

JMS Letters

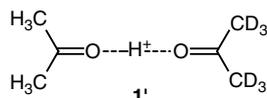
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Dear Sir,

The proton-bound dimer of acetone

Kinetic isotope effects (KIE) affect rates of ion–molecule reactions and provide access to important information on binding patterns of gaseous ions and neutral molecules and their reaction mechanisms.¹ Mass spectrometric techniques have been widely used to measure KIE, and Cooks' kinetic method has been invaluable to measure the intrinsic nature and extents of KIE, most particularly the relatively small values normally associated with secondary KIE.²

Recently, using electrospray ionization mass spectrometry (ESI-MS), Schröder *et al.*³ used Cooks' kinetic method to measure the secondary KIE associated with the 5–20 eV collision-induced dissociation (CID) of the proton-bound dimer of acetone-*d*₀ and acetone-*d*₆, presumably the loosely bonded ion **1'**, and found an *inverse* secondary KIE of 0.82–0.79. This value is in marked contrast to the *normal* KIE of 1.17 reported by us⁴ for 15 eV CID with argon of the mass-selected proton-bound dimer of acetone-*d*₀ and acetone-*d*₆ generated in the gas-phase by chemical ionization (CI). For the metastable ion, KIE of 1.01^{2d} and 0.93³ have also been measured. Hence, for ions presumed to be **1'**, different instruments and methods provide KIE ranging widely from 1.17 to 0.79. These values vary far beyond the experimental uncertainties, *from normal to inverse KIE!*



Such large and qualitative differences in KIE suggest, therefore, that isomeric ions have been sampled. Although Schröder *et al.* offer no conclusive explanation, they suggested that the covalent species **2** (Fig. 1) is formed under CI. Isomer **2** was predicted by B3LYP calculations to be a local minimum being placed 78 kJ mol⁻¹

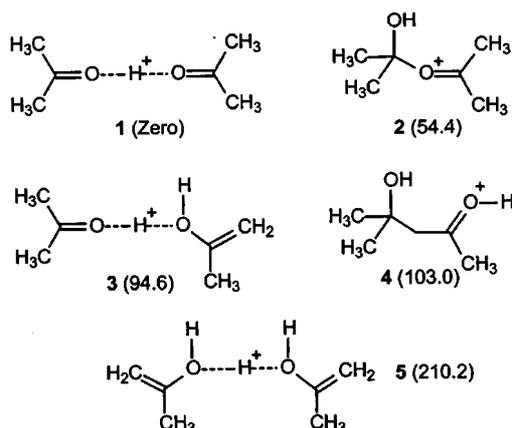


Figure 1. The proton-bound dimer of acetone (**1**) and its isomers (**2**–**5**). Relative B3LYP/6–311G(d,p) energies in kJ mol⁻¹ are shown in parentheses.

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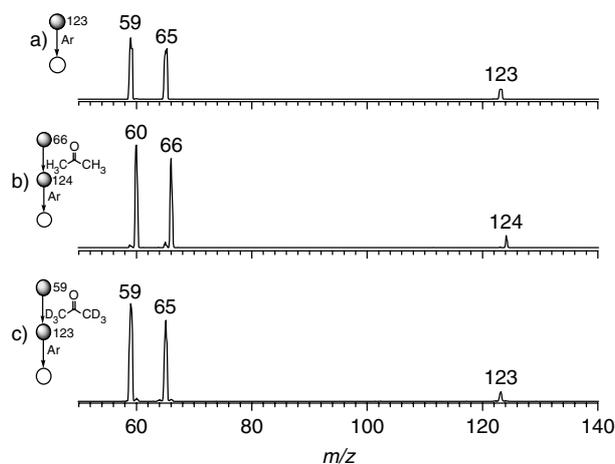


Figure 2. (a) CI tandem and (b, c) triple-stage sequential product ion mass spectra for the putative H⁺ (a, c) or D⁺ (b) bound dimer of acetone-*d*₀ and acetone-*d*₆ of *m/z* 123 (*m/z* 124 for D⁺).

above **1** but 73 kJ mol⁻¹ below the reactants (acetone and protonated acetone).³ As proposed by Nourse and Cooks,^{2d} the participation of acetone enol structures such as **3** and **5** for the gaseous ion is unlikely owing to lack of H/D exchange between the two acetone units.

We decided to contribute to the elucidation of the puzzling structure of the proton-bound dimer of acetone by performing additional calculations and, particularly, reactions with mass-selected ions to form the gaseous ion via MS³ experiments in a pentaquadrupole mass spectrometer.⁵ We first performed B3LYP/6–311G(d,p) calculations for **1** and **2** and also for three other loosely and covalently bonded isomers **3**–**5** involving enolic forms of acetone. As Fig. 1 summarizes, the 'classical' and loosely bonded dimer **1** is found to be, intrinsically, by far the most stable isomer, with the second most stable isomer **2** placed 54.4 kJ mol⁻¹ above **1**. The 'enolic' isomers **3**, **4** and **5** also lie considerably higher in energy than **1**.

For the MS³ experiments,⁶ we rationalized that if indeed gaseous **2** is formed under CI conditions as a local minimum and is trapped in a sufficiently deep potential well, either one or at least different proportions of the two isotopomeric ions **2'** and **2''** (Eqns (1) and (2)) could be formed if the order of addition is controlled by using specific isotopologue reactant ions. That is, unless proton exchange between the reactants is very rapid (which would otherwise favor the formation of the most stable isomer **1**), addition of neutral acetone-*d*₀ to the mass-selected protonated acetone-*d*₆ in an MS² experiment would be expected to form isotopomer **2'** (Eqn (1)). The opposite reaction would otherwise occur by addition of neutral acetone-*d*₆ to the mass-selected protonated acetone-*d*₀ to form isotopomer **2''** (Eqn (2)). Both isotopomeric (and therefore 'isotopically asymmetric') covalently bonded species would be expected to dissociate in MS³ experiments via CID to form contrasting ratios of fragment ions. That is, **2'** is expected to dissociate mainly to protonated acetone-*d*₆ of *m/z* 65 whereas **2''** should dissociate preferentially to protonated acetone-*d*₀ of *m/z* 59.

However, as Fig. 2 clearly shows, all three gaseous ions generated either by CI (Fig. 2(a)) or via reactions with mass-selected ions in opposite addition orders (Fig. 2(b) and (c)) form similar ratios of product ions (variations within the experimental uncertainty of ~10%) with KIE > 1. Note that, in fact, the isotopologue D⁺ dimer of *m/z* 124 was sampled in Fig. 2(b) as we used self-CI of acetone-*d*₆ to form the reactant ion (CD₃)₂COD⁺ of *m/z* 66.

In the gas phase, the calculation and MS³ results therefore seem to exclude the covalently bonded ion **2** as the main constituent of the ionic population of *m/z* 123 arising from self-CI of acetone. Using a quadrupole time-of-flight mass spectrometer (for experimental conditions, see Ref. 7), we also mass-selected and dissociated

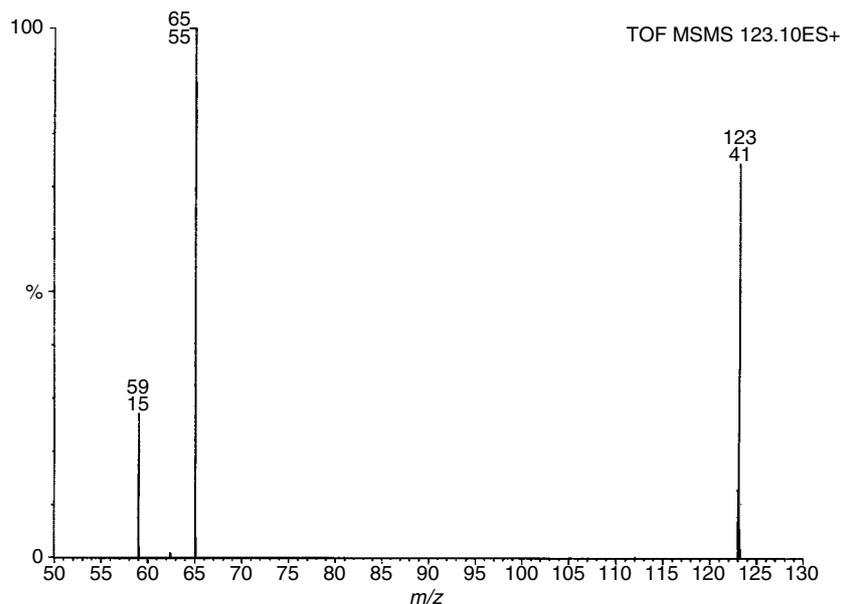
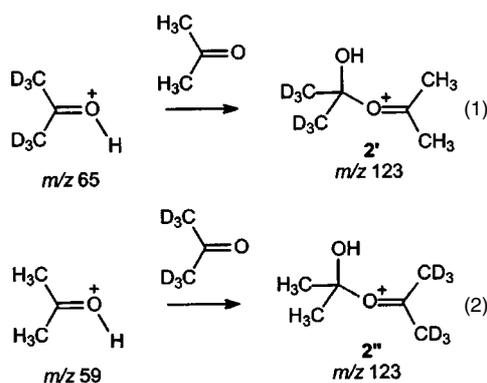


Figure 3. ESI tandem mass spectra for CID of the ion of m/z 123 'fished' to the gas phase from an acetone- d_0 /acetone- d_6 acid solution.



the ion of m/z 123 'fished'⁸ to the gas phase by ESI from an acetone- d_0 /acetone- d_6 acid solution (Fig. 3). We were astonished to observe that the *inverse* KIE that we measured for the ion by ESI-MS (0.27 ± 0.05) under conditions similar to those described by Schröder *et al.*³ is much larger than the inverse KIE they measured (0.79 ± 0.05). These contrasting KIE therefore indicate that the ESI-MS data on such an ion is heavily affected by slight variations of solution properties or ESI conditions, or both.

We therefore argue that, in fact, the gaseous ion of m/z 123 formed either via self-CI of acetone or under more gentle and controlled conditions via reactions with mass-selected ions in MS² experiments is predominantly the loosely bound species **1**, which is by far the most intrinsically stable isomer as predicted by B3LYP/6-311G(d,p) calculations. Regardless of the reactant isopologue ion (Fig. 1), the same 'isotopically symmetrical' species **1'** was likely formed in our MS³ experiments. Hence, a normal KIE (>1) for the dissociation of the proton-bound dimer of acetone- d_6 /acetone- d_0 **1'** is observed, as ZPE calculations predict.⁴

For the ion of m/z 123 pre-formed in solution, a possible rationale for its contrasting behavior could consider that solvent or counter-ion effects, or both, may alter the stability order as compared with that prevailing for the gaseous ions (Fig. 1). Therefore, the most stable solvated isomer may not be **1**, and such a relatively cold ion may be gently transferred by ESI and remain as such in the gas phase owing to substantial isomerization barriers.

Cooks' kinetic method is therefore likely to provide reliable KIE for the dissociation of the proton-bound dimer of acetone and other higher homologues as long as the most intrinsically

stable loosely bound species **1'** (or analogues) are formed in the gas phase. In fact, as previously demonstrated,⁹ unexpected KIE or ion affinities measured by the method serve as indications of 'anomalous' structures since the method is also applicable to probe structures of gaseous ions.

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Yours,

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