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Determination of heats of tautomerization of nitrile–ketenimine by mass spectrometry

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Tautomerism of some nitriles has been studied by mass spectrometry. The analysis of the corresponding mass spectra has allowed some fragmentations to specific tautomers to be assigned and the heats of tautomerization to be determined through temperature effects and electron energy studies. Experimental determinations are supported by theoretical calculations. The joint analysis of mass spectrometry and DFT-B3LYP data indicate that this tautomeric equilibrium can be studied by the experimental spectrometric strategy employed.

Keywords: heats of tautomerization, nitriles, mass spectrometry, quantum chemical calculations

Introduction

A few studies where enolization of nitriles is proposed to take place have been found in the recent literature.[1–3] Most of nitriles appear to strongly favor the cyano form in this equilibrium. Kasturi *et al*. have carried out the study of the ultraviolet (UV absorption spectra of a number of 1,2-dicyano esters and 1,1,2-tricyano compounds demonstrating the presence of nitrile–ketenimine tautomerism.[2] Among these tautomeric compounds, those which involve a methylene hydrogen γ to the nitrile group and electron withdrawing groups such as CN or COOR (Scheme 1)[3] are of particular interest.

In connection with the synthesis of heterocyclic-containing compounds, Kasturi *et al*. have synthesized several condensation products of β-ketoesters with malonitrile and ethylcyanoacetate. From the analysis of the UV spectra in ethanol and in ethanol/sodium hydroxide solution, the observed hyperchromic effect on the band around 355 nm (detectable only in polar hydroxylic solvents) was assigned to the ocurrence of a ketenimine structure.[3] Contrarily, the long wavelength UV absorption band observed in the spectra of some alkylidene malononitriles and cyanoacetates has been claimed to be a consequence of the anion formation and not of nitrile–ketenimine tautomerism.[4]

In addition, absorption bands between 2100 cm^{-1} and 1500 cm^{-1} in the infrared (IR) spectra of these compounds (which could be expected if any ketenimine had been present) were not observed.[5] On the other hand, the use of a highly enantioselective direct dialkyl allylic electrophilic functionalization by the addition of diethyl azodicarboxylates to alkylidene cyanoacetates and malononitriles has been demonstrated and can be applied to other electrophilic addition reactions.[6]

Additional experimental evidence can be taken into account considering that some reactions can only take place through

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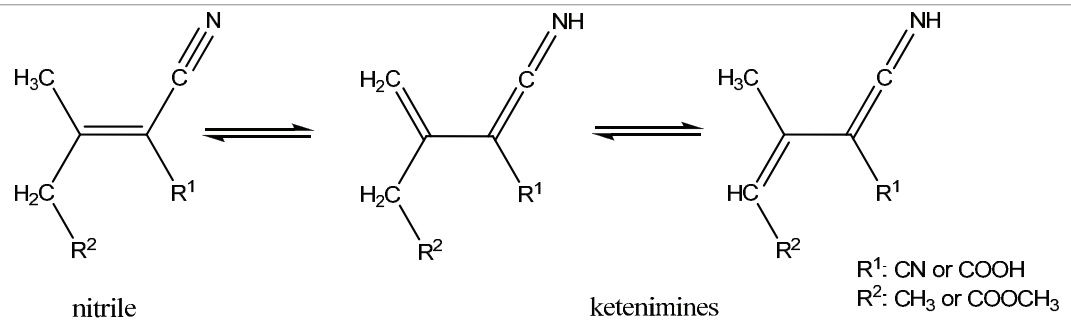


Scheme 1.

a specific tautomer (ketenimine). Amination was selected and, although a mechanistic study of amination of ketenimines is missing, it is known that amination of ketenimines forms amidines.[7] High level *ab initio* calculations conducted by Sung *et al*. concluded that amination of ketenimines proceeds via amine addition across the C=N bond rather than the C=C bond, followed by tautomerization to form the amidine product. An intermediate with vinylidendiamine structure has been directly observed by low-temperature ^{1}H nuclear magnetic resonance (NMR) spectroscopy.[8]

Mass spectrometry has already been demonstrated as a useful tool for the study of tautomerism.[9–23] This is the reason for the selection of this methodology to study the nitrile–ketenimine equilibrium trying to find experimental evidence of the occurrence of the ketenimine tautomer through the interpretation of the mass spectral peaks of the selected nitriles.

The study of temperature effects (injector vs ion source) on the tautomerism of selected compounds has demonstrated that equilibration occurs inside the injection system prior to ionization, which might be considered as evidence of the lack of contribution to the mass spectral data (used to evaluate these equilibria) by tautomerization of radical ions. In fact, it has been claimed that tautomerization also occurs in the molecular ions, although some reports proposed that enolization should be considered to occur before ionization, since no evidence of tautomerism of ionc species could be observed.[10,24]

From β-diketones, the analysis of their mass spectra demonstrated that fragmentation patterns are influenced by the keto–enol content of these compounds. This simplified analysis might have the disadvantage that the ion abundances may not only depend on tautomerization but also among other parameters, on bond strength differences. Notwithstanding it has been demonstrated not to be the case for some compound families. Based on temperature effects, Zamir and co-workers[24] reported for selected β-diketones that a change in injection temperature results in changes of relative peak intensities for fragments assigned to the enol form, while changes in the ion source temperature did not exert any effect.

In a similar study, but for open–closed chain tautomerization, Cooks *et al*.[25] observed that the ion abundance ratios for fragments assigned specifically to both tautomers also vary with small changes in the ion source temperature which would indicate that tautomerism in this case is unimolecular. The simplest interpretation takes into account the pressure at different instrument points: the injection system where intermolecular collisions can occur (tautomerization is usually bimolecular) and the ion source where only unimolecular processes can take place (an intramolecular mechanism on the low pressure side could also explain those results).

Although NMR is particularly useful in the determination of equilibrium constants, this methodology not always provides the expected data for several reasons (very low concentration of tautomers can be one of them). Mass spectrometry represents a versatile tool for the evaluation of thermodynamic data on gas-phase ions.[26] This methodology has been already used for the calculation of heats of tautomerization of selected thioamides and measurably reliable results have been found. Very good correlations with theoretical data for such thermodynamic property have given support to this approach.[20]

Experimental

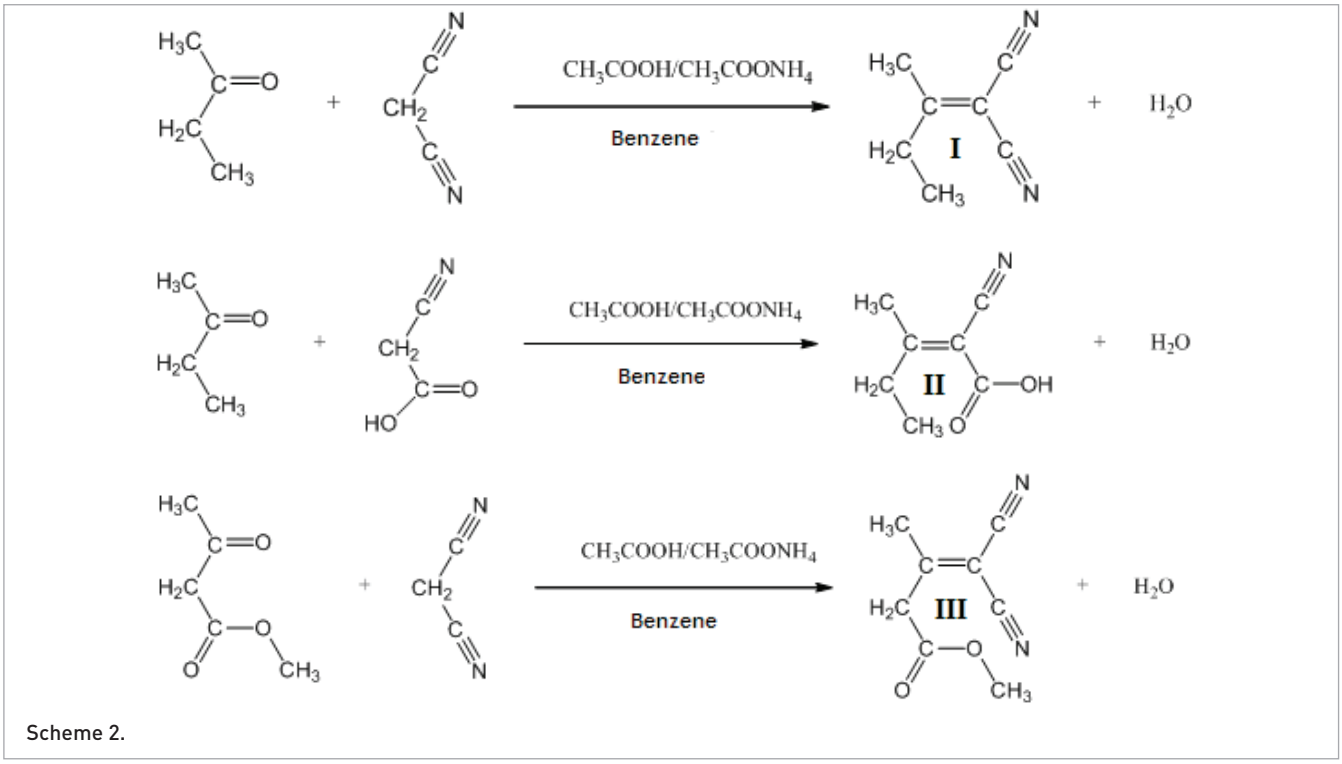
Synthesis of nitriles

The 2-*sec*-butylidenmalononitrile (**I**), 2-cyano-3-methylpentan-2-oic acid (**II**) and 4,4-dicyano-3-methyl-3-butenoic methyl ester (**III**) were synthesized according to the condensation procedure of Cope–Knoevenagel (Scheme 2).[27–31]

All compounds were characterized by spectrometric methods including IR, MS and NMR techniques.

Gas chromatography–mass spectrometry–single quadrupole

These measurements were recorded on a GCMS-QP2010 SHIMADZU instrument using helium as the carrier phase (column head pressure 100 kPa). The column used was a HP-5 (30 m × 0.32 mm × 0.25 mm film thickness). A 1 µL injection of the compounds dissolved in acetone was chromatographed under the following conditions: injector temperatures were 250°C, 275°C and 300°C. The column temperature program was as follows: 70°C (2 min), 7°C min^{-1}, 200°C (2 min), 5°C min^{-1}, 300°C (2 min). In the spectrometer the ion source



Scheme 2.

was kept at 230°C for most determinations. Temperature effects at the ion source were assayed at 185°C. The electron energies were 70 eV, 50 eV and 30 eV. The pressure in the mass spectrometer was lower than 10^{-5} Torr, thus precluding ion molecule reactions.

Gas chromatography–mass spectrometry–ion trap

These determinations were carried out by injection of solutions of compounds **I–III** in acetone (1 µL) in a Thermo Quest Trace 2000 Chromatograph coupled to a Finnigan Polaris ion trap detector (unit mass resolution) under the same temperature, pressure and electron energy conditions mentioned for the quadrupole system. The ion trap was utilized to confirm the proposed fragmentation pathways by collision-induced dissociation (CID) using helium as the damping gas, a CID voltage of 4–8 eV and an excitation energy of 0.3–0.5 (optimized for each transition). Tandem mass spectrometry (MS/MS) full scan ion product spectra were recorded for selected precursor ions.

Vibrational spectroscopy

IR spectra of the liquid 2-*sec*-butylidenmalononitrile and both solid 2-cyano-3-methylpentan-2-oic acid and solid 4,4-dicyano-3-methyl-3-butenoic methyl ester in KBr pellets) were recorded with a resolution of 2 cm^{-1} in the 4000–400 cm^{-1} range on a Bruker EQUINOX 55 FTIR spectrometer.

Signal assignments (cm^{-1}) are given for the three compounds under investigation:

2-sec-butilydenmalononitrile (**I**): 2983 (s, νC–H), 2944 (m, νC–H), 2883 (m, νC–H), 2232 (vs, νC≡N), 1600 (vs, νC=C), 1463 (s, ρCH_2), 1378 (s, νC–CN), 1071 (m, $\nu C–CH_2$), 877 (w, ρCH_2), 794 (w, ρCH_3).

2-cyano-3-methylpentan-2-oic acid (**II**): 3474 (s, broad, νO–H), 2986 (s, νC–H), 2943 (m, νC–H), 2224 (s, νC≡N), 1718 (vs, νC=O), 1602 (vs, νC=C), 1434 (vs, ρCH_2),1374 (s, νC–O), 1291 (vs, ρCH_2), 1260 (vs, ρO–H), 1224 (m, νC–CN), 1101 (w, ρCH_2), 1066 (m, ρCH_3), 925 (m, ρCH_2), 799 (w, ρCH_3) , 742 (m, ρCOOH).

4,4-dicyano-3-methyl-3-butenoic methyl ester (**III**): 2958 (s, νC–H), 2236 (s, νC≡N), 1744 (vs, νC=O), 1608 (vs, νC=C), 1435 (vs, ρCH_2) 1375 (vs, νC–C(O)), 1332 (vs, ρCH_2), 1250 (m, νC–CN), 1195 (s, νC(O)–O), 1177 (s, $\nu H_3C–O$), 1070 (m, $\nu C–CH_2$), 1024 (w, ρCH_3), 998 (m, ρCH_2), 862 (w, ρCC(O)C), 766 (w, ρOCO).

Quantum chemical calculations

The calculations were performed using the GAUSSIAN 03 program package. Optimum equilibrium geometries were computed for the singlet ground states of all pertinent molecular systems using DFT-B3LYP with the 6-31G* and the more extended 6-311++G**(d,p) basis sets. Numerous conformations were computed in order to ensure that the lowest energy conformation was obtained for each molecular system. For each conformation, harmonic vibrational frequencies were also calculated at the same level of computation to guarantee that each optimized geometry corresponds to a true local minimum and obtain the zero-point energy correction (ZPE).

Error calculations[32,33]

When simple linear correlations and graphical methods are used, the experimental error can be calculated by linear regression (minimum square method). In this work thermodynamic

data are calculated from the slope of linear plots, so that this approach was chosen and the errors in Table 3 calculated accordingly. The standard error for the slops of the linear plots, ($S_{(b)}$), is calculated by a Microsoft Excel program using the following equations:

$$S_{(b)} = S_{(y)}/S_{(x,x)}^{1/2}$$

$$S_{(y)} = \{[S_i(y_i - y_a)^2]/(n-1)\}^{1/2}$$

and

$$S_{(x,x)} = Sx_i^2 - nx_a^2$$

where n is the number of data points, x_i and y_i are the plotted data and x_a and y_a the corresponding averaged values.

Results and discussion

Mass spectrometry

The relevance of spectrometric data as a predictive tool in regard to tautomeric equilibria depends mainly on the fact that the contribution due to tautomerization of molecular ions in the gas phase does not take place or can be ignored. The importance of this point comes from the physicochemical properties of ionic and radicalary species, quite different from the neutral ones. This could be the reason for possible distortion of results and loss of the desirable predictive power of the methodology. High-energy ionic species as the molecular ions of the selected nitriles can undergo 1,5-hydrogen shifts (many rearrangements are shown in the schemes) although the main tautomer structure seems to be not affected: C=C–C≡$\overset{+}{\text{N}}$H is thermodynamically more stable than $\overset{+}{\text{C}}$–C=C=NH.

It has been demonstrated in the case of keto–enol tautomerism of a variety of carbonylic and thiocarbonylic compounds[9–23] that there is no significant interconversion of the tautomeric forms in the gas phase following electron impact ionization in the mass spectrometer (molecular ions, $M^{+\bullet}$ do not seem to undergo unimolecular tautomerization) and, even more surprising, for gas chromatography (GC)/MS experiments, once the solvent is separated after injection in the injection port of the gas chromatograph, tautomerism mechanisms (intermolecular, unimolecular) would not seem to take place, even with no GC separation (under the selected experimental conditions). These conclusions are supported by temperature studies at the ion source (negligible effect) and at the injection port of the gas chromatograph with a shifting effect in agreement with the corresponding heats of tautomerization.[20] In fact, this process would take place very fast under the working conditions in the GC.

Separation of tautomers in the analytical column is frequently very difficult, consequently the different pathways of fragmentation of the tautomeric forms have to be used for identification of individual tautomers.[20] For this reason and because of the high similarity between MS (commercial databases) and GC/MS spectra, analytical separation has not been considered critical for the present work. Analogously, it is thought that most of the conclusions could be useful to analyze spectra registered with mass spectrometers equipped with direct insertion probes.

The mass spectrum of 2-*sec*-butilydenmalononitrile (**I**) at 70 eV is shown in Figure 1. The peaks corresponding to *m/z* 119 $(M–H)^+$, *m/z* 105 $(M–CH_3)^+$, *m/z* 93 $(M–CNH)^{+\bullet}$, *m/z* 92 and *m/z* 64 can be explained from both tautomers, as shown in Scheme 3(a) (nitrile form) and Scheme 3(b) (ketenimine form).

Ionization on the CN triple bond allows, through hybridization change, the necessary spatial interaction for the detailed rearrangements. α-Ruptures and inductive cleavages would be responsible for the corresponding fragment ions. The ion

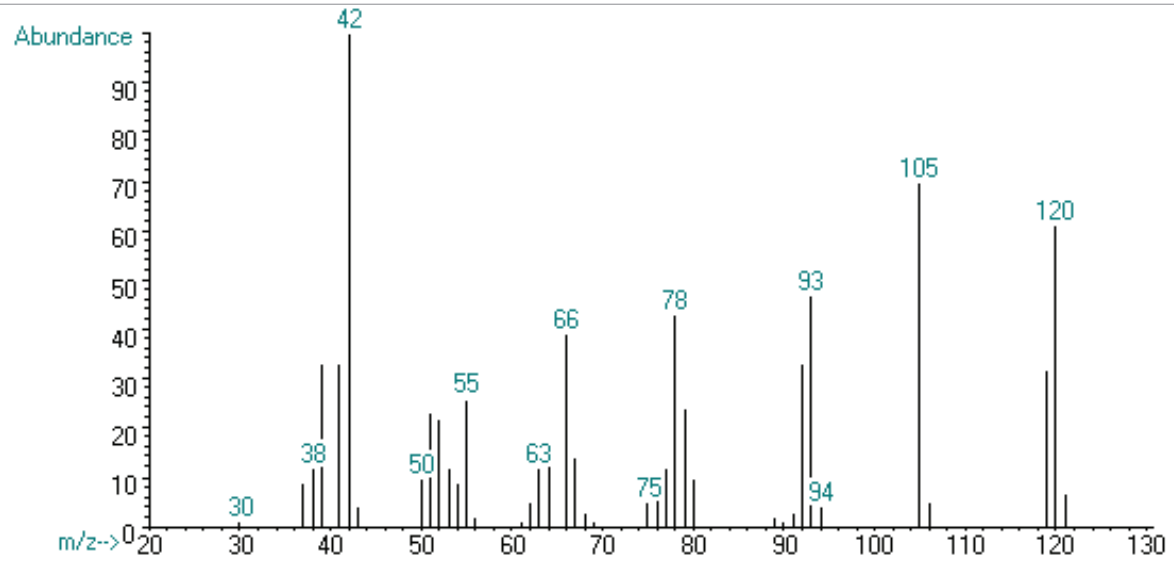


Figure 1. Mass spectrum of the 2-*sec*-butilydenmalononitrile (I) at 70 eV.

at *m/z* 105 is stabilized by electron shifts to a ketenimine-like structure.

The ion at *m/z* 91 can also be assigned to the ethyl loss from the ketinimine structure by assuming that the initial ionization involves the ketenimine C=C double bond. The ion at *m/z* 78 can only be explained from the nitrile form as depicted in Scheme 4 and as a loss of CNH from the fragment ion at *m/z* 105 in Scheme 3(a).

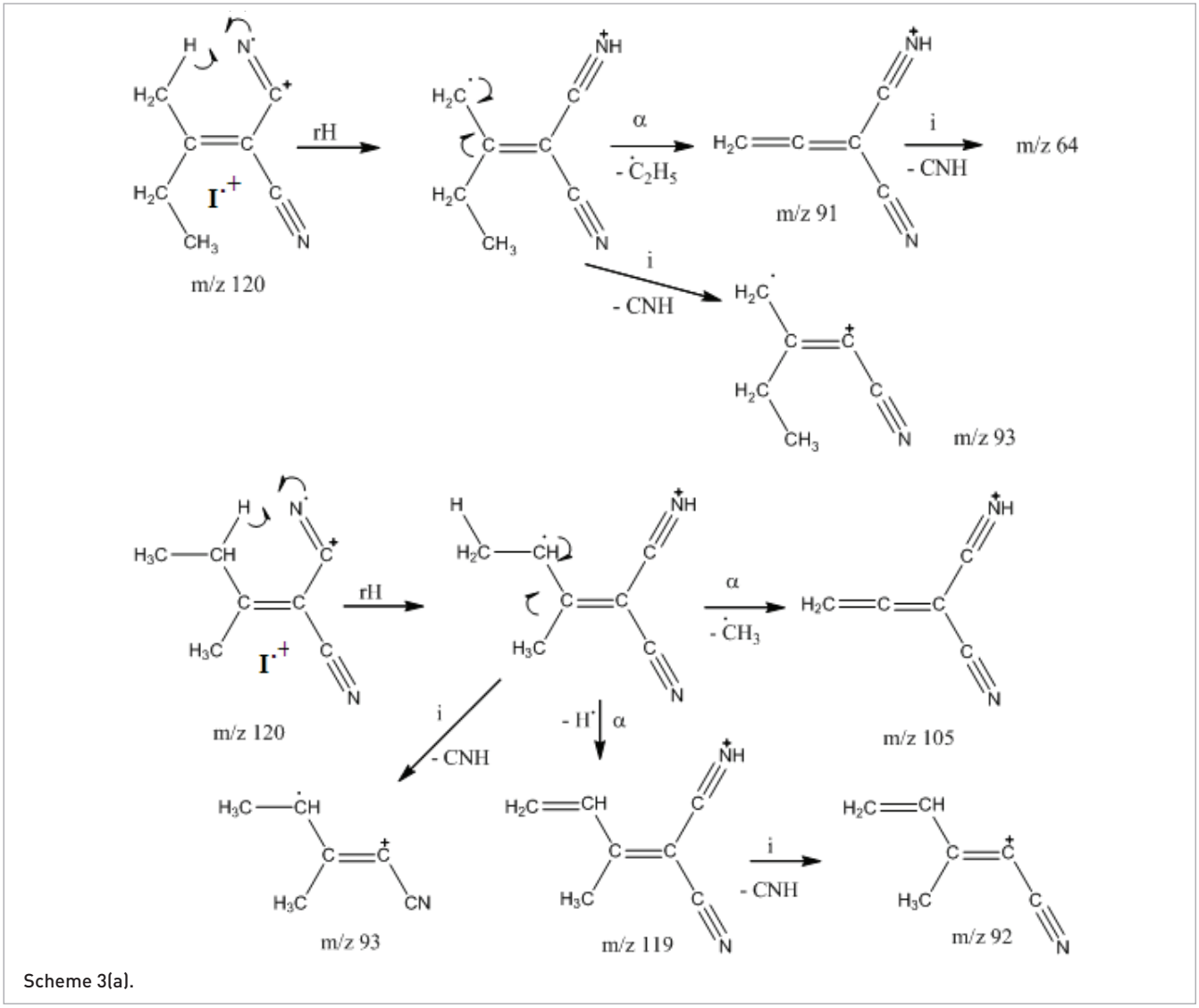
The fragment ions at *m/z* 91, *m/z* 64 and *m/z* 78 can be described by a structure with charge migration to account for the energy involved when cumulative double bonds are formed.

The ions at *m/z* 39, *m/z* 50, *m/z* 55 and *m/z* 66 are assignable to the ketenimine form, as shown in Scheme 5. Initial ionization of the ketenimine form would involve the CN triple bond of the nitrile moiety or the CNH double bond of the ketenimine. It is interesting that the abundant *m/z* 66 [isobaric with that in Scheme 3(b)] is a particularly stable ion. The ion at *m/z* 55 is formed by inductive cleavage and its stability would become the corresponding driving force for the fragmentation.

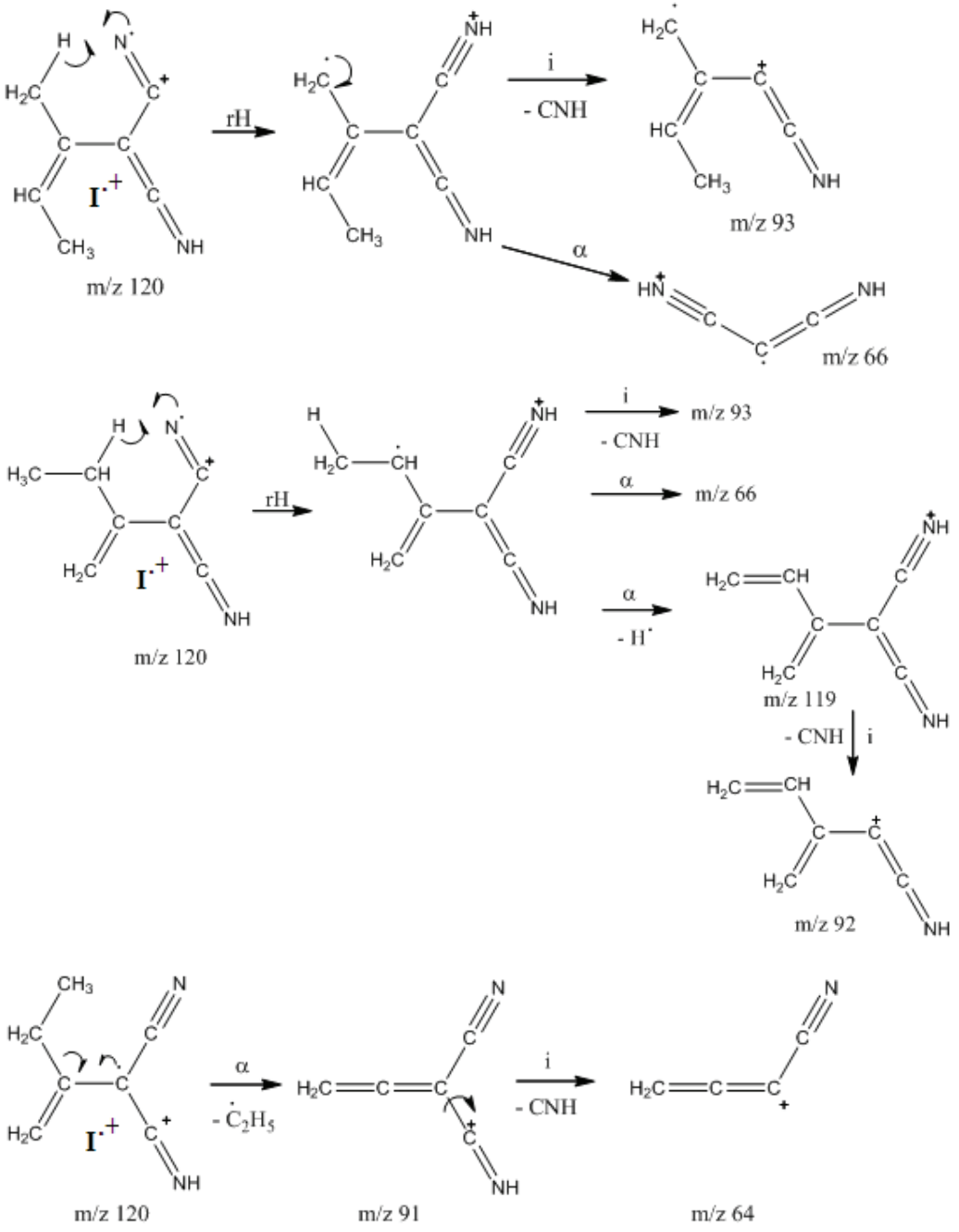
For graphical simplicity, neutral species with cumulative double bonds (rather energy demanding) have been drawn in some of the schemes although cyclization/isomerization might occur to circumvent relative high energy barriers. In case of ionic fragments drawn with this structural feature, stability can be assumed by charge migration as already mentioned. Although not clear, isomerization to cyclic compounds cannot be discarded to facilitate the fragmentation process.

It seems clear from the analysis of the main fragment peaks that ketenimine occurs, since fragment ions exist which can only be explained through this tautomer. A relative estimation of the tautomers occurrence could be the ratios *m/z* 50 to *m/z* 78, and *m/z* 39 to *m/z* 78.

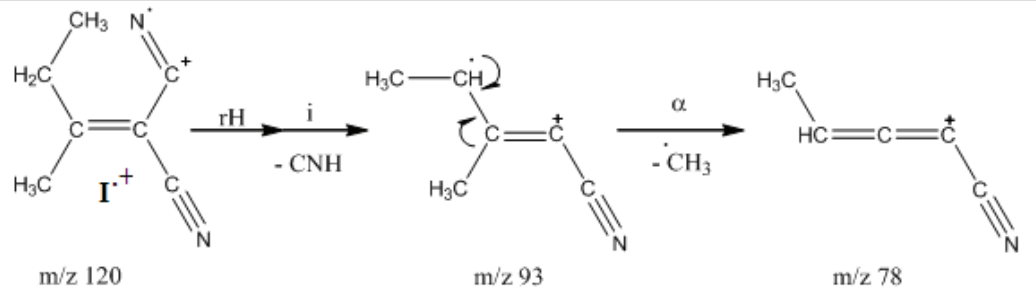
The mass spectrum of 2-cyano-3-methylpentan-2-oic acid (**II**) at 70 eV is shown in Figure 2. The peaks at *m/z* 124, *m/z* 122 $(M–OH)^+$, *m/z* 112 $(M–CNH)^{+\bullet}$, *m/z* 110, *m/z* 94 $(M–COOH)^+$, *m/z* 93 can be explained through both tautomeric forms



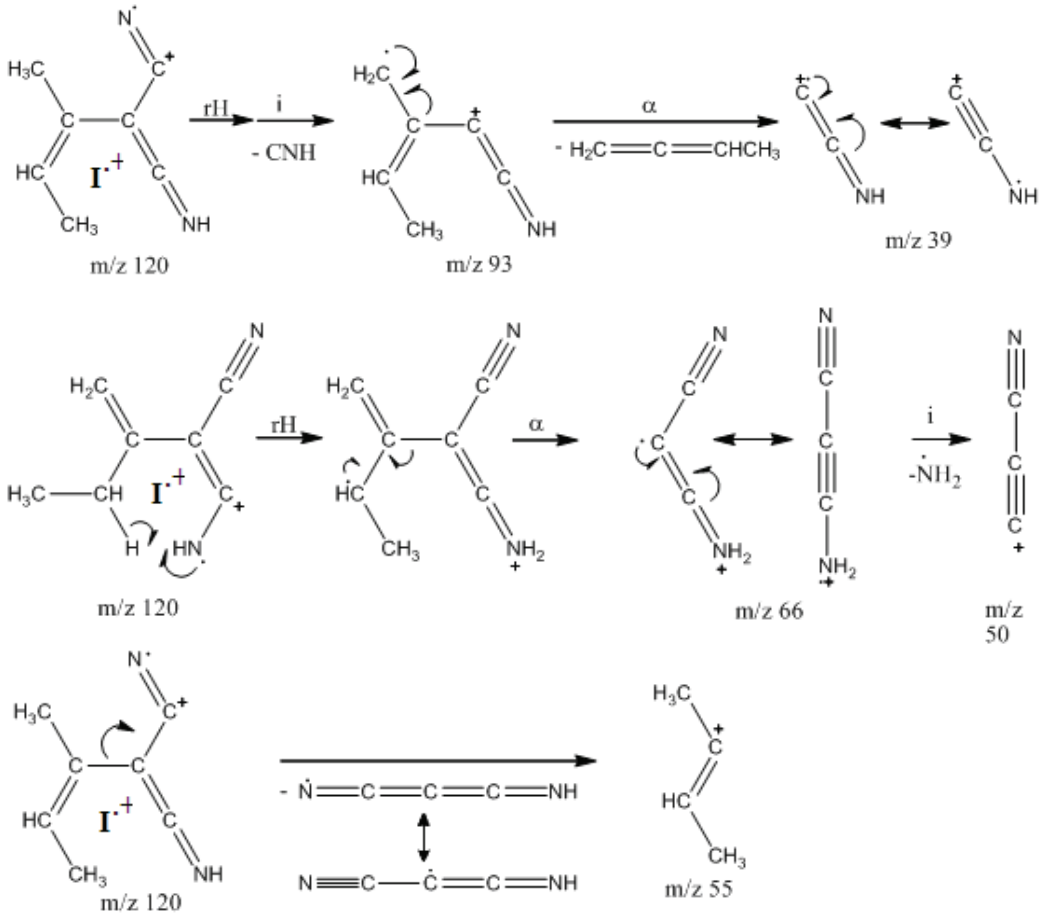
Scheme 3(a).



Scheme 3(b).



Scheme 4.



Scheme 5.

(Scheme 6). In Scheme 6(a) initial ionization of the CN triple bond is proposed prior to hydrogen rearrangement and simple α-ruptures and inductive cleavage fragmentation mechanisms; analogously initial ionization occurs in the OH oxygen of the carboxylic group in Scheme 6(b), in the carbonyl oxygen of the same group in Scheme 6(c), in the C=C double bond in Scheme 6(d). Scheme 6(e) shows fragmentations that might take place from the ketenimine tautomers and can also be

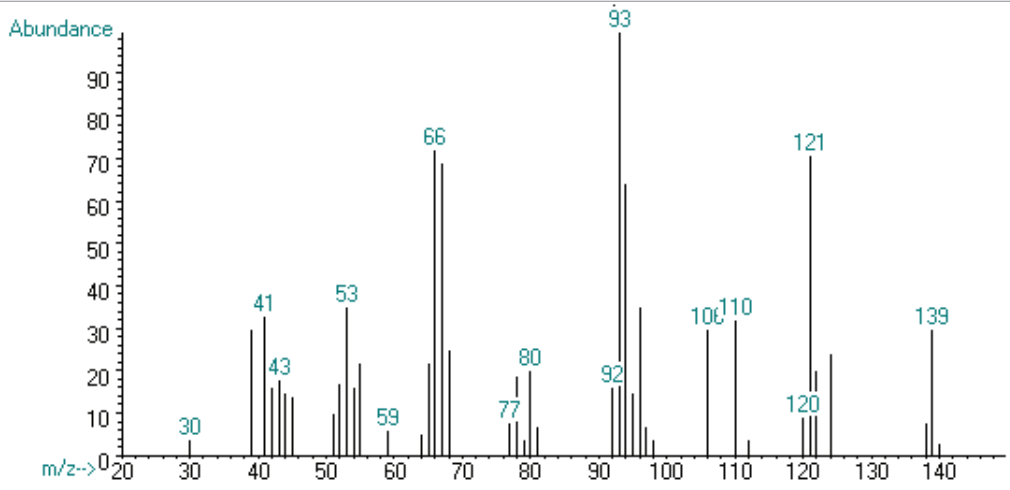
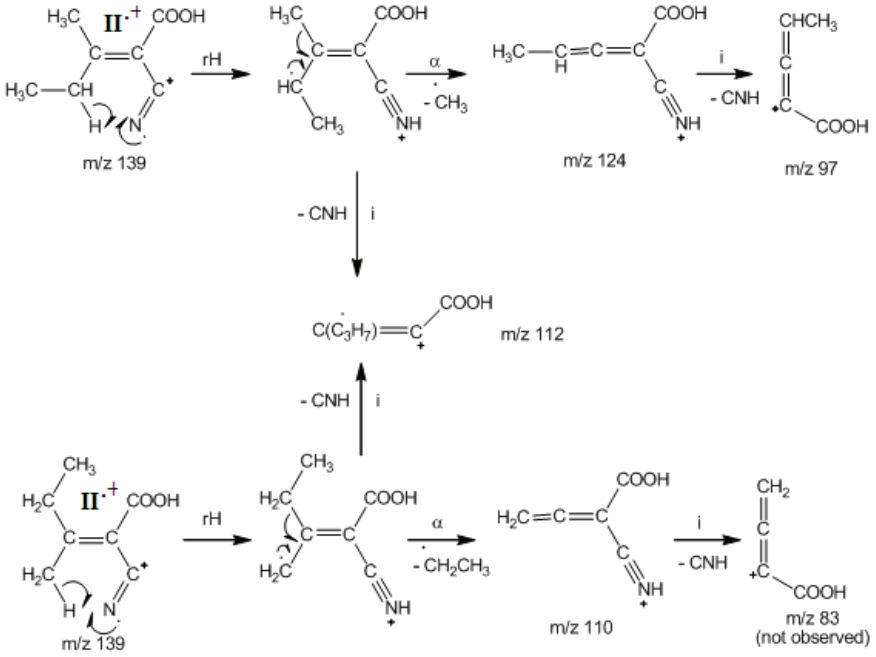
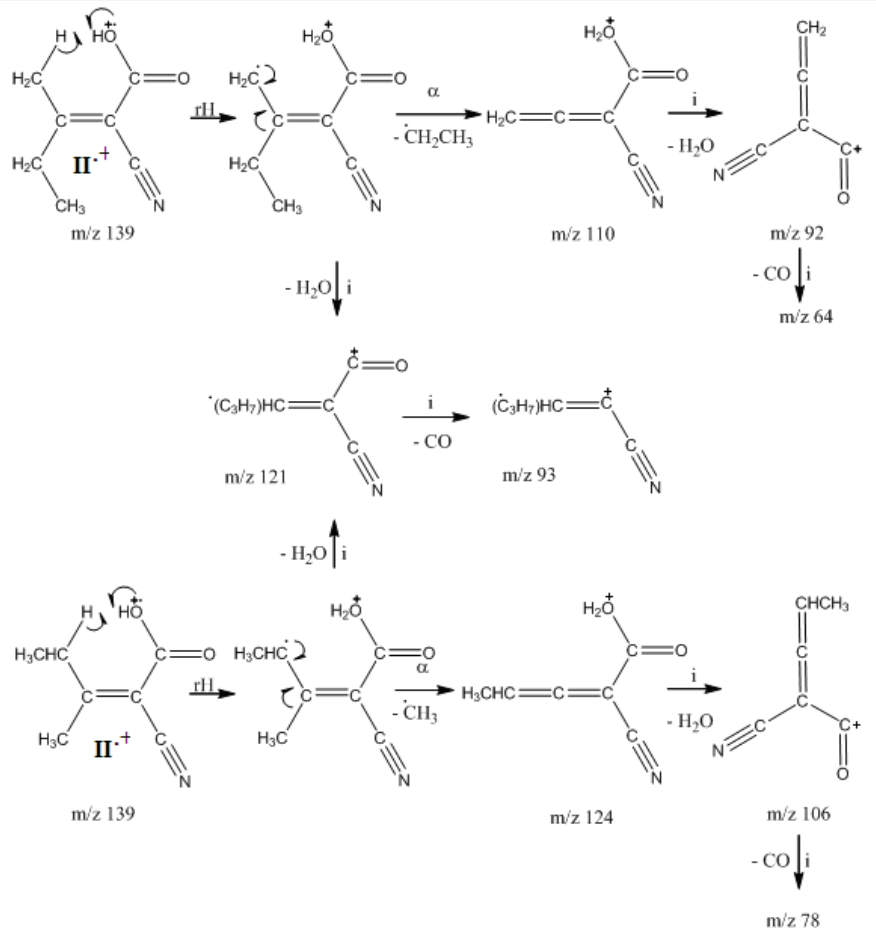


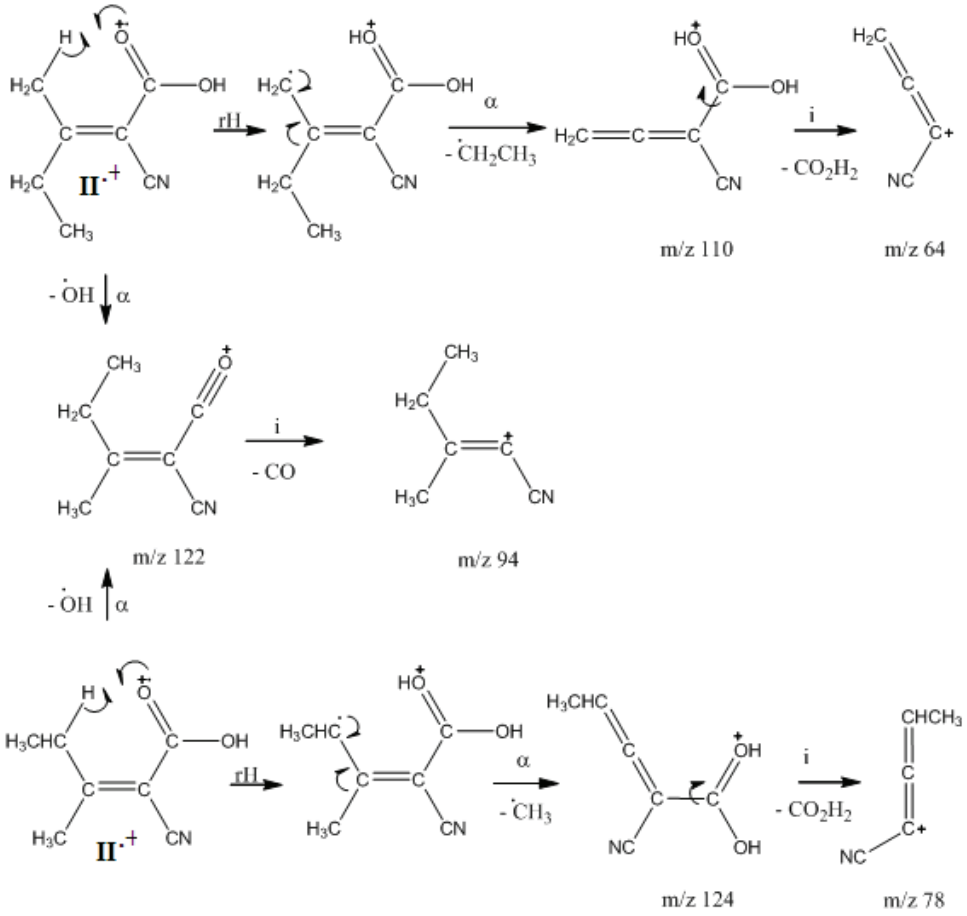
Figure 2. Mass spectrum of 2-cyano-3-methylpentan-2-oic acid (II) at 70 eV.



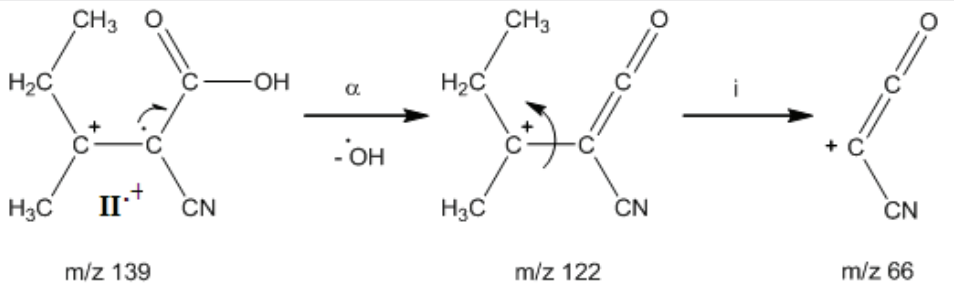
Scheme 6(a).



Scheme 6(b).



Scheme 6(c).



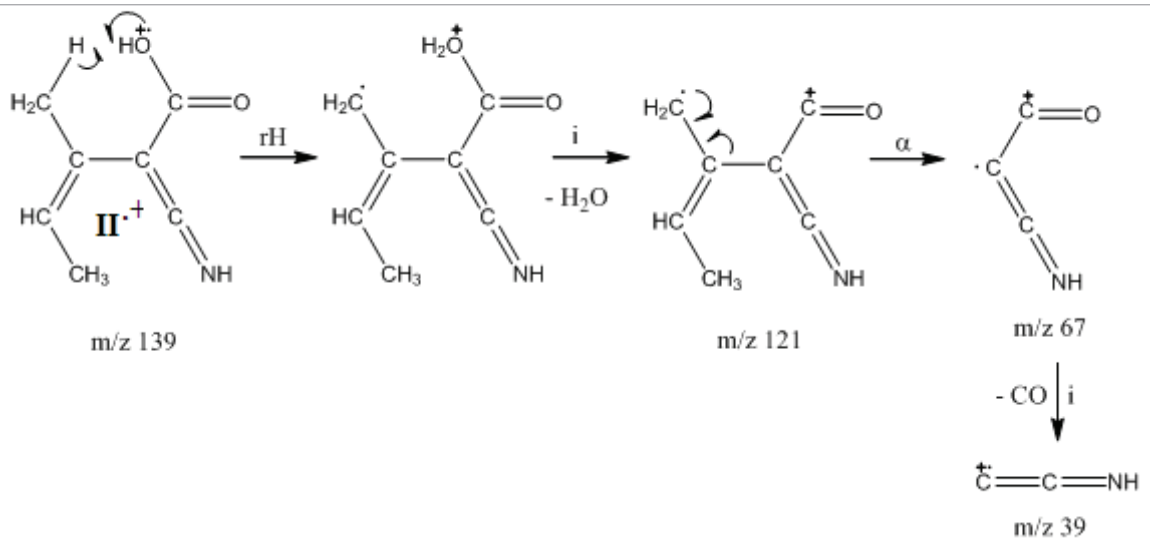
Scheme 6(d).

explained by the nitrile forms (with the exception of the ion at *m/z* 55 that seems to be explained as coming exclusively from the ketenimine tautomer).

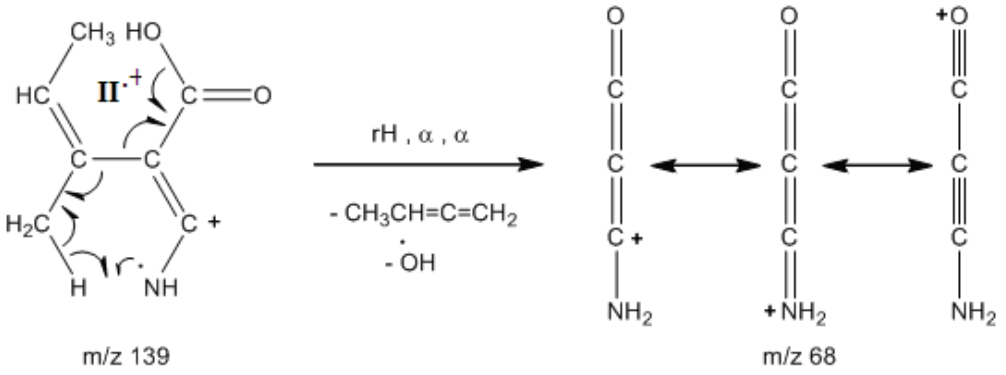
The peaks at *m/z* 39, *m/z* 55 and *m/z* 68 would be assignable to the ketenimine form [Scheme 6(e) and Scheme 7]. The ion at *m/z* 67 can also be assigned to the nitrile tautomer but with a different structure ($OC–CH–CN^{\bullet+}$). Scheme 7(a) starts with hydrogen rearrangement in the OH oxygen of the carboxyl group while Scheme 7(b) does so with hydrogen rearrangement in the CNH nitrogen of the ketenimine.

The ions at *m/z* 112 $(M–CNH)^{+\bullet}$, *m/z* 106 $(M–CH_3–H_2O)^+$, *m/z* 97, *m/z* 92 $(M–CH_2CH_3–H_2O)^+$, *m/z* 78, *m/z* 66, and *m/z* 64 can be justified from the nitrile form [Schemes 6(a)–d)]. A relative estimation of the tautomers occurrence could be the ratios *m/z* 39 to *m/z* 97 and *m/z* 68 to *m/z* 97.

The mass spectrum of 4,4-dicyano-3-methyl-3-butenoic methyl ester (**III**) at 70 eV is shown in Figure 3. Peaks at *m/z* 149 $(M–CH_3)^+$, *m/z* 138 $(M–CN)^+$, *m/z* 137 $(M–CNH)^{+\bullet}$, *m/z* 133 $(M–OCH_3)^+$ are observed. The fragment ions at *m/z* 133, *m/z* 132, *m/z* 106, *m/z* 105, *m/z* 104, *m/z* 59 and *m/z* 31,



Scheme 7(a).



Scheme 7(b).

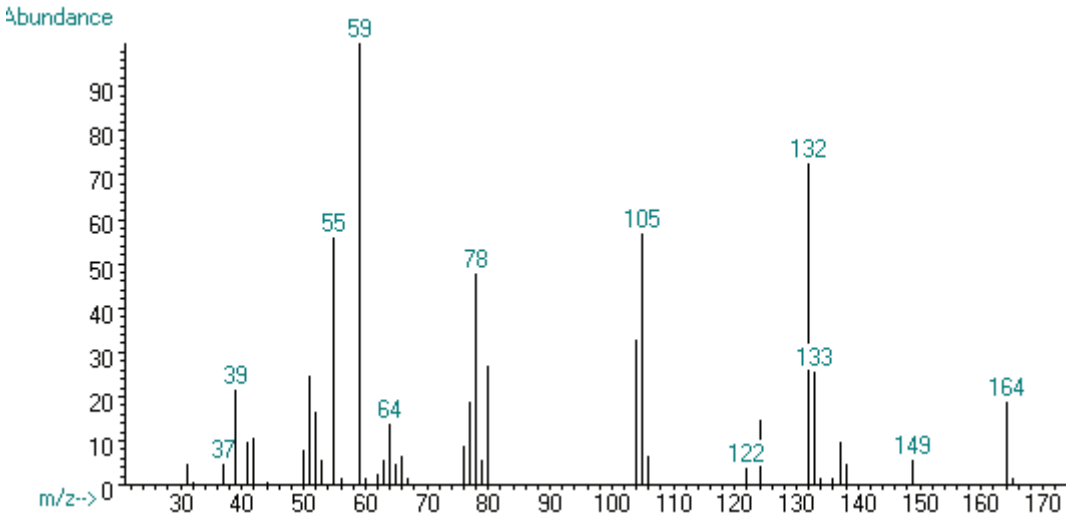
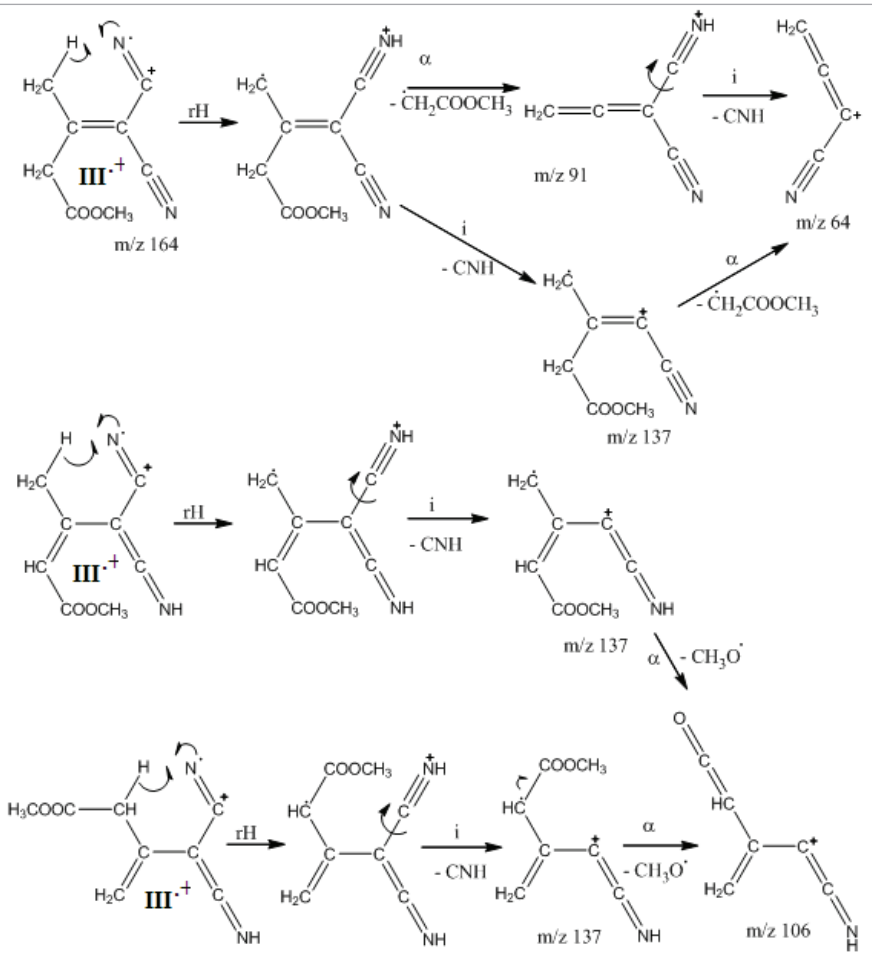
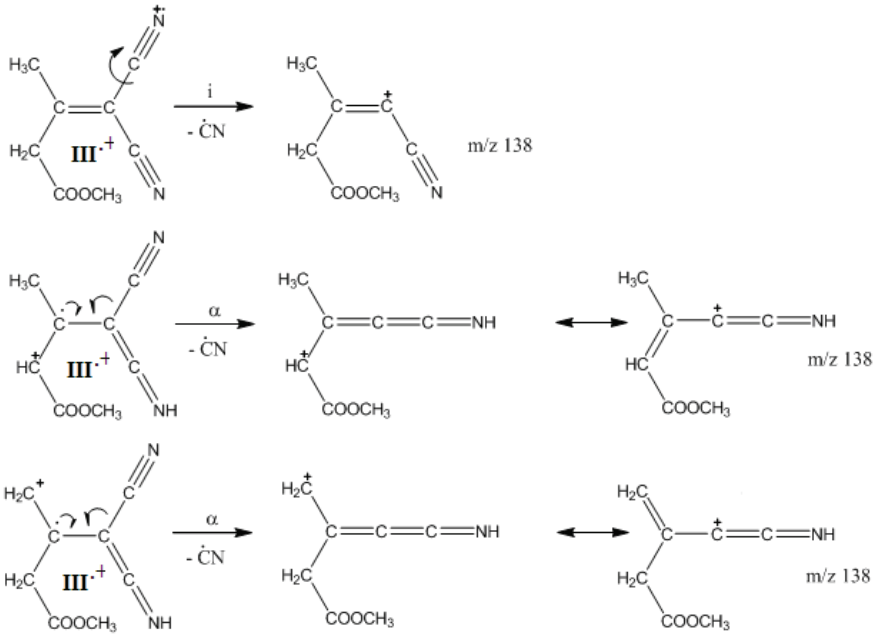


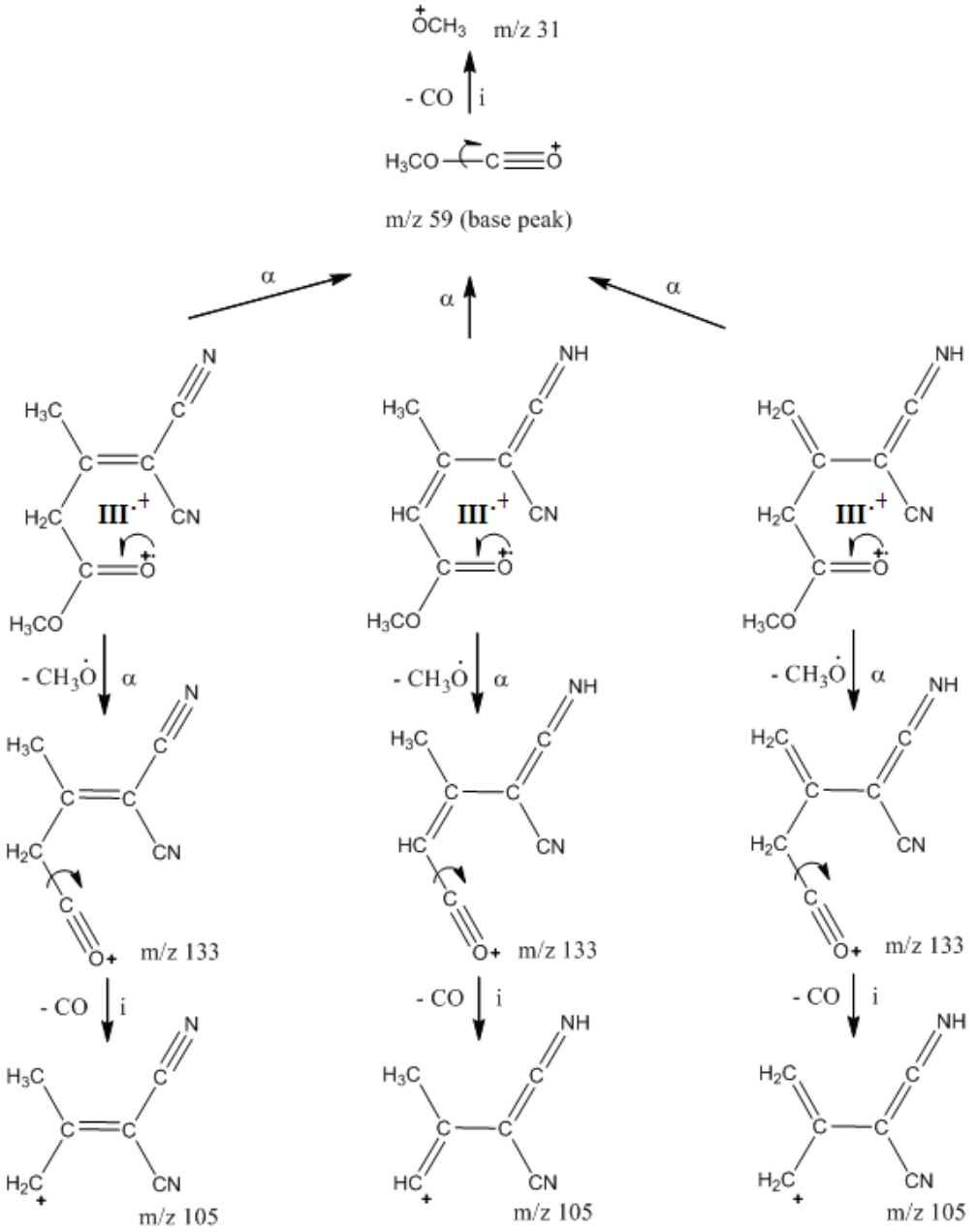
Figure 3. Mass spectrum of 4,4-dicyano-3-methyl-3-butenoic methyl ester (III) at 70 eV.



Scheme 8(a).



Scheme 8(b).



Scheme 8(c).

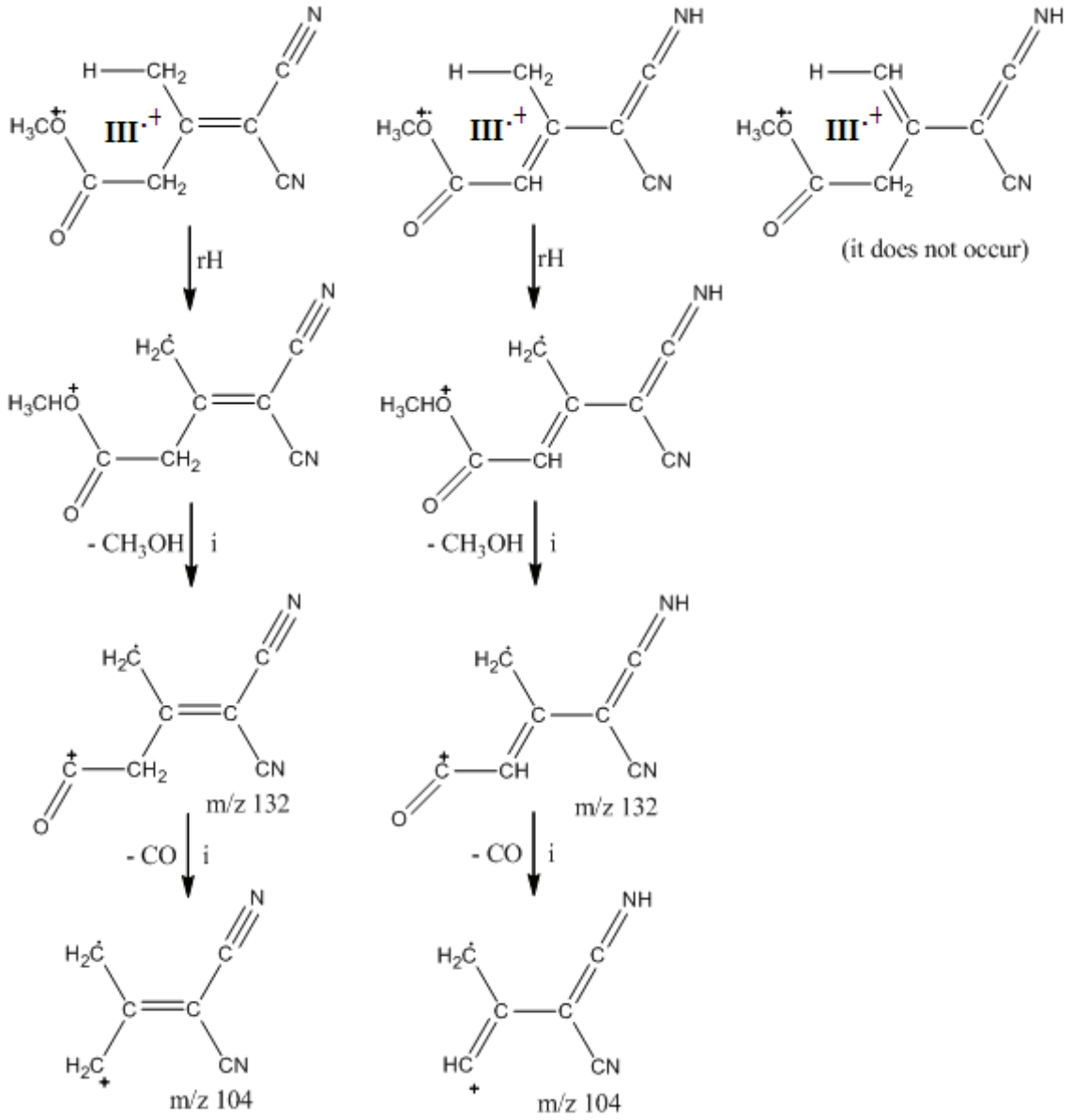
are reasonable from both tautomeric forms, according to Schemes 8(a)–(d).

Scheme 8(a) show fragmentations initiated by hydrogen rearrangement to the nitrogen after ionization of the CN triple bond. Scheme 8(b) depicts different fragmentation pathways for the formation of the ion at *m/z* 138 from both tautomers (CN loss). Scheme 8(c) explains fragmentations initiated by hydrogen rearrangement to the carbonyl oxygen of the ester moiety while Scheme 8(d) does it by hydrogen rearrangement to the other oxygen atom.

As observed before, fragment ions with cumulative double bonds can also be described by structures that exhibit charge migration. The ion at *m/z* 104 with the ketenimine structure would fragment to the ion at *m/z* 39 by α-rupture.

The ions at *m/z* 66, *m/z* 50 and *m/z* 39 can be justified only through the ketenimine form (Scheme 9) involving rearrangements to the nitrile nitrogen or ketenimine nitrogen as shown. In all these cases, stability of the ions is the driving force for the corresponding fragmentation.

The fragment ion at *m/z* 122 can be explained from the nitrile form (Scheme 10). The depicted pathway offers a likely fragmentation mechanism and its stability is better explained taking into consideration the charge migration (not drawn).



Scheme 8(d).

A relative estimation of the tautomers occurrence could be the ratios *m/z* 39 to *m/z* 122 and *m/z* 66 to *m/z* 122. The proposed fragmentation pathways in the mass spectra of nitriles **I**, **II** and **III** were confirmed by MS/MS experiments in an ion trap mass spectrometric detector. Table 1 summarizes this data.

Table 2 indicates the relative abundances for selected ion fragments which were assigned to specific structures, nitrile and ketenimine, at different injection port temperatures and electron energies. Negligible effects were found for different ion source temperatures (at 230°C and 185°C, data not reported).

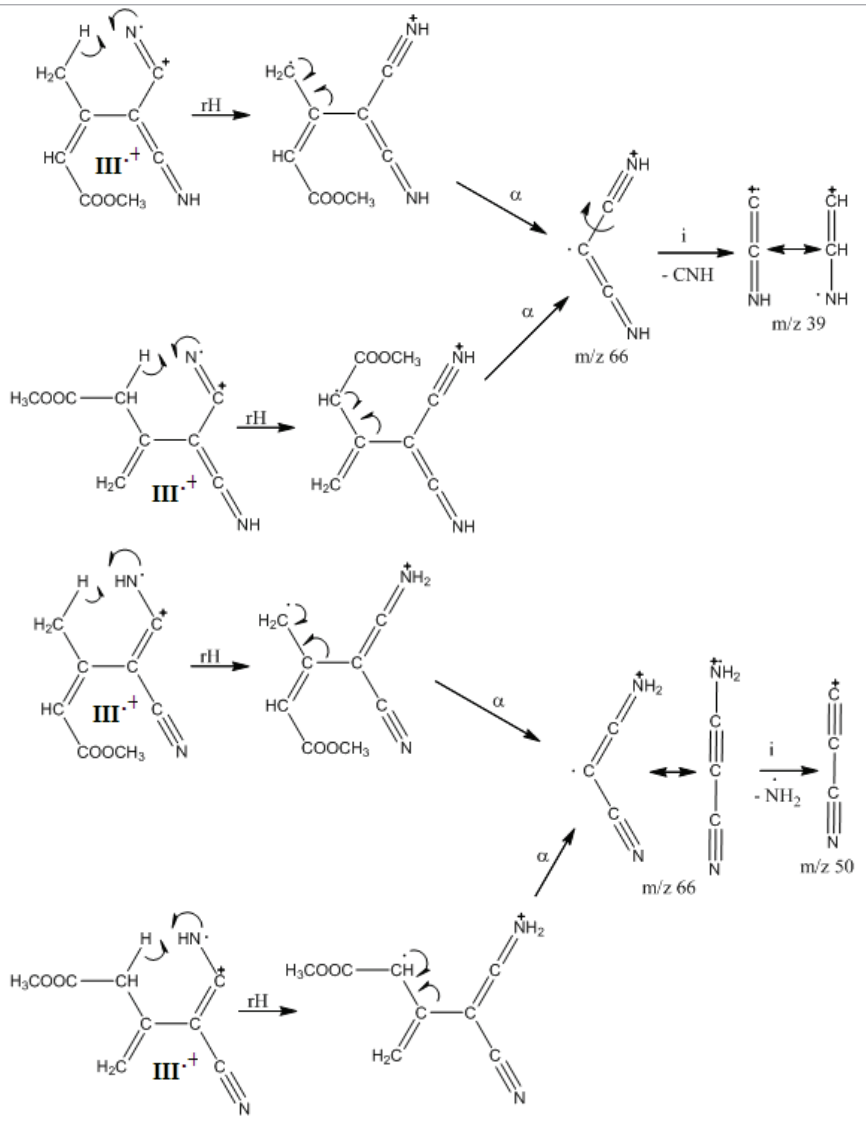
The values measured are in agreement with the occurrence of an endothermic process as expected for the equilibrium nitrile-ketenimine.

The calculated slopes from Figures 4–6 can be used directly to determine the enthalpy changes [Equation (1)]. The decreasing order observed from **I** to **II** and **III** could be rationalized by substituent effects on both tautomers.

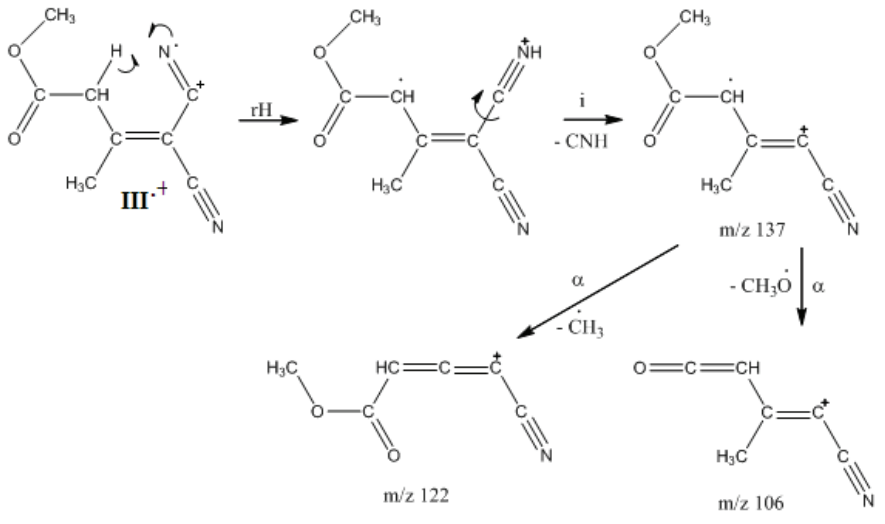
$$\text{Ln } K = \ln \frac{[\text{ketenimine}]}{[\text{nitrile}]} = \ln \frac{[\text{f ketenimine}]}{\text{f nitrile}} = -\frac{\Delta H}{RT} + C \quad (1)$$

where [f ketenimine] and [f nitrile] are the abundance of the fragments corresponding to the ketenimine and nitrile forms, assuming that the concentration ratios are proportional to the ion fragment abundance ratios.

The correlation between the heats of tautomerization calculated from the slopes of Figures 4–6 and those determined by



Scheme 9.



Scheme 10.

Table 1. MS/MS data for the selected nitriles.

Compound	Precursor ions (*m/z*)	Relevant product ions (*m/z*)
I	119 105 93 66	92 78 78, 39 50
II	124 121 110 93	106, 97, 78 93, 67, 39 92, 64 39
III	137 133 132 66	122, 106, 64 105 104, 39 50, 39

Table 2. Mass spectral data of nitriles at different sample introduction system temperatures and electron energies.[a]

Compound	70 eV			50 eV			30 eV		
	T_1 (300°C)	T_2 (275°C)	T_3 (250°C)	T_1 (300°C)	T_2 (275°C)	T_3 (250°C)	T_1 (300°C)	T_2 (275°C)	T_3 (250°C)
I *m/z* 39 (ketenimine) *m/z* 50 (ketenimine) *m/z* 78 (nitrile)	33.4 16.2 43.4	26.4 17.6 95.6	15.3 7.6 117.7	20.4 5.2 12.9	15.3 3.0 21.1	10.5 2.3 34.9	10.2 8.1 22.7	8.4 9.1 49.7	5.1 4.2 9.7
II *m/z* 39 (ketenimine) *m/z* 68 (ketenimine) *m/z* 97 (nitrile)	68.9 28.9 7.7	60.1 24.2 14.3	53.2 23.5 25.0	37.1 30.0 9.1	30.4 21.3 13.1	26.2 20.1 25.2	31.4 25.9 8.3	23.4 19.4 12.5	17.2 14.3 18.3
III *m/z* 39 (ketenimine) *m/z* 66 (ketenimine) *m/z* 122 (nitrile)	22.0 6.7 4.2	15.4 4.0 5.0	10.2 3.0 7.0	20.1 7.0 4.1	16.4 6.4 6.5	10.2 3.7 7.5	10.4 7.1 4.0	7.4 5.0 5.4	5.6 3.8 7.3

[a]Relative abundances are reported as (ion abundance × 1000/total ion abundance) with 5% error. Independent duplicate determinations were carried out.

quantum chemical calculations are very good (see next section) and constitutes strong support to the experimental findings.

Quantum chemical calculations

In a first step, geometry optimization of several nitrile and ketenimine tautomers were calculated at the B3LYP method with the modest 6-31G* basis sets. The most stable form for all the studied systems correspond to the nitrile tautomer. For the studied species, tautomerization can be originated in either the $-CH_3$ or the $-CH_2$ groups attached to the C=C bond. Both alternatives were considered in the calculations and in all the species considered here the lower energy form in the ketenimine tautomer resulted from the proton migration between the $-CH_2-$ and C≡N groups.

Moreover, several conformations were calculated for each nitrile and ketenimine forms. For the acid derivative, the possibility of configurational isomerism arises, with the (*E*) form being slightly preferred over the (*Z*) structure. A synperiplanar conformation of the C=O and C=C double bonds, as well as for the C=O and O–H bonds in the carboxylic group, is adopted in the most stable conformer of both ketenimine and nitrile tautomers of the acid compound.

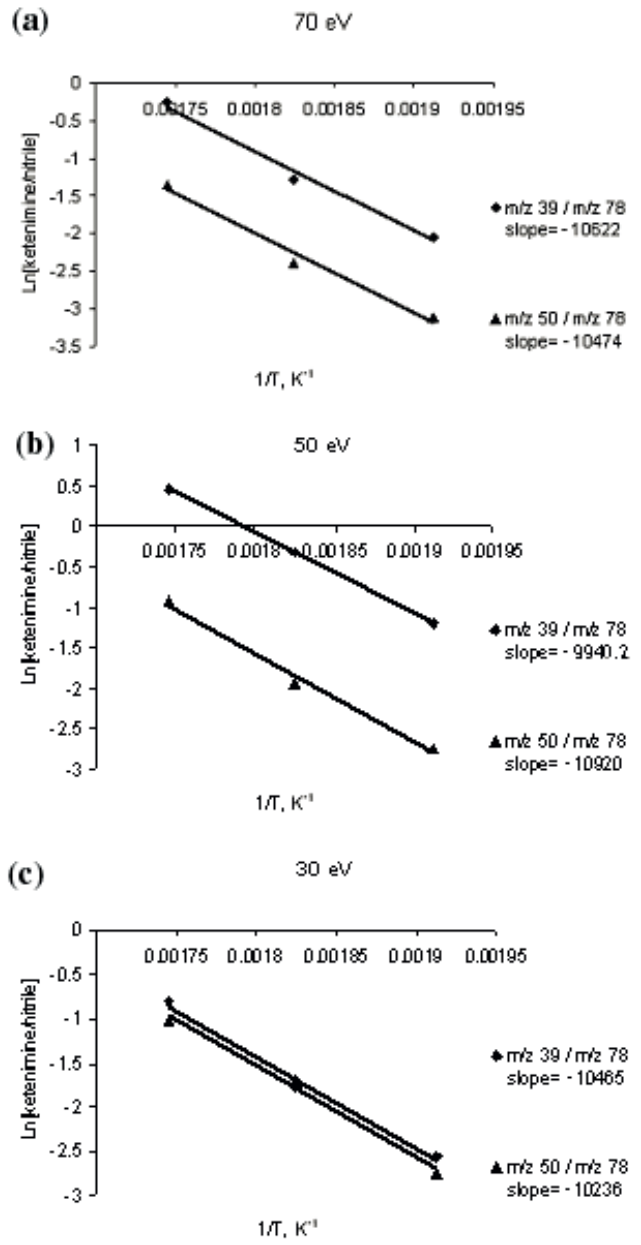


Figure 4. Effects of the sample introduction system temperature and the electron beam energy on ion abundance ratios for 2-*sec*-butylidenmalononitrile (I).

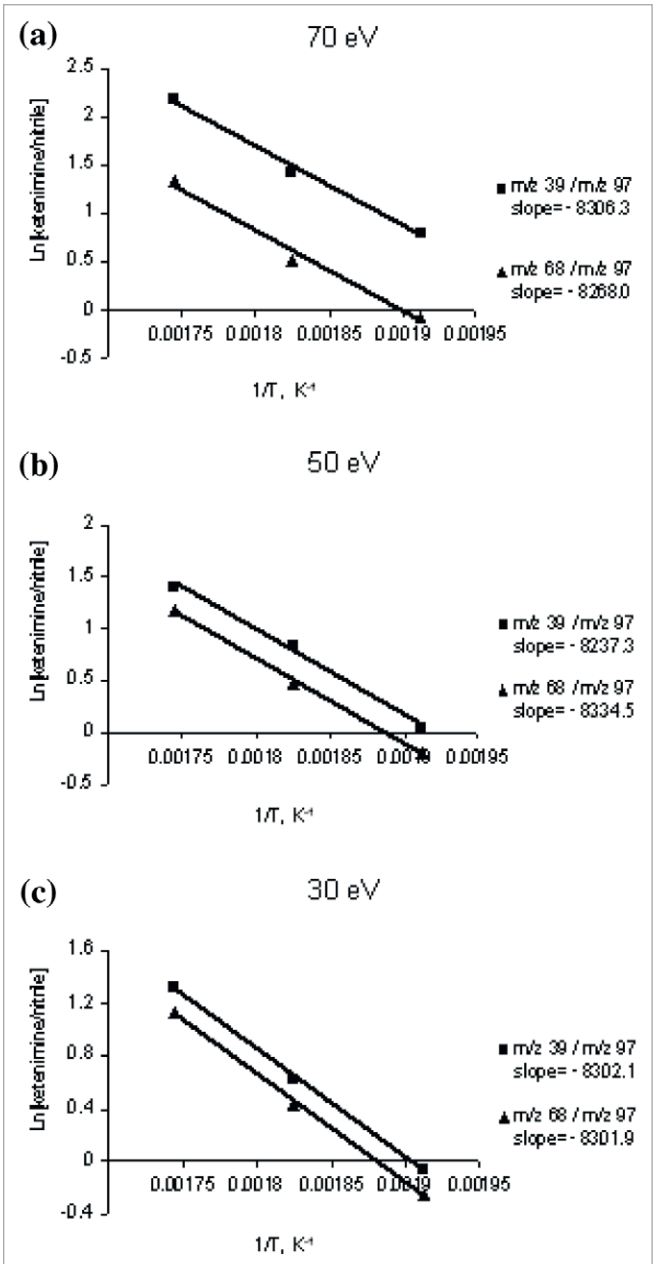


Figure 5. Effects of the sample introduction system temperature and the electron beam energy on ion abundance ratios for 2-cyano-3-methylpentan-2-oic acid (II).

For the ester species, a mutual syn conformation between the C=O double bond and the O–C simple bond was found as the most stable form, in accordance with previous results reported for related methoxycarbonyl species.[34]

In a second step, the geometries of the minima were fully optimized, including frequency calculations, with the B3LYP method using 6-31G* and the more extended 6-311++G** basis sets.[35]

Calculated relative energies (corrected for zero point energy, ΔE^{o}) and gas-phase tautomerization enthalpies ($\Delta H = H_{ketenimine} - H_{nitrile}$) show that the nitrile form is definitively favored. The use of a split-valence triple-zeta basis set with the inclusion of diffuse and polarization functions leads to slightly lower differences in both energy and enthalpy of tautomerization. Regarding the experimental results obtained by mass spectrometry, it is interesting to observe the consistency of the calculations with the indicated fragmentation pathways. After applying the van't Hoff equation [Equation (1)] to the slopes of Figures 4–6, the values for the experimental heats of tautomerization are in very good agreement with the theoretical ones (Table 3).

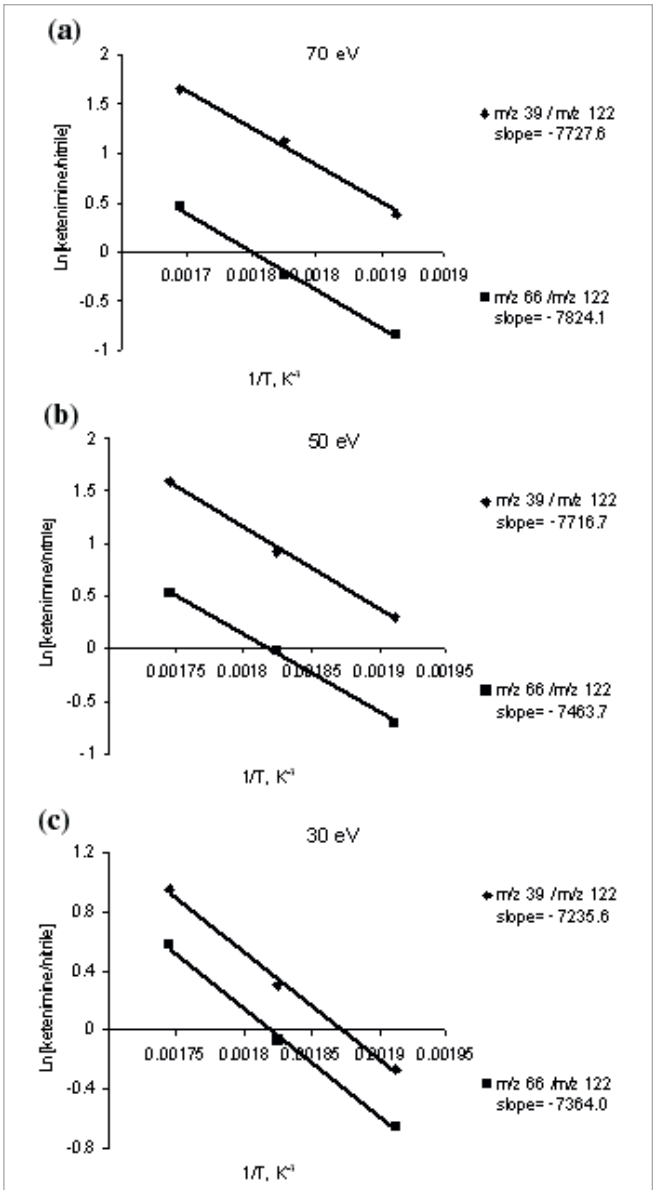


Figure 6. Effects of the sample introduction system temperature and the electron beam energy on ion abundance ratios for 4,4-dicyano-3-methyl-3-butenoic methyl ester (III).

Conclusions

Mass spectrometry is not only a useful tool for the prediction of the feasibility of tautomerization for the compound families that have been considered in this and previous investigations[9–23] but it also provides experimental results for the determination of equilibrium data for rapid reactions, provided that there is evidence that these transformations do not occur or are insignificant after ionization. The reported evidence found by mass spectrometry with regard to the occurrence of the nitrile–ketenimine tautomerism has been supported through theoretical calculations. The value of mass spectrometry as a tool to predict the occurrence of tautomerism has been demonstrated.

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Table 3. Correlation between experimental and theoretical values for the enthalpy change of the nitrile–ketenimine tautomeric equilibrium.

Compound	Average slopes from figures	Experimental ΔH (kJ mol^{-1})	Calculated ΔH^a (kJ mol^{-1})
I	10334.8 ± 334.9	86.4 ± 2.8	84.0
II	8291.7 ± 346.5	69.4 ± 2.9	68.5
III	7711.7 ± 263.4	64.4 ± 2.2	63.1

[a] Computed at the B3LYP/6-311++G** level of approximation.

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