

Application of Ion Cyclotron Resonance to the Structure Elucidation of the $C_3H_6O^+$ Ion Formed in the Double McLafferty Rearrangement¹⁻³

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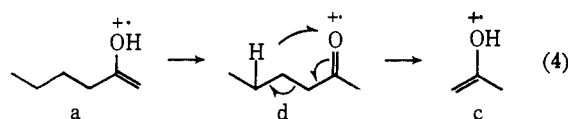
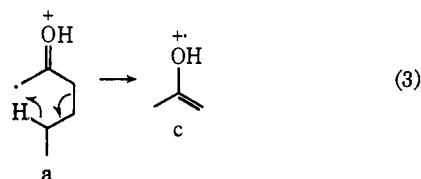
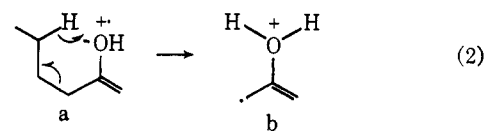
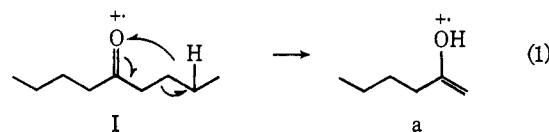
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Abstract: The electron impact induced "double McLafferty" rearrangement of the appropriate aliphatic ketones can produce a $C_3H_6O^+$ ion which could conceivably exist in either the enol (c) or symmetrical oxonium ion (b) structure. Ion cyclotron resonance and pulsed double resonance spectroscopy are used to establish that at least a substantial part of the double McLafferty ion exists in the enol structure. Furthermore, these experiments demonstrate that the enol ion is formed directly, and not by isomerization of the oxonium ion, or by ketonization of the intermediate enol ion (a) followed by hydrogen migration to the carbonyl oxygen.

The mass spectral behavior of aliphatic ketones has been widely studied, and is now relatively well understood.⁶ Only recently, however, has the problem of establishing the structure of the product resulting from the well-known "double McLafferty" rearrangement been seriously attacked.

Dialkyl ketones containing one or more γ -hydrogens in each alkyl group undergo the double McLafferty rearrangement on electron impact. The first stage, the McLafferty rearrangement, involves transfer of a γ -hydrogen atom to the carbonyl oxygen with concomitant β -cleavage (I \rightarrow a). *A priori*, the second step of the double McLafferty rearrangement could proceed according to three distinct pathways: (1) transfer of a γ -hydrogen atom to the enolic oxygen atom with β -cleavage (a \rightarrow b) to produce the symmetrical oxonium ion, b; (2) transfer of a γ -hydrogen atom to the terminal carbon atom of the carbon-carbon double bond with β -cleavage (a \rightarrow c) to give the enol species c; (3) ketonization of the intermediate McLafferty ion (a \rightarrow d), followed by γ -hydrogen atom transfer to the carbonyl oxygen and β -cleavage (d \rightarrow c) to yield again the enolic ion c.

The third alternative (eq 4) appears to be the least likely; consideration of ionization potentials,⁷ metastable correlations,⁸ collision-induced metastable studies,⁹ mass spectral studies,¹⁰ and ion cyclotron resonance



results¹¹ leads to the conclusion that the McLafferty ion exists in the enol form (a) and does not tautomerize to the keto form (d).

However, even if it is assumed that the second step of the double McLafferty rearrangement must proceed through the enolic intermediate a, it remains to be established whether hydrogen atom transfer occurs to the enolic oxygen (eq 2) or to carbon (eq 3). This problem has been attacked using a variety of techniques. On the basis of metastable ion characteristics^{8,9} McLafferty and Pike have concluded that "a substantial part of the $C_3H_6O^+$ ions from 4- and 5-alkanones must not correspond to" structure c. However, Ocolowitz¹² has questioned the validity of structural correlations based on the intensities of a single pair of metastables, and part of McLafferty and Pike's evidence⁸ rested on just such a comparison. Molecular orbital calculations¹³ appear to be in accord with the

(1) Paper CXCVI in the series "Mass Spectrometry in Structural and Stereochemical Problems." For preceding paper, see P. D. Woodgate and C. Djerassi, *Org. Mass Spectrom.*, in press.

(2) Financial assistance by the National Institutes of Health (Grants AM-12758 and AM-04257) is gratefully acknowledged. We are indebted to Professor J. D. Baldeschwieler for generously providing access to his ion cyclotron resonance spectrometer, which was purchased on funds supplied by the National Science Foundation (GP-4924-X), NASA (NGL 05-020-S1), and the Center for Materials Research, Stanford University.

(3) Part of this material was reported in preliminary form in a Communication to the Editor by G. Eadon, J. Diekman, and C. Djerassi, *J. Amer. Chem. Soc.*, **91**, 3986 (1969).

(4) National Institutes of Health Predoctoral Fellow, 1968-present.

(5) National Science Foundation Predoctoral Fellow, 1966-1967; National Institutes of Health Predoctoral Fellow, 1967-1969.

(6) For a detailed and recent summary, see H. Budzikiewicz, C. Djerassi, and D. H. Williams, "Mass Spectrometry of Organic Compounds," Holden-Day, Inc., San Francisco, Calif., 1967, Chapter 3.

(7) S. Meyerson and J. D. McCollum, *Advan. Anal. Chem. Instrum.*, **2**, 187 (1963); J. L. Ocolowitz, *Aust. J. Chem.*, **20**, 2387 (1967); E. Murad and M. G. Inghram, *J. Chem. Phys.*, **40**, 3263 (1964).

(8) F. W. McLafferty and W. T. Pike, *J. Amer. Chem. Soc.*, **89**, 5953 (1967); F. W. McLafferty, T. Wachs, and W. T. Pike, *Advan. Mass Spectrom.*, **4**, 153 (1968).

(9) W. F. Haddon and F. W. McLafferty, *J. Chem. Soc.*, **90**, 4745 (1968).

(10) J. K. McLeod, J. B. Thomson, and C. Djerassi, *Tetrahedron*, **23**, 2095 (1967).

(11) J. Diekman, J. K. MacLeod, C. Djerassi, and J. D. Baldeschwieler, *J. Amer. Chem. Soc.*, **91**, 2069 (1969).

(12) J. L. Ocolowitz, *ibid.*, **91**, 5202 (1969).

(13) F. P. Boer, T. W. Shannon, and F. W. McLafferty, *ibid.*, **90**, 7239 (1968).

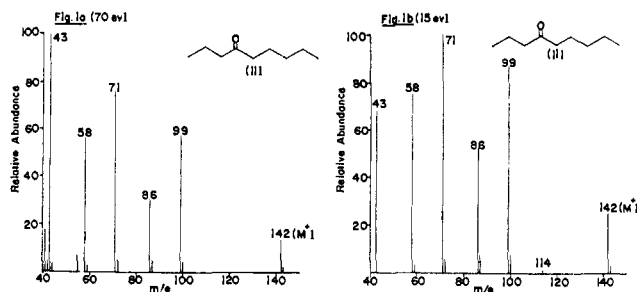


Figure 1. The mass spectrum of 4-nonanone (II) determined at 70 and 15 eV.

symmetrical oxonium structure b, since hydrogen transfer to the enol oxygen (eq 2) was predicted to be the energetically favored process. This conclusion, in turn, was questioned in a recent ion cyclotron resonance study¹¹ which favored the enolic formulation c.

The principles, theory, instrumentation, and applications of ion cyclotron resonance spectroscopy have already been described in considerable detail.¹⁴ Ion cyclotron resonance single resonance spectra are similar to ordinary mass spectra, except that higher operating pressures (10^{-7} to 10^{-5} Torr) and longer ion residence times (10^{-3} to 10^{-2} sec) permit the ready observation of reactions between the ions and the neutral molecules in the cell. The useful pulsed double-resonance technique makes possible the verification of ion reaction sequences. Consider the reaction $AH^+ + B \rightarrow A + BH^+$. By using pulsed double resonance and phase-sensitive detection, the signal from BH^+ can be monitored while the irradiating radiofrequency field is swept through a range of frequencies. When the irradiating frequency equals the natural cyclotron frequency of AH^+ , the translational energy of AH^+ increases. Because reaction rate constants are generally energy dependent, the population of BH^+ changes, and this change produces a peak in the double resonance spectrum. Thus, if the irradiating frequency is swept through the cyclotron frequencies of all ions, it is possible to determine the genesis of the product ion.

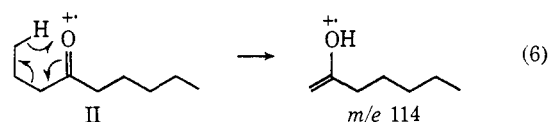
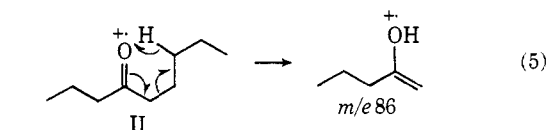
A recent paper¹¹ utilizing these powerful techniques reported seven ion-molecule reactions capable of distinguishing between the keto (e) and enol (c) forms of the m/e 58 ion. In every case, the double McLafferty ion and the independently generated enol ion reacted identically. Since there is no precedent for ions of different structure exhibiting identical reactivity, these observations strongly imply the enol structure for the product of the double McLafferty ion.

In order to resolve this apparent conflict between our results¹¹ and those based on metastable^{8,9} and molecular orbital¹³ studies, a new experimental program was initiated, with ion cyclotron resonance being again the technique of choice.

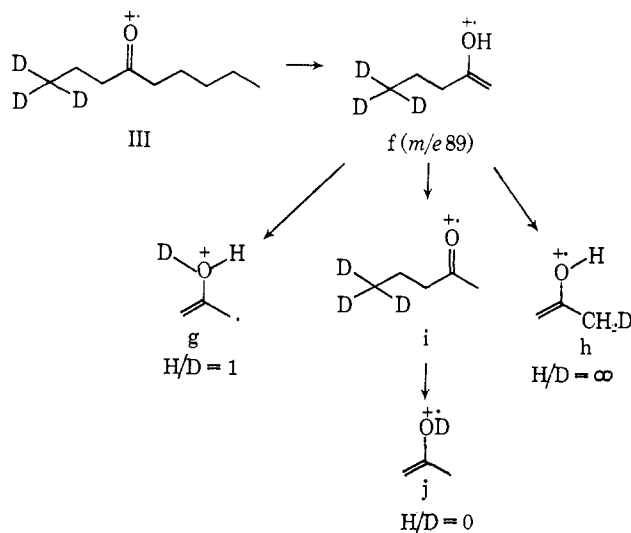


Discussion and Results

It has been established¹⁵ that secondary hydrogens participate in the McLafferty rearrangement ten to twenty times as readily as primary ones. The mass spectrum (Figure 1) of 4-nonanone (II) illustrates this point. The peak corresponding to the McLafferty rearrangement involving migration of a secondary γ -hydrogen appears at m/e 86 (eq 5), and is about 50 times as intense as the peak at m/e 114, corresponding to migration of a primary γ -hydrogen (eq 6). This marked difference in migratory aptitude between secondary and primary hydrogen atoms can be utilized to generate a specifically labeled double McLafferty ion. For example, 4-nonanone-1,1,1- d_3 (III), on undergoing the McLafferty rearrangement, generates almost exclusively ions of structure f. The second step of the double McLafferty rearrangement of this labeled



ion may proceed by three distinct pathways; each pathway must generate a double McLafferty ion with a different protium-deuterium ratio on the oxygen atom. If deuterium migration occurs to the enolic oxygen (f \rightarrow g), the resulting oxonium ion must have approximately (small isotope effect) equal amounts of protium and deuterium bound to the oxygen atom. If deuterium migration occurs to the terminal carbon of the carbon-carbon double bond (f \rightarrow h), only protium will be attached to the enolic oxygen. Finally, if ketonization occurs, followed by deuterium migration to the carbonyl oxygen (f \rightarrow i \rightarrow j), only deuterium will be attached to the oxygen atom.



The results of our earlier ion cyclotron resonance study¹¹ permit experimental differentiation of these

(14) J. L. Beauchamp and J. T. Armstrong, *Rev. Sci. Instr.*, **40**, 123 (1969); J. D. Baldeschwieler, *Science*, **159**, 263 (1968); J. L. Beauchamp, Ph.D. Thesis, Harvard University, 1968.

(15) H. Budzikiewicz, C. Fenselau, and C. Djerassi, *Tetrahedron*, **22**, 1391 (1966).

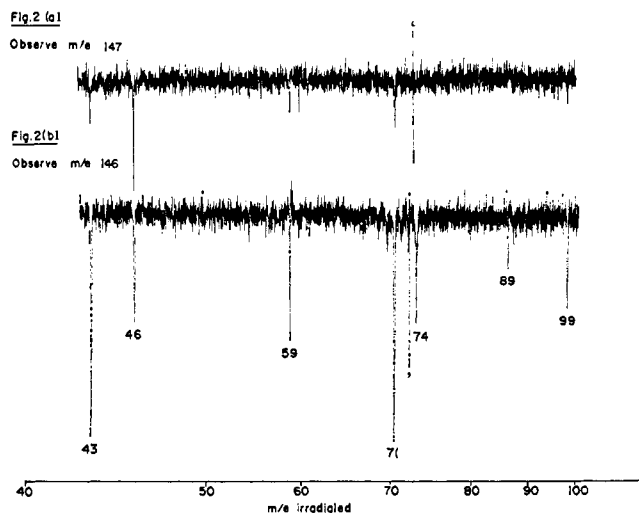
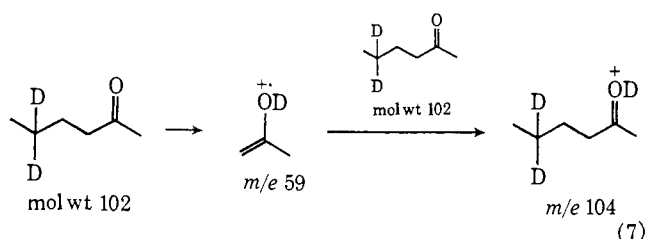


Figure 2. The pulsed double resonance spectra of the $M + 2$ (m/e 147) and $M + 1$ (m/e 146) ions of 4-nonanone-1,1,1- d_3 (III). The species of mass 147 (146) is observed with $\omega_1/2\pi = 145$ kcps, while frequency ω_2 is swept through the mass range 40–100. The change in intensity of the mass 147 (146) signal is plotted as a function of the mass corresponding to ω_2 . Signals corresponding to protium donation from hydrocarbon ions to the neutral ketone (mol wt 145) appear in Figure 2b at m/e 43, 46, and 71; from the acylium ions at m/e 74 and 99; from the single McLafferty ion (*f*) at m/e 89; and from the double McLafferty ion at m/e 59. The signal at m/e 46 in Figure 2a corresponds to deuterium donation from a hydrocarbon ion to the neutral ketone, while the signals at m/e 43 and 71 are attributed to proton donation to neutral ketone of mass 146 (present due to the natural abundance of ^{13}C). The origin of the weak signal appearing at m/e 59 in Figure 2a is discussed in the text. The sharp spike appearing at the frequency (290 kHz) corresponding to m/e 73.5 (Figure 2a) and m/e 73 (Figure 2b) is due to the irradiating oscillator exciting the first overtone of the marginal oscillator. Both spectra were recorded under identical conditions at 2×10^{-6} Torr, 0.1 V irradiating voltage, and 20 eV ionizing voltage.

three situations. The products of the single and double McLafferty rearrangements are known to donate a proton to most neutral ketones and deuterium-labeling experiments have demonstrated that *only hydrogens situated on the oxygen atom are transferred* (eq 7).



The specificity of this reaction permits distinguishing among ions *g*, *h*, and *j*. If the double McLafferty ion exists in the symmetrical oxonium structure *g*, it must donate nearly equal amounts of protium and deuterium to the neutral ketone, and thus the mass 59 ion must contribute equally to the formation of the $M + 1$ and $M + 2$ ions of 4-nonanone-1,1,1- d_3 (III) (*cf.* eq 8). If, on the other hand, the second step of the double McLafferty rearrangement proceeds *via* deuterium migration to the terminal carbon of the carbon-carbon double bond, the resulting enol ion *h* will donate only protium to neutral 4-nonanone-1,1,1- d_3 , and the mass 59 ion will contribute only to the formation of the $M + 1$ ion of the parent ketone (eq 9). Finally, if the reaction proceeds *via* ketonization, followed by deu-

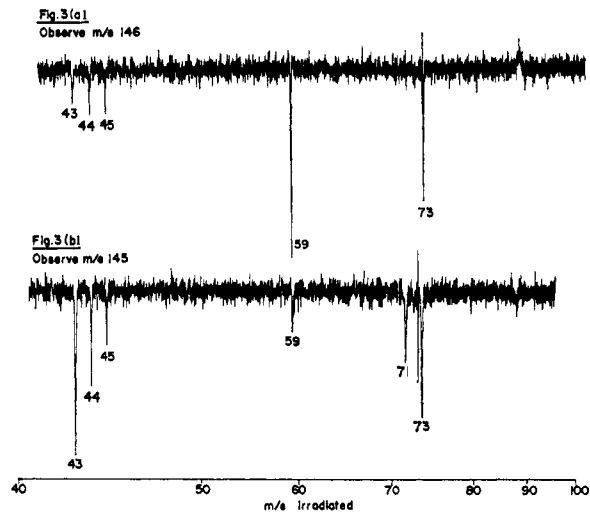
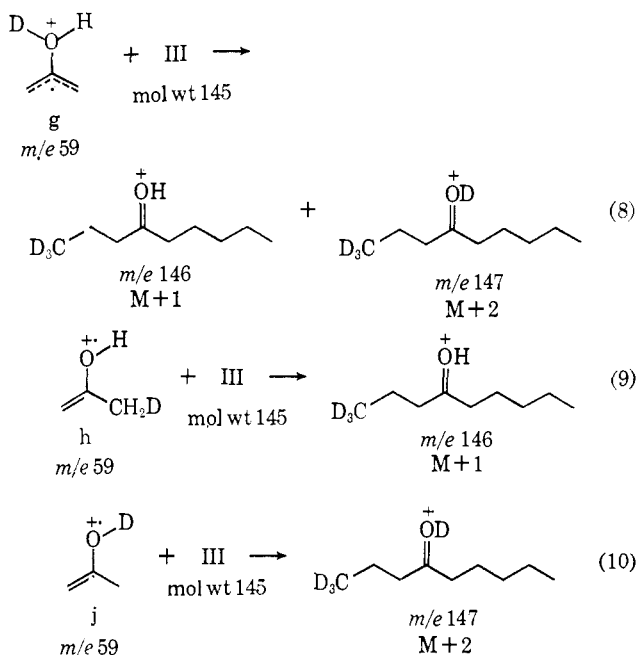


Figure 3. The pulsed double resonance spectra of the $M + 2$ (m/e 146) and $M + 1$ (m/e 145) ions of 4-nonanone-7,7- d_2 (IV). Signals appearing at m/e 43, 44, 45, and 73 in Figure 3b correspond to protium donation from hydrocarbon ions to the neutral ketone (mol wt 144). The signal at m/e 71 corresponds to protium transfer from the acylium ion. The origin of the weak signal at m/e 59 in Figure 3b is discussed in the text. The signal at m/e 43 in Figure 3a arises from protium donation to neutral ketone of mol wt 145; signals at m/e 44, 45, and 73 must, however, be largely attributed to deuterium donation from hydrocarbon ions to the neutral ketone. The signal at m/e 59 in Figure 3a corresponds to deuterium donation from the double McLafferty ion, and is quite intense. The sharp spike appearing at the frequency (290 kcps) corresponding to m/e 73 (Figure 3a) and m/e 72.5 (Figure 3b) is due to the irradiating oscillator exciting the first overtone of the marginal oscillator. Both spectra were recorded under identical conditions, with $\omega_1/2\pi = 145$ kcps, a pressure of 2×10^{-6} Torr, 0.1 V irradiating voltage, and 20 eV ionizing voltage.

terium migration to the carbonyl oxygen, the resulting ion *j* (m/e 59) can only contribute to the formation of the $M + 2$ ion of 4-nonanone-1,1,1- d_3 (eq 10). The ratio of the intensity of the m/e 59 peak in the double resonance spectrum of the m/e 146 ($M + 1$) ion to its intensity in the double resonance spectrum of the 147 ($M + 2$) ion corresponds closely to the ratio of protium transfer to deuterium transfer from the double McLafferty ion. Inspection of the appropriate double resonance spectra (Figure 2) indicates that protium transfer (eq 9) predominates heavily (*ca.* 5:1) over deuterium transfer (eq 8 and 10).

It might be argued that this result merely reflects the existence of a large hydrogen-deuterium isotope effect which discriminates heavily against deuterium transfer. In order to preclude this possibility, 4-nonanone-7,7- d_2 (IV) was prepared and an analogous experiment performed. Again, the intermediate single McLafferty ion *k* might fragment according to three pathways. Hydrogen migration to the enol oxygen would yield the symmetrical oxonium species *g*, which must donate nearly equal amounts of protium and deuterium (eq 11). Hydrogen migration to the carbon-carbon double bond would give the enol ion *j* which must donate only deuterium (eq 12). Ketonization, followed by hydrogen migration to the carbonyl oxygen, would generate the enol ion *h*, which must donate only protium (eq 13). Consideration of Figure 3 demonstrates that deuterium transfer (eq 12) occurs roughly six times as readily as protium transfer, an observation which excludes the operation of a large isotope effect.

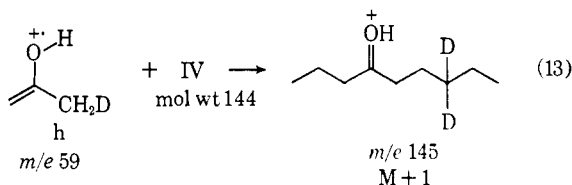
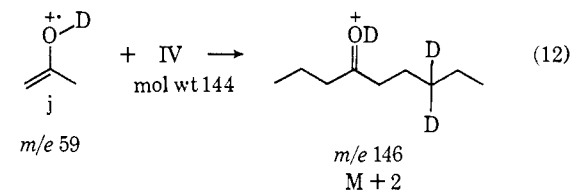
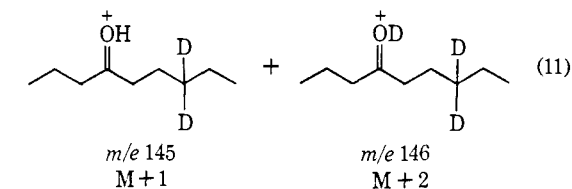
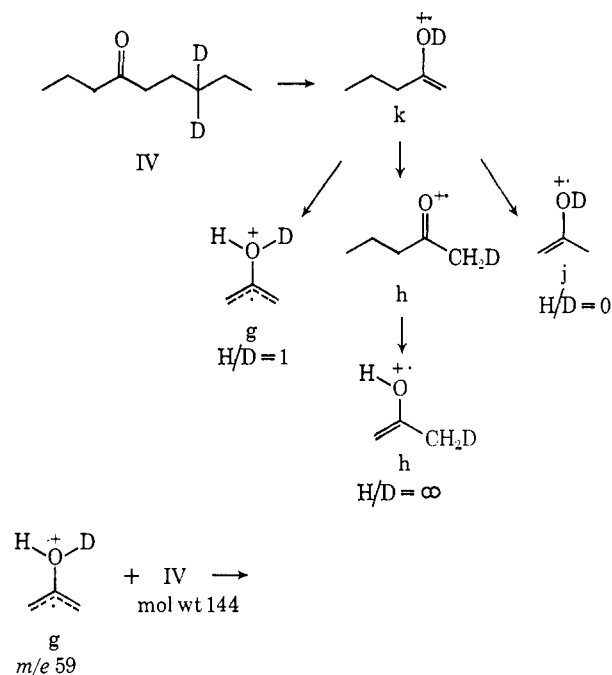


Essentially identical results were obtained using several different ketones as proton acceptors, and using ionizing voltages varying between 70 and 15 eV. Thus, these observations confirm the assumption that the single McLafferty ion does not ketonize prior to undergoing the second step of the double McLafferty rearrangement. More importantly, these experiments provide unequivocal demonstration that at least a substantial portion of the double McLafferty ion must, in fact, correspond to the enol structure c.

Further evidence supporting these conclusions was forthcoming from a study of the reactions of the isotopically labeled double McLafferty ion with 1-methylcyclobutanol. The results of our earlier investigation¹¹ indicated that the product ions of the single and double McLafferty rearrangements condensed with 1-methylcyclobutanol, splitting out the elements of ethylene and water; isotopic labeling experiments demonstrated¹¹ that the hydrogen bound to the enolic oxygen atom was specifically eliminated. Thus, if the double McLafferty ion from 4-nonanone-1,1,1-*d*₃ (III) exists in the symmetrical oxonium structure (g), nearly equal amounts of protium and deuterium must be eliminated in the reaction of the mass 59 ion with 1-methylcyclobutanol-1,1,1-*d*₃ (V),¹⁶ and it must contribute nearly equally to the *m/e* 101 and 102 peak (eq 14). If, on the other hand, the double McLafferty ion existed in the enolic form h, only protium should be eliminated in its reaction with 1-methylcyclobutanol-1',1',1'-*d*₃; the mass 59 ion should contribute only to the *m/e* 102 peak (eq 15). Double resonance experiments (Figure 4) on the *m/e* 101 and 102 peaks confirm that elimination of protium (eq 15) predominates heavily (roughly 4:1). Similarly, comparison of the intensity of the *m/e* 59 peak in the double resonance spectra (Figure 5) of VI¹⁷ with the *m/e* 98 and 99 ions formed in a mixture of 1-methyl-

(16) Isotopically labeled 1-methylcyclobutanol was used in this experiment to shift the mass of the product ions away from the large peak at *m/e* 99 corresponding to simple α -cleavage of the parent ketone.

(17) The presence of an intense peak corresponding to α -cleavage of the parent ketone at *m/e* 101 precluded the use of 1-methylcyclobutanol-1',1',1'-*d*₃ in this experiment.



cyclobutanol and 4-nonanone-7,7-*d*₂ (IV) indicates that elimination of deuterium (eq 17) predominates over the elimination of protium (eq 17). These experiments confirm our earlier¹¹ conclusion that at least a substantial amount of the double McLafferty ions must exist in the enol structure (c).

Previous MO calculations suggested¹³ that the symmetrical oxonium ion b is the initial product of the double McLafferty rearrangement. Therefore, the possibility that the enol ion c is formed by hydrogen rearrangement of b must be considered. If the symmetrical oxonium ion g isomerizes to the enol form, it must produce nearly equal amounts of j and h (eq 18); such a mixture must donate protium and deuterium to neutral ketone to a nearly equal extent (eq 9 and 10). Similarly, protium and deuterium must be eliminated to a nearly equal extent in the condensation with 1-methylcyclobutanol (eq 15 and 17). The results described earlier do not correspond to such behavior. Thus, the enol ion c must be a direct product of the double McLafferty rearrangement and is not formed in sig-

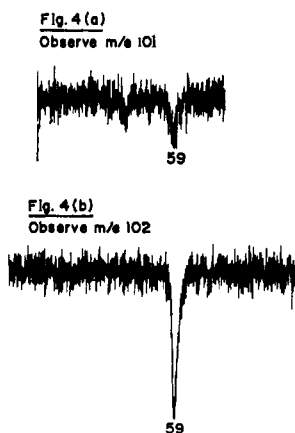
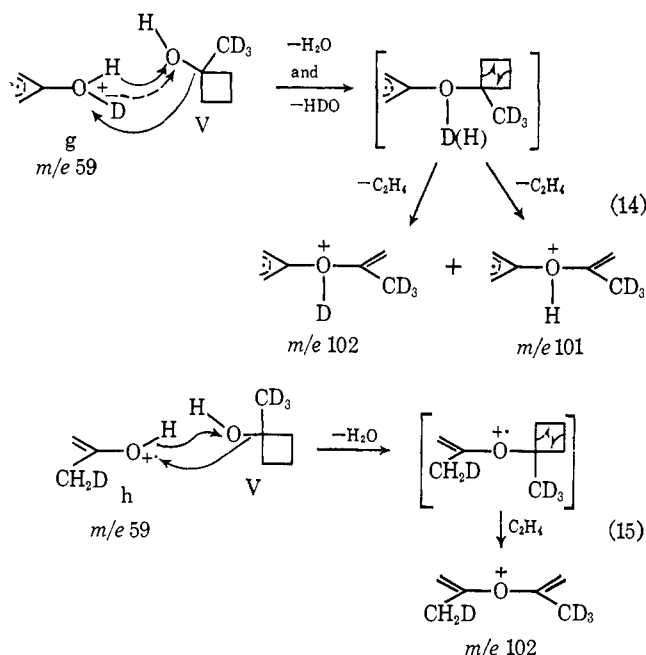


Figure 4. Pulsed double resonance spectra of the m/e 101 and 102 ions formed in a mixture of 4-nonanone-1,1,1- d_3 (III) and 1-methylcyclobutanol-1',1',1'- d_3 (V). The contribution of the m/e 59 ion to the m/e 102 peak (eq 15) is observed to be much larger than its contribution to the m/e 101 peak. Both spectra were recorded under identical conditions at 4×10^{-6} Torr, with $\omega_1/2\pi = 153.5$ kcps, an irradiating voltage of 0.1 V, and an ionizing voltage of 20 eV.

nificant amounts by rearrangement of b. Since, as already described, these experiments demonstrate that ketonization of the intermediate enol ion a followed



by γ -hydrogen migration to the carbonyl oxygen (eq 4) is not an important route to the double McLafferty ion, the unambiguous mechanistic conclusion can be drawn that the second step of the double McLafferty rearrangement must, at least to a substantial extent, proceed by hydrogen atom migration to the carbon-carbon double bond (eq 3).

Inspection of Figure 3 demonstrates that, although the mass 59 ion produced from 4-nonanone-7,7- d_2 (IV) contributes very strongly to the $M + 2$ ion, it also, to a much lesser extent, contributes to the formation of the $M + 1$ ion. The small peak in Figure 3b at m/e 59 probably arises as a result of a number of small contributing factors.

For example, the phenomenon of hydrogen-deuterium randomization in the molecular ions of aliphatic

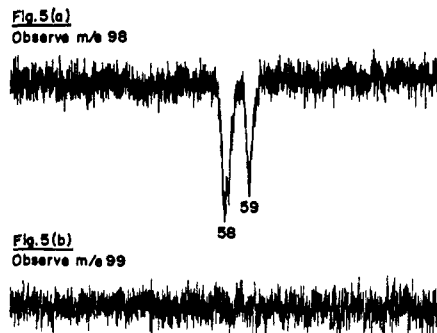
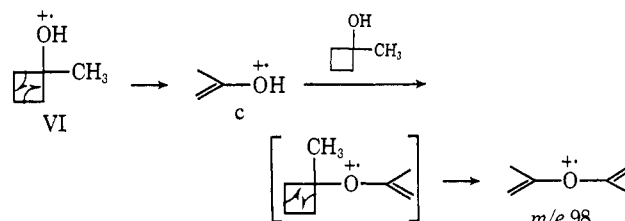
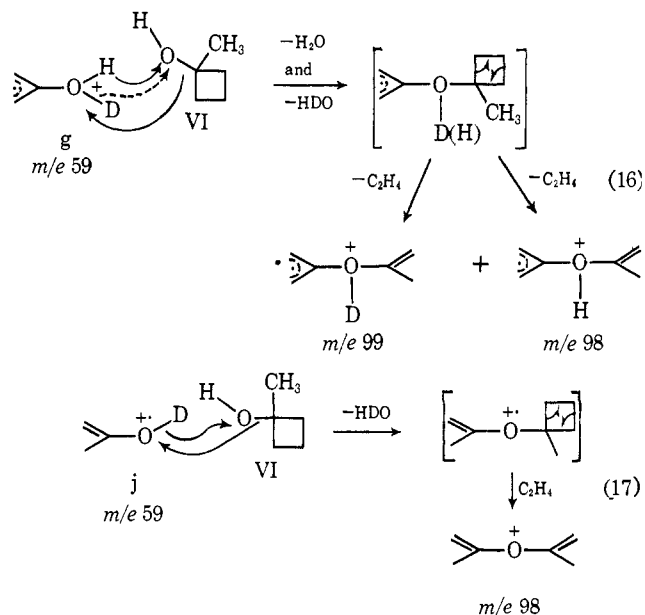


Figure 5. Pulsed double resonance spectra of the m/e 98 and 99 ions formed in a mixture of 1-methylcyclobutanol (VI) and 4-nonanone-7,7- d_2 (IV). (The presence of an intense peak corresponding to α -cleavage of the parent ketone at m/e 101 precluded use of 1-methylcyclobutanol-1',1',1'- d_3 (V), the compound used in the experiments whose results are depicted in Figure 4.) The double McLafferty ion (m/e 59) contributes more strongly to the formation of the m/e 98 ion (eq 17) than to the m/e 99 ion. The signal appearing at m/e 58 in Figure 5a corresponds to the reaction of the enol ion (c) formed from 1-methylcyclobutanol with neutral 1-methylcyclobutanol according to the equation



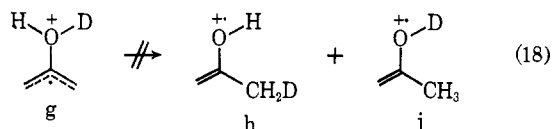
Both spectra were recorded under identical conditions at a pressure of 7×10^{-6} Torr, with $\omega_1/2\pi = 153.5$ kcps, an irradiating voltage of 0.1 V, and an ionizing voltage of 20 eV.

ketones is well established.¹⁸ If significant hydrogen-deuterium exchange occurred between the positions γ and α to the carbonyl group, a nonspecifically labeled

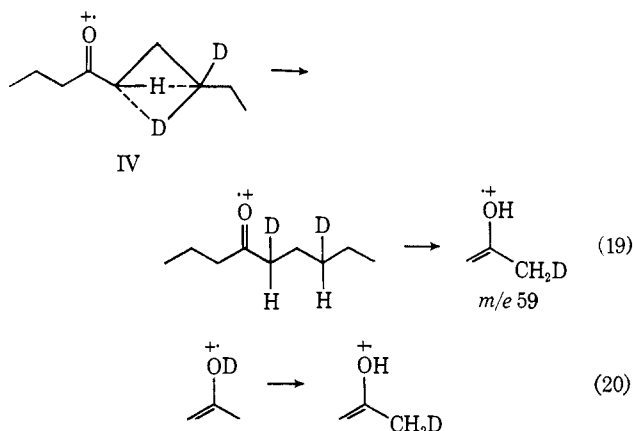


ion of mass 59 would be formed (eq 19). Alternatively, the possibility of hydrogen-deuterium randomization in the mass 59 ion itself must be considered, especially

(18) A. N. H. Yeo, R. G. Cooks, and D. H. Williams, *Chem. Commun.*, 1269 (1968); A. N. H. Yeo and D. H. Williams, *J. Amer. Chem. Soc.*, **91**, 3582 (1969).

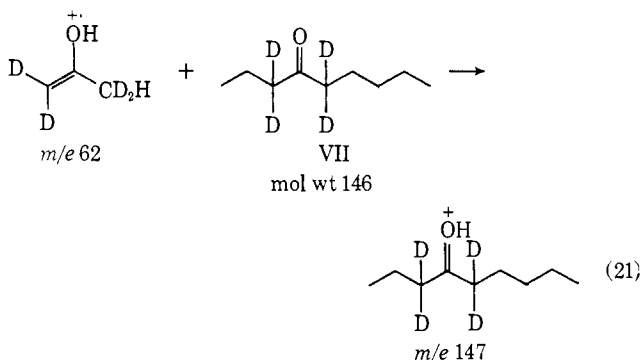


in light of recent isotopic labeling experiments on the $\text{C}_2\text{H}_5\text{O}^+$ ion.¹⁹ If significant hydrogen–deuterium exchange occurred between carbon and oxygen in the mass 59 ion (eq 20), the protium donation observed from the $\text{C}_3\text{H}_3\text{DO}^+$ ion could be rationalized. Finally, if the proton abstraction reaction were not completely specific to the oxygen hydrogen, the protium donation might also be explained.



In order to evaluate the importance of these effects, the double resonance spectra of the $M + 1$ (147) and $M + 2$ (148) ions of 4-nonanone-3,3,5,5- d_4 (VII) were recorded. The ratio of the double McLafferty ion's intensity in the $M + 2$ ions double resonance spectrum to its intensity in the $M + 1$ ion's double resonance spectrum was 0.15; in the absence of randomization, and if only the protium on oxygen were donated (eq 21) (and regardless of whether the double McLafferty rearrangement produces the enol or oxonium species), a value of 0.10 would be anticipated.²⁰ Thus, one or some combination of these alternatives probably contributes to the protium transfer observed from the m/e 59 ion of 4-nonanone-7,7- d_2 .

This result permits another interesting conclusion: not more than 5% of the protium on oxygen randomizes in the fragment ion, even during the extended lifetimes

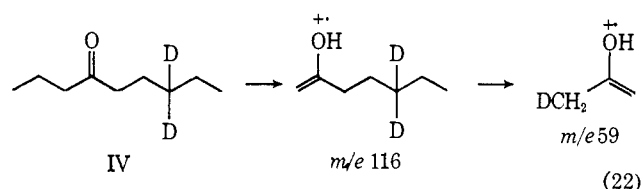


(19) D. Van Raalte and A. G. Harrison, *Can. J. Chem.*, **41**, 3118 (1963); A. G. Harrison and B. G. Keyes, *J. Amer. Chem. Soc.*, **90**, 5046 (1968); A. G. Harrison, A. Ivko, and D. Van Raalte, *Can. J. Chem.*, **44**, 1625 (1966).

(20) A value of 0.10 is expected because of the natural abundance of ^{13}C . This effect is discussed in greater detail below.

(ca. 1 msec) of ions in the ion cyclotron resonance spectrometer.

Another obvious source of excess deuterium transfer exists. Throughout these discussions it has been assumed that the double McLafferty rearrangement always occurs with initial migration of the secondary γ -hydrogen (eq 5). If, however, the double McLafferty rearrangement occurred with initial migration of a primary γ -hydrogen, then the resulting ion would be isotopically labeled in a different manner (eq 22). In the mass spectrum of 4-nonanone-7,7- d_2 the ratio of the intensity of the peaks from the single McLafferty rearrangement corresponding to primary hydrogen migration (m/e 116) to the intensity of the peak corresponding to secondary deuterium migration (m/e 87) is about 0.02 at 15 eV. Since ions originating from a single McLafferty rearrangement containing a secondary γ -deuterium probably undergo the second step of the double McLafferty rearrangement more readily than those containing a primary γ -hydrogen, this process may well represent an important source of the protium transfer observed.

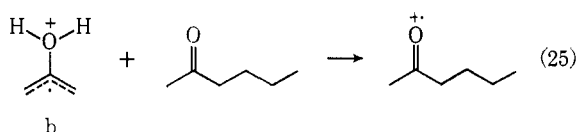
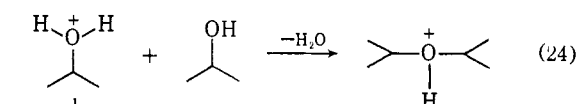
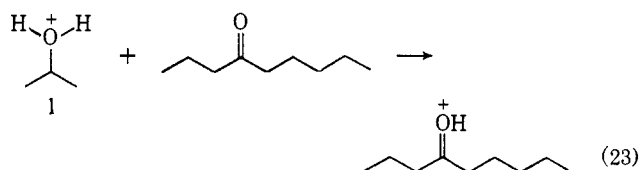


These and similar effects could account for the small amount of protium transfer observed from the ion derived from the double McLafferty rearrangement of 4-nonanone-7,7- d_2 .

Because of the natural abundance of ^{13}C , the molecular ion of 4-nonanone-1,1,1- d_3 should exhibit a peak at m/e 146 corresponding to 10% of the relative abundance of the m/e 145 peak. Thus, if the product ion of the double McLafferty rearrangement transferred only protium to the parent ketone (eq 9), the expected ratio of the intensity of the m/e 59 peak in the double resonance spectrum of the m/e 146 ion to its intensity in the spectrum of the m/e 147 ion should be 0.10, whereas a slightly higher ratio was observed experimentally. It seems likely that effects similar to those already discussed could account for this small discrepancy. Similar semiquantitative arguments can be used to rationalize the spectra exhibited in Figures 4 and 5. Because of the uncertain magnitude of many of the effects discussed earlier, a fully quantitative evaluation of these results is impossible. However, these results appear entirely consistent with the existence of the double McLafferty rearrangement ion solely in the enolic form. No evidence has been obtained for the presence of significant amounts of the oxonium ion from the double McLafferty rearrangement.

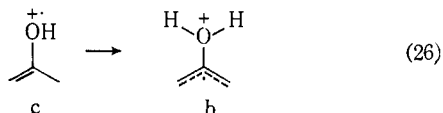
These results, in fact, exclude the presence of significant amounts of the oxonium ion unless a number of postulates are granted: (1) the oxonium ion does not participate in protium donation to the neutral ketones utilized as bases in these studies. If this were, in fact, the case, a double resonance signal might not be observed for hydrogen transfer from this species, and the absence of a significant double resonance signal corresponding to the donation of the "wrong" isotope would not exclude the presence of the oxonium

ion. It should be pointed out, however, that in our hands, protonated 2-propanol (1), a structurally similar ion, gives a strong double resonance signal for the donation of proton to 4-nonanone (eq 23) (Figure 6); (2) the oxonium ion cannot participate in the condensation with 1-methylcyclobutanol (eq 16). An analogous reaction of protonated 2-propanol with a number of alcohols has, however, been reported (eq 24);²¹ (3) the oxonium ion cannot transfer charge to 2-hexanone (eq 25), or participate in the condensation reactions which the molecular ion of acetone undergoes (but which the enol ion does not).¹¹ Unless these three statements are correct, the oxonium ion b can be, at most, a very minor constituent of the double McLafferty ion.



On the other hand, if these three postulates are correct, the situation may be much more complex. The oxonium ion b may be a significant (but certainly not exclusive) product of the double McLafferty rearrangement; it could be formed directly (eq 2) or indirectly, by the isomerization of the initially formed enol ion (eq 20). In fact, if the latter process were important, then even the ion resulting from a single McLafferty rearrangement of 2-alkanones should consist of a mixture of substantial amounts of the enol (c) and oxonium (b) ions.

It must be pointed out that the sole experimental evidence for the formation of the symmetrical oxonium ion (b) in the double McLafferty rearrangement is derived from a study of metastable ion characteristics.^{8,9} A recent reevaluation of those metastable results has led to a conclusion more consistent with those reached here: "most of the $\text{C}_3\text{H}_6\text{O}^+$ ions formed from both the single and double hydrogen rearrangement of aliphatic ketones have the enol structure."²²



Conclusion

The present experiments shed considerable light on the structure of the product of the double McLafferty rearrangement and on the mechanism of its formation

(21) J. L. Beauchamp, *J. Amer. Chem. Soc.*, **91**, 5925 (1969).

(22) F. W. McLafferty, R. A. Kornfield, D. J. McAdoo, H. D. R. Schüddemage, and J. S. Smith, Abstracts, International Mass Spectrometry Conference, Kyoto, Japan, 1969, p 217.

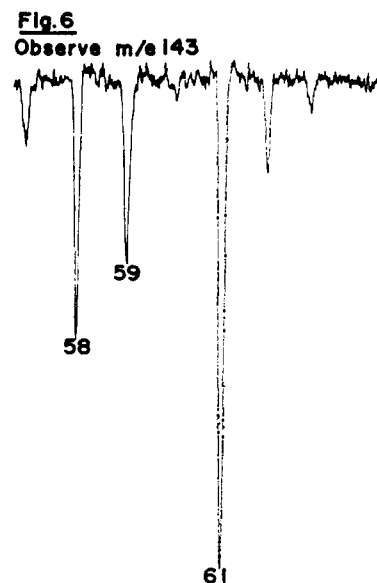


Figure 6. Pulsed double resonance spectra of the m/e 143 ion formed in a mixture of 2-propanol and 4-nonanone. The spectrum was recorded under conditions such that the number density of the m/e 58 ion in the analyzer region was approximately three-fourths that of the m/e 61 ion. A strong signal is observed corresponding to proton donation from the m/e 61 ion (protonated 2-propanol (1)) to neutral 4-nonanone (eq 23). Weaker signals are observed for proton donation from the product ion of the double McLafferty rearrangement (m/e 58), and from the m/e 59 ion ($M^+ - 1$ ion of 2-propanol). The spectrum was recorded at 10^{-6} Torr, with $\omega_1/2\pi = 153.5$ kcps, an irradiating voltage of 0.1 V, and an ionizing voltage of 20 eV.

and also illustrate again the power of the ion cyclotron resonance technique. At least a substantial part of the double McLafferty ion must consist of ions in the enolic form c. The enol ion is a direct product of the double McLafferty rearrangement; it is formed by hydrogen migration to the carbon-carbon double bond (eq 3), and not by the isomerization of the oxonium ion (eq 2), or by ketonization of the intermediate enol ion a followed by hydrogen migration to the carbonyl oxygen (eq 4). No evidence was obtained for the existence of the oxonium ion b. In fact, unless the ion-molecule chemistry of the oxonium ion conforms to three restrictive conditions, the double McLafferty ion must exist essentially completely in the enol structure.

Experimental Section²³

4-Nonanone-1,1,1- d_3 (III). Perdeuterioacetic acid²⁴ (8.0 g, 0.125 mol) was treated with 20% molar excess of lithium aluminum hydride in anhydrous diglyme according to the procedure of Friedman and Jurewicz;²⁵ ethanol-2,2,2- d_3 was isolated in 85% yield (5.2 g). Conversion to bromoethane-2,2,2- d_3 was accomplished in good yield by treatment with triphenylphosphine dibromide in dry dimethylformamide according to the procedure of Wiley, *et al.*²⁶

(23) The basic ion cyclotron resonance spectrometer used in this study is the Varian V-5900 spectrometer. Conventional mass spectral data were obtained by Mr. R. Ross on an MS-9 mass spectrometer using a heated glass inlet system with steel manifold. All ionizing voltages mentioned are nominal values.

(24) Purchased from Mallinckrodt Chemical Works, St. Louis, Mo.

(25) L. Friedman and A. T. Jurewicz, *J. Org. Chem.*, **33**, 1254 (1968).

(26) G. A. Wiley, R. L. Herzhkowitz, B. M. Remm, and B. C. Chung, *J. Amer. Chem. Soc.*, **86**, 964 (1964).

Condensation of bromoethane-2,2,2- d_3 (5.6 g, 0.05 mol) with diethyl malonate, followed by hydrolysis and decarboxylation,²⁷ gave 2.49 g (55%) of butanoic acid-4,4,4- d_3 .

Treatment of the acid with thionyl chloride resulted in the formation of butyryl chloride-4,4,4- d_3 ; a benzene solution of the crude acid chloride was added to a solution containing an equivalent amount of dipentylcadmium.²⁸ The desired ketone, 4-nonanone-1,1,1- d_3 (97% d_3), was isolated in high yield and purified further by repeated vapor phase chromatography on a 10-ft Carbowax 20M column operated at 170°.

4-Nonanone-7,7- d_2 (IV). Propionic acid was reduced with lithium aluminum deuteride in dry diglyme.²⁵ The resulting propanol-1,1- d_2 was converted to the corresponding bromide by the procedure of Wiley, *et al.*,²⁶ and homologated by condensation with diethyl malonate, followed by hydrolysis and decarboxylation.²⁴ The

(27) R. Adams and R. M. Kamm, "Organic Syntheses," Coll. Vol. I, Wiley, New York, N. Y., 1932, p 250; E. B. Vliet, C. S. Marvel, and C. M. Hseuh, "Organic Syntheses," Coll. Vol. II, Wiley, New York, N. Y., 1943, p 416.

(28) J. Cason and F. S. Prout, "Organic Syntheses," Coll. Vol. III, Wiley, New York, N. Y., 1955, p 601.

resulting pentanoic acid-3,3- d_2 was converted to 1-bromopentane-3,3- d_2 by the usual procedures.^{25, 28}

Conversion of the bromide to the corresponding organocadmium reagent, followed by treatment with an equivalent amount of butyryl chloride, gave 4-nonanone-7,7- d_2 . Purification was accomplished by vapor phase chromatography. The resulting ketone was of 98% d_2 isotopic purity.

4-Nonanone-3,3,5,5- d_4 was prepared by the repeated equilibration of the parent ketone with deuteriomethanol containing 10% heavy water and a catalytic amount of sodium deuterioxide. The product was recovered by removing the solvent under vacuum. The discolored liquid was further purified by vapor phase chromatography through a 10-ft Carbowax column (170°) preequilibrated with heavy water.²⁹ The resulting d_4 -ketone was 94% pure.

1-Methylcyclobutanol and 1-Methylcyclobutanol-1',1',1'- d_3 . The preparation of these compounds has already been described.^{11, 30}

(29) M. Senn, W. J. Richter, and A. L. Burlingame, *J. Amer. Chem. Soc.*, **87**, 680 (1965); W. J. Richter, M. Senn, and A. L. Burlingame, *Tetrahedron Lett.*, 1235 (1965).

(30) D. A. Semenov, E. F. Cox, and J. D. Roberts, *J. Amer. Chem. Soc.*, **78**, 3221 (1956).

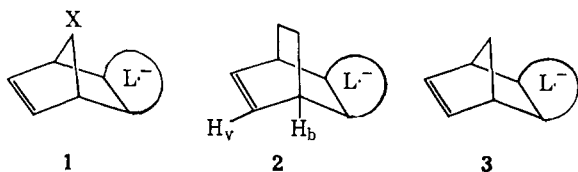
Heterocyclic Radical Ions. IV. Electron Spin Resonance Spectra of Conformationally Mobile Semifuraquinones¹

Stephen F. Nelsen² and Erroll D. Seppanen

Contribution from the Department of Chemistry, University of Wisconsin, Madison, Wisconsin 53706. Received January 22, 1970

Abstract: The esr spectra of anions of dimethylmaleic anhydride, tetrahydrophthalic anhydride, 3,6-dihydrophthalic anhydride, and three methylated derivatives are reported and discussed. The methyl and vinyl splittings of 4-methyl-3,6-dihydrophthalic anhydride were about the same size, but it was concluded that the methyl splitting was not arising solely from π spin density in the 4,5-vinyl π system.

The mechanisms involved in spin delocalization to protons γ to spin-bearing p orbitals have been a subject of considerable discussion in recent years, especially since the discovery by the groups of Russell³ and Stock⁴ that the esr splitting constants of such γ protons are considerably enhanced in rigid, strained systems. One case of interest has been the interaction of a homoconjugated vinyl group with a spin-bearing π system, as that generalized in structure **1** below.⁵



The vinyl splitting is considerably enhanced when a bridging X group is present in the cyclohexadienyl system, but larger splittings are observed for X =

(1) For Part III see S. F. Nelsen and E. D. Seppanen, *J. Amer. Chem. Soc.*, **89**, 5740 (1967).

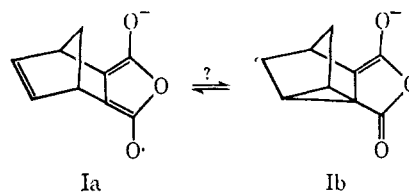
(2) Alfred P. Sloan Fellow, 1968-1970.

(3) G. A. Russell, G. W. Holland, and K. Y. Chang, *J. Amer. Chem. Soc.*, **89**, 6629 (1967), and references therein.

(4) D. Kosman and L. M. Stock, *ibid.*, **91**, 2011 (1969), and references therein.

(5) F \cdot is used to symbolize the [(=C-CO) $_2$ O] \cdot "spin label" common to many of the compounds discussed. The suffix a will be used for semifuraquinones, b for semiquinones, and c for semidiones.

CH₂-CH₂ (**2a** and **2b**) than when X = CH₂ (**3a** and **3b**) in semiquinones and semifuraquinones. Since the C₂-C₆ distance should be larger for **2** than for **3**, we have argued¹ that this is evidence against a mechanism in which spin is transmitted by simple physical overlap of the label and vinyl π systems. Furthermore, the vinyl splitting of **2c** is only 37% as large as that of **2a**, although the α spin density of semidiones is greater than that of semifuraquinones. One possibility which has been considered¹⁻³ for the spin delocalization has been a homoallylic interaction of the sort depicted in Ia-b. If such delocalization or tautomerism were



important, the vinyl splitting would arise from π spin density being introduced into the vinyl π system. If this were the case, replacing a vinyl hydrogen by a methyl group should result in a methyl splitting about the same size as the vinyl splitting. Russell's group³ investigated a substituted 5,6-dimethyl **2c**, which had a methyl splitting slightly larger than the vinyl splitting of **2c** itself (0.49 vs. 0.41 G); they interpreted this in