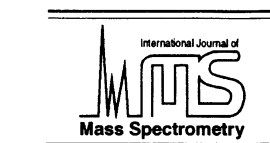




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# Catalyzed keto-enol tautomerism of ionized acetone: a Fourier transform ion cyclotron resonance mass spectrometry study of proton transport isomerization

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## Abstract

The unimolecular isomerization of  $\text{CH}_3\text{COCH}_3^+$  **1** into its more stable enol counterpart  $\text{CH}_3\text{C}(\text{OH})\text{CH}_2^+$  **2** is known not to occur, as a significant energy barrier separates these ions. However, it is shown in this work that this isomerization can be catalyzed within a 1 : 1 ion-neutral complex. For instance, a Fourier transform ion cyclotron resonance mass spectrometry study shows that one, and only one, molecule of isobutyronitrile catalyzes the isomerization of **1** into **2**. The rather low efficiency of the reaction (12%), as well as the strong isotope effect observed when  $\text{CD}_3\text{COCD}_3^+$  is used as the reactant ion, suggest that the catalyzed isomerization implicates a substantial intermediate energy barrier. This was confirmed by ab initio calculations that allow us to propose an isomerization mechanism in agreement with this experiment. The efficiency of different catalysts was studied. To be efficient, the catalyst must be basic enough to abstract a proton from the methyl group of ionized acetone but not too basic to give back this proton to oxygen. In other words, the proton affinity (PA) of an efficient catalyst must lie, in a first approximation, between the PA of the radical  $\text{CH}_3\text{COCH}_2$  at the carbon site ( $\text{PA}_\text{C}$ ) and its PA at the oxygen site ( $\text{PA}_\text{O}$ ), which have been determined to be, respectively, 185.5 and 195.0 kcal mol<sup>-1</sup>. Most of the neutral compounds studied follow this PA rule. The inefficiency of alcohols in the catalytic process, although their PAs lie in the right area, is discussed. (Int J Mass Spectrom 210/211 (2001) 429–446) © 2001 Elsevier Science B.V.

**Keywords:** Catalyzed keto-enol tautomerism; gas-phase proton transport; isomerization kinetics; proton affinity rule; FT-ICR mass spectrometry

## 1. Introduction

We are pleased to dedicate this article to our colleague and friend Nico M. M. Nibbering for his outstanding contributions to gas phase ion chemistry

[1] and his pioneering work in the use of Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR) to study ion–molecule reactions, ion structures, and thermodynamics [2]. One of Nico's numerous interests in this field is weakly bonded complexes, such as dimer radical cations [3] or solvated species [4], and their intramolecular reactivity, such as water-assisted proton mobility in peptides [5].

Within an ion-neutral complex in the gas phase, the

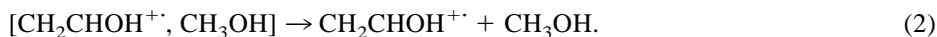
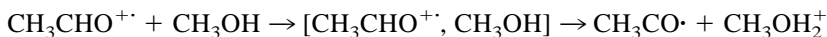
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Dedicated to Professor Nico Nibbering on the occasion of his retirement.

catalyzed isomerization of the ion by the neutral moiety is a rather common phenomenon [6,7]. Such isomerizations by “H<sup>+</sup> transport” [6] can occur by 1,2 [8–14] [Eq. (1)], 1,3 [15–23], or 1,4 [24] proton shifts. In contrast, the 1,2 and 1,3-H transfers are generally not observed in metastable radical cations as a consequence of high-energy barriers for such unimolecular isomerizations [25].



Two main experimental methods are generally used to study such solvent-assisted isomerizations. The first one involves the use of a high-pressure ionization source (chemical ionization [CI] conditions) to let the ions interact with the putative catalyst—the structure of the isomerized ions being analyzed by mass spectrometry (MS)/MS-CID (collision-induced dissociation) experiments [8,19,20]. The second method involves the direct study of the ion–catalyst reactions within the cell of an FT-ICR spectrometer [8,21–23]. The structure of the isomerized ions can be studied either by CID or by selective ion–molecule reactions.

It is worth noting that of the two methods, only FT-ICR experiments give an unambiguous answer about the number of molecules involved in the catalytic process. For instance, protonated formaldehyde exchanges its oxygen atom with H<sub>2</sub><sup>18</sup>O in the high-pressure ion source of a mass spectrometer, whereas such an exchange does not occur in the FT-ICR cell where the ion reacts with only one molecule of water [15c]. In contrast, under the same FT-ICR conditions, the solvated ion [<sup>+</sup>CH<sub>2</sub>OH, H<sub>2</sub>O] exchanges both oxygen atoms with H<sub>2</sub><sup>18</sup>O [15c]



Ionized acetone is a better model to measure the rate constant for catalyzed tautomerization because, for this radical cation, the competing reactions with the neutral reactant have a relative efficiency that is often comparable to that of the isomerization reaction.

Keto-enol tautomerization is a well-known process in solution [26]. In contrast, in the gas phase, unimolecular keto-enol isomerization of ketone or aldehyde radical cations does not occur spontaneously, the keto radical cation and its enol counterpart being separated by high-energy energy barriers [27]. However, conversion of carbonyl ions into their more stable enolic counterparts [28] can be catalyzed by appropriate neutral molecules, as shown by the behavior of cations such as H<sub>3</sub>C-O-C(O)CH<sub>2</sub>CO<sup>+</sup> [17], or of radical cations, such as ionized cyclohexa 2,4-dienone [16], acetaldehyde [22], acetone [20], acetophenone [21], acetamide [23], or methyl acetoacetate [19].

To get more information about the role of the solvent, one needs to study two aspects of the behavior of solvated keto radical cations. The first goal is to determine which catalysts are efficient in the keto-enol conversion in relation with their functional groups and their proton affinity (PA). The second goal is to determine how many molecules of solvent are necessary to catalyze the isomerization.

The simplest model for keto-enol isomerization is acetaldehyde. We have shown that methanol catalyzes a 1,3-H transfer that converts ionized acetaldehyde into the more stable enol counterpart [Eq. (2)] [17,18,22]. A detailed study of this model [22] indicates that the rate constant for isomerization is rather low and competes with fast protonation of methanol. This low catalytic effect in the 1,3-H transport can be usefully compared with the great efficiency observed for the known catalyzed 1,2-H transports [8–12].

Trikoupis et al. [20] have shown that, in the CI ion source of a mass spectrometer, benzonitrile converts ionized acetone into its enol isomer. However, the method used does not allow an exact knowledge of how many molecules of catalyst are required for the

catalysis to take place. Nor does it lead to a quantitative evaluation of the rate constant and of the yield of the process.

In this work, the isomerization of  $\text{CH}_3\text{COCH}_3^+$  **1** into its enol counterpart  $\text{CH}_3\text{C}(\text{OH})\text{CH}_2^+$  **2** is studied by the FT-ICR technique. For this purpose, the bimolecular reactivity of **1** was investigated by use of a number of neutral molecules with various functional groups within a wide PA range. The focus of this article being the keto-enol tautomerism **1**  $\rightarrow$  **2**, the other reactions observed only briefly are reported. Evidence for isomerization is presented, and quantitative results, derived from the analysis of reaction kinetics, are discussed in the light of ab initio calculations.

## 2. Experimental

### 2.1. General

Experiments were performed with a Bruker CMS-47X FT-ICR mass spectrometer (Fällanden, Switzerland) [29] equipped with an external ion source [30] and an infinity cell [31]. The background pressure was  $<10^{-9}$  mbar.

The neutral reactants were introduced into the cell through a leak valve at a pressure of  $1 \times 10^{-8}$  to  $4 \times 10^{-8}$  mbar (depending on the experiment) and then diluted with argon to give a total pressure of  $2 \times 10^{-7}$  mbar. Where appropriate, the neutral reactant was introduced by means of a solenoid pulsed valve.

The ionization gauge (Bayard-Alpert type) was calibrated by rate measurements of the reaction  $\text{CH}_4^+ + \text{CH}_4$  ( $k = 1.14 \times 10^{-9} \text{ cm}^3 \text{ s}^{-1}$ ) [32] and by exothermic proton transfer from  $\text{CH}_2\text{OH}^+$  to acetone or diethyl ether (assumed to occur at collision rate). The relative values of the sensitivities  $S$  for the gauge response towards these three compounds agree with the literature values [33]. The pressure for other compounds was determined using the sensitivities either listed by Bartmess and Georgiadis [33] or calculated using the empirical formula giving  $S$  from the polarizability [33]

$$S = 0.36\alpha + 0.30,$$

where the polarizability  $\alpha$  (in  $\text{\AA}^3$ ), when not available, was calculated according to K. J. Miller [34]. Within experimental errors, we found that deuterated compounds exhibit for  $S$  the same value that to the undeuterated ones.

Ion–molecule reactions were examined after isolation and thermalization of the reactant ions formed in the external ion source. After transfer into the cell (trapping voltage 1 V), the ion of interest was first isolated by on-resonance radio frequency (rf) ejection of all unwanted ions. After a 1.5-s delay (usually sufficient to thermalize the ions by successive collisions with argon), the isolation procedure was repeated by the use of low-voltage single rf pulses (“soft shots”;  $18 \text{ V}_{p-p}$ , duration of 3 ms per pulse) at the resonance frequencies of the product ions formed during the relaxation time. The exact isotopic composition of all ions was checked by high-resolution measurements.

Ions were generated in the external source by electron ionization (EI) (25–35 eV). Protonated formaldehyde was produced by fragmentation of ionized ethanol. Ion **2** was obtained by a McLafferty rearrangement of ionized 2-hexanone.  $\text{CD}_3\text{C}(\text{OH})\text{CH}_2^+$  was generated by EI fragmentation of 1- $\text{CD}_3$  cyclobutanol prepared by the appropriate Grignard reaction on cyclobutanone. 1,1,1- $d_3$  acetone was prepared from acetoacetic acid by thermal decarboxylation of  $\text{CH}_3\text{COCD}_2\text{COOD}$ .

Hexadeuterated acetone and other labeled and unlabeled products were commercially purchased (Sigma-Aldrich, St. Quentin, France, and Eurisotop, Saclay, France) and used as received.

### 2.2. Kinetic measurements

The rate constants were determined by the method detailed below and, dividing by the number density of the neutral reactant, are expressed in  $\text{cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ . The efficiencies of the reactions are given as the ratio, expressed in percentage, of the experimental values of the various rate constants (see section 3.3) to the collision rate constant  $k_{\text{coll}}$  calculated according to

the trajectory variational method of Su and Chesnavich [35]; for example,  $E = 100 \times k_{\text{exp}}/k_{\text{coll}}$ .

In some cases, the isomerization rate constant  $k_{\text{isom}}$  (see section 3.3) was determined by performing, at variable reaction times, the reaction of the remaining  $m/z$  58 ions with pulsed propene (see section 3). Following the chosen reaction time,  $m/z$  58 ions were reselected by on-resonance “soft” ejection of all other ions, and then propene was pulsed into the cell at a peak pressure of about  $3 \times 10^6$  mbar, followed by a 1-s delay for reaction and pumping out. This procedure was convenient for a complete consumption of the  $m/z$  58 ions, regardless of their structure. The IGOR Pro 3.1 package (Wavemetrics Inc., Lake Oswego, OR, USA, 1996) was used for the curve-fitting procedures.

### 2.3. Calculations

Calculations were performed using density functional theory with the GAUSSIAN 98 program package [36] to determine the relative energies and the geometries of the key structures on the potential energy profile. The geometries were optimized at the B3LYP/6-31G9(d) level of theory [37]. Diagonalization of the computed Hessian was performed to confirm that the structures were minima or transition states on the potential energy surface. Zero point energies and thermal enthalpies at 298.15 K were computed at this level of theory, and a single point calculation was further performed at the B3LYP/6-311 + G(3df,2p) level of theory.

## 3. Methodology

### 3.1. Evidence for the catalyzed isomerization $1 \rightarrow 2$ : reaction with propene

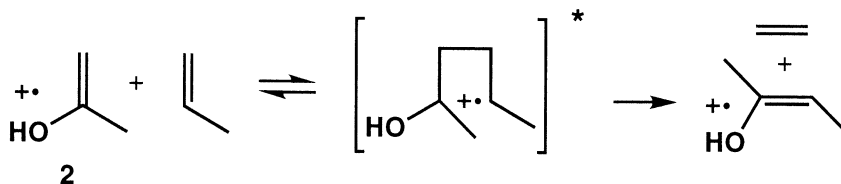
To study the isomerization process and, therefore, to clearly distinguish between structures **1** and **2**, we

used their reactions with propene. Ion **1** ( $m/z$  58) reacts with propene only by H• abstraction to yield protonated acetone ( $m/z$  59) (Fig. 1a). In contrast, ion **2** reacts, besides H• abstraction (20%), by methyl loss (60%,  $m/z$  85) and by loss of ethylene from the collision complex (20%,  $m/z$  72) corresponding to the formation of the  $\text{CH}_3\text{C}(\text{OH})\text{CHCH}_3^+$  enol radical cation (Fig. 1b). This latter reaction, which occurs in several steps, can be formally written as a cycloaddition-cycloreversion process (Scheme 1) [38]. Therefore, the spectrum **I** (Fig. 1a) is obtained when ion **1**, generated in the external ion source, reacts with propene (pulsed into the cell up to  $3 \times 10^{-6}$  mbar, pump-down time 1s). Enol ion **2**, in the same conditions, gives the spectrum **II** (Fig. 1b). However, if **1** is allowed to undergo sufficient thermal energy collisions with isobutyronitrile, the resulting reselected  $m/z$  58 ions react with propene as shown in spectrum **III** (Fig. 1c), which is very similar to spectrum **II**. This clearly demonstrates that isobutyronitrile converts **1** into **2**. This method also affords a tool to evaluate the extent of isomerization, and it was systematically used to complement the analysis of the kinetic results.

### 3.2. Reactions of the enol **2**

As isomerization process leads to an isobaric ion, a kinetic approach of the system requires the knowledge of the reactivity of the ionized enol **2** with the neutral reactants listed in Table 1. In all cases, the logarithmic plot of the relative intensity of  $m/z$  58 versus time was found to be linear and was used to determine the rate constants  $k_c$  listed in Table 1. The results for propene, used for keto/enol differentiation, are also reported.

It was found that as long as the PA of the neutral partner is in the low range ( $<193$  kcal mol<sup>-1</sup>), the



Scheme 1.

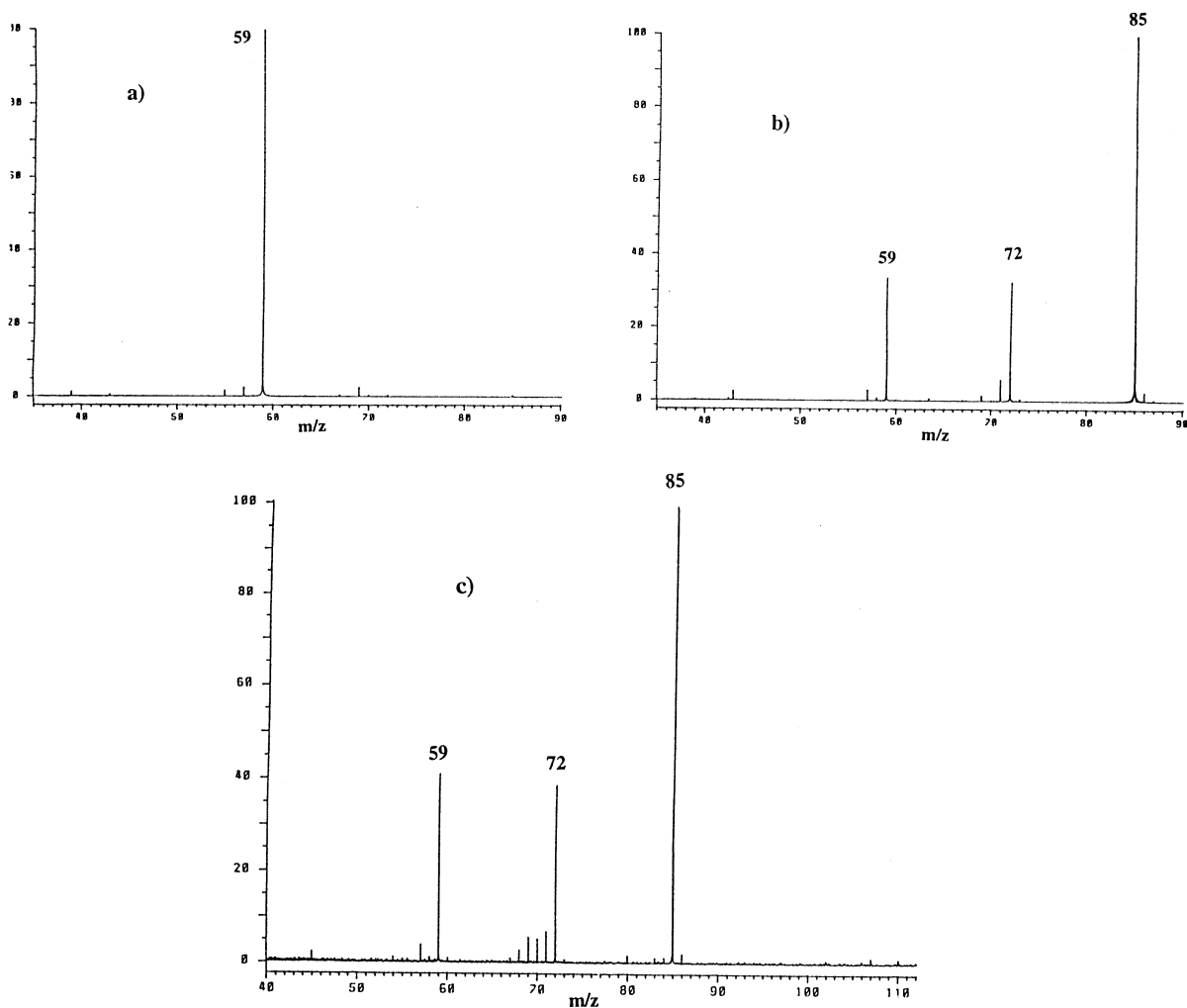


Fig. 1 Reactions with propene of acetone radical cation **1** and its enol isomer **2**. (a) Reaction of ionized acetone **1**; (b) reaction of the enol  $\text{CH}_2\text{C}(\text{OH})\text{CH}_3$  **1**; (c) reaction of the remaining  $m/z$  58 ions from acetone, after a 30 s reaction with isobutyronitrile (pressure  $10^{-8}$  mbar). Propene was pulsed into the cell at a peak pressure of  $3 \times 10^{-6}$  mbar, followed by a 1 s pumping delay before detecting ions.

reactions of **2** are generally slower than those of the acetone radical cation, and slow direct association is often observed (Table 1). For higher PAs, the reaction rate increases and proton transfer becomes the dominant reaction. It is worth noting that **2** reacts rather rapidly with alcohols and dimethyl ether by H· abstraction.

The rate constants of proton transfer were further used to determine experimentally, by the thermokinetic method [39], the O-proton affinity of the  $\cdot\text{CH}_2\text{COCH}_3$  radical, which was found to be  $194.3 \text{ kcal mol}^{-1}$  [40].

### 3.3. Analysis of the kinetic results

Kinetics results for the reactions of the acetone radical cation **1** ( $m/z$  58) were analyzed, as usual, on the basis of a bimolecular first-order analysis. For a majority of compounds whose PAs fall into the range of  $186\text{--}197 \text{ kcal mol}^{-1}$ , the logarithmic plot versus time of the relative intensity of  $m/z$  58 is not linear, indicating that (at least) two structures are involved in the reaction. The characteristic reaction with propene mentioned above shows that, in these cases, the ionized enol **2**, which is virtually absent from the  $m/z$

Table 1  
Reactions of the enol radical cation **2**.

Neutral	PA <sup>a</sup> (kcal mol <sup>-1</sup> )	$k_{\text{coll}}$ ( $\times 10^{-10}$ ) <sup>b</sup>	$k_{\text{e}}$ (eff. %) <sup>c</sup> ( $\times 10^{-10}$ )	$k_{\text{eto}}/k_{\text{enol}}$ <sup>d</sup>	Reactions <sup>e</sup>
Propene	179.6	12.7	2.8 (22)	2.9	CH <sub>3</sub> loss (60%); CA/CR (20%); H abstraction (20%)
Methanol	180.3	20.3	0.2 (1)	20	H abstraction (100%)
Ethanol	185.6	19.4	2.8 (15)	3	H abstraction (100%)
Acetonitrile	186.2	37.3	0.015 (0.04)	450	Association (100%)
Acetic acid	187.3	18.5	0.068 (0.4)	41	(C, O <sub>2</sub> , H <sub>2</sub> ) loss (55%); H abstraction (30%); assoc. (15%)
Acrylonitrile	187.5	36.7	0.2 (0.5)	40	Losses of H (53%), CH <sub>3</sub> (22%), CO(16%); assoc. (9%)
1-Butanol	188.6	18.9	7.3 (39)	1.5	Loss of (C,H <sub>5</sub> ,O) (73%); H abstraction (27%)
CH <sub>3</sub> OCH <sub>3</sub>	189.3	16.6	2.3 (14)	3.4	H abstraction (100%)
2-propanol	189.5	18.9	6.8 (36)	1.3	H abstraction (100%)
C <sub>2</sub> H <sub>5</sub> CN	189.8	36.2	0.07 (0.2)	130	Association (100%)
HCOOC <sub>2</sub> H <sub>5</sub>	191.1	20.3	0.21 (1)	25	H abstraction (67%); association (33%)
Cyclobutanone	191.8	27.6	1.14 (4)	15	DET (70%); H abstraction (15%); C <sub>3</sub> H <sub>5</sub> O loss (15%)
iPr-CN	192.1	35.0	0.40 (1.1)	30	Association (100%),
Cyclopropylcyanide	193.2	35.2	0.54 (1.5)	25	H <sup>+</sup> transfer (70%); assoc. (26%); H abstraction (4%)
Benzonitrile	194.0	35.1	2.8 (8)	7	H <sup>+</sup> transfer (66%); association (33%)
Acetone	194.1	27.6	5.2 <sup>f</sup> (19)	2.3 <sup>g</sup>	H <sup>+</sup> transfer (100%)
Acetone-d <sub>6</sub>	194	26.9	4.8 (18)	3.5	H <sup>+</sup> transfer (100%)
Methyl acetate	196.4	18.4	10.8 (59)	1	H <sup>+</sup> transfer (100%)
Diethylether-d <sub>10</sub>	198.0	15.5	11.2 (72)	1	H <sup>+</sup> transfer (85%); C <sub>2</sub> D <sub>5</sub> loss (15%)
Ethyl acetate	199.7	19.8	13.8 (70)	1	H <sup>+</sup> transfer (100%)

<sup>a</sup>PA taken from ref. [41].

<sup>b</sup> $k_{\text{coll}}$  in cm<sup>3</sup> molecule<sup>-1</sup> s<sup>-1</sup> ( $\times 10^{-10}$ ) according to Su and Chesnavich [35].

<sup>c</sup> $k_{\text{e}} = k_{\text{exp}}(\text{enol}^+)$  in cm<sup>3</sup> molecule<sup>-1</sup> s<sup>-1</sup> ( $\times 10^{-10}$ ); see Eq. (3). Efficiency (eff) =  $100 \times k_{\text{e}}/k_{\text{coll}^+}$ .

<sup>d</sup>Ratio  $k_{\text{exp}}(\text{acetone}^+)/k_{\text{exp}}(\text{enol}^+)$ .

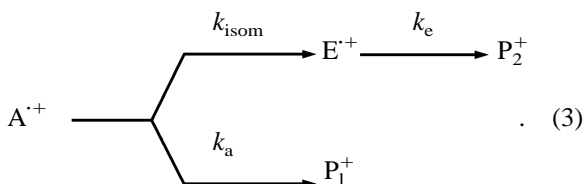
<sup>e</sup>CA/CR = cycloaddition/cycloreversion (see text); assoc. = association; loss = loss from the encounter complex; DET = dissociative electron transfer.

<sup>f</sup>obtained indirectly from acetone<sup>++</sup>/acetone: the direct reaction cannot avoid the initial presence of acetone radical cation because of charge exchange during relaxing time.

<sup>g</sup>Electron transfer (ET) excluded for the reaction of ionized acetone (hidden process).

58 ions at 0 time, becomes part, if not all, of the remaining  $m/z$  58 ions at long reaction times.

The decay of the relative intensity  $I[m/z$  58] was analyzed on the basis of Eq. (3), where  $A^+$  is the acetone radical cation,  $E^+$  the isobaric ionized enol,  $P_1^+$  the product ions of the apparent reaction of  $A^+$  (i.e., of  $m/z$  other than 58), and  $P_2^+$  the product ions resulting from the consecutive reaction of  $E^+$ :



Solving the differential equations derived from Eq. (3) for  $A^+$  and  $E^+$  versus time  $t$ , the relative

abundance of the enol ions is given by Eq. (4), where  $[N]$  is the number density of the neutral reactant:

$$[E^+] = \frac{k_{\text{isom}}}{k_{\text{isom}} + k_{\text{a}} - k_{\text{e}}} [e^{k_{\text{e}}[N]t} - e^{-(k_{\text{a}} + k_{\text{isom}})[N]t}], \quad (4)$$

and the decay of the  $m/z$  58 ions is therefore given by the following expression (Eq. [5]):

$$\begin{aligned}
 I[m/z\ 58] &= [A^+] + [E^+] = \\
 &= \frac{k_{\text{isom}}}{k_{\text{a}} + k_{\text{isom}} - k_{\text{e}}} e^{-k_{\text{e}}[N]t} + \frac{k_{\text{a}} - k_{\text{e}}}{k_{\text{a}} + k_{\text{isom}} - k_{\text{e}}} e^{-(k_{\text{a}} + k_{\text{isom}})[N]t}
 \end{aligned} \quad (5)$$

Fitting the experimental decay of  $m/z$  58 by Eq. (5) leads theoretically to the determination of the three rate constants. However, as the best fit is obtained by varying four parameters simultaneously, several different sets of ( $k_a$ ,  $k_{\text{isom}}$ ,  $k_e$ ) generally can be obtained with comparable confidence factors. Therefore, the fit was performed while fixing  $k_e$  (further reaction of ion **2**) to the experimental value obtained for the corresponding reaction of the ionized enol (Table 1). This procedure is legitimated by using the same conditions on the same equipment for all experiments, so that the relative errors on the various rate constants are minimized (<15%, mostly pressure-reading errors).

It is useful to point out that the ratio  $r = [E^{+}]/[A^{+}]$ , which can be experimentally estimated at any reaction time by the reaction of remaining  $m/z$  58 ions with propene, is given, by Eq. (6). This ratio  $r$ , according to its positive first derivative with respect to time (Eq. [7]) in all cases increases with time, whatever the relative values for the rate constants:

$$r = \frac{[E^{+}]}{[A^{+}]} = \frac{k_{\text{isom}}}{k_a + k_{\text{isom}} - k_e} [e^{(k_a + k_{\text{isom}} - k_e)[N]t} - 1], \quad (6)$$

$$\frac{dr}{dt} = k_{\text{isom}}[N]e^{(k_a + k_{\text{isom}} - k_e)[N]t} \geq 0. \quad (7)$$

It follows that the isomerization test by pulsing propene is best performed when the major part of  $m/z$  58 ions has reacted. Moreover, according to the respective product ions when acetone and enol radical cations react with propene (Fig. 1; Tables 1 and 2), the ratio  $r$  can be evaluated at any reaction time by using Eq. (8):

$$r = (\mathbf{I}[m/z\ 85] + 2 \times \mathbf{I}[m/z\ 72]) / (\mathbf{I}[m/z\ 59] - \mathbf{I}[m/z\ 72]). \quad (8)$$

When the enol radical cation **2** reacts much slower (two orders of magnitude or more) than ionized acetone, which is the case for many neutral reactants with PA lower than 193 kcal mol<sup>-1</sup>, Eq. (5) reduces

to a single exponential (Eq. [9]) from which  $k_a$  and  $k_{\text{isom}}$  are immediately obtained.

$$(k_e = 0) [A^{+}] + [E^{+}] = \frac{k_{\text{isom}}}{k_{\text{exp}}} + \frac{k_a}{k_{\text{exp}}} e^{-k_{\text{exp}}[N]t} \quad (9)$$

$$(k_{\text{exp}} = k_a + k_{\text{isom}}).$$

A borderline case is encountered with compounds of rather high PA, for which the rate constants of enol and ketone radical cations have similar values. In these cases, Eq. (5) is no longer valid because the denominator vanishes. However, when the enol is produced, the ratio  $r$  increases with time according to Eq. (10):

$$(k_e = k_{\text{exp}} = k_a + k_{\text{isom}})$$

$$\frac{dr}{dt} = k_{\text{isom}}[N] \Rightarrow r = \frac{[E^{+}]}{[A^{+}]} = k_{\text{isom}}[N]t. \quad (10)$$

The decay of  $m/z$  58 ions is, therefore, in this case given by Eq. (11):

$$(k_e = k_{\text{exp}} = k_a + k_{\text{isom}})$$

$$[A^{+}] + [E^{+}] = e^{-k_{\text{exp}}[N]t} [1 + k_{\text{isom}}[N]t]. \quad (11)$$

This case was encountered with methyl acetate as catalyst, and the decay of  $m/z$  58 ions was fitted with Eq. (11). Alternatively,  $k_{\text{isom}}$  can be obtained from the ratio  $r$  (measured by pulsing propene, Eq. [8]), which, according to Eq. (10), increases linearly with time.

Another borderline case to be considered arises when  $k_a$  has a value close or equal to  $k_e$ . In this case, Eq. (5) reduces to Eq. (12), a single exponential that does not allow the determination of  $k_{\text{isom}}$ :

$$(k_a = k_e) [A^{+}] + [E^{+}] = e^{-k_e[N]t} \quad (12)$$

In this case, the only way to determine  $k_{\text{isom}}$  is to determine the ratio  $r$  by pulsing propene, this ratio being given by Eq. (13):

$$(k_a = k_e) \frac{dr}{dt} = k_{\text{isom}}[N]e^{k_{\text{isom}}[N]t} \Rightarrow$$

$$r = [E^{+}]/[A^{+}] = e^{k_{\text{isom}}[N]t} - 1. \quad (13)$$

Table 2  
Reactions of acetone radical cation **1**

Neutral (IE, eV) <sup>a</sup>	PA (kcal mol <sup>-1</sup> ) <sup>b</sup>	$k_a (\times 10^{-10})$ (eff. %) <sup>c</sup>	Reactions (other than isomerization) <sup>d</sup>
Propene (9.73)	179.6	8.0 (63)	H abstraction (100)
Formaldehyde (10.87)	170.4	2.0 (8)	H abstraction (100)
Methanol (10.85)	180.3	4.0 (20)	H abstraction (95), acylation (5)
Ethanol (10.47)	185.6	9.0 (46)	Loss of CH <sub>3</sub> from EtOH (PBD) (63), H abstraction (30), H <sup>+</sup> transfer (7)
Acetonitrile (12.19)	186.2	6.6 (18)	Acylation (100)
Acetic acid (10.66)	187.3	2.5 (13)	H abstraction (90), acylation (10)
Acrylonitrile (10.91)	187.5	6.4 (17)	Acylation (100)
1-Butanol (10.06)	188.6	10.8 (57)	H abstraction (68), loss of C <sub>3</sub> H <sub>1</sub> (PBD) (25), loss of (C,O,H <sub>3</sub> ) (7)
CH <sub>3</sub> OCH <sub>3</sub> (10.47)	189.3	7.6 (46)	H abstraction (100)
2-propanol (10.12)	189.5	8.9 (47)	Loss of CH <sub>3</sub> from i-propanol (PBD) (50), H abstraction (50)
C <sub>2</sub> H <sub>5</sub> CN (11.84)	189.8	7.8 (21)	Acylation (100)
HCOOC <sub>2</sub> H <sub>5</sub> (10.61)	191.1	2.9 (14)	H abstraction (86), acylation (14)
Cyclobutanone (9.35)	191.8	16.8 (61)	Electron transfer (100)
iPr-CN (11.3)	192.1	8.6 (25)	Acylation (100)
cyclopropyl-CN (10.25)	193.2	8.2 (23)	Acylation (93), H <sup>+</sup> transfer (4), H abstraction (3)
Benzonitrile (9.62)	194.0	11 (31)	Acylation (50) H <sup>+</sup> transfer (25), ET (25)
Acetone (9.705)	194.1	5.2 (19) <sup>e</sup>	H <sup>+</sup> transfer (60), acylation (30), H abstraction (10)
d6-Acetone (9.7)	194	9.8 (37)	ET(47), H <sup>+</sup> transfer (33), acylation (14), D abstraction (6),
Methyl acetate (10.27)	196.4	5.8 (31)	H <sup>+</sup> transfer (84), H abstraction (8), acylation (8)
C <sub>2</sub> D <sub>5</sub> OC <sub>2</sub> D <sub>5</sub> (9.51)	198.0	13 (84)	ET (50), D abstraction (30), C <sub>2</sub> D <sub>5</sub> loss (13), H <sup>+</sup> transfer (7)
Ethyl acetate (10.01)	199.7	12 (61)	H <sup>+</sup> transfer (97), acylation (3)

<sup>a</sup>IE taken from ref. [42]; underlined numbers correspond to IE lower than IE(acetone).

<sup>b</sup>PA taken from ref. [41].

<sup>c</sup> $k_a$  in cm<sup>3</sup> molecule<sup>-1</sup> s<sup>-1</sup> ( $\times 10^{-10}$ ), efficiencies (eff) are given in percentage of the capture rate constant  $k_{\text{coll}}$  determined according to Su and Chesnavich [35] (see Table 3).

<sup>d</sup>By acylation, it is meant that a net transfer of CH<sub>3</sub>CO<sup>+</sup> is observed by loss of a methyl group from acetone, with no implication for the structure of the product ion. ET=electron transfer. The branching ratios (in percentages) are determined at the beginning of the reaction for products ions other than enol.

<sup>e</sup>ET excluded (hidden process).

Fitting linearly the natural logarithm of  $(r + 1)$  versus time gives  $k_{\text{isom}}[N]$  directly.

The efficiency of the reaction for ionized acetone, expressed in percentages, is derived from the ratio of the experimental rate constant  $k_{\text{exp}} = k_a + k_{\text{isom}}$  over the capture collision rate  $k_{\text{coll}}$ .

## 4. Results and calculations

### 4.1. Reactions of the acetone radical cation **1**

Several kinds of reactions are observed whose relative importance strongly depends on the neutral reactant (Table 2): (i) Electron transfer, observed when the neutral reactant has a lower ionization energy (IE) than acetone; (ii) H<sup>•</sup> abstraction from the neutral; (iii) protonation of the neutral, which, as might be expected, is important only for compounds

possessing a rather high PA; (iv) loss of a radical from the neutral moiety of the encounter complex with formation of a proton-bound dimer (PBD) [11]; (v) loss of a methyl group from the acetone moiety, corresponding at least formally to an acylation of the neutral partner: this will be the subject of a forthcoming paper; and (vi) catalyzed isomerization of **1** into the enol **2**, which is a hidden reaction and, therefore, requires the more detailed investigation reported in this work.

### 4.2. Catalyzed isomerization: kinetic results

The characteristic reaction of ions **1** and **2** with propene proves that a number of molecules, with various functional groups, catalyzes the conversion of ionized acetone **1** into its enol counterpart **2**.

The results for the 21 neutral reactants examined



Table 3

Kinetic results for the catalyzed isomerization of acetone radical cation **1** into its enol isomer **2**

Neutral (IE, eV)	PA (kcal mol <sup>-1</sup> )	$k_{\text{coll}} (\times 10^{10})$	$k_{\text{exp}} (\times 10^{10})$ (eff, %) <sup>a</sup>	$k_{\text{isom}} (\times 10^{10})$	Enolization efficiencies <sup>b</sup>	
					$E_{\text{abs}}$ (% $k_{\text{coll}}$ )	$E_{\text{ref}}$ (% $k_{\text{exp}}$ )
Propene (9.73)	179.6	12.7	8.0 (63)	0	0	0
Formaldehyde (10.87)	170.4	25.4	2.0 (8)	0	0	0
Methanol (10.85)	180.3	20.3	4.0 (20)	<0.06	—	—
Ethanol (10.47)	185.6	19.4	9.0 (46)	<0.06	—	—
Acetonitrile (12.19)	186.2	37.3	6.8 (18)	0.2	0.5	3
Acetic acid (10.66)	187.3	18.5	2.8 (15)	0.3	1.5	10
Acrylonitrile (10.91)	187.5	36.7	8.0 (22)	1.6	4	18
1-Butanol (10.06)	188.6	18.9	10.8 (57)	<0.04	—	—
CH <sub>3</sub> OCH <sub>3</sub> (10.47)	189.3	16.6	7.9 (48)	0.3	2	4
2-propanol (10.12)	189.5	18.9	8.9 (47)	<0.08	—	—
C <sub>2</sub> H <sub>5</sub> CN (11.84)	189.8	36.2	9.5 (26)	1.7	5	19
HCOOC <sub>2</sub> H <sub>5</sub> (10.61)	191.1	20.3	5.2 (25)	2.3	11	44
Cyclobutanone (9.35)	191.8	27.6	17.6 (64)	0.8	3	5
iPr-CN (11.3)	192.1	35.0	12.9 (37)	4.3	12	32
cyclopropyl-CN (10.25)	193.2	35.2	13.7 (39)	5.5	16	41
Benzonitrile (9.62)	194.0	35.1	16.4 (47)	5.4	15	32
Acetone (9.705)	194.1	27.6	12.0 (43)	6.8 <sup>c</sup>	25 <sup>c</sup>	57 <sup>c</sup>
d6-Acetone (9.695)	194	26.9	17 (63)	7.2	27	43
		26.9	11.6 <sup>d</sup> (43)	8 <sup>c,d</sup>	30 <sup>c,d</sup>	69 <sup>c,d</sup>
Methyl acetate (10.27)	196.4	18.4	10.2 (55)	4.4	24	44
				4.1 <sup>e</sup>	22 <sup>e</sup>	41 <sup>e</sup>
C <sub>2</sub> D <sub>5</sub> OC <sub>2</sub> D <sub>5</sub> (9.51)	198.0	15.5	13 (84)	0	0	0
Ethyl acetate (10.01)	199.7	19.8	12 (61)	0	0	0

<sup>a</sup>Rate constants are expressed in cm<sup>3</sup> molecule<sup>-1</sup> s<sup>-1</sup>, efficiencies (eff) are given in percentages of the capture rate constant  $k_{\text{coll}}$  determined according to Su and Chesnavich [35].

<sup>b</sup>Enolisation efficiencies defined respectively as  $E_{\text{abs}} = 100 \times k_{\text{isom}}/k_{\text{coll}}$  and  $E_{\text{rel}} = 100 \times k_{\text{isom}}/k_{\text{exp}}$ .

<sup>c</sup>Cases where  $k_{\text{a}} = k_{\text{e}}$  (see text).  $k_{\text{isom}}$  obtained by pulsing propene,  $k_{\text{exp}} = k_{\text{e}} + k_{\text{isom}}$ .

<sup>d</sup>ET excluded (continuous ejection of  $m/z$  64).

<sup>e</sup> $k_{\text{isom}}$  obtained by pulsing propene (see text).

are reported in Table 3. The reaction of ionized acetone with propene, used for keto/enol differentiation, is included in this table. The absolute efficiencies for enolization ( $E_{\text{abs}} = 100 \times k_{\text{isom}}/k_{\text{coll}}$ ) are reported in the fifth column. The ratio  $E_{\text{rel}} = 100 \times k_{\text{isom}}/k_{\text{exp}}$  is reported in the last column as an indication for the relative effectiveness of the compound for the tautomerization.

#### 4.2.1. Enolization efficiency

As an example, the decay versus time of  $m/z$  58 ions of ionized acetone for the reaction with isobutyronitrile is depicted in Fig. 2 and shows clearly that

the reaction slows down after consumption of about 2/3 of the parent ions. On the basis of Eq. (6), the ratio  $R$  of the relative proportion of ionized enol **2** in the remaining  $m/z$  58 ions can be evaluated with Eq. (14):

$$R = [E^{+}]/([E^{+}] + [A^{+}]) = r/(1+r). \quad (14)$$

The variation of  $R$  with reaction time, as shown Fig. 2, indicates clearly that the ~30% of  $m/z$  58 ions remaining at long reaction time are enol ions **2** ( $R \cong 1$ ), which strengthens the results obtained by pulsing propene and is reported above (section 3.1).

Most of the neutral reactants were found to catalyze the keto-enol conversion as far as their PAs [41]

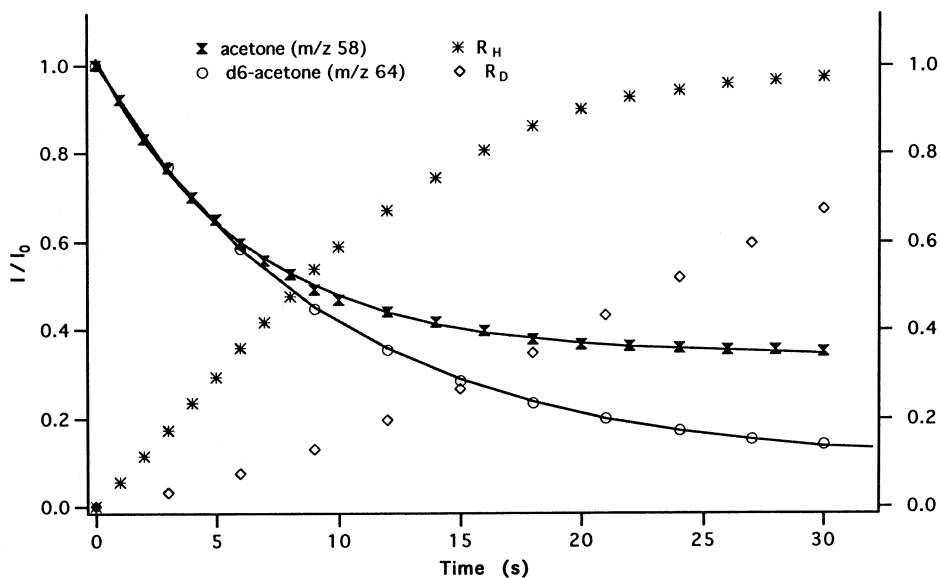


Fig. 2 Kinetics plots of the relative intensities versus time of  $m/z$  58 ions from acetone and of  $m/z$  64 ions from  $d_6$ -acetone for the reaction with isobutyronitrile ( $10^{-8}$  mbar). The ratio  $R$  of the relative proportion of enol **2** in the remaining  $m/z$  58 (respectively,  $m/z$  64) ions (i.e.,  $R = [E^+]/([E^+] + [A^+])$ ) is also represented. Solid lines result from fitting the data with Eq. (9).

belong to the range of 186–197 kcal mol<sup>-1</sup>. The enolization efficiency  $E_{\text{abs}}$  (Table 3) shows, in this PA range, a clear tendency to increase with increasing PA.

However, alcohols were found to be inefficient to promote the tautomerization, even when their PAs fall into the above range. Noteworthy, in these cases, is that the main reaction of ion **1** (H $\cdot$  abstraction) is the same than for ionized enol **2**, with comparable efficiencies (Tables 1 and 3). Therefore, it cannot be excluded that enolization occurs within the reacting complex, but there is no open channel to give the ionized enol **2** as a product ion.

Nitriles and esters were found to be efficient catalysts, even when electron transfer is a competitive reaction channel (e.g., benzonitrile).

For dimethylether and cyclobutanone, the general trend of  $E_{\text{abs}}$  increasing with PA is no longer followed. The low IE of cyclobutanone (9.35 eV) [42] could be responsible for its behavior. In the case of dimethylether,  $E_{\text{abs}}$  is twice as small as for acrylonitrile, notwithstanding the lower PA of the latter. The only other reaction is H abstraction and, similar to the case of alcohols, the ionized enol reacts in the same

way with a rather good efficiency (Table 1). Here again, a hidden isomerization within the reactive complex cannot be discarded.

It is worth noting that proton transfer is the main reaction of both ions **1** and **2** with methyl acetate, with comparable high efficiencies (Tables 1 and 2). Accordingly, the rate constants were obtained by fitting the kinetic results with Eq. (11) and the value derived for  $k_{\text{isom}}$  is in agreement with that obtained by pulsing propene (Eqs. [8], [10]; Fig 3).

For compounds having a PA  $\geq 198$  kcal mol<sup>-1</sup>, no isomerization is observed.

#### 4.2.2. Catalysis by acetone

Acetone itself was found to be a good catalyst to promote keto-enol tautomerization of acetone radical cation (efficiency 25%–30%). However, in this case,  $k_{\text{isom}}$  cannot be directly derived from the decay of the  $m/z$  58 ions because the rate  $k_a$  of the apparent reactions is very close to  $k_c$ , the reaction rate of the enol itself (Tables 1 and 2). It follows that the decay of the  $m/z$  58 ions fits a single exponential and is given by Eq. (12), from which only  $k_e \approx k_a$  can be obtained. The isomerization rate constant  $k_{\text{isom}}$  is thus deter-

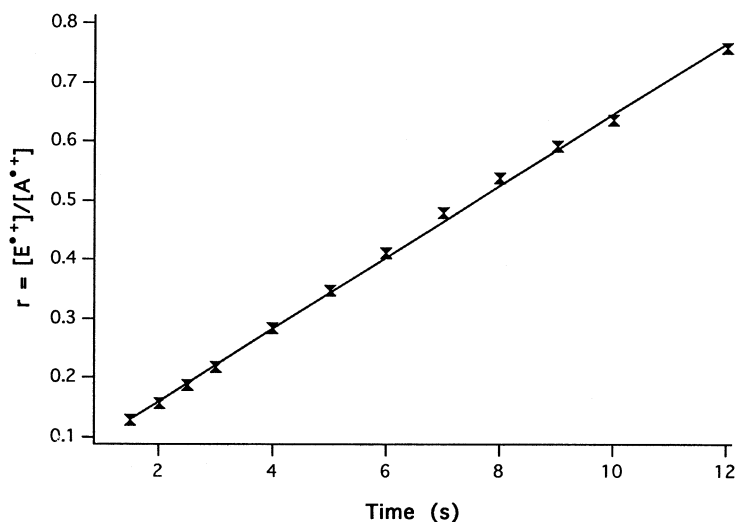


Fig. 3 Plot versus time of the ratio  $r = [E^{\bullet+}]/[A^{\bullet+}]$  obtained by pulsing propene (Eq. [8]) for the reaction of ionized acetone with methyl acetate ( $1.1 \cdot 10^{-8}$  mbar). The line result from a least square linear fit.

mined by pulsing propene at various reaction times on the reselected  $m/z$  58 ions, calculating the ratio  $r = [\text{enol}^{\bullet+}]/[\text{ketone}^{\bullet+}]$  according to Eq. (8), and fitting linearly  $\text{Ln}(r + 1)$  versus time (Eq. [13]; Fig. 4).

It is worth noting that in this experiment, a new kind of hidden reaction occurs, namely, electron transfer from acetone to ionized acetone. This is no

longer the case if acetone- $d_6$  is used as the catalyst, and in this case, Eq. (5) is convenient to fit the kinetic results. Alternatively, this latter experiment was also performed with continuous ejection of the  $m/z$  64 ions resulting from electron transfer, and a result similar to the blank experiment was obtained, estimating  $k_{\text{isom}}$  by pulsing propene (Fig. 4). The consistency of the

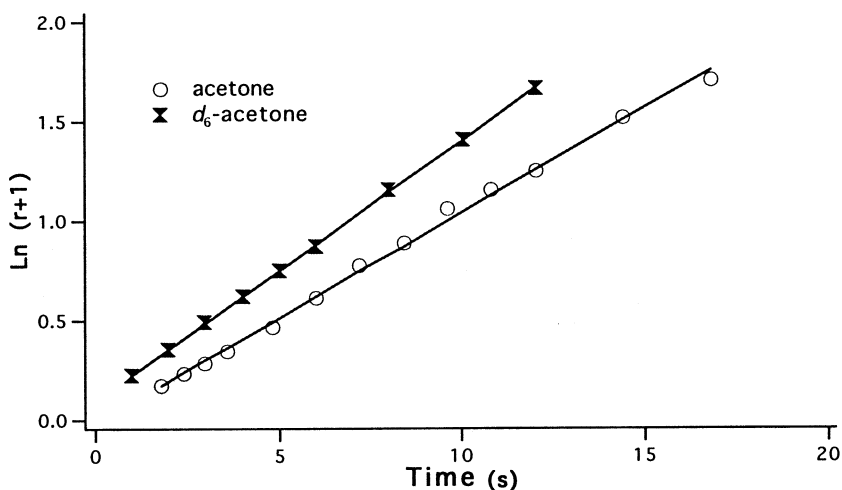


Fig. 4 Plot versus time of the natural logarithm of  $(1 + r)$ , where  $r = [E^{\bullet+}]/[A^{\bullet+}]$  is obtained by pulsing propene (Eq. [8]), for the reaction of ionized acetone ( $m/z$  58), respectively, with acetone (open circles) on one hand and  $d_6$ -acetone (filled symbols) while ejecting continuously  $m/z$  64 ions resulting from ET on the other hand. In these two cases, Eqs. (12) and (13) apply. The pressure of the neutral reactant is  $10^{-8}$  mbar. The lines result from least square linear fits of the data.

Table 4  
Reactions of  $d_6$  acetone radical cation

Neutral (IE, eV)	$k_{\text{coll}}$ ( $\times 10^{-10}$ )	$k_{\text{exp}}^{\text{a}}$ ( $\times 10^{10}$ ) (eff, %)	$k_{\text{isom}}$ ( $\times 10^{10}$ )	Isotope effect $k_{\text{isom}}(\text{H})/k_{\text{isom}}(\text{D})$	Enolization efficiencies		Reactions <sup>b</sup> (other than enolization)
					$E_{\text{abs}}$ (% $k_{\text{coll}}$ )	$E_{\text{rel}}$ (% $k_{\text{exp}}$ )	
HCOOC <sub>2</sub> H <sub>5</sub> (10.61)	19.8	4.5 (23)	1.0	2.3	5.1	22	H abstr. (70), acylation (30)
iPr-CN (11.3)	34.1	8.4 (25)	0.78	5.4	2.3	9	Acylation (100)
	34.3	11.4 (33)	2.2	2.5	6.3	19	Acylation (100)
Benzonitrile (9.62)	34.0	15.3 (45)	2.5	2.1	7.4	16	Acylation (50), D <sup>+</sup> transfer (30), ET (20)
Acetone (9.705)	26.9	14.4 (53)	0.6	5.2	2.3	4	ET (57), H abstr. (21), acylation (15), D <sup>+</sup> transfer (7)
$d_6$ -acetone	26.3	6.3 <sup>c</sup> (24)	1.3	3.5	4.8	20	acylation (50), D <sup>+</sup> transfer (50)
Methyl acetate (10.27)	17.9	9.9 (55)	4.9	1	27	51	D <sup>+</sup> transfer (52), H abstr. (28), acylation (20)

<sup>a</sup>Rate constants are expressed in  $\text{cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ , efficiencies (eff) are given in percentage of the capture rate constant  $k_{\text{coll}}$  determined according to Su and Chesnavich [35].

<sup>b</sup>Acylation = loss of a CD<sub>3</sub> group from the complex. The branching ratios (in percentages) are determined at the beginning of the reaction for products ions other than enol (abstr. = abstraction, ET = electron transfer).

<sup>c</sup>ET excluded (hidden process).

three values obtained, for  $k_{\text{isom}}$  (6.8, 7.2, and  $8 \times 10^{-10} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ ) confirms the high efficiency of acetone in enolizing its own radical cation.

#### 4.2.3. H/D Isotope effect

Among the neutral reactants reported in Table 1, six of them are particularly efficient in catalyzing the keto/enol conversion: ethyl formate, isobutyronitrile, cyclopropylcyanide, benzonitrile, methyl acetate, and acetone itself. For these compounds, the reactions of CD<sub>3</sub>COCD<sub>3</sub><sup>+</sup> were also investigated to determine the deuterium isotope effect in the H transport involved in the enolization process. It was found that, except for methyl acetate, this isotope effect, taken as  $k_{\text{isom}}(\text{H})/k_{\text{isom}}(\text{D})$ , was significant, ranging from 2 to 5 (Table 4).

In an attempt to determine absolute isotope effects, experiments were conducted starting from CD<sub>3</sub>COCH<sub>3</sub>. The ratio of H transport versus D transport could be determined if there were a mean of measuring, in the presence of the parent keto ion, the relative proportions of the respective ionized enol produced; that is CD<sub>3</sub>C(OH)CH<sub>2</sub><sup>+</sup> and CH<sub>3</sub>C(OD)CD<sub>2</sub><sup>+</sup>. Unfortunately, the enol CD<sub>3</sub>C(OH)CH<sub>2</sub><sup>+</sup>, specifically prepared, undergoes many H/D exchanges with pro-

pene before it reacts by methyl or ethylene losses, preventing any specific characterization of the two isomers of interest. We were not able to find a suitable reaction for this purpose.

#### 4.4. Calculations

To get an insight into the possible mechanism of the catalyzed tautomerization, the potential energy profiles have been calculated for the reactions of the [ionized acetone, acetonitrile] and [ionized acetone, isobutyronitrile] systems. These two qualitatively identical profiles are presented in Fig. 5. Four stable complexes, **a**, **b**, **c**, and **d**, were localized, along with the transition state TS<sub>b/d</sub> connecting **b** and **d**, and the geometries of these structures are drawn in Fig. 6. The three complexes **a**, **b**, and **c** are symmetric with respect to the  $O = C \cdots N$  plane, with the nitrile lying in a plane perpendicular to the main plane of acetone for complexes **a** and **b** and in the same plane than that of the acetone moiety for complex **c**.

The relative energies of the possible final states and of the intermediate stable complexes are listed in Table 5.

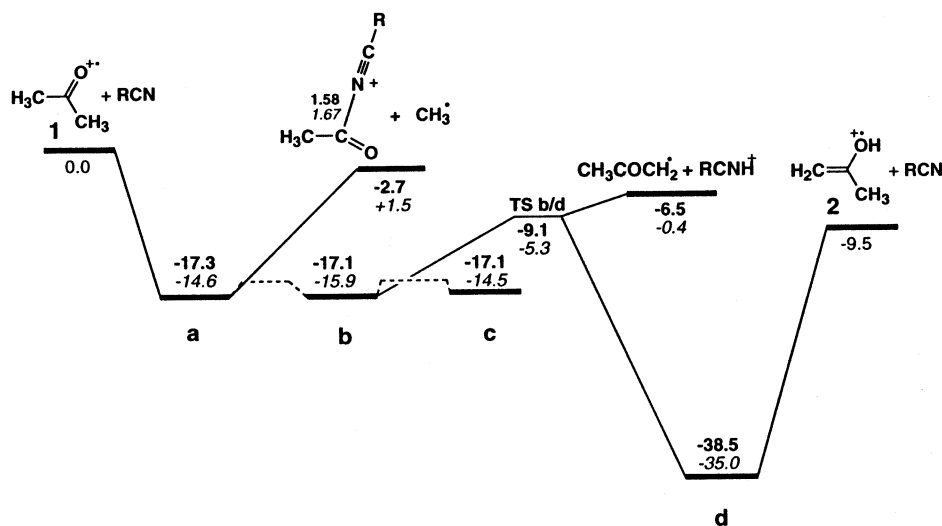


Fig. 5 Potential energy profile for the reactions of ionized acetone with acetonitrile [ $R = \text{CH}_3$ ] and isobutyronitrile [ $R = \text{CH}(\text{CH}_3)_2$ ]. Relative energies are quoted in italic numbers for acetonitrile and in bold numbers for isobutyronitrile. Calculations: B3LYP/6-311+G(3df,2p)//B3LYP/6-31G(d).

## 5. Discussion

The most striking fact is that the isomerization efficiencies are rather low compared with the conversion, by catalyzed 1,2-H transport, of  $\text{CH}_3\text{OH}^+$  into  $\text{CH}_2\text{OH}_2^+$  [8] or with the catalyzed 1,3-H transport in the  $\text{HOCH}_2\text{OH}_2^+$  cation [15c], which have been shown to occur almost at collision rate. For most neutral reactants, the enolization efficiencies vary from 0.5% to 16% in the PA range of 186–194 kcal mole<sup>-1</sup> (Table 3). For instance, when isobutyronitrile is used as catalyst, the isomerization efficiency is only 12%. Moreover, when  $\text{CD}_3\text{COCD}_3^+$  is used as the reactant ion, the efficiency falls down to 2.3% (Table 4), which indicates a strong isotope effect. Similar H/D isotope effects were found with other efficient catalysts (Table 4). These results suggest that the catalyzed isomerization involves a significant energy barrier.

It is also important to note that for these ICR experiments, the low pressures used in all cases discard the intervention of termolecular collisions [43]. Therefore, our results clearly establish that one, and only one, molecule of catalyst is able to effectuate the conversion within a single 1:1 ion-neutral complex.

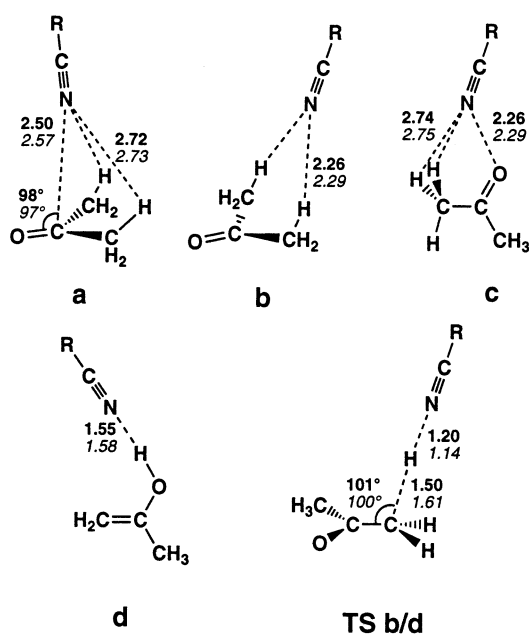


Fig. 6 Geometries calculated for stable complexes **a**, **b**, **c**, and **d**, and for the transition state  $\text{TS}_{b/d}$ . Distances (Å) and angles (degree) are quoted in italic numbers for acetonitrile and in bold numbers for isobutyronitrile. [B3LYP/6-311+G(3df,2p)//B3LYP/6-31G(d)].

Table 5

Relative energies ( $\Delta E$ ), zero-point energies ( $\Delta E + \text{ZPVE}$ ), and relative enthalpies ( $\Delta H_{298.15}^0$ ) of the species presented in Figs. 5 and 6. Values in kcal mol<sup>-1</sup>, relative to the reactants level.

	B3LYP/6-31G(d)	B3LYP/6-311+G(3df,2p)	$\Delta E$ B3LYP/6-311+G(3df,2p)	$\Delta(E+\text{ZPVE})$ B3LYP/6-311+G(3df,2p)	$\Delta H_{298.15}^0$ B3LYP/6-311+G(3df,2p)
CH <sub>3</sub> COCH <sub>3</sub> <sup>+</sup> + CH <sub>3</sub> CN	-325.56621	-325.68369	0.0	0.0	0.0
CH <sub>3</sub> COHCH <sub>2</sub> <sup>+</sup> + CH <sub>3</sub> CN	-325.57747	-325.70025	-10.4	-9.2	-9.5
CH <sub>3</sub> C(O)NCCH <sub>3</sub> <sup>+</sup> + CH <sub>3</sub>	-325.55757	-325.67843	+3.3	+0.2	+1.5
CH <sub>3</sub> COCH <sub>2</sub> + CH <sub>3</sub> CNH <sup>+</sup>	-325.55928	-325.68346	+0.1	-0.4	-0.4
<b>a</b>	-325.59651	-325.71179	-17.6	-14.8	-14.6
<b>b</b>	-325.59553	-325.71091	-17.1	-16.4	-15.9
<b>c</b>	-325.59740	-325.71077	-17.0	-14.3	-14.5
<b>d</b>	-325.62334	-325.74418	-38.0	-35.7	-35.0
TS <sub>b/d</sub>	-325.56934	-325.68865	-3.1	-5.1	-5.3
CH <sub>3</sub> COCH <sub>3</sub> <sup>+</sup> + (CH <sub>3</sub> ) <sub>2</sub> CHCN	-404.19438	-404.33759	0.0	0.0	0.0
CH <sub>3</sub> COHCH <sub>2</sub> <sup>+</sup> + (CH <sub>3</sub> ) <sub>2</sub> CHCN	-404.20564	-404.35415	-10.4	-9.2	-9.5
CH <sub>3</sub> C(O)NCCH(CH <sub>3</sub> ) <sub>2</sub> <sup>+</sup> + CH <sub>3</sub>	-404.19353	-404.33943	-1.2	-4.1	-2.7
CH <sub>3</sub> COCH <sub>2</sub> + (CH <sub>3</sub> ) <sub>2</sub> CHCNH <sup>+</sup>	-404.19768	-404.34719	-6.0	-6.4	-6.5
<b>a</b>	-404.22702	-404.36770	-18.9	-17.8	-17.3
<b>b</b>	-404.22581	-404.36674	-18.3	-17.6	-17.1
<b>c</b>	-404.22899	-404.36768	-18.9	-17.5	-17.1
<b>d</b>	-404.25486	-404.40130	-40.0	-38.7	-38.5
TS <sub>b/d</sub>	-404.20404	-404.34824	-6.7	-9.2	-9.1

### 5.1. Mechanism of isomerization: the nitrile case.

The theoretical results obtained for the reaction of ionized acetone with acetonitrile and isobutyronitrile agree with experimental results. On the one hand, they confirm that the isomerization process is possible with a single molecule of neutral reactant. On the other hand, they reveal the existence of an important energy barrier ( $\sim 10$  kcal mol<sup>-1</sup>; Fig. 5) for the isomerization step on the reaction potential energy profile.

The calculated potential energy profile (Fig. 5) shows that the reaction begins with the approach of the nitrile to ionized acetone, yielding three intermediate complexes, **a**, **b**, and **c** (Figs. 5, 6). In the complex **a**, the nitrile interacts with the positively charged carbon atom of the CO group. In the second complex, **b**, the nitrile interacts with the hydrogens of the two methyl groups of acetone. In the third complex, **c**, the nitrile interacts both with two hydrogens of the methyl group and with the positively charged oxygen of the CO group.

Ions **a**, **b**, and **c** are weakly bound complexes and are formed with almost the same interaction energy ( $\approx 15$  kcal mol<sup>-1</sup> for acetonitrile and 17 kcal mol<sup>-1</sup> for isobutyronitrile). The interconversion between **a**, **b**, and **c** is very easy, as this region of the potential energy surface (PES) is almost flat, preventing the localization of transition states between the three complexes. The interconversion **b**  $\leftrightarrow$  **c** simply involves a rotation of the nitrile moiety around a methyl group and a transfer toward the positively charged oxygen atom.

In the intermediate **b**, the nitrile molecule can catalyze the proton transfer to yield the complex **d** via a linear transition state TS<sub>b/d</sub>, located, respectively, at 5.3 kcal mol<sup>-1</sup> (acetonitrile) and 9.1 kcal mol<sup>-1</sup> (isobutyronitrile) below the energy of the reactants. It was verified by intrinsic reaction coordinate (IRC) calculations [44] that the precursors of TS<sub>b/d</sub> are **b** and **d**. The complex **d**, which corresponds to the enol radical cation **2** H-bonded to a molecule of nitrile (Fig. 6), is strongly stabilized (35 and 38.5 kcal mol<sup>-1</sup>

for acetonitrile and isobutyronitrile, respectively). Dissociation of **d** leads to the final products ( $\text{CH}_3\text{C}(\text{OH})\text{CH}_2^+ + \text{RCN}$ ), an overall exothermic process ( $9.5 \text{ kcal mol}^{-1}$  below the reactants' energy). The other possible cleavage of complex **b**, giving protonated nitrile and the  $\text{CH}_3\text{COCH}_3$  radical, is an energetically less favorable outcome ( $-0.4$  and  $-6.5 \text{ kcal mol}^{-1}$ ), which is not experimentally observed. In fact, the part of the potential energy surface leading to protonated nitrile from complex **b** most probably involves structures similar to  $\text{TS}_{\text{b/d}}$  on the way to this outcome, and formation of complex **d** is at some stage highly favored.

The structure of  $\text{TS}_{\text{b/d}}$  resembles a proton-bound dimer between the nitrile and the radical  $\text{CH}_3\text{COCH}_2$  (Fig. 6), where the proton is closer to the nitrogen atom than to the  $\text{CH}_2$  radical site, so that the rotation of the radical moiety is facilitated. The rate-determining step in the isomerization process is the nitrogen-assisted stretching of a C–H bond of one methyl group of acetone. The weak interaction energy between the nitrile and the radical  $\text{CH}_3\text{COCH}_2$  allows the oxygen atom to approach the binding proton to give the more stable complex **d**. This situation, along with the lower relative energy of  $\text{TS}_{\text{b/d}}$  when the PA of the neutral increases, allows us to predict that isomerization will be even easier, as this PA is higher. However, increasing the PA also lowers the protonation pathway. It is worth noting that this mechanism of isomerization differs from that encountered for  $1,2\text{-H}^+$  transports, where a three-centers intermediate is involved [10,12].

The other reaction channel involves a simple cleavage of the complex **a**, leading to  $\text{RCNC}(\text{O})\text{CH}_3^+$  (loss of a methyl group from acetone), which is slightly endothermic with acetonitrile ( $+1.5 \text{ kcal mol}^{-1}$ ) and energetically allowed with isobutyronitrile ( $-2.7 \text{ kcal mol}^{-1}$ ) but, in both cases, is apparently less favored than the isomerization pathway. Nevertheless, methyl loss is the dominant process observed experimentally in both cases (Tables 2 and 3), being 36 times faster for acetonitrile (albeit with an overall efficiency of 18%) and two times faster for isobutyronitrile. These results can be explained by the fact that the loss of a methyl from complex **a** is a C–C

bond cleavage occurring without energy barrier and is, therefore, more entropically favored.

### 5.2. Isomerization efficiency versus proton affinity: the PA rule

As reported earlier in this article, the enolization of ionized acetone is experimentally observed with catalysts whose PAs belong to the range  $186\text{--}197 \text{ kcal mol}^{-1}$ , and the efficiency of this reaction is generally even better as the PA increases. If we apply to the isomerization process studied in this work the reasoning we proposed to understand the  $\text{CH}_3\text{OH}^+/\text{H}_2\text{O}$  system [10–12], the catalyst must be basic enough to abstract a proton from the methyl group of ionized acetone but not too basic to give back this proton to oxygen. In other words, the PA of an efficient catalyst must lie, in a first approximation, between the PA of the radical  $\text{CH}_3\text{COCH}_3$  at the carbon site ( $\text{PA}_{\text{C}}$ ) and its PA at the oxygen site ( $\text{PA}_{\text{O}}$ ), which have been formerly estimated to be, respectively, 182 and  $196 \text{ kcal mol}^{-1}$  [20]. A reevaluation of these values was done for this work, both from experiment and calculations.

The  $\text{PA}_{\text{O}}(\text{CH}_3\text{COCH}_2) = 194.3 \text{ kcal mol}^{-1}$  was experimentally determined, as reported in section 3.2. [40]. Taking  $\Delta H_{\text{f}}(\text{CH}_3\text{COCH}_2) = -8.3 \pm 2 \text{ kcal mol}^{-1}$  [40] and  $\Delta H_{\text{f}}^0(\text{CH}_3\text{COCH}_3^+) = -171.9 \text{ kcal mol}^{-1}$  [28], one obtains  $\text{PA}_{\text{C}}(\text{CH}_3\text{COCH}_2) = 185.5 \pm 2 \text{ kcal mol}^{-1}$ . Our calculations at the B3LYP/6-311+G(3df,2p) level of theory give  $\text{PA}_{\text{O}}(\text{CH}_3\text{COCH}_2) = 195.0 \text{ kcal mol}^{-1}$  and  $\text{PA}_{\text{C}}(\text{CH}_3\text{COCH}_2) = 185.5 \text{ kcal mol}^{-1}$ , in good agreement with the experimental data and previous ab initio calculations [40,45].

As expected, formaldehyde ( $\text{PA} = 170.4 \text{ kcal mol}^{-1}$ ) [41] and methanol ( $\text{PA} = 180.3 \text{ kcal mol}^{-1}$ ) [41], whose PA is too low, are inefficient catalysts. At the highest PA investigated, no isomerization is observed with diethylether ( $\text{PA} = 198.0 \text{ kcal mol}^{-1}$ ) [41] and ethyl acetate ( $\text{PA} = 199.7 \text{ kcal mol}^{-1}$ ) [41], whose PA is too high. However, no conclusion can be made about the occurrence or lack thereof of tautomerization within the complex before its decomposition to  $\text{CH}_3\text{COCH}_2$  and the protonated neutral re-

agent. A good indication that such a hidden isomerization could well occur is the behavior of methyl acetate, which is an efficient catalyst although its PA ( $196.4 \text{ kcal mol}^{-1}$ ) [41] is slightly above  $\text{PA}_{\text{O}}(\text{CH}_3\text{COCH}_2)$ . It is worth noting that no H/D isotope effect is found in this case, confirming that the energy barrier for isomerization is lowered when the PA of the catalyst increases.

The behavior of alcohols is unexpected. Ethanol (PA =  $185.6 \text{ kcal mol}^{-1}$ ) [41], 1-butanol (PA =  $188.6 \text{ kcal mol}^{-1}$ ) [41] and isopropanol (PA =  $189.5 \text{ kcal mol}^{-1}$ ) [41] are inefficient, although their PA lie in the good area. This could be because of the fact that, for alcohols, the formation of a H-bonded encounter complex, followed by the loss of a radical, is particularly easy and, therefore, highly favored [11]. Alternatively, as the EI of 1-butanol ( $10.06 \text{ eV}$ ) [42] and isopropanol ( $10.12 \text{ eV}$ ) [42] are only slightly higher than the EI of acetone ( $9.705 \text{ eV}$ ) [42], the stable complex with ionized acetone could, in these cases, involve a two-center/three-electron interaction between the two oxygen atoms of the system. Such an interaction was found to occur in the ionized acetaldehyde/methanol system [22], giving a well-stabilized structure, which makes less favorable than expected the 1,3-proton transport required for enolization. Finally, a third explanation could also be a hidden isomerization, as explained in section 4.2.1. Further calculations are in progress to check these hypothesis in the case of ionized acetone.

It remains that for other neutral compounds, the isomerization is catalyzed within a PA range, which is in good agreement with the PAs determined for the  $\text{CH}_3\text{COCH}_2$  radical on the carbon site and on the oxygen site, respectively. In other words, the PA rule, suggested [8,10,12] to predict whether isomerization by  $\text{H}^+$  transport will take place or not, applies well for the keto-enol catalysis of ionized acetone.

## 6. Conclusions

A great variety of compounds (ethers, ketones, nitriles, acids, esters) can be used to catalyze the 1,3- $\text{H}^+$  transfer isomerizing ionized acetone **1** into its

enol isomer **2**. The PA range where isomerization is best observed is  $186\text{--}195 \text{ kcal mole}^{-1}$ , in agreement with the range determined by the PA rule ( $185.5\text{--}195.0 \text{ kcal mole}^{-1}$ ). For compounds of greater PA, the enol itself protonates the substrate at collision rate, and isomerization, although possibly occurring, can no longer be observed by our method. With the exception of alcohols and dimethylether, the enolization efficiency increases regularly with the PA of the catalyst.

Compared with the catalyzed 1,2- $\text{H}^+$  transfers studied until now, which occur at near collision rates [8,9], the 1,3- $\text{H}^+$  transport required for keto-enol isomerization appears to be less efficient (from 0.5% to 30% of  $k_{\text{coll}}$ ). Calculations show that this is because of a substantial energy barrier that must overcome for the keto-enol conversion. This barrier was found to be very low for 1,2- $\text{H}^+$  transfers [10–12].

According to calculations for the isomerization of ionized acetone by nitriles, the isomerization mechanism was found to be distinct from that established for the ionized acetaldehyde/methanol system. It remains to be determined if that difference could be because of the nature of the catalyst and, particularly, to the various interactions within the ion-neutral complex.

Finally, these results, obtained by FT-ICR in experimental conditions where only bimolecular collisions are observed, clearly establish that one, and only one, molecule of the catalyst is able to effect the conversion of ionized acetone **1** into its enol counterpart **2**. From this point of view, the FT-ICR method is unambiguous, whereas the intervention of several molecules of catalyst in the same complex cannot be discarded when isomerization occurs in the conditions of a high-pressure ion source.

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## References

- [1] (a) N.M.M. Nibbering, Phil. Trans. R. Soc. Lond. A293 (1979) 103; (b) N.M.M. Nibbering, Ann. Chim. 71 (1981) 3;



- (c) N.M.M. Nibbering, *Recl. Trav. Chim. Pays-Bas* 100 (1981) 297; (d) S. Ingeman, J.C. Kleingeld, N.M.M. Nibbering, in *Ionic Processes in the Gas Phase*, M.A. Almoester Ferreira (Ed.), D. Reidel, Dordrecht, 1984, p. 87; (e) J.J. Zwinselman, N.M.M. Nibbering, B. Ciommer, H. Schwarz, in *Tandem Mass Spectrometry*, F.W. McLafferty (Ed.), Wiley, New York, 1983, p. 67; (f) N.M.M. Nibbering, *Mass Spectrom. Rev.* 3 (1984) 445; (g) N.M.M. Nibbering, *Recl. Trav. Chim. Pays-Bas* 105 (1986) 245; (h) N.M.M. Nibbering, *Adv. Phys. Org. Chem.* 24 (1988) 1; (i) N.M.M. Nibbering, S. Ingemann, L.J. de Koning, in *The Structure, Energetics and Dynamics of Organic Ions*, T. Baer, C. Ng, I. Powis (Eds.), Wiley, Chichester, 1996, p. 281; (j) M. Born, S. Ingemann, N.M.M. Nibbering, *Mass Spectrom. Rev.* 16 (1997) 181; (k) N.M.M. Nibbering, *Adv. Mass Spectrom.* 14 (1998) 43; (l) N.M.M. Nibbering, *Int. J. Mass Spectrom.* 200 (2000) 27.
- [2] (a) N.M.M. Nibbering, *Nachr. Chem. Tech. Lab.* 32 (1984) 1044; (b) N.M.M. Nibbering, in *Mass Spectrometry, Specialist Periodical Reports*, M.E. Rose (Ed.), The Royal Society of Chemistry, London, Vol. 8, 1985, p. 141; (c) N.M.M. Nibbering, *Adv. Mass Spectrom.* 10 (1985) 417; (d) N.M.M. Nibbering, *Comments At Mol. Phys.* 18 (1986) 223; (e) N.M.M. Nibbering, *Acc. Chem. Res.* 23 (1990) 279; (f) N.M.M. Nibbering, *Analyst* 117 (1992) 289; (g) N.M.M. Nibbering, *Trends Anal. Chem.* 13 (1994) 223.
- [3] (a) T. Drewello, C.B. Lebrilla, H. Schwarz, L.J. de Koning, R.H. Fokkens, N.M.M. Nibbering, E. Anklam, K.-D. Asmus, *J. Chem. Soc. Chem. Commun.* 18 (1987) 1381; (b) S.P. de Visser, L.J. de Koning, N.M.M. Nibbering, *J. Phys. Chem.* 99 (1995) 15444; (c) S.P. de Visser, L.J. de Koning, N.M.M. Nibbering, *Int. J. Mass Spectrom. Ion Processes* 157/158 (1996) 283; (d) S.P. de Visser, L.J. de Koning, N.M.M. Nibbering, *J. Am. Chem. Soc.* 120 (1998) 1517; (e) F.M. Bickelhaupt, A. Diefenbach, S.P. de Visser, L.J. de Koning, N.M.M. Nibbering, *J. Phys. Chem. A* 102 (1998) 9549; (f) S.P. de Visser, F.M. Bickelhaupt, L.J. de Koning, N.M.M. Nibbering, *Int. J. Mass Spectrom.* 179/180 (1998) 43.
- [4] (a) A.J.R. Heck, T. Drewello, L.J. de Koning, N.M.M. Nibbering, *Int. J. Mass Spectrom. Ion Processes* 100 (1990) 611; (b) A.P. Tinke, C.E.M. Heeremans, R.A.M. van der Hoeven, W.M.A. Niessen, J. van der Greef, N.M.M. Nibbering, *Rapid Comm. Mass Spectrom.* 5 (1991) 188; (c) I.L. Freriks, L.J. de Koning, N.M.M. Nibbering, *J. Org. Chem.* 57 (1992) 5976; (d) F.M. Bickelhaupt, E.J. Baerends, N.M.M. Nibbering, *Chem. Eur. J.* 2 (1996) 206.
- [5] C.G. Sinnige, L.J. de Koning, N.M.M. Nibbering, *Int. J. Mass Spectrom.* 195/196 (2000) 115.
- [6] D.K. Bohme, *Int. J. Mass Spectrom. Ion Processes* 115 (1992) 95.
- [7] For early works, see (a) C.G. Freeman, J.S. Knight, J.G. Love, M.J. McEvans, *Int. J. Mass Spectrom. Ion Processes* 80 (1987) 255; (b) S. Petrie, C.G. Freeman, M. Mautner, M.J. McEvans, E.E. Ferguson, *J. Am. Chem. Soc.* 112 (1990) 7121.
- [8] H.E. Audier, D. Leblanc, P. Mourgues, T.B. McMahon, S. Hammerum, *J. Chem. Soc. Chem. Commun.* (1994) 2329.
- [9] P.K. Chou, R.L. Smith, L.J. Chyall, H.I. Kenttämaa, *J. Am. Chem. Soc.* 117 (1995) 4374.
- [10] J.W. Gauld, L. Radom, J. Fossey, H.E. Audier, *J. Am. Chem. Soc.* 118 (1996) 6299.
- [11] H.E. Audier, J. Fossey, P. Mourgues, T.B. McMahon, S. Hammerum, *J. Phys. Chem.* 100 (1996) 18380.
- [12] J.W. Gauld, L. Radom, *J. Am. Chem. Soc.* 119 (1997) 9831.
- [13] S.P. de Visser, L.J. de Koning, N.M.M. Nibbering, *J. Am. Chem. Soc.* 120 (1998) 1517.
- [14] M.A. Trikoupis, D.J. Lavorato, J.K. Terlouw, P.J.A. Ruttink, P.C. Burgers, *Eur. Mass Spectrom.* 5 (1999) 431.
- [15] (a) H.E. Audier, T.B. McMahon, *J. Mass Spectrom.* 32 (1997) 201; (b) S. Okada, Y. Abe, S. Tanigushi, S. Yamabe, *J. Am. Chem. Soc.* 109 (1987) 296; (c) G. van der Rest, P. Mourgues, J. Fossey, H.E. Audier, *Int. J. Mass Spectrom. Ion Processes* 160 (1997) 107.
- [16] H. Becker, D. Schröder, W. Zummack, H. Schwarz, *J. Am. Chem. Soc.* 116 (1994) 1096.
- [17] G. van der Rest, P. Mourgues, J. Tortajada, H.E. Audier, *Int. J. Mass Spectrom. Ion Proc.* 179/180 (1998) 293.
- [18] G. van der Rest, J. Chamot-Rooke, P. Mourgues, D. Leblanc, H.E. Audier, *Book of Abstracts of the 14th International Mass Spectrometry Conference, Tampere (Finland)*, E.J. Karjalainen, A.E. Hesso, J.E. Jalonen, U.P. Karjalainen (Eds): Helsinki, 1997, p. 185.
- [19] G. van der Rest, H.E. Audier, P. Mourgues, *Proceedings des 15èmes Journées Françaises de Spectrométrie de masse*, Lyon (France), 1998, p. 45.
- [20] M.A. Trikoupis, J.K. Terlow, *J. Am. Chem. Soc.* 120 (1998) 12131.
- [21] J. Chamot-Rooke, G. van der Rest, P. Mourgues, H.E. Audier, *Int. J. Mass Spectrom.* 195 (2000) 385.
- [22] G. van der Rest, H. Nedev, J. Chamot-Rooke, P. Mourgues, T.B. McMahon, H.E. Audier, *Int. J. Mass Spectrom.* 202 (2000) 161.
- [23] P. Mourgues, J. Chamot-Rooke, H. Nedev, H.E. Audier, *J. Mass Spectrom.* 36 (2001) 102.
- [24] V. Brenner, A. Milliet, P. Mourgues, G. Ohanessian, H.E. Audier, *J. Phys. Chem.* 99 (1995) 10837.
- [25] B. Yates, W.J. Bouma, L. Radom, *J. Am. Chem. Soc.* 109 (1987) 2250.
- [26] R. Keefe, A.J. Kresge, in *The Chemistry of Enols*, Z. Rappoport (Ed.), Wiley, Chichester, 1990, p. 399.
- [27] (a) G. Bouchoux, *Mass Spectrom. Rev.* 7 (1988) 1; (b) F. Tureček, in *The Chemistry of Enols*, Z. Rappoport (Ed.), Wiley, Chichester, 1990, p. 95.
- [28] S.G. Lias, J.E. Bartmess, J.F. Liebman, J.L. Holmes, R.D. Levin, W.G. Mallard, *J. Phys. Chem. Ref. Data* 17 Supplement 1, (1988).
- [29] M. Allemann, H. Kellerhals, K.P. Wanczek, *Int. J. Mass Spectrom. Ion Processes* 46 (1983) 139.
- [30] P. Kofel, M. Allemann, H. Kellerhals, K.P. Wanczek, *Int. J. Mass Spectrom. Ion Processes* 65 (1985) 97.
- [31] P. Caravatti, M. Allemann, *Org. Mass Spectrom.* 26 (1991) 514.
- [32] V.G. Anicich, *J. Phys. Chem. Ref. Data* 22 (1993) 1469.
- [33] J.E. Bartmess, R.M. Georgiadis, *Vacuum* 33 (1983) 149.
- [34] K.J. Miller, *J. Am. Chem. Soc.* 112 (1990) 8533.
- [35] T. Su, W.J. Chesnavich, *J. Chem. Phys.* 76 (1982) 5183.
- [36] M.J. Frisch, G.W. Trucks, H.B. Schlegel, G.E. Scuseria, M.A. Robb, J.R. Cheeseman, V.G. Zakrzewski, J.A. Montgomery

- Jr., R.E. Stratmann, J.C. Burant, S. Dapprich, J.M. Millam, A.D. Daniels, K.N. Kudin, M.C. Strain, O. Farkas, J. Tomasi, V. Barone, M. Cossi, R. Cammi, B. Mennucci, C. Pomelli, C. Adamo, S. Clifford, J. Ochterski, G.A. Petersson, P.Y. Ayala, Q. Cui, K. Morokuma, D.K. Malick, A.D. Rabuck, K. Raghavachari, J.B. Foresman, J. Cioslowski, J.V. Ortiz, B.B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. Gomperts, R.L. Martin, D.J. Fox, T. Keith, M.A. Al-Laham, C.Y. Peng, A. Nanayakkara, C. Gonzalez, M. Challacombe, P.M.W. Gill, B. Johnson, W. Chen, M.W. Wong, J.L. Andres, C. Gonzalez, M. Head-Gordon, E.S. Replogle, J.A. Pople, GAUSSIAN 98, Gaussian, Pittsburgh, PA, 1998.
- [37] (a) A.D. Becke, *J. Chem. Phys.* 98 (1993) 5648; (b) W.J. Hehre, R. Ditchfield, J.A. Pople, *J. Chem. Phys.* 56 (1972) 2257.
- [38] (a) C. Dass, *Mass Spectrom. Rev.* 9 (1990) 1; (b) F. Berruyer-Penaud, G. Bouchoux, *Rapid Comm. Mass Spectrom.* 4 (1990) 476; (c) P. Mourgues, C. Monteiro, H.E. Audier, S. Hammerum, *Org. Mass Spectrom.* 25 (1990) 389.
- [39] G. Bouchoux, J.-Y. Salpin, D. Leblanc, *Int. J. Mass Spectrom. Ion Processes* 153 (1996) 37; (b) G. Bouchoux, J.Y. Salpin, *J. Am. Chem. Soc.* 118 (1996) 6516.
- [40] G. Bouchoux, J. Chamot-Rooke, D. Leblanc, P. Mourgues, M. Sablier, *Chem. Phys. Chem.* 2001, in press.
- [41] E.P.L. Hunter, S.G. Lias, *J. Phys. Chem. Ref. Data* 27 (1998) 413.
- [42] NIST Chemistry Webbook, NIST Standard Reference Database Number 69, W.G. Mallard, P.J. Lindstrom (Eds.), National Institute of Standards and Technology, Gaithersburg, MD, 2000 (<http://webbook.nist.gov>).
- [43] A.G. Harrison, *Chemical Ionization Mass Spectrometry*, 2nd ed., CRC Press, Boca Raton, FL, 1992, p. 23.
- [44] (a) C. Gonzalez, H.B. Schlegel, *J. Chem. Phys.* 90 (1988) 2154; (b) C. Gonzalez, H.B. Schlegel, *J. Phys. Chem.* 94 (1990) 5523.
- [45] F. Tureček, C.J. Cramer, *J. Am. Chem. Soc.* 117 (1995) 12243.