

ACID-CATALYZED ALDEHYDE-KETONE REARRANGEMENTS IN THE GAS PHASE.
CYCLOPENTANE- AND CYCLOHEXANECARBOXALDEHYDE.

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Abstract: Protonation by gaseous H_3^+ , $C_nH_5^+$ ($n=1,2$), $s-C_3H_7^+$ and $t-C_4H_9^+$ cations promotes rearrangement of cyclopentane- and cyclohexanecarboxaldehyde to cyclohexanone and cyclopentylmethyl ketone, respectively. The reaction was investigated by radiolytic and mass spectrometric methods.

The mechanism of the acid-catalyzed rearrangement of aldehydes to ketones has long been studied in solution with somewhat puzzling results, owing inter alia to the fact that the carbonium ions formed, following protonation at the carbonyl group and alkyl migration, can rapidly interconvert in the reaction medium.¹ Special consideration was also devoted to the rearrangement of cyclic aldehydes leading to ring expansion, as in the case of cyclopentanecarboxaldehyde that yields cyclohexanone, or contraction as in the unusual conversion of cyclohexanecarboxaldehyde into the cyclopentylmethyl ketone.^{1,2} On the other hand, the collision-induced dissociation (CID) mass spectra of protonated cyclohexanone,³ as well as theoretical calculations,⁴ were taken as evidence that the reverse process, i.e. isomerization of the protonated ketone to the aldehyde structure, was likely to occur under unimolecular conditions at low pressure (10^{-8} Torr).

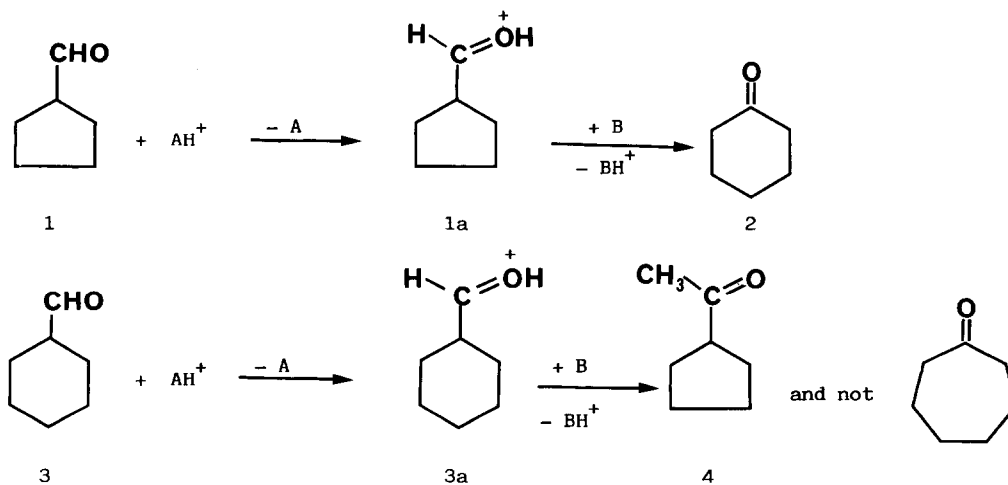
The present paper reports on a preliminary radiolytic study of the title reaction in the dilute gas state at "high pressure", under conditions that ensure complete thermalization of the reagents and the intermediates, and allow direct structural identification of the neutral end products. Kinetic energy release data for the decomposition reactions of the $(M+H)^+$ ions, produced in the source of a VG-Analytical, ZAB-2F mass spectrometer following protonation by the same Brønsted acids employed in radiolytic experiments, are also reported.

The gaseous acids were formed by irradiating suitable precursors (760-100 Torr) in a ^{60}Co 220-Gammacell from Nuclear Canada Ltd., at 30°C and to a total dose of 2 Mrad.⁵ Neopentane, propane, methane and hydrogen (D_2) were used as the precursors of, respectively, $t-C_4H_9^+$, $s-C_3H_7^+$, $C_nH_5^+$ and H_3^+ (D_3^+) ions. The gases were contained into sealed pyrex bulbs, in the presence of O_2 (5 Torr), as a thermal radicals scavenger, and of the substrate (0.5 Torr). The reaction mixtures, extracted with acetone containing methylisobutyl ketone as an internal standard, were analyzed by glc on the following columns: 6 ft-0.1% SP1000 on Carbowax C, operated at 90°C, and 6 ft-20% SP2100+0.1% Carbowax 1500 on Supelcoport 100/120, at 70°C. The products were identified by comparing

their retention volumes with those of authentic samples and their identity was checked by GC-MS, using a Hewlett-Packard mod.5982A mass spectrometer.

Protonation of cyclopentanecarboxyaldehyde **1** with all the acids employed gave cyclohexanone **2** as the only isomerization product. The yields, expressed as G(+M) values, were: H_3^+ (D_3^+), 0.25; $C_nH_n^+$, 0.05; $s-C_3H_7^+$, 0.02; $t-C_4H_9^+$, 0.02, at 760 Torr. Cyclohexanecarboxyaldehyde **3** isomerized, following protonation, to cyclopentylmethyl ketone **4** with the yields (760 Torr): H_3^+ (D_3^+), 0.8; $C_nH_n^+$, 0.13; $s-C_3H_7^+$, 0.02; $t-C_4H_9^+$, 0.07. Protonation of cycloheptanone did not produce **4**. No detectable yields of the aldehydes **1** and **3** were observed from the protonation of ketones **2** and **4**, even when the strongest acid, H_3^+ , was employed. At lower pressures (100 Torr) the yields of the ketones increased by a factor 6-10. The ionic nature of the processes leading to the neutral end products was confirmed by control experiments, showing the drastically inhibiting effects of a strong base ($N(CH_3)_3$) which intercepts the charged reagents.

Chemical ionisation (C.I.) mass spectra of the aldehydes display the major peaks at m/e values typical of the $(M+H)^+$ and $(M+H-H_2O)^+$ ions. The relative intensity of the $(M+H)^+$ peak increases i) as the proton affinity (P.A.) difference between the substrates and the conjugate base of the reactant ion decreases, and ii) as the source pressure increases, i.e. by decreasing the internal energy of the protonated molecular ions. The low intensity of $(M-H)^+$ excludes any significant contribution of these ions to the isomerization process as well as the occurrence of appreciable proton transfer to the ring carbons, even by the strongest gaseous acids.

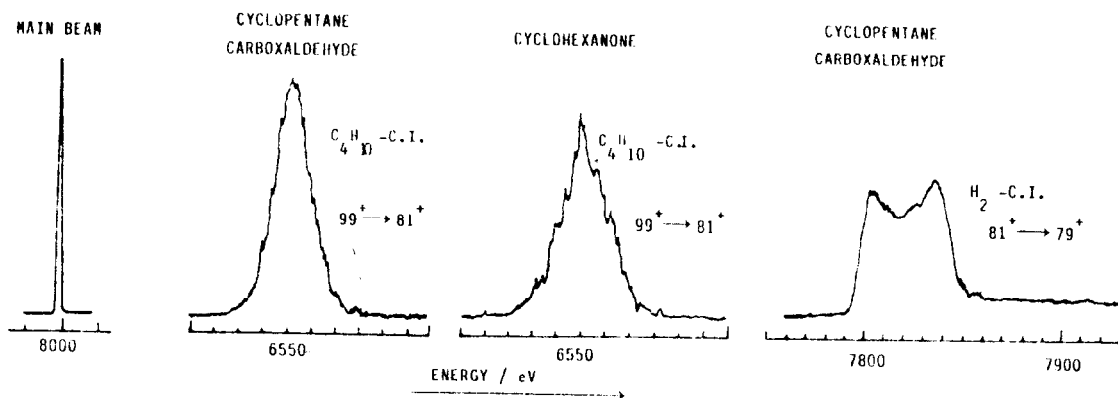


The O-protonated aldehydes **1a** and **3a** are therefore likely to be by far the most abundant ionic intermediates formed in the radiolytic systems, where efficient collisional quenching is ensured by the high pressure of the bulk gas and decomposition processes are minimized. This was also experimentally demonstrated by the lack of appreciable fragmentation products.

1a and **3a**, excited by the exothermicity of the proton transfer, can undergo unimolecular

rearrangement before losing a proton to any base contained in the system to give ketones 2 and 4. In the systems studied the isomerization of intermediates should be a rather fast process, occurring within 10^{-8} - 10^{-9} s from their formation. The radiolytic experiments have shown, with the degree of certainty allowed by the identification of neutral end products, that: i) the acid-catalyzed rearrangement of 1 and 3 in the dilute gas phase has the same course as in solution, giving the same ketones, and, in particular, 3 isomerizes to the 5-membered ring ketone rather than to cycloheptanone; ii) the activation energy barrier for the isomerization should be quite low, since the reaction occurs with the mildest acid employed ($t\text{-C}_4\text{H}_9^+$) as well. An upper limit to the height of this barrier can be tentatively deduced from the P.A. difference between 1 and isobutene (11 Kcal/mol), which sets the maximum excitation energy available to 1a ions.⁶ The situation is likely to be analogous for compound 3, whose P.A. is not known.

At lower pressures (10^{-1} - 10^{-2} Torr) the ions from the protonation of 1, 2, 3 and 4, using H_2 or CH_4 as the reactant gases, fragment to some extent in the source of the mass spectrometer, operated at 180°C in the C.I. mode. The process is obviously much reduced with $\text{iso-C}_4\text{H}_{10}$ and is comparatively more extensive for the aldehydes than for the ketones. The $(\text{M}+\text{H})^+$ ions ($m/e=99$ for 1,2 and 113 for 3,4) formed from all the reagents undergo metastable unimolecular water loss both in the 1st and in the 2nd field-free regions (FFR) of the ZAB-2F, giving rise to apparently simple gaussian-shaped peaks, as shown by the MIKES spectra reported as an example (energy resolving power greater than 6000 fwhm at 8 kV accelerating voltage).⁷



The kinetic energy release and the relative abundances of the peaks were calculated by averaging 10 scans, collected on a VG-2350 Data System (10^5 digital samples for a 100 eV-energy span) and are reported in Table 1 for compounds 1 and 2. The reaction $113^+ \rightarrow 95^+ + 18$ for the aldehyde 3 and ketone 4 (CH_4 -C.I.) gave the following results: 3: $T_{0.5} = 15.5$ meV, $\langle T \rangle = 39.9$ meV, $I_{95}/I_{113} = 5.6 \times 10^{-4}$; 4: $T_{0.5} = 18.0$ meV, $\langle T \rangle = 47.9$ meV; $I_{95}/I_{113} = 9 \times 10^{-4}$.

The $(\text{M}+\text{H}-\text{H}_2\text{O})^+$ ions formed in the source, following C.I. of 1, 2, 3 and 4 with H_2 and CH_4 , may undergo metastable H_2 -loss giving rise to dish-shaped peaks characterized by higher kinetic

energy releases than those from water loss (see figure). This indicates either that ions at m/e 81 and 95 are a mixture of isomeric structures or, more likely, that they fragment to yield isomeric daughter ions. Furthermore, also metastable $(M+H-H_2O)^+$ ions formed in the 1st FFR undergo consecutive H_2 -loss in the 2nd FFR of the instrument, giving rise to peaks of the same shape and width as those from the ions formed in the source.⁸

TABLE 1. Kinetic Energy Release (meV) from MIKES Spectra for the H_2O -loss from $(M+H)^+$ Ions

Reactant gas	CYCLOPENTANECARBOXALDEHYDE			CYCLOHEXANONE		
	$T_{0.5}$	$\langle T \rangle$	I_{81}/I_{99}	$T_{0.5}$	$\langle T \rangle$	I_{81}/I_{99}
H_2	14.0	38.6	5.5×10^{-4}	17.6	50.7	2.3×10^{-4}
CH_4	15.2	40.9	3.6×10^{-4}	17.6	46.9	1.2×10^{-4}
iso- C_4H_{10}	12.8	28.8	2.9×10^{-4}	15.2	35.9	4.0×10^{-6}

The small differences between the T values, which could reflect the P.A. difference between the aldehydes and the ketones, and the complex nature of the water loss reaction do not allow to draw firm conclusions on the structure of the reacting ions, i.e. on the possible isomerization of the ketone to aldehyde, once enough energy has been accumulated in the protonation.

The same reaction, induced by collisions with 10^{-7} Torr He in the 2nd FFR gas cell, did not allow to discriminate between the ions from 1 and those from a 1:1 mixture of 1 with 2, owing to the expected peak broadening with respect to unimolecular dissociation.

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