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(23) The protonation of the imidazole ring of adenine occurs at fairly low pH values as shown by the absence of any autocatalytic pathway for the tautomeric interconversion.[12] Assuming that the *difference* of basicity between pyrazole and imidazole rings in *4APP and adenine,* respectively, is similar to the difference of basicity between pyrazole (pK_a = 2.47) and imidazole (pK_a = 6.95) leads to the reasonable conclusion that the common cation of 4APP would have a p*K* of formation around zero.

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(26) For difficulties related to the synthesis of the nontautomerizable model compounds of the various H tautomers, the attribution of the relaxation spectrum cannot be achieved by the usual comparison of the relaxation amplitude with the differential spectrum. The assignments will be tentatively made on the basis of other kinds of evidence provided by NMR or UV spectroscopy, as well as by the consistency of the hypothesis with the subsequent observations and conclusions.

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Five-Membered-Ring Hydrogen Rearrangement in Mass Spectral Fragmentations. Another Mechanism of γ Cleavage

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Abstract: A new mechanism of γ cleavage in the mass spectra of aliphatic carbonyl compounds was characterized by examining the spectra of deuterium-labeled butanoic acids. γ cleavage occurs following five-membered-ring hydrogen transfer from the β carbon to an oxygen and the shift of a hydrogen atom from the α to the β carbon. This five-membered-ring hydrogen rearrangement is competitive with and occurs up to ⅓ as frequently as the six-membered-ring hydrogen transfer which precedes the well known β-cleavage loss of an olefin.

The best known mass spectral rearrangement involves transfer of a γ hydrogen to a carbonyl oxygen in conjunction with olefin loss by β cleavage.[2-4] Much evidence[3,4] has indicated that six-membered-ring hydrogen transfer is highly specific, though competing hydrogen rearrangements by larger sized rings sometimes occur.[4] We here demonstrate that five-membered-ring hydrogen rearrangement followed by γ cleavage[3] competes significantly with six-membered-ring hydrogen transfer–β cleavage.

Results

Table I gives the intensities of the ions formed by γ cleavage and γ cleavage followed by the loss of a water molecule in the normal mass spectra of several deuterium-labeled butanoic acids and the intensities of the ions of the corresponding compositions in the spectra of 2-ethylbutanoic acid and 2-ethylbutanoic acid-*O*-d_1. The only detected metastable decompositions of the $C_4H_8O_2^{+\cdot}$ ions were the losses of methyl

Table I. Abundances of Ions Formed by Losses of Methyl and of Methyl plus Water from Labeled Butanoic Acids

		Ion abundances[a]							
Compd	Isotopic composn	$C_3H_5O_2^+$	$C_3H_4DO_2^+$	$C_3H_3D_2O_2^+$	$C_3H_2D_3O_2^+$	$C_3HD_4O_2^+$	$C_3H_3O^+$	$C_3H_2DO^+$	$C_3HD_2O^+$
$CH_3CH_2CH_2CO_2H$		0.127					0.028		
$CH_3CH_2CH_2CO_2D$[b]	84% d_1, 16% d_0	<0.010	0.112				0.032	0.003	
$CH_3CH_2CD_2CO_2H$[c,d]	97% d_2, 3% d_1	0.014	0.004	0.100			0.001	0.003	0.018
$CH_3CD_2CH_2CO_2H$[c,e]	95% d_2, 5% d_1	0.005	0.005	0.081			0.002	0.019	0.006
$CD_3CH_2CH_2CO_2H$[c,f]	96% d_3, 4% d_2	0.12	0.012	0.004	0.008		0.027	<0.001	<0.001
$CD_3CH_2CH_2CO_2D$[b,f]	77% d_4, 22% d_3	0.011	0.10	0.008	0.003	0.006	0.023	0.001	0.001
$(CH_3CH_2)_2CHCO_2H$		0.164					0.101		
$(CH_3CH_2)_2CHCO_2D$[b]	87% d_1, 13% d_0	0.002	0.152				0.098	0.006	

[a] All spectra were obtained at 70 eV at a source temperature of 210 °C on a Du Pont 21-491 mass spectrometer. All compounds were purified by gas chromatography. [b] Obtained by exchange with D_2O in the mass spectrometer inlet. [c] Corrected for a 0.015 contribution from the loss of OH. [d] Prepared from the Grignard reagent of 1-bromopropane-*1,1*-d_2, which was obtained by the reduction of propanoic anhydride to 1-propanol-*1,1*-d_2 with $LiAlD_4$ and conversion of the alcohol to 1-bromopropane-*1,1*-d_2 with HBr/H_2SO_4. [e] Prepared by the addition of bromoethane-*2,2*-d_2 to diethylmalonate.[8] [f] Prepared by the addition of bromoethane-*2,2,2*-d_3 to diethylmalonate.

and ethylene, and the only metastable decomposition of $C_3H_5O_2^+$ was the loss of H_2O. The intensities of the peaks resulting from those transitions are given in Table II. Loss of water followed by the loss of methyl from ionized butanoic acid probably does not contribute significantly to $C_3H_3O^+$ formation, as the ion formed by the loss of H_2O is only 2% as abundant as that formed by the loss of methyl.

Discussion

γ-Hydrogen rearrangement-β cleavage of 2-ethylbutanoic acid gives ion **4** in Scheme I. Metastable decompositions (Table II) demonstrate that ionized butanoic acid and **4** both lose methyl. Loss of methyl from **4** gives **5** by γ cleavage, as enolic ions fragment in a parallel fashion.[5,6] Methyl is also lost from butanoic acid by γ cleavage, as 86% of the methyls lost from butanoic acid-*4,4,4*-d_3 were $\cdot CD_3$. This implies that ionized butanoic acid rearranges to **4** and then loses methyl to form **5**.

Metastable decompositions (Table II) demonstrate that $C_3H_5O_2^+$ formed from both butanoic acid and 2-ethylbutanoic acid fragments by loss of H_2O. Largely HDO was lost from **5**-*O*-d_1 derived from 2-ethylbutanoic acid-*O*-d_1. Therefore, both hydrogens in the water lost from **5** must be on the oxygens, i.e., **5** must decompose by **5** → **6**, as at least 50% H_2O would be lost from **5**-*O*-d_1 by any other mechanism. Since $C_3H_4DO_2^+$ formed by loss of methyl from butanoic acid-*O*-d_1 also lost mostly HDO, **5** must be formed by the loss of methyl from ionized butanoic acid. Thus, the butanoic acid ion must rearrange to **4** prior to losing methyl, as **4** is the only logical $C_4H_8O_2^{+\cdot}$ precursor of **5**. HDO was also predominantly lost from **5** formed from butanoic acid-*3,3*-d_2, while dominantly D_2O was lost from **5** obtained from butanoic acid-*3,3*-d_2-*O*-d_1. This demonstrates that the second hydrogen on the oxygen of **5** generated from butanoic acid comes from the β carbon, and therefore the occurrence of **1** → **3**. Other mechanisms placing a β hydrogen in the water lost are very improbable. The rearrangement of a β hydrogen to oxygen in $\cdot CH_2CH_2C(=O^+)OH$ formed by the loss of methyl directly from **1** or the concerted loss of H_2O containing a β hydrogen from that species would give energetically highly unfavored $:CHCH_2C\equiv O^+$. It is also unlikely that the loss of water specifically containing a β hydrogen would occur from the cyclic ions which have been suggested[3] as possible products of this γ cleavage. Thus, **1** → **3**, **4** → **5**, and **5** → **6** occur in sequence in the decomposition of ionized butanoic acid, so the predominant mechanism for the reported losses of methyl and water must be **1** → **3** → **4** → **5** → **6**.

5 is 22% as abundant as **7** in the normal spectrum of buta-

Scheme I

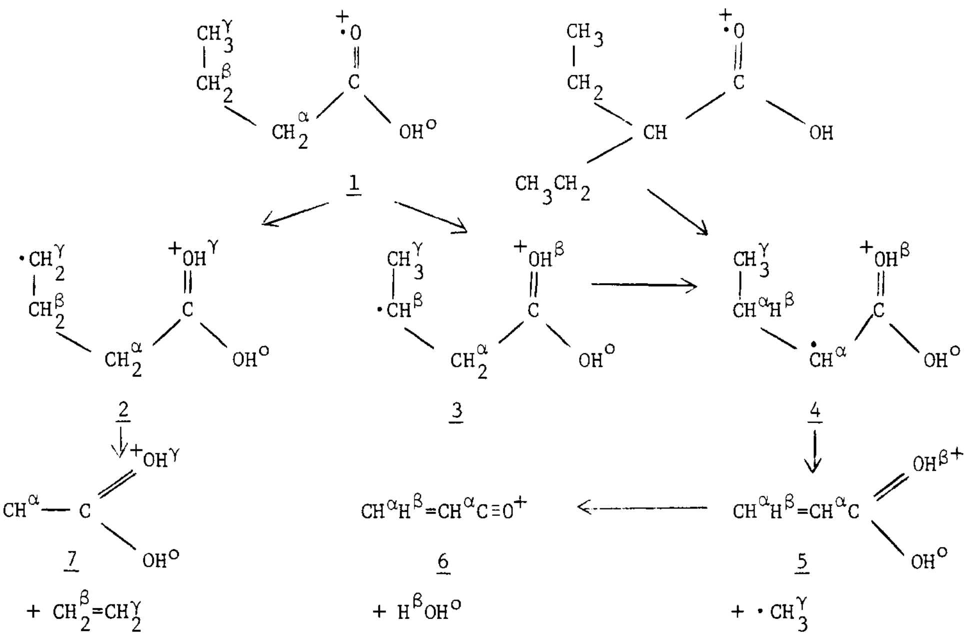

Table II. Metastable Decompositions of $C_4H_8O_2^{+\cdot}$ and $C_3H_5O_2^+$ [a]

Compd	Ion	$-CH_3$	$-C_2H_4$	$-H_2O$
$CH_3CH_2CH_2CO_2H$	**1**	2.4×10^{-2}	1.2×10^{-2}	
$(CH_3CH_2)_2CHCO_2H$	**4**	9.6×10^{-3}	9.0×10^{-5}	
$CH_3CH_2CH_2CO_2H$	**5**			4.5×10^{-3}
$(CH_3CH_2)_2CHCO_2H$	**5**			2.0×10^{-3}

[a] Values are the intensities of the peaks representing the metastable transitions divided by the intensities of the peaks in the normal spectra representing the precursor ions. The intensities of the peaks representing metastable transitions were determined by metastable defocussing achieved by lowering the electrostatic analyzer potential at constant accelerating potential.

noic acid. The average of the ratios of the intensities of the ions produced by γ cleavage to those produced by γ-hydrogen rearrangement-β cleavage is ~0.3 in the mass spectra[7] of acids, esters, and aldehydes with *n*-propyl and *n*-butyl moieties attached to their carbonyl groups. Therefore, five-membered-ring hydrogen rearrangements occur up to 1/3 as frequently as competing six-membered-ring hydrogen rearrangements.

Hydrogen rearrangements via six-, seven-, and eight-membered rings followed by further rearrangement to ions analogous to **5** also lead to γ cleavage.[5,8] HDO was lost in 44% of the metastable decompositions of the $C_3H_3D_2O_2^+$ ions formed from hexanoic acid-*3,3-d*$_2$. The first step leading to the formation of the ions that lost Hdo must have been five-membered-ring hydrogen transfer to an oxygen. Since the γ-cleavage product $C_3H_3D_2O_2^+$ was 45% as abundant as $C_2H_4O_2^+$ formed by γ-hydrogen rearrangement-β cleavage in the spectrum of hexanoic acid-*3,3-d*$_2$, five-membered-ring hydrogen rearrangements probably generally accompany six-membered-ring rearrangements.

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Degenerate Rearrangements in Solvolytic Studies with *cis*- and *trans*-2-Phenyl-1,2-di-*p*-tolylvinyl-*2*-^{13}*C* Bromides

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Abstract: Acetolysis in the presence of AgOAc of either *cis*- or *trans*-2-phenyl-1,2-di-*p*-tolylvinyl-*2*-^{13}*C* bromide (*cis*- or *trans*-**1**-Br-2-^{13}C) gave a 1:1 mixture of cis and trans products. After conversion of this product mixture to 2-phenyl-1,2-di-*p*-tolylethanol-*x*-^{13}*C* (**2**-x-^{13}C) and upon analysis of its ^{13}C NMR spectrum, about the same extent (1.5–2.0%) of scrambling of the ^{13}C label from C-2 to C-1 was found for either the cis or trans reactant. Nearly the same rate was also observed for the acetolysis, in the presence of NaOAc, with either *cis*- or *trans*-**1**-Br as substrate. Similarly, trifluoroacetolysis in the presence of CF_3COOAg of either *cis*- or *trans*-**1**-Br-2-^{13}C also gave about the same extent of ^{13}C scrambling (34–35%). All of these results point to the formation, without phenyl participation, of a free 2-phenyl-1,2-di-*p*-tolylvinyl cation which could then undergo competitively degenerate rearrangement by 1,2-phenyl shift and solvent capture to give product, the less nucleophilic the solvent, the greater the extent of isotopic scrambling. A solvent isotope effect, k_H/k_D, of 3.4–3.9 was observed for the reaction of *cis*- and *trans*-**1**-Br in CF_3COOH or CF_3COOD, without the presence of any Ag salt. This finding indicated that, in the reaction with CF_3COOH in the absence of Ag salt, an electrophilic addition-elimination process must have played an important role. Reaction of *cis*- and *trans*-**1**-Br-2-^{13}C with CF_3COOH, without any CF_3COOAg, gave 45 and 48–49% scrambling after ~2.5 and 6 half-lives. It is suggested that these latter results may be chiefly attributable to a subsequent ionization, in the reaction medium, of the addition-elimination product, followed by degenerate 1,2-phenyl shifts and recombination with solvent.

Degenerate rearrangements from 1,2-aryl shifts across the double bond in a number of labeled triarylvinyl cations, with various combinations of phenyl and/or *p*-anisyl as the aryl groups, have been studied in this laboratory,[1] and by Rappoport and coworkers.[2] 1,2-Phenyl and 1,2-anisyl shifts in triphenylvinyl and trianisylvinyl cationic systems have been investigated using the ^{14}C label as tracer,[1a,b,e] and using ^{13}C labeling coupled with analysis by ^{13}C NMR,[1b,c] while the ^{13}C NMR technique has also been applied in a study on the possible 1,2-phenyl shift in the reaction of *cis*- and *trans*-1,2-dianisyl-2-phenylvinyl-*2*-^{13}*C* bromide with HOAc–AgOAc.[1d] Rappoport et al. have utilized a D-labeled phenyl group and ^{1}H NMR as well as mass spectrometry in investigating degenerate 1,2-anisyl shifts during the solvolysis of *cis*- and *trans*-2-anisyl-1,2-diphenylvinyl bromides.[2a] Degenerate rearrangements in the trianisylvinyl and the *cis*- and *trans*-1,2-dianisyl-2-phenylvinyl systems have also been studied by Rappoport et al. in a number of solvolytic reactions with a $CD_3OC_6H_4$ group as label and again with analyses by ^{1}H NMR and mass spectrometry.[2b] Very recently, we have in-