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Charge-Remote Fragmentations of Closed-Shell Ions. A Thermolytic Analogy

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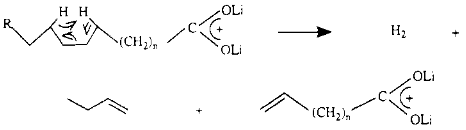
Abstract: Mechanisms for the slow (metastable) decompositions of closed-shell ions of β-hydroxyalkenoic acids, an alcohol, and an ester are determined by deuterium-labeling, linked-scanning mass spectrometry (B/E), and tandem mass spectrometry (MS/MS, MS/CA-MS, and CA-MS/CA-MS). The parent ions, desorbed by fast atom bombardment as either $(M + Li)^+$, $(M + 2\,Li - H)^+$, or $(M - H)^-$ ions, decompose both in the ion source and as metastable ions to lose either H_2O or an aldehyde by mechanisms that do not involve the charge site (i.e., by "charge-remote" decompositions). Loss of the aldehyde occurs by a charge-remote, pericyclic *O*-hydro-*C*-allyl elimination, and loss of H_2O occurs by a charge-remote hydro–hydroxy elimination. Both eliminations occur without electronic interaction with the charge site, and thus the mechanisms for these gas-phase elimination reactions are identical with pericyclic Ei mechanisms of analogous thermolytic elimination reactions of neutral molecules. Evidence is also provided that supports the previously proposed charge-remote, pericyclic 1,4-elimination mechanism for the collision-induced losses of C_nH_{2n+2} from long-chain carboxylate ions. These studies show that charge-remote fragmentations are not limited to high-energy collisional activation and they may be the only class of mass spectrometric decompositions that are directly comparable to gas-phase thermolysis.

High-energy collisional activation (CA) of closed-shell ions containing a long hydrocarbon chain and a localized site of charge results in a specific and unique type of fragmentation termed "charge-remote".[1] The CA decompositions involve losses of the elements of C_nH_{2n+2} that arise from the alkyl termini of carboxylate, alkyl sulfate, steroid, and alkyl sulfonate anions,[2] alkylammonium and -phosphonium ions,[3] and $(M + H)^+$ ions of alkyl amines, amides, and carboxylic acid pyrrolidides and picolinyl esters.[1d,4] Losses of the elements of C_nH_{2n+2} from the alkyl terminus also occur from collisionally activated $(M + Li)^+$ ions of fatty alcohols, acids, and esters and from $(M + 2\,Li - H)^+$ ions of fatty acids and prostaglandins.[1b–c,5,6]

The chain-scission decompositions are structurally specific only as a result of the site of charge being "fixed" remote from the site of reaction: it is from this that the utility of collision-induced charge-remote fragmentations originates. Double-bond migration and hydrogen scrambling, characteristics of charge-driven decompositions, do not occur. The uniqueness of charge-remote fragmentations is established by comparing the CA decomposition (CAD) spectra of $(M + H)^+$ ions of unsaturated fatty alcohols and acids to the CAD spectra of the lithiated molecules.[1b,c] The protonated fatty alcohols and acids lose one and two molecules of H_2O, respectively, resulting in the formation of carbocations that subsequently undergo charge-driven, nonspecific hydrogen scrambling and double-bond migration. In contrast, the lithiated species, and carboxylate anions, do not undergo analogous charge-driven decompositions, and the locations of double bonds and other structural features can be directly determined from the CAD spectra. Other examples showing the stark contrast between charge-driven and charge-remote fragmentations are decompositions of protonated fatty acids vs protonated amines and fatty acid picolinyl esters[1d,4] and decompositions of anions of glucouronides vs steroid sulfates and bile salts.[2d] Charge-remote CA decompositions of closed-shell ions provide a way, without prior derivitization, to identify directly the type of compound and to locate structural features, such as double bonds, branch points, and other functional groups, in compounds for which structural elucidation is either difficult or not possible by other methods such as NMR, IR, and UV–vis.[1–6]

The mechanism for the structurally informative collision-induced losses of the elements of C_nH_{2n+2} was shown to be the same for ions containing different types of charge sites.[1] Decompositions of deuterium-labeled saturated fatty acid anions, $(M + H)^+$ ions of fatty acid picolinyl esters, $(M + Li)^+$ ions of fatty alcohols, and $(M + 2\,Li - H)^+$ ions of fatty acids are consistent with a mechanism involving 1,4-eliminations of H_2 to give terminally unsaturated ions and neutral alkenes (see eq 1).[1] The proposed mechanism is a thermally allowed, concerted pericyclic elimination that involves a six-membered cyclic transition state, and the elimination reaction occurs remote from the charge site. This type of mechanism is unusual in mass spectrometry because mass spectrometric decompositions are usually initiated by either a charge or radical site.[7] The proposed mechanism is also unusual because the transition state involves departure of three groups, as opposed to two groups, that apparently bond to each other at about the same time.



(1)

Recently, Wysocki, Cooks, and co-workers[8] proposed that the mechanism for the collision-induced losses of the elements of C_nH_{2n+2} is more complex than we propose, that the charge site plays a role in the decompositions, and that the fragmentation may occur via a charge-mediated ion–molecule complex following activation as opposed to the charge-remote 1,4-eliminations. However, we previously showed that the collision-induced decompositions of dodecyl benzenesulfonate anion, an ion in which coiling to bring the closest members of the alkyl chain in proximity to the charge site is precluded, still produce all the characteristic losses of the elements of C_nH_{2n+2}.[1a] We similarly showed that

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CADs of $(M - H)^-$ ions of cholesteryl hemisuccinate[1a] and steroid sulfates[2d] and $(M + Li)^+$ ions of sterols[9] result in losses of the elements of C_nH_{2n+2} from the alkyl side chain attached to the steroidal ring remote from the site of charge. The steroidal ions are large, rigid structures, and direct interaction of the charge site with the site of decomposition is not feasible. Although Longevialle[10] has convincingly shown that charge-mediated ion–molecule proton-transfer complexes play an important role in the metastable ion decompositions of bifunctional steroids, our experimental results do not support the intervention of such complexes for the closed-shell ions studied here. The fact that charge-remote decompositions of closed-shell steroidal ions and the 1,4-eliminations of H_2 only occur upon collisional activation[1a,2d,9] contradicts their being a result of ion–neutral complexes: it has been well established that ion–molecule complexes are predominantly reactions of longer lived, low-energy (metastable) ions.[11]

The activation energy (E_a) for the collision-induced 1,4-eliminations of H_2 was estimated experimentally by bracketing methods, and the estimated activation energies for the decompositions are similar for ions containing different types of charge sites. For fatty alcohol $(M + Cat)^+$ ions,[1b] amine and alcohol $(M + H)^+$ ions,[4] and amine and acid $(M + Na)^+$ and $(M + Li)^+$ ions,[9] E_a is estimated to be between 1.3 and 1.9 eV, 1.4 and 2.7 eV, and 0.9 and 2.3 eV, respectively.

The constancy of the mechanism and of the estimates of activation energy is in accord with the concept that the nature of the charge site has little or no impact upon the decompositions, in contrast to the proposal of Wysocki, Cooks, and co-workers.[8] Because the charge site is not interacting electronically with the atoms undergoing the rearrangements, the mass spectrometric pericyclic elimination reactions may be directly analogous to gas-phase thermolytic decompositions. One reason this was originally proposed[1a] is because the mass spectrometric 1,4-elimination mechanism also explains the formation of products arising by thermal decomposition of deuteriated long-chain carboxylic acid esters.[12] However, the closest established thermal analogy to the 1,4-eliminations may be the 1,4 conjugate eliminations of HX from unsaturated molecules containing HCC=CCX structures.[13] Thermolytic 1,4 conjugate eliminations involve a pericyclic Ei, as opposed to free-radical, mechanism in which the transition state is six-membered.[14] However, unlike the collisionally induced process, only two groups concertedly leave and bond to each other.

Here, we present new experimental evidence that strongly supports the direct thermolytic analogy of mass spectrometric charge-remote fragmentations. Some of the evidence is in accord with the collision-induced 1,4-elimination mechanism and its thermallike nature. Other evidence arises from investigations of the unimolecular decompositions of $(M + Li)^+$, $(M + 2\,Li - H)^+$, and $(M - H)^-$ ions of β-hydroxyalkenoic acids and $(M + Li)^+$ ions of a β-hydroxyalkenoic alcohol and an ester. We make use of deuterium-labeling, linked-scanning mass spectrometry, and tandem mass spectrometry to confirm the identity of fragment ions and to determine the mechanisms of decomposition.

Results and Discussion

1,4-Eliminations of H_2. Fast atom bombardment (FAB) of saturated fatty acids dissolved in a matrix of 3-nitrobenzyl alcohol saturated with LiI results in the desorption of abundant $(M + Li)^+$ and $(M + 2\,Li - H)^+$ ions.[1c] The lithiated molecules decompose neither in the FAB ion source nor as metastable ions. However, high-energy collisional activation results in the production of a series of closed-shell ions arising by losses of the elements of CH_4, C_2H_6, ..., C_nH_{2n+2}. Typical CA decomposition spectra of saturated fatty acid $(M + 2\,Li - H)^+$ ions are shown in parts A and B of Figure 1. Spectrum 1A was acquired in a tandem-MS experiment by mass-selecting the FAB-desorbed parent ion, collisionally activating it, and then energy-analyzing the fragment ions (MS/CA-MS) by using a Kratos MS-50 Triple Analyzer tandem mass spectrometer (Nebraska). Spectrum 1B was acquired by performing linked (B/E) scans by using a VG 70-S double-focusing mass spectrometer (Emory). We previously showed that two abundant radical cations of m/z 58, $(CO_2Li_2)^{\bullet+}$, and 72, $(C_2H_2O_2Li_2)^{\bullet+}$, are formed.[1c] Linked (B/E) scans performed at Emory (Figure 1B) show that there is another homologous radical cation of m/z 86, $(C_3H_4O_2Li_2)^{\bullet+}$, which is also a characteristic ion in CAD spectra of lithiated fatty acids: the ion of m/z 86 is unresolved from the ion of m/z 85 in spectra acquired in MS/CA-MS experiments (Figure 1A). The MS/CA-MS spectra, however, show weakly abundant ions of m/z 7, Li^+, and 14, $Li_2^{\bullet+}$: linked (B/E) scans do not show these ions because of the inability to scan to the low mass range (see the Experimental Section).

The fragment ions formed by the pericyclic 1,4-eliminations of H_2 were proposed to be terminally unsaturated lithiated carboxylate ions (see eq 1).[1c] This hypothesis was tested here for the first time. A model fatty acid, 10-hendecenoic acid, was FAB-desorbed as $(M + 2\,Li - H)^+$ ions, and its MS/CA-MS and linked (B/E) scan spectra are shown in parts C and D of Figure 1, respectively. The fragmentation pattern shown is typical of terminally unsaturated fatty acid $(M + 2\,Li - H)^+$ ions: there are an abundant ion (a of m/z 155 in parts C and D of Figure 1) formed by allylic cleavage and a series of closed-shell ions beginning with m/z 141 and continuing through m/z 85 that would arise by 1,4-eliminations of H_2. The three radical cations, of m/z 58, 72, and 86, which are suggested to be distonic ions,[9] are also produced.

According to the proposed 1,4-elimination mechanism, the fragment ion of m/z 141 (parts C and D of Figure 1), which is only formed by collision-induced decompositions, should have the structure of lithiated 6-heptenoic acid. To determine the structure of the ion of m/z 141, it is necessary first to form the fragment ion by CA of the parent ion and then to acquire the fragment ion's CAD spectrum: this is accomplished by performing a tandem CA-MS/CA-MS, or MS^3, experiment by using the Kratos MS-50 Triple Analyzer.[15] Therefore, the parent $(M + 2\,Li - H)^+$ ions of 10-hendedenoic acid were accelerated from the ion source and collisionally activated in the *first* field-free region of the MS-50 Triple Analyzer. The CAD-formed fragment ion of m/z 141 was energy- and mass-selected and then collisionally activated in the third field-free region. The fragment ions formed by CA of the ion of m/z 141 were then energy-analyzed (see the Experimental Section for more details). The resulting CAD spectrum of the fragment ion of m/z 141 is shown in Figure 2A. Although the signals are weak (>100 scans averaged), a comparison of the CAD spectrum of the fragment ion (Figure 2A) to the CAD spectrum of authentic 6-heptenoic acid $(M + 2\,Li - H)^+$ ions (Figure 2B) shows that the fragmentation patterns are the same.[16]

This experiment unquestionably shows that the closed-shell fragment ions formed by high-energy CA are indeed terminally unsaturated carboxylate ions, consistent with the proposed 1,4-elimination mechanism. The neutral products of the decompositions, proposed to be H_2 and terminally unsaturated alkenes,

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[16] There are slight differences in the relative abundances of fragment ions shown in the spectra in parts A and B of Figure 2. The differences may be caused by the greater average internal energy of the ions of m/z 141 consecutively produced by FAB and CA (Figure 2A) as compared to the ions produced by FAB alone (Figure 2B). Other differences may be related to the poorer signal-to-noise ratio for the CA-MS/CA-MS experiment and the larger number of cycles used in smoothing the data.

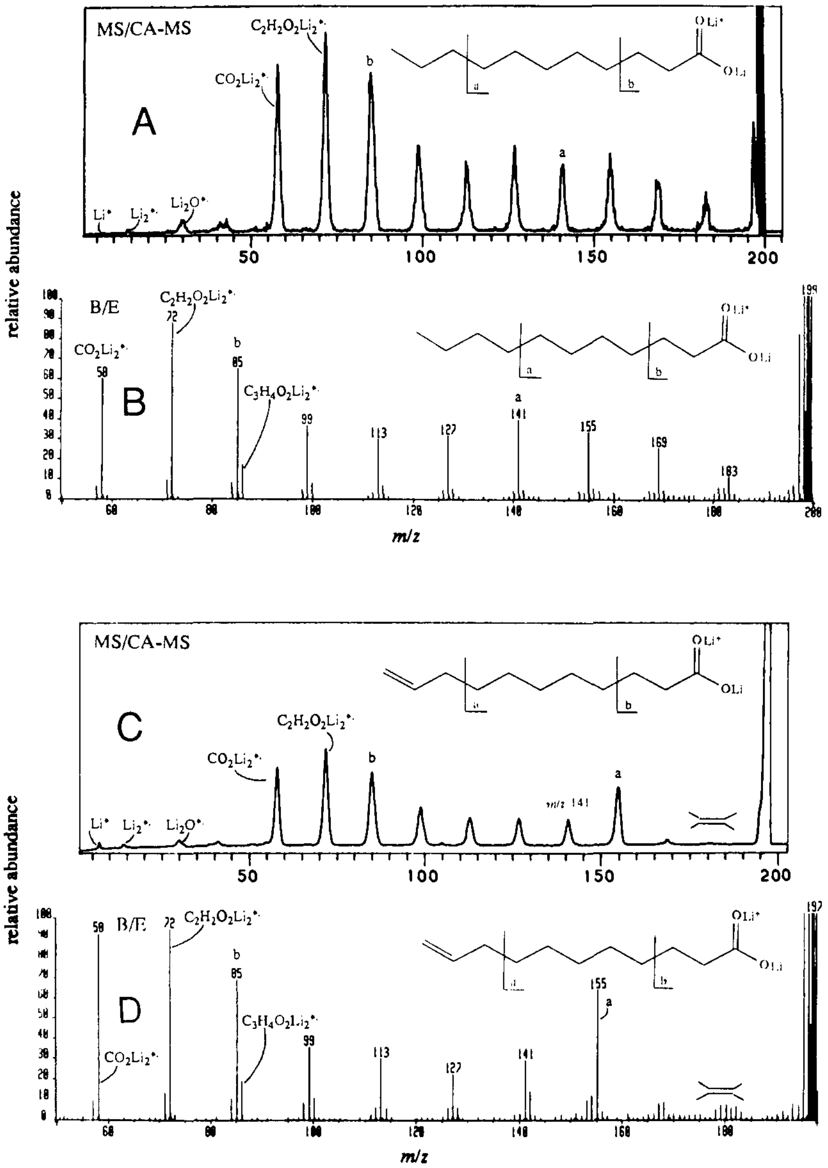

Figure 1. CAD spectra of $(M + 2\,Li - H)^+$ ions of hendecanoic acid (A and B) and 10-hendecenoic acid (C and D). Spectra in (A) and (C) are MS/CA-MS spectra acquired by using the Kratos MS-50 Triple Analyzer (Nebraska); spectra in (B) and (D) are linked (B/E) scan spectra acquired by using the VG 70-S (Emory). Symbols for double bonds are shown at locations where fragment ions formed by cleavages at double bonds would be seen.

cannot be unequivocally determined without using alternative mass spectrometric techniques.[17] However, as discussed previously,[1a] 1,2-eliminations of alkanes are not supported by the experimental results, and 1,4-eliminations of H_2 also account for the unsaturated esters and alkenes formed from pyrolytic decompositions of fatty acid esters.[12]

***O*-Hydro-*C*-allyl Elimination.** In contrast to saturated fatty acid ions, $(M + 2\,Li - H)^+$, $(M + Li)^+$, and $(M - H)^-$ ions of the β-hydroxyalkenoic fatty acids ricinelaidic and ricinoleic (*trans*- and *cis*-12-hydroxy-9-octadecenoic, respectively) and $(M + Li)^+$ ions of ricinoleyl alcohol and methyl ricinelaidate decompose unimolecularly in the FAB ion source and as metastable ions by losing either H_2O or $C_7H_{14}O$. Collisional activation, however, results in other fragment ions that arise from 1,4-eliminations of H_2 and from other types of decompositions. The CAD spectra of ricinoleic acid $(M + 2\,Li - H)^+$ ions, shown in parts A and B of Figure 3, generally typify the CAD spectra of all the parent ions. Loss of either H_2O or $C_7H_{14}O$ yields either the ion of *m/z* 293 or of *m/z* 197, respectively. The fragmentation pattern shown in the CAD spectra is exactly what one might expect from CA of $(M + 2\,Li - H)^+$ ions of a fatty acid containing a β-hydroxy olefinic substituent,[1c,5] except for the unusual, abundant ion of *m/z* 197. The most structurally informative ions are those arising by 1,4-eliminations, allylic cleavage on the carboxylate-terminus side of the double bond (*m/z* 141, c in parts A and B of Figure 3), allylic cleavage on the alkyl-terminus side of the double bond (*m/z* 195, shown most clearly as b in Figure 3B), and cleavage on the alkyl side of the –CHOH group (*m/z* 225, a in parts A and B of Figure 3).

The fragment ions produced by metastable ion and CA decompositions of ricinelaidic acid $(M + 2\,Li - H)^+$ ions are completely analogous to the ions produced by metastable and CA decompositions of ricinoleic acid $(M + 2\,Li - H)^+$ ions. The $(M - H)^-$ ions of the two β-hydroxyalkenoic fatty acids also decompose in an analogous manner. The $(M + Li)^+$ ions of the two acids, ricinoleyl alcohol, and methyl ricinelaidate also decompose analogously, except there are additional fragment ions that are formed as a result of lithiation of the β-hydroxy group as opposed to lithiation of the terminal carbonyl oxygen. We have observed similar competitive decompositions from $(M + Li)^+$ ions of other fatty acids, alcohols, and esters in cases where there is a functional

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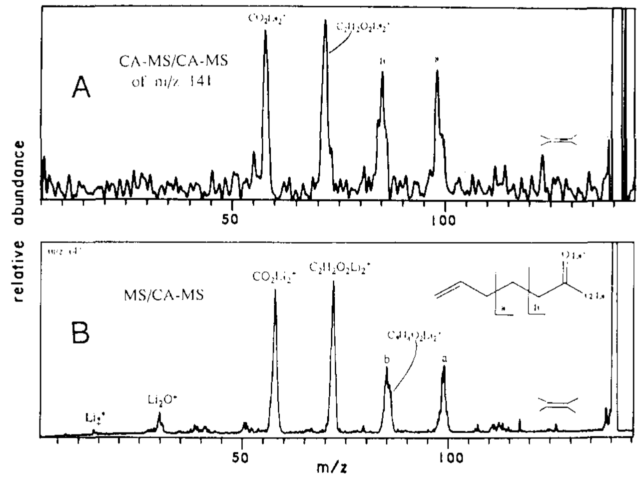


Figure 2. CA-MS/CA-MS spectrum of the fragment ion of m/z 141 produced by CA of $(M + 2\ Li - H)^+$ ions of 10-hendecenoic acid in the first field-free region of the Kratos MS-50 Triple Analyzer (A); and MS/CA-MS spectrum of $(M + 2\ Li - H)^+$ ions of 6-heptenoic acid (B). Symbols for double bonds are shown at locations where fragment ions formed by cleavages at double bonds would be seen.

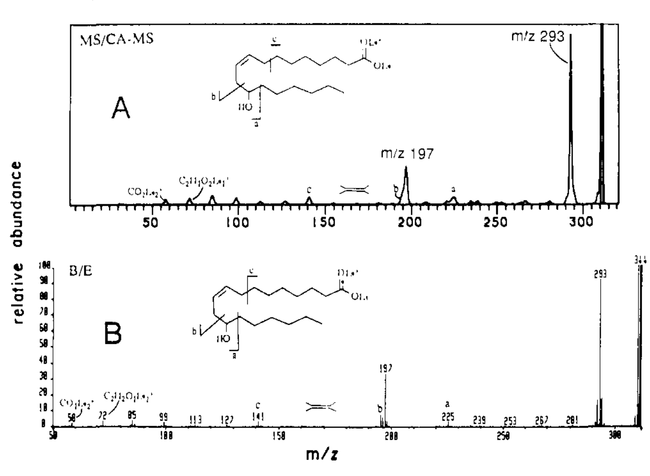


Figure 3. CAD spectra of $(M + 2\ Li - H)^+$ ions of ricinoleic acid. Spectrum in (A) is a MS/CA-MS spectrum acquired by using the Kratos MS-50 Triple Analyzer (Nebraska); spectrum in (B) is a linked (B/E) scan spectrum acquired by using the VG 70-S (Emory). The fragment ion of m/z 197 arises by loss of $C_7H_{14}O$, and the ion of m/z 293 arises by loss of H_2O. Symbols for double bonds are shown at locations where fragment ions would be seen.

group that can effectively compete for the Li^+ ion.[1b-c,5,6,9] In these cases, fragmentation still arises remote from the site of charge, but for some parent ions the site of charge is at a different location.

The structures of the unusual fragment ions that are formed by loss of $C_7H_{14}O$ in decompositions that occur both in the FAB ion source and in the field-free regions of the mass spectrometers were determined. The VG 70-S was used to investigate the structures of FAB-formed fragment ions: the fragment ions were collisionally activated in the first field-free region of the VG 70-S, and CAD spectra were acquired by performing B/E scans. The Kratos MS-50 Triple Analyzer was used to investigate the structures of fragment ions formed in the field-free regions: fragment ions formed by CA in the first field-free region of the Triple Analyzer were energy- and mass-selected and then collisionally activated in CA-MS/CA-MS experiments. A comparison of the CAD spectrum of the fragment ion of m/z 197 produced by collision-induced decompositions of $(M + 2\ Li - H)^+$ ions of ricinelaidic acid (Figure 4A) to the CAD spectrum of lithiated 10-hendecenoic acid (Figure 1C) reveals that the fragmentation pattern is the same. Fragment ions formed either in the FAB ion source or in the field-free regions by loss of $C_7H_{14}O$ from the other parent ions of the acids, alcohol, and ester are also terminally unsaturated 11-carbon species.

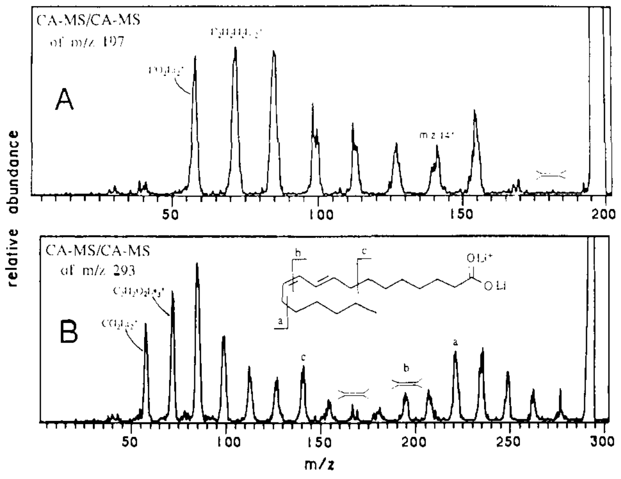
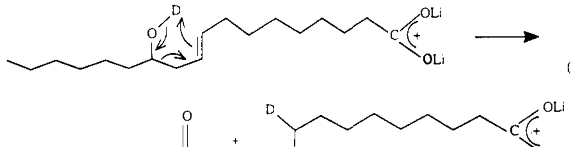


Figure 4. CA-MS/CA-MS spectra of the fragment ions of m/z 197 (A) and m/z 293 (B) produced by CA of $(M + 2\ Li - H)^+$ ions of ricinelaidic acid in the first field-free region of the Kratos MS-50 Triple Analyzer. The structure of the ion of m/z 197 is that of 10-hendecenoic acid $(M + 2\ Li - H)^+$ ions (compare Figure 1C); the structure of the ion of m/z 293 was deduced by comparing its spectrum to spectra of other unsaturated fatty acids. Symbols for double bonds are shown at locations where fragment ions formed by cleavages at double bonds would be seen.

The mechanism of the decomposition was further studied by investigating the decompositions of the $(M + 2\ Li - H)^+$ ions of hydroxyricinelaidic-12-d_1 acid. Here, decompositions of the parent ion result in the same loss of $C_7H_{14}O$, which produces a fragment ion of m/z 198 that contains deuterium: $C_{11}H_{18}DO_2Li_2^+$. CA-MS/CA-MS of the fragment ion of m/z 198 produces abundant ions that are the same as those in the corresponding spectrum of the unlabeled fragment ion of m/z 197 shown in Figure 4A. However, narrow scans (>200 scans averaged) of the regions of the two CA-MS/CA-MS spectra between m/z 155 and 175 show that the deuterium-containing ion of m/z 198 decomposes to give an ion of m/z 169, whereas the fragment ion formed by the analogous reaction of the unlabeled ion of m/z 197 yields an ion of m/z 168. Thus, the deuterium atom in the product ion of m/z 198 must be attached to the allylic carbon, and the mechanism shown in eq 2 describes the unimolecular decomposition of the



(2)

$(M + 2\ Li - H)^+$ ions of hydroxyricinelaidic-12-d_1 acid to give the ion of m/z 198, lithiated 10-hendecenoic-9-d_1 acid. There is little question that the decomposition is occurring remote from the charge site and that the charge site is not interacting electronically with the atoms undergoing the rearrangement.

This mechanism for the unimolecular mass spectrometric decomposition of the $(M + 2\ Li - H)^+$ ions of ricinelaidic acid is a thermally allowed, concerted pericyclic reaction that occurs via a six-membered cyclic transition state: specifically, an *O*-hydro-*C*-allyl elimination.[14] The *O*-hydro-*C*-allyl elimination is a pyrolytic Ei mechanism, as opposed to a pyrolytic free-radical mechanism, involving a cyclic transition state in which two groups concertedly leave and bond to each other, although bond breaking and bond making do not have to occur at the same time.[14] Thermolytic Ei mechanisms are characterized by first-order kinetics. The thermal *O*-hydro-*C*-allyl elimination specifically occurs upon pyrolysis of a variety of β-hydroxy olefins;[18] the reverse

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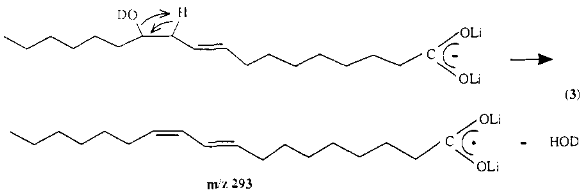
[18] (a) Arnold, R. T.; Smolinsky, G. *J. Am. Chem. Soc.* **1959**, *81*, 6443. (b) Arnold, R. T.; Smolinsky, G. *J. Org. Chem.* **1960**, *25*, 129. (c) Smith, G. G.; Taylor, R. *Chem. Ind.* **1961**, 949. (d) Smith, G. G.; Yates, B. L. *J. Chem. Soc.* **1965**, 7242. (e) Smith, G. G.; Voorhees, K. J. *J. Org. Chem.* **1970**, *35*, 2182.

reaction is an ene reaction.[14] Both charge-remote mass spectrometric decompositions of the β-hydroxyalkenoic ions and thermal decompositions of the neutral deuterium-labeled compounds result in transfer of the deuterium to the allylic position in the product olefin.[18b] As a matter of historical fact, the pyrolysis of ricinoleic acid was used as a convenient route to 10-hendecenoic acid and heptaldehyde in the late 1800s.[19] The geometric configuration around the carbon–carbon double bond has no effect on the pyrolytic reactions,[18a] and we find that $(M + 2\ Li - H)^+$ ions of ricinoleic acid similarly decompose to give the same product ion.

Hydro–Hydroxy Elimination. FAB, metastable ion, and CAD spectra of the closed-shell β-hydroxyalkenoic ions also show an abundant fragment ion that is caused by loss of H_2O (see parts A and B of Figure 3). Loss of H_2O also occurs as a facile decomposition reaction of lithiated hydroxy-substituted fatty acids[5] and of lithiated prostaglandins.[6] Ricinelaidic and hydroxyricinelaidic-12-d_1 acid $(M + 2\ Li - H)^+$ ions lose H_2O and HOD, respectively, both giving an ion of m/z 293. The structure of the ion of m/z 293 arising from decompositions of lithiated ricinelaidic acid was determined in order to evaluate the mechanism for its formation. The results of CA of the fragment ion of m/z 293 formed in the first field-free region of the Kratos MS-50 Triple Analyzer are presented in the CAD spectrum shown in Figure 4B. The structure of the ion of m/z 293 that is drawn in Figure 4B was determined by comparing its fragmentation pattern to the fragmentation patterns shown in CAD spectra of $(M + 2\ Li - H)^+$ ions of *cis*-9-octadecenoic, *cis*-11-octadecenoic, and *cis*-9,12-octadecadienoic acids. (The CAD spectra do not differentiate between cis and trans isomers.) The fragment ion formed by loss of HOD from $(M + 2\ Li - H)^+$ ions of hydroxyricinelaidic-12-d_1 acid is lithiated 9,11-octadecadienoic acid. Fragment ions formed by loss of H_2O from the other parent ions of ricinelaidic and ricinoleic acids, ricinoleyl alcohol, and methyl ricinelaidate are also 9,11-octadecadienoate species.

The mechanism for the unimolecular loss of HOD from hydroxyricinelaidic-12-d_1 acid $(M + 2\ Li - H)^+$ ions is thus a charge-remote hydro–hydroxy elimination[14] (eq 3). Here, as to be expected, the product ion contains the new double bond in conjugation with the double bond already present: product stability is probably an important driving force for this reaction.[7] Such 1,2-eliminations of H_2O are unusual in mass spectrometry; most radical cations of acyclic alcohols undergo dehydration by 1,4- and 1,3-eliminations.[20] In contrast, 1,2-eliminations of HX immediately suggest a thermal, as opposed to a mass spectrometric or charge-driven, decomposition[20] because 1,2-eliminations of H_2O and HX from HCCX structures to give olefins are classic pyrolytic eliminations.[14,19,21] The pyrolysis of β-hydroxy olefins almost invariably results in dehydration to give a diunsaturated olefin as a side product.[18a,b] Because concerted four-center 1,2-eliminations are symmetry-forbidden, the ease by which such thermal decompositions occur has been explained by suggesting that the C–X bond is cleaved to a greater extent than the C–H bond in the transition state, thus giving the transition-state carbocationlike character.[14] This theory is supported here by the fact that the mass spectrometric 1,2-elimination is characterized by a small kinetic energy release (0.07 eV), and the peak is Gaussian in shape.[9] In contrast, true symmetry-forbidden decomposition reactions are accompanied by large kinetic energy releases as manifested by wide, flat-topped or dish-shaped peaks.[22]



(3)

Conclusions

All previously reported charge-remote fragmentations require high-energy collisional activation to transfer enough energy into the parent ion to induce the decompositions.[1-5] Here, however, some charge-remote fragmentations are shown to occur by unimolecular decompositions of metastable ions. The activation energies of the two unimolecular elimination reactions described here are thus probably less than 1.3 eV, which is the lower limit estimated for the activation energy of the collision-induced 1,4-eliminations.[1b] The energy requirements for the two lower energy decompositions are the subject of continuing work.[9]

The results presented here, in conjunction with all our previous experimental results,[1-6,9] do not support charge-mediated ion–molecule mechanisms for the metastable losses of H_2O and $C_7H_{14}O$ from the β-hydroxy olefin ions. If classic ion–neutral complexes were involved,[10,11] we would expect to observe other types of fragment ions possibly resulting from hydrogen, or deuterium (if the molecule were labeled), and lithium exchanges between the charge site and the site of reaction. These exchanges are not seen. Moreover, the anions of the β-hydroxy fatty acids also lose H_2O and $C_7H_{14}O$ by the same mechanism as the closed-shell positive ions. If the anionic site were involved in a charge-mediated ion–neutral decomposition mechanism, we would not expect to observe the exact same chemistry occurring for the anions as is observed for the cations.

The results of these investigations, besides shedding light on a new mass spectrometric process that is important for assigning structures, have broader implications in the fields of mass spectrometry, synthesis, and theoretical chemistry. For years, ion chemists have searched for analogies between gas-phase ion decompositions and either thermolysis or photolysis.[13,23,24] One "quasi-thermal" reaction that previously was proposed to occur remote from the charge site is the "quasi-" retro-ene reaction postulated by Kraft and Spiteller[25a] for the decomposition of an even-electron ion formed from dihexylmalonic acid. However, this reaction is probably charge-driven because the charge is delocalized over the whole conjugated part of the ion, including the carbon onto which the proton is transferred.[25b] Another possible thermal analogy may be the proposed 1,2-elimination of $HSCH_3$ from a protonated alkylamine produced in the decomposition of a parent radical cation.[7] Although this reaction was suggested to arise by one-electron shifts via an "incipient radical site" mechanism, it may be indeed an example of a charge-remote, four-centered thermal elimination. Unfortunately, no information about metastable ions was given.

Two better known examples of possible thermolytic and photolytic analogies are the retro-Diels–Alder reaction and the McLafferty rearrangement of radical cations. The former also has been called a quasi-thermal reaction,[26] and the latter has been compared to Norrish type II photochemical reactions.[23] Because these mass spectrometric reactions occur for radical cations, as

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opposed to closed-shell neutral molecules, the charge or radical site is almost always involved in the decomposition mechanism. Although the retro-Diels–Alder reaction periodically has been suggested to occur remote from the charge or radical site, Bukovits and Budzikiewicz[26] presented strong evidence that a true quasi-thermal retro-Diels–Alder reaction does not occur because the decompositions are indeed triggered by the charge site. As a result of the interaction between the charge or radical site and the site of reaction, mass spectrometric decompositions of radical cations do not necessarily correlate with either thermolytic or photolytic reactions, and theoretical justifications correlating the gas-phase ion decompositions with their neutral counterparts are tenuous.[13] Although some similarities exist, there are numerous examples in which pyrolytic and photochemical reactions are significantly different from mass spectrometric decompositions both in type and mechanism.[23b–c,24]

In contrast, results presented here strongly indicate that the mechanisms for charge-remote fragmentations of closed-shell ions are directly comparable to thermolytic decompositions of closed-shell neutrals. This is not surprising because the fragmentation chemistry is occurring from the "neutral" end of the closed-shell ions. Because of this unique chemistry, this new class of gas-phase ion decompositions may serve an important role in predicting courses of thermolytic reactions and in suggesting new routes to products in organic synthesis.[13] Charge-remote fragmentations also may provide important, direct experimental data for theoretical investigations of thermolytic rearrangement reactions.[13]

Experimental Section

Reagents and Procedures. Fatty acids, alcohol, and ester were obtained from either Sigma, Applied Science, or Analabs. 3-Nitrobenzyl alcohol, alkali iodides, triethanolamine, glycerol, dithiothreitol, and dithioerythreitol were from Aldrich. Deuterium-exchanged ricinelaidic (*trans*-12-hydroxy-9-octadecenoic) acid was prepared by dissolving the acid in dry ether, adding D_2O, and evaporating the solvent, three times. Deuterium-exchanged 3-nitrobenzyl alcohol saturated with LiI was prepared in a like manner.

For fast atom bombardment, small amounts (micrograms) of the fatty acids, alcohol, or ester were mixed on either a gold or a stainless steel FAB probe tip with a FAB matrix. Lithiated ions were prepared by mixing sample with a matrix of 3-nitrobenzyl alcohol saturated with LiI (3-NBA/LiI). Lithiated, deuteriated (12-d_1-ol) ricinelaidic acid was FAB-desorbed from a matrix of deuterium-exchanged 3-NBA/LiI. Negative ions were prepared by mixing sample with a matrix of either triethanolamine or a 5 to 1 mixture of dithiothreitol/dithioerythreitol.

Instrumentation. Mass spectrometric experiments were performed by using either a VG 70-S (Emory) or a Kratos MS-50 Triple Analyzer (Nebraska). The VG 70-S is a normal-geometry (EB configuration, where E is an electrostatic analyzer or ESA and B is a magnetic sector), Nier–Johnson mass spectrometer, in which the first field-free region is between the ion source and the ESA. The Kratos MS-50 Triple Analyzer is a tandem mass spectrometer of configuration E_1BE_2: MS-I is a Kratos MS-50 (E_1B), and MS-II is an ESA (E_2).[27] The Triple Analyzer has three field-free regions: the first is between the ion source and E_1, and the third is between MS-I and MS-II.

Both mass spectrometers are equipped with Ion Tech saddle-field fast atom bombardment guns and commercial FAB ion sources. FAB-desorbed ions were produced by bombarding the sample with 7-keV Ar atoms at an atom gun current of 2 mA: this setting of the FAB gun corresponds to maximum sensitivity for both mass spectrometers. Ions produced were accelerated to 8-keV translational energy.

Full-scan FAB and linked-scanning (B/E) experiments were performed with the VG 70-S at a resolution of approximately 1500 (10% valley). Full-scan FAB spectra show fragmentations that occur in the FAB ion source. Linked B/E scan spectra show fragmentations that arise by metastable or collisional activation decompositions that occur in the first field-free region or in a collision cell in the first field-free region, respectively. Magnet calibration over the range of 7–393 amu was performed by using a mixture of LiI, NaI, RbI, and CsI in H_2O: the lowest mass accessible in a linked (B/E) scan is equal to [(lowest calibration mass) × (mass of parent ion)]$^{1/2}$. All spectra were acquired by using VG software, and linked (B/E) scan spectra are the results of averaging 10–20 scans. Helium was used as collision gas in the CA experiments, and the ion beam was suppressed to 50% transmission.

MS/MS (metastable) and MS/CA-MS (CAD) spectra were acquired by using the Kratos MS-50 Triple Analyzer at a resolution of approximately 2500 (10% valley). These experiments consisted of first mass-selecting a FAB-desorbed ion of interest by using MS-I. For MS/MS, the metastable mass-selected ion decomposes unimolecularly in the third field-free region. For MS/CA-MS, the mass-selected ion is induced to decompose by collision with He (50% suppression of the ion beam) in a collision cell in the third field-free region. Metastable and CA decomposition spectra, respectively, were obtained by scanning MS-II and by averaging the results of 10–30 scans by using software written at the University of Nebraska.

CA-MS/CA-MS experiments (sometimes called MS^3)[15] were also performed by using the Triple Analyzer. Here, the experiments consisted of collisionally activating, in the first field-free region, all ions accelerated from the ion source. A fragment ion of interest, arising by CA, was energy-selected by using E_1 and mass-selected by using B. After CA in the third field-free region, CA decomposition spectra were obtained by scanning MS-II and by averaging the results of 50–250 scans. Narrow scans were acquired by using a scan generator designed and built at Nebraska.

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Registry No. (9*E*,11*Z*)-$CH_3(CH_2)_5CH{=}CHCH{=}CH(CH_2)_7CO_2Li_2^+$, 117897-56-0; hendecanoic acid, 112-37-8; 10-hendecenoic acid, 112-38-9; ricinoleic acid, 141-22-0; ricinelaidic acid, 540-12-5; hendecanoic acid dilithium salt, 117897-52-6; 10-hendecenoic acid dilithium salt, 117897-53-7; ricinoleic acid dilithium salt, 117897-54-8; ricinelaidic acid dilithium salt, 117897-55-9; ricinelaidic-*12-O-d* acid dilithium salt, 117897-57-1; ricinelaidic-*12-O-d* acid, 117897-58-2; 3-nitrobenzyl alcohol-*d*, 117897-59-3; 3-nitrobenzyl alcohol, 619-25-0.

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