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Why Does Pivalaldehyde (Trimethylacetaldehyde) Unexpectedly Seem More Basic Than 1-Adamantanecarbaldehyde in the Gas Phase? FT-ICR and High-Level Ab Initio Studies

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Abstract: Fourier transform ion cyclotron resonance spectroscopy (FT ICR) techniques, including collision-induced dissociation (CID) methodology, were applied to the study of the gas-phase protonation of pivalaldehyde (**1**) and 1-adamantanecarbaldehyde (**2**). A new synthetic method for **2** was developed. The experiments, together with a thor-

ough computational study involving ab initio and density functional theory (DFT) calculations of high level, conclusively show that upon monoprote-

Keywords: ab initio calculations • cations • gas-phase reactions • ion-molecule reactions • isomerization

tion in the gas phase, compound **1** yields monoprotinated methyl isopropyl ketone **3**. The mechanism of this gas-phase acid-catalyzed isomerization is different from that reported by Olah and Suryah Prakash for the reaction in solution. In the latter case, isomerization takes place through the diprotonation of **1**.

Introduction

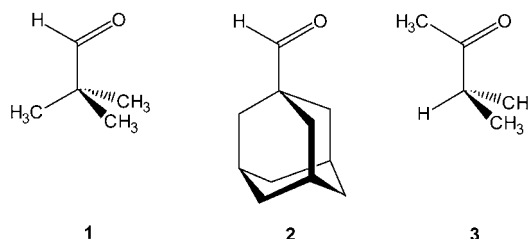
A great deal of quantitative thermodynamic data on structural effects on the gas-phase basicity of aliphatic and alicyclic carbonyl compounds is currently available,^[1] an important exception being the family of aldehydes, R-CHO. We summarize in Table 1 representative gas-phase basicities and proton affinities for aliphatic and alicyclic aldehydes report-

ed in the literature, the gas-phase basicity (GB) and the proton affinity (PA) of a base B being the standard Gibbs energy [$\Delta_r G_m^\circ(1)$] and enthalpy [$\Delta_r H_m^\circ(1)$] changes for the reaction given in Equation (1), respectively.



The National Institute of Standards and Technology (NIST) compilation of GB and PA values embodies both experimental and high-level computational results and frequently reports recommended values obtained from the average of both kinds of data.^[1] Here we use the NIST database to obtain the purely experimental values of GB and PA presented in Table 1. Details regarding the uncertainties on these properties are given in the Supporting Information.

Initially, we intended to extend this database through the experimental determination of the gas-phase basicities of trimethylacetaldehyde (pivalaldehyde, *t*BuCHO, **1**) and 1-ad-



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Table 1. Total energies (E), gas-phase basicities (GB), and proton affinities (PA) of the aldehydes and ketones under investigation.

Substituents		E [hartrees] ^[a]		ZPE ^[b]	GB [kJ mol ⁻¹]		Exptl ^[d,g]	PA [kJ mol ⁻¹]		Exptl ^[d,g]
R ¹	R ²	B3LYP	G2(MP2)	[hartrees]	B3LYP ^[b]	G2(MP2)		B3LYP ^[b]	G2(MP2)	
H	H	114.549401	114.333205	0.026076	679.7 (684.1)	683.3	680.9 ± 2.6	716.6	712.1	711.1 ± 1.4
		114.831261	114.602371	0.039120						712.1 ± 5.5 ^[e]
Me	H	-153.89229	-153.56901	0.053511	741.4 (738.6)	737.9	737.9 ± 5.3	775.6 (772.4)	770.6	768.2 ± 4.0
		-154.19842	-153.86016	0.065755						772.8 ± 5.9 ^[e]
Me	Me	-193.23088	-192.80342	0.080274	792.9 (784.0)	785.8	785.1 ± 5.0	820.0 (811.6)	812.8	812.6 ± 4.4
		-193.55367	-193.11064	0.092276						812.2 ± 5.6 ^[e]
Et	H	-193.21968	-192.79246	0.081203	751.4 (747.4)	746.6	752.6 ± 5.1	783.3 (779.2)	778.0	784.5 ± 5.7 ^[e]
		-193.52916	-193.08639	0.093693						
Et	Me	-232.43934	-232.02604	0.120657	801.3 (791.4)	790.1	795.5 ± 6.0	837.2 (826.8)	826.3	831.4 ± 6.5 ^[e]
		-232.75590	-232.33836	0.134651						
<i>i</i> Pr	H	-232.42750	-232.01631	0.121234	770.4 (764.1)	769.6	765.5 ± 5.1	802.5 (796.5)	801.7	798.9 ± 5.7 ^[e]
		-232.73027	-232.31930	0.135266						
<i>i</i> Pr	Me	-271.73415	-271.24972	0.151278	810.1 (799.2)	797.5	804.4 ± 5.1	843.5 (832.3)	830.9	837.8 ± 5.7 ^[e]
		-272.05314	-271.56438	0.163841						
<i>t</i> Bu	H	-271.72660	-271.24534	0.147505	778.3 (771.1)	770.7	800.1 ± 10.1 ^[f]	811.3 (803.9)	802.1	833.1 ± 10.4 ^[e,f]
		-272.03330	-271.54850	0.151075				863.6 (850.1)^[c]	843.9	836.3^[f]
<i>t</i> Bu	Me	-311.03151	-310.51498	0.161914	819.7 (807.7)	810.7	808.3 ± 4.5	853.5 (841.2)	842.2	842.1 ± 5.1 ^[e]
		-311.35424	-310.98063	0.174111						
1-Ad	H	-503.94658	503.368006	0.271370	807.2 (796.6)	791.6	792.7 ± 4.3 ^[e]	839.7 (829.0)	823.0	825.2 ± 5.0 ^[e,f]
		-504.26406	503.693648	0.285719						
1-Ad	Me	-543.25172			845.2 (830.1)	(830.1)	833.1 ± 4.7	877.0 (861.9)	(861.9)	864.9 ± 5.3 ^[f]
		-543.58335								

[a] The first entry corresponds to the total energy of the neutral. The second entry is the total energy of the protonated species. [b] Values within parentheses correspond to G2(MP2) estimated values from the linear correlation between B3LYP and G2(MP2) calculated gas phase basicities and proton affinities. [c] Values in boldface correspond to the PA of **1** assuming that, upon protonation, it isomerizes to yield the protonated isopropyl methyl ketone. [d] Average of purely experimental values from reference [1]. [e] From the experimental GB values and the corresponding entropy corrections obtained at the B3LYP/6-311+G(d,p) level in this work. [f] This work. [g] Further details concerning the estimate of the uncertainties are given in the Supporting Information. [h] Uncorrected values correspond to HF/6-31G(d).

mantanecarbaldehyde (1-AdCHO **2**), by means of Fourier transform ion cyclotron resonance spectroscopy (FT ICR).^[2] As it turned out, this formally straightforward study led us to some unexpected results that prompted us to further examine methyl isopropyl ketone (**3**). These results are reported and discussed below, together with their analysis, both experimental and theoretical.

Abstract in Spanish: *La técnica espectroscópica de Resonancia Ciclotrónica de Iones con Transformada de Fourier (FT ICR) junto con la metodología de Disociación Inducida por Colisión (CID) se han aplicado al estudio de la protonación en fase gaseosa del pivalaldehído (**1**) y adamantanocarbaldehído (**2**). Se ha desarrollado un nuevo método para la síntesis de **2**. Los experimentos, junto con un minucioso estudio computacional que incluye cálculos de nivel considerable, tanto ab initio como por medio de la Teoría del Funcional de Densidad (DFT) llevan a la conclusión de que la monoprotonación en fase gaseosa de **1** da lugar a metilisopropilcetona (**3**) monoprotonada. El mecanismo de esta isomerización en fase gaseosa catalizada por ácidos es diferente al descrito por Olah y Suryah Prakash para la reacción en disolución. En el último caso, la isomerización ocurre a través de la diprotonación de **1**.*

Experimental Section

Materials: Pivalaldehyde (**1**) and methyl isopropyl ketone (**3**) were purchased from Aldrich and used without further purification. GC analyses of their vapors showed a purity of 99 % and, in particular, the absence of pivalic acid (formed by oxidation of **1** and likely to be more basic).

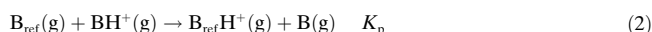
Synthesis of 1-adamantanecarbaldehyde (2**):** Compound **2** was synthesized by the Bouveault reaction^[3] starting from dry 1-bromoadamantane (1.07 g, 5.0 mmol), anhydrous *N,N'*-dimethylformamide (5.2 mmol), and a 25 % lithium dispersion in mineral oil or lithium wire (10.5 mmol, both containing 1 % sodium; with a lesser amount of Na, for instance 0.05 %, the reaction did not work) in anhydrous THF (50 mL) under argon and external cooling with ultrasonic radiation from a VIRSONIC 300 CELL Disrupter Model #175893 (20 kHz). The reaction was completed at room temperature in 5 min when the lithium dispersion was utilized or in 50 min with lithium wire (the reaction was followed by thin-layer chromatography). The excess lithium was filtered and the traces of it remaining in the reaction mixture were destroyed with ammonium chloride in an ice bath. The product was then extracted with diethyl ether or dichloromethane and the solvent evaporated off. Filtration over dry silica gel 60 (30–400 mesh) with hexane separated the unreacted 1-bromoadamantane and high R_f secondary products. The elution with hexane:ethyl acetate (75:25) afforded pure 1-adamantanecarbaldehyde (**2**). Yields 50 to 75 %; m.p 160–162 °C (literature:^[3] 160–162 °C); R_f = 0.52 in hexane:ethyl ether (9:1); IR: $\bar{\nu}$ = 1720 cm⁻¹ (C=O; literature:^[3] 1720 cm⁻¹).

Gas-phase studies

The FT ICR spectrometer: In this work, use was made of a modified Bruker CMS 47 FT ICR mass spectrometer. A detailed description of the original instrument is given in reference [4]. It has already been used in a number of studies.^[5] Some salient features are as follows. The spectrometer was linked to an Omega Data Station (IonSpec, CA). The high-vacuum was provided by a Varian TURBO V550 turbomolecular pump (550 Ls⁻¹). Inert gases for CID studies were admitted by means of a

Parker 009-1380-900 solenoid valve. The magnetic field strength of the superconducting magnet was 4.7 T.

Determination of gas-phase basicities:^[6] Mixtures of the base under scrutiny (B) and a reference base (B_{ref}) of known gas-phase basicity were introduced into the high-vacuum section of the instrument. Typical partial pressures were in the range 5×10^{-8} – 5×10^{-7} mbar. The average temperature of the cell was about 331 K. The mixture was ionized by electron ionization, using energies in the range 12–18 eV, and ionic fragments of B and B_{ref} acted as proton sources (to generate BH^+ and $B_{\text{ref}}H^+$ ions). In cases in which the total pressures were below 5×10^{-7} mbar, argon was added up to a total pressure of this order. After reaction times of 3–8 s, either BH^+ or $B_{\text{ref}}H^+$ ions were formed and isolated by means of ion-selection techniques; however, while these ions were reacting with the neutral species, the system was monitored during 10–20 s. In the cases of compound **2**, the reaction given in Equation (2) reached a state of equilibrium during this time.



From experiment to experiment, the ratio of the abundances of the two ions remained constant within 5%, irrespective of whether the BH^+ or $B_{\text{ref}}H^+$ ions were selected. In other experiments, no selection was carried out, but the ratio was the same within these limits. The pressures of the neutral species were measured with a Bayard–Alpert ion gauge. Its readings were corrected according to the method by Bartmess and Georgiadis,^[7] using the polarizabilities ($\alpha[\text{ahc}]$) calculated following Miller's method^[8] for each compound. The gas-phase basicity of B can be obtained from $GB(B_{\text{ref}})$ and K_p through Equation (3).

$$GB[B] = GB(B_{\text{ref}}) - RT \ln K_p \quad (3)$$

In each case, the K_p values were taken as the average of six different experiments involving different ratios of the pressures of the neutral bases. Experimental results are summarized in Table 2.

Table 2. Experimental results pertaining to the determination of GB (**2**).^[a]

	B_{ref}	$GB(B_{\text{ref}})^{[b]}$	ΔG	GB
1-AdCHO (2)	MeOAc	790.7	+1.5	792.2
	THF	794.7	–1.5	793.2
	MeCOEt	795.5	–2.8	792.7
Average				$792.7 \pm 4.3^{[c]}$

[a] All values in kJ mol^{-1} . [b] From reference [1]. [c] Full details can be found in the Supporting Information.

Furthermore, because purely experimental PA values are generally scarce, the entropic term linking GB and PA values is generally estimated from changes in symmetry numbers of the neutral and protonated species.^[1] Here we used the NIST database to obtain purely experimental values of PA and GB. In cases in which only GB values are of experimental origin, we obtained the corresponding PAs by using the relevant entropies computed in this work at the B3LYP/6–311+G(d,p) level. Full details are given in the Supporting Information.

The apparent gas-phase basicity of pivalaldehyde (1): Proton exchange experiments similar to those indicated above were performed on mixtures of **1** and **2**. It was observed that in a 1:1 mixture of these compounds, $2H^+(g)$ was slowly but irreversibly deprotonated by **1(g)** and the same applied to the protonated forms of MeOAc ($GB = 790.7$), THF ($GB = 794.7$), and butanone ($GB = 795.5 \text{ kJ mol}^{-1}$). Under the same conditions, **1(g)** was unable to deprotonate the protonated forms of EtOAc ($GB = 804.7$) and methyl benzoate ($GB = 805.7 \text{ kJ mol}^{-1}$). From these results, the apparent GB of **1** can be estimated at $800.1 \pm 9.2 \text{ kJ mol}^{-1}$.

Collision-induced dissociation (CID) experiments: In all cases, nominal partial pressures of the reagents, that is, **1(g)** or **2(g)** and the corresponding reference base were in the range 5 – 8×10^{-9} mbar. Each experiment

started with a quench pulse aimed at removing any ions left within the ICR cell. Protonation of the neutral species by fragment ions involved ionization energies in the 14–17 eV range and 12–15 s reaction times. The protonated molecules BH^+ and $B_{\text{ref}}H^+$ thus formed represent about 90% of the total number of ions. Species BH^+ were isolated by means of broadband and soft excitation chirps and cooled after 300 ms by a 7 ms argon pulse leading to pressures of approximately 9×10^{-6} mbar. Next, after 300 ms, a second pulse of argon, 9 ms long (maximum pressure of ca. 1.2×10^{-5} mbar) was applied. BH^+ ions were excited by 25 μs “on-resonance” RF pulses applied 300 ms later (time corresponding to the maximum pressure). Peak-to-peak voltages ($V_{\text{p-p}}$) applied to the excitation plates were such that the upper limit of the center of mass energies^[9] varied between 1 and 32 eV. Broad-band detection was carried out after 350 ms. We summarize in Figure 1 the evolution of the relative abundances

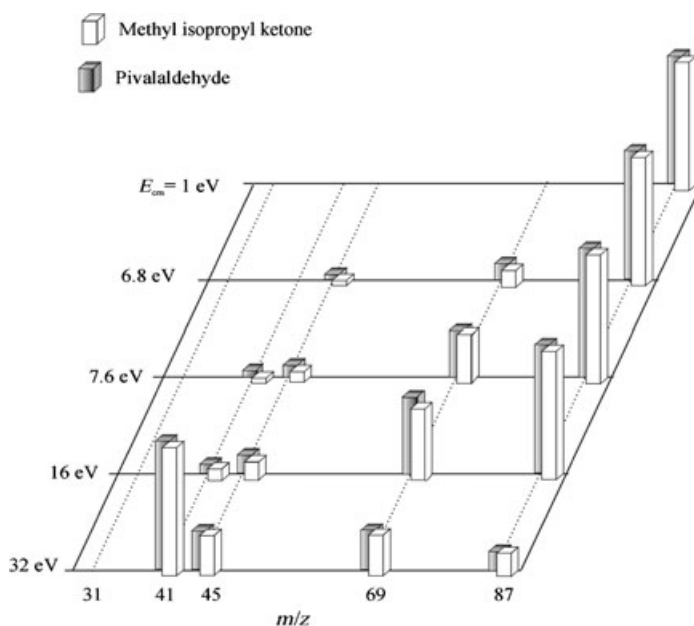


Figure 1. Comparative evolution of the relative ion abundances obtained from CID experiments on protonated pivalaldehyde (**1**) and protonated methyl isopropyl ketone (**3**). E_{cm} stands for the maximum energy at the center of mass in each experiment.

of the fragment ions obtained from protonated **1** and **3** as a function of the maximum energies at the center of mass, E_{cm} (in eV). The fragmentation patterns of protonated **1** and **3** are indistinguishable both in terms of the m/z ratios of the daughter ions as well as of their relative abundances (agreement within 10% or better from experiment to experiment). The m/z values for the daughter ions (in Th units) are 69 [C_3H_5O]⁺, 45 [C_2H_5O]⁺, and 41 [C_3H_5]⁺. Similar studies were performed using 2H_2O as a source of $^2H^+$; in these experiments the partial pressure of 2H_2O was about 2.0×10^{-7} mbar. The results were quite similar to those reported above, except for the fact that the m/z ratio for all the parent ions was 88. In the case of deuterated **1** and **3**, the only different daughter ion has an m/z value of 46 and the ion with an m/z value of 45 is absent.

Computational methods: Full details are given in the Supporting Information. Here we indicate that, with the exception of 1-adamantyl methyl ketone, GB and PA values for all aldehydes and ketones were obtained using the G2(MP2) method,^[10] a high-level ab initio technique in the framework of the general G2 theory. In the case of 1-adamantyl methyl ketone, these thermodynamic properties were obtained using the excellent correlation between the G2(MP2) and B3LYP/6–311+G(3df,2p) data.^[11]

Results and Discussion

The gas-phase protonation of 1-adamantanecarbaldehyde (2):

As indicated in above, this is a reversible process. The gas-phase basicity of **2** as determined by FT ICR experiments amounts to $792.7 \pm 1.1 \text{ kJ mol}^{-1}$, in excellent agreement with the G2(MP2) value, $791.6 \text{ kJ mol}^{-1}$. Furthermore, using the data reported in Table 1, we find that there is an excellent linear relationship between the experimental gas phase basicities of aliphatic and alicyclic aldehydes and the corresponding methyl ketones (Figure 2). The size of the

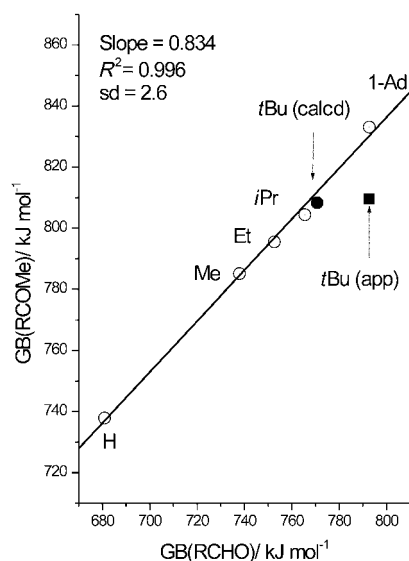


Figure 2. Experimental PA values for relevant methyl ketones (RCOMe) versus those for the corresponding aldehydes (RCHO). The *t*Bu data are not included in the correlation. sd is the standard deviation of fit.

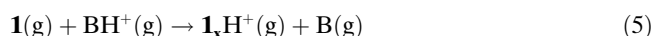
slope is fully consistent with the larger electron demand in protonated aldehydes relative to protonated methyl ketones (or, alternatively, the lower electronic density on carbonyl group in the case of protonated aldehydes). The only deviating datum corresponds to the couple **1**/*tert*-butyl methyl ketone, discussed below.

The gas-phase protonation of pivalaldehyde (1): At variance with the case of **2**, we find that the gas-phase protonation of **1** by a protonated reference base, $B_{\text{ref}}H^+$ [Eq. (3)], does not seem to be a reversible process. Bracketing experiments lead to an apparent GB(**1**) of $800.1 \pm 9.2 \text{ kJ mol}^{-1}$. Interestingly, this value is larger than GB(**2**) and this is experimentally confirmed by the fact that **1**(g) irreversibly deprotonates $2H^+(g)$. As shown in Figure 2, compound **1** is a clear outlier in the correlation between GB values of aldehydes and methyl ketones (Figure 2, solid square). On the other hand, the GB(**1**) value calculated at the G2(MP2) level assuming “normal” carbonyl protonation equals $770.7 \text{ kJ mol}^{-1}$, and this value is nicely consistent with the

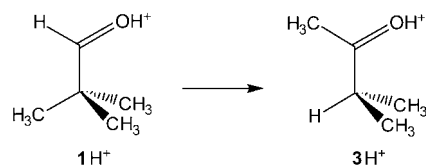
correlation discussed above (see Figure 2, solid circle). These facts and further evidence discussed below tend to suggest that the structure of protonated pivalaldehyde in the gas phase is not that corresponding to the “normal” protonation of an aliphatic or alicyclic aldehyde [Eq. (4)].



The structure of the ion obtained by gas-phase protonation of pivalaldehyde: On the basis of the above, we assume that the protonation of **1** in the gas phase [Eq. (5)] leads to an ion $1_xH^+(g)$ and deprotonation of this ion by a base B [Eq. (6)] leads to a neutral species 1_x endowed with a structure different from that of **1**.



As indicated in reference [12], it has long been known that in condensed phases and in the presence of very strong acids, compound **1** isomerizes to yield 3-methyl-2-butanone (methyl isopropyl ketone, **3**) [Eq. (7)].



Thus, we first explored the possibility that 1_x might be ketone **3**. The key result is that the fragmentation patterns of $1_xH^+(g)$ and $3H^+(g)$ obtained by CID using Ar as the collision gas (see the Experimental Section) are identical within the experimental limits of the method. It is particularly important that the CID spectrum of $1_xH^+(g)$ does not show the peak at $m/z = 57$, corresponding to the *tert*-butyl cation. These facts indicate that 1_x is different from **1** and, most likely, that 1_x no longer incorporates the *tert*-butyl moiety initially present in **1**. In this respect, we observed that the CID spectrum of $2H^+$, a “well-behaved” aldehyde, only shows a single peak at m/z 135 (1-adamantyl cation). We carried out experiments involving deuteration instead of protonation (see Experimental Section). The CID spectra of $1_x^2H^+(g)$ and $3^2H^+(g)$ are again identical within the experimental limits.

All these results strongly suggest that the isomerization reaction in Equation (7) takes place in the gas phase and that it is also an acid-catalyzed process. Interestingly, in moderately to strongly acidic solutions, compound **1** undergoes reversible protonation. Isomerization only occurs under very strongly acidic conditions (close to the superacid borderline).^[12] This point has important mechanistic consequences and is discussed in detail below.

The experimental results reported above raise two important questions: 1) Why does protonation of **1** in the gas phase yield 3H^+ instead of the non-rearranged 1H^+ ion? and 2) Why does protonation of **1** lead to isomerization, while no isomerization occurs in the case of, for example, isobutyraldehyde? These questions call for the computational study reported below.

Computational rationale of the experimental results: As indicated in the previous section the agreement between the calculated and the experimental proton affinities is very good, with the exception of **1**. In fact, according to our theoretical results, either at the B3LYP or the G2(MP2) levels, and in agreement with what should be expected in terms of the polarizability effects^[13] of the different substituents considered, compound **1** is predicted to be more basic than isobutyraldehyde, but less basic than **3** and *tert*-butyl methyl ketone. This clearly ratifies our previous conclusion that the structure of **1** is not preserved in the protonation process, and that very likely the protonated species being formed is protonated isopropyl methyl ketone.

The potential-energy surface associated with this isomerization, evaluated at the G2(MP2) level, is shown in Figure 3. The first step implies a methyl transfer from the

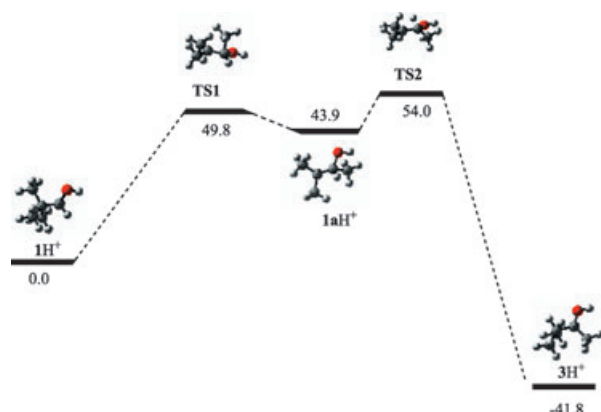


Figure 3. 0 K energies profile for the isomerization of the oxygen protonated form of pivalaldehyde (**1**) to yield the oxygen protonated form of methyl isopropyl ketone (**3**). All values (in kJ mol⁻¹) were obtained at the G2(MP2) level of theory.

*t*Bu moiety in **1** towards the carbonyl carbon atom to yield a stable carbocation **1aH**⁺, which is 43.9 kJ mol⁻¹ less stable than **1H**⁺. This methyl transfer involves the TS1 transition state, which at the G2(MP2) level lies 49.8 kJ mol⁻¹ above the oxygen protonated form of pivalaldehyde. Once the intermediate species **1aH**⁺ is formed, a subsequent hydrogen transfer, which involves an activation barrier of 10.1 kJ mol⁻¹ (relative to **1aH**⁺ and 54.0 kJ mol⁻¹ above **1H**⁺) through the transition state TS2, yields **3H**⁺, which lies 41.8 kJ mol⁻¹ below the oxygen protonated form of **1**. In summary, the overall isomerization process is exothermic by more than 40 kJ mol⁻¹. Similar qualitative conclusions, based on B3LYP/6-31G(d) calculations have been reported previ-

ously in the literature by Olah et al.,^[12] in a study of the acid-catalyzed isomerization of **1**.

For the process **1H**⁺ → **3H**⁺ to take place under experimental ICR conditions, it is necessary to prove that the initially formed protonated species **1H**⁺ has enough internal energy to pass over the activation barriers. Under normal experimental conditions, collision complexes are formed between neutral and protonated species. The energy liberated (mostly by general ion-induced dipole interactions as well as by strong hydrogen bonds) is able to drive the process to completion. To confirm this from a more quantitative point of view we have evaluated, as an example, the interaction energy between **1** and its "normal" protonated form. The structure of this adduct was obtained at the B3LYP/6-31G(d) level and is shown in Figure S1 in the Supporting Information. Its harmonic vibrational frequencies were obtained at the same level of accuracy to confirm that the stationary point found corresponds to a minimum of the potential-energy surface and to estimate the zero-point energy. The corresponding interaction energy was evaluated at the B3LYP/6-311+G(3df,2p) level. The value obtained was 119.2 kJ mol⁻¹, which clearly indicates that the formation of the dimer is exothermic enough to induce the aforementioned **1H**⁺ → **3H**⁺ isomerization.

Hence, we can safely conclude that as a consequence of the isomerization process, **1H**⁺ → **3H**⁺ [Eq. (7)], and because of the enhanced stability of the latter ion relative to its precursor, the apparent proton affinity measured for **1** should be about 46.2 kJ mol⁻¹ higher than expected, and therefore about 21.0 kJ mol⁻¹ higher than that of 1-adamantanecarbaldehyde. One may wonder why this possibility is only open for **1** and does not occur for similar compounds as isobutyraldehyde (**4**). Indeed, following a similar mechanism to that outlined above, the oxygen protonated form of the latter (**4H**⁺) could isomerize to yield the protonated form of butanone (**5H**⁺). Should this possibility be open, the proton affinity calculated for **4** should be significantly smaller than the measured value, which is not the case.

It seems quite evident that, as expected, the isomerization barriers should be much higher in this reaction. Indeed, as shown in Figure 4, the methyl transfer implies in this case an activation barrier (116.9 kJ mol⁻¹) almost twice as large as that estimated for the *t*Bu derivative. Also the activation energy associated with the hydrogen migration (165.0 kJ mol⁻¹) is much higher than that found for the *t*Bu derivative (10.1 kJ mol⁻¹). As mentioned above, these results are not surprising, since the intermediate carbocation **4aH**⁺, at the MP2/6-31G(d) level, is 112.2 kJ mol⁻¹ less stable than the oxygen protonated form of isobutyraldehyde (**4H**⁺), because an ethyl group is significantly less able to stabilize the positive charge than an isopropyl group. In summary, in the case of the isobutyraldehyde, the internal energy of the protonated species is not sufficient to overcome the isomerization barriers and, under the usual ICR experimental conditions, the ion **4H**⁺ cannot evolve to yield species **5H**⁺. It is interesting to mention that **2H**⁺ does not isomerize under our experimental conditions, most likely because this pro-

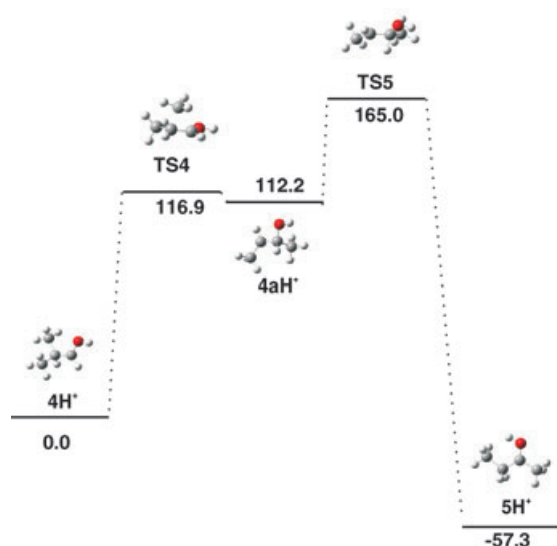
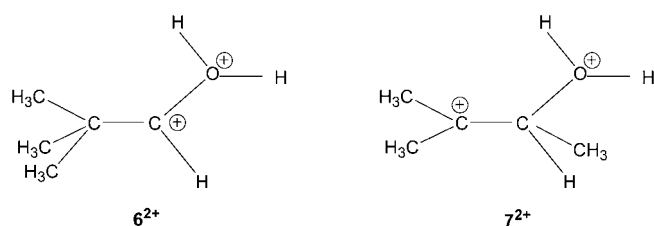


Figure 4. 0 K energies profile for the isomerization of the oxygen protonated form of isobutyraldehyde ($4H^+$) to yield the oxygen protonated form of butanone ($5H^+$). All values (in kJ mol^{-1}) were obtained at the MP2/6–31G(d)//HF/6–31G(d) level of theory.

cess would bring about an increase in the strain of the system, when evolving to yield protonated 4-homoadamantanone. For the sake of consistency with the G2(MP2) calculation, harmonic vibrational frequencies were obtained at the HF/6–31G(d) level and corrected with the 0.8929 factor.

It has recently been shown experimentally by Olah^[12a] and co-workers that in moderate to strongly acidic solutions, compound **1** reversibly protonates to yield unrearranged $1H^+$. More precisely, at an $H_0^{[12b]}$ value of -7.7 , the yield of $3H^+$ is only 17%, while already half of the pivalaldehyde is already monoprotonated. The optimal acidity for isomerization is -10.9 , close to the superacid limit ($H_0 = -12$). The mechanism for the high-acidity isomerization of **1** in solution as suggested by these authors,^[12a,14,15] involves high energy dications 6^{2+} and 7^{2+} . They finally lead to $3H^+$.



We have shown in this paper that in the gas phase, the system overcomes the activation barrier for isomerization, most likely thanks to the energy released in the formation of the encounter complex between neutral **1**(g) and a protonated base $BH^+(g)$. In solution, this mechanism no longer operates. We have recently reported a similar situation in the case of the protonation of cubylamine.^[5a] In water, protonation takes place at the nitrogen atom, whereas in the gas phase, it takes place on the cubane framework. The

physical origin of this behavior is similar. Of course the possible relationship between the gas- and solution-phase mechanisms of rearrangement monocationic protonated pivalaldehyde is a moot point at this time.

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- [1] E. P. L. Hunter, S. G. Lias, *J. Phys. Chem. Ref. Data* **1998**, 27, 413–656.
- [2] a) A. G. Marshall, C. L. Hendrickson, *Int. J. Mass Spectrom.* **2002**, 215, 59–75; b) J.-F. Gal, P.-C. Maria, E. W. Raczyńska, *J. Mass Spectrom.* **2001**, 36, 699–716; c) “Energetics of Stable Molecules and Reactive Intermediates”: J.-L. M. Abboud, R. Notario, *NATO Sci. Ser. C* **1999**, 535, 281–302; d) A. G. Marshall, C. L. Hendrickson, G. S. Jackson, *Mass Spectrom. Rev.* **1998**, 17, 1–35.
- [3] D. Sanz, M. A. Ponce, R. M. Claramunt, C. Fernández-Castaño, C. Foces-Foces, J. Elguero, *J. Phys. Org. Chem.* **1999**, 12, 455–469.
- [4] “Fourier Transform Mass Spectrometry. Evolution, Innovation and Applications”: F. H. Laukien, M. Allemann, P. Bischofberger, P. Grossmann, P. Kellerhals, P. Kofel, *ACS Symp. Ser.* **1987**, 359, 81–99.
- [5] a) J.-L. M. Abboud, I. A. Koppel, I. Alkorta, E. W. Della, P. Müller, J. Z. Dávalos, P. Burk, I. Koppel, V. Pihl, E. Quintanilla, *Angew. Chem.* **2003**, 115, 2383–2387; *Angew. Chem. Int. Ed.* **2003**, 42, 2281–2284; b) J. M. Abboud, O. Castaño, J. Z. Dávalos, P. Jiménez, R. Gomperts, P. Müller, M. V. Roux, *J. Org. Chem.* **2002**, 67, 1057–1060.
- [6] For recent applications of this methodology, see, for example: a) J.-L. M. Abboud, M. Esseffar, M. Herreros, O. Mó, M. T. Molina, R. Notario, M. Yáñez, *J. Phys. Chem. A* **1998**, 102, 7996–8003; b) R. Notario, J.-L. M. Abboud, *J. Phys. Chem. A* **1998**, 102, 5290–5297; c) R. Notario, J.-L. M. Abboud, C. Cativiela, J. I. García, M. Herreros, H. Homan, J. A. Mayoral, L. Salvatella, *J. Am. Chem. Soc.* **1998**, 120, 13224–13229; d) M. Lamsabhi, M. Alcamí, O. Mó, W. Bouab, M. Esseffar, J.-L. M. Abboud, M. Yáñez, *J. Phys. Chem. A* **2000**, 104, 5122–5130.
- [7] J. E. Bartmess, R. M. Giorgiadis, *Vacuum* **1983**, 33, 149–153.
- [8] K. J. Miller, *J. Am. Chem. Soc.* **1990**, 112, 8533–8542.
- [9] J. Laskin, M. Byrd, J. Futrell, *Int. J. Mass Spectrom.* **2000**, 195/196, 285–302, and references therein.
- [10] L. A. Curtiss, K. Raghavachari, J. A. Pople, *J. Chem. Phys.* **1993**, 98, 1293–1298.
- [11] a) B. J. Smith, L. Radom, *J. Phys. Chem.* **1995**, 99, 6468–6471; b) B. Amekraz, J. Tortajada, J.-P. Morizur, A. I. González, O. Mó, M. Yáñez, I. Leito, P.-C. Maria, J.-F. Gal, *New J. Chem.* **1996**, 20, 1011–1021; c) O. Mó, M. Yáñez, M. Decouzon, J.-F. Gal, P.-C. Maria, J. C. Guillemin, *J. Am. Chem. Soc.* **1999**, 121, 4653–4663; d) M. Lamsabhi, M. Esseffar, W. Bouab, El T. Messaoudi, El M. Messaoudi, J.-L. M. Abboud, M. Alcamí, M. Yáñez, *J. Phys. Chem. A* **2002**, 106, 9359–9368.
- [12] a) G. A. Olah, T. Mathew, E. R. Martinez, P. M. Esteves, M. Etzkorn, G. Rasul, G. K. Surya Prakash, *J. Am. Chem. Soc.* **2001**, 123, 11556–11561; b) H_0 was developed as a measure of the tendency of concentrate acidic solutions to protonate a family of weak reference bases (L. P. Hammett, A. J. Deyrup, *J. Am. Chem. Soc.* **1932**, 54, 2721–2739). It becomes identical to pH in dilute aqueous solutions of acids and changes from 7.0 in pure water to -12.5 in pure sulfuric acid. For a comprehensive review of the topic, see, for example: R. A. Cox, *Adv. Phys. Org. Chem.* **2000**, 35, 1–66.
- [13] R. W. Taft, R. D. Topsom, *Prog. Phys. Org. Chem.* **1987**, 16, 1–80.

- [14] Regarding the synthesis and reactivity of “superelectrophilic” species and the general topic of protosolvation, see, for example:
a) G. A. Olah, D. A. Klumpp, *Acc. Chem. Res.* **2004**, *37*, 211–220;
b) G. A. Olah, *Angew. Chem.* **1993**, *105*, 805–827; *Angew. Chem. Int. Ed. Engl.* **1993**, *32*, 767–788.
- [15] To the best of our knowledge, the most recent study on organic dications (in this case, derived from adamantane) is by G. Rasul, G. A.

Olah, G. K. Surya Prakash, *Proc. Natl. Acad. Sci. USA* **2004**, *101*, 10868–10871.

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