A GLC purified sample of **12** (14.0 mg, 0.071 mmol) was reduced with $LiAlH_4$ (0.071 mmol) and worked up as in the preceding experiment. The SE-30 fractionation yielded one peak (49% yield), t_R 14.0 min, and the elemental analysis was obtained for this material. Chromatography with Carbowax 20M gave two peaks of approximately equal size, t_R 12.7 and 13.5 min, which were designated **14a** and **14b**, respectively.

14a: infrared spectrum (CCl_4) 2985, 2945, 2895, 1462, 1382, 1130, 1112, 1045, 1040, 925, 920, 900 cm^{-1}; mass spectrum *m/e* (rel intensity) 27 (11), 29 (32), 41 (11), 43 (15), 55 (14), 57 (100), 72 (31), 81 (7), 96 (4), 114 (10), 128 (6), 140 (4), 170 (M^+, 10).

14b: infrared spectrum (CCl_4) 2985, 2940, 2885, 1453, 1378, 1122, 1105, 1043, 1030, 913 cm^{-1}; mass spectrum *m/e* (rel intensity) 27 (12), 29 (26), 41 (12), 43 (16), 55 (14), 57 (100), 72 (31), 81 (7), 96 (4), 114 (11), 128 (5), 140 (4), 170 (M^+, 9).

Anal. Calcd for $C_{10}H_{18}O_2$; C, 70.66; H, 10.59. Found: C, 70.51; H, 10.78.

Acknowledgments. The authors gratefully acknowledge the support of the U.S. Forest Service, the Elm Research Institute, the Rockefeller Foundation, and the College of Environmental Science and Forestry. We wish to thank Dr. J. W. Peacock and Mr. R. A. Cuthbert, U.S. Forest Service, Delaware, Ohio, and Drs. G. N. Lanier and J. B. Simeone, State University of New York, College of Environmental Science and Forestry, for their assistance in the various entomological aspects of this research program; and Mrs. Hazel Jennison and Mr. Larry McCandless for their help in obtaining mass spectra and NMR spectra. The Varian XL-100 NMR spectrometer was obtained through a grant from the National Science Foundation.

Registry No.—**2**, 80-62-6; **6**, 25044-01-3; **7**, 18707-60-3; **10**, 57428-74-7; **11a**, 57428-75-8; **11b**, 57457-89-3; **12**, 57428-76-9; **14a**, 57428-77-0; **14b**, 57428-78-1; **16**, 57428-79-2; **18**, 4513-62-6.

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Mass Spectrometric Studies of the Dioxabicyclo[3.2.1]octanes Multistriatin, Frontalin, and Brevicomin

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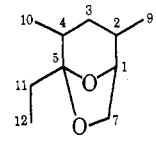
Received July 9, 1975

Mass spectra were recorded for three alkyl-substituted dioxabicyclo[3.2.1]octanes, 2,4-dimethyl-5-ethyl-6,8-dioxabicyclo[3.2.1]octane (multistriatin), 1,5-dimethyl-6,8-dioxabicyclo[3.2.1]octane (frontalin), and 5-methyl-7-ethyl-6,8-dioxabicyclo[3.2.1]octane (*exo*-brevicomin), and for the corresponding deuterium-labeled compounds 4,11-11-trideuteriomultistriatin, 4,4,10,10,10-pentadeuteriofrontalin, and 4,4,9,9,9-pentadeuterio-*exo*-brevicomin, and structures were assigned for the characteristic ions. Where possible the relative abundances of the observed ions were related to the alkyl group substituents, and a general fragmentation pattern was proposed.

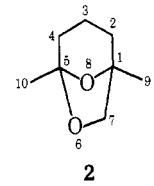
Multistriatin (**1**) was isolated and identified as one component of a three-component aggregation pheromone of the European elm bark beetle.[1] In the initial phase of the identification process, the mass spectrum exhibited several distinctive peaks, but this information did not provide definitive evidence for the bicyclic ketal ring system or the type of ring substitution.

After the structure of **1** was proved, the mass spectrum of **1** was compared with the reported spectra of known bicyclo[3.2.1]octane derivatives, including two insect pheromone components, frontalin (**2**)[2] and *exo*-brevicomin (**3**),[3] and to the known fragmentation patterns for cyclic ketals.[4] Inspection of the available data revealed that some ions were common to two or more of the bicyclic ketals. However, the identities of most of the ions were uncertain, and a fragmentation pattern for the substituted dioxabicyclo[3.2.1]octanes was not obvious.

We collected three types of data for the dioxabicyclo[3.2.1]octanes **12**, and **3**: (1) unit resolution electron impact (EI) mass spectra, (2) unit resolution EI spectra of deuterium labeled compounds, (3) high-resolution EI spectra of unlabeled compounds. The objective of these experiments was to determine the characteristic fragments of these dioxabicyclo[3.2.1]octanes and the effects of alkyl substituents on the fragmentation pattern.



1



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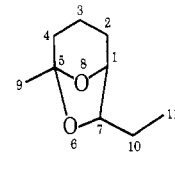


3

Results and Discussion

Multistriatin (**1**) exists as four diastereomers which have been synthesized and purified,[5] and the unit resolution spectrum of each isomer was recorded. Since no qualitative and only minor quantitative differences were observed in

Table I
Mass Spectral Data for α-Multistriatin (1)

Peak, m/e	Rel abundance (% of base peak)	Corresponding peak in 1′,[a] m/e	Formula[b]
27	11		
29	28		
39	9		
41	13		
43	6		
55	21	55	
57	100	59	
71	13	71	C_4H_7O
72	4		
81	10	82	C_6H_9
86	5		$C_5H_{10}O$
96	15	97	C_7H_{12}
99	3		
128	9	130	$C_7H_{12}O_2$
140	4		
170	4	173	$C_{10}H_{18}O_2$

[a] 1′ is multistriatin-d_3. [b] Formulas obtained from high-resolution MS data of 1.

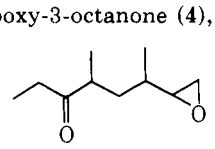
Table II
Mass Spectral Data for Frontalin (2)

Peak, m/e	Rel abundance (% of base peak)	Corresponding peak in 2′,[a] m/e	Formula[b]
27	8		
29	5		
39	10		
41	13		
43	100	46	
54	9		
55	8		
67	7		
69	5		
71	16	71	C_4H_7O
72	49	73	C_4H_8O
85	4		C_5H_9O
99	4		
100	23	103	$C_6H_{12}O$
112	6	117	$C_7H_{12}O$
142	9	147	$C_8H_{14}O_2$

[a] 2′ is frontalin-d_5. [b] Formulas obtained from high-resolution MS data of 2.

the four MS spectra, the data shown in Table I for the α isomer were regarded as representative of each of the multistriatin isomers. Similarly, no stereochemical effects were reported for *endo*- and *exo*-brevicomin,[6] and we have confined our experiments to the exo isomer, **3**. The compiled MS data for **2** and **3** are given in Tables II and III, respectively.

The mass spectra of the isomers of the precursor to **1**, 4,6-dimethyl-7,8-epoxy-3-octanone (**4**), were identical with



4

those recorded for **1**. Similar results have been observed in mass spectral studies,[7] and the conversion of a related keto epoxide to the bicyclic ketal structure has been reported.[8,9] The thermal conversion of **4** to **1** has been observed in this laboratory,[10] and this reaction could occur in the mass spectrometer inlet.

Acid-catalyzed D–H exchange at positions α to the ketal

Table III
Mass Spectral Data for *exo*-Brevicomin (3)

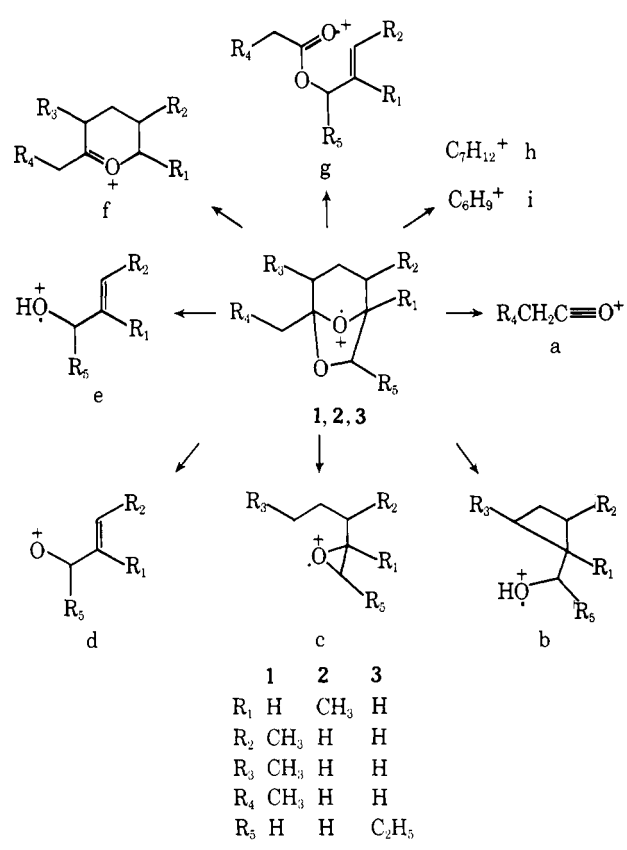
Peak, m/e	Rel abundance (% of base peak)	Corresponding peak in 3′,[a] m/e	Formula[b]
27	13		
29	9		
39	8		
41	12		
43	100	46	
55	7		
57	9		
68	15	68	
71	8		C_4H_7O
72	4		C_4H_8O
85	29	85/86	C_5H_9O
86	11	87	$C_5H_{10}O$
98	13	103	$C_6H_{10}O$
99	5		$C_6H_{11}O$
114	26	117	$C_7H_{14}O$
127	4	132	$C_7H_{11}O_2$
156	4	161	$C_9H_{16}O_2$

[a] 3′ is *exo*-brevicomin-d_5. [b] Formulas obtained from high-resolution MS data of 3.

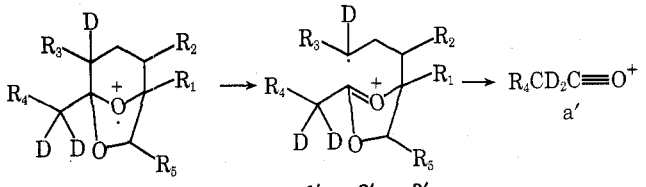
carbon atom occurred without decomposition of the bicyclic ketals,[5] and this method was used to prepare 4,11,11-trideuterio-α-multistriatin (**1′**), 4,4,10,10,10-pentadeuteriofrontalin (**2′**), and 4,4,9,9,9-pentadeuterio-*exo*-brevicomin (**3′**). The unit resolution MS for each compound was recorded, and the data for **1′**, **2′**, and **3′** are given in Tables I, II, and III, respectively.

The most abundant species observed for **1**, **2**, and **3** was the $R_4CH_2O^+$ ion. The retention of two D atoms in the *m/e* 59 ion in **1′** and three D atoms in the *m/e* 45 ions in **2′** and

Chart I
Mass Spectral Fragments from Multistriatin (1), Frontalin (2), and Brevicomin (3)

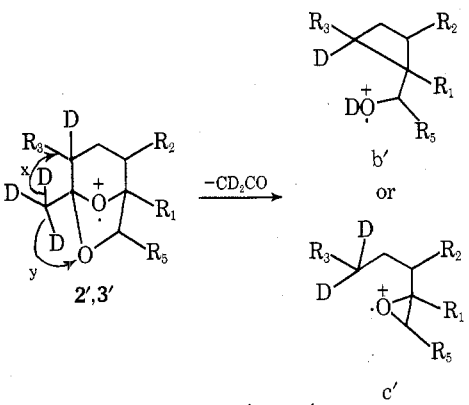


3′ supported the assignment of structure a′ for these ions and structure a for the corresponding ions *m/e* 57 in **1** and *m/e* 43 in **2** and **3**, as shown in Chart I. Fragment a was the predominant species observed for several other bicyclic ketals,[7,11] and a was also observed for the 2,2-dialkyldioxolanes.[4] The mode of formation of this ion in the bicyclic ketals was probably similar to that described for the cyclic ketals.[4] A possible mechanism for the formation of a′ (or a) is shown here.



	1′	2′	3′
R_1	H	CH_3	H
R_2	CH_3	H	H
R_3	CH_3	D	D
R_4	CH_3	D	D
R_5	H	H	C_2H_5

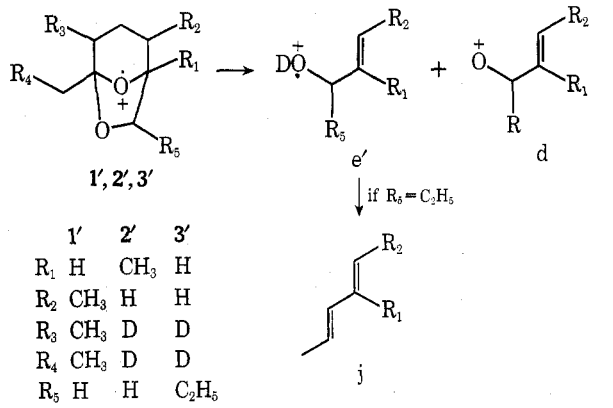
The loss of a related fragment with the formation of ions *m/e* 100 and 114 was observed in **2** and **3**, respectively. High-resolution data confirmed that CH_2CO was lost from the molecular ion, and deuterium labeling demonstrated that the intramolecular transfer of one D atom had occurred. A D shift from C-10 in **2′** or C-9 in **3′** to C-4 (path x) or to O-6 (path y) with the expulsion of CD_2CO could yield species c′ or b′, respectively. The corresponding M − CH_3CHCO peak in **1** was not observed.



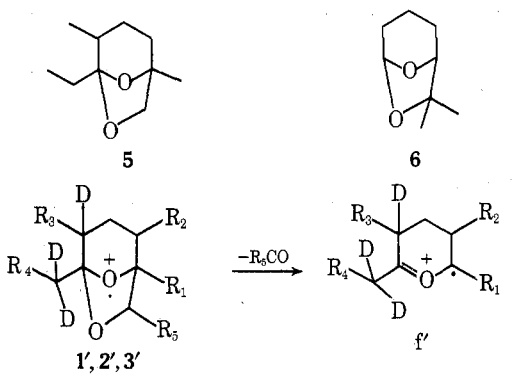
	2′	3′
R_1	CH_3	H
R_2	H	H
R_3	D	D
R_5	H	C_2H_5

The ions in **1** and **2** with *m/e* 71 ($C_4H_7O^+$) occurred with the *m/e* 72 ($C_4H_8O^{\cdot+}$) ions; and *m/e* 85 ($C_5H_9O^+$), 86 ($C_5H_{10}O^{\cdot+}$), and 68 ions were present in **3**. No D atoms were incorporated into the *m/e* 71, 85, or 68 ions, but one D atom was in the *m/e* 72 ions in **1′** and **2′** and the *m/e* 86 ion in **3′**. This evidence indicated that the *m/e* 71 and 85 ions were derived from C-7, C-1, and C-2, the attached alkyl groups, and one of the oxygen atoms; and that *m/e* 72 and 86 ions were the protonated forms of these species. Structures d and e were consistent with these data, and the *m/e* 68 ion (j) in **3** and **3′** can result from the elimination of H_2O from fragment e or HDO from e′. The incorporation of one D atom into e′ supported the hypothesis that an intramolecular H shift from C-9 to one of the oxygen atoms occurred during fragmentation.

An interesting substituent effect was observed for fragments d and e. In **1** and **3**, d was the more abundant ion (d:e 13:4 in **1**; 29:11 in **3**), but e was the most abundant ion in **2** (d:e 16:49). The same pattern was observed in the spectrum of 1,4-dimethyl-5-ethyl-6,8-dioxabicyclo[3.2.1]octane (**5**) (d:e = 7:31),[12] and this effect was attributed to the presence of an alkyl substituent at C1.

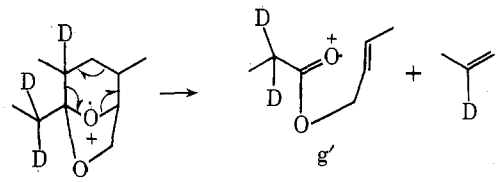


	1′	2′	3′
R_1	H	CH_3	H
R_2	CH_3	H	H
R_3	CH_3	D	D
R_4	CH_3	D	D
R_5	H	H	C_2H_5



The $C_6H_{10}O^{\cdot+}$ ion (*m/e* 98) in **3** retained all five D atoms in **3′** and was assigned structure f′. The corresponding ions which result from the loss of CH_2O were observed in the spectra of **1** and **2**, but the relative abundances were low. Substituent effects for alkyl groups at C-7 were important since the relative abundances of species f were 4, 6, and 13% in **1**, **2**, and **3**, respectively. Furthermore, in the reported MS data for the bicyclic acetal, 7,7-dimethyl-6,8-dioxabicyclo[3.2.1]octane (**6**),[11] f was the most abundant species.

A unique ion (*m/e* 128) which corresponded to M − CH_3CHCH_2 was present in the spectrum of **1**. The loss of C_3H_5D from **1′** with the retention of two deuterium atoms in the *m/e* 130 ion suggested that bonds C-2–C-3 and C-4–C-5 were broken. The formation of ion g or g′ via a retro-Diels–Alder process was consistent with the D labeling and the *m/e* data.



Once again, substituent effects were important since this species was observed for **1** but not for **2** and **3**. The C-2 methyl group in **1** could be related to the formation of this species; however, this possibility was precluded by the MS data obtained for **5**. This dioxabicyclo[3.2.1]octane did not contain a C-2 substituent, but the abundance of the M − CH_3CHCH_2 species was equal to that found in **1**.[12] These data did not exclude the possibility that the ethyl group at

C-5 in **1**, as opposed to the methyl groups in **2** and **3**, was related to this fragmentation pattern; however, the C-4 substituent was adjacent to the site of bond breaking and appeared to be the more important factor in this fragmentation pathway.

The loss of $CH_3CH_2CO_2H$ in **1** yielded a hydrocarbon fragment, $C_7H_{12}^+$ (h, *m/e* 96). One deuterium atom was retained in this ion and in the $C_6H_9^+$ ion (i, *m/e* 81), and the corresponding ions were not observed in **2** and **3**. The formation of h and i appeared to be a complex process, and neither the structure of the ions nor the substituent effects could be described with confidence.

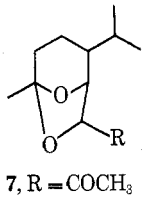
Conclusion

Ion species a–i, which are shown in Chart I, represent an ensemble of ions that appeared in the mass spectra of **1, 2,** and **3**. The relative abundances of these ions for a given dioxabicyclo[3.2.1]octane reflected the location of ring substituents, and the *m/e* for a given species was related to the structure of the substituent. Substituents at C-1 and C-2 contributed to the *m/e* of ions d and e, and the presence of alkyl groups at C-1 can be determined on the basis of the relative abundances of d and e. The presence of groups at C-4 and C-5 was related to ions a, b or c, and g. Alkyl substitution at C-5 was apparent in ion a and ions b or c, and our evidence suggested that C-4 substituents can be detected in the ionic species g.

The MS data for **1, 2,** and **3** and data obtained from literature[11] demonstrated that the relative abundance of f was determined by alkyl substituents at C-7. The elimination of water from e was possible when a C-7 alkyl substituent was present, and our data suggested that the e $- H_2O$ peak was evidence for a C-7 substituent.

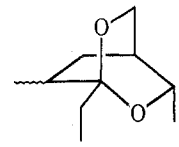
Ions a–g can be derived from the dioxabicyclo[3.2.1]octane ring system, and we have indicated how these ions can arise from **1, 2,** and **3**. Compounds 1 and 4 give identical mass spectra, and our evidence suggests that **4** is converted to **1** and that **1** is the primary ion source for the mass spectrum of both compounds. In laboratory experiments the thermal conversion of **4** to **1** is facile and high yielding,[10] and the reversal of this reaction in the spectrometer inlet seems unlikely. However, acyclic intermediates similar to **4** may be involved in the ionization process.

A recent communication described three dioxabicyclo[3.2.1]octanes: 5-methyl-2-isopropyl-7-acetyl-6,8-dioxabicyclo[3.2.1]octane (**7**), 5-methyl-2-isopropyl-7-hydroxyethyl-6,8-dioxabicyclo[3.2.1]octane (**8**), and 5-methyl-2-isopropyl-7-(1-methylhydroxyethyl)-6, 8-dioxabicyclo [3. 2. 1]-octane (**9**).[7] A small M $- CH_3CH_2$ peak was observed for **3**, and prominent peaks corresponding to the loss of the C-7 substituent were reported for **7, 8,** and **9**. A peak corresponding to a was the base peak for **7, 8,** and **9**, but most of the remaining fragments did not correspond to ions b–i. These data suggested that complex substituents may make a significant contribution to the mass spectra of substituted dioxabicyclo[3.2.1]octanes.



7, R = $COCH_3$
8, R = $C(OH)HCH_3$
9, R = $C(OH)(CH_3)_2$

Mass spectral data can supply considerable information about the structure of the dioxabicyclo[3.2.1]octanes; however, some potential sources of difficulty should be noted. The mass spectrum of a related bicyclic ketal structure, 3,7-dimethyl-1-ethyl-2,6-dioxabicyclo[2.2.2]octane (**10**),[12]



10

was compared to the spectrum of **1**. Most of the spectral characteristics observed in **1** were present in **10**, thereby indicating that mass spectrometry was not the method of choice for distinguishing the two ring systems.

The M $- CH_2CO$ peak (b, c) and the M $- CH_3CHCH_2$ peak g were coincident (P $- 42$) in **1**. This peak assignement problem can be solved by recording the spectrum of the D-labeled compound. Deuterium labeled compounds can also be utilized for the assignment of other peaks and for the determination of the number of substituents α to the ketal carbon atom.

Experimental Section

Preparation of Deuterium-Labeled Compounds. A sample of multistriatin (**1**, 50 mg) was refluxed in a mixture of 2.5 ml of 1 *M* deuteriophosphoric acid and 2.5 ml of THF for 48 hr.[5] The solution was saturated with NaCl, the THF layer was removed, and the water layer was extracted with 1 ml of fresh THF. The combined THF extracts were washed twice with 0.5-ml volumes of salt water. The THF solutions were dried initially over anhydrous potassium carbonate and then over 4-Å sieves. The products were separated by preparative GLC and the mass spectrum of each isomer fraction of **1** was recorded. The procedure was repeated for frontalin (**2**) and *exo*-brevicomin (**3**).

Mass Spectra. The unit resolution spectra were recorded on an Hitachi RMU-6E mass spectrometer at 70 eV ionization potential. The high-resolution spectra were recorded and empirical formulas were calculated with an AEI-9 computer–spectrometer system.

Acknowledgments. The authors gratefully acknowledge the support of the U.S. Forest Service, the Elm Research Insitute, the Rockefeller Foundation, and the College of Environmental Science and Forestry. We wish to thank Mrs. Hazel Jennison for her assistance in obtaining the unit resolution mass spectra and Dr. John D. Henion, Cornell University, for providing the high-resolution mass spectra. We would also like to acknowledge Dr. J. W. Peacock and Mr. R. A. Cuthbert, U.S. Forest Service, Delaware, Ohio, and Drs. G. N. Lanier and J. B. Simeone, State University of New York, College of Environmental Science and Forestry, for their continuing assistance throughout this research program.

Registry No.—**1**, 54815-06-4; **2**, 28401-39-0; **3**, 20290-99-7.

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