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Mass Spectrometry of Chromen-2-ones (Coumarins) and of Furo- and Pyrano-chromenones

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Mass-spectrometric results for the coumarins, furocoumarins, and pyranocoumarins are summarised. The characteristic elimination of carbonyl groups characteristic of coumarin itself can be traced also in the spectra of substituted (halogenated, hydroxylated, methoxylated, carbonylated, *O*- and *C*-alkylated, and *O*- and *C*-acylated) coumarins, but the nature of the substituent has a decisive influence on the way in which derivatives break down, and in many cases elimination of carbonyl groups takes place only after partial or complete elimination of the substituent. With bicoumarins elimination of carbonyl groups is observed in the later stages of decomposition or not at all. The regularities reported for coumarins are found also with furo- and pyrano-coumarins. Differences in the spectra of positional isomers are usually apparent only in differences in the peak intensities of the characteristic ions. There is a list of 59 references.

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I. INTRODUCTION

We began the mass-spectrometric investigation of natural chromen-2-ones (coumarin, umbelliferone, herniarin, and osthol) in 1963.[1] Independently, but a little later (1964), the same chromenones were studied by Barnes and Occolowitz[2]. The largely identical results obtained in the two investigations showed that, because of the specificity of the breakdown of chromen-2-ones on electron bombardment and the characteristic influence of the number, nature, and position of substituents on this process, mass spectrometry is an extremely promising method in this case as with other classes of naturally occurring compounds. This promise has been fully confirmed by the further accumulation of experimental information. The number of mass-spectrometric investigations on chromenones and their derivatives, including furo- and pyrano-chromenones, has now become very considerable, which has led us to attempt in this Review to systematise and summarise the accumulated results.

II. CHROMEN-2-ONE AND ITS HALOGENO-DERIVATIVES

The spectrum of chromen-2-one itself (I) is very simple (Fig. 1*a*), containing only five peaks—one due to the molecular ion having $m/e = 146$, peaks due to the repeated elimination of 28 amu (atomic mass units) ($m/e = 118$ and 90) and the loss of 29 amu at the second stage (or the detachment of 1 amu after the second elimination of 28 amu) ($m/e = 89$), and a fifth peak with $m/e = 63$, caused by breakdown of the aromatic ring and devoid of diagnostic significance.

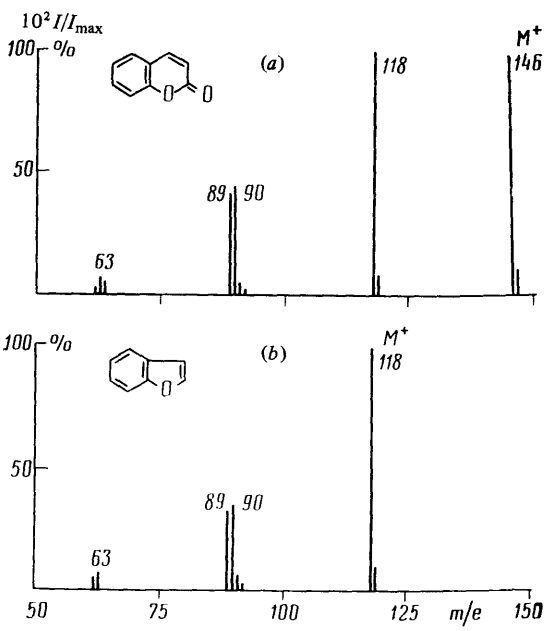


Figure 1. Mass spectra of: *a*) chromen-2-one; *b*) benzofuran.

It was reasonable to suppose that the first stage of decomposition involved elimination of the lactonic carbonyl, although the possibility of elimination of an ethylene molecule involving the 3- and 4-carbon atoms with migration

of two hydrogen atoms from the charged fragment could not be completely excluded. The first hypothesis is unambiguously supported by Zakharov's observations[3] of shifts of 1 amu to 119 and 91 (m/e) respectively in the peaks due to the ions $[M - 28]^+$ and $[M - 2 \times 28]^+$ in the mass spectra of the 3- and 4- deutero-analogues of chromen-2-one (Table 1). Similarly, double elimination of 28 amu occurs in the spectra of 3-chloro-, 4-chloro-, and 3,4-dichlorochromen-2-ones. Only in the spectrum of 3-bromochromen-2-one is this sequence changed: a molecule of carbon monoxide is eliminated first, then the bromine atom, and after this another carbon monoxide molecule.

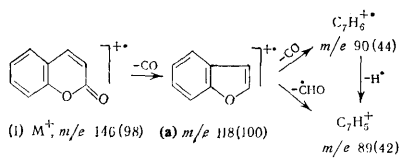
Table 1. Peaks (m/e) of main ions in the mass spectra of chromen-2-one and its deutero- and halogeno-derivatives (values of $100I/I_{max}$ given in parentheses, where I_{max} is the maximum intensity in the spectrum).

Chromenone derivative	M+	M—CO	M—2CO	M—Hal	M—Hal—CO	M—2CO—Hal
Chromen-2-one (I)	146 (98)	118 (100)	90 (44)	—	—	—
3-Deutero	147 (86)	119 (100)	91 (75)	—	—	—
4-Deutero	147 (88)	119 (100)	91 (41)	—	—	—
3-Chloro	180 / 182 (75)	152 / 154 (43)	124 / 126 (18)	145 (8)	117 (6)	89 (100)
4-Chloro	180 / 182 (99)	152 / 154 (44)	124 / 126 (15)	145 (10)	117 (10)	89 (100)
3,4-Dichloro	214 / 216 (83)	186 / 188 (47)	158 / 160 (23)	—	—	123 / 125 (100)
3-Bromo	224 / 226 (74)	196 / 198 (22)	—	145 (40)	117 (8)	89 (100)

A second mode of decomposition is also evident in the spectra of all the halogenated chromen-2-ones: elimination of the halogen atom from the molecular ion is followed by double elimination of carbonyl (Table 1).

In order to ascertain the possible structure of the $[M - CO]^+$ ion both the Reviewers[1] and the Australian workers[2] compared the mass spectra of chromen-2-one and benzofuran (a and b in Fig. 1), and concluded from their identity, beginning with the 118 peak ($[M - 28]^+$ for chromenone and the peak due to the molecular ion of benzofuran), that the molecular ion of chromenone, on losing a carbonyl group, is converted into a benzofuran ion (a), which in turn loses the second carbonyl group and then a hydrogen atom or else a formyl group at once (Scheme 1).

Scheme 1



The structure of the 118 ion has since been discussed many times, with arguments both for[4] and against[5-8] the benzofuran structure. The latter view was based on the difference between the appearance potential of the 118 ion on breakdown of the molecular ion of chromenone and the ionisation potential of benzofuran. In the Reviewers' opinion a more convincing argument is the similarity in the spectra of these two compounds, not only in the m/e values but also in the intensities of corresponding peaks (a and b in Fig. 1). However, this question has not been finally settled.

The spectrum of the corresponding dihydro-derivative—chroman-2-one, melilitol (II)—is very similar to that of the chromenone[2]: it too is characterised by successive double elimination of 28 amu with subsequent loss of a hydrogen atom (or elimination of 29 amu together at the second stage). In this case, however, elimination of an ethylene molecule instead of a carbonyl group is more probable at the first stage, since with (II) this process does not require the migration of two hydrogen atoms from the charged fragment.

The mass spectra of substituted chromenones reflect their specific characteristics resulting from the nature, number, and positions of substituents, as has already been partly shown by the halogeno-derivatives.

III. HYDROXYCHROMEN-2-ONES

The mass spectra of the hydroxychromenones, e.g. umbelliferone (III), are distinguished merely by an increase in the number of carbonyl groups ejected[1,2] (Scheme 2). As with coumarin itself, elimination of 28 amu at the second stage is accompanied by removal of 29 amu (formyl or carbonyl plus hydrogen). In contrast to the unsubstituted chromenone, later eliminations of a carbonyl group drop sharply in intensity (Table 2).

Scheme 2

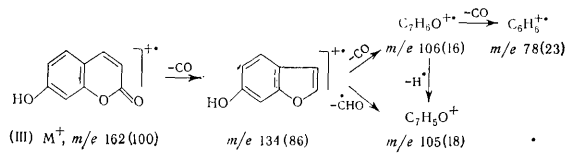


Table 2. Values of m/e and $100I/I_{max}$ for peaks due to ions involved in elimination of carbonyl groups in the mass spectra of hydroxychromen-2-ones.

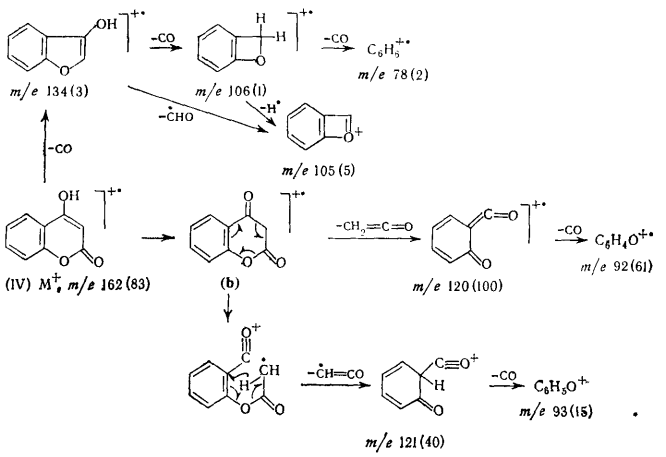
Derivative	M+	M—CO	M—2CO	M—2CO—H	M—3CO	M—4CO
4-Hydroxy (IV)	162 (86)	134 (3)	106 (1)	105 (5)	78 (3)	—
6-Hydroxy	162 (100)	134 (69)	106 (6)	105 (5)	78 (18)	—
7-Hydroxy (umbelliferone, III)	162 (100)	134 (86)	106 (16)	105 (18)	78 (20)	—
6,7-Dihydroxy (aesculetin)	178 (100)	150 (75)	122 (3)	121 (3)	94 (8)	66 (6)

The appearance potential of the 134 ion $[M - 28]^+$ for umbelliferone (10.6 eV) is closer to that of the corresponding ion for the chromenone (11.6 eV) than that of the same ion in the case of phenol (12.3 eV), which indicates elimination of the lactonic carbonyl at the first stage of decomposition[2].

The Reviewers have observed a significant difference between the breakdown of 4-hydroxychromenone (IV) and that of other hydroxychromenones. Decomposition involves mainly elimination of 42 amu from the molecular

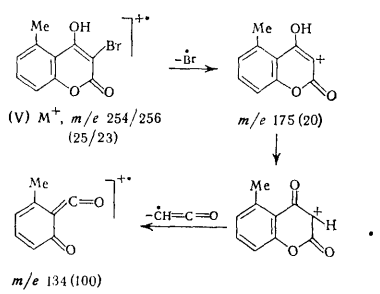
ion (the 120 peak at m/e is the most intense in the spectrum) followed by elimination of carbonyl (92 peak) (Scheme 3). Although the successive elimination of three carbonyl groups can be traced in the spectrum of the 4-hydroxy-derivative (Table 2), this process takes place to only a slight extent.

Scheme 3



On electron bombardment the molecular ion of 4-hydroxychromenone probably undergoes tautomerisation into the ion of chroman-2,4-dione (b), which then decomposes by a retrodiene reaction with elimination of a keten molecule and formation of a radical-ion having $m/e = 120$, or with removal of a keten radical and formation of an ion having $m/e = 121$. Analogous elimination of a keten molecule is evident in the mass spectrum of the monocyclic analogue of 4-hydroxychromenone—triacetic acid.

Scheme 4

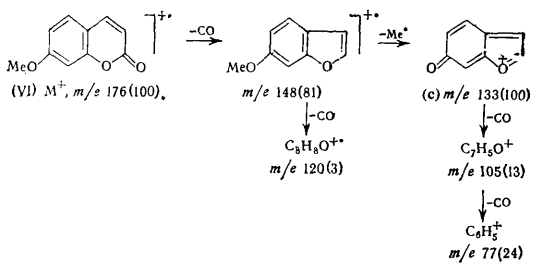


According to Johnson and Pelter[9] 3-aryl-4-hydroxychromenones also eliminate an arylketen molecule or radical on electron bombardment. With 3-bromo-4-hydroxy-5-methylchromenone (V),[10] as with the halogenated chromenones described above, the bromine atom is eliminated first, and a keten radical is subsequently eliminated after tautomeric ketonisation of the 175 ion (Scheme 4).

IV. METHOXYCHROMEN-2-ONES

The mass spectra are greatly affected by methylation of the hydroxyl in hydroxychromen-2-ones[1,2]. Although elimination of a carbonyl group is still the first stage in decomposition of the molecular ion of the methyl ether of umbelliferone—herniarin (VI)—elimination of the methyl group with formation of a 133 ion (Scheme 5, ion c), evidently stabilised by a quinonoid structure, predominates at the second stage. After this another carbonyl group is eliminated. It must be emphasised that neither methyl nor methoxyl is eliminated from the molecular ion in the case of herniarin (Table 3).[1,2,11]

Scheme 5



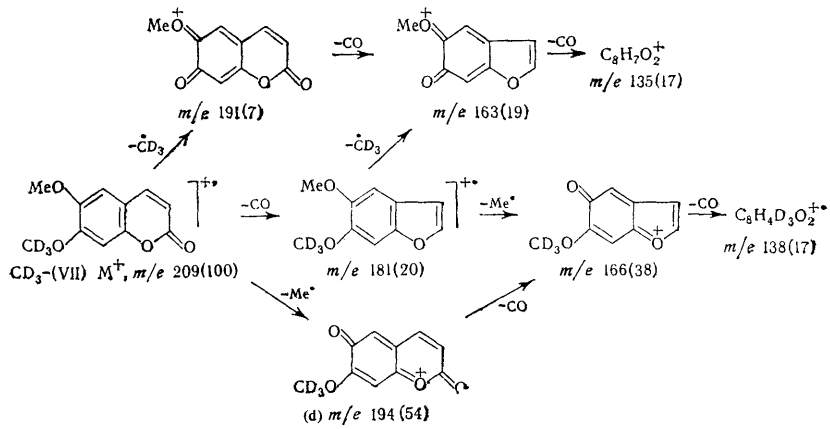
The Reviewers have observed a similar pattern in the mass spectrum of 7-hydroxy-6-methoxychromen-2-one (scopoletin), and the Australian workers[2] in that of 6,7-dimethoxychromen-2-one (scoparin) (VII). However, a significant feature of the behaviour of these compounds under electron bombardment is elimination of a methyl group from the molecular ion together with the first elimination of a carbonyl group, the peak of the $[M - CH_3]^+$ ion being more intense than that of the $[M - CO]^+$ ion. The sequence of subsequent eliminations in this mode of decomposition is included in Table 3.

Table 3. Values of m/e and $100I/I_{max}$ for peaks due to main ions in the mass spectra of methoxychromen-2-ones.

Derivative	M+	M—Me	M—CO	M—2CO	M—CO—Me M—Me—CO	M—CO—Me—CO M—Me—2CO	M—CO—Me—2CO M—Me—3CO	M—CO—Me—3CO M—Me—4CO
7-Methoxy (herniarin, VI)	176 (100)	—	148 (81)	120 (3)	133 (100)	105 (13)	77 (14)	—
7-Hydroxy-6-methoxy (scopoletin)	192 (100)	177 (43)	164 (22)	—	149 (37)	121 (14)	93 (1)	65 (4)
6,7-Dimethoxy- (scoparin, VII)	206 (100)	191 (30)	178 (20)	—	163 (30)	135 (19)	107 (20)	79 (6)

Shapiro and Djerassi[12] compared the spectra of (VII) and its 7-trideuteromethyl analogue and showed that formation of the $[M - CH_3]^+$ ion involves elimination of the methyl group predominantly from the 6-methoxyl with formation of a *p*-quinonoid 194 ion (ion (d) in Scheme 6). This observation is fully consistent with the absence of the $[M - CH_3]^+$ peak in the spectrum of herniarin and its presence in that of scopoletin. In contradistinction to this, loss of a methyl group by the $[M - CH]^+$ ion occurs with equal probability from either the 6- or the 7-methoxyl in scoparin, as is indicated by the fact that the peaks of the resulting 163 and 166 ions have approximately the same intensities as the 135 and 138 peaks in the spectrum of the 7-trideuteromethyl analogue of scoparin (Fig. 2). As with *o*-dimethoxybenzene, elimination of a formaldehyde molecule from the methoxyl is not observed here[11].

Scheme 6



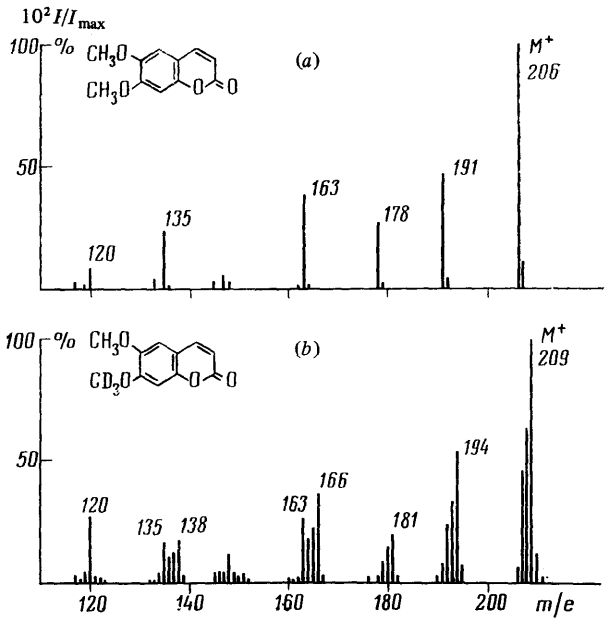


Figure 2. Mass spectra of: *a*) scoparin; *b*) 7-trideuteromethylscoparin.

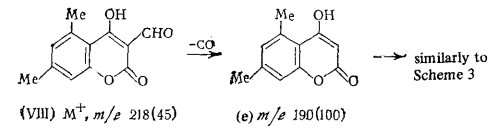
The fragmentation paths are little affected by introduction of a methyl group at any of the carbon atoms[10] or of a 4-phenyl group in the chromenone molecule or its hydroxy- or methoxy-derivatives[13-15]. Introduction of an ethyl group, however, leads to elimination of a methyl group, which is favoured by the possibility of formation of a tropylium ion[10].

V. 3-CARBONYL-CONTAINING CHROMEN-2-ONE DERIVATIVES

Aldehydes

The only aldehyde derivative whose mass spectrum has been reported—3-formyl-4-hydroxy-5,7-dimethylchromen-2-one (VIII) [10]—undergoes elimination of a carbonyl group with formation of the 190 ion (e) (Scheme 7) (whose peak is the most intense in the spectrum), having the structure 4-hydroxy-5,7-dimethylchromenone. Subsequent breakdown of the ion is analogous to that described for 4-hydroxychromenone (Scheme 3).

Scheme 7



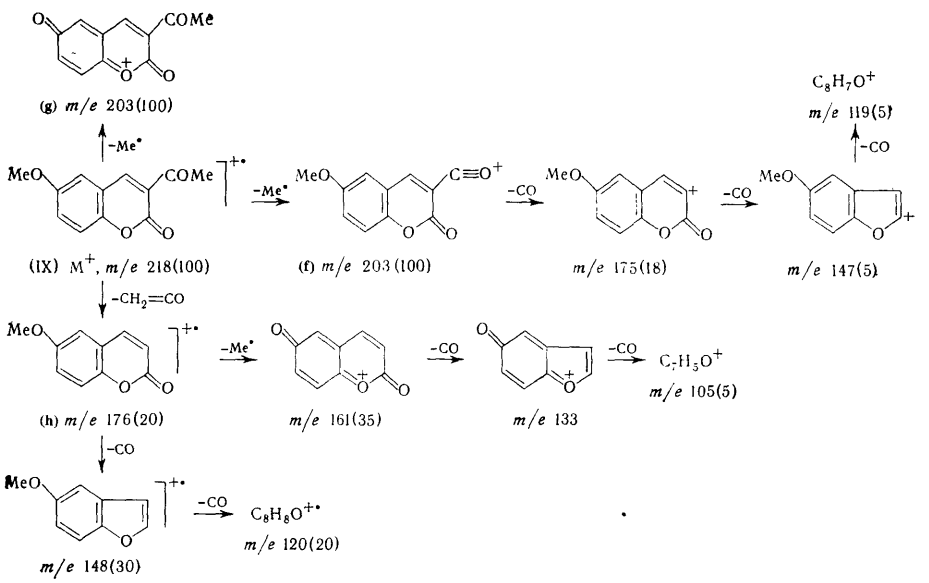
Ketones

The most intense peaks in the mass spectrum of 3-acetyl-6-methoxychromen-2-one (IX) [10] are due to the molecular ion and to the 203 ion $[M - CH_3]^+$. Formation of the latter is due to the equal probability of loss of methyl from the acetyl group (Scheme 8, ion f) and from the 6-methoxy-group (ion g). This is followed by the repeated loss of carbonyl groups. The molecular ion of the ketone (IX) can break down also by elimination of a keten molecule with formation of the 176 ion (h), which then either loses successively a methyl group and two molecules of carbon monoxide or else eliminates the two molecules (Scheme 8).

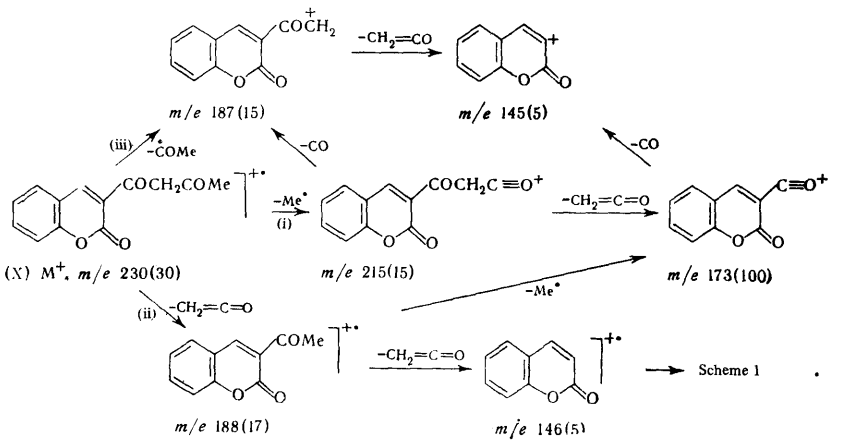
3-Acetoacetylchromen-2-one (X) can break down in three ways[10] (Scheme 9): (i) successive loss of a methyl group, a keten molecule, and a carbonyl group involves formation of a 145 ion analogous to the 175 ion formed from the ketone (IX) (Scheme 8); (ii) preliminary elimination of a keten molecule entails formation of an ion identical with the molecular ion of 3-acetylchromen-2-one, which then loses either another keten molecule or a methyl group followed by carbonyl; or (iii) preliminary elimination of an acetyl group and then a keten molecule yields an ion with $m/e = 145$.

Introduction of 4-hydroxyl and 6-methyl into the 3-acetoacetylchromenone has no significant effect on breakdown of the molecular ion under electron bombardment[10]. Only after elimination of the acetoacetyl group does decomposition characteristic of 4-hydroxychromenone begin.

Scheme 8



Scheme 9

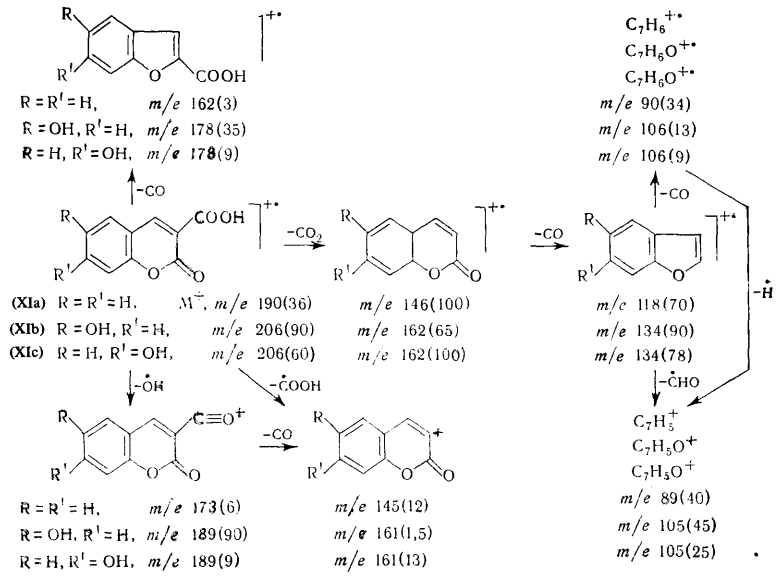


Acids and their Esters

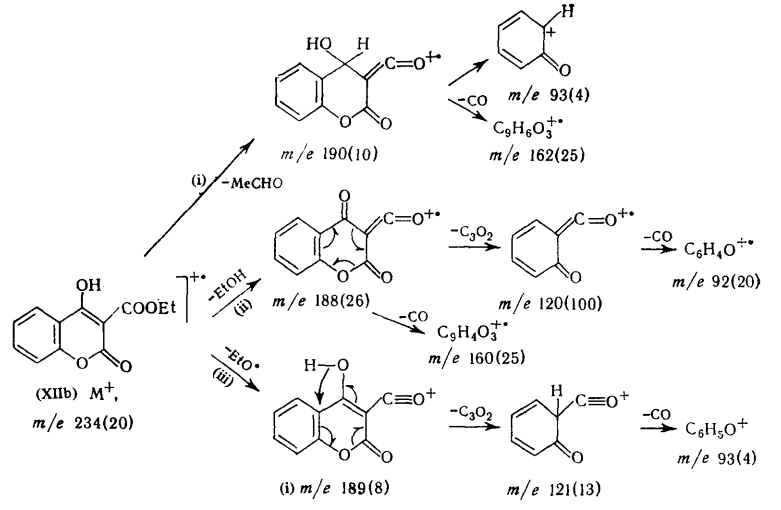
The Reviewers have found three independent modes of decomposition for 2-oxochromen-3-carboxylic acid (XIa) and its 6- and 7-hydroxy-derivatives (XIb) and (XIc) (Scheme 10). The first of these (traditional for coumarins), involving successive elimination of a carbonyl group, is strongly repressed. The second begins with elimination of a carboxyl as OH–CO and COOH (the peak due to the $[M - OH]^+$ ion is extraordinarily intense (90%) in the spectrum of the 6-hydroxy-derivative (XIb)). This is accompanied by very slight removal of formic acid to give the ion $[M - HCOOH]^+$. The third and main mode of breakdown of the oxochromencarboxylic acid entails detachment of a molecule of carbon dioxide, probably via a four-membered transition state. The $[M - CO_2]^+$ ion, which has the structure of the corresponding chromenone, breaks down further with successive elimination of carbonyl groups (elimination of a formyl group again accompanies elimination of a carbonyl group).

The pattern of fragmentation is still more complicated when the carboxyl has been esterified, as a consequence of breakdown of the alkoxycarbonyl group. Johnstone et al.[10] reported the mass spectra of methyl (XIIa) and ethyl (XIIb) 4-hydroxy-2-oxochromen-3-carboxylates, and of the 8-methyl (XIII) and 5,7-dimethyl (XIV) derivatives of (XIIa). Esters that were unsubstituted in the aromatic ring—(XIIa) and (XIIb)—could decompose in three independent ways (Scheme 11): (i) initial elimination of an aldehyde molecule is followed by cleavage of the heterocyclic ring and migration of a hydrogen atom to the charged particle or loss of a carbonyl group; (ii) initial elimination of an alcohol molecule from the alkoxycarbonyl group is followed by rupture of the heterocyclic ring (due to elimination of a carbon suboxide molecule) and then elimination of a carbonyl group or by immediate elimination of carbonyl from position 2 or 4; and (iii) initial detachment of alkoxyl gives the ion (i), which then loses a carbon suboxide molecule and a carbonyl group in succession.

Scheme 10



Scheme 11



The Reviewers suppose that the latter two routes may result from initial tautomeric ketonisation of the molecular ion followed by elimination of an alcohol molecule or alkoxyl and then a retrodiene decomposition, accompanied in (iii) by migration of a hydrogen atom to the charged particle (see Scheme 3).

Methylation of the aromatic ring in the ester (XIIa)—to give (XIII) and (XIV)—has no significant effect on the modes of decomposition of their molecular ions under electron bombardment, and is apparent merely in a decrease in intensity of peaks due to ions of type (i).

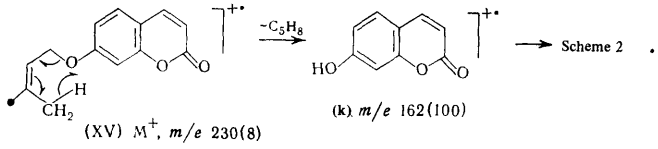
Introduction of an *O*- or a *C*-alkyl or -cycloalkyl substituent with a large number of carbon atoms into the chromenone molecule complicates appreciably the pattern of fragmentation of the molecular ion, since processes involving rupture of bonds in these substituents begin to play a significant part. Direct loss of a carbonyl group by the molecular ion becomes less characteristic, and often this process becomes apparent only in the later stages of decomposition.

VI. *O*-ALKYLATED CHROMEN-2-ONES

Naturally occurring chromenones, which usually contain an isopentenyl or a still longer isoprenoid residue attached to the ring through oxygen, are characterised by extreme ease of decomposition under electron bombardment. As a consequence, peaks in the range of high mass numbers are usually weak in their mass spectra. Thus according to Bohlmann et al.[16] 7-isopentenyloxychromen-2-one (XV) first loses the side-chain as a result of rupture of the carbon–oxygen bond with migration of a hydrogen atom to the charged particle. The 162 ion (k) thus formed

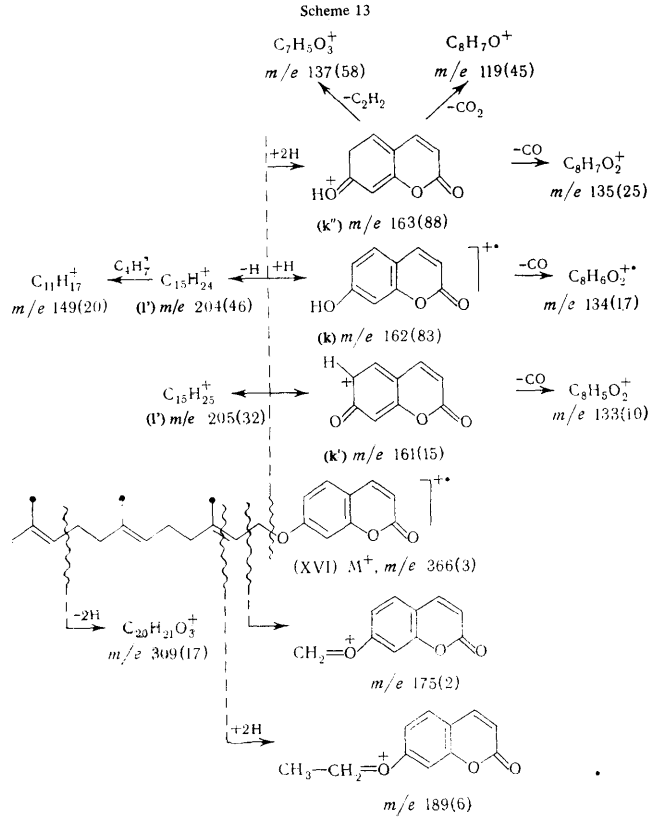
(Scheme 12) is identical with the molecular ion of umbelliferone (III), and subsequently breaks down as described above (Scheme 2 and Table 2).

Scheme 12



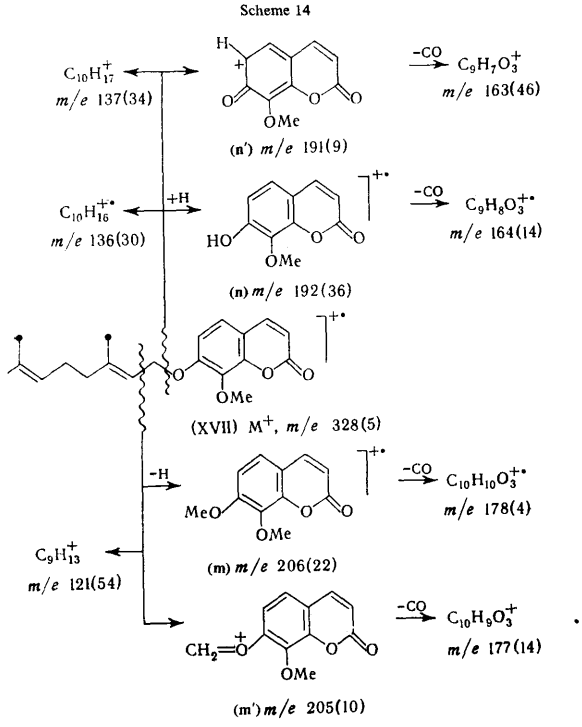
The Reviewers have found a similar situation in the mass spectrum of umbelliprenin (XVI). Cleavage of the side-chain at the carbon–oxygen bond with migration of a hydrogen atom to the charged fragment gives the 162 ion (k), accompanied by the 161 and 163 ions (k′) and (k″) formed respectively by simple rupture of the carbon–oxygen bond and by such rupture with migration of two hydrogen atoms to the charged particle. Localisation of the charge on the side-chain residue yields the 204 and 205 ions (l) and (l′) (Scheme 13).

Scheme 13

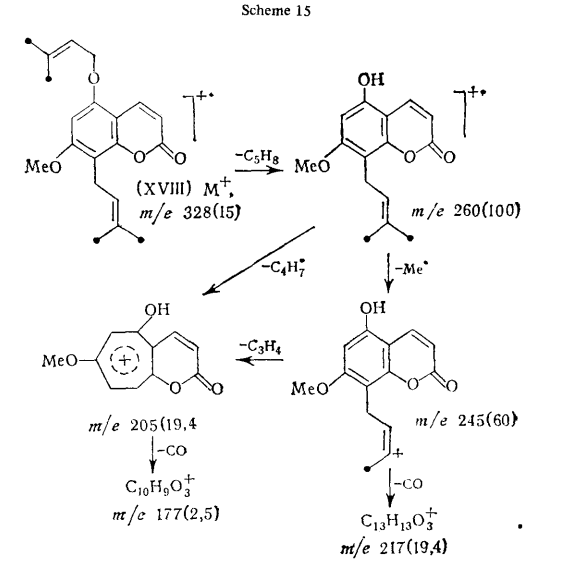


It must be borne in mind, however, that a long side-chain may break into fractions as a result of cleavage of allyl bonds. Nor can the possibility of migration of double bonds along the carbon chain be excluded. This is probably responsible for the peaks due to 309, 267, and 254 ions (17%, 2%, and 4%) in the spectrum of umbelliprenin. A 175 ion (2%) is formed by simple cleavage of the α-carbon–carbon bond, and corresponds to a deprotonated form of the molecular ion of herniarin. The ion (k) and the accompanying ions (k′) and (k″) then eliminate carbonyl groups in stages.

Scheme 14

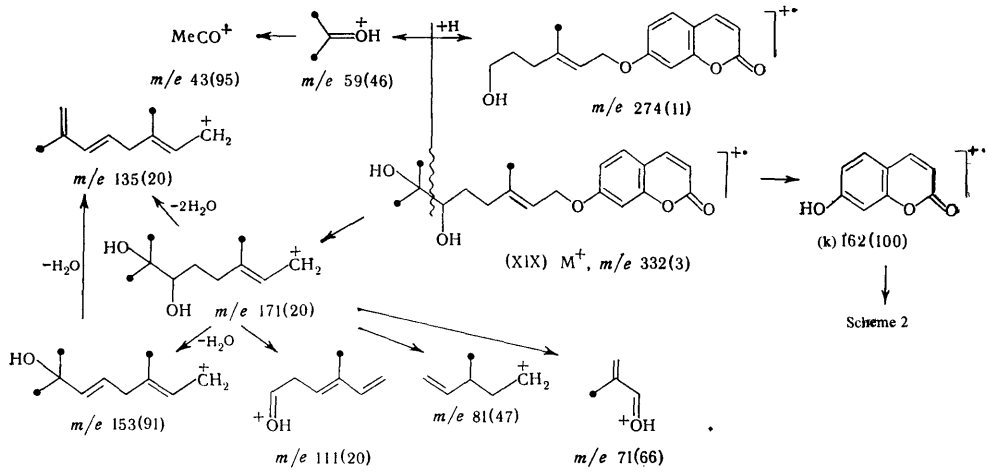


Scheme 15



In contrast to the above, according to Barnes and Occolowitz[2] collinin—7-geranyloxy-8-methoxychromen-2-one (XVII)—undergoes α-cleavage of the carbon chain with migration of a hydrogen atom to the charged fragment and formation of a 206 ion (m) identical with the molecular ion of 7,8-dimethoxychromen-2-one (Scheme 14). This ion is accompanied by a 205 ion (m′) formed by simple

Scheme 16

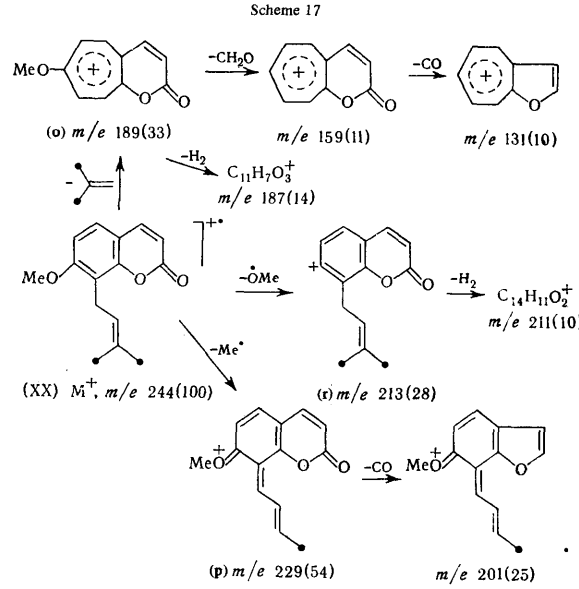


α-cleavage. With collinin the above rupture of the carbon–oxygen bond also occurs, with the formation of ions 192 and 191 (n and n'), the former identical with the molecular ion of 7-hydroxy-8-methoxychromen-2-one, and the latter with its deprotonated form. Rupture of the same bonds but with localisation of the charges on the aliphatic chain yields ions having m/e = 121, 136, and 137.

Loss of an isopentenyl substituent with migration of a hydrogen atom to oxygen has been observed also by Seshadri and Vishwapaul[17] in the mass spectrum of sesibiricin—8-isopentenyl-5-isopententyloxy-7-methoxychromen-2-one (XVIII) (Scheme 15)—isolated from *Sesili sibiricum*. Subsequent breakdown of the 260 ion is governed by the presence of the *C*-isopentenyl residue (Section VII).

Decomposition of the more complicated 7-(6,7-dihydroxy-3,7-dimethyloct-2-enyloxy)chromen-2-one (XIX) follows a similar pattern[18]. Besides rupture of the carbon–oxygen bond with migration of a hydrogen atom to the charged fragment with formation of the ion (k) (Scheme 16), the presence of an α-diol group in the side-chain stimulates formation of ions having m/e = 274, 171, 153, 135, 111, 81, 71, 59, and 53.

Scheme 17



VII. *C*-ALKYLATED CHROMEN-2-ONES

When an isopentenyl residue is directly attached to the chromenone ring system, as e.g. in osthol[1,2]—8-isopentenyl-7-methoxychromen-2-one (XX)—part of the side-chain is lost as an isobutenyl radical with formation of a tropylium ion (o) having m/e = 189 (Scheme 17), which then loses a molecule of formaldehyde from the methoxy-group (similarly to anisole[19] and methoxy-quinones[20,21]) and a carbonyl group. Successive elimination of carbonyl groups takes place only after loss of a terminal methyl from the molecular ion, i.e. from a 229 ion. Elimination of only methoxyl from the molecular ion, which has not been observed in the above cases, is evidently due to the proximity of the unsaturated isopentenyl residue. A 213 ion (r) is thus formed, which then loses a molecule of hydrogen.

Fragmentation of the isomeric suberosin—6-isopentenyl-7-methoxychromen-2-one (XXI)—is in principle very similar to that of osthol[22,23]. The difference in the position of the isopentenyl residue is reflected, however, in a fairly considerable change in intensity of several peaks, especially those due to breakdown of the side-chain (Table 4).

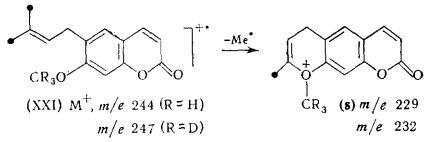
Table 4. Values of m/e and $100I/I_{max}$ for the peaks due to the main ions in the mass spectra of osthol and suberosin.

Compound	M+	M—Me	M—CH_2O	M—MeO	M—C_4H_7	M—C_5H_9
Osthol (XX)	244 (100)	229 (54)	214 (5)	213 (28)	189 (33)	176 (7)
Suberosin (XXI)	244 (97)	229 (100)	214 (3)	213 (4)	189 (13)	176 (5)

Compound	M—C_5H_9	M—Me—CO	M—C_4H_7—H_2	M—C_4H_7—CH_2O	M—C_4H_7—CH_2O—CO
Osthol (XX)	175 (8)	201 (25)	187 (14)	159 (11)	131 (10)
Suberosin (XXI)	175 (4)	201 (3)	187 (3)	159 (4)	131 (3)

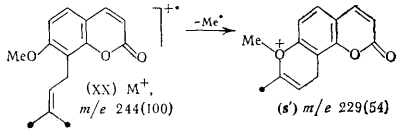
From the mass spectrum of the trideuteromethyl analogue of suberosin, in which the 229 peak of the $[M - 15]^+$ ion is almost completely (98%) displaced to 232, MacLeod confirmed experimentally[23] that methyl is eliminated from the side-chain. He assigned the cyclic structure (s) (Scheme 18) to this ion. For the rest his results are consistent with the scheme of decomposition of osthol (Scheme 17).

Scheme 18



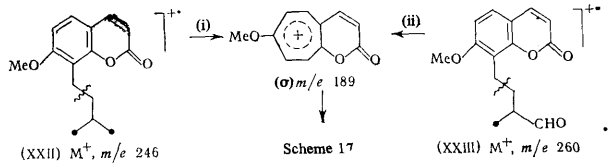
It cannot be excluded that the $[M - 15]^+$ ion from osthol also has an angular cyclic structure (s') (Scheme 19). The molecular ion of the recently reported 8-isopentenyl-5,7-dimethoxychromen-2-one decomposes similarly to osthol and suberosin on electron bombardment[24].

Scheme 19



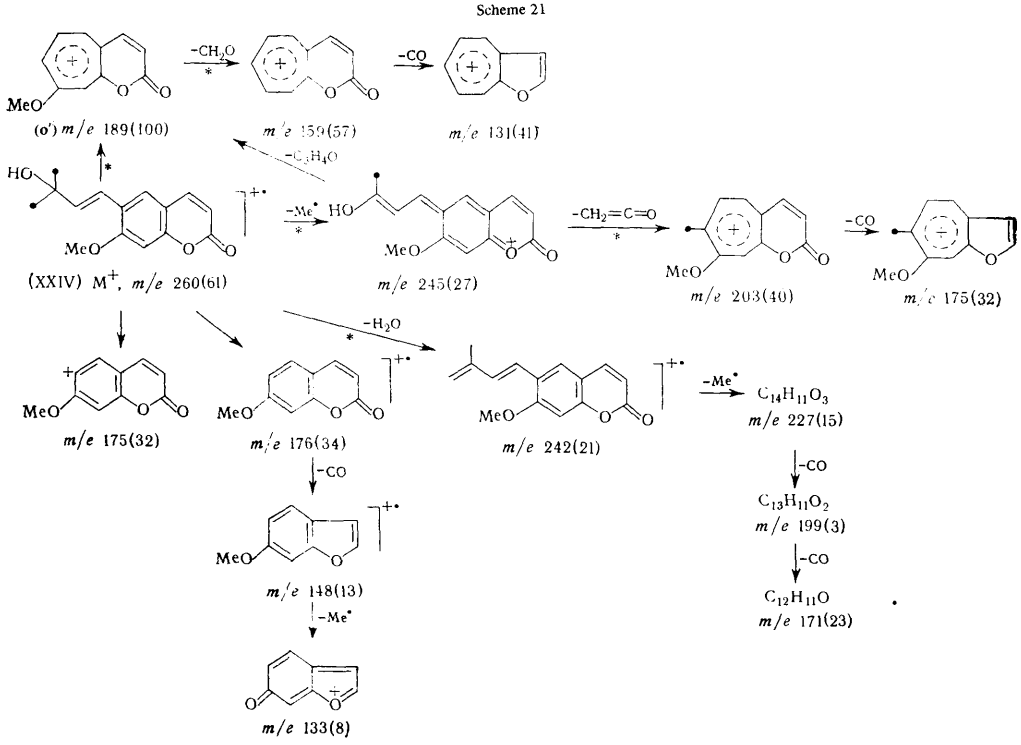
The peak due to the $[M - CH_3]^+$ ion is of negligible intensity in the spectrum of dihydro-osthol (XXII),[2] owing to the saturated character of the side-chain, and is completely absent from the spectrum of dihydrosuberosin[23], which can be attributed to the impossibility of stabilising the charge by a conjugated system of double bonds. Elimination of methoxyl as formaldehyde is also absent. The main mode of decomposition of dihydro-osthol[2] and dihydrosuberosin[23] is elimination of the side-chain by rupture of the benzylic carbon–carbon bond with formation of the tropylium ion (o) having $m/e = 189$ (Scheme 20i). Similar decomposition with formation of the ion (o) is evident also in the mass spectrum of 8-3'-formylbutyl-7-methoxychromen-2-one (XXIII)[25] (Scheme 20ii). It is curious that the $[M - CH_3]^+$ ion is not formed even in this case.

Scheme 20



Hydroxylation or epoxidation of the side-chain causes additional decomposition in the side-chain, as has been shown above for the derivative (XIX) (Scheme 16). Thus Australian workers have shown[22] that the molecular ion of suberenol—6-(3-hydroxy-3-methylbut-1-enyl)-7-methoxychromen-2-one (XXIV)—breaks down along three main paths (Scheme 21). (i) Elimination of a methyl group from the side-chain is followed by detachment of C_3H_4O and migration of a hydrogen atom to the charged fragment. The resulting tropylium ion (o') having $m/e = 189$ (whose peak is the strongest in the spectrum) can also be obtained directly from the molecular ion in a single-stage process analogous to that described above. The ion (o') loses further the methoxy-group as formaldehyde, and then a carbonyl group; the 245 ion $[M - CH_3]^+$ also loses a keten molecule, being converted into a 203 ion and subsequently eliminating a carbonyl group. (ii) Loss of the whole side-chain results from simple rupture of the carbon–oxygen bond (175 ion) or with migration of a hydrogen atom to the charged fragment

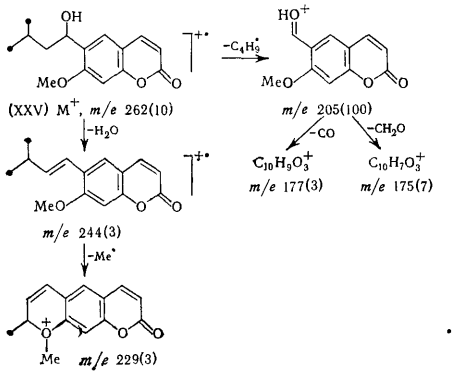
Scheme 21



through a six-membered transition state (176 ion). The 175 peak may be composite, with its second component arising from elimination of a carbonyl group from the 203 ion. The 176 ion then loses carbonyl and methyl. (iii) Loss of a water molecule by the molecular ion leads to formation of a 242 ion, from which one methyl and two carbonyl groups are then split off (the methyl probably from the side-chain). The mass spectrum of suberenol (XXIV) given by MacLeod[23] differs from the above merely in a considerably less intense peak due to the ion (o').

The mass spectrum of 6-(1-hydroxy-3-methylbutyl)-7-methoxychromen-2-one—tetrahydrogeijerin (XXV)—is very meagre[23]. The most intense peak is due to the 205 ion $[M - C_4H_9]^+$ ion (Scheme 22), which then loses a formaldehyde molecule or a carbonyl group. Another mode of decomposition of the molecular ion involves detachment of a water molecule followed by a methyl group. All the peaks due to these ions, including the molecular ion, are weak.

Scheme 22



In contrast, the mass spectrum of 6-(2,3-dihydroxy-3-methylbutyl)-7-methoxychromen-2-one—dihydrodihydroxysuberenol (XXVI) [23]—like that of the α-glycol (XIX) described earlier (Scheme 16), contains a considerable number of peaks due to ions formed by the rupture of bonds in the side-chain. The modes of decomposition indicated in Scheme 23 are supported by the mass spectra of the trideuteromethyl and 2-deuteroxyl analogues, as well as by the presence of many metastable peaks in the spectra.

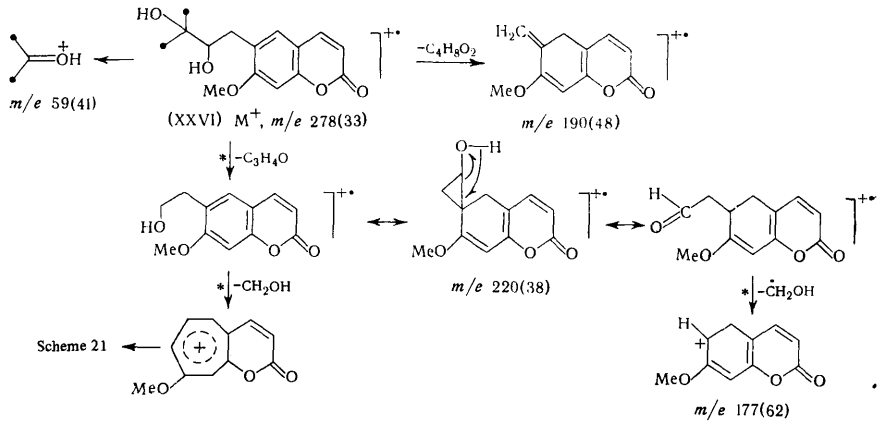
The same compound was isolated by Abyshev et al.[26] from *Prangos ulopteria* D.C. and termed *ulopterol*. Its mass spectrum corresponds essentially to Scheme 23. The spectrum of the isomeric 8-(2,3-dihydroxy-3-methylbutyl)-7-methoxychromen-2-one—merancin hydrate (XXVII)—is described in the same paper. The spectra of the isomers are very similar, differing mainly in the relative intensities of peaks due to individual ions. The chief difference is that the most intense peak in the spectrum of ulopterol is due to the 220 ion, whereas in the spectrum of merancin hydrate the 177 peak is the strongest.

According to Chakraborty et al.[27] the molecular ion of 8-(2,3-dihydroxy-3-methylbutyl)-5,7-dimethoxychromen-2-one—mexoticin (XXVIII), isolated from *Murraya exotica* L.—breaks down somewhat differently. In this case the most characteristic process is loss of the whole side-chain at position 8 with migration of a hydrogen atom to the charged fragment and formation of a 206 ion isomeric with ion (m) (Scheme 14). Rupture of the benzyl bond gives the tropylium ion (o") at 219 (Scheme 24), but simultaneous migration of a hydrogen atom to the charged fragment gives a 220 ion. The above cleavage of the α-glycolic carbon–carbon bond also occurs, with the appearance in the spectrum of peaks due to ions at 249 (t) and 59.

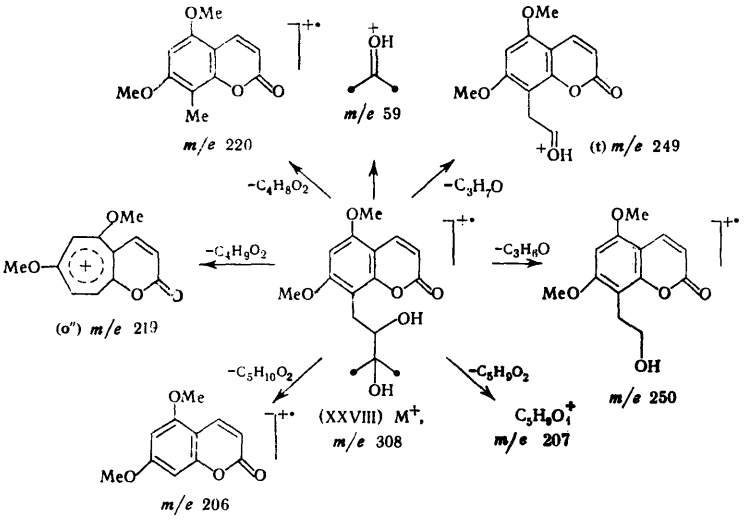
A formally similar but essentially different pattern is observed in the mass spectra of the monoacetates of ulepterol (XXIX) [26] and of merancin hydrate (XXX), [28] the latter isolated from *Prangos ferulacene* L. Decomposition can take place in two ways (Scheme 25) on electron bombardment: (i) elimination of a molecule of acetic acid from the molecular ion with formation of a 260 ion—respectively identical and isomeric with the molecular ion of suberenol—which breaks down further according to Scheme 17 or 21; or (ii) rupture of the α-glycolic carbon–carbon bond accompanied by elimination of a keten molecule, leading to the formation of ions 59 and 219. As in previous cases, the mass spectra of positional isomers (6- or 8-substituted) differ only in the relative intensities of peaks due to individual ions: for example, the most intense peak in the spectrum of (XXIX) is due to the 189 ion, but the most intense in the spectrum of (XXX) is at 219. Acetylation of the second hydroxyl in merancin hydrate has no significant effect on the decomposition of the diacetate on electron bombardment[28].

The mass spectrum of 6-(2,3-epoxy-3-methylbutyl)-7-methoxychromen-2-one—epoxysuberosin (XXXI) [23]—represents a still more complicated process, involving

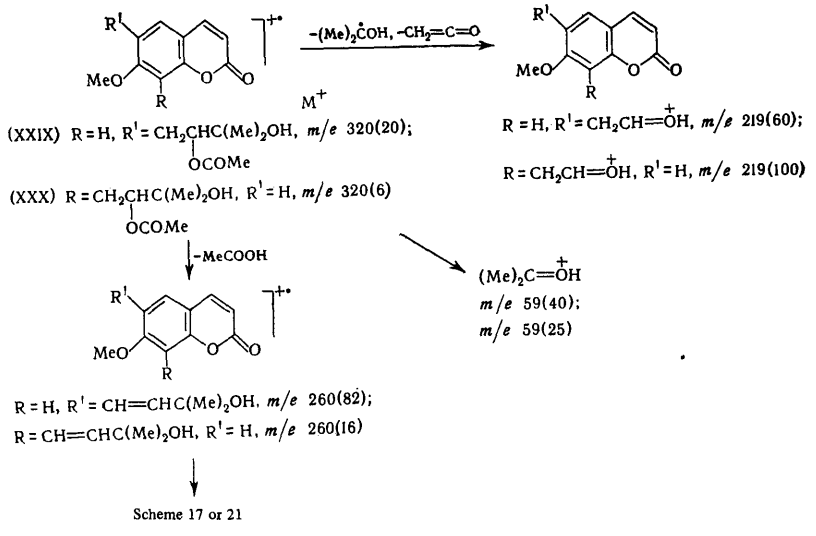
Scheme 23



Scheme 24



Scheme 25

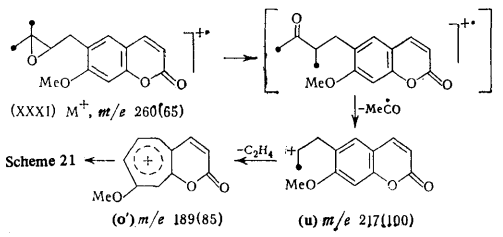


Scheme 17 or 21

a pinacolinic type of rearrangement in the side-chain of the molecular ion followed by ejection of an acetyl group and formation of the 217 ion (u) (Scheme 26). The latter ion then eliminates a molecule of ethylene and is converted into the tropylium ion (o') (189), which decomposes further in conformity with Scheme 21. This route is confirmed by the mass spectrum of the trideuteromethyl analogue and by the presence of many metastable peaks.

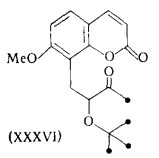
MacLeod's results[23] for the high-resolution mass spectrum of 7-methoxy-6-(3-methyl-2-oxobutyl)chromen-2-one (XXXII) (Scheme 32) and the absence of the elimination of a C_3H_7 radical (43 amu) from the molecular ion indicate that the epoxide ring does not undergo direct cleavage. They are inconsistent with Bohlmann and Rode's studies[29] of the mass spectra of 8-(2,3-epoxy-3-methylbutyl)-5,7-dimethoxychromen-2-one (XXXIII) and 8-(2,3-epoxy-3-methylbutyl)-7-isopentenyloxy-5-methoxychromen-2-one (XXXIV), both isolated from *Libanotis buchtormenis*. The latter workers regard elimination of 43 amu from the molecular ions of these two compounds as involving preliminary cleavage of the epoxide ring and formation of an ion of type (v) (at 247 and 301 respectively) (Scheme 27). Furthermore, Bohlmann and Rode[29] consider formation of the tropylium ion (o"), whose peak at 219 is the strongest in the spectrum of (XXXIII), to result from a single-stage elimination of the side-chain by cleavage of the benzylic carbon–carbon bond. Another discrepancy must be noted between the two sets of results. Bohlmann and Rode find in the spectrum of (XXXIII) quite clear evidence of the elimination from the molecular ion of an acetone molecule followed by formaldehyde (peaks at 232 and 202), whereas peaks due to the corresponding ions are almost completely absent from the spectrum of (XXXI).[23] The spectrum of (XXXIV), moreover, reveals elimination of the isopentenyl residue with migration of a hydrogen atom to the charged fragment and formation of the 7-dimethyl analogue of the molecular ion of (XXXIII), which then decomposes similarly to the latter.

Scheme 26



A rearrangement similar to that described by MacLeod for the epoxide (XXXI) has been examined by Kutney et al.[30] for 6-(1,2-epoxy-3-methylbut-3-enyl)-7-methoxychromen-2-one (XXXV), whose molecular ion eliminates a formyl radical. The $[M - CHO]^+$ ion, whose peak at 229 is the most intense in the spectrum, then loses either methyl to form a 214 ion or C_3H_4 with conversion into the ion (o') (Scheme 28). However, it is also possible that this last ion (o') is obtained as a result of fission of the epoxy-group to give a keto-form of the molecular ion, which is supported by the fairly intense peak due to the 69 ion.

Besides the above chromenones containing isoprenoid side-chains Abyshev et al.[31] described an optically inactive chromenone $C_{18}H_{22}O_5$, which they had isolated from *Prangos ferulaceae* L. and termed *pranferin*. On the basis of its chemical reactions and ultraviolet, infrared, and nuclear magnetic resonance spectra they regarded this compound (XXXVI) as 8-(2-t-butoxy-3-oxobutyl)-7-methoxychromen-2-one

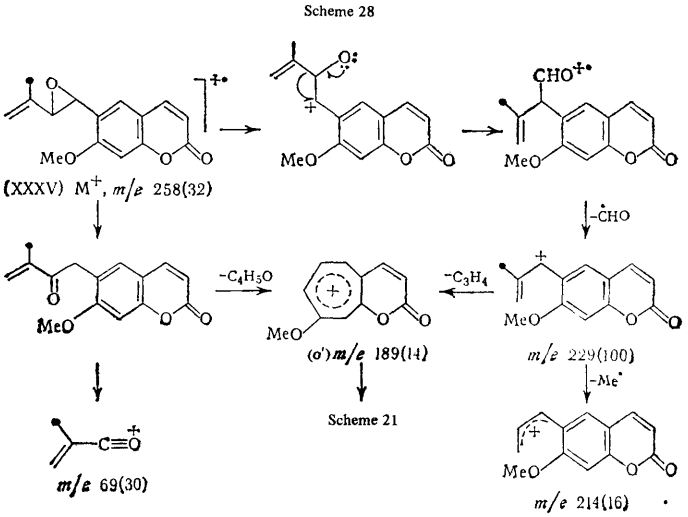


The authors state that this structure agrees well with the mass spectrum, which they do not analyse in detail. However, the one- and two-stage elimination of acetic acid from the $[M - 15]^+$ ion, clearly traceable in the spectrum, completely contradicts the proposed structure for the side-chain at position 8, although the presence of a fairly intense peak due to a 189 ion confirms that pranferin is a 7-methoxychromen-2-one derivative. Furthermore, the proposed[31] formula (XXXVI) contains an asymmetric carbon atom, which is inconsistent with the stated absence of optical activity, whereas other chromenones isolated by these workers from the same plant and containing an analogous

$$-CH_2-\underset{|}{CH}-O-$$

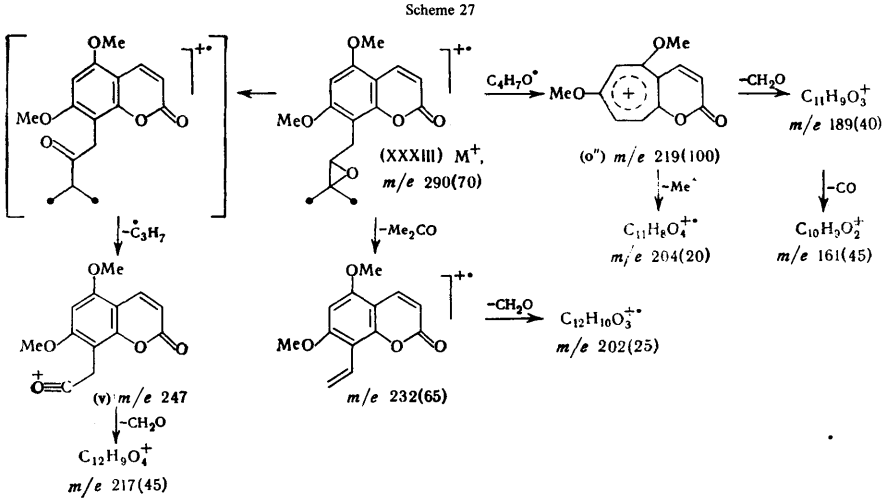
group are optically active[28].

Scheme 28

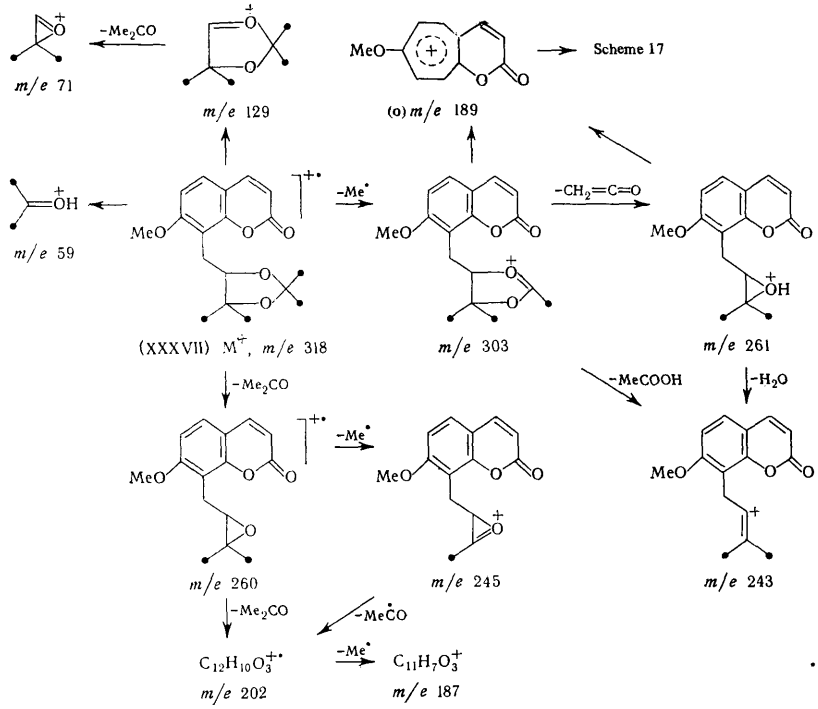


Nikonov and Saidzhadzhiev[32] analysed the n.m.r. data given by Abyshev et al.[31], and concluded that pranferin is an acetonide of merancin hydrate (XXXVII), which was confirmed by synthesis from osthol via the corresponding epoxide and merancin hydrate. The published mass spectrum of pranferin[31] agrees well with formula (XXXVII) (Scheme 29).

Scheme 27

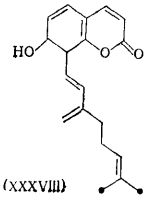


Scheme 29



VIII. CHROMEN-2-ONES CONTAINING CYCLOALKYL SUBSTITUENTS

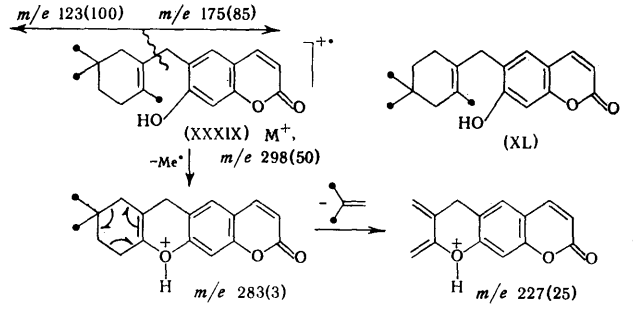
The first representative of this type of chromenone whose mass spectrum has been reported is peucenol (peumorisine), isolated from the roots of *Peucedanum morisonii* Bes. The Reviewers originally assigned to it the structure 8-(7-methyl-3-methylenocta-1,6-dienyl)-7-hydroxychromen-2-one[33]



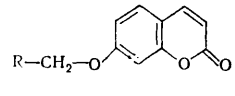
(XXXVIII) ,

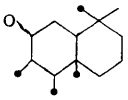
but this formula was not confirmed by subsequent study of the n.m.r. spectrum. Examination of the n.m.r. and mass spectra of peucenol suggested a cyclic structure, either (XXXIX) or (XL) [34] (Scheme 30), both consistent with biogenetic considerations. Perel'son later showed unambiguously, on the basis of the nuclear magnetic double resonance spectrum, that peucenol has the structure (XXXIX), in good agreement with the mass spectrum: detachment of the carbocyclic substituent by rupture of the benzylic bond yields 175 and 176 ions of tropylium type (by simple rupture and by rupture with migration of a hydrogen atom to the charged fragment). If the charge resulting from this process is localised on the other part of the molecule, a 123 ion is formed. The peaks at 283 and 227 are due to loss by the molecular ion of a methyl group (probably that adjacent to the double bond of the cyclohexene ring) followed by retrodiene decomposition in the cyclohexene ring with ejection of isobutene.

Scheme 30

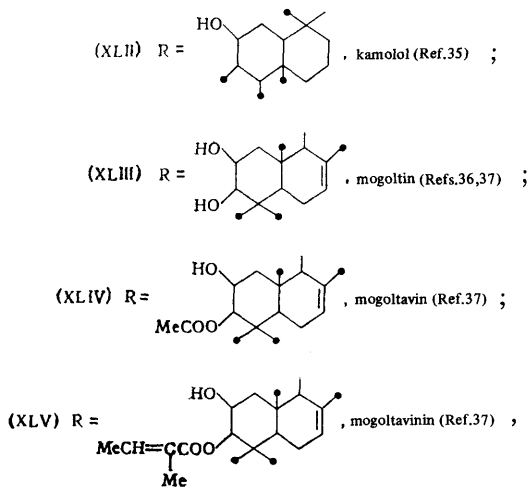


During recent years mass spectra have been reported for the umbelliferone derivatives (XLI)-(XLV) isolated from *Ferula peninervis*[35] and *Peucedanum mogeltovicum* Korov[36,37], in which the phenolic hydroxyl has been alkylated with sesquiterpenoid bicyclic residues. The mass spectra of all these compounds



(XLI)† R =  , kamolone (Ref.35) ,

† From biogenetic considerations Paknikar and Kirtany[59] have recently assigned to the sesquiterpenoid substituent of kamolone the structure decahydro-1,2,4a,5-tetramethyl-6-oxonaphthylmethylene.

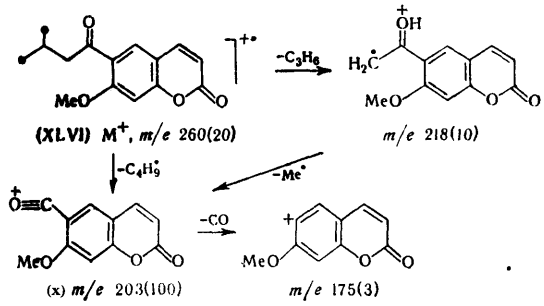


indicate rupture of a carbon–oxygen bond and the α-carbon–carbon bond in the side-chain, both alone and accompanied by migration of hydrogen atoms. The charge is localised on either moiety, chromenone or sesquiterpenoid. The spectra, of course, contain many peaks due to ions formed by further breakdown of the sesquiterpenoid ions, but information on the structure of this part of the molecules is obtained mainly from an analysis of the n.m.r. spectra.

IX. CHROMEN-2-ONES CONTAINING A KETO-GROUP IN THE SIDE-CHAIN

Study by MacLeod[23] of the mass spectra of two isomeric ketones—7-methoxy-6-(3-methyl-1-oxobutyl)chromen-2-one geijerin (XLVI) and 7-methoxy-6-(3-methyl-2-oxobutyl)chromen-2-one (isogeijerin) (XXXII)—and their deuterated analogues showed that the route of decomposition of the molecular ions is significantly influenced by the position of the keto-group in the side-chain.

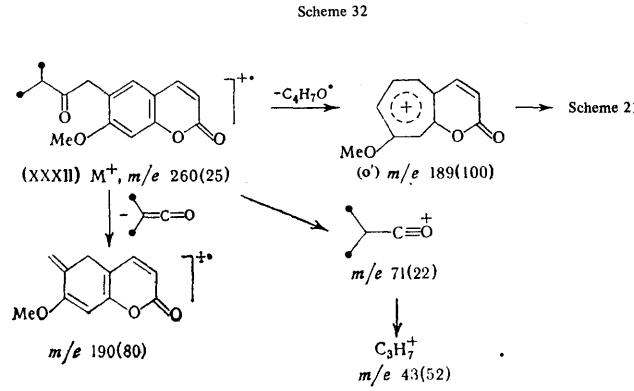
Scheme 31



The most intense peak in the mass spectrum of geijerin is due to the 203 ion (x), which may be formed in a single stage by elimination of an isobutyl radical or in two stages by the successive elimination of a propene molecule and a methyl group (Scheme 31).

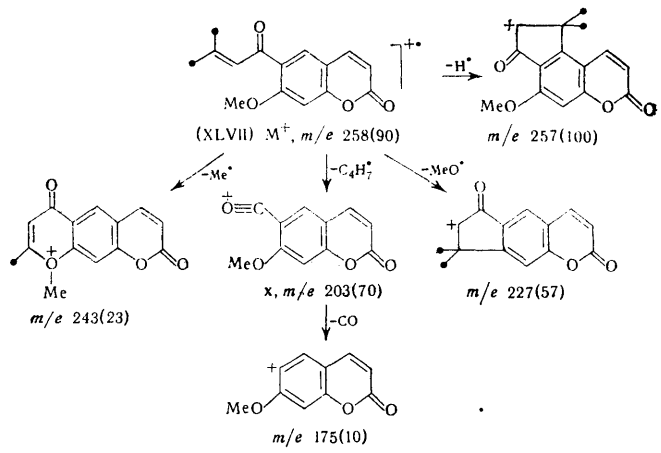
In the mass spectrum of isogeijerin, however, the strongest peak is due to the tropylium ion (o') at 189, and is accompanied by a very intense peak due to a 190 ion (Scheme 32).

Scheme 32



The spectrum of 7-methoxy-6-(3-methyl-1-oxobut-2-enyl)chromen-2-one—dehydrogeijerin (XLVII)—is considerably more complicated[23] than those of the above saturated ketones. The peak due to the molecular ion is very strong, while the most intense peak is due to the ion $[M - 1]^+$, to which a tricyclic structure was assigned (Scheme 33). The molecular ion readily loses a methyl group to give a 243 ion, a methoxy-group to form a 227 ion (owing to the presence of an unsaturated substituent in the *ortho*-position), and a C_4H_7 radical to form the 203 ion (x).

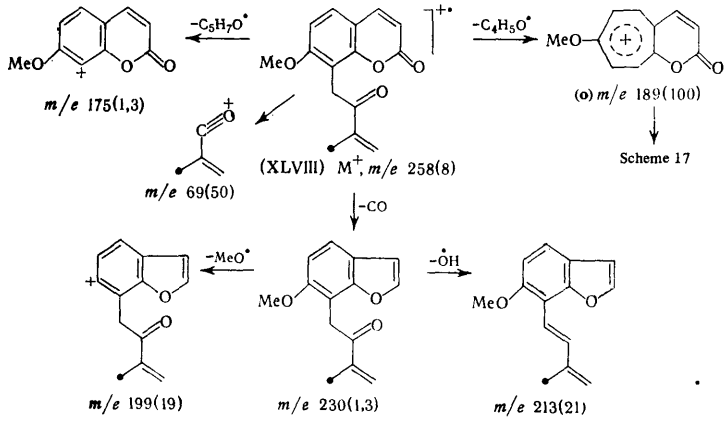
Scheme 33



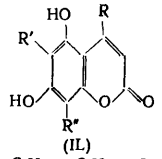
Another chromenone containing a keto-group in an unsaturated side-chain—7-methoxy-8-(3-methyl-2-oxobut-3-enyl)chromen-2-one (XLVIII), isolated from *Murraya exotica* L.—has been described by Subba Rao et al.[38] Its decomposition on electron bombardment (Scheme 34) differs significantly from that described above (Scheme 31) for the ketone (XLVI). Formation of the 189 ion (o) and a 69 ion, the latter produced by localisation of the charge on the side-chain residue, is accompanied by elimination from the molecular ion of a carbonyl group (230 ion) followed by elimination of methoxyl (199 ion) or of a hydroxyl resulting from enolisation (213 ion).

This type of compound includes a large group of 4-alkyl and 4-phenyl-5,7-dihydroxychromen-2-ones containing isopentenyl and various *C*-acyl radicals in the aromatic

Scheme 34



ring, isolated from *Mammea americana* L.[13,39] and from *M. africana*,[14,40] which can be represented by the general formula



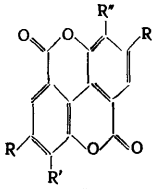
(IL)

R=H, *n*-C_3H_7, *n*-C_4H_9, s-C_4H_9, *n*-C_5H_{11} or C_6H_5.
R'=H, $Me_2C{=}CHCH_2$, iso-C_5H_7CO, iso-C_4H_9CO or s-C_4H_9CO.
R"=H, $Me_2C{=}CHCH_2$, *n*-C_5H_7CO, iso-C_4H_9CO or s-C_4H_9CO.

The decomposition of these compounds conforms in principle to the above rules, but interpretation of the mass spectra is greatly complicated by the presence of many diverse substituents, each of which makes its own contribution.

X. BICHROMENONES

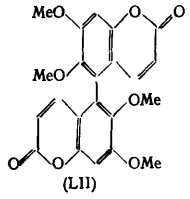
The mass spectra of the dimethyl ether (L) of nasutin A—a metabolite of termites—and the 3,3',4-trimethyl ether (LI) of ellagic acid[41]



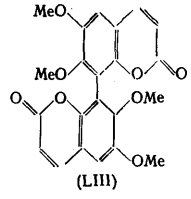
R=OH, R'=R" H, nasutin A;
(L), R=OMe, R'=R"=H;
R=R'=R"=OH, ellagic acid;
(LI), R=R'=OMe, R"=OH,

are characterised by maximum intensities of the peaks due to the molecular ions (in the case of (L) the $[M-14]^+$ ion is present) and the detachment of methyl and methoxyl groups. Elimination of a carbonyl group is not observed.

The mass spectrum of euphorbetin—the tetramethyl ether of 6,6',7,7'-tetrahydroxy-5,5'- or -8,8'-bichromenyl-2,2'-dione (LII) or (LIII)



(LII)



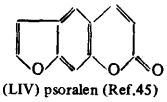
(LIII)

isolated from *Euphorbia lathyris* L.[42], is also characterised by preliminary elimination of methyl and methoxyl groups from the molecular ion. Elimination of a carbonyl group is observed only in the later stages of breakdown, and rupture of the bond between the chromen ring systems does not take place.

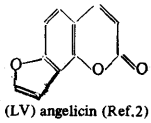
XI. FUROCHROMEN-2-ONES

The above regularities in the decomposition of chromenones under electron bombardment are largely applicable also to the more complicated furo- and pyranochromenones. The account of these will therefore be less detailed.

Unsubstituted furochromen-2-ones—the linear psoralen (LIV)[3] and the angular angelicin (LV)[2]



(LIV) psoralen (Ref.45)

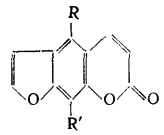


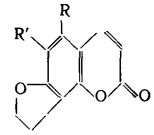
(LV) angelicin (Ref.2)

lose three carbonyl groups in succession. It is difficult to make a quantitative assessment of the results obtained by various workers with different apparatus under different experimental conditions, but a striking difference is evident in the intensities of certain peaks in the spectra of these compounds (Table 5).

The presence in the furochromenone molecule of one methoxy-group--bergapten (LVI),[2,43] xanthotoxin (LVII),[2]

isobergapten (LVIII) [44]—or of two methoxy-groups—isopimpinellin (LIX) [2,43,44] and pimpinellin (LX) [43,44]





(LVI) R = OMe, R′ = H, bergapten (Refs.2,43)
(LVII), R = H, R′ = OMe, xanthotoxin (Ref.2),
(LIX), R = R′ = OMe, isopimpinellin (Refs.2,43,44).
(LVIII), R = OMe, R′ = H, isobergapten (Ref.44),
(LX), R = R′ = OMe, pimpinellin (Ref.44),

leads to competitive elimination of a methyl group in the early stages, and this dominates the mass spectra of the latter pair of compounds. The spectra of isomers differ in the relative intensities of characteristic peaks (Tables 6 and 7).

Table 5. Values of m/e and $100I/I_{max}$ for peaks due to the main ions in the mass spectra of psoralen and angelicin.

Compound	M+	M—CO	M—2CO	M—3CO
Psoralen (LIV) (Ref.43)	186 (100)	158 (84)	130 (22)	102 (24)
Angelicin (LV) (Ref.2)	186 (72)	158 (100)	130 (24)	102 (40)

Table 6. Values of m/e and $100I/I_{max}$ for peaks due to the main ions in the mass spectra of bergapten, xanthotoxin, and isobergapten.

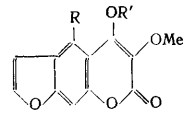
Compound	M+	M—Me	M—CO	M—Me—CO	M—2CO	M—Me—2CO	M—3CO	M—Me—3CO
Bergapten (LVI)	216	201	188	173	160	145	132	117
(Ref.2)	(100)	(38)	(21)	(78)	(4)	(40)	(3)	(3)
Xanthotoxin (LVII)	216	201	188	173	160	145	132	117
(Ref.2)	(100)	(21)	(12)	(56)	(1)	(12)	(3)	(2)
Isobergapten	216	201	188	173	—	145 (19)	—	—
(LVIII) (Ref.44)	(100)	(22)	(28)	(55)				

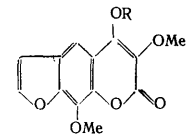
Table 7. Values of m/e and $100I/I_{max}$ for peaks due to the main ions in the mass spectra of pimpinellin and isopimpinellin.

Compound	M+	M—Me	M—2Me	M—Me—CO	M—Me—2CO
Pimpinellin (LX) (Ref.44)	246 (100)	231 (86)	216 (5)	203 (10)	175 (14)
Isopimpinellin (LIX)	246 (91)	231 (100)	216 (4)	203 (15)	175 (14)

Compound	M—Me—3CO	M—2Me—CO	M—2Me—2CO	M—2Me—3CO
Pimpinellin (LX) (Ref.44)	147 (22)	188 (10)	160 (15)	132 (6)
Isopimpinellin (LIX)	147 (9)	188 (16)	160 (16)	132 (6)

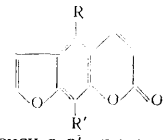
Analogous decomposition is undergone by the molecular ions of furochromen-2-ones from *Halfordia kendack* and *H. skleroxyla*, [45] containing substituents at other positions in the chromenone ring system—halkendin (LXI), norhalkendin (LXII), halfordin (LXIII), norhalfordin (LXIV), halfordinin (LXV), isohalfordin (LXVI), and norisohalfordin (LXVII)

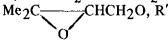
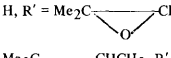
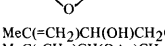




(LXI), R = H, R′ = Me, halkendin;
(LXII), R = R′ = H, norhalkendin;
(LXIII), R = OMe, R′ = Me, halfordin;
(LXIV), R = OMe, R′ = H, norhalfordin;
(LXV), R = OMe, R′ = $OCMe_2CH=CH_2$, halfordinin (Ref.45).
(LXVI), R = Me, isohalfordin;
(LXVII), R = H, norisohalfordin (Ref.45);

When the aromatic ring of the furochromenone contains more complicated substituents—isopentenyl groups (isoimperatorin (LXVIII), [43,46] imperatorin (LXIX) [43]), their epoxides (oxypeucedanin (LXX), prangenin (LXXI), [43] the epoxide of the methyl ether of alloimperatorin (LXXII) [30]), and others (gosferol (LXXIII), isolated from *Prangos ferrulaceae* Lindl, and its acetate (LXXIV), [47] the ethyl ether of oxypeucedanin hydrate (LXXV), [48] and also a furochromenone containing a formyl group in a long isoprenoid chain (LXXVI) isolated from grapefruit[25])



(LXVIII), R = $Me_2C=CHCH_2O$, R′ = H, isoimperatorin (Refs.43,46);
(LXIX), R = H, R′ = $Me_2C=CHCH_2O$, imperatorin (Ref.43);
(LXX), R =  R′ = H, oxypeucedanin (Ref.43);
(LXXI), R = H, R′ = , prangenin (Ref.43);
(LXXII), R =  R′ = OMe, methyl ether of epoxyalloimperatorin (Ref.30);
(LXXIII), R = $MeC(=CH_2)CH(OH)CH_2O$, R′ = H, gosferol (Ref.47);
(LXXIV), R = $MeC(:CH_2)CH(OAc)CH_2O$, R′ = H, gosferol acetate;
(LXXV), R = $Me_2C(OEt)CH(OH)CH_2O$, R′ = H, ethyl ether (Ref.48) of oxypeucedanin hydrate;
(LXXVI), R = $Me_2(CHO)CH_2CH_2C(Me)=CHCH_2O$, R′ = H (Ref.25).

the mass spectra exhibit peaks due to ions formed in the types of decompositions considered above for the corresponding substituted chromenones.

Table 8. Values of m/e, (intensities, % on total ion current), and ratios of intensities of peaks due to characteristic ions in the mass spectra of certain furochromenone derivatives[43].

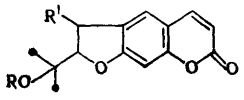
Compound	M+	M—68 *	M—84 *	M—71**	$\frac{I(M)}{I(M-68)}$	$\frac{I(M)}{I(M-84)}$	$\frac{I(M)}{I(M-71)}$
Isoimperatorin (LXVIII)	270 (0.2)	202 (5.8)	—	—	0.03	—	—
Imperatorin (LXIX)	270 (0.25)	202 (18.5)	—	—	0.01	—	—
Oxypeucedanin (LXX)	286 (5.7)	—	202 (11.6)	215 (0.6)	—	0.49	9.50
Prangenin (LXXI)	286 (5.8)	—	202 (23.2)	215 (4.3)	—	0.25	1.35

* Detachment of the side-chain and a hydrogen atom.
** Detachment of part of the side-chain.

A difference in the position of a substituent (5 or 9) is apparent only in a change in the relative intensities of the peaks due to certain ions, as can be seen from the isomers (LXVIII)–(LXXI) (Table 8). The ratio of the intensity of the peak due to the molecular ion to that of the peaks due to ionic fragments is evidently larger with the

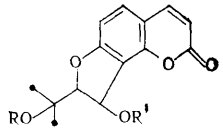
5-substituted derivatives, which will probably be useful for diagnostic purposes.

Mass spectra have been reported for mono- and di-hydroxylated linear and angular dihydrofurochromen-2-ones—marmesin (LXXVII) and its acetate (LXXVIII), angelate (deltoin) (LXXIX), senecionate (prantschimgin) (LXXX), and ω-methylthiocrotonate (seseliflorin) (LXXXI),[49] smyrniorin (LXXXII)[50,51] and its methanolysis product (LXXXIIa),[51] smyrnioridin (LXXXIII)[50,51]



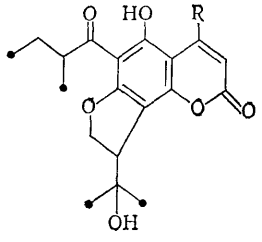
(LXXVII) R = R′ = H, marmesin;
(LXXVIII) R = MeCO, R′ = H, marmesin acetate;
(LXXIX) R = MeCH = CH(Me)CO-*trans*, R′ = H, deltoin;
(LXXX) R = Me_2C = CHCO, R′ = H, prantschimgin;
(LXXXI) R = MeSCH = CHCO, R′ = H, seseliflorin (Ref.49);
(LXXXII) R = MeCO, R′ = MeCOO, smyrniorin (Refs.50,51);
(LXXXIIa) R = MeCO, R′ = MeO, methanolysis product of smyrniorin (Ref.51);
(LXXXIII) R = MeCO, R′ = MeCH = CH(Me)COO-*trans*, smyrnioridin (Refs.50,51);

peucenidin (LXXXIV),[50] athamantin (LXXXV), and libanotin (LXXXVI)[51]



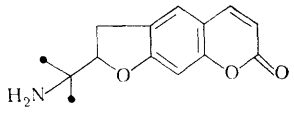
(LXXXIV) R = Me_2C = CHCO, R′ = Me, peucenidin (Ref.50);
(LXXXV) R = R′ = Me_2CHCH_2CO, athamantin (Ref.51);
(LXXXVI) R = MeCO, R′ = MeCH = C(Me)CO-*trans*, libanotin (Ref.51).

Analogous angular furochromenones



(LXXXVII) R = Ph[40];
(LXXXVIII) R = Pr[40]

isolated from *Mammea africana* G. Don are biogenetically related to the polysubstituted chromenones described in Section IX and encountered in the same plants. A mass spectrum has been reported also for the alkaloid prangosine



(LXXXIX) prangosine (Ref.52).

isolated from *Prangos pabularia* Lindl, which is a derivative of psoralen, containing a 1-amino-1-methylethyl group in the furan ring.

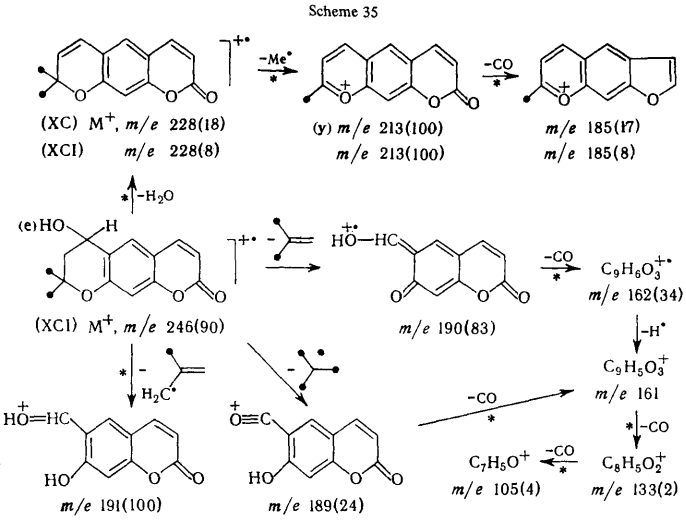
Compounds (LXXVII)–(LXXVI) undergo elimination of an acyl radical and an acid molecule (an acetyl residue is often removed as keten), and a methyl group is eliminated in the later stages of decomposition. Compound (LXXXVII) eliminates (i) a carbonyl group, an isopropoxy-group, a C_4H_9 radical from the 6-acyl substituent, and then a water molecule or (ii) an isopropoxy-group with part of the dihydrofuran ring. Only the latter type of decomposition occurs with (LXXXVIII).

Prangosine on electron bombardment eliminates a methyl group or an ammonia molecule, being converted in the latter case into an isopropenylfurochromen-2-one ion, which then loses successively a carbonyl group, a methyl group, and two more carbonyl groups.

XII. PYRANOCHROMEN-2-ONES

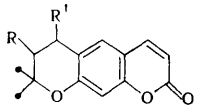
The mass spectrum of the simplest linear pyranochromen-2-one—xanthyletin (XC)[53]—indicates elimination of a methyl group to form the completely aromatised 213 ion (y) (Scheme 35), which then loses a carbonyl group.

Scheme 35



The pattern of decomposition of the molecular ion is considerably complicated when a 6-hydroxyl is introduced into dihydroxanthyletin to give (XCI).[53] Dehydration yielding an ion identical with the molecular ion of (XC) is accompanied by a retrodiene decomposition yielding a 190 ion together with migration of a hydrogen atom to or from the charged fragment (191 or 189 ion). These latter ions then eliminate a carbonyl group (Scheme 35). The corresponding ketone (XCII) decomposes similarly (Scheme 36).[53]

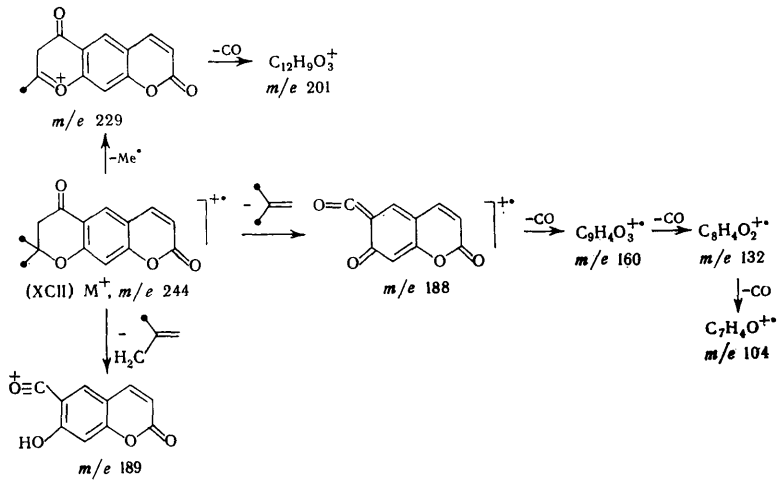
Mass spectra have been described also for the isomeric (with XCI) alcohol—agasyllol (XCIII)—its acetate (XCIV) and angelate—agasyllin (XCV)[54]—and the diacyldihydropyranochromen-2-one—andelin (XCVI)[55]



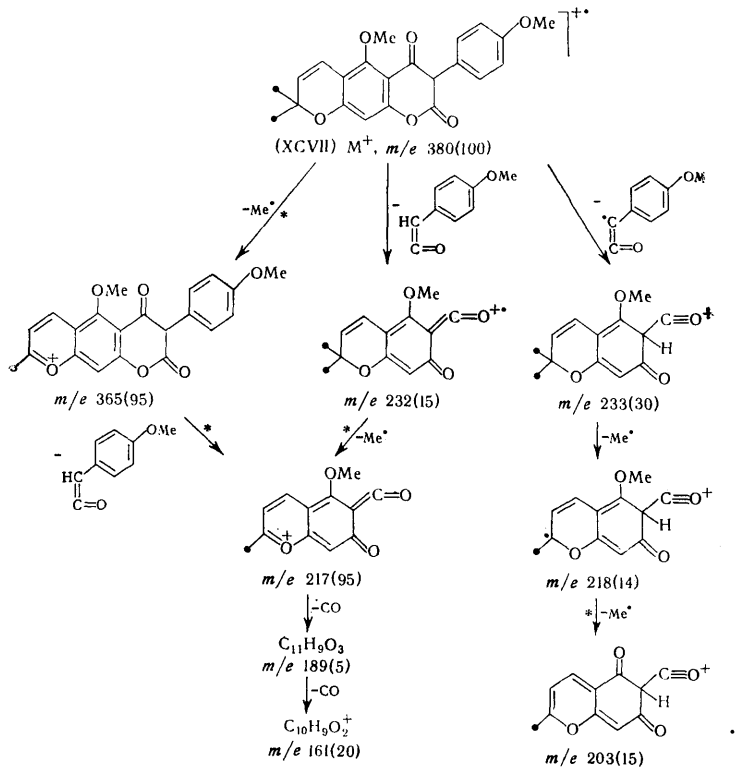
(XCIII) R = R′ = H, agasyllol;
(XCIV) R = MeCO, R′ = H, agasyllol acetate;
(XCV) R = MeCH = CH(Me)CO-*trans*, R′ = H, agasyllin (Ref.54);
(XCVI) R = Me_2C = CHCO, R′ = MeCH = C(Me)CO-*trans*, andelin (Ref.55).

Decomposition of the molecular ion of agasyllol is analogous to that described for (XCI), but breakdown of its acyl derivatives resembles that of acyl derivatives of furochromenones: i.e. the acid molecule or radical is split off. Elimination of a methyl group plays an important

Scheme 36



Scheme 37



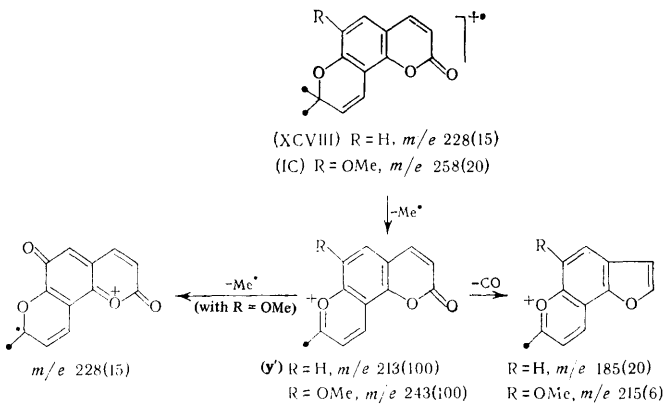
part, since, in combination with the detachment of an acid molecule, it leads to aromatisation of the pyran ring.

A more complicated example of a linear pyranochromenone is robustic acid, isolated from *Derris robusta*, which contains a 3-phenyl group (XCVII).[9,56] The breakdown of its molecular ion on electron bombardment is indicated in Scheme 37.

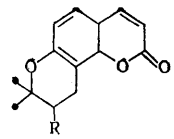
Angular pyranochromenones are considerably more widely distributed in Nature, so that mass spectra has been reported for an appreciably larger number of these compounds. The mass spectrum of the simplest angular pyranochromenone—seselin (XCVIII) [2]—is analogous to that of xanthyletin (XC). Elimination of a methyl group from the molecular ion yields the completely aromatised 213 ion (y'), which then loses a carbonyl group (Scheme 38). The spectrum of 6-methoxyseselin—brayelin (IC) [2]—differs from that of (XCVIII) only in the elimination of another methyl group in the second stage of decomposition, with formation of a quinonoid 228 ion (Scheme 38).

Mass spectra have been reported for dihydroseselin (C), a hydroxy-derivative (xanthogallol) (CI), and its acetate (CII), angelate (xanthogalin) (CIII),[54] senecionate[29]

Scheme 38

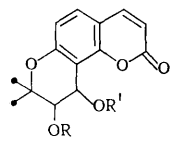


(buchtarmin) (CIV),[54] and isovalerate (CV),[29] as well as lomatin angelate (selenidin) (CVI)[57]



(C) R = H, dihydroseselin;
(CI) R = OH, xanthogallol;
(CII) R = MeCOO, xanthogallol acetate;
(CIII) R = MeCH = C(Me)COO-*trans*, xanthogalin (Ref.54);
(CIV) R = Me_2C = CHCOO, buchtarmin (Refs.29,54);
(CV) R = Me_2CHCH_2COO, xanthogallol isovalerate (Ref.29);
(CVI) R = MeCH = C(Me)COO-*trans*, selenidin (Ref.57).

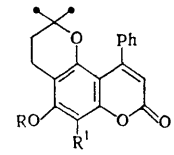
The dihydroxy-derivatives of (C) include the diol itself (kellactone) (CVII) and its diacetate (CVIII),[55] methylkellactone (CIX),[16,55] pterixin (CX),[16,55,58] its methanolysis product (CXI),[58] epoxypterixin (CXII),[58] and dihydropterixin (CXIII),[55] visnadin (CXIV), dihydrosamidin (CXV), anomalin (CXVI),[55] its monoepoxide (CXVII), and its diepoxide (CXVIII),[58] floroselin (CXIX), and its methanolysis product (CXX)[55]



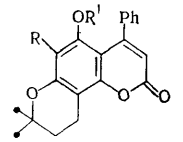
(CVII) R = R' = H, kellactone;
(CVIII) R = R' = MeCO, kellactone diacetate (Ref.55);
(CIX) R = H, R' = Me, methylkellactone (Refs.16,55);
(CX) R = MeCO, R' = MeCH = C(Me)CO-*trans*, pterixin (Refs.16,55,58);
(CXI) R = Me, R' = MeCH = C(Me)CO-*trans*, methanolysis product of pterixin;
(CXII) R = MeCO, R' = MeCH–C(MeCO, epoxypterixin (Ref.58)
O
(CXIII) R = MeCO, R' = $MeCH_2CH(Me)CO$, dihydropterixin;
(CXIV) R = MeCH = C(Me)CO-*trans*, R' = MeCO, visnadin;
(CXV) R = Me_2CHCH_2CO, R' = MeCO, dihydrosamidin;
(CXVI) R = R' = MeCH = C(Me)CO-*trans*, anomalin (Ref.55);
(CXVII) R = MeCH = C(Me)CO-*trans*,
R' = MeCH—C(Me)CO;
O
(CXVIII) R = R' = MeCH—C(Me)CO (Ref.58);
O
(CXIX) R = MeCH = C(Me)CO-*trans*,
R' = MeSCH = CHCO, floroselin;
(CXX) R = MeCH = C(Me)CO-*trans*,
R' = Me, methanolysis of floroselin (Ref.55).

On the whole all the above compounds undergo the same types of decomposition on electron bombardment as do linear pyranochromenones.

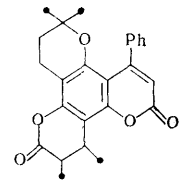
Mass spectra have been described also for several 4-phenylpyranochromen-2-ones with a different mode of fusion of the rings[15]



(CXXI) R = Me, R' = H;
(CXXII) R = Me, R' = MeCH = C(Me)CO-*trans*;
(CXXIII) R = MeCO, R' = $MeCH_2CH(Me)CO$ (Ref.15),



(CXXIV) R = H, R' = Me;
(CXXV) R = Me_2CHCH_2CO, R' = H (Ref.15),



(CXXVI)

as well as polyfunctional angular pyranochromenones isolated from *Mammea americana* L.[13] and *M. africana* G. Don.[40] Molecular ions of these compounds break down on electron bombardment similarly to the furochromenones and linear pyranochromenones described above.

Another type of angular pyranochromenone, in which the two pyran rings are fused together—4-methylpyrano-[5,6-*c*]chromen-2,5-dione (CXXVII)—was described by Johnstone et al.[10] Its mass spectrum represents a four-stage elimination of carbonyl groups and includes a metastable peak, indicating that the second and third carbonyls may be eliminated in a single stage. Such an observation is not unique, and has been reported in particular for monocyclic 2-pyrones. This simultaneous elimination of two carbonyl groups suggests that they may be contiguous. Measurement of the ionisation and appearance potentials at each stage, together with a study of the mass spectrum of the 5-carbon-13 analogue, made it possible to assess the sequence in which the carbonyl groups were ejected.

In order to elucidate the structure of the 200 ion $[M - CO]^+$ the mass spectrum of this pyranochromenone was compared with that of a similarly fused furochromenone. Although the spectra were qualitatively and quantitatively almost identical in the region of 200 and below, it was considered that these two 200 ions differed in structure, since the appearance potential of one differed appreciably from the ionisation potential of the other. An open-chain structure was therefore assigned to the 200 ion $[M - CO]^+$ in the case of the pyranochromenone (CXXVII). As has been stated earlier in connection with chromen-2-one itself, the Reviewers regard this conclusion as questionable.

Finally it must be emphasised that this Review makes no claim to exhaustive coverage of published information,

but nevertheless the Reviewers hope that it will show quite clearly the possibilities and limitations of mass spectrometry for determining the structure of naturally occurring chromen-2-ones, furochromenones, and pyranochromenones.

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