Influence of Alkyl Chain Length on Fragmentations and Ion-Molecule Reactions of Ionized c-C$_6$H$_{11}$-(CH$_2$)$_n$CO$_2$H

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Fragmentations and ion-molecule reactions of ionized cyclohexane propionic acid and cyclohexane butyric acid were studied using FTMS and theoretical calculations. The difference in bond dissociation depending on the aliphatic chain length was investigated and mechanisms for the possible rearrangements depending on the aliphatic carbon length were suggested. The most abundant fragment ion of the ionized cyclohexane propionic acid was c-C$_6$H$_{11}$CH$_2$$^+$ formed from the molecular ion by the direct C-C bond cleavage, while that of the ionized cyclohexane butyric acid was c-C$_6$H$_9$C(OH)=OH$^+$ formed by rearrangement of the molecular ion from the acid to diol form and loss of propyl radical. Stabilities of the radical and distonic ions of C$_n$H$_{2n}$O$^{+\bullet}$ formed from the molecular ion were compared. Protonated molecules were dissociated into smaller ions by losing one or two water molecules. The [nM + H]$^+$, [nM + H - H$_2$O]$^+$, and [nM + H - 2H$_2$O]$^+$ with n = 2 and 3 were generated by solvation with the neutral molecules in the ICR cell at long ion trapping time.

Key Words : Fragmentation, Ion-molecule reaction, FTMS, Cyclohexane propionic acid, Cyclohexane butyric acid

Introduction

Molecules with specific functional group undergo typical fragmentation patterns, which are used to obtain structural information.[1-7] For example, the mass spectra of alcohols and ethers show prominent ions of general formula with C$_n$H$_{2n}$O$^{+\bullet}$.[1,2] Ionized alcohols are fragmented and rearranged by loss of water molecule.[3,4] A five-membered ring involving oxygen was formed by loss of water molecule from HO(CH$_2$)$_4$OH$^{+\bullet}$ and cyclohexane ion was also formed by loss of two water molecules from HO(CH$_2$)$_6$OH$^{+\bullet}$.[5] Srinivas and coworkers[8] reported that the relative abundances of [M + H]$^+$ and [M + H - ROH]$^+$ formed from ROOCCR' = CHCOOR (R and R' = H, CH$_3$, or C$_2$H$_5$) were different depending on the functional groups. Fragmentation of an ionized molecule can be occurred by direct bond cleavage or rearrangement. It is easy to expect kind of product ions formed by direct bond cleavages, but it can be often hard to expect the species generated by rearrangements. For example, RC(=CH$_2$)OH$^{+\bullet}$ can be formed from the ionized O=CR(CH$_2$)$_n$CH$_3$ by rearrangements not by direct bond cleavages.[9]

Cyclohexane propionic acid and cyclohexane butyric acid have two different functional groups of cyclohexyl and carboxyl. Their alkyl chain lengths are n = 2 and 3 of c-C$_6$H$_{11}$-(CH$_2$)$_n$CO$_2$H, respectively. In the present work, we investigated fragmentations and ion-molecule reactions of cyclohexane propionic acid and cyclohexane butyric acid ions by varying the ion trapping time using Fourier transform mass spectrometry (FTMS). FTMS has been widely used to study gas phase chemistry.[10-14] The capability of both trapping and high resolution of FTMS has motivated researchers to utilize it as one of the premier methods for exploring gas phase ion-molecule chemistry. We focused on the difference in fragmentations with the alkyl chain length. The fragmentation mechanisms were explained with the observed relative abundances and heats of reaction. Formations of product ions with m/z larger than the molecular ion were explained by ion-molecule reactions.

Experimental Section

All the experiments were carried out on an Extrel FTMS 2000 Fourier transform ion cyclotron resonance (FT/ICR) mass spectrometer. The instrument is equipped with two diffusion pumps attached to dual ion trapping cells aligned collinearly in a superconducting magnet of 3.1 Tesla. The cells are 2 inch cubic and a conductance limit is shared between the two cells. The nominal value of background pressure was lower than 1×10^{-8} Torr. Samples were introduced into the cell through a heated batch inlet. The electron impact energy was 50 eV. The ion trapping time was varied in range of 1-1000 ms.

Cyclohexane propionic acid and cyclohexane butyric acid obtained from Aldrich Co. were used without further purification. The heats of formation of ions, which were not available from literature,[15] were calculated by AM1 semi-empirical method. The calculational results were used to elucidate the heats of reaction to understand fragmentations of cyclohexane propionic acid and cyclohexane butyric acid.

Results and Discussion

Fragmentation of cyclohexane propionic acid. Figure 1 shows the mass spectra of cyclohexane propionic acid with varying ion trapping times. The fragment ions with the
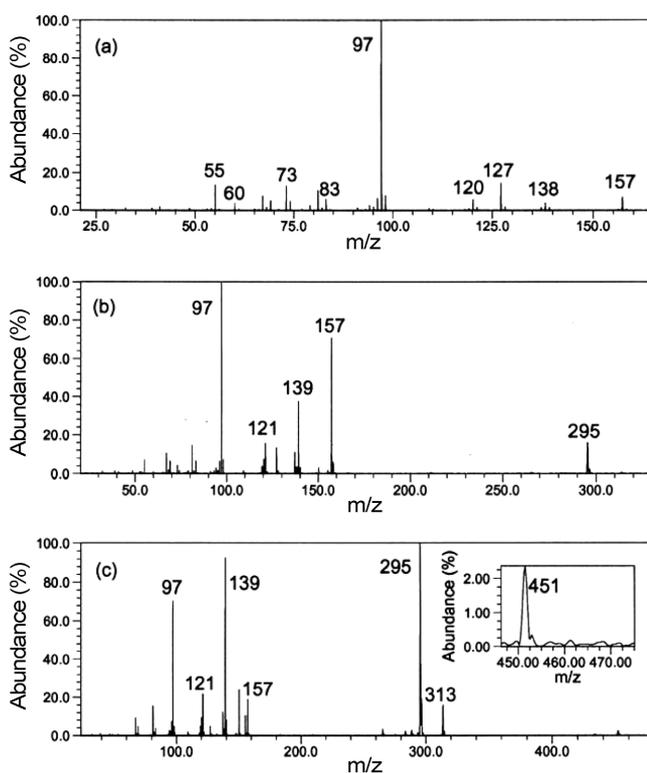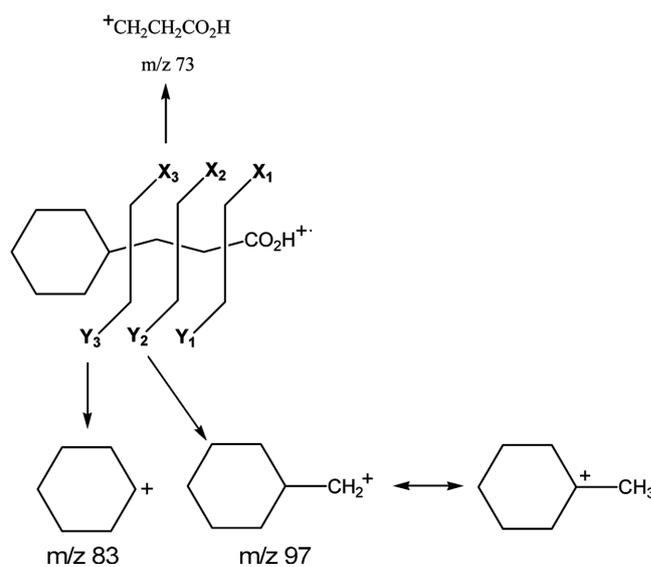
Figure 1. Variation of the mass spectra of cyclohexane propionic acid with the ion trapping time. The electron impact energy is 50 eV. The sample pressures and ion trapping times are 4.0×10^{-6} Torr/1 ms (a), 3.0×10^{-6} Torr/50 ms (b), and 2.5×10^{-6} Torr/300 ms (c).

relative ion abundance more than 10% in Figure 1(a) are m/z 55, 73, 81, 97, and 127 assigned to $C_4H_7^+$, $C_3H_5O_2^+$, $C_6H_9^+$, $C_7H_{13}^+$, and $C_7H_{11}O_2^+$, respectively. Among the fragmentations of the molecular ion, direct C-C bond cleavages can be considered first as shown in Scheme 1. The m/z 97, 83, and 77 ions are formed by the direct C-C bond cleavages. From the a-cleavages of X_1 and Y_1, the CO_2H^+ (m/z 45) and $C_8H_{15}^+$ (m/z 111) can be formed but they were not observed in the mass spectrum. From the β-cleavages of X_2 and Y_2, the $C_2H_3O_2^+$ (m/z 59) and $C_7H_{13}^+$ (m/z 97) can be formed but the m/z 59 was not observed. From the γ-cleavages of X_3 and Y_3, the $C_3H_5O_2^+$ (m/z 73) and $C_6H_{11}^+$ (m/z 83) can be formed and they were observed in the mass spectra. Thus, among the direct C-C bond cleavages, only the X_3, Y_2, and Y_3 occur. The m/z 97 is the most abundant ion as shown in Figure 1(a), which leads to a fact that the formation of m/z 97 can be the most favorable although the formation of m/z 83 is more favorable than that of m/z 97 in terms of heat of
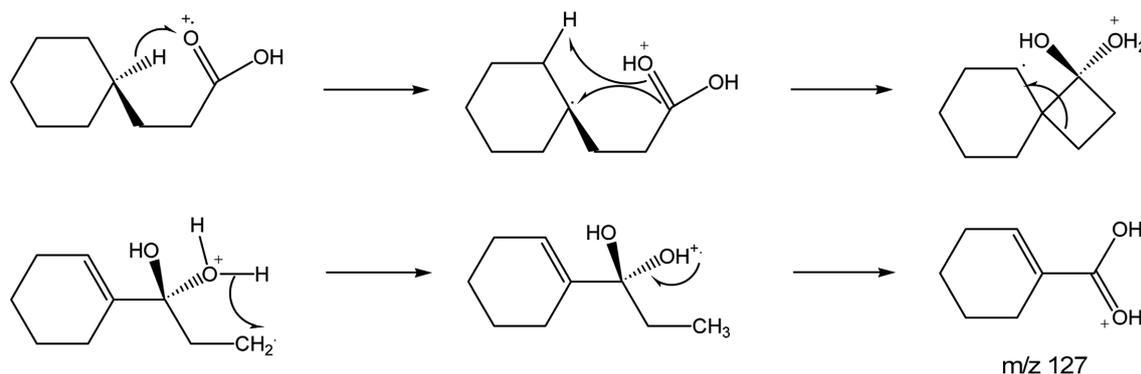

Scheme 1

reaction as listed in Table 1. This can be explained with the stable resonance form of m/z 97 as shown in Scheme 1. The c-$C_6H_{11}CH_2^+$ formed from the direct C-C bond breaking can have the stable resonance form of c-$C_6H_{10}CH_3^+$.

The m/z 138 and 120 are the dehydrated ions of the molecular ion, $[M - H_2O]^{+\bullet}$ and $[M - 2H_2O]^{+\bullet}$, respectively. The m/z 127 can be generated from the molecular ion by loss of a radical or neutral species having the mass of 29. The possible species having the mass of 29 is CH_3CH_2 or CHO. Mechanism for the loss of CHO from the molecular ion is not possible. The loss of CH_3CH_2 directly from the molecular ion is not possible but it is possible through the rearrangement as shown in Scheme 2. The molecular ion can be rearranged into a form of diol by shifting the γ-hydrogen atom.[9] The m/z 127 can be generated from the 1-cyclohexenyl-1,1'-propanediol ion and loss of ethyl radical.

The m/z 60 and 74 have formulas of $C_nH_{2n}O_2^{+\bullet}$ with n = 2 and 3, respectively, which can be radical ions or distonic ions. They can not be formed by the direct C-C bond breakings. Distonic ions with formulas of $C_nH_{2n}O_2^{+\bullet}$ are more stable than their corresponding radical ions by more than 100 kJ/mol as listed in Table 2. If the m/z 60 and 74 have structures of distonic ions, they can be formed by rearrangement involving hydrogen atom migration as shown in Scheme 3. The m/z 60 is formed through the rearrangement path (b) while the m/z 74 is formed through the rearrangement path (a). The number of hydrogen atom to participate in path (a) is four, while that to participate in path

Table 1. Heats of reaction for the fragmentation of cyclohexane propionic acid. Values in parentheses are heats of formation in kJ/mol

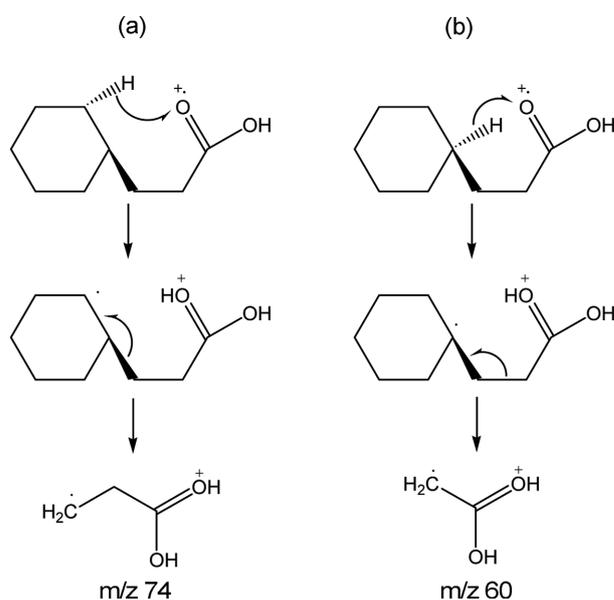| reaction		ΔH (kJ/mol)
c-C_6H_{11}-$CH_2CH_2CO_2H^{+\bullet}$ (451) ⟶	c-C_6H_{11}-CH_2^+ (776) + $^\bullet CH_2CO_2H$ (-264)	61
c-C_6H_{11}-$CH_2CH_2CO_2H^{+\bullet}$ (451) ⟶	c-$C_6H_{11}^+$ (733) + $^\bullet CH_2CH_2CO_2H$ (-306)	−24
c-C_6H_{11}-$CH_2CH_2CO_2H^{+\bullet}$ (451) ⟶	$^+CH_2CH_2CO_2H$ (561) + c-$C_6H_{11}^\bullet$ (-27)	83
c-C_6H_{11}-$CH_2CH_2CO_2H^{+\bullet}$ (451) ⟶	c-1-C_6H_9-$C(OH)_2CH_2CH_3^{+\bullet}$ (364)	−87
c-1-C_6H_9-$C(OH)_2CH_2CH_3^{+\bullet}$ (364) ⟶	c-1-C_6H_9-$C(OH)=OH^+$ (286) + $C_2H_5^\bullet$ (117)	39

Scheme 2

(b) is only one. Both rearrangements proceed under analogous conditions of steric hindrance and geometrical strain. Nevertheless, the m/z 60 and 74 are observed by almost same abundance as shown in Figure 1(a). Thus, we can say that the path (b) is more favorable than the path (a).

Fragmentation of cyclohexane butyric acid. The fragment ions having cyclohexyl or carboxyl group are formed by direct C-C bond breakings of α-, β-, γ-, and δ-linkages as shown in Scheme 4. Empirical formulas of plausible fragment ions formed by C-C bond cleavages such as X_1, Y_1, X_2, Y_2, X_3, Y_3, X_4, and Y_4 are CHO$_2^+$, C$_9$H$_{17}^+$, C$_2$H$_3$O$_2^+$, C$_8$H$_{15}^+$, C$_3$H$_5$O$_2^+$, C$_7$H$_{13}^+$, C$_4$H$_7$O$_2^+$, and C$_6$H$_{11}^+$ corresponding to m/z 45, 135, 59, 111, 73, 97, 87, and 83, respectively. The m/z 111, 73, 97, 87, and 83 ions were observed in the mass spectrum of Figure 2(a) but the m/z 45, 135, and 59 ions were not observed. The m/z 111 can be formed by the Y_2 β-bond cleavage and loss of $^\bullet$CH$_2$CO$_2$H radical. The m/z 97 and 73 are formed by the γ-cleavages and loss of $^\bullet$CH$_2$CH$_2$CO$_2$H and (c-C$_6$H$_{11}$)CH$_2^\bullet$ radicals, respectively, while the m/z 83 and 87 are formed by the δ-cleavage and loss of $^\bullet$CH$_2$CH$_2$CH$_2$CO$_2$H and c-C$_6$H$_{11}^\bullet$ radicals, respectively.

The m/z 127 is the most abundant fragment ion in the mass spectra of cyclohexane butyric acid as shown in Figure 2(a), while the m/z 97 is the most abundant fragment ion in mass spectra of cyclohexane propionic acid as shown in Figure 1(a). The m/z 97 is observed only by 10.28% in the mass spectra of cyclohexane butyric acid as shown in Figure 2(a). The reason about the observation of m/z 127 as the most abundant fragment ion for cyclohexane butyric acid can be considered the easiness of rearrangement from cyclohexane butyric acid ion to 1-cyclohexenyl-1,1-butanediol ion. The rearrangement of the ionized cyclohexane butyric acid (Scheme 5) can be more favorable than that of the ionized cyclohexane propionic acid (Scheme 2) because the
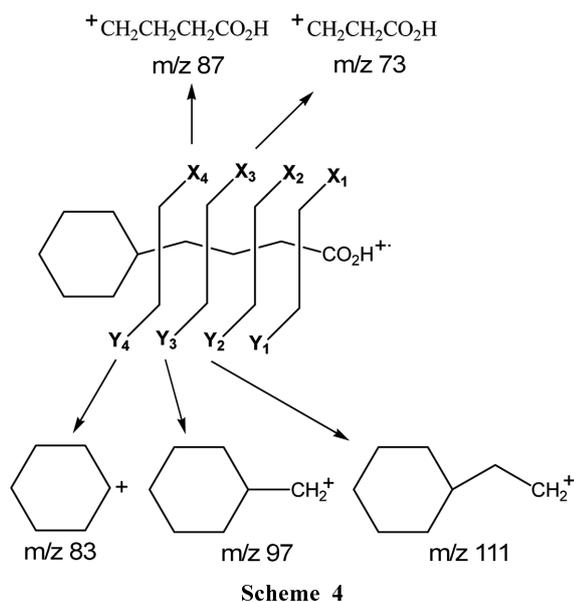

Scheme 3

structure of cyclohexane butyric acid is less strained than that of cyclohexane propionic acid. The intermediate structures of the ionized cyclohexane propionic acid and cyclohexane butyric acid are five- and six-membered rings, respectively. The m/z 127 can be formed by loss of $^\bullet$CH$_2$CH$_2$CH$_3$ radical from 1-cyclohexenyl-1,1-butanediol ion generated by rearrangement as shown in Scheme 5. The m/z 127 can be further dissociated into m/z 109 by loss of a water molecule and the m/z 109 is observed by 17.45% as shown in Figure 2(a).

The C$_n$H$_{2n}$O$_2^{+\bullet}$ such as m/z 60, 74, and 88 with n = 2, 3, and 4, respectively, were observed in the mass spectra of cyclohexane butyric acid. The m/z 88, 74, and 60 are formed

Table 2. Heats of formation of radical and distonic ions of C$_n$H$_{2n}$O$_2^{+\bullet}$ with n = 2, 3, and 4

ion formula	ΔH_f (kJ/mol)	
	radical ion	distonic ion
C$_2$H$_4$O$_2^{+\bullet}$	CH$_3$CO$_2$H$^{+\bullet}$ (623)	$^\bullet$CH$_2$C(OH)=OH$^+$ (486)
C$_3$H$_6$O$_2^{+\bullet}$	CH$_3$CH$_2$CO$_2$H$^{+\bullet}$ (605)	$^\bullet$CH$_2$CH$_2$C(OH)=OH$^+$ (455)
C$_4$H$_8$O$_2^{+\bullet}$	CH$_3$CH$_2$CH$_2$CO$_2$H$^{+\bullet}$ (580)	$^\bullet$CH$_2$CH$_2$CH$_2$C(OH)=OH$^+$ (428)

Scheme 4

Figure 2. Variation of the mass spectra of cyclohexane butyric acid with the ion trapping time. The electron impact energy is 50 eV. The sample pressures and ion trapping times are 1.6×10^{-6} Torr/1 ms (a), 2.1×10^{-6} Torr/50 ms (b), and 3.6×10^{-6} Torr/200 ms (c).

by the paths (a), (b), and (c), respectively, in Scheme 6. Their structures can be radical ions or distonic ions. According to the heats of formation, the distonic ions are more stable than radical ions as demonstrated in Table 2. Among them, the m/z 74 was observed much less than the m/z 60 and 88. This may be due to not only the number of hydrogen atom participating in the rearrangement but also steric hindrances by increasing the alkyl chain. The numbers of hydrogen atoms participating in the rearrangements (a), (b), and (c) are 4, 1, and 2, respectively, as shown in Scheme 6.

Ion-molecule reactions and dehydrations. Typical fragments of the protonated molecule are dehydrated ions such as $[M + H - H_2O]^+$ and $[M + H - 2H_2O]^+$. The $[M + H]^+$, $[M + H - H_2O]^+$, and $[M+H - 2H_2O]^+$ (m/z 157, 139, and 121, respectively, for cyclohexane propionic acid and m/z 171, 153, and 135, respectively, for cyclohexane butyric acid) were observed in the mass spectra as shown in Figures 1 and 2. At the short ion trapping time of 1 ms, the $[M + H]^+$, $[M + H - H_2O]^+$, and $[M + H - 2H_2O]^+$ are minor products as shown in Figures 1(a) and 2(a). By increasing the ion trapping time, the $[M + H]^+$s are increased by proton transfer reactions and their dehydrated fragment ions are also increased.

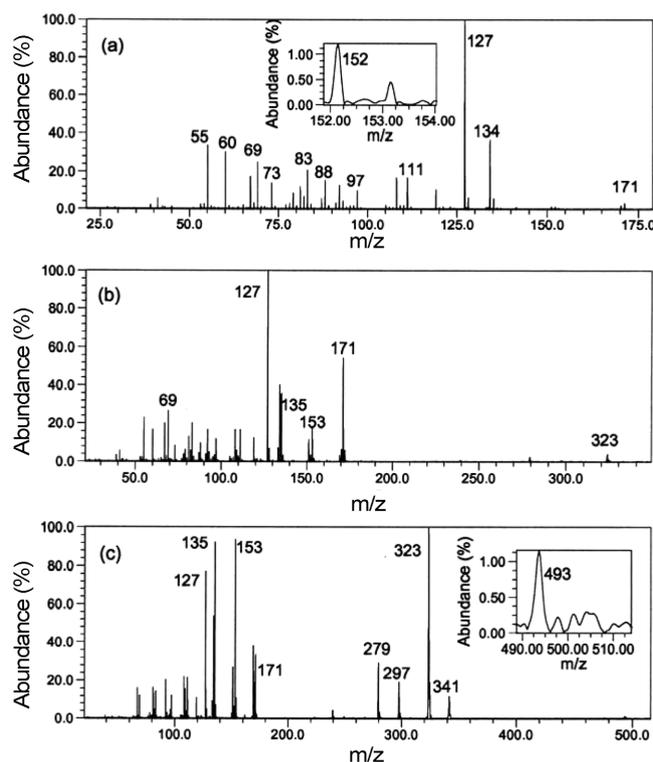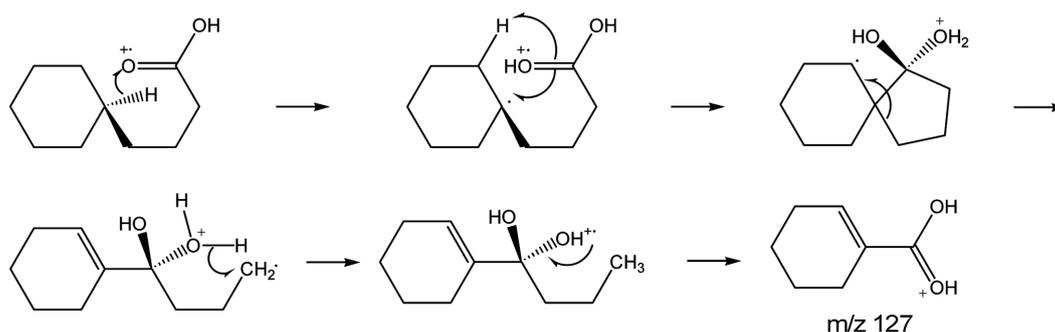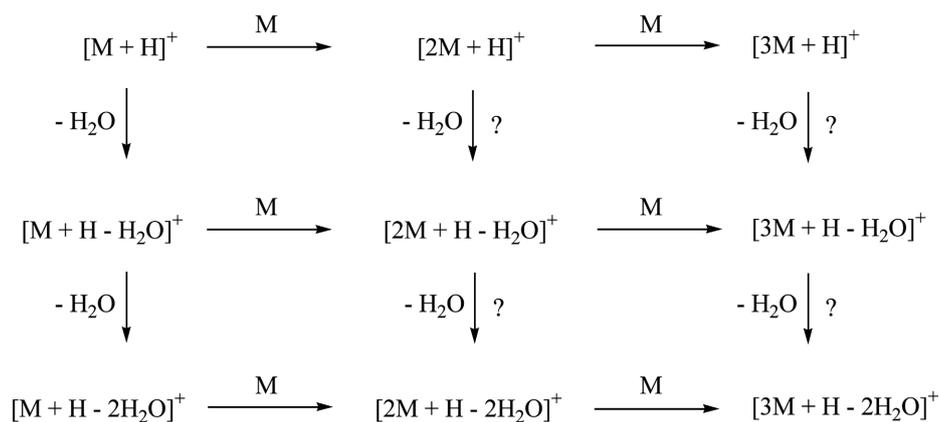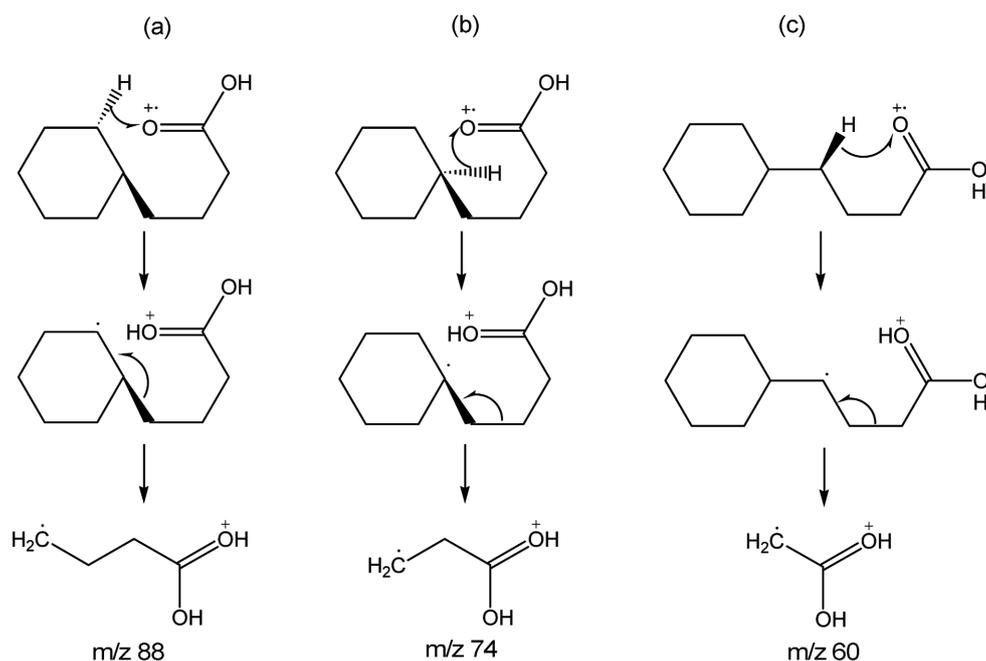At the long ion trapping time, the product ions heavier

than the $[M + H]^+$ were observed as shown in Figures 1 and 2. They can be generated by ion-molecule reactions between the fragment ions and neutral molecules. For cyclohexane propionic acid, the m/z 295, $[2M + H - H_2O]^+$, was prominently observed at the long ion trapping time of 50 ms as shown in Figure 1(b). At the longer ion trapping time of 300 ms, the m/z 313 and 451 assigned to $[2M + H]^+$ and $[3M + H - H_2O]^+$ were also observed. The $[3M + H - H_2O]^+$ is the dehydrated ion of $[3M + H]^+$ (m/z 469), but the m/z 469 was not observed in the mass spectra. This is an evidence that the $[3M + H - H_2O]^+$ is formed by solvation of neutral molecule with $[2M + H - H_2O]^+$ not from the $[3M + H]^+$. Thus, the $[nM + H - H_2O]^+$ with n = 2 and 3 can be formed by solvation not by dehydration (Scheme 7) because the internal energy of a product ion decreases with increase of

Scheme 5

(a)   (b)   (c)

m/z 88   m/z 74   m/z 60

Scheme 6

$$[M + H]^+ \xrightarrow{M} [2M + H]^+ \xrightarrow{M} [3M + H]^+$$

$-H_2O \downarrow \qquad -H_2O \downarrow ? \qquad -H_2O \downarrow ?$

$$[M + H - H_2O]^+ \xrightarrow{M} [2M + H - H_2O]^+ \xrightarrow{M} [3M + H - H_2O]^+$$

$-H_2O \downarrow \qquad -H_2O \downarrow ? \qquad -H_2O \downarrow ?$

$$[M + H - 2H_2O]^+ \xrightarrow{M} [2M + H - 2H_2O]^+ \xrightarrow{M} [3M + H - 2H_2O]^+$$

Scheme 7

the ion trapping time.

For cyclohexane butyric acid, the m/z 323, 341, and 493 assigned to $[2M + H - H_2O]^+$, $[2M + H]^+$, and $[3M + H - H_2O]^+$ were also observed. It is interesting that the m/z 279 and 297 assigned to $[M + 109]^+$ and $[M + 127]^+$ were also observed in the mass spectrum of cyclohexane butyric acid as shown in Figure 2(c). For cyclohexane butyric acid, the m/z 109 and 127 are the major fragment ions and the $[M + 109]^+$ and $[M + 127]^+$ can be generated by solvation of the m/z 109 and 127 with a neutral molecule. Among the observed product ions with m/z larger than the $[M + H]^+$, the predominant species are found to be $[nM + H - H_2O]^+$ with n = 2 and 3.

Conclusion

Typical fragmentation patterns of the molecular ions of cyclohexane propionic acid and cyclohexane butyric acid

were direct C-C bond cleavages, rearrangements, and dehydrations. The most abundant fragment ions were m/z 97 and 127 for cyclohexane propionic acid and cyclohexane butyric acid, respectively. The m/z 97 was formed from the molecular ion by the direct C-C bond cleavage, while the m/z 127 was formed by rearrangement of the molecular ion from the acid to diol form and loss of alkyl radical. The m/z 88, 74, and 60 were formed by rearrangements and their structures are distonic ions. The rearrangement from cyclohexane butyric acid to 1-cyclohexenyl-1,1-butanediol occurred easier than that from cyclohexane propionic acid to 1-cyclohexenyl-1,1-propanediol because the intermediate structures were six- and five-membered rings for cyclohexane butyric acid and cyclohexane propionic acid, respectively. The six-membered ring was less strained than 5-membered ring. The $[nM + H]^+$, $[nM + H - H_2O]^+$, and $[nM + H - 2H_2O]^+$ with n = 2 and 3 were observed, which formed by ion-molecule reactions between the product ions

and neutral molecules. The $[nM + H - H_2O]^+$ and $[nM + H - 2H_2O]^+$ with n = 2 and 3 were formed by solvation of the neutral molecules not by dehydration.

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