salicylate coated RCA 935 phototube. The relative quantum yields were calculated from

$$\frac{\Phi_{2537}}{\Phi_{2380}} = \left(\frac{A_{2537}}{A_{2380}}\right)\left(\frac{(R_o - R_e)_{2380}}{(R_o - R_e)_{2537}}\right)\left(\frac{t_{2380}}{t_{2537}}\right)$$

where A is the chromatogram area, R_o and R_e are the phototube readings when the cell is filled with water and with lactone, respectively, and t is the time of irradiation. The absolute quantum yield at 2380 Å was then obtained from the known absolute quantum yields at 2537 Å.

The formates were identified by comparison of their retention times and infrared spectra with authentic samples. In the case of crotyl formate, the spectra of the known and unknown sample were identical, except that the unknown sample exhibited a band at 849 cm^{-1}, but the known sample did not show this band. Since the band at 849 cm^{-1} is characteristic of a carbon–hydrogen bending mode for *cis* olefins, it was concluded the unknown sample was a mixture of the *cis* and *trans* isomers, whereas the known sample was the *trans* isomer. Complete separation of the two isomers by glpc was not achieved, but with a benzylcyanide–$AgNO_3$ column, it was possible to partially resolve the single peak appearing on a Carbowax 20M column into one peak with a shoulder.

Succinaldehyde was identified by comparison of its infrared spectrum to that reported in the literature and by comparison of the retention time to that of an authentic sample. In addition, the photoproducts of the unknown material were identical with those of independently synthesized succinaldehyde. α-Methylsuccinaldehyde was identified by its infrared spectrum and retention time.

A sufficient amount of the product obtained from valerolactone, with a retention time close to the aldehydes obtained from the other lactones, could not be obtained for infrared analysis and its identity is not certain. However, by analogy with the formation of the dialdehydes from butyrolactone and α-methylbutyrolactone and from the similarity of the retention time of this compound to those of the dialdehydes, it is probably pentanal-4-one.

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Mechanism of Ketene Formation from Cyclohexenones upon Electron Impact. Correlations with Photochemistry[1]

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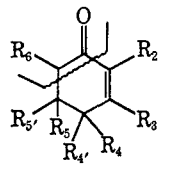
Abstract: The high-resolution mass spectra and the metastable ions of a number of alkyl-substituted 2-cyclohexenones and related bicyclic and steroidal unsaturated ketones, together with deuterium-labeled analogs, have been measured and the course and the scope of electron impact induced rearrangements and fragmentations occurring in these compounds discussed. A similar study of alkyl-substituted bicyclo[3.1.0]hexan-2-ones, derived from the cyclohexenones by photochemical transformation, is reported. A variety of data support the postulate that on electron impact, a portion of the molecular ions of 2-cyclohexenones rearrange to molecular ions resembling those formed from related bicyclo[3.1.0]hexan-2-ones, and it is from these rearranged ions that ketene is eliminated.

The elimination upon electron impact of the elements of ketene from various cyclohexenones[3,4] and from cyclohexenone systems in steroids[5–8] and 2-octalones[9,10] has been frequently observed. The identity and the origin of the atoms lost have been confirmed by isotope labeling and exact mass measurements[3–11] and the elimination is shown, at least formally, below.



The loss of ketene, as indicated, requires the scission of a vinylic bond. It has been shown in a number of cases that cleavage of such a bond is severely repressed or inoperative when compared to scission of the corresponding σ bond in the saturated analog.[12–15] Since ketene elimination is rarely seen in the fragmentation of saturated six-ring ketones,[16–18] it seems unlikely that

(1) This work was supported, in part, by the National Aeronautics and Space Administration, Grant NsG 101, and PHS Grant No. AM-709, National Institute of Arthritis and Metabolic Diseases, U. S. Public Health Service.

(2) Public Health Service Predoctoral Fellow, 1965–1967.

(3) A. L. Burlingame, C. Fenselau, W. J. Richter, W. G. Dauben, G. W. Shaffer, and N. D. Vietmeyer, *J. Amer. Chem. Soc.*, 89, 3346 (1967).

(4) R. L. N. Harris, F. Komitsky, and C. Djerassi, *ibid.*, 89, 4765 (1967).

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(9) H. Budzikiewicz, C. Djerassi, and D. H. Williams, "Interpretation of Mass Spectra of Organic Compounds," Holden-Day, Inc., San Francisco, Calif., 1964, pp 155–159.

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(13) K. Biemann, "Mass Spectrometry," McGraw-Hill Book Co., Inc., New York, N. Y., 1962, pp 98–99, 328–330.

(14) G. P. Happ and D. W. Stewart, *J. Amer. Chem. Soc.*, 74, 4404 (1952).

(15) L. Friedman and F. A. Long, *ibid.*, 75, 2832 (1953).

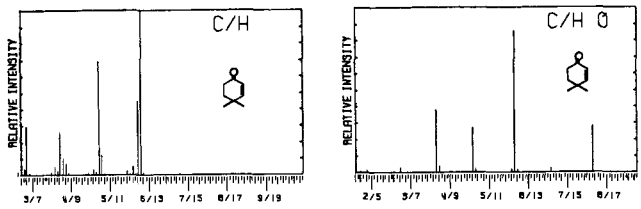


Figure 1. High-resolution mass spectrum of 4,4-dimethyl-2-cyclohexenone (7).

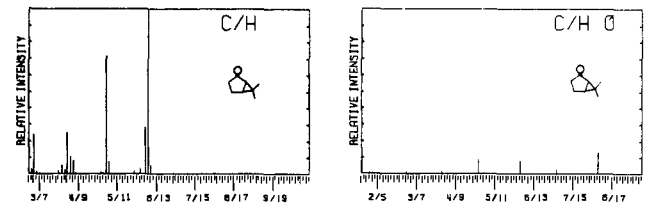


Figure 2. High-resolution mass spectrum of 6,6-dimethylbicyclo[3.1.0]hexan-2-one (12).

the facile loss of ketene observed in the α,β-unsaturated ketones involves direct scission of the vinyl bond and interruption of the conjugation of the system.

In order to circumvent the mechanistic awkwardness of the direct fragmentation of a vinyl bond, mechanisms can be postulated which involve molecular rearrangement to a species which allows a more probable fragmentation of the bond in question. The rearrangements considered fall into two categories, those which convert the unsaturated ketone to a cyclopropyl conjugated ketone and those which convert the conjugated ketone to a β,γ-unsaturated ketone. Similar rearrangements are known to occur in the photochemistry of unsaturated ketones and so a comparison of the enone reactions in the mass spectrometer and with ultraviolet irradiation has been made.

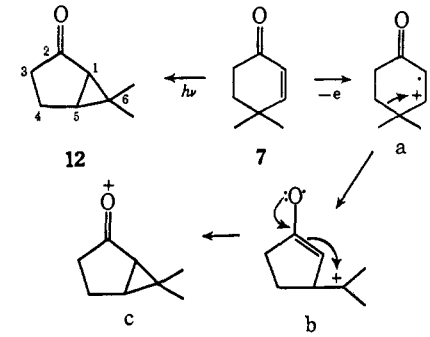
Fragmentations Yielding Ketene. A major fragmentation pathway of 2-cyclohexenones is the loss of C-5 and C-6 as ethylene. This fragmentation is usually the dominant reaction and in Table I a comparison of the loss of ketene ($M - C_2H_2O$) relative to this ethylene elimination ($M - C_2H_2$) for a series of monocyclic 2-cyclohexenones is summarized.

Table I. Loss of Ketene from 2-Cyclohexenones[a]

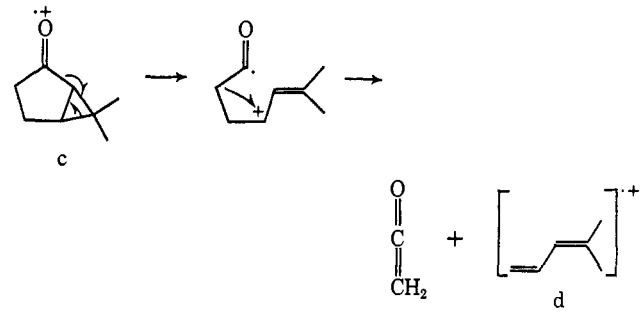
Compound	Mass $M - C_2H_2O$	$\%\Sigma_{39}$ $M - C_2H_2O$	Rel intensity $M - C_2H_2O$	Rel intensity $M - C_2H_4$
1, $R_2, R_6 = H$	54	0.61	2	100
2, $R_2 = CH_3$	68	0.95	1	100
3, $R_2, R_3 = CH_3$	82	<0.80	3	100
4, $R_3 = CH_3$	68	0.41	1	100
5, $R_3, R_4 = CH_3$	82	4.69	21	100
6, $R_4 = CH_3$	68	6.72	34	100
7, $R_4, R_4' = CH_3$	82	15.92	100	90
8, $R_5, R_5' = CH_3$	82	<0.94	2	100[b]
9, $R_3, R_5, R_5' = CH_3$[c]	96	<0.33	2	100[b]
10, $R_6 = CH_3$	54[d]	<0.56	1	100[e]
11, $R_4, R_4', R_6 = CH_3$	82[d]	4.27	20	100[e]

[a] Values are calculated from complete high-resolution spectra for all compounds except **3**, **8**, **9**, and **10**. All R = H unless otherwise specified. [b] In the case of **8** and **9**, the peak occurs at $M - (26 + 2R_5)$. [c] J. H. Bowie, *Aust. J. Chem.*, **19**, 1619 (1966). [d] In the case of **10** and **11**, the peak occurs at $M - (41 + R_6)$. [e] In the case of **10** and **11**, the peak occurs at $M - (27 + R_6)$.

The loss of ketene is prominent in the fragmentation of only those compounds which have at least one methyl substituent at C-4.[3,4] A related minimal structural requirement has been established for the photoinduced rearrangement of cyclohexenone derivatives to the bicyclo[3.1.0]hexan-2-one system, *i.e.*, two alkyl substituents are required at C-4 before rearrangement of the type **7** to **12** is observed.[19] This similarity in the minimal structural requirements is suggestive that before fragmentation occurs in the vibronically excited state, there occurs a rearrangement of some of the molecular ions of **7** to molecular ion c, a species formally analogous to the photoisomer **12**. One pathway by



which the ketene could be lost would be the subsequent fragmentation of this rearranged molecular ion c. An



alternative interpretation is also possible, whereby both compounds **7** and **12** decompose through a common intermediate. However, the interest here is in testing the possibility of a photochemical analogy, and the decomposing molecular ions will be discussed primarily in terms of the ionized photoproduct **12**.

The high-resolution mass spectra of **7** and **12** are shown in Figures 1 and 2, respectively. All the mass peaks in Figure 2 are present in Figure 1. In the fragmentation of **7**, the elimination of ethylene leads to a number of oxygen-containing ions which are present but are not prominent in the spectrum of **12**. These oxygen fragmentation pathways will be discussed in a later section. The $C_6H_{10}^+$ ion (M − ketene) is an important ion in the spectra of both compounds and in

(16) J. Seibl and T. Gaumann, *Helv. Chim. Acta*, **46**, 2857 (1963). Ketene is lost to a small extent in the fragmentation of 4-methylcyclohexanone. The spectrum of 2,2,6,6-d_4 derivative reveals that only one α-deuterium atom is found in the ketene and thus, a completely different mechanism from that required in the unsaturated systems under consideration is in operation.

(17) See ref 9, pp 147–153.

(18) H. Budzikiewicz, C. Djerassi, and D. H. Williams, "Structure Elucidation of Natural Products by Mass Spectrometry," Vol. 2, Holden-Day, Inc., San Francisco, Calif., 1964, pp 64–91.

(19) W. G. Dauben, G. W. Shaffer, and N. D. Vietmeyer, *J. Org. Chem.*, in press.

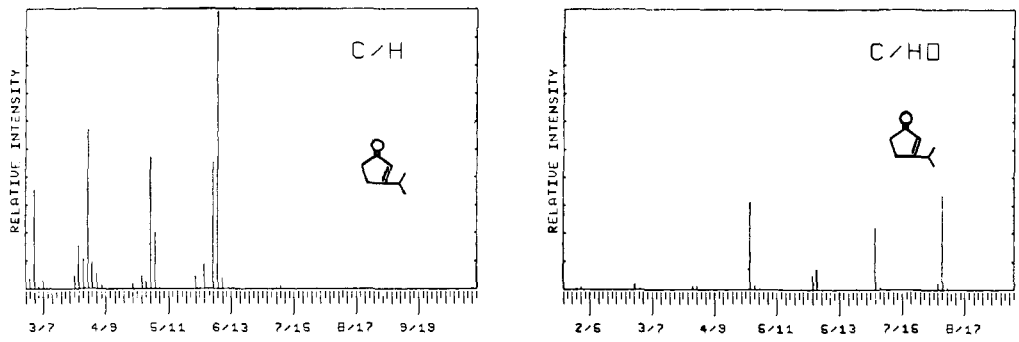


Figure 3. High-resolution mass spectrum of 3-isopropyl-2-cyclopentenone (**13**).

the case of the bicyclo[3.1.0]ketone **12**, this ion carries the major portion of the ion current, Σ_{39} 27.47. The appearance of a metastable peak at 54.3 supports the suggestion of the direct formation of this ion from the molecular ion by loss of ketene. Also, both deuterium atoms in 3,3-d_2-6,6-dimethylbicyclo[3.1.0]hexan-2-one appear in 89% of the ketene molecules, confirming the origin of the ketene from C-2 and C-3. The M − ketene ion is also a major one in the fragmentation of 3,6,6-trimethylbicyclo[3.1.0]hexan-2-one, and 5-methylbicyclo[3.1.0]hexane-2-one. Thus, elimination of ketene is a characteristic and an important mode of fragmentation of the bicyclo[3.1.0]hexan-2-one ring system. Since these latter types of compounds are also derived from related cyclohexenones by ultraviolet irradiation,[19] it is suggestive that this series of compounds is another example in which rearrangement observed on photon absorption also occurs on electron impact.[20-22]

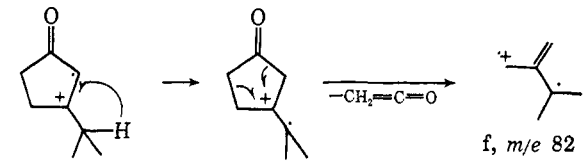
To further evaluate the correctness of the rearrangement postulate for the process leading to the elimination of ketene, the metastable peaks for **7** and its two photoisomers,[23] **12** and 3-isopropyl-2-cyclopentenone (**13**) were measured. All three spectra possess a metastable peak at 54.7, *i.e.*, $67^2/82$, corresponding to the process for the moiety (M − ketene) losing a methyl group and a metastable peak at 35.6, *i.e.*, $54^2/82$, for the elimination of ethylene from the M − ketene ion. The ratios of the intensities of the two peaks are reported in Table II. The agreement in the value for the ratios for compounds **7** and **12**, as compared with the value for **13**, confirms[24,25] the structural and energetic similarity of the mass 82 ions formed by loss of ketene from the two molecular ions of **7** and **12**. The triangular and Gaussian shapes of metastable peaks 54.7 and 35.6, respectively, are the same in all three spectra.

Table II. Intensity Ratio of Metastable Peaks

Compd	Intensity ratio[a]
7	27 ± 6
12	29 ± 6
13	15 ± 33

[a] Of peaks at 54.7 and 35.6.

The different intensity ratios of the metastable peaks for the α,β-unsaturated ketone **13** indicates the (M − ketene) peaks arose by a mechanism different from that followed by **7** and **12**. The high resolution spectra of **13** is shown in Figure 3 and the elimination of ketene again leads to the base peak but the intensities in the remainder of the spectrum are different. One possible mechanism for the fragmentation of **13** involves the



migration of the tertiary hydrogen from the isopropyl group with the formation of ion e, an ionized β,γ-unsaturated enone. Elimination of ketene from e would lead to an ion f of mass 82 which differs structurally from the ion d postulated in the fragmentation of **7** and **12**. Such a difference between d and f is consistant with the nonequivalent ratio of intensities of the two metastable ions given in Table II.

The loss of ketene from an α,β-unsaturated cyclopentenone is not a general fragmentation process. The base peak in the mass spectrum of 3-isopropyl-5-methyl-2-cyclopentenone is generated by the elimination of C_3H_4O from the molecular ion. However, the elimination of ketene is not observed in the fragmentation of 3-methyl-2-cyclopentone. Thus, if deconjugation of the double bond does precede the loss of a ketene, apparently such an isomerization can occur only when the hydrogen to be transferred is tertiary.

The low-resolution spectra of a second pair of photoisomers, 4,4,6-trimethyl-2-cyclohexenone (**11**) (Figure 4) and 3,6,6-trimethylbicyclo[3.1.0]hexan-2-one (**14**) (Figure 5), are compatible with the suggestion that methylketene is eliminated in the fragmentation of **11** after rearrangement of a small portion of the molecular ions to bicyclic molecular ion resembling **14**. The (M − C_3H_4O) ions formed in the decomposition of **11** (see Table I) lead to a relatively small peak (15% RI) at *m/e* 82, and the peak intensities in Figure 5 must be reduced proportionately in order to make a comparison.

Two points remain unexplained in this analogy to the photorearrangement. (a) Compounds **5** and **6** which do lose ketene on electron impact have not been

(20) F. W. McLafferty, *Anal. Chem.*, 31, 82 (1959).
(21) N. J. Turro, D. C. Neckers, P. A. Leermakers, D. Seldner, and P. D. Angelo, *J. Amer. Chem. Soc.*, 87, 4097 (1965).
(22) P. Brown, J. Kossanyi, and C. Djerassi, *Tetrahedron Suppl.*, [I], 8, 241 (1966).
(23) O. L. Chapman, T. A. Rettig, A. I. Dutton, and P. Fitton, *Tetrahedron Lett.*, 2049 (1963).
(24) H. M. Rosenstock, V. H. Dibeler, and R. N. Harlee, *J. Chem. Phys.*, 40, 591 (1964).
(25) T. W. Shannon and F. W. McLafferty, *J. Amer. Chem. Soc.*, 88, 5021 (1966).

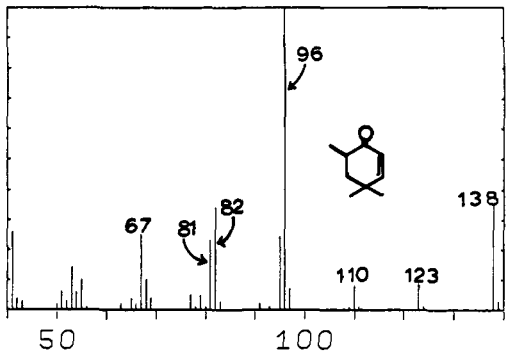


Figure 4. Mass spectrum of 4,4,6-trimethyl-2-cyclohexenone (**11**).

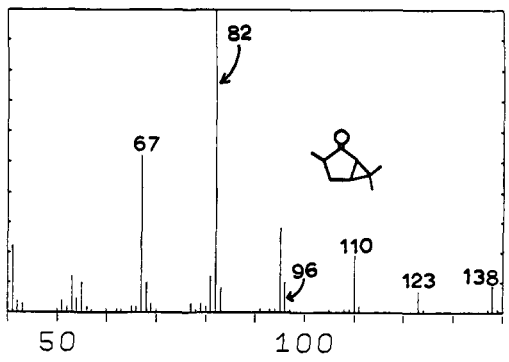


Figure 5. Mass spectrum of 3,3,6-trimethylbicyclo[3.1.0]hexan-2-one (**14**).

found to rearrange to a bicyclic system upon ultraviolet irradiation.[19] (b) Comparison of the mass spectra of the bicyclo[3.1.0]hexane photoproducts of polynuclear unsaturated ketones with those of their precursors (*i.e.*, the photoproduct of cholestenone (**22**)[26] with that of cholestenone, itself) indicates that "photorearrangement" cannot be the major path under electron impact leading to the loss of ketene from polynuclear systems.

To evaluate the first point, let us consider the cyclohexenone derivatives which lose ketene on electron impact but which have been found not to rearrange, photochemically. A complete parallel between the reactions might not be expected as it has been established[27] that a molecule is excited on electron impact into a multiplicity of electronic states, including optically forbidden ones, and photoionization studies[28] suggest that much fragmentation takes place from these higher electronic states. To evaluate the effect of the energy retained in the vibronically excited state, the mass spectrum of one of the ketones which does not photochemically rearrange, 4-methyl-2-cyclohexenone (**6**), was compared with the spectrum of 4,4-dimethyl-2-cyclohexenone (**7**), at 70 and 12 eV. In Table III it can be seen that the extent of ketene elimination in the dimethyl compound **7** is doubled at low ionizing energy.

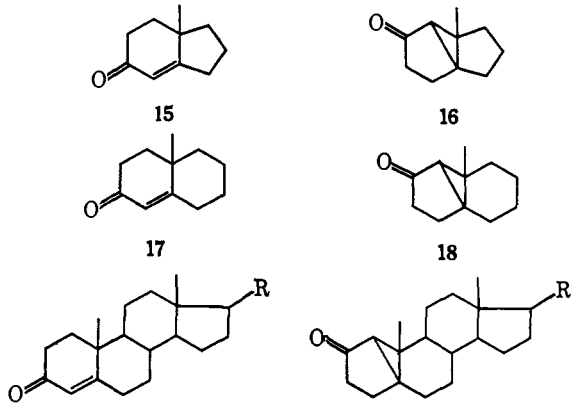
Table III. Per Cent Total Ionization of M − Ketene Ion at Two Ionizing Voltages for 4-Methyl-2-cyclohexenone (**6**) and 4,4-Dimethyl-2-cyclohexenone (**7**)

Compd	M − C_2H_2O, 70 eV	M − C_2H_2O, 12 eV[a]
6[b]	Σ_{39} 4.26	Σ_{39} 5.62
7	Σ_{39} 16.66	Σ_{39} 32.62

[a] Both samples were measured at low electron voltage without changing instrument settings. [b] Both values are calculated for the $C_6H_6^+$ ion only, its contribution to **6** being 38% of the peak at 70 eV and 41% at 12 eV.

The prominence of the M − 42 peak in the low electron voltage spectrum indicates that this elimination is one of the fragmentation pathways which requires the lesser energy. On the other hand, in the decomposition of the monomethyl compound **6**, the extent of ketene elimination changes little between 12 and 70 eV. The facility with which these two compounds eliminate ketene on electron impact is in the same relative order as their ability to undergo photorearrangement to the bicyclo-[3.1.0]hexan-2-one structure.

Turning to the second point, a number of bicyclic and polycyclic unsaturated ketones have been found to undergo the photorearrangement to a bicyclo[3.1.0]-hexane upon irradiation with ultraviolet light. The mass spectra of these rearranged compounds have been compared with those of the starting unsaturated ketones in the same manner as discussed earlier. The mass spectra of $\Delta^{4(9)}$-8-methyltetrahydroindan-5-one (**15**) and its photoproduct **16**[19] are compatible with the suggestion that one of the paths of fragmentation of the unsaturated ketone goes through an intermediate resembling the molecular ion of the photoproduct. The spectra of $\Delta^{1(9)}$-10-methyl-2-octalone (**17**) and its photoproduct **18** are similar but the close correlation desired is lacking. The spectrum of the photoproduct **20** from testosterone acetate (**19**) and photoproduct **22**



19, R = OAc
21, R = C_8H_{17}
20, R = OAc
22, R = C_8H_{17}

from cholestenone (**21**) are quite different from those of their unsaturated ketone precursors (see Table IV). Thus, the photorearrangement lumiproduct does not lie in the major pathway leading to elimination of ketene upon electron impact of these steroidal enones.

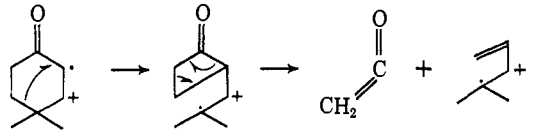
Recently,[4] an alternative type of rearrangement of the molecular ion prior to fragmentation to ketene has been suggested. In this process, it was postulated that a bond migration to form a cyclobutanone species occurred and this latter system underwent rearrangement to yield ketene. Such a rearrangement to a cyclobutanone has been found to occur to a minor extent when 4,5-diphenyl-2-cyclohexenone is irradiated with

(26) B. A. Shoulders, W. W. Kwie, W. Klyne, and P. D. Gardner, *Tetrahedron*, **21**, 2973 (1965).
(27) A. Kupperman and L. M. Raff, *Discussions Faraday Soc.*, **35**, 30 (1963).
(28) Professor James D. Morrison (LaTrobe University, Melbourne), private communication.

Table IV. Intensities of Selected Peaks in the Spectra of **19**, **20**, **21**, and **22**

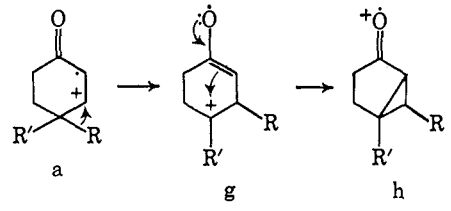
Compd	M	m/e 42	147	124	123	109
19	48	48	100	83	24	16
20	52	36	36	26	66	100
21	100	29	14	87	12	10
22	83	7	13	22	49	100

ultraviolet light. The major product, however, is the expected diphenylbicyclo[3.1.0]hexan-2-one. This 4,5-diphenyl derivative is the only cyclohexenone which has been found to yield any cyclobutanone.[29] In



view of the experimental evidence linking together the unsaturated ketone and the related bicyclo[3.1.0]-hexan-2-one, in at least one case (**7** and **12**) the bicyclo-[3.1.0]hexanan-2-one system remains a more attractive and more reasonable general intermediate from which to lose ketene.

In evaluating the role of bicyclic intermediates it must be realized that such an intermediate can be generated by any of several bond migrations in the cyclohexenone molecular ion in addition to the lumirearrangement to an ion of type c. For example, migration of a methyl group from C-4 to C-3, as shown in a, could lead to formation of the ionized bicyclo[3.1.0]-

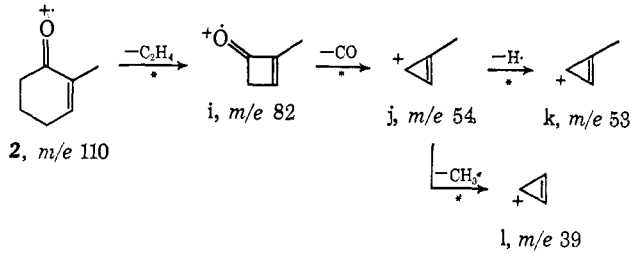


a g h

hexan-2-one h *via* g, in a manner analogous to the pathway b to c. In polycyclic systems like steroids, three different alkyl migrations are possible from the quaternary center γ to the carbonyl group. In **5** and **6**, migration of a tertiary γ-hydrogen also could lead to a bicyclo[3.1.0]hexan-2-one (a to h, R = H). Thus, a general mechanism can be postulated for the loss of ketene from a cyclohexenone derivative *via* a rearranged bicyclohexan-2-one system whose formation required migration of one of the substituents on the γ-carbon atom.

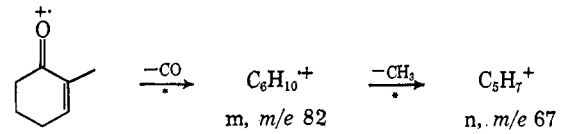
The structural features discussed above are necessary for the loss of ketene from cyclohexenones. The relative importance of such an elimination, however, may be altered by the presence of additional functional groups[30] and by the stereochemistry in the rigid steroidal system.[31]

Other Fragmentation Pathways. a. Substituted 2-Cyclohexenones. The major fragmentation paths for 2-cyclohexenone (**1**) have been delineated using exact mass measurements and by studying metastable ions.[32] This present investigation of a number of cyclohexenone analogs, some details of whose spectra are summarized in Table V, permits extension of this general scheme illustrated below for 2-methyl-2-cyclohexenone (**2**).[33] In the spectrum of **2**, however, one peak at *m/e* 67 (12%) which does not arise from the ion



2, *m/e* 110 i, *m/e* 82 j, *m/e* 54 k, *m/e* 53 l, *m/e* 39

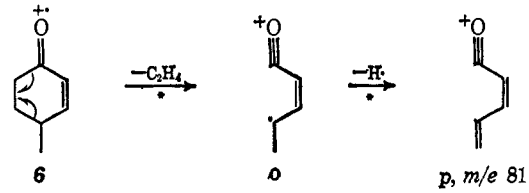
i, requires attention. This peak corresponds entirely to the $C_5H_7^+$ ion. The presence of a metastable ion at 54.7 supports the formation of this ion *via* the two-step process, M → M − 28 → M − 43, *i.e.*, 2 → m → n.



2, *m/e* 110 m, *m/e* 82 n, *m/e* 67

Ions of the type m, formed by loss of carbon monoxide from the molecular ions, account for about 2% of the base peak at *m/e* 82 (see Table V). The formation of M − C_2H_3O ions was confirmed in the high-resolution mass spectra of most of the other substituted cyclohexenones, and metastable ions which support the two-step mechanism postulated were also observed in the spectra of **5**, **7**, and **11** at 68.3, 68.5, and 82.0, respectively. This same fragmentation sequence has been postulated earlier,[4] but the exact mass measurements of this present study establish the quantitative importance of the process.

The relative intensity of the M − 29 peak varied with experimental conditions but in a set of low-resolution spectra all obtained under the same temperature and instrumental (modified CEC 21-103) conditions this peak was observed to be enhanced by the presence of a methyl group on C-4. Thus, in the spectra of compounds **2**–**4** and **8** and **10** the M − 29 peak has a relative intensity of 21, 12, and 12%, respectively. High-resolution mass spectra indicate that these latter three peaks correspond entirely to M − C_2H_5 ions. Metastable ions at *m/e* 94.0 for compound **5**, 82.0 for **6**, and 94.1 for **7** support a two-step mechanism, **6** → o → p, the loss of ethylene followed by the loss of



6 o p, *m/e* 81

hydrogen atom. The apparent enhancement of the secondary hydrogen loss by substituents at C-4 suggests that at least some of the M − C_2H_4 ions are not

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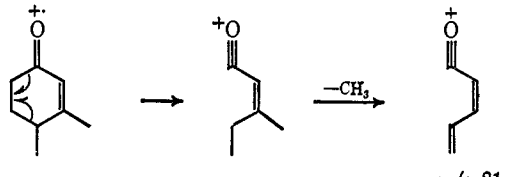
(33) The asterisk under the arrow denotes that an appropriate metastable peak for the transformation has been observed in the spectrum.

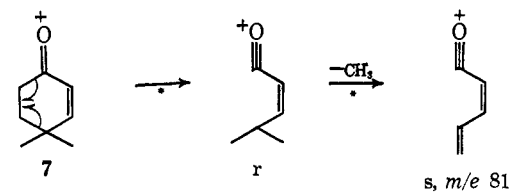
Table V. Relative Intensity and Composition of M − 28, M − 42, and M − 56 in the Mass Spectra of Several 2-Cyclohexenones

Compound	*m/e*	RI[a]	Isobars: % CH	Isobars: % CHO	Deuterated analogs	Occurrence in analog
1, R_2–R_6 = H	68	100	4	96		
	54	4	50	50		
	40	22	100	0		
2, R_2 = CH_3	82	100	2	98		
	68	3	33	67		
	54	39	100	0		
4, R_3 = CH_3	82	100	1	99		
	68	1	80	20		
	54	20	99	1		
5, R_3, R_4 = CH_3	96	100	0	100		
	82	37	57	43		
	68	14	94	6		
6, R_4 = CH_3	82	100	4	96	2,4,6,6-d_4	91% 84, 9% 86
	68	85	38	62		26–57% 70, 43–74% 71
	54	31	98	2		
7, R_4, R_4' = CH_3	96	90	0	100	6,6-d_2	95% 96, 5% 98
	82	100	98	2		84–87% 82, 13–16% 84
	68	33	24	76		40–50% 68, 37–50% 70
8, R_5, R_5' = CH_3	96	2	28	72		
	82	2	60	40		
	68	100	0	100		
10, R_6 = CH_3	82	2				
	68	100				
	54	1				
11, R_4, R_4, R_6 = CH_3	110	8	39	61	6-d_1	46% 110, 54% 111
	96	100	8	92		91% 96, 9% 97
	82	34	45	55		33% 82, 67% 83

[a] RI = relative intensity.

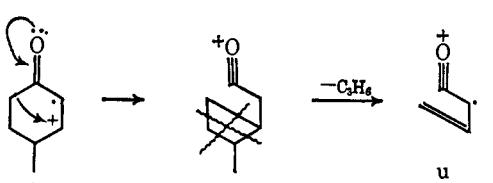
cyclic ions of type i as has been suggested,[32] but are open ions of type o. In the spectrum of 4,4,6-trimethyl-2-cyclohexenone (**11**) a metastable ion at 94.0 indicates that analogous loss of C_3H_6 and a hydrogen atom, although the process is kinetically less competitive in this larger system. Peaks corresponding to the loss of C_3H_7 from the molecular ion are prominent in the spectra of 3,4-dimethyl-2-cyclohexenone (**5**), where about 75% of the M − 43 peak (35% RI) corresponds to C_5H_5O ions, and in the spectrum (Figure 1) of 4,4-dimethyl-2-cyclohexenone, where about 38% of the M − 43 peak (71% RI) corresponds to C_5H_5O ions. The M − C_3H_7 peak is small or absent in the spectra of the monosubstituted and the 5,5-dimethyl compounds. Again such ions can best be rationalized by a two-step formation involving open ions like o, *i.e.*, q from **5** and r from **7** shown below. The metastable





ions for the sequence **7** → r → s are ambiguous since the elimination of carbon monoxide and methyl radical could produce diffuse peaks at nearly the same values. In the spectrum of 6,6-d_2-4,4-dimethyl-2-cyclohexenone about half the ions of mass 81 have lost both deuterium atoms, and presumably, carbon-6 as required by the above rationale.

The occurrence in the spectra of 4,4,6-trimethyl- and 4,4-dimethyl-2-cyclohexenone of prominent peaks corresponding to M − C_4H_8 ions (see Table V) and in the spectra of 4-methyl- and 3,4-dimethyl-2-cyclohexenone of large M − C_3H_6 peaks suggest a mode of fragmentation whereby C-4 and C-5 and their substituents are lost. In the spectrum of 6-methyl-2-cyclohexenone, the loss of 28 mass units is quite small, suggesting that substituents on C-4 promote the fragmentation. In Table V, it can be seen that the spectra of the deuterium-labeled analogs are compatible with the loss, to varying extents, of the two carbons suggested. Again, the elimination requires formal cleavage of a vinylic bond and to circumvent this undesirable process, the fragmentation sequence **6** → t → u can be postulated.



Here again bond migration occurs to the β-carbon of the double bond, this time leading to a familiar oxonium ion. The resulting cyclobutyl ring could cleave in two ways, forming a conjugate ion radical by loss of C_2H_4 or C_3H_6 moieties. It should be recalled that two other mechanisms (**2** → i and **6** → o) have already been discussed for the loss of the same C_2H_4 unit.

Finally, from Table V, it is clear that a larger portion of the M − C_4H_8 ions in the spectrum of 4,4-dimethyl-2-cyclohexenone has lost the deuterium labels and, thus, also C-6. This over-all loss of the C_4H_8 unit most

likely proceeds by stepwise elimination of two ethylene molecules by an undetermined mechanism.

In summary, therefore, the general fragmentation sequences observed for the 2-cyclohexenones studied are

$$M \longrightarrow M_{\text{bicyclo[3.1.0]hexan-2-one}} \longrightarrow$$

$$M - C_2H_2O \longrightarrow M - C_2H_2O - CH_3 \quad (1)$$

$$\longrightarrow M - C_2H_2O - C_2H_4$$

$$M \longrightarrow M - C_2H_4 \longrightarrow \begin{cases} \longrightarrow M - C_2H_4 - CH_3 \\ \longrightarrow M - C_2H_4 - CO \longrightarrow \begin{cases} M - C_2H_4 - CO - CH_3 \\ M - C_2H_4 - CO - H \end{cases} \quad (2) \\ \longrightarrow M - C_2H_4 - H \end{cases}$$

$$M \longrightarrow M - CO \longrightarrow M - CO - CH_3 \quad (3)$$

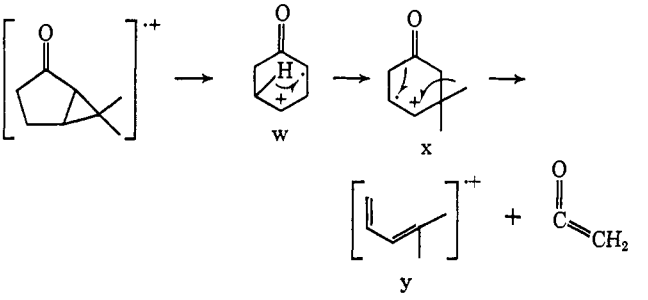
b. Substituted Bicyclo[3.1.0]hexan-2-ones. The mass spectra of three methyl-substituted bicyclo-[3.1.0]hexan-2-ones have been obtained and it has been found that the more methyl substituents the compound has, the smaller is the relative intensity of its molecular ion. There are at least four common fragmentation pathways followed by these compounds, the first pathway leading to the loss of ketene has been discussed earlier, the second is the loss of carbon monoxide by the molecular ion. In the high-resolution mass spectrum of 3,6,6-trimethylbicyclo[3.1.0]hexan-2-one (**14**), the major portion (85%) of the M − 28 peak (RI 10%) arises from the M − CO ion, *i.e.*, C_8H_{14} ion. In the spectrum of 5-methylbicyclo[3.1.0]hexan-2-one (**12**) only about 6% of a small M − 28 peak (see Figure 2) is due to the loss of carbon monoxide.

The loss of ethylene from the molecular ion, a process which dominates the fragmentation of the isomeric cyclohexenones, is not generally as prominent in the fragmentation of the bicyclic systems. The fragmentation of the 3,3-d_2 analog of 5-methylbicyclo[3.1.0]-hexan-2-one confirms the loss of carbon 3, and presumably 4, leading to a large peak at *m/e* 82 in the spectrum. However, the M − 28 peak in the spectrum of 6,6-dimethylbicyclo[3.1.0]hexan-2-one (**12**) is small, and in the spectrum of its 3,3-d_2 analog, the M − 28 peak is found to have several origins. The most abundant species, however, does arise from the loss of C-3 and presumably 4. The presence of a small peak at *m/e* 96, corresponding to M − C_3H_6 ions, in the mass spectrum of the 3,6,6-trimethyl compound **14** (see Figure 5) also is consistent with the loss of C-3, C-4, and the C-3 methyl substituent.

The loss of a methyl group has been observed in at least three different fragmentation sequences in this series of compounds. First, in the 6,6-dimethyl compound (**12**) a methyl group is lost from the molecular ion to give an ion which leads to a series of secondary fragmentations, as evidenced by metastable peaks for the processes 109 → 81, 109 → 67, and 109 → 55. Metastable peaks also document a number of decomposition paths from ions of mass 81, *i.e.*, 81 → 79 → 81 → 55, and 81 → 53. Second, in the subsequent fragmentation of the M − C_2H_2O moiety from molecular ion of **12**, the peaks at *m/e* 67 arise only from the C_5H_7 species and in the spectrum of the d_2 analog, this species is found to contain no deuterium. These facts are compatible with formation of an ion by loss of a methyl radical from the M − C_2H_2O ion, a process confirmed by a large metastable ion (RI 1%) at 57.4. Also, ions of mass 67 in the spectrum of the trimethyl compound **14** are similarly a homogeneous C_5H_7 species and again a prominent metastable peak at 54.7 confirms the formation of the C_5H_7 ion by loss of a methyl radical from the C_6H_{10} ion of mass 82. Third, in all three cases the M − 28 ion further fragments by loss of a methyl group as shown by the presence of metastable peaks at 68.3 in their spectra.

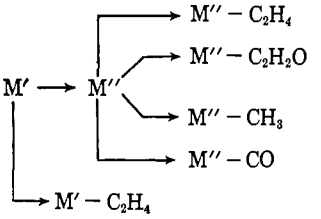
Finally, the study of the deuterated analogs of the 5-methyl- and the 6,6-dimethylbicyclic systems revealed that a small portion, 11 and 16% respectively, of the M − C_2H_2O ions retain both deuterium atoms. This result requires the loss of a carbon atom other than C-3 in the ketene moiety and the loss of C-1 together with the carbonyl carbon atom is reasonable. In agreement with such a suggestion, in the high resolution spectrum of the 3,6,6-trimethylbicyclic ketone, a small M − C_2H_2O peak is present in addition to the M − C_3H_4O base peak.

As shown in Table V, 6,6-d_2-4,4-dimethyl-2-cyclohexenone yields a M − ketene ion (*m/e* 84) retaining 11–14% of the deuterium label. Such a result demands a second fragmentation pathway stemming from the previously established bicyclic intermediate. One such new pathway which could arise from the molecular ion of **12** is the ion w formed by the cleavage of the internal



bond of the three-membered ring. This latter ion, in turn, could by hydrogen migration yield ion x which then could lose ketene and yield the ion y.

As a general summary the fragmentation scheme shown below correlates the major, first formed, ions from both the 2-cyclohexenones and bicyclo[3.1.0]-hexen-2-ones. In this summary, the difference in composition of the fragment due to a substituent is not noted, *i.e.*, C_2H_4 could be C_3H_6, etc.



M′ = 2-cyclohexenone molecular ion
M″ = bicyclo[3.1.0.]hexan-2-one molecular ion

Experimental Section

Mass Spectrometry. Low-resolution mass spectra were obtained on a modified CEC 21-103C mass spectrometer and also on a CEC 21-110 instrument. For the steroid derivatives **19–22** the direct inlet probe was used with source temperature at approximately 210°. All other compounds were inserted through the glass inlet

system at temperatures between 180 and 230°. Complete high-resolution mass spectra were measured on the CEC 21-110 mass spectrometer.

The low electron voltage spectra also were obtained on the model 21-110B mass spectrometer. Metastable ion measurements reported in Table II were made on an Associated Electrical Industries MS-12 mass spectrometer with a glass inlet system at 200°.

Deuterium Exchange. The appropriate compound was subjected to exchange on a deuterium oxide treated potassium hydroxide–Carbowax vapor phase chromatography column.[34] 4,4-Dimethyl-2-cyclohexenone yielded 76% 6,6-d_2 and 24% 6-d_2; 6,6-dimethylbicyclo[3.1.0]hexan-2-one yielded 75% 3,3-d_2 and 18% 3-d_1; 4,4,6-trimethyl-2-cyclohexenone yielded 79% 6-d_1; and 4-methyl-2-cyclohexenone yielded 58%, 2,4,6,6-d_4 and 34% d_3. 5-Methylbicyclo[3.1.0]hexenone was exchanged to the 3,3-d_2 derivative of greater than 99% isotopic purity by stirring in deuterium oxide and methanol-OD with sodium methoxide.

Synthesis of the Ketones. The syntheses of the ketones used in this study have been described in a separate publication.[10]

Acknowledgment. The authors express their appreciation to Professor A. L. Burlingame for his interest and assistance in this work.

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The Two Mechanisms for the Acid-Catalyzed Hydrolysis of Enol Acetates[1]

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Abstract: Hydrolysis of α-acetoxy-*p*-nitrostyrene (**6**) in 1 *M* sulfuric acid shows the characteristics of normal ester hydrolysis. In D_2O, the solvent isotope effect, k_{H_2O}/k_{D_2O}, is 0.75; the rate of hydrolysis is very similar to the rate of hydrolysis of isopropyl acetate. Increasing the concentration of sulfuric acid causes an increase in rate which is nonlinear with the acidity function H_0, but which closely parallels the increasing rate of hydrolysis of isopropyl acetate. In sulfuric acid concentrations greater than 55%, the rate of hydrolysis of **6** increases very rapidly. In 69% sulfuric acid, the solvent isotope effect, k_{H_2O}/k_{D_2O}, is now 3.25. Thus, the mechanism has changed to one involving initial, and rate-determining, olefin protonation. The effect of substituents in substituted α-acetoxystyrenes further serves to substantiate the two mechanisms, and to delineate the circumstances under which each of the two mechanisms will be dominant.

Recently there has been a good deal of interest in the acid-catalyzed hydrolysis of enol derivatives.[2-4] Studies with enol ethers have shown that these reactions involve rate-determining protonation at carbon and that they show general acid catalysis and a high order of reactivity. Studies of the hydrolysis of enol acetates have been somewhat less extensive. DePuy has studied the alkaline hydrolysis of several enol acetates.[5] The hydrolysis of vinyl acetate in relatively concentrated hydrochloric acid has been examined very carefully by Yrjänä,[6] and he concludes that normal ester hydrolysis is occurring. Though Kiprianova and Rekasheva[7] and Landgrebe[8] propose mechanisms involving initial protonation on carbon, Yrjänä[6] gives very compelling reasons for preferring a mechanism for the hydrolysis which is normal ester hydrolysis, including a consideration of the relative rate of reaction, the entropy of activation and the solvent isotope effect.

It was noted by Hammett[9] that in acid hydrolysis of esters the effect of structure in the alcohol component is very small in marked contrast to the large effect observed in alkaline hydrolysis. Variation from *t*-butyl to benzyl or phenyl caused a change of less than a factor of 2 in rate.

The acid hydrolysis of benzyl acetates[10] has a ρ of only -0.05.

We have examined the rates for the acid-catalyzed hydrolysis of a series of ring-substituted α-acetoxystyrenes and we find that enol acetates may hydrolyze through two different pathways. The first is that proposed by Yrjänä,[6] which is the same mechanism by which most saturated esters hydrolyze. The second involves protonation of the carbon–carbon double bond. Two different factors determine which mechanism is to be active in any given situation. The first is the acidity and the second is the stability of the carbonium ion formed by the protonation of the carbon-carbon double bond.

Experimental Section[11]

Preparation of Materials. The following general procedure was used to prepare the substituted α-acetoxystyrenes used in this study.

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(11) Analyses are by the Microanalytical Laboratory, University of California, Berkeley, Calif. Melting points and boiling points are uncorrected.