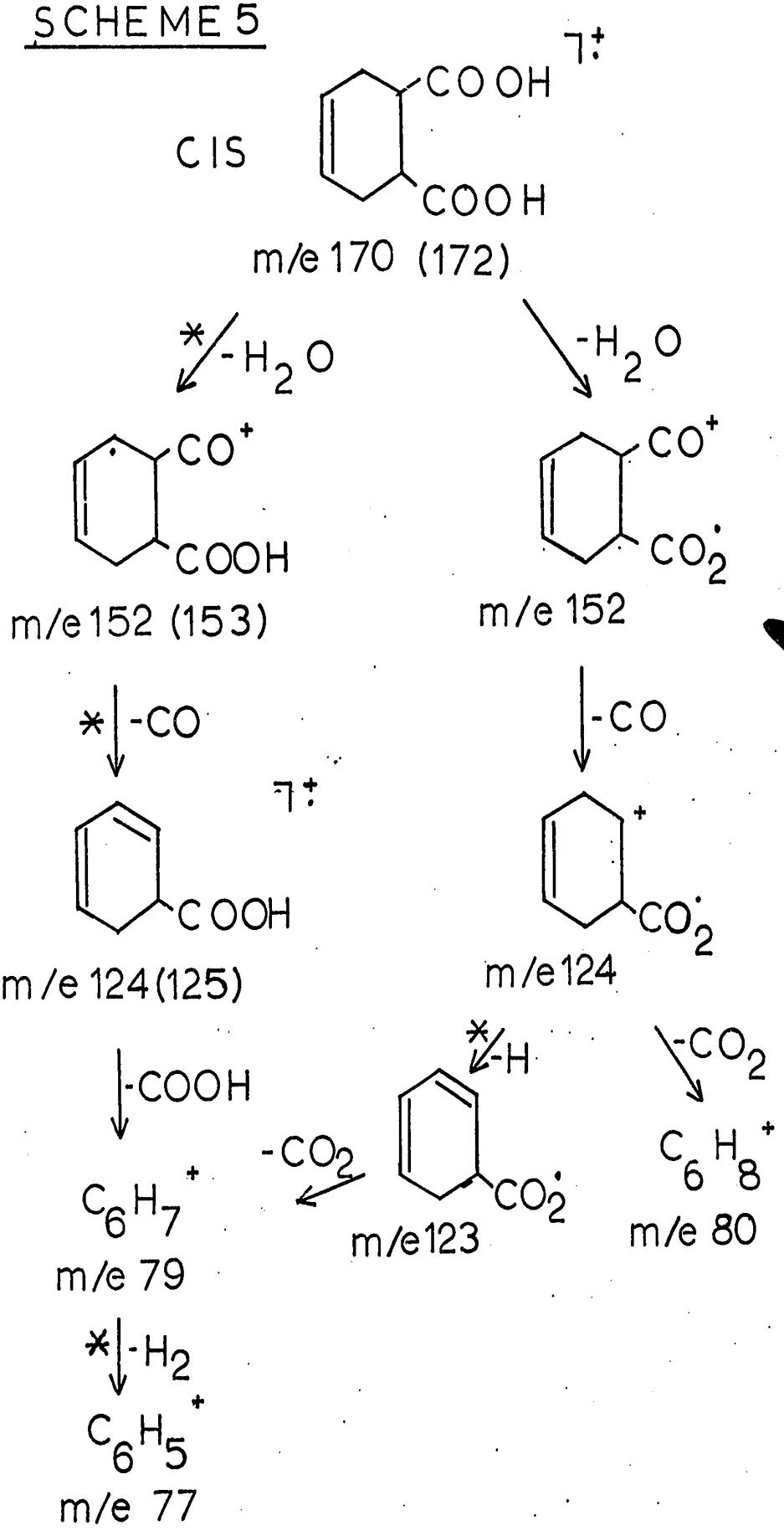
FIG 5

molecular ions. The m/e 123 ion arises by loss of H from m/e 124 and m/e 77 by loss of H_2 from m/e 79 species (Scheme 5). No loss of CO_2 from the molecular ion is observed and only 33% of the water loss involves both carboxyl hydrogen atoms. Therefore, very little fragmentation is due to an ortho effect.

The lack of distinction between the mass spectra of these two compounds may be attributed to the unsaturation of the cyclohexyl ring. The presence of the double bond within the ring removes two unfavourable 1,3 axial hydrogen interactions. An axial carboxyl function in cyclohexane suffers an unfavourable steric interaction with the axially oriented hydrogen atoms in the 3 - positions (the carboxyl group being in the 1 position). For this reason an equatorial orientation of the carboxyl groups was preferred to an axial arrangement in trans-cyclohexane-1,2-dicarboxylic acid. Here, however, the trans isomer can assume an axial - axial arrangement because of the removal of two of the unfavourable interactions. In such a conformation, interaction between carboxyl groups is impossible and the similarity in the mass spectra of these stereoisomers can be interpreted as due to their similar carboxyl - ring interactions.

The origin of the ring hydrogen atom in the water loss is of interest. In the cis acid it was found from the 3,3,6,6-d_4 analogue, that 55% of the water loss involved a hydrogen atom from the 3 or 6 ring positions. We show this abstraction as from the position adjacent to the carboxyl function because the subsequent successive H_2O and CO losses can generate a

SCHEME 5


CIS
COOH
COOH
m/e 170 (172)
-H2O
-H2O
CO+
COOH
m/e 152 (153)
CO+
CO2·
m/e 152
-CO
-CO
COOH
m/e 124 (125)
CO2·
m/e 124
-COOH
-H
-CO2
-CO2
C6H7+
m/e 79
m/e 123
C6H8+
m/e 80
-H2
C6H5+
m/e 77

conjugated cyclohexadiene carboxylic acid (m/e 124) (Scheme 5). The latter transition (m/e 152→m/e 124) is accompanied by a "flat top" metastable in both the cis and trans isomers. A similar metastable is also observed in the mass spectra of cis and trans 3-cyclohexene-1,2-dicarboxylic acid and 2-cyclohexene-1,2-dicarboxylic acid. Thus the explanation for its presence is the same for all these acids.

It has been shown[10] that flat top metastables arise when there is a kinetic energy release upon fragmentation. This energy release occurs by conversion of internal energy to translational energy and is associated with the production of a highly stable fragment ion[5]. The resultant energy release has the effect of broadening the metastable ion peak. Beynon and Fontaine[11] developed an equation correlating the width of the metastable peak with the amount of energy released.

$$d = \left(\frac{4m_2^2}{m_1}\right)\sqrt{\frac{\mu T}{eV}}$$

where d = metastable peak width in atomic mass units
m_2 = mass of daughter ion
m_1 = mass of precursor ion
$\mu = \frac{(m_1 - m_2)}{m_2}$
T = energy released in electron volts
e = electronic charge
V = accelerating potential

The metastable widths and energy released for each acid are listed in Table 1. The energy release in cis-4-cyclohexene-1,2-dicarboxylic acid must be associated with the generation of

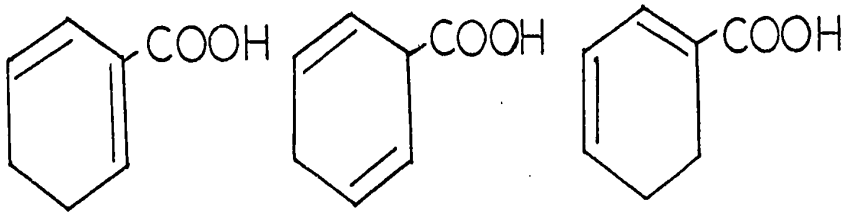
Table 1

Cyclohexene-1,2-dicarboxylic acid	m*-152→124 Width at half height in a.m.u.	Energy release in Kcals/mole
cis 4-	2.0 ± 0.2	4.3 ± 0.5
trans 4-	2.4 ± 0.2	6.4 ± 0.5
cis 3-	1.9 ± 0.2	3.9 ± 0.5
trans 3-	1.9 ± 0.2	3.9 ± 0.5
2-	2.1 ± 0.2	4.8 ± 0.5

the conjugated cyclohexadiene - carboxylic acid. We propose that similar dienes are generated in the mass spectra of the other acids that exhibit the flat top metastable for the transition m/e 152→m/e 124.

(4) cis and trans-3-cyclohexene-1,2-dicarboxylic acid

The mass spectra, figs 6 and 7, and fragmentation modes of these two acids are essentially the same as that described above for the 4-cyclohexene-1,2-dicarboxylic acids. However, there are three possible structural representations for the fragment ions (M-H_2O-CO), m/e 124, depending upon the position of abstraction of the hydrogen atom. These are shown below.



(5) 2-cyclohexene-1,2-dicarboxylic acid

The mass spectrum of this acid is shown as fig. 8. The main fragmentation sequence is the same as that described for the 4-cyclohexene-1,2-dicarboxylic acids and shown in scheme 5. However, in this acid there is some evidence for the operation of an "ortho effect"; minor peaks for the successive losses of CO_2 and H_2O (or vice versa) are observed. This indicates that the carboxyl groups can interact in this acid but the interaction between the carboxyl groups and the ring still constitutes the major dissociation route.

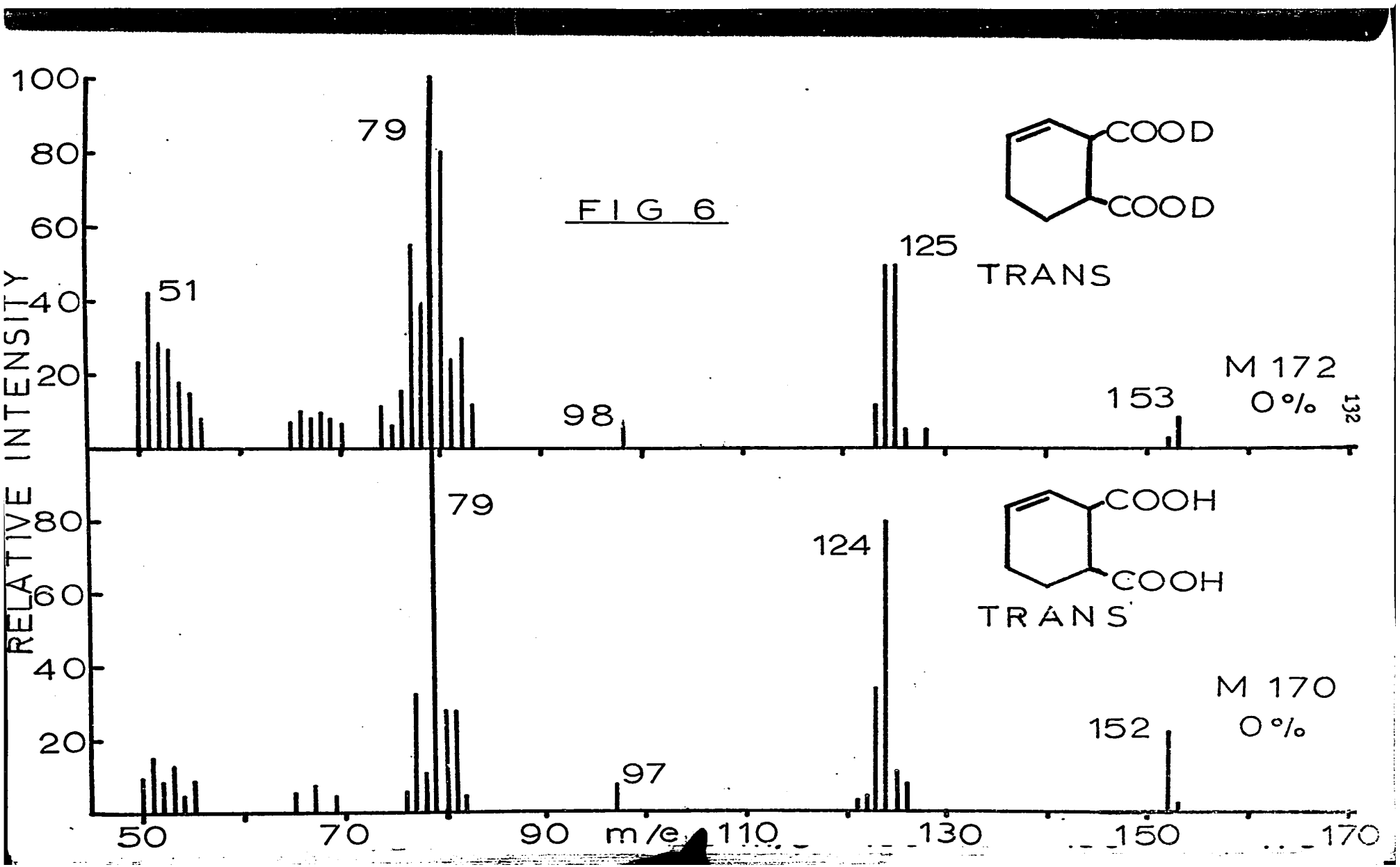


FIG 6
RELATIVE INTENSITY
100
80
60
40
20
79
51
98
125
153
M 172
0%
132
TRANS
COOD
COOD
79
124
97
152
M 170
0%
TRANS
COOH
COOH
50
70
90
m/e
110
130
150
170

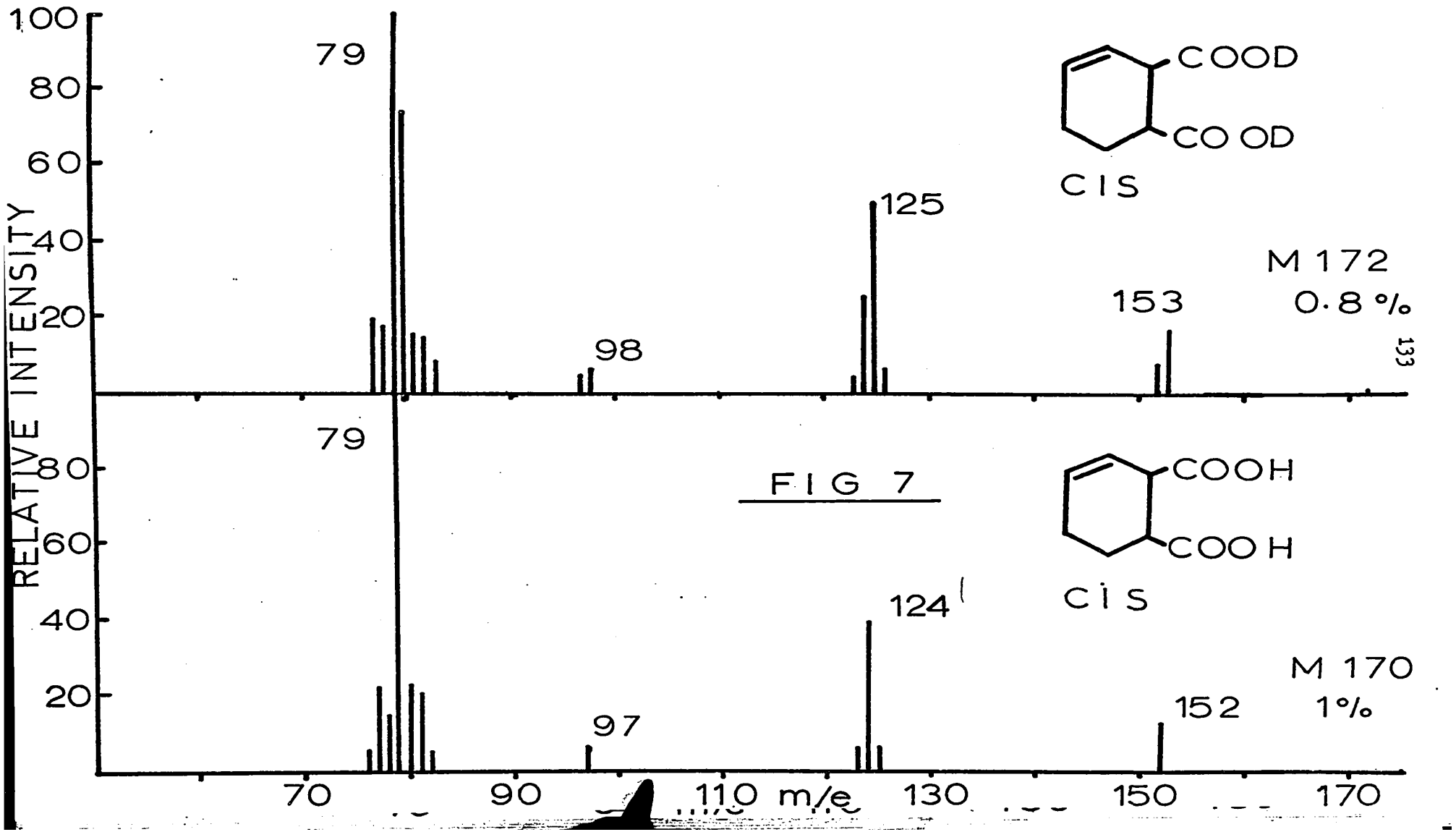

100
80
60
40
20
RELATIVE INTENSITY
79
98
125
153
M 172
0.8 %
133
COOD
COOD
CIS
79
124
97
152
M 170
1%
COOH
COOH
CIS
70
90
110 m/e
130
150
170

FIG 7

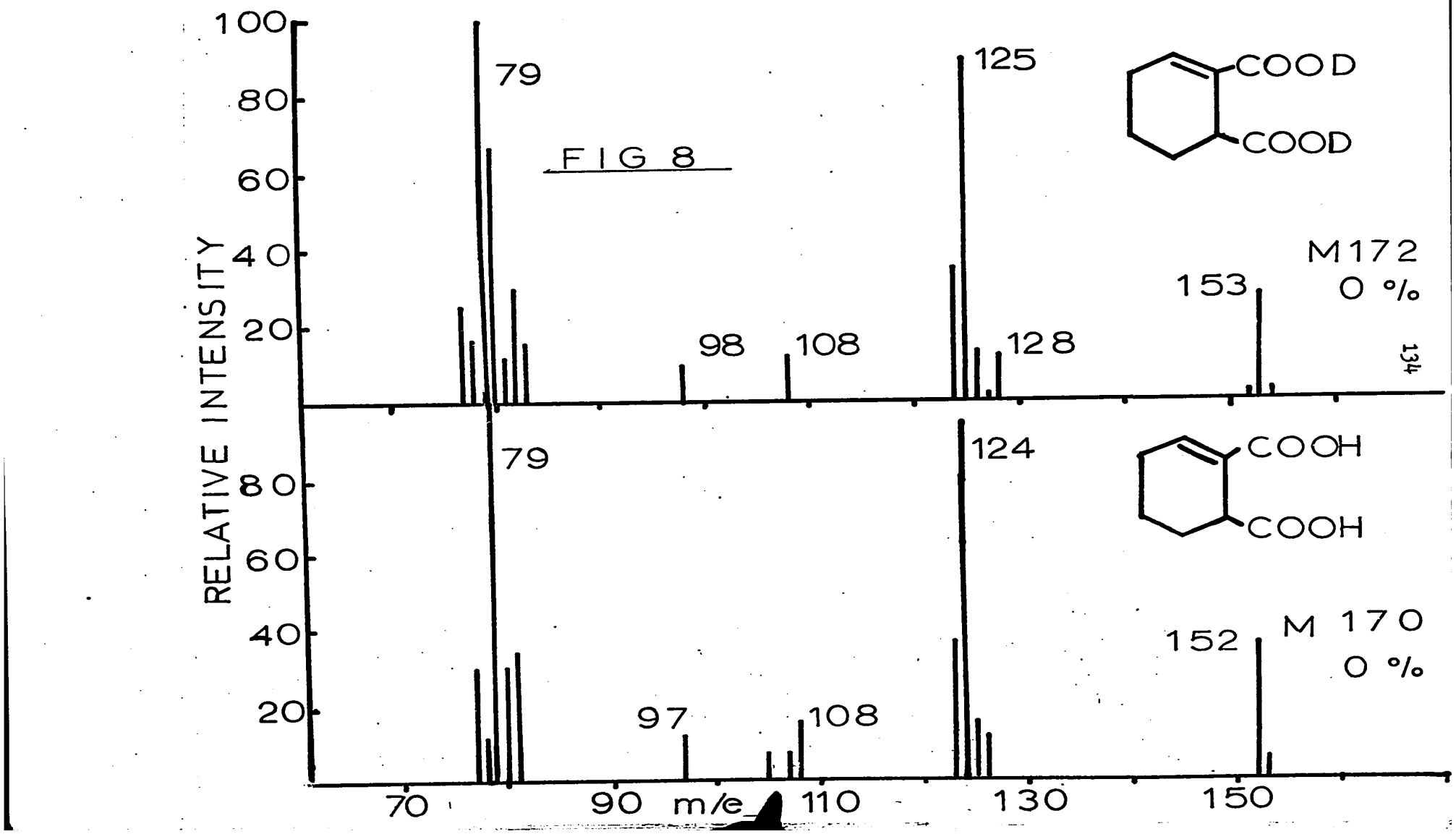

100
80
60
40
20
RELATIVE INTENSITY
79
125
COOD
COOD
M172
0 %
153
98
108
128
134
79
124
COOH
COOH
M 170
0 %
152
97
108
70
90
m/e
110
130
150

FIG 8

(6) 1-cyclohexene-1,2-dicarboxylic acid

The mass spectrum (fig. 9) of this acid is very different from those of the previous five cyclohexene-1,2-dicarboxylic acids. In this acid dissociation occurs by the successive losses of H_2O, CO_2, CO and H from the molecular ion (Scheme 6). The water loss involves only the carboxyl hydrogen atoms indicating the presence of a strong "ortho effect". In this acid, there is no interaction between the carboxyl group and the ring as was observed in all the other cyclohexene-1,2-dicarboxylic acids. All of the fragmentation results from the operation of an "ortho effect" in the molecular ion.

(7) 1-cyclopentene-1,2-dicarboxylic acid

The mass spectrum of this compound is shown as fig. 10. The fragmentation of this acid is unexpectedly more complex than that of 1-cyclohexene-1,2-dicarboxylic acid. There is an intense M - CO_2 peak at m/e 112 and 33% of the water loss involves both carboxyl hydrogen atoms ; thus, the "ortho effect" is prominent in this acid (Scheme 7). The remaining dissociation routes are shown in scheme 7.

An interesting phenomenon occurs in the carboxyl deuterated analogue. In the labeled material the metastables for HDO and D_2O losses are in the ratio of 2:1. A similar ratio is observed for the corresponding fragment peaks. This result can be satisfactorily explained by proposing that the intact carboxyl hydroxyl group can with equal probability abstract a hydrogen from either the adjacent carboxyl group or a ring site. The 2:1 ratio can then be a simple reflection of the statistical

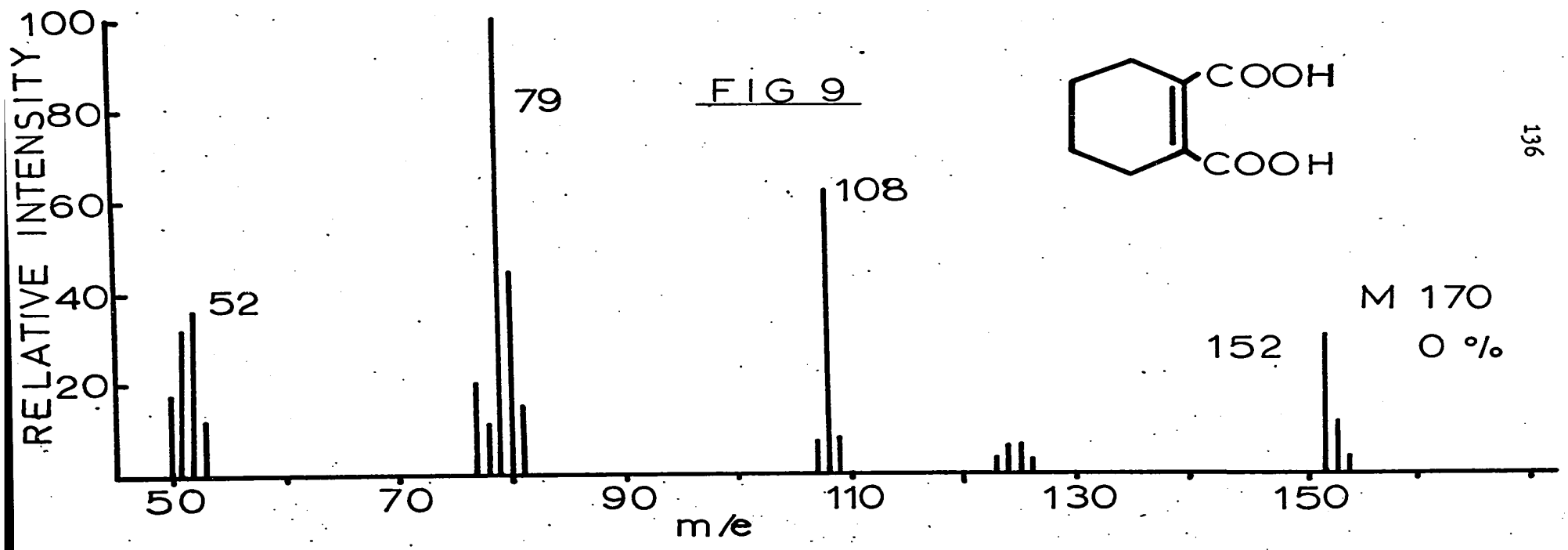
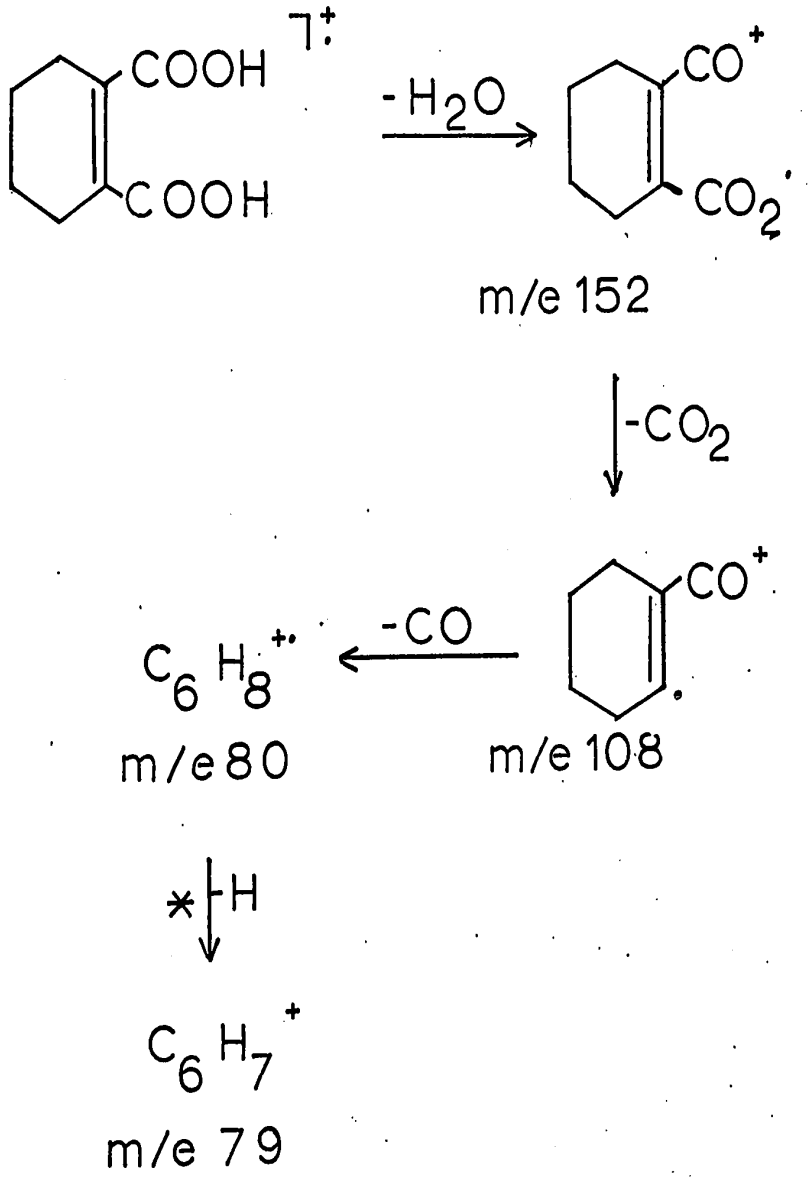

RELATIVE INTENSITY
100
80
60
40
20
50
70
90
110
130
150
m/e
52
79
108
152
M 170
0 %
COOH
COOH

FIG 9

SCHEME 6


COOH
COOH
7+
-H2O
CO+
CO2
m/e 152
-CO2
CO+
-CO
C6 H8 +•
m/e 80
m/e 108
*
H
C6 H7 +
m/e 79

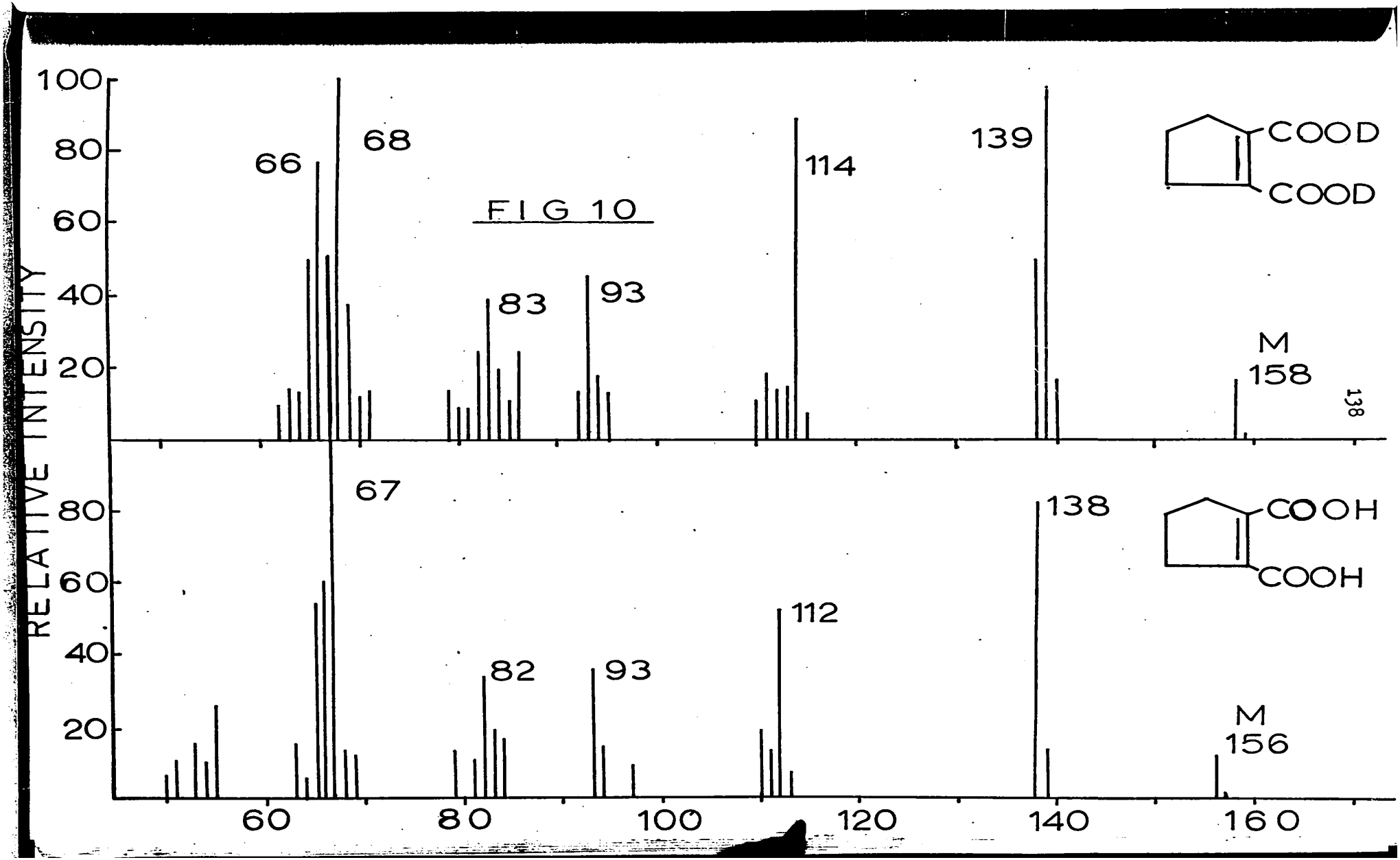
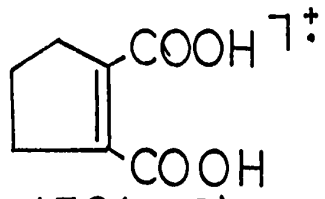
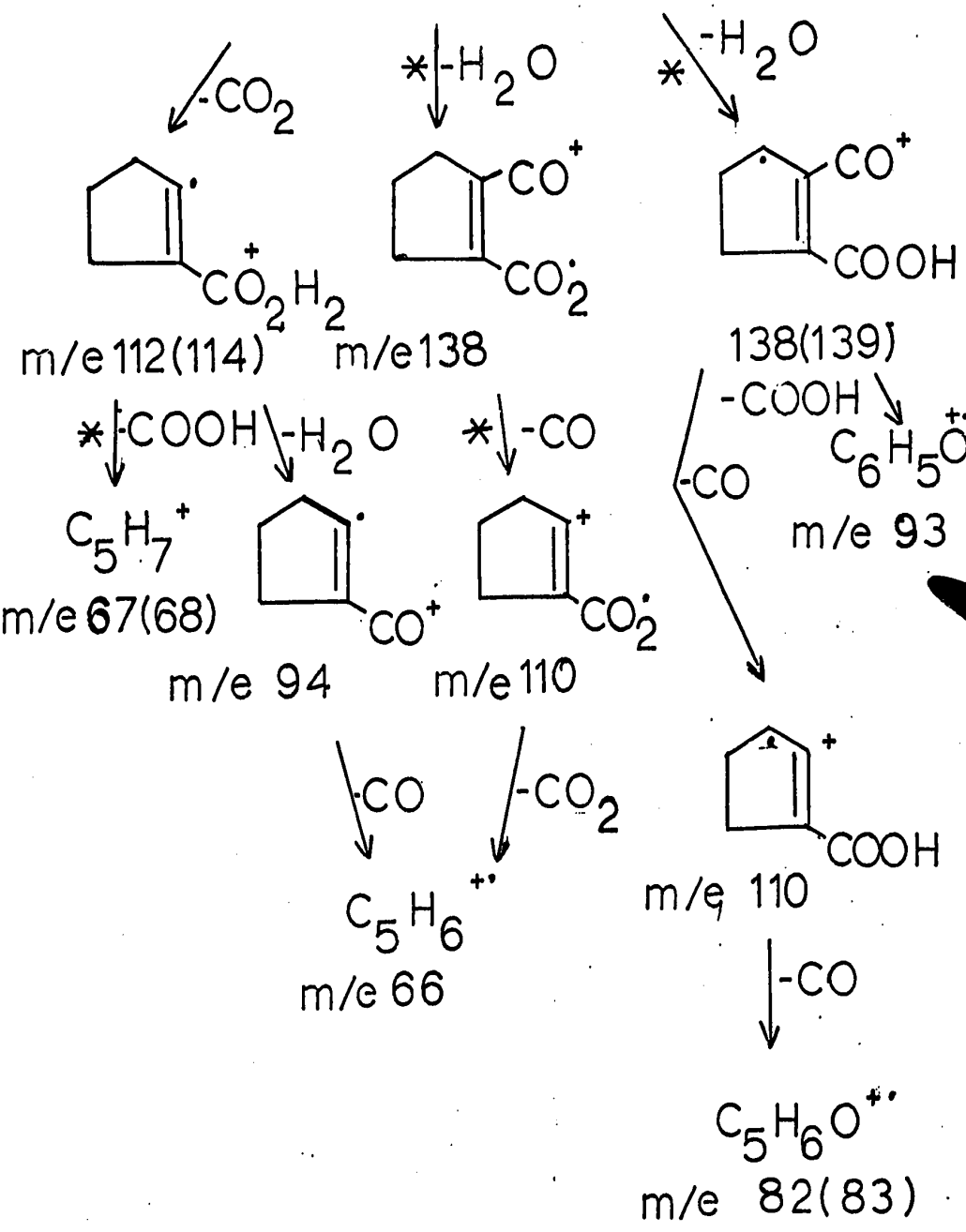

RELATIVE INTENSITY
100
80
60
40
20
66
68
83
93
114
139
M
158
138
COOD
COOD
67
82
93
112
138
M
156
COOH
COOH
60
80
100
120
140
160

FIG 10

SCHEME 7



m/e 156(158)



excess of ring hydrogen atoms. The absence of H_2O loss from the molecular ion of the labeled compound, indicates that the carboxyl hydrogen atoms do not "mix" with the ring hydrogen atoms. The ratio of the peak heights is maintained at low electron energies (down to 9eV nominal) and thus the results cannot be explained as due to two competing reactions.

This fragmentation is an example of hydrogen atoms from more than one position becoming indistinguishable. In general, unexpected retention of the deuterium label has been explained by postulating that the hydrogen atoms could "scramble" or migrate from one site to another within the ion,i.e. via a kinetic process. In 1-cyclopentene-1,2-dicarboxylic acid retention of the deuterium label does not occur in this way but rather by the inability of the hydroxyl group to distinguish between the hydrogen atoms from two different sites, namely the carboxyl and one ring position. This mechanism may also operate in other instances where hydrogen scrambling has been proposed.

Base peak at m/e 67 arises from m/e 112 by COOH loss. This requires migration of a hydrogen atom back to the ring, most likely to the adjacent vacant site.

(8) <u>1-cyclobutene-1,2-dicarboxylic acid</u>

The only intense peak in the mass spectrum of this compound (fig. 11) is base peak at m/e 98 which corresponds to loss of CO_2 from the molecular ion (Scheme 8). The loss of water from the molecular ion is only a minor process (2%

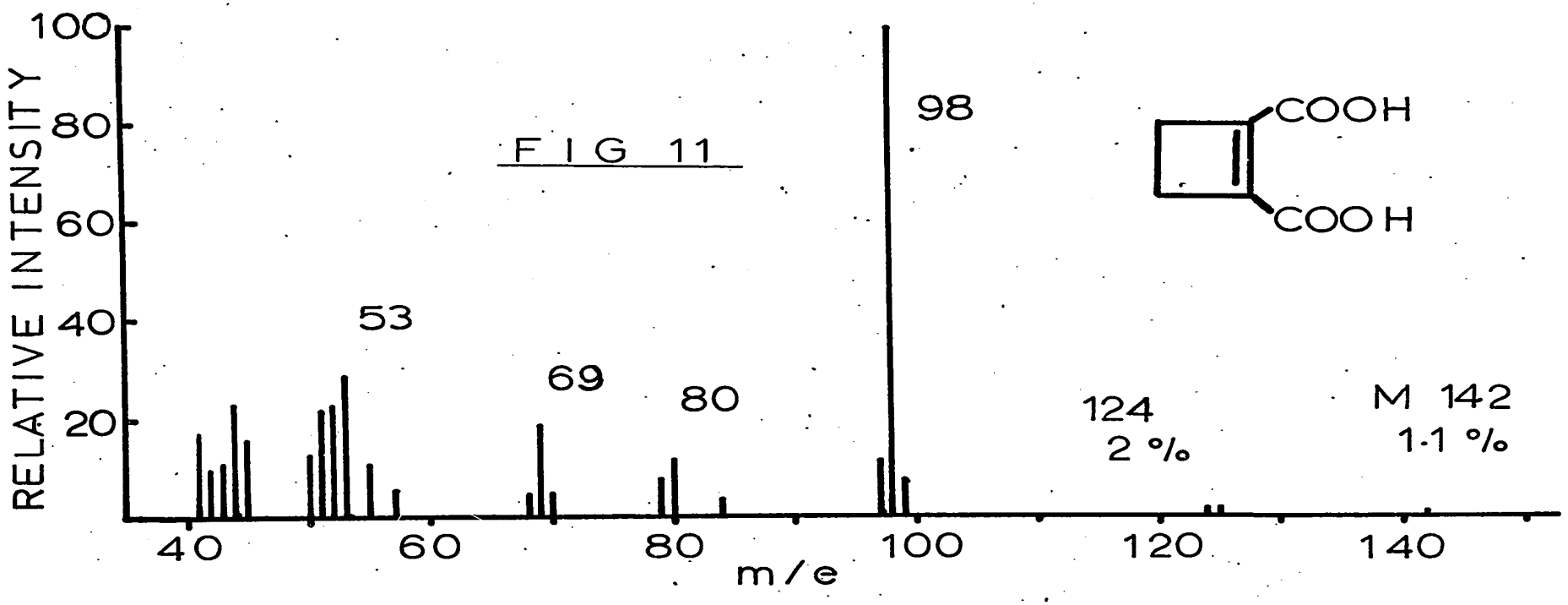
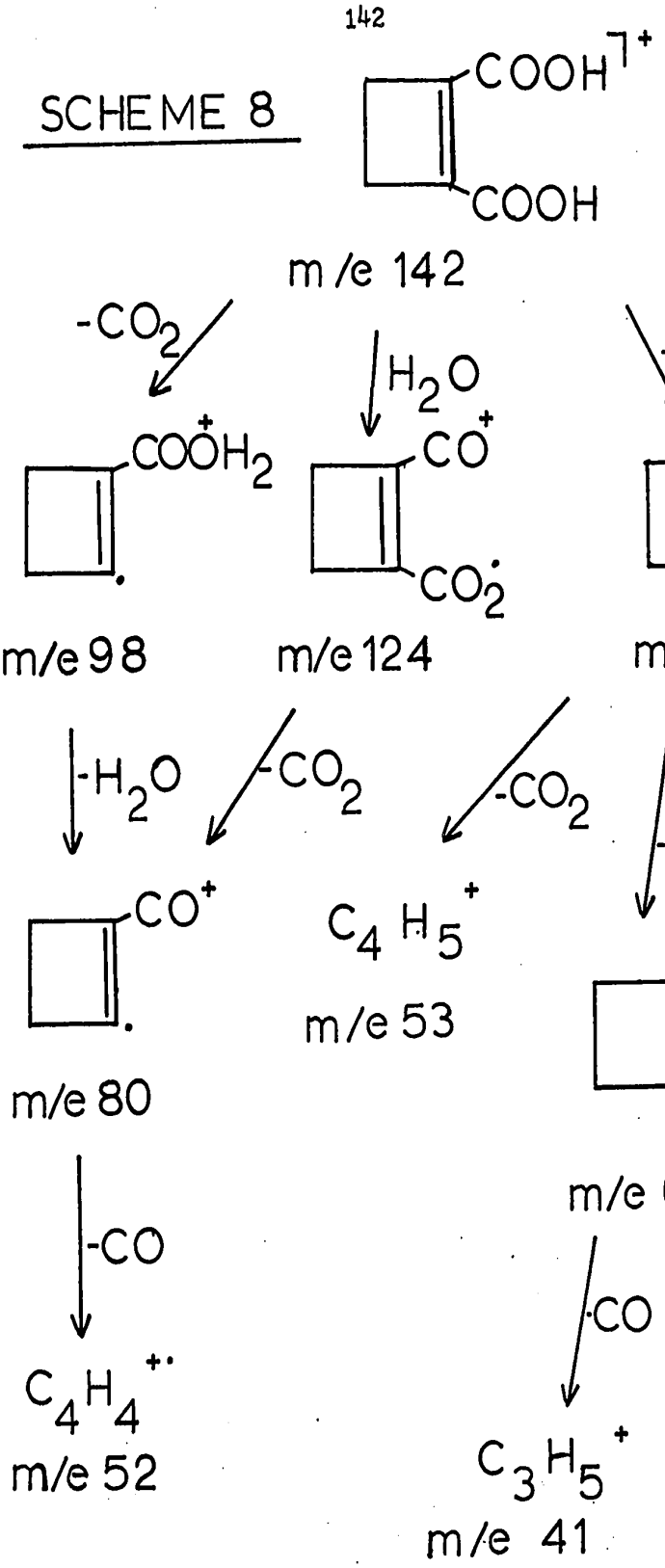

RELATIVE INTENSITY
100
80
60
40
20
40
60
80
100
120
140
m/e
53
69
80
98
124
2 %
M 142
1·1 %
COOH
COOH

FIG 11

SCHEME 8


COOH
COOH
m/e 142
-CO2
H2O
-COOH
COOH2
CO
CO2
COOH
m/e 98
m/e 124
m/e 97
-H2O
-CO2
-CO2
-CO
-H2O
CO
C4H5
C5H3O
m/e 53
m/e 79
m/e 80
OH
m/e 69
-CO
-CO
C4H4
C4H3
m/e 52
C3H5
m/e 41
m/e 51

base peak). Loss of COOH from the molecular ion is (probably) followed by hydroxyl migration to the adjacent site and loss of CO. A similar proposal was made in Chap 2 (p. 29) to account for loss of CO from (c) in Scheme 1.

There is no simple relationship between the ortho effect and ring size. The ortho effect operates in all three Δ^1 unsaturated acids described above. However, the fragmentation mechanisms for these three acids are not the same. This could be a reflection of the different stabilities of the fragment ions due to the different ring sizes.

(9) cis and trans 3,5-cyclohexadiene-1,2-dicarboxylic acids

These two acids exhibit mass spectra having sufficient differences to allow one to distinguish between them on this basis alone (figs 12 - 13). The trans isomer fragments via the loss of H_2O and COOH from the molecular ion (Scheme 9). Very little loss of CO_2 (3% b.p.) is observed. The water loss from the molecular ion is made up of 40% carboxyl-carboxyl interaction and 60% carboxyl-ring interaction. The 1-and 2-ring positions are involved in this latter loss because the molecular ion of the carboxyl deuterated-1,2-d_2 analogue loses D_2O exclusively. Two species of m/e 150 are thus generated and these both fragment by loss of CO to afford the m/e 122 species. In one instance the m/e 122 species is formally the molecular ion of benzoic acid and behaves as such , in the other, an isomeric species such as (b) that fragments by loss of CO_2 to yield m/e 79 is produced.

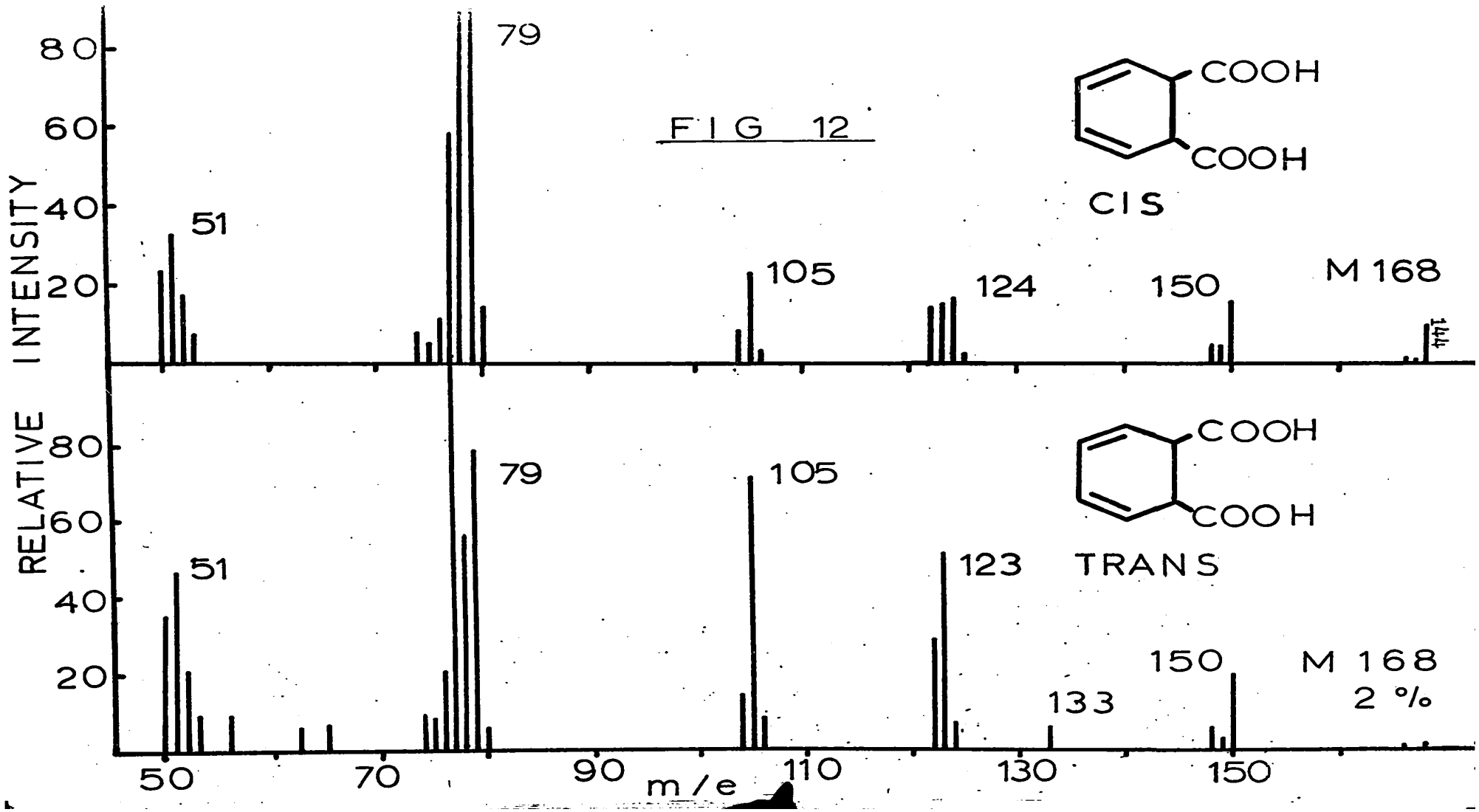

RELATIVE INTENSITY
80
60
40
20
79
51
105
124
150
M 168
COOH
COOH
CIS
79
105
51
123
TRANS
150
M 168
2 %
133
50
70
90
110
130
150
m/e

FIG 12

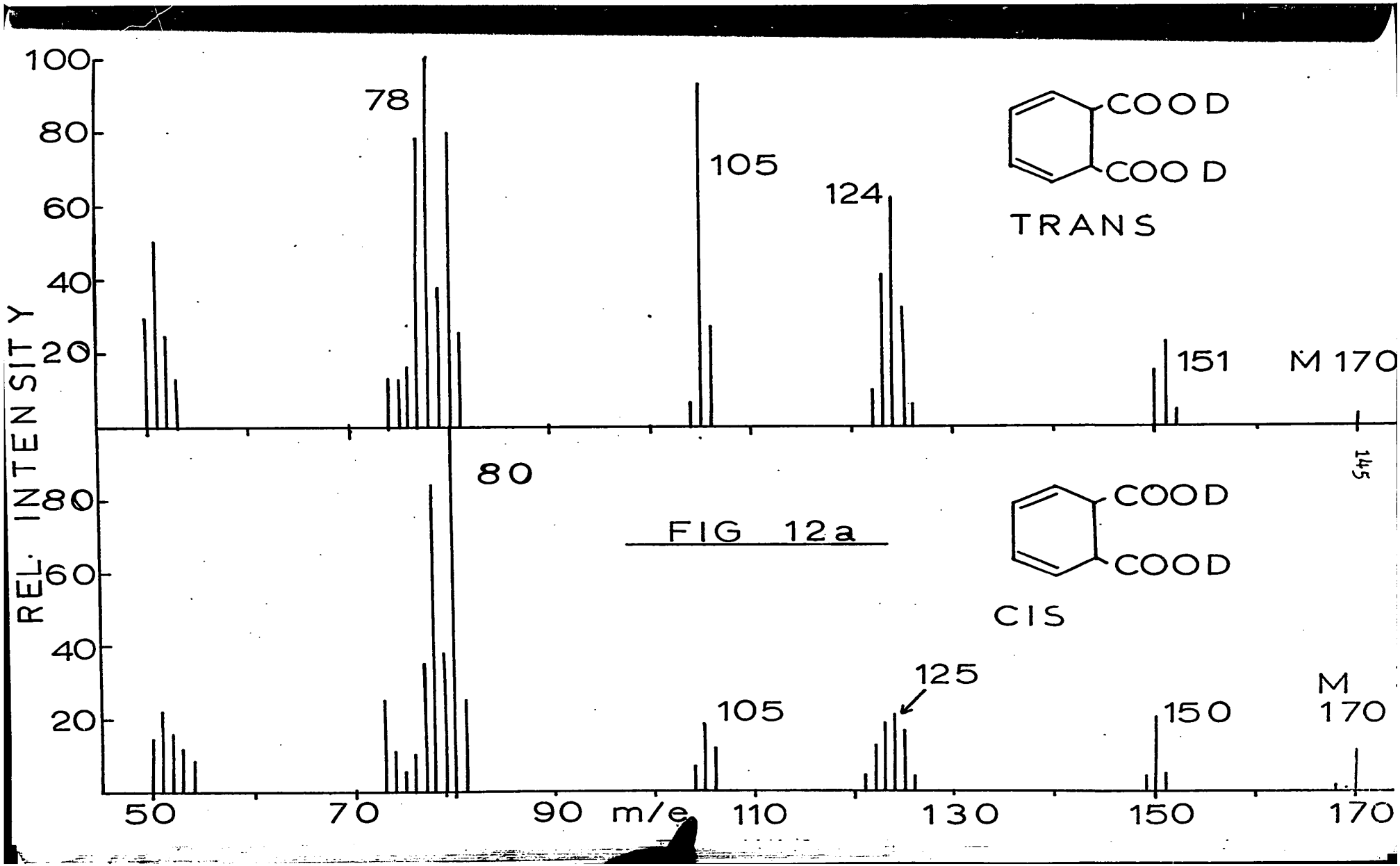

100
80
60
40
20
REL. INTENSITY
78
105
124
151
M 170
COOD
COOD
TRANS
80
145
80
60
40
20
125
105
150
M
170
COOD
COOD
CIS
50
70
90
m/e
110
130
150
170

FIG 12a

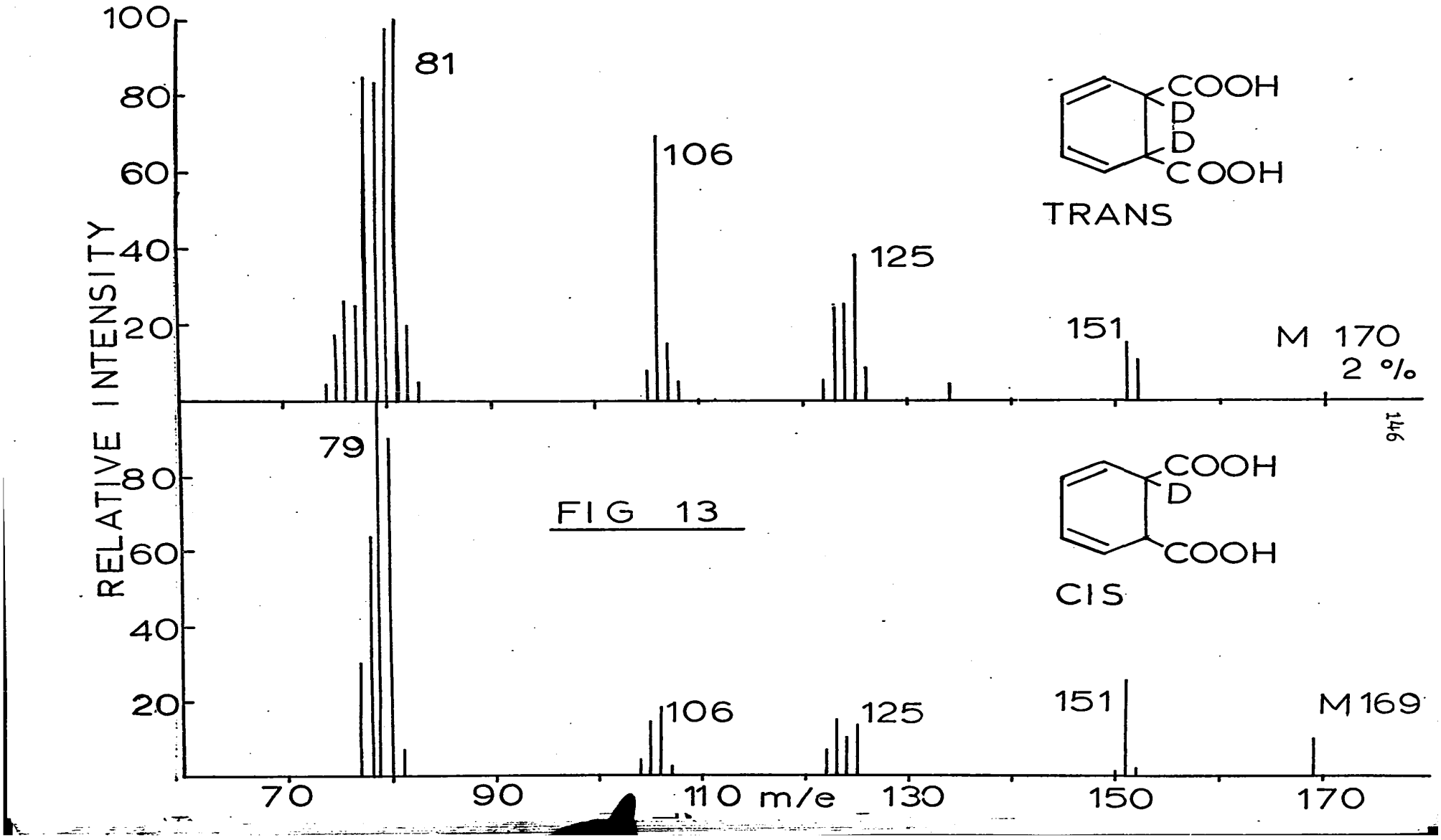
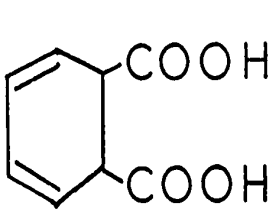

RELATIVE INTENSITY
100
80
60
40
20
81
106
125
151
M 170
2 %
COOH
D
D
COOH
TRANS
79
106
125
151
M 169
COOH
D
COOH
CIS
70
90
110 m/e
130
150
170

FIG 13

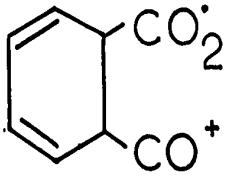
SCHEME 9

TRANS

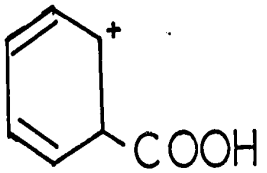


m/e 168 (170)

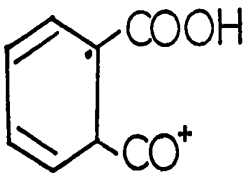
$-H_2O$ | $-COOH$ | $-H_2O$



m/e 150

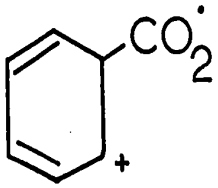


m/e 123 (124,125)



m/e 150 (151)

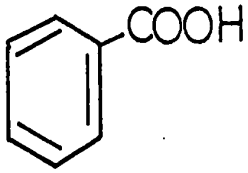
$-CO$ | $-CO$ | $-CO$



(b) m/e 122

$C_6H_7^+$

m/e 79 (80,81)



m/e 122 (123)

$-CO_2$ | $-H_2$ | $-OH$

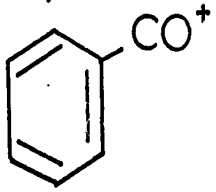
$C_6H_6^{+\cdot}$

m/e 78

$C_6H_5^+$

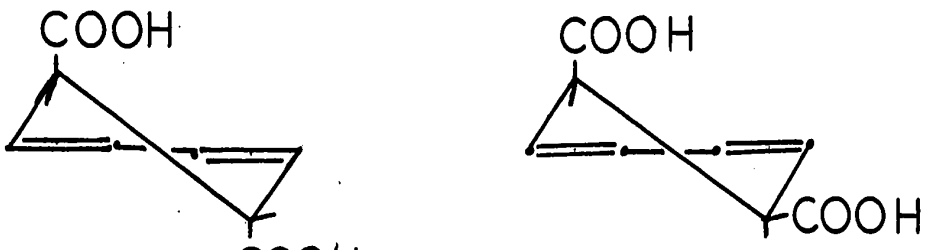
m/e 77 (78,79)

$-CO$



m/e 105 (105,106)

In contrast to the trans compound, the cis isomer fragments via three different routes. A major feature of this acid is the presence of an appreciable molecular ion peak (10% b.p.). The fragmentation discussed above for the trans acid is also observed in this acid, however, an important difference is the loss of CO_2 from the molecular ion (16% b.p.) (Scheme 10). In the carboxyl deuterated analogue, the ratio of $(M-D_2O)$: (M-HDO) is 9:1. Thus the operation of an "ortho effect" in this acid is significant; its presence in this isomer can be explained by the axial-equatorial arrangement of the carboxyl groups which permits interaction while the diaxial arrangement in the trans acid prevents interaction between the acid functions. In the trans acid, the diaxial arrangement is preferred over the diequatorial configuration because of the absence of any 1,3 hydrogen interactions; a similar argument was proposed to explain the preferred diaxial arrangement of the carboxyl groups in the cyclohexene-1,2-dicarboxylic acids discussed above.

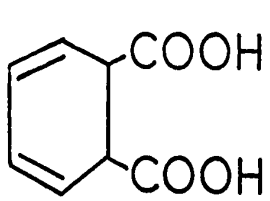


TRANS (diaxial) CIS

3,5-CYCLOHEXADIENE-1,2-DICARBOXYLIC ACID

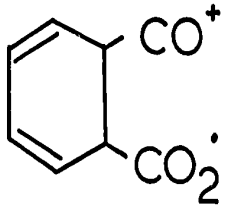
SCHEME 10

CIS

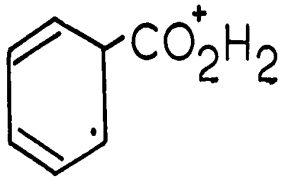


m/e 168 (170)

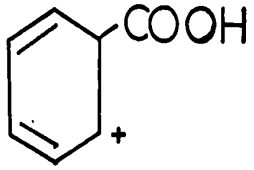
$-H_2O$ | $-CO_2$ | $-COOH$



m/e 150

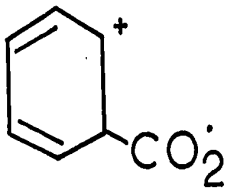


m/e 124 (126)

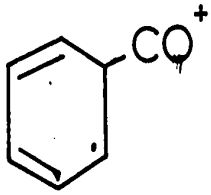


m/e 123 (124)

$-CO$ | $-H_2O$ | $-CO_2$



m/e 122



m/e 106

$C_6H_7^+$

m/e 79 (80)

$-CO_2$ | $-CO$ | $-H_2$

$C_6H_6^{+\cdot}$

m/e 78

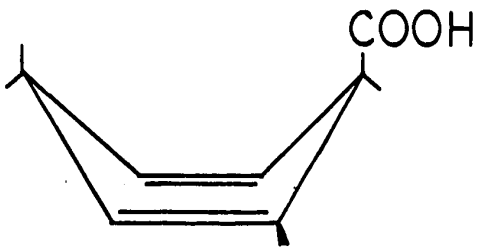
$C_6H_5^+$

m/e 77 (78)

If the trans acid were to assume a diequatorial arrangement, one would expect to observe the loss of CO_2 from the molecular ion because the dihedral angle and carboxyl-carboxyl distance would then be the same as in the cis isomer.

(10) 2,5-cyclohexadiene-1,2-dicarboxylic acid

The mass spectra of this acid and its deuterated analogues are shown as figs 14 and 15. Losses of H_2O, CO_2 and COOH from the molecular ion are observed (fig. 14). About 40% of the $(M-H_2O)$ daughter ions result from an "ortho effect" ; the remaining water loss involves abstraction of a hydrogen atom from either the 1 or 4 position because of the observed DHO loss from the $1,4\text{-}d_2$ analogue (fig 15).



2,5-CYCLOHEXADIENE-1,2-DICARBOXYLIC ACID

With the exception of the CO_2 loss this acid fragments essentially in the same manner as the trans 3,5-cyclohexadiene-1,2-dicarboxylic acid discussed above (Scheme 9), i.e. successive losses of H_2O and CO to generate a species which is formally the molecular ion of benzoic acid and the major loss of COOH

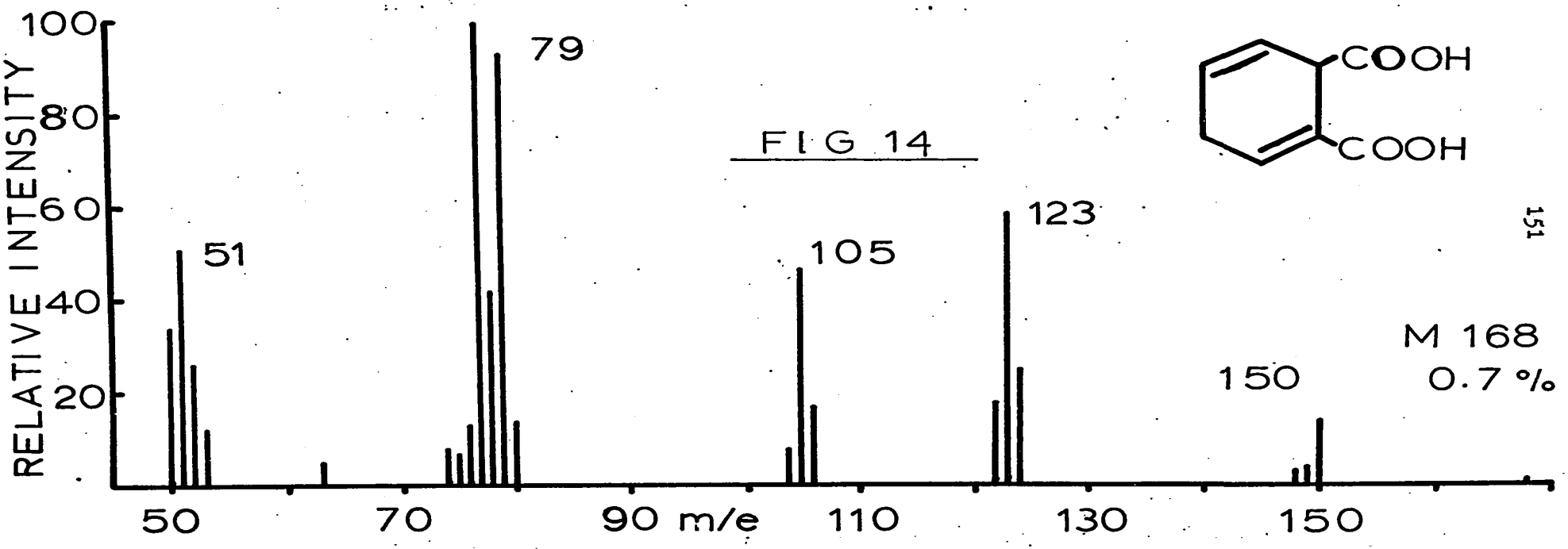

RELATIVE INTENSITY
100
80
60
40
20
51
79
105
123
150
M 168
0.7 %
50
70
90 m/e
110
130
150
COOH
COOH

FIG 14

from the molecular ion. This latter loss is accompanied by hydrogen scrambling because of the prominent M-COOH ion in the carboxyl deuterated analogue.

The conjugate losses of CO_2 and H_2O (due to an "ortho effect") are not the major fragmentation sequences thus indicating that, while the two acid functions can come together in this acid (possibly during interconversion of one boat form to another) they behave independently most of the time. A similar result was noted in 2-cyclohexene-1,2-dicarboxylic acid above.

(11) 2,6-cyclohexadiene-1,2-dicarboxylic acid

The mass spectrum of this acid is shown as fig 16. The fragmentation is very similar to that of the 2,5-cyclohexadiene acid discussed above. Indeed, their mass spectra exhibit the same peaks there only being some intensity differences. However, the operation of an "ortho effect" in the water loss is more prominent in this acid (2,6-) than in 2,5-cyclohexadiene 1,2-dicarboxylic acid. In 2,6-cyclohexadiene-1,2-dicarboxylic acid, daughter ions arising from a water loss involving both carboxyl hydrogen atoms constitute ~60% of the peaks due to water loss (compared with 40% in the 2,5-cyclohexadiene acid) and the loss of CO_2 is greater in the 2,6-acid than in the 2,5-acid. Thus in the 2,6-acid the arrangement of the carboxyl groups is more favourable for interaction than in the 2,5-acid. The loss of COOH from the molecular ion is also accompanied by hydrogen scrambling, there being an appreciable loss of COOH from the labeled analogue.

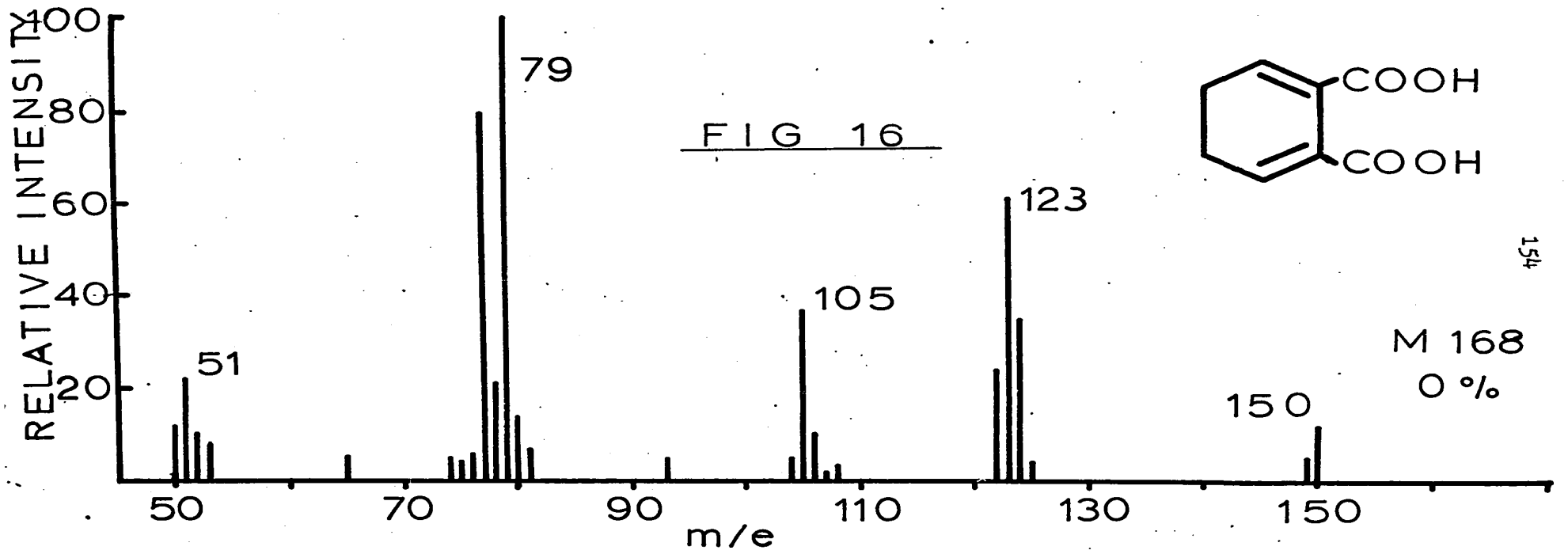

RELATIVE INTENSITY
100
80
60
40
20
79
51
105
123
150
50
70
90
110
130
150
m/e
COOH
COOH
M 168
0 %

FIG 16

It is surprising that the interaction between the carboxyl groups is not greater than observed because the carboxyl groups are virtually coplanar. It is possible, however, that appreciable dissociation occurs from a linear molecular ion following rupture of the 1-2 bond.

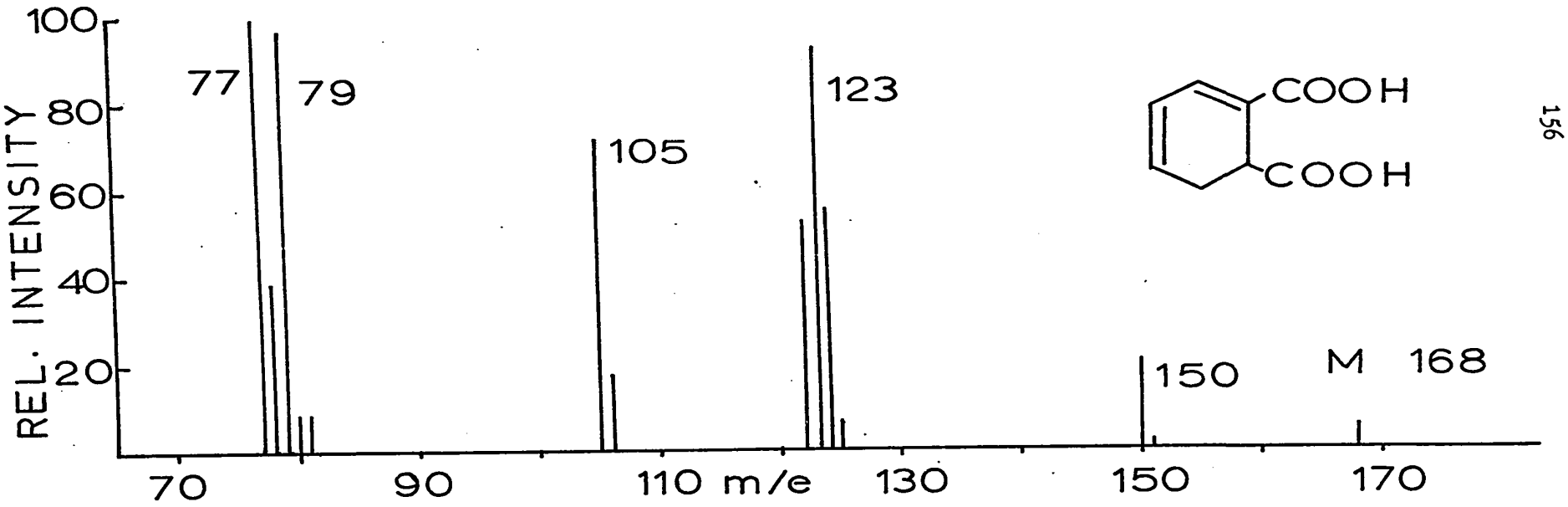
(12) 2,4-cyclohexadiene-1,2-dicarboxylic acid

The mass spectrum of this compound is shown as fig. 17. The fragmentation is essentially the same as that discussed for the above acid although there are quantitative differences in the relative intensity of some peaks. The molecular ion fragments by all three previously discussed losses. The loss of CO_2 is however quite intense here and 85% of the daughter ions resulting from water loss involve both carboxyl hydrogen atoms. Thus the "ortho effect" is quite prominent in the mass spectrum of this compound.

(13) 1,4-cyclohexadiene-1,2-dicarboxylic acid

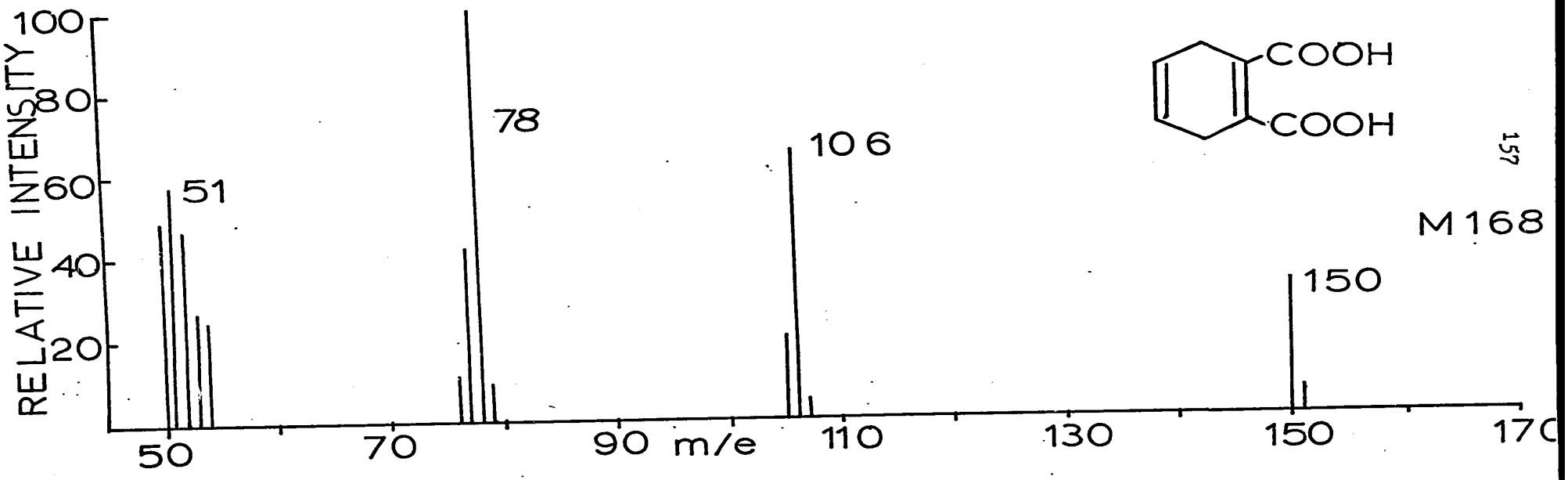
The mass spectrum of this compound is shown as fig. 18. The fragmentation of this acid (Scheme 11) is appreciably different from that of its isomers. Indeed, this acid fragments by the successive losses of H_2O, CO_2 and CO ; the first loss being initiated solely by an "ortho effect". This result is not unexpected ; the presence of the double bond in the 1-position holds the carboxyl groups sufficiently close to one another for interaction to take place. Similar results were obtained in the Δ^1 - acids above.

FIG 17

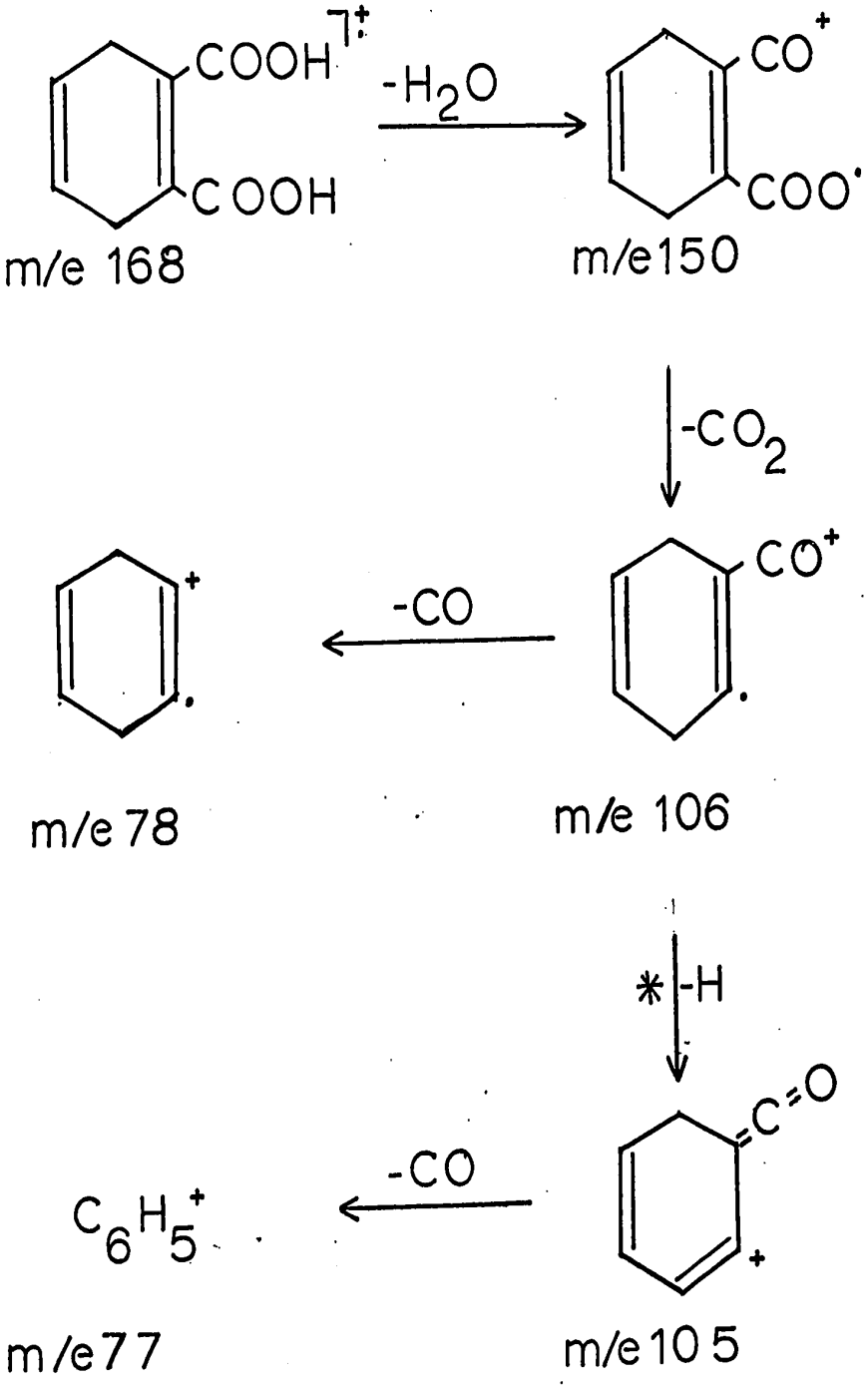

100
80
60
40
20
REL. INTENSITY
77
79
105
123
150
M 168
70
90
110 m/e
130
150
170
COOH
COOH

156

FIG 18


RELATIVE INTENSITY
100
80
60
40
20
51
78
106
150
157
M 168
COOH
COOH
50
70
90 m/e
110
130
150
170

SCHEME 11


COOH
COOH
-H2O
CO+
COO·
m/e 168
m/e150
-CO2
CO+
-CO
m/e 78
m/e 106
*
-H
C=O
-CO
C6H5+
m/e77
m/e105

Conclusions

The "ortho effect" in cyclic 1,2-dicarboxylic acids is not only dependent on the relationship between the carboxyl groups but also on the relationship between the carboxyl group and the ring. Indeed, in those acids in whose ground state geometries interaction between the carboxyl group and the ring is possible, the major fragmentation sequence is initiated by abstraction of a ring hydrogen atom and loss of water from the molecular ion. Thus in the mass spectra of cis cyclohexane-1,2-dicarboxylic acid, and the cyclohexene-1,2-dicarboxylic acids (except the 1-ene) the "ortho effect" is either negligible or absent. In those acids where interaction between the carboxyl group and the ring is not feasible and where interaction of the acid functions is possible, the ortho effect is prominent. Thus, in the mass spectra of trans cyclohexane-1,2-dicarboxylic acid, cis cyclobutane-1,2-dicarboxylic acid, the Δ^1 unsaturated acids, cis 3,5, 2,4-, and 2,6-cyclohexadiene-1,2-dicarboxylic acids fragmentations resulting from an "ortho effect" are significant.

It should be noted that where an acid can exist in two conformations of similar stability (i.e. can convert from one form to another by ring inversion) the "ortho effect" is negligible and the dissociation due to carboxyl-ring interactions are dominant in the mass spectra. A possible explanation for this feature is that the interaction of the carboxyl group and the ring occurs during the interconversion when the ring structures are more flexible. The presence of the "boat form" of the cyclohexane and

cyclohexene rings cannot be dismissed.

In contrast, where only one form of the acid is possible (or highly favoured due to steric interactions in its other forms) and the carboxyl groups can interact the "ortho effect" is more prominent. This is the case in the Δ^1 unsaturated acids, the cyclohexadiene-1,2-dicarboxylic acids (except the trans 3,5-isomer) and trans cyclohexane-1,2-dicarboxylic acid.

Thus, for the operation of an "ortho effect" in the mass spectra of cyclic 1,2-dicarboxylic acids, the important feature is the flexibility of the carbon skeleton. In highly flexible systems, the carboxyl group will preferentially interact with the ring. Where this interaction is hindered or impossible, the carboxyl groups may interact (if it is possible). Examples of this are found in the mass spectra of cis cyclohexane-1,2-dicarboxylic acid and cis 3,5-cyclohexadiene-1,2-dicarboxylic acid whose carboxyl groups geometries are closely similar; whereas in the highly flexible cyclohexane acid the "ortho effect" is negligible, in the relatively rigid cyclohexadiene acid it is prominent. We thus conclude that the interaction between carboxyl groups is not a highly favoured one, but that it occurs when other interactions are absent or hindered.

The operation of an "ortho effect" in the mass spectra of 1,2-dicarboxylic acids leads to the losses of either CO_2 or H_2O from the molecular ion. In most of the acids discussed, where there was an "ortho effect", losses of both H_2O and CO_2 were observed. In some acids, however, a peak due to one of

these losses is more prominent than that due to the other. Indeed in two cases only one loss due to an "ortho effect" was observed (the molecular ion of 1-cyclohexene-1,2-dicarboxylic acid loses only H_2O while that of 1-cyclobutene-1,2-dicarboxylic acid only CO_2). One cannot, however, conclude that one particular fragmentation route is preferred over the other on the sole basis of the heights of the daughter ion peaks because the abundance of a fragment ion is dependent not only on its rate of formation from its precursor but also on its rate of further dissociation. Thus, the abundance of a fragment ion peak depends on both the number of molecular ions that dissociate in that fashion and the stability of the resulting ion to further dissociation. Present lack of knowledge of ion stabilities in these compounds precludes further speculation.

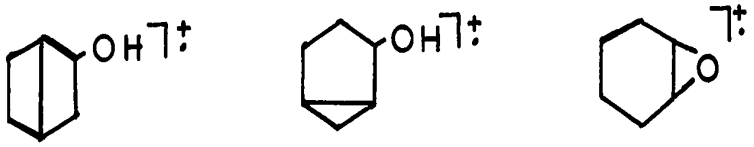
CHAPTER 6

Water Loss from the Molecular Ion of 1,2-cyclohexanediols

The electron impact fragmentation of 1,2-cyclohexanediols, aided by the appropriate deuterium analogues, has recently been investigated by Buchs[28] and Strong and Djerassi[29]. The deuterated derivatives revealed that the dissociation was complex. Indeed, they observed three modes of water loss (H_2O, HDO and D_2O) from the molecular ion of the hydroxyl labeled analogue. Buchs was unable to formulate a fragmentation mechanism consistent with all his results when he compared the relative heights of fragment ion peaks in the deuterium labeled analogues. He stated that "even though we possessed a very complete series" (thirteen)" of deuterated derivatives of cis and trans 1,2-cyclohexanediols we think that it would be hazardous to attempt to establish a detailed fragmentation scheme by assigning a definite structure for

each ion". He did, however, conclude that water loss occurred via three mechanisms: (i) by interaction between the two hydroxyl groups, (ii) by interaction between a hydroxyl group and a hydrogen atom in the 4 or 5 position, (iii) without participation of the hydroxyl hydrogen atoms. This conclusion was based on the observed losses of D_2O, DHO and H_2O from the O-d_2 analogue, of H_2O from the 1,3,3-d_3 analogue, of HDO and H_2O from the 4-d_1 analogue and of D_2O, DHO and H_2O from the 3,3,5,5-d_4 analogue.

Sample and Djerassi[29] likewise suggested that at least four processes (distinguishing ii) above as two) were involved in the loss of water from the molecular ion. They proposed specific ion structures (a, b and c) shown below as representative of the M-H_2O species. It was suggested that (a)



(a) (b) (c)

and (b) were produced by mechanism (ii) while (c) arose by mechanism (i). It was further suggested that (iii) possibly involved the intermediate formation of an aldehydic ion by analogy with the observed water loss from hexanal[30]. Both groups of workers attempted to explain the fragmentation of

the molecular ion by water loss in terms of competing specific interactions within the molecular ion.

An equally puzzling problem is that of the water loss from cyclohexanol. In the O-d_1 analogue appreciable loss of H_2O (17% of total water loss) is observed in addition to the expected loss of HDO[30]. Indeed in the earlier study of this molecule it was found that 17% of the water loss involved only the hydrogen atoms from the 3,4 or 5 carbon positions. The remaining water loss consisted of the abstraction of a hydrogen atom from the 3, 4 or 5 carbon positions by the intact hydroxyl function. Green et al.[31] showed that this latter mode of water loss occurred by two distinct processes ; one the cis-stereospecific abstraction of a hydrogen atom from the 4 position, the other a non stereospecific 1, 3 elimination. It was further postulated that the ring opening occured prior to the 1,3 elimination reaction ; cleavage of the 1,2 or 1,6 bond was suggested. They further concluded that scrambling of the hydrogen atoms did not intervene in the dissociation of this molecule. This conclusion had also been reached by a group of earlier workers[32].

Williams et al.[33] also studied this system but they were unable to reach a definite conclusion. They confirmed the operation of the cis-1,4 elimination reaction but were unable to distinguish between a competing direct 1,2 or 1,3 elimination and a scrambling of the C-3 (C-5) and C-2 (C-4) hydrogen atoms into the hydroxyl and cis C-4 positions followed by a

cis-1,4 elimination. These authors noted that the loss of H_2O from the 0-d_1 derivative and of D_2O and DHO from the 3, 3,5,5d_4 derivatives were important. It is difficult to account for these latter losses other than by invoking hydrogen scrambling, i.e. at least a portion of the fragmentation must involve hydrogen scrambling.

In 1,2-cyclohexanediol the loss of water is accompanied by a metastable peak and the relative heights of the metastable and fragment peak in some deuterium labeled analogues will be compared to see whether hydrogen scrambling precedes fragmentation. In benzoic acid (Chap 3) such a comparison revealed that the two ortho hydrogen atoms equilibrated with the carboxyl hydrogen atom. The use of the relative heights of metastable peaks in conjunction with isotopic labeling is useful in the investigation of fragmentations wherein unexpected retention of label is observed in deuterated derivatives. It is assumed in such experiments that the relative intensities of a group of metastable peaks are directly proportional to the relative abundances of their precursor ions. This is valid, so long as the process which produces the group of metastables is the same for each member. Also, if the relative abundances of the metastables and the peaks are to be compared successfully, any scrambling process which occurs in the molecular ions that dissociate in the ion source must also be operative in those that dissociate in the field free region, i.e. the degree of hydrogen scrambling must be the same in

both instances.

To obtain the results described below we have used a modification of Jenning's[8] method of metastable defocused (Chap 1 p. 9). We have scanned magnetically at a series of constant electrostatic sector voltages varied by 0.1 V intervals, such that each metastable was examined in narrow sections thus enabling virtually complete resolution of metastables which otherwise would have overlapped each other. Provided that the energy profile of the ion beam exiting the ion source is both narrow and uniform, graphical summation of the sections produces the total metastable and the results of such summations are presented in the figures described below.

Results

The mass spectrum of 1,2-cyclohexane diol is presented as fig. 1. The initial fragmentation is the loss of water from the molecular ion to generate the m/e 98 ion. The mechanism for this process is important because the M - H_2O species is the precursor of many of the other ions in the mass spectrum and knowledge of its structure will greatly assist the analysis of these other dissociations.

Our results for loss of H_2O, HDO and D_2O obtained by comparing fragment peak heights in the mass spectrum of cis-1,2-cyclohexanediol-O-d_2(1) agree closely with those of Strong and Djerassi. We also observe that the cis and trans isomers yield identical spectra. The separated, defocused metastable peaks for water loss from 1 and cis-1,2-cyclohexanediol-3,3,5,5-d_4(2) were of identical shape and those for (2) are shown

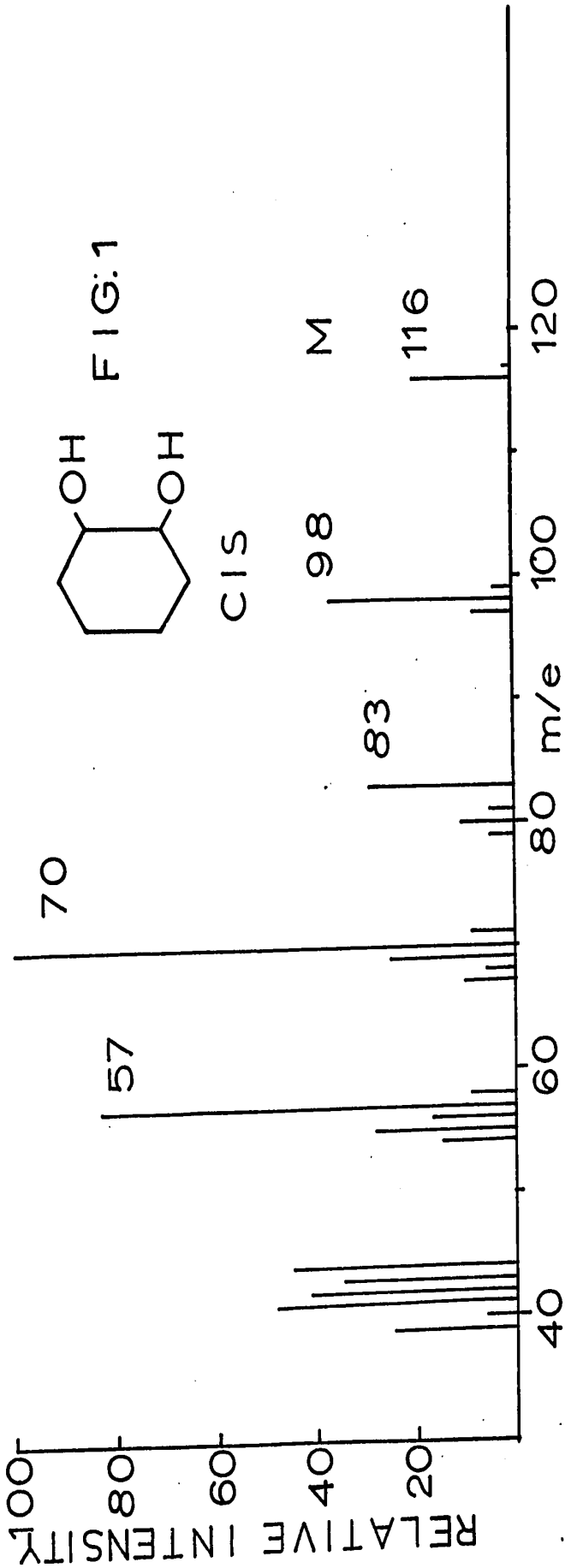


FIG:1
OH
OH
CIS
M
116
98
83
70
57
RELATIVE INTENSITY
100
80
60
40
20
40
60
80
100
120
m/e

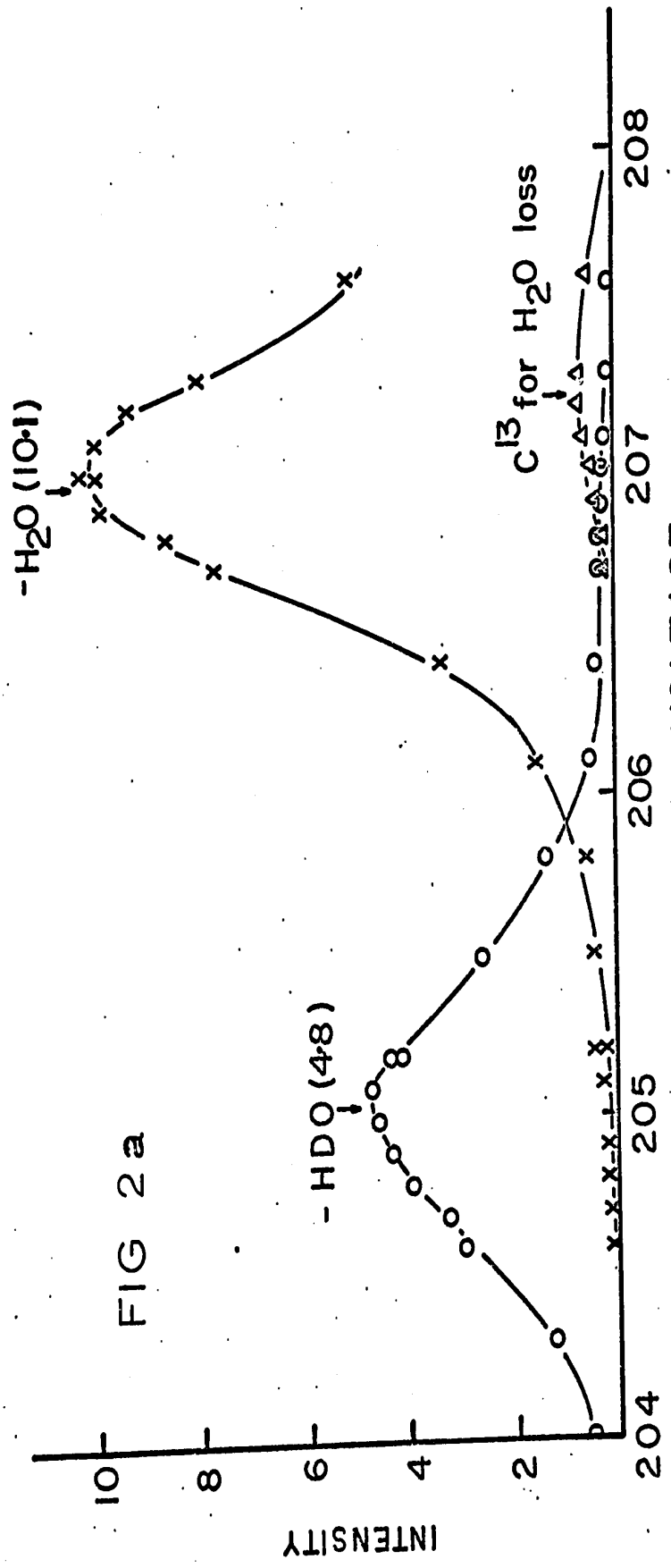

INTENSITY
10
8
6
4
2
204
205
206
207
208
SECTOR VOLTAGE
-H2O (10-1)
-HDO (48)
C13 for H2O loss

FIG 2a

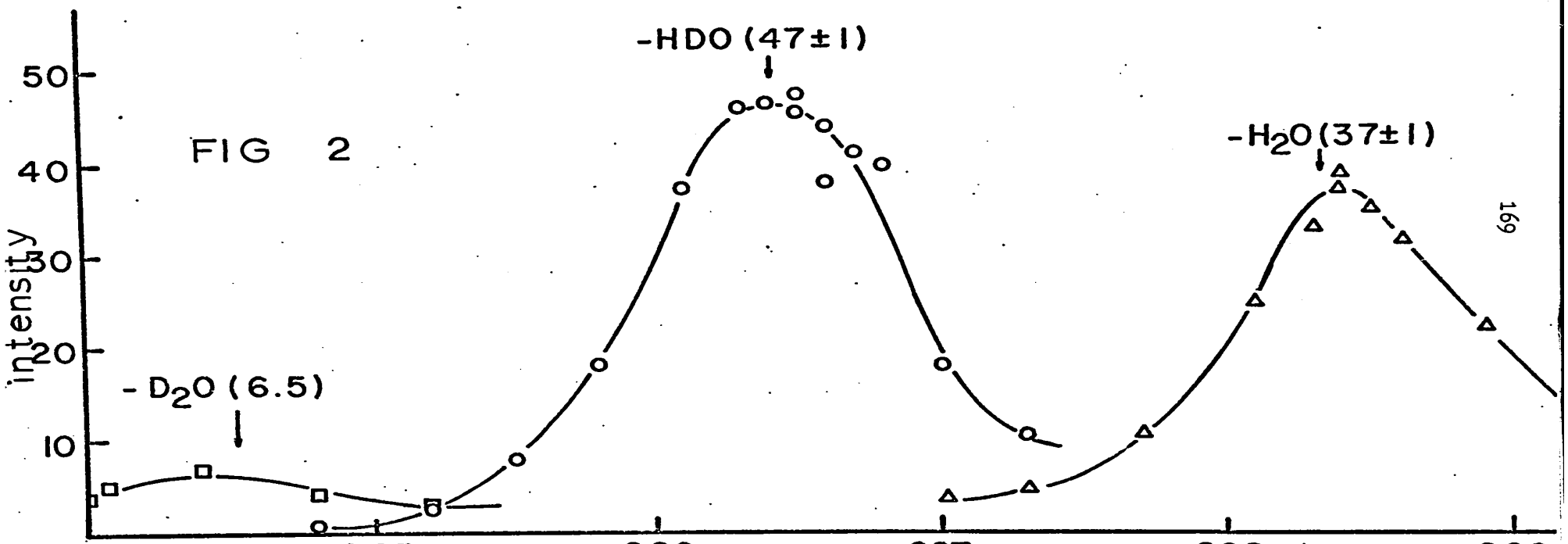
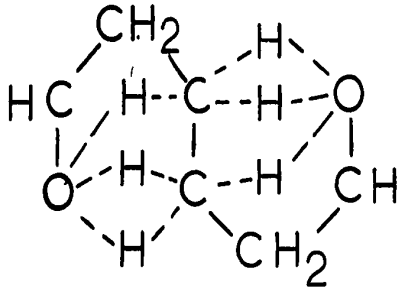

-HDO (47±1)
-H2O (37±1)
-D2O (6.5)
50
40
30
20
10
intensity
204
205
206
207
208
209
SECTOR VOLTAGE

FIG 2

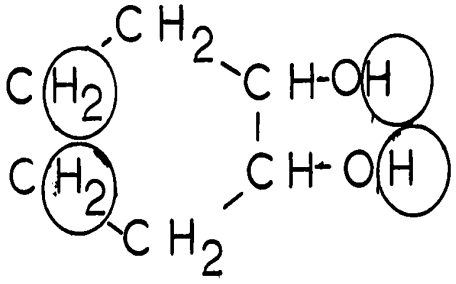
in Fig. 2. Their heights are in the approximate ratio 6:8:1 for loss of H_2O, HDO and D_2O respectively. Fig. 2a shows the metastable peaks for water loss (HDO and H_2O) from trans-1,2-cyclohexanediol-4-d_1 (3); these are in the ratio 2:1 for H_2O and HDO respectively. In our experience, such sets of metastable peaks for the loss of labeled neutral fragments have the same width at half height and thus their heights may be taken as a proper measure of their relative abundances (given an energetically homogeneous ion beam).

Although it is formally possible that the observed metastables are unrelated and/or overlapping sets, it is probable that a single process gives rise to the above-mentioned metastables and that the mechanism involves "equilibration" or loss of distinguishability of four hydrogen and two deuterium atoms in 1 and 2 and 5 hydrogen and 1 deuterium atoms in 3. From the previous work[29] hydrogen atoms at the 4 and 5 ring positions have been shown to be involved in water loss while those in the 3 position are not. We suggest that this equilibration may take place via a symmetrical species(d) such as that shown below, in which the 1,2 carbon bond is



(d)

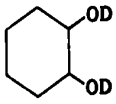
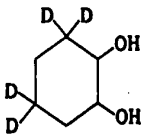
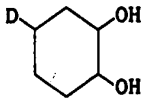
broken thus allowing independent interaction of the hydroxyl groups with the 4 and 5 ring methylenes. The dotted lines are used to indicate possible and not partial bonding. In a structure such as(d)any of the six hydrogen atoms may be bonded to either a C-4 or C-5 carbon or oxygen atom and thus have become indistinguishable. The location of the oxygen atoms is indeterminate but positioning them directly above and below the 4-5 carbon bond would allow their interaction with any of the six hydrogen atoms. Such a structural representation is compatible with the experimental observations. Since structural representation of such ions must be highly speculative, we propose that in fragmentation schemes, atoms which have become indistinguishable and are randomly lost in a neutral or charged fragment be ringed. As an example the present system is illustrated below:



The above results indicate that some of the water lost from the molecular ion contains randomly selected hydrogen atoms; if this were the only mode of water loss then the frag-

ment ion peaks will be in the same ratio as the metastables, provided that those ions which fragment in the source with loss of water, are, before dissociation, as "scrambled" as those which dissociate in the first field-free region. This is not so; the metastable peaks are not in the same ratio as the fragment ion peaks. For example, the relative peak heights corrected for ^{13}C natural abundance and $(M-H_2O-H)$ for water loss from 1 are in the ratio 35:49:16 for loss of H_2O, HDO and D_2O respectviely, in good agreement with the previous work . If it is assumed that H_2O loss (35 units) from 1 can only occur via a "scrambling" mechanism then on the basis of the relative heights of the metastables, 88% of the total water loss occurs via this mechanism. The residual water loss is D_2O (10 units) and it could arise from the simple hydroxyl-hydroxyl interaction noted previously[28] . This discrepancy is not due to partial "scrambling" in those ions giving rise to the normal spectrum because such an effect would be expected to yield an excess of (M-HDO) fragment ions. Thus 98% of the water loss can be accounted for by the above two mechanism. Using this result and a similar calculation it should be possible also to correlate the relative peak and metastable heights in 2 and 3. The results of the calculations are presented in Table 1. They show that when correction is made for the simple mechanism (10%) the relative peak heights are in good accord with the relative metastable heights. It should be stressed that these calculations do not allow evaluation of the relative abundances of the molecular ions which are dissociating by the two mechanistically distinguishable

TABLE 1.
(All peak heights normalized to 100 units)

M	$M - H_2O$			$M - HDO$			$M - D_2O$		
	Peak heights		Meta-stables	Peak heights		Meta-stables	Peak heights		Meta-stables
	Found*	Calcd.†		Found*	Calcd.†		Found*	Calcd†	
	35	40	40	49	53	53.3	16	7	6.7
	49	42	40	45	51	53.3	6	7	6.7
	71	67	66.6	29	33	33.3	—	—	—

*Peaks are corrected for ^{13}C and M-H_2O-H (*m/e* 97) in 1,2-cyclohexanediol ~ 20%.
†Corrected for 12% water loss by mechanisms other than equilibrating one.

pathways.

Conclusion

Whereas previous workers needed to invoke three or four mechanisms to account adequately for the water loss from 1,2-cyclohexanediol, our investigation reveals that this fragmentation can better be explained by two mechanisms, one involving a direct interaction between hydroxyl groups, the other a complex interaction resulting in the loss of distinguishability of six hydrogen atoms (the four C-4 and C-5 methylene hydrogens and the two hydroxyl hydrogens) which are then randomly lost in the eliminated water molecule.

At present the events which lead to random losses of hydrogen atoms in ion fragmentations are poorly understood but the frequent appearance of the appropriate metastable peaks indicates that the necessary rearrangements require an appreciable time to take place. It is still uncertain as to whether "scrambling" is a time and/or energy dependent effect or whether it is always complete before the ion dissociates. Some recent evidence[34] indicates that the former is the case, particularly at low electron energies, but other results are equivocal[35].

CHAPTER 7

Conclusions

In the above study, three different "ortho effects" were encountered ; these are,

1) transfer of a hydrogen atom between ortho substituents,
2) migration of part of a substituent to the ortho site,
3) mixing of hydrogen atoms from the substitutent group and hydrogen atoms in the ortho positions.

In the first case (1 above), bicyclic intermediates were necessary to adequately describe the behaviour of the rearranged molecular or fragment ions in some compounds, indicating a greater participation of the ortho substituent than simple hydrogen atom transfer (Chap. 2). The second mechanism (2 above) is proposed in the fragmentations of nitro compounds wherein an ortho site has become vacant (Chap. 2) , of benzoic acid (as a minor route) (Chapter 3) and of some cyclic dicarboxylic acids

(Chap. 5). The third mechanism (3 above) was observed in the dissociation sequences of benzoic acid (Chap. 3) and 1-cyclopentene-1,2-dicarboxylic acid (Chap. 5)

It was proven that the fragmentation mechanism of nitrobenzene by NO loss involves "in situ" nitro to nitrite conversion without participation of the ortho sites. However, nitro to nitrite isomerization was found to be aided by some ortho substituents in ortho substituted nitro arenes (Chap. 2).

The hydrogen atom scrambling process operative in benzoic acid yields, upon hydroxyl loss, a species whose characteristics appear to be different from those of the benzoyl cation generated from an unrearranged molecular ion. Participation of ortho-hydrogen atoms was minimal in the fragmentation of the thio- and amide analogues. In the water loss from the molecular ion of 1-cyclopentene-1,2-dicarboxylic acid, hydrogen atoms from a carboxyl group and a ring methylene position were found to be indistinguishable.

The "ortho effect" observed in some 1,2-dicarboxylic acids in which the carboxyl groups were joined by doubly bound carbon atoms (Chap. 4) was also seen in cyclic 1,2-dicarboxylic acids where the relatively rigid ring structures holds the carboxyl functions in close proximity (Chap. 5). Where the ring structures are more flexible, the "ortho effect" is negligible and carboxyl-ring methylene interaction predominates.

In 1,2-cyclohexanediol (Chap. 6), the mechanism of water loss from the molecular ion was shown to involve hydrogen atom

"scrambling" in addition to a minor direct interaction between hydroxyl groups.

Appendix I

Experimental

All mass spectra were obtained using an Hitachi RMU-6D mass spectrometer. Liquids were inserted via the all glass inlet system while solids were inserted via the direct inlet probe at a sufficiently high source temperature to allow volatilization of the sample without thermal degradation. The mass spectra were run at an electron energy of 70eV unless otherwise stated. Metastable defocusing was achieved using a modified Hitachi RMU-7.

Deuterium Labeling

Whenever materials labeled with deuterium in an easily exchangeable position was analyzed, the instrument was previously "deuterated" by insertion of D_2O through the liquid inlet system prior to and during analysis. This minimized exchange within the instrument and thus assured high percentage labeling.

Technique 1 - the sample was dissolved in D_2O (warming if required) and the solvent subsequently removed under vacuum. Good labeling was usually obtained after three to four such treatments.

Technique 2 - The sample was placed in a direct inlet sample holder, fixed to a vacuum line and evacuated. About 15 c.c. DCl was allowed into the system and condensed onto the sample by freezing in liquid nitrogen. Upon slow warming the DCl is evaporated.

Sample purity

All prepared samples were purified, either by recrystallization (solids), or by distillation (liquids) according to the procedures reported in the literature reference describing the particular preparation. The purity of a prepared sample was determined from its melting point and mass spectrum. A sharp melting point, that agreed with that reported in the literature, and the absence of unexplainable peaks in the mass spectrum of the compound was taken as evidence that the compound was pure. Where cis and trans forms of a dicarboxylic acid were possible, the configuration was determined from the presence(or absence) of the M-CO_2 peak in the mass spectrum of the cyclohexane-1,2-dicarboxylic acid that results from the hydrogenation of the dicarboxylic acid under investigation. In order to prevent thermal degradation of a sample in the mass spectrometer, all compounds were analysed in a "cold" source with a probe temperature no higher than that required to volatilize the sample. Where thermal degradation was suspected, a temperature study, wherein the mass spectrum of the compound was measured at a series of increasing temperatures, was conducted. An increase in background CO_2 or H_2O peaks is proof that thermal reactions have occurred. If background peaks remain constant, no degradation has taken place.

The purity of labeled compounds (deuterium, ^{13}C and ^{18}O) was determined from the shift in the parent molecular or other suitable fragment ion peaks (where the molecular ion peak is absent).

List of compounds analyzed

1. ($1\text{-}^{13}C$)- nitrobenzene: prepared from ($1\text{-}^{13}C$)-benzoic acid by procedures of Bachmann and Goldmacher[36] (conversion into aniline) and of Emmons[37] (oxidation to nitrobenzene
2. ($1\text{-}^{13}C$)-p-nitroaniline: prepared from ($1\text{-}^{13}C$)-aniline[38]
3. o-nitrobenzoic acid: Matheson Coleman & Bell, 6434 x 551
4. o-nitrobenzoic acid-carboxyl-d_1: Technique 1
5. o-nitrobenzoic acid-carboxyl-^{18}O: prepared from o-nitrobenzyl chloride by hydrolysis with $Na^{18}OH$ in a sealed tube at 100°C for one hour
6. o-nitroanisole: J.T. Baker Chemical Co R 875
7. o-nitroanisole-methoxy-d_3: prepared from o-nitrophenol by reaction with CD_3I[39]
8. o-nitrobenzaldehyde: Matheson Coleman and Bell 6689 NX512
9. o-nitrosobenzoic acid: prepared by the photochemical reaction of o-nitrobenzaldehyde[40]
10. o-nitrobenzamide: prepared from o-nitrobenzoyl chloride by action of NH_3
11. o-nitrobenzamide-N-d_2: Technique 2
12. o-nitrobenzyl alcohol: Aldrich Chem. Co. N1280
13. o-nitrobenzyl alcohol-O-d_1: Technique 1

14. o-nitrobenzyl alcohol-^{18}O: prepared from α-bromonitrotoluene by hydrolysis with $Na^{18}OH$ at $60^{\circ}C$ for 1 hr in a sealed tube.

15. o-nitrobenzyl alcohol- -d : prepared from o-nitrobenzaldehyde by reduction with sodium boro-deuteride in water.

16. o-nitrosobenzaldehyde: from o-nitrobenzyl alcohol[41]

17. 2,4-dinitrophenylhydrazine: Matheson Coleman and Bell 6129

18. 2,4-dinitrophenylhydrazine-N_1N-d_3: Technique 2

19. p-nitrophenylhydrazine: Eastman Kodak 691

20. p-nitrophenylhydrazine-N,N-d_3: Technique 2

21. o-nitrophenylhydrazine: Aldrich Chem Co, N 2158-8

22. o-nitrophenylhydrazine-N,N-d_3: Technique 2

23. benzoic acid: Aldrich Chem Co, 10, 947-9

24. benzoic acid-carboxyl-d: Technique 1

25. benzoic acid -1-^{13}C- : Merck, Sharpe and Dohme MS917

26. phthalic acid: Eastman Organic Chemicals, 454

27. phthalic acid carboxyl-d_2: Technique 1

28. phthalaldehydic acid: Aldrich Chem. Co, 11,601-7

29. phthalaldehydic acid - carboxyl-d_1: Technique 1

30. thiobenzoic acid: Aldrich Chem. Co , T 2820-7

31. benzamide: Aldrich Chem. Co, 13,582-8

32. benzamide-N-d_2: Technique 2

33. thiobenzamide: Aldrich Chem Co 14,822-9

34. thiobenzamide-N-d : Technique 2

35. maleic acid: Aldrich Chem. Co Inc, M 15-3

36. maleic acid-2,3-d_2: by oxidation of C_6D_6 over V_2O_5/MoO_3

37. fumaric acid: Aldrich Chem. Co. Inc, 12,842-2

38. fumaric acid-2,3-d_2: by Atkinson's method[42]

39. citraconic acid: Aldrich Chem. Co. Inc, C8260-4

40. itaconic acid: Aldrich Chem Co. Inc, 1-2920-4

41. mesaconic acid: Aldrich Chem. Co. Inc, 13,104-0

42. cis-cyclohexane-1,2-dicarboxylic acid: by hydrogenation of cis-4-cyclohexene 1,2-dicarboxylic acid in C_2H_5OH over PtO_2

43. cis-cyclohexane-1,2-dicarboxylic acid carboxyl-d_2: Technique 1

44. cis-cyclohexane-1,2-dicarboxylic acid-4,5-d_2: by hydrogenation with D_2 in dioxane over PtO_2 of the anhydride, followed by hydrolysis.

45. cis-cyclohexane-1,2-dicarboxylic acid-1-d_1: by hydrogenation of cis-3,5-cyclohexadiene-1,2-dicarboxylic acid-1-d_1

46. cis-cyclohexane-1,2-dicarboxylic acid-3,3,5,5-d_4: by hydrogenation of cis-4-cyclohexene-1,2-dicarboxylic acid-3,3,5,5-d_4 in ETOH over PtO_2

47. trans cyclohexane-1,2-dicarboxylic acid: by hydrogenation of 3,5-cyclohexadiene-1,2-dicarboxylic acid in ETOH over PtO_2

48. trans cyclohexane-1,2-dicarboxylic acid - carboxyl-d_2: Technique 1

49. trans cyclohexane-1,2-dicarboxylic acid 4,5-d_2: by hydrogenation with D_2 in dioxane over PtO_2 of trans-4-cyclohexene-1,2-dicarboxylic acid.

50. trans cyclohexane-1,2-dicarboxylic acid-1,2-d_2: by hydrogenation of trans 3,5-cyclohexadiene-1,2-dicarboxylic acid in EtOH over PtO_2

51. cis cyclobutane-1,2-dicarboxylic acid: by hydrolysis of cis cyclobutane-1,2-dicarboxylic acid anhydride

52. trans cyclobutane-1,2-dicarboxylic acid: Aldrich Chem Co Inc, 14,531-9

53. cis 4-cyclohexene-1,2-dicarboxylic acid: Eastman Org. Chemicals P 5743

54. cis-4-cyclohexene-1,2-dicarboxylic acid-3,3,5,5-d_4: by reaction of maleic acid and butadiene sulfone-3,3,5,5-d_4[43]

55. cis 4-cyclohexene-1,2-dicarboxylic acid - carboxyl-d_2: Technique 1

56. trans 4-cyclohexene-1,2-dicarboxylic acid: reaction of butadiene and fumaryl chloride followed by hydrolysis[44].

57. trans 4-cyclohexene-1,2-dicarboxylic acid - carboxyl-d_2: Technique 1

58. cis-3-cyclohexene-1,2-dicarboxylic acid: by reaction of trans butadiene-1-carboxylic acid and acrylic acid[45]

59. cis 3-cyclohexene-1,2-dicarboxylic acid - carboxyl-d_2: Technique 1

60. trans 3-cyclohexene-1,2-dicarboxylic acid: by reduction of phthalic anhydride[46]

61. trans 3-cyclohexene-1,2-dicarboxylic acid - carboxylic-d_2: Technique 1

62. 2-cyclohexene-1,2-dicarboxylic acid: by reduction of phthalic anhydride[46].

63. 2-cyclohexene-1,2-dicarboxylic acid - carboxyl-d_2: Technique 1

64. 1-cyclohexene-1,2-dicarboxylic acid: from ethyl 2-cyclohexanone carboxylate[47]

65. 1-cyclohexene-1,2-dicarboxylic acid - carboxyl-d_2: Technique 1

66. 1-cyclopentene-1,2-dicarboxylic acid: from ethyl 2-cyclopentanonecarboxylate[48]

67. 1-cyclopentene-1,2-dicarboxylic acid - carboxyl-d_2: Technique 1

68. 1-cyclobutene-1,2-dicarboxylic acid: from cis-cyclobutane-1,2-dicarboxylic acid anhydride[49]

69. trans-3,5-cyclohexadiene-1,2-dicarboxylic acid: by reduction of phthalic acid[50]

70. trans-3,5-cyclohexadiene-1,2-dicarboxylic acid-carboxyl-d_2: Technique 1

71. trans 3,5-cyclohexadiene-1,2-carboxylic acid-1,2-d_2: from phthalic acid using D_2O instead of H_2O[50]

72. cis 3,5-cyclohexadiene-1,2-dicarboxylic acid: from trans 3,5-cyclohexadiene-1,2-dicarboxylic acid[51]

73. cis 3,5-cyclohexadiene-1,2-dicarboxylic acid-1-d_1: from trans 3,5-cyclohexadiene-1,2-dicarboxylic acid-1,2-d_2[51]

74. cis 3,5-cyclohexadiene-1,2-dicarboxylic acid - carboxyl-d_2: Technique 1

75. 2,5-cyclohexadiene-1,2-dicarboxylic acid: from trans 3,5-cyclohexadiene-1,2-dicarboxylic acid[50]

76. 2,5-cyclohexadiene-1,2-dicarboxylic acid - carboxyl-d_2: Technique 1

77. 2,5-cyclohexadiene-1,2-dicarboxylic acid-1,4-d_2: from trans 3,5-cyclohexadiene-1,2-dicarboxylic acid by using D_2O in place of H_2O[50]

78. 2,6-cyclohexadiene-1,2-dicarboxylic acid: from phthalic acid anhydride[52]

79. 2,6-cyclohexadiene-1,2-dicarboxylic acid - carboxyl-d_2: Technique 1

80. 2,4-cyclohexadiene-1,2-dicarboxylic acid: from 2,6-cyclohexadiene-1,2-dicarboxylic acid[51]

81. 2,4-cyclohexadiene-1,2-dicarboxylic acid - carboxyl-d_2: Technique 1

82. 1,4-cyclohexadiene-1,2-dicarboxylic acid: by reaction of butadiene and acetylene dicarboxylic acid[51]

83. 1,4-cyclohexadiene-1,2-dicarboxylic acid - carboxyl-d_2: Technique 1

84. trans cyclohexane-1,2-diol: Aldrich Chem Co Inc, 14,171-2

85. cis cyclohexane-1,2-diol-O-d : Technique 1

86. cis cyclohexane-1,2-diol-4d_1 and the 3,3,5,5-d_4 analogue: obtained from Dr. G. Singy[28]

Claims to Original Research

1. The mechanisms of NO loss from the molecular ions of nitrobenzene and p-nitroaniline were proven by ^{13}C labeling experiments.

2. The mass spectra of the following compounds are presented and fragmentation schemes for their dissociations are proposed (based on the appropriate labeling experiments and presence of metastable peaks).

- o-Nitrobenzoic acid
- o-Nitroanisole
- o-Nitrobenzamide
- o-Nitrobenzyl alcohol
- o-Nitrosobenzoic acid
- 2,4-Dinitrophenylhydrazine
- o- and p-Nitrophenylhydrazine
- Phthalaldehydic acid
- Phthalic acid
- Thiobenzoic acid
- Benzamide
- Thiobenzamide
- Maleic acid
- Citraconic acid
- Fumaric acid
- Mesaconic acid
- Itaconic acid
- *cis* and *trans* Cyclohexane-1,2-dicarboxylic acids
- *cis* and *trans* cyclobutane-1,2-dicarboxylic acids

- cis and trans 4- and 3-cyclohexene-1,2-dicarboxylic acids
- 2- and 1-cyclohexene-1,2-dicarboxylic acids
- 1-cyclopentene-1,2-dicarboxylic acid
- 1-cyclobutene-1,2-dicarboxylic acid
- cis and trans 3,5-cyclohexadiene-1,2-dicarboxylic acids
- 2,5-, 2,6-, 2,4-, 1,4-cyclohexadiene 1,2-dicarboxylic acids

3. The problem of the identity of the $C_7H_5O^+$ ion that results from the scrambling of the ortho hydrogen atoms was reexamined and results indicate that this species is different from the benzoyl cation.

4. An examination of the geometric requirements for an "ortho effect" in some cyclic 1,2-dicarboxylic acids has been performed. Results show that ring flexibility is a major factor in the competitive carboxyl-carboxyl and carboxyl-ring interactions.

5. The loss of water from the molecular ion of cyclohexane-1,2-diols has been explained by two mechanisms; these are

1) scrambling of hydrogen atoms from the hydroxyl, C-4, and C-5 ring positions, and
2) direct interaction between the hydroxyl groups.

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