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Bifunctional Even-electron Ions

III. Fragmentation Behaviour of Aliphatic Hydroxonium Ions Containing an Additional Carbomethoxy Group

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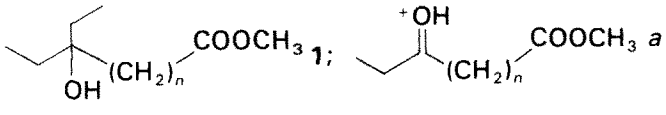
The primary and subsequent fragmentations of the bifunctional oxonium ions $R-\overset{+}{C}(OH)-(CH_2)_n-COOCH_3$ ($n = 0$–5), *a*, are dominated by functional group interactions. Loss of CH_3OH is the only appreciable primary fragmentation of the higher homologues, but for the lowest homologue (a_0) this reaction is missing. Instead, CO loss is observed. The next homologue (a_1) shows loss of CH_2CO besides loss of CH_3OH. The mode of the subsequent fragmentations is dependent on the chain length separating the functional group, and formation of cyclic ions is typical of the fragmentation behaviour of a_2 and a_3. Evidence for proton transfer from the carbonyl oxygen to the methoxy group of a protonated ester group is presented.

INTRODUCTION

In continuation of our work on aliphatic bifunctional even-electron ions[1,2] we have now investigated the hydroxonium ions *a*, containing an additional methyl ester group. The results on the corresponding methoxonium ions are published in the succeeding paper.[3]

Bifunctional tertiary alcohols are very suitable precursors for generating bifunctional ions of this type by electron impact (EI). At reduced electron energies (20 eV) the mass spectra of these compounds are so simple that the spectra of the bifunctional oxonium ions can be obtained from them with success, without applying the technique of collision activation (CA). In the present study tertiary aliphatic alcohols (**1**) containing an additional carbomethoxy group at the end of a side chain served as the precursors for the ions of interest (*a*). As in the previous cases, the EI mass spectrometry of **1** did not impose any problems on obtaining the desired informations on ions *a*.



The main goal of these investigations was to get a global picture of the reactions of aliphatic hydroxonium ions in the presence of an ester group at different chain distances of the two functionalities. Therefore, mass spectral comparison of homologous ions plays a major role. The reaction pathways elucidated have generally been obtained by these comparisons, by appropriate metastable ion transitions, by deuterium labelling studies and by investigations of some other related ions. In pursuit of these reaction pathways some interesting insights concerning proton migration within a protonated ester group have been obtained. Unambiguous proof of ion structures was not intended. However, structures have been formulated, assuming that the corresponding ions are formed by well-founded reactions and that other structures are not plausible from the present results; certainly they are valid in most cases.

Related simpler hydroxonium ions (*d*) already aroused attention in connection with the unexpected fragmentations of hydroxy-substituted straight-chain methyl alkanoates.[4] The experimental results of these early studies in general are in accordance with the present findings, but the conclusions drawn previously must be revised in several instances. These ions have also been given general considerations by Winnik in a review of mass spectral fragmentations of esters.[5]

RESULTS AND DISCUSSION

Compound series **1a–1f** served as the precursors for the generation of the bifunctional ions a_0–a_5. To suppress high-energy successive fragmentations and to avoid thermal decompositions the mass spectra of **1** have been measured at reduced electron energies (20 and 14 eV) and at low source temperature (~80 °C). Other compounds and deuterium-labelled **1**, which have additionally been used to establish reaction pathways, are presented at the appropriate place.

Mass spectra of the parent compounds

As is the case for the other bifunctional tertiary alcohols measured,[1] the fragmentations of **1** are strongly dominated by the α-fissions characteristic of unsubstituted tertiary alcohols, as depicted in Scheme 1.

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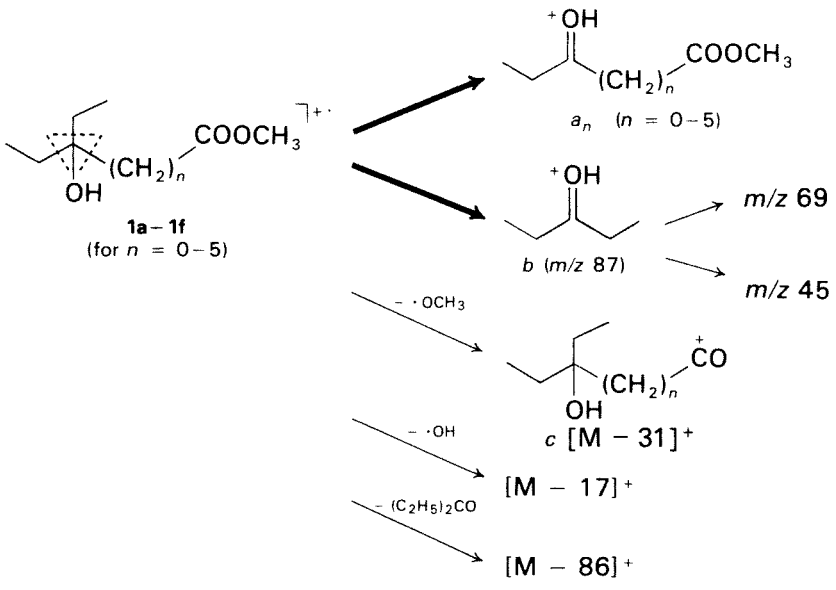


Scheme 1

Beside these fissions, loss of OCH_3 from the ester group, loss of the hydroxy group and loss of $(C_2H_5)_2CO$, originating from the $(C_2H_5)_2C(OH)$ moiety, are found for **1**, except for **1a** (Scheme 1). Loss of OCH_3 and of OH, respectively, lead to ions of very low relative abundances, whereas the latter reaction is weak for **1b–1d**, but gets increasingly pronounced from **1e** to **1f**. Normal McLafferty rearrangements starting from the methyl ester group are not observed, but formation of $[M - 86]^{+\cdot}$ may be interpreted as involving migration of a hydrogen radical from the OH group to the ester carbonyl (complete retention of D in the resulting ion starting from *O*-deuterated **1**). A corresponding observation has been made for straight-chain hydroxy-substituted methyl esters.[4]

The low members **1a** and **1b** show small peaks of $[M + H]^+$ ions, and at elevated temperatures all compounds **1** tend to lose methanol, probably in a thermal reaction.

Some ions of low abundances could not be correlated to an established fragmentation.

The fragmentations of *a* do not lead to ions of the same masses as those from the other fragmentations and, thus, are easily separated.

Mass spectra of the bifunctional ions *a* and *b*, general

The 20- and 14-eV mass spectra of a_0–a_5 (obtained from the spectra of **1a–1f** in the same manner as described previously[1]) are summarized in Fig. 1. The ion abundances are given as fractions of the total ion abundance of a particular spectrum. Abundances of such daughter ions which are not presented in the diagram are added to the abundances of the corresponding parent fragments.

Figure 1 reveals that the degree of decomposition of a_0–a_5 and the degree of formation of the different fragment ions is strongly dependent on the carbon chain separating the functional groups. With the exception of a_0 the main primary fragmentation of *a* is loss of CH_3OH, which has also been observed previously for

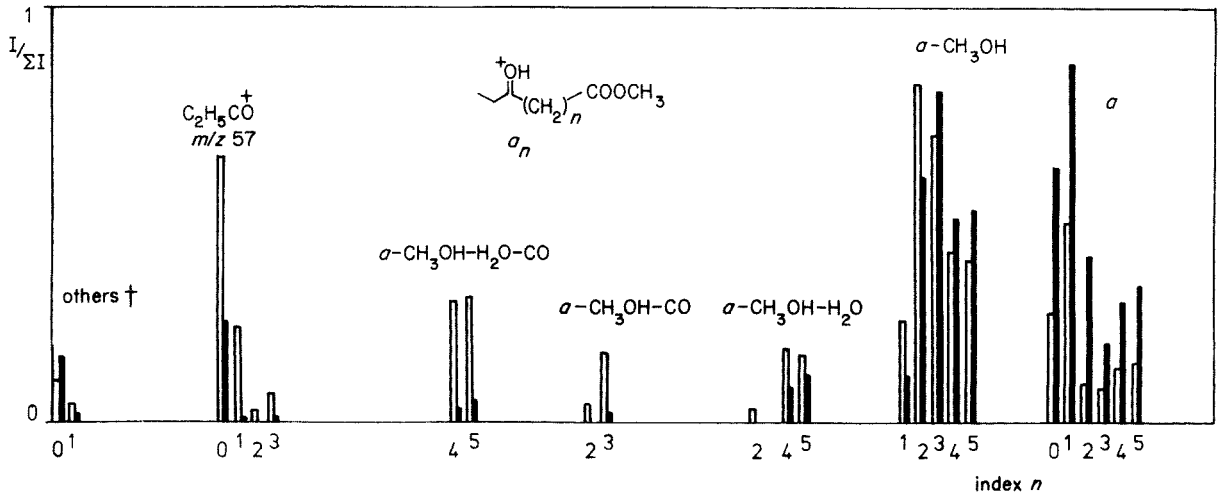
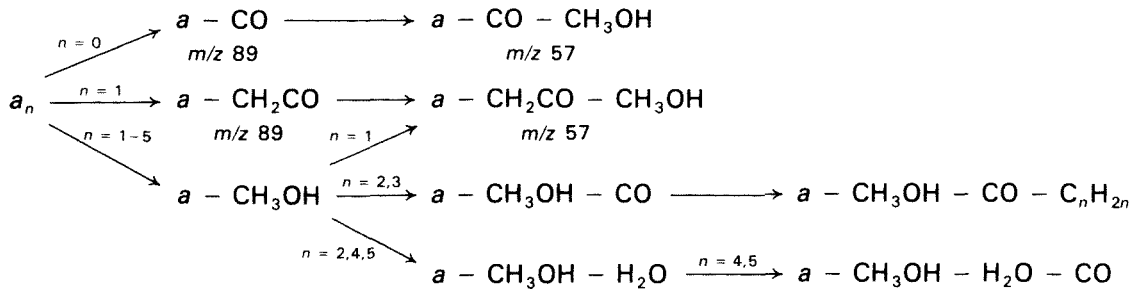
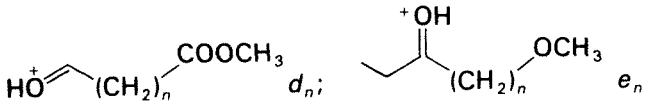


Figure 1. Schematic mass spectra of ions a_n: †for a_0 $a - CO$ (*m/z* 89); for a_1 $a - CH_2CO$ (*m/z* 89). □ 20 eV ■ 14 eV



Scheme 2

d.[4] For a_0 only loss of CO is found as a primary reaction. For a_1 loss of CH_2CO is observed besides loss of CH_3OH. No reactions typical of ordinary oxonium ions as, e.g., *b* have been detected. This is characteristic of strong interactions between the functional groups, as has been previously discussed for *e*.[1]



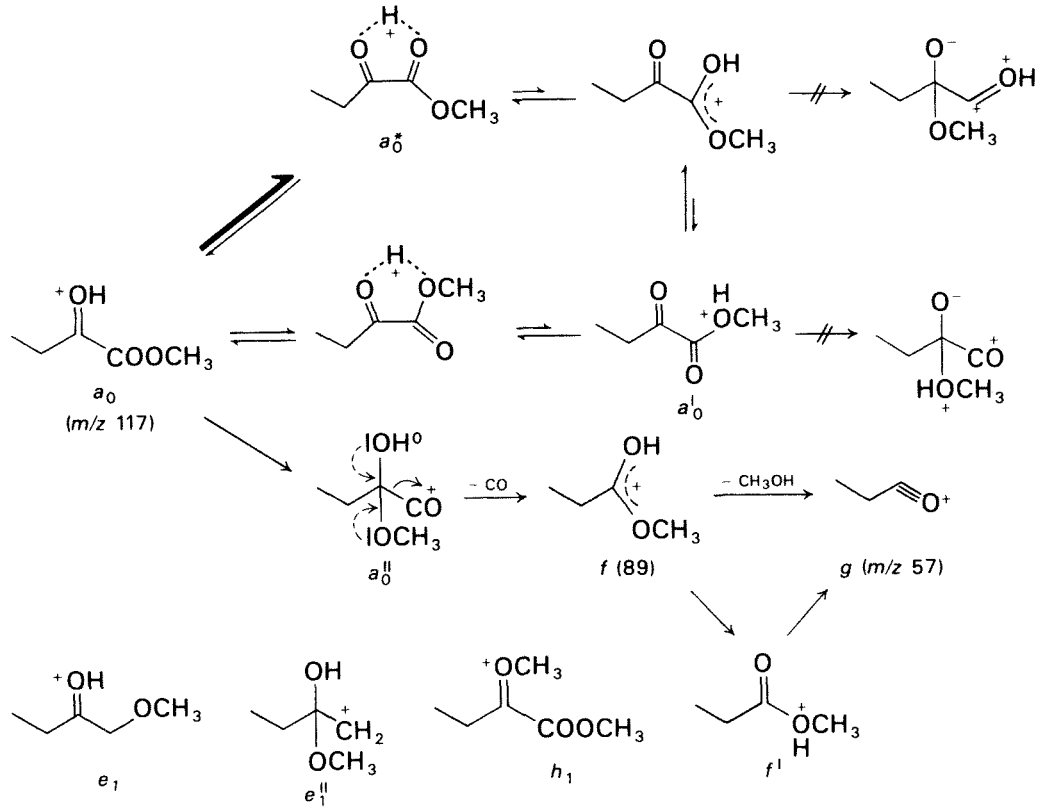
The maximum and high degree of decomposition of *a* at a chain distance of $n = 2, 3$ (a_2, a_3) typically points to through-space interaction in the rate-determining step of the main fragmentation reactions (5- and 6-membered cyclic transition states, respectively).

The formal fragmentation routes of *a*, derived from the spectra and from appropriate metastable ion transitions, are depicted in Scheme 2. The neutrals lost are taken from the discussion of the fragmentation pathways below.

The general inspection of the spectra and fragmentation routes shows that ions a_0–a_5 can be subdivided into four categories, namely a_0 and a_1 as unique ions and a_2–a_3 and a_4–a_5 as groups of different reaction behaviour. Therefore, the detailed discussion of these ions is presented for each group separately.

Discussion of the fragmentation pathways of *a*

$CH_3OOC-(C_2H_5)C=\overset{+}{O}H$ (a_0). This lowest member of a_0–a_5 is the only one which does not lose CH_3OH but, instead, eliminates a neutral of mass 28. Ion $CH_3OOC-(C_3H_7)C=\overset{+}{O}H$, a homologue of a_0, shows loss of the same neutral, which proves without high resolution that this neutral is CO. Thus, obviously skeletal rearrangement precedes this reaction. Furthermore, this rearrangement prior to CO loss must directly lead from a_0 to an ion of structure a_0^{II} by methoxy anion migration. This kind of migration with sub-



Scheme 3

sequent CO loss has already been observed for similar ions, generated from substituted phenyl alkanoates.[6] For a_0 migrations of OCH_3 or CH_3OH (from e.g. a_0^I) to form other intermediates cannot be considered to be realistic alternatives (see Scheme 3), and methoxy anion migration from a carbomethoxy group to the centre of the positive charge generally seems to be a favourable reaction, as can be deduced from previous investigations[7,8] and from own results (discussed below and in the succeeding paper). Comparing the two ions a_0 and e_1 of the same chain distance between the OCH_3 group and the charged centre, the strong tendency of a_0 to rearrange to a_0^{II} is certainly due to the stability of the carbonyl cation in a_0^{II} relative to the primary alkyl cation in e_1^{II} (Scheme 3).

Loss of CO from a_0^{II} is straightforward and definitely leads to *f*, a methyl alkanoate ion protonated at the carbonyl unit. These ions successively lose CH_3OH and CO.[9] The possibility of proton transfer within a protonated ester group has been considered[10] and has been denied by Winnik[5] from orbital symmetry considerations. Interestingly, from *O*-deuterated a_0 exclusive loss of CH_3OD is found for $f \rightarrow g$. Since from the arguments above *f* is formed from a_0 directly via a_0^{II}, this shows that CH_3OH loss leads via f^I and, therefore, contradicts Winnik's statement. As will be shown below, ion *f* is also formed from a_1 via another well-defined pathway, and the same results are obtained in that case. Thus, there is strong evidence that proton migration from the OH to the OCH_3 group of a protonated methyl ester is a favourable reaction.

The missing loss of CH_3OH from a_0 also is a great surprise in the light of the fragmentation behaviour of a_1–a_5, e_1 and h_1, which all exhibit CH_3OH loss. This cannot be caused by a hindered proton migration to the carbonyl or methoxy moiety, because e_1 with a comparable spatial distance of the functionalities shows CH_3OH loss as the main primary reaction and because a_0* certainly is a structure with an energy minimum in the reaction coordinate of the isomerizations of a_0. Therefore, it is more likely that a_0 assumes the conformation a_0* in a high population, and in concert with the favourable isomerization of a_0 to a_0^{II} this prohibits the formation of the reactive species a_0' in sufficient probability to undergo methanol loss.

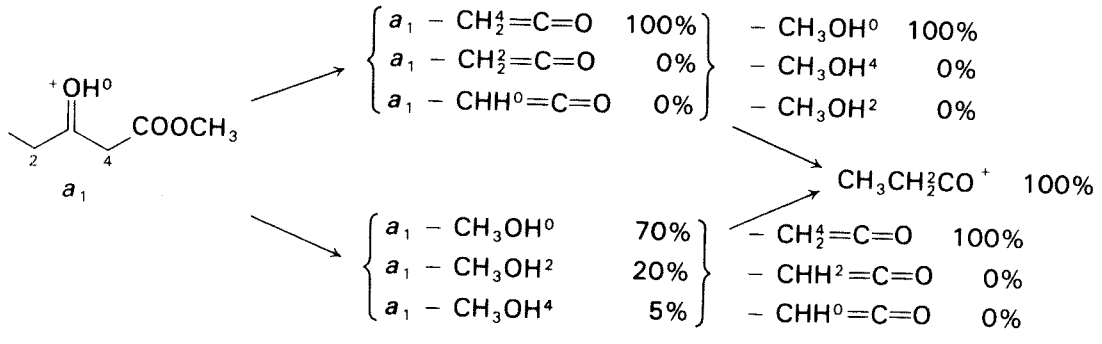
$CH_3OOC-CH_2-(C_2H_5)\overset{+}{C}=\overset{+}{O}H$ (a_1). The primary fragmentations of a_1 are loss of CH_3OH and of a neutral of 42 u (see Fig. 1). From deuterium labelling experiments and from the mass spectra of the homologous ions $C_2H_5OOC-CH_2-(C_2H_5)\overset{+}{C}=\overset{+}{O}H$ and $CH_3OOC-CH_2-(C_3H_7)\overset{+}{C}=\overset{+}{O}H$ it is established that this neutral is $CH_2=C=O$, containing the original ester carbonyl and the adjacent CH_2 group. The same result has been obtained by Zirrolli and McMurphy[8] from labelling experiments on $CH_3OOC-CH=\overset{+}{O}CH_3$, implying methoxy anion migration from the carbomethoxy group to the carbon atom of the charge centre (compare a_0 above).

The fragmentation behaviour of a_1 has been studied by inclusion of the labelled species $CH_3OOC-CH_2-(C_2H_5)\overset{+}{C}=\overset{+}{O}D$ (a_1–OD), $CH_3OOC-CD_2-(C_2H_5)\overset{+}{C}=\overset{+}{O}H$ (a_1–$4D_2$) and $CH_3OOC-CH_2-(CH_3CD_2)\overset{+}{C}=\overset{+}{O}H$ (a_1–$2D_2$) (for numbering see Scheme 4). The labelling results are presented in Scheme 4. Interpretation of these data, metastable ion peak analysis of the labelled species and regard of the ion abundances (Fig. 1) lead to the fragmentation pathways and ion structures depicted in Scheme 5, as will be discussed.

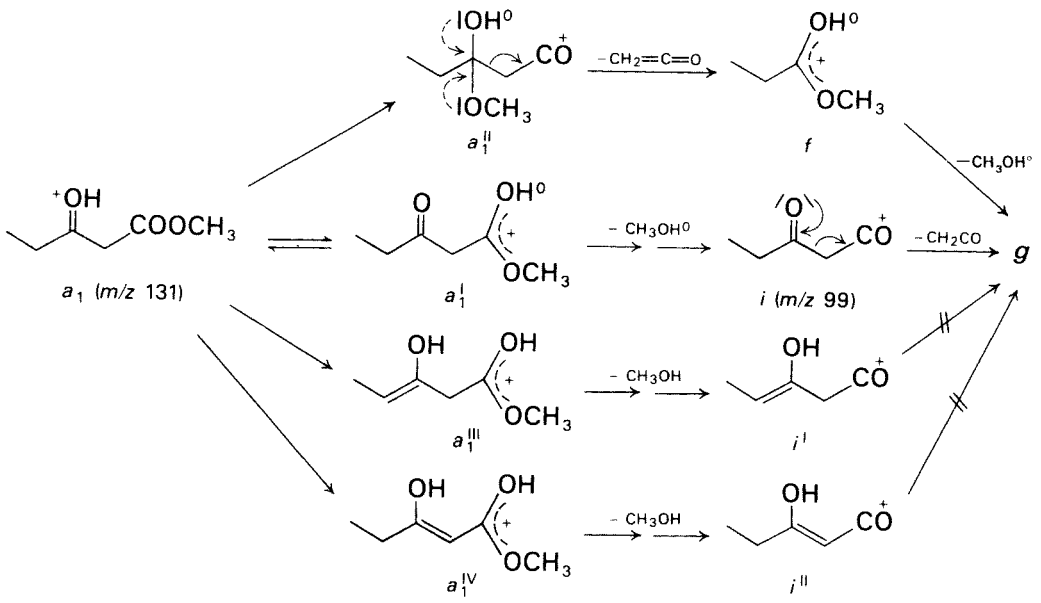
For the reaction sequence $a_1 \rightarrow f \rightarrow g$ the positional integrity of all hydrogens marked in Scheme 4 is retained within the error limit. Therefore a_1^{II}, the reactive species from which ketene loss occurs, is formed from a_1 without any preceding hydrogen shifts (except for reversible reaction to a_1^I). Formation of *f* from a_1^{II} is straightforward and has its driving force from the repulsive through-bond interaction of the functional groups involved and from the high stability of *f*. The specific loss of H^0 in the reaction $f \rightarrow g$ confirms the proton migration between the oxygens of *f* discussed for a_0 above, because H^0 cannot migrate to OCH_3 in this reaction channel before *f* is formed.

For the sequence $a_1 \rightarrow a_1 - CH_3OH \rightarrow g$ the proton transfer prior to methanol loss originates from three different positions, but the second step (ketene loss) leads to *g* with the two hydrogens at C(2) retained. This leads to the following conclusions: (i) proton transfer prior to methanol loss does not only occur from different positions, but the three isomers of a_1 thus formed do not appreciably interconvert and have separate reaction channels for CH_3OH elimination; (ii) ketene elimination from $a_1 - CH_3OH$ occurs predominantly from the isomer (*i*) which is formed after H^0 migration.

The structures of a_1 after proton transfer are assumed to be a_1^I, a_1^{III} and a_1^{IV}, respectively, because proton



Scheme 4



Scheme 5

transfer to the carbonyl oxygen is energetically more favourable than transfer to the OCH_3 group. Based on the findings on *f* there is no need to postulate proton transfer directly to the OCH_3 group, and the idea of a stepwise migration via the more stable structures, e.g. $a_1 \rightarrow a_1^{I} \rightarrow CH_3\overset{+}{O}H{-}CO{-}CH_2{-}CO{-}C_2H_5 \rightarrow i$ (not explicitly shown in Scheme 5), is preferred.

The high abundance of a_1 and the low abundance of $a_1 - CH_3OH$ compared to the higher homologues (Fig. 1) suggests that for a_1 methanol loss is not promoted by functional group interaction, and therefore, the open-chain structures *i*, i^{I} and i^{II} are formulated for the ions formed. From these structures it is plausible that *i* has the most pronounced tendency to react to *g*.

$CH_3OOC{-}(CH_2)_2{-}(C_2H_5)C{=}\overset{+}{O}H$ (a_2) and $CH_3OOC{-}(CH_2)_3{-}(C_2H_5)C{=}\overset{+}{O}H$ (a_3). For a_2 and a_3 the only primary fragmentation found is loss of methanol. From the *O*-deuterated ions only loss of CH_3OD is observed. The high relative abundances of $a_2 - CH_3OH$ and $a_3 - CH_3OH$ and the low tendency of these ions for further decomposition (Fig. 1) point to strong functional group interaction through space in the rate-determining step of the methanol elimination and to formation of stable cyclic ions. This is in accordance with the generally observed preferential formation of 5- and 6-membered rings from sterical reasons. Together with the deuterium-labelling results this leads to $j_{2,3}$ as the most probable structure of these ions, formed via the pathway depicted in Scheme 6. Formation of $j_{2,3}$ is confirmed by the independent generation of these ions (see below). A corresponding cyclization has been formulated by Sheehan *et al.*[11] for methanol loss from a fragment of $RO{-}CH_2{-}CH_2{-}CH_2{-}COOCH_3$, although the details of the reactions are different.

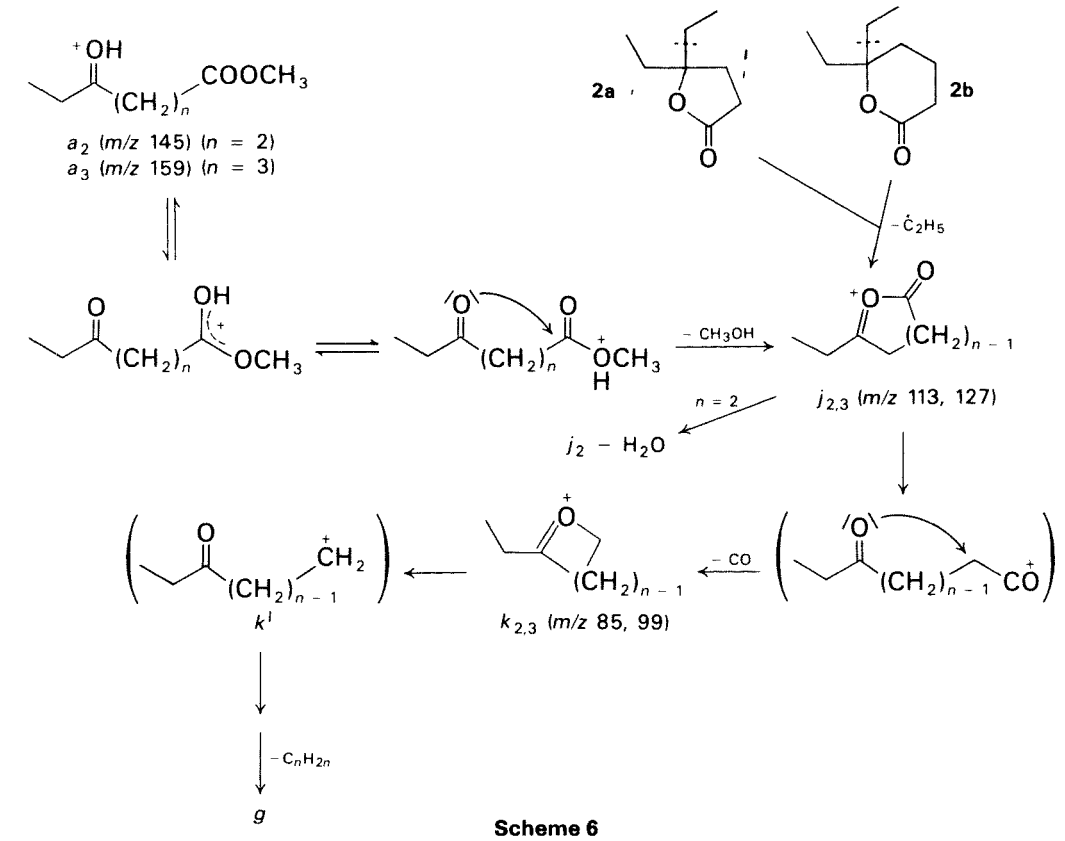
The subsequent reactions of $a_2 - CH_3OH$ and $a_3 - CH_3OH$ are CO loss followed by formation of *g*. Additionally, $a_2 - CH_3OH$ loses H_2O to a low degree. Although this latter reaction seems to speak for an open-chain structure, formation of *j* from a_2 and a_3 is fully confirmed by the fragmentation behaviour of this ion independently generated from **2a** and **2b** (Scheme 6), respectively. Ions $j_{2,3}$ thus formed show all features of $a_2 - CH_3OH$ and $a_3 - CH_3OH$, respectively, including loss of H_2O from j_2 and very similar fragment ion abundances.

The high tendency for cyclization of a structural arrangement as in a_2 and a_3 is also reflected in the chemistry of the precursor compounds **1c** and **1d**; **1d** is very difficult to isolate because of its inherent high ability to cyclize to **2a** by methanol elimination, and to a lesser degree this is also true for **1d**.

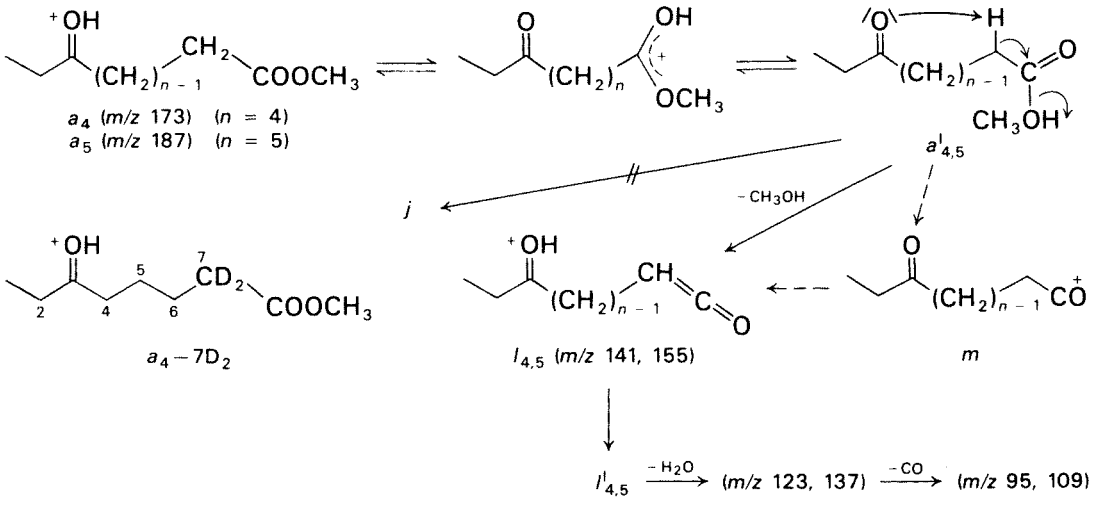
Fragmentation of *j* is formulated as in Scheme 6 without detailed discussion, but the subsequent losses of CO and C_nH_{2n} are established. Formation of *k* by cyclization displacement from related ions and its fragmentation behaviour in accordance with the above formulation have been described previously.[1] The open-chain ion k^{I} is not formed without preceding formation of *k* and certainly is not stable enough to reach the detector. It is merely the initial structure from which loss of C_nH_{2n} finally occurs.

$CH_3OOC{-}(CH_2)_4{-}(C_2H_5)C{=}\overset{+}{O}H$ (a_4) and $CH_3OOC{-}(CH_2)_5{-}(C_2H_5)C{=}\overset{+}{O}H$ (a_5). As for a_2 and a_3, methanol loss is the only primary fragmentation observed for a_4 and a_5, and again the migrating hydrogen originates solely from the OH group of the oxonium moiety. The same result has previously been obtained for d_4.[3a] The resulting ions are formed in ratios comparable to those of $a_2 - CH_3OH$ and $a_3 - CH_3OH$ (compare abundances of undecomposed a_2–a_5 in Fig. 1), which points to promotion of methanol loss by through-space interaction of the functional groups.

Despite these similarities between a_2, a_3 and a_4, a_5, the subsequent fragmentations of $a - CH_3OH$ are so different that $a_4 - CH_3OH$ and $a_5 - CH_3OH$ cannot



Scheme 6



Scheme 7

have the cyclic structures *j* found for $a_2 - CH_3OH$ and $a_3 - CH_3OH$. No loss of CO and consequently no subsequent loss of C_nH_{2n} is found. Instead, loss of H_2O followed by loss of CO is the only but very pronounced fragmentation mode observed.†

Keeping in mind that the proton lost with methanol originates exclusively from the OH group and, therefore, $a^l_{4,5}$ must be the reactive species for methanol loss, the only plausible reaction modes beside formation of *j* (which is excluded) are formation of *l*, triggered by proton abstraction from (the activated) C(7) or C(8), and formation of *m* by CH_3OH loss without functional group interaction, respectively (Scheme 7). Ion *m* does not seem to be a major component, because functional group interaction probably is involved in the CH_3OH loss (see above); but reaction $m \rightarrow l$ may be a bypass.

From a_4-7D_2 (Scheme 7) subsequent loss of 25% HOD and 75% H_2O after methanol loss is found. This shows that transfer of one proton from C(7) is involved, supporting formation of *l*. However, due to the expected hydrogen scrambling prior to loss of water a clear decision in favour of *l* as the main component is very difficult without carrying out extensive labelling experiments. In any case, H_2O loss must occur from an isomeric ion ($l^l_{4,5}$). Structures for this and the resulting fragment ions cannot be given because of the ambiguities from H_2O loss.

† For a_4 these results have been confirmed by mass-analysed ion kinetic energy spectrometry and linked-scan spectra of the corresponding daughter and parent ions.

Comparison of the carbomethoxy substituted (*a*) and the methoxy substituted (*e*) hydroxonium ions

The influence of a carbomethoxy group on the decomposition rates of the hydroxonium ions *a* in dependence of the chain length separating the functional groups is very similar to the corresponding influence of the methoxy group on ions *e*,† with the exception of the lowest homologues. Loss of methanol is by far the most pronounced primary fragmentation in both cases except for a_0, where no CH_3OH loss is observed. The ions thus formed (*i*, *j* and *l*, respectively, in series *a*) are rather stable according to their moderate to high relative abundances.

The pathways for methanol loss from *a* and *e* show similar features. If the geometry allows formation of 5- and 6-membered cyclic ions, respectively, cyclization displacement is the only observed reaction (a_2, a_3, e_3, e_4), leading to *j* for *a* and *k* for *e*. Through-space interaction via proton abstraction from the carbon atom adjacent to the C-position bearing the $CH_3\overset{+}{O}H$ unit seems to be the competing mechanism for larger chain lengths between the functional groups (a_4, a_5, e_5, e_6), leading to open-chain products. At short chain distances CH_3OH loss occurs preferentially via through-bond interaction of the functional groups (formation of *i* from a_1). These differences of the reaction pathways are more pronounced for *a* than for *e*, and for *a* the product ions after methanol loss differ very much with respect to further fragmentation. This is certainly due to the carbonyl unit in *a*, which stays as an inherent functional group within the product ions after methanol loss.

Comparison of *a* with the analogous carbomethoxy substituted methoxonium ions in connection with a general survey of the methoxy and carbomethoxy-substituted hydroxonium and methoxonium ions, respectively, is presented in the succeeding paper.[3]

EXPERIMENTAL

The mass spectra were obtained at 14 and 20 eV (nominal) using a Varian MAT CH 5 mass spectrometer. The general experimental conditions and the introduction of the undeuterated samples correspond to those described in Ref. 1. The spectra of the deuterated samples were recorded via gas chromatography/mass spectrometry (GC/MS) from slow gas chromatographic runs using a packed SE-30 column. For the *O*-deuterated samples the column had been saturated with D_2O by several injections of 2–4 μl D_2O before every sample introduction. For control, the undeuterated samples were measured under the same GC/MS conditions.

† Compare data in Ref. 1.

Preparation of compounds 1

1a: $(COOEt)_2$ + 2 EtMgBr (reverse Grignard reaction)
$\xrightarrow[30\text{ min, }0\,^\circ C]{\text{ether}}$ $Et_2-C(OH)-COOEt$ $\xrightarrow{KOH/CH_3OH}$
$Et_2-C(OH)-COOK$
isolated, dried) $\xrightarrow[5\text{ h, }60\,^\circ C]{CH_3J/\text{acetone}}$ $Et_2-C(OH)-COOMe$ (**1a**)

1b: $Et_2CO + BrCH_2COOEt \xrightarrow[2\text{ h, }80\,^\circ C]{Zn/THF:\text{benzene}}$
$Et_2-C(OH)-CH_2COOEt$
$\xrightarrow[2\text{ h, room temp.}]{NaH/CH_3OH}$ $Et_2-C(OH)-CH_2COOMe$ (**1b**)

1c: $Et_2-C(OH)-(CH_2)_3OH \xrightarrow{KMnO_4/OH^-} \xrightarrow{H^+}$
$Et_2-C(-O-)-(CH_2)_2-CO$ (**2a**)
$\longrightarrow$ $Et_2-C(OH)-(CH_2)_2COOK$ (isolated, dried)
$\xrightarrow[1\text{ day, room temp.}]{CH_3J/\text{acetone}}$ $Et_2-C(OH)-(CH_2)_2COOMe$ (**1c**)

(other procedures did not lead to **1c** but to **2a**).

1d–1f: accordingly, but in the first step the free acid (instead of the lactone) is preferentially formed, which was isolated prior to salt formation.

All compounds were purified by distillation *in vacuo* and by successive preparative GC (SE-30, 110–190 °C).

Preparation of the deuterated compounds 1

O-Deuterated **1**: according to Ref. 2. Deuterium content evaluated after GC/MS introduction ⩾95%.

C-deuterated **1**; **1b** (precursor for a_1-2D_2 and a_1-4D_2):

(a) deuteration, see Ref. 2, transesterification as for a_1 above → $(CH_3CD_2)_2-C(OH)-CH_2COOMe$ (precursor for a_1-2D_2). Deuterium-content (mass spectrometry) 88 ± 2%;

(b) $Et_2-C(OH)-CD_2COOMe$ (precursor for a_1-4D_2) see Ref. 1.

1e (precursor for a_4-7D_2):

$Et_2-C(OH)-(CH_2)_4COOMe \xrightarrow[4\text{ h, }60\,^\circ C]{NaH,\ CH_3OD} \xrightarrow{H^+}$
$Et_2-C(OH)-(CH_2)_3CD_2COOMe$

Deuterium-content (mass spectrometry) 92 ± 1%.

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