

Gas-phase Protonation of Unsaturated Ethers: Experimental and Theoretical Study of 2,3- and 2,5-Dihydrofuran and Related Compounds

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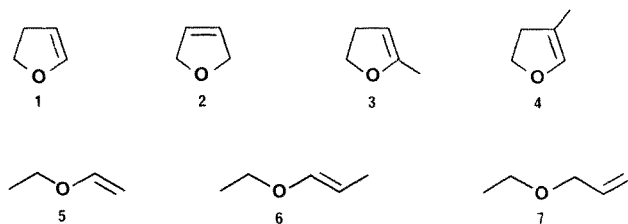
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The protonation of 2,3- and 2,5-dihydrofuran is examined in gas-phase equilibrium proton transfer reactions conducted in an ion cyclotron resonance spectrometer. The thermodynamically favoured site of protonation in the two compounds is seen to be different: whereas the first isomer forms a carbocation upon protonation, the second isomer protonates on the oxygen atom to form an oxonium ion. The results obtained with substituted derivatives and with linear analogues confirm these conclusions. Molecular orbital calculations on the various structures for protonated bases are performed at the 4-31G level with correction for configuration interaction effects and at the 4-31G* level. The latter basis set provides the best results owing to the introduction of d-type orbitals on the oxygen atom. The calculation results substantiate the experimental observations and provide details on the molecular structure of the protonated species.

Protonation is the simplest form of electrophilic attack, but in the condensed phase this simplicity is often obscured by intermolecular effects. In contrast, low-pressure gas-phase experiments afford intrinsic acid-base properties of isolated systems. In particular, ion cyclotron resonance (ICR) spectrometry yields reliable thermodynamic quantities for reactions conducted under equilibrium conditions.¹ However, the structures of the isolated ions are not gained directly from experiment, especially when the system under study contains several basic sites. This difficulty may be circumvented by comparing gas-phase basicities of unknown and of related monofunctional compounds, or, by calculating the potential energy of the presumed ionic products. Accordingly, the approach used here combines information obtained from experimental and theoretical methods.

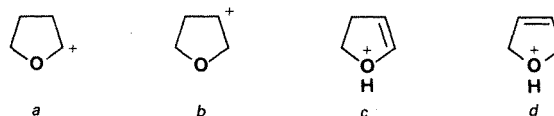
The present study is concerned with the gas-phase basicity of the five-membered cyclic α,β - and β,γ -unsaturated ethers 1-4 and their linear analogues 5-7. It is known from solution chemistry that in acidic



media ethers 1 and 2 react very differently; the former undergoes hydrolysis accompanied by a ring opening yielding γ -hydroxybutyraldehyde, whereas the latter is less sensitive to acids.² We have therefore examined the protonation processes by ICR spectrometry in

order to help in the understanding of these opposite reactions in the gas phase.

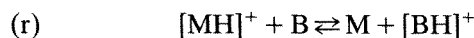
In addition, *ab initio* molecular orbital (MO) calculations have been used to obtain the relative energies of the four cations *a-d* and to thus reinforce the conclusions as to the preferred protonation site in 1 and 2.



RESULTS





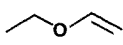
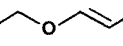
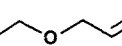
Experimental gas-phase basicities and proton affinities

Equilibrium proton transfer reactions between unsaturated ethers 1-7 and reference bases were carried out in the ICR instrument built at EPF (Lausanne). It was operated in the trapped mode under the same conditions as previously described.³ Determination of the equilibrium constant K_{eq} for the reaction (r):



was made for $M = 1-7$ and several reference bases B under a total pressure of $\approx 10^{-6}$ Torr at the temperature of 313 K. The gas-phase basicity of M is given by $GB(M) = GB(B) + \Delta G_r^\circ$ where ΔG_r° is the free energy change associated with reaction (r). The latter term is calculated using $\Delta G_r^\circ = -RT \ln K_{eq}$. All

Table 1. Free energy changes ΔG_i° in the proton transfer equilibrium $[\text{MH}]^+ + \text{B} \rightleftharpoons \text{M} + [\text{BH}]^+$ and related gas-phase basicities (GB)^a





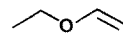
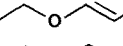
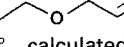
	M	Reference base B	GB(B)	ΔG_i°	GB(M) ^a
1		Pentan-2,5-dione	837 ^b	-0.4	837
		<i>p</i> -Methylstyrene	836 ^c	-0.4	
2		Diethyl ether	808 ^b	-5.0	802
		Tetrahydropyran	806 ^b	-4.1	
3		3-Bromopyridine	869 ^e	1.7	871
		Ethylamine	873 ^b	-2.1	
4		Pentan-2,5-dione	837 ^b	-0.5	837
5		3-Penten-2-one	835 ^b	3.8	837
		<i>p</i> -Methylstyrene	836 ^c	0.0	
6		4-Methyl-3-pentene-2-one	847 ^d	+1.	848
7		<i>n</i> -Propyl acetate	813 ^b	-1.	812

^a All values expressed in kJ mol⁻¹.^b Ref. 1.^c Ref. 7a.^d Unpublished value.^e Revised value, this compound was found to be less basic than ethylamine by 5 kJ mol⁻¹.^f Ref. 7b.^g ± 1 kJ mol⁻¹, deviation on the experimental determination of ΔG_i° .

these experimentally determined basicity data are collected in Table 1.

The proton affinities (PA) may be obtained after correction of the GB value by the appropriate entropic term: $PA(\text{M}) = GB(\text{M}) + T\Delta S$. If the symmetry numbers σ of M and $[\text{MH}]^+$ are the same, ΔS

Table 2. Proton affinities PA(M) and heats of formation ΔH_f° of M and $[\text{MH}]^+$ (kJ mol⁻¹)

	M	PA(M)	$\Delta H_f^\circ(\text{M})$	$\Delta H_f^\circ([\text{MH}]^+)$
1		870 ^b	-115	545
2		835 ^b	-82	613
3		904 ^b	-150	476
4		870 ^b	-150	510
5		872 ^c	-146	512
6		883 ^c	-179	468
7		845 ^b	-140	545

^a ΔH_f° calculated by the increment group method of Benson.⁵^b $T\Delta S = 33$ kJ mol⁻¹ (see text).^c $T\Delta S = 35$ kJ mol⁻¹, a new internal rotation appears in the protonated products.

may be approximated by the translational entropy for the isolated proton thus yielding $T\Delta S = 33$ kJ mol⁻¹ at 313 K. This correction can be applied to **1** and **3-7** whatever the protonation site and to **2** if protonation occurs on the oxygen atom. In the case where the protonation of the symmetric molecule **2** ($\sigma = 2$) gives ion *b* ($\sigma = 1$) the $T\Delta S$ term should be reduced by $RT \ln 2$. As will be seen in the discussion, the latter ion is not expected to be formed by protonation of **2** under equilibrium conditions and thus $T\Delta S = 33$ kJ mol⁻¹ should be used in this case also. A slightly different correction is applied for the linear ethers **5** and **6**, owing to the modification in the number of rotational degrees of freedom upon protonation. The PA values so deduced from experimental GB are listed in Table 2. The heats of formation of the protonated molecule $[\text{MH}]^+$ are also estimated (Table 2) using $\Delta H_f^\circ(\text{H}^+) = 1530$ kJ mol⁻¹⁴ and ΔH_f° for neutral M calculated by additivity.⁵

Ab initio molecular orbital calculations

The geometries of the four $[\text{C}_4\text{H}_7\text{O}]^+$ ion structures *a-d* were optimized using the split valence 3-21G atomic orbital basis set and by the gradient techniques implemented in the MONSTERGAUS suite of programs.⁶ The four resulting structures are displayed in Fig. 1.

More accurate calculations of total energies were made with the 4-31G and 4-31G* basis sets and with inclusion of the correlation energy at the 4-31G level. These latter configuration interaction (CI) calculations have been performed with the perturbational and variational algorithm CIPSI.⁷ Assuming additivity of electron correlation and polarization effects, an estimate of the relative energies at the CI/4-31G* level can be made from:

$$\Delta E(\text{CI}/4\text{-}31\text{G}^*) = \Delta E(\text{CI}/4\text{-}31\text{G}) + \Delta E(4\text{-}31\text{G}^*) - \Delta E(4\text{-}31\text{G})$$

This method of evaluation, first suggested by Lipscomb^{8a} and Radom,^{8b} is now supported by several investigations on oxygenated closed-shell carbocations.⁹ Total and relative calculated energies are presented in Tables 3 and 4.

At this stage it can be observed that the four structures have quite different stabilities, which should render unambiguous the assignment of the protonation site. The stabilizing effect due to electron correlation is approximately the same for the four structures. In contrast, the incidence of the basis set enhancement is noteworthy. On going from 4-31G to 4-31G* there is a large increase in the calculated energy difference between carbon-protonated (*a* and *b*) and oxygen-protonated (*c* and *d*) cations. It is believed that introduction of d-type functions (for example using the 4-31G* basis set) is necessary to afford the (hyper)valences of the oxygen atom in *c* and *d*. Such inadequacies of the simple, non-polarized, basis set are unprecedented.^{9a} The best prediction of the theory concerning the stabilities of the four $[\text{C}_4\text{H}_7\text{O}]^+$ ions *a-d* is found in the two last columns of Table 4.

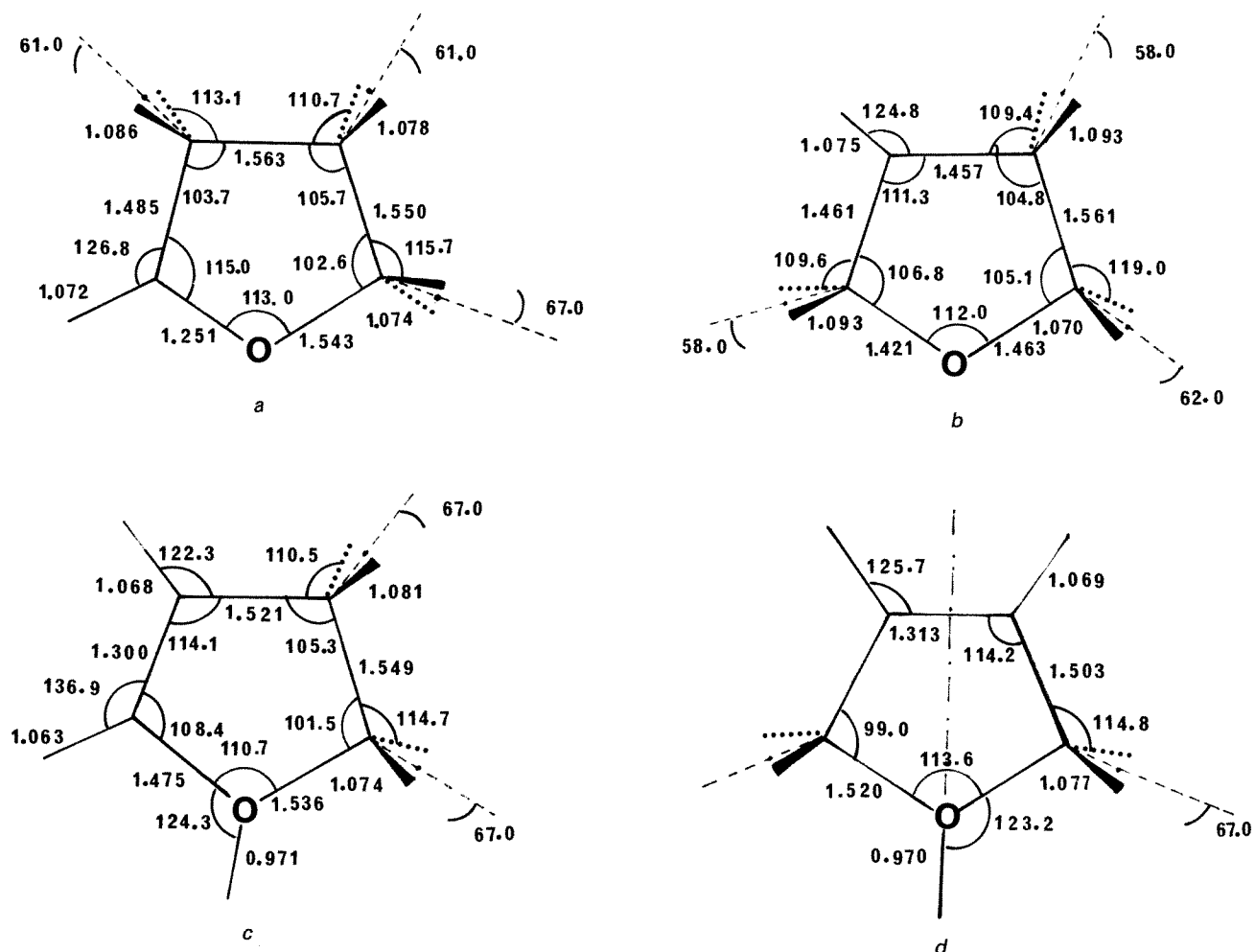


Figure 1. Geometries of optimized 3-21G structures (bond lengths in Å, bond angles in degrees).

DISCUSSION

Protonation of α,β -unsaturated ethers

Protonation of 2,3-dihydrofuran (**1**) may lead to the three $[\text{C}_4\text{H}_7\text{O}]^+$ ions *a*, *b* and *c* (Scheme 1). The MO calculations presented above indicate that formation





of ion *a* is favoured by 123 kJ mol^{-1} with respect to *c* and by 221 kJ mol^{-1} with respect to *b*. These results indicate that protonation occurs preferentially on the β -carbon atom in the equilibrium proton transfer experiments.

The situation described in Scheme 1 should apply to all other molecules containing one oxygen atom conjugated to one carbon-carbon π bond. The

Table 3. Calculated total energies (Hartree) of $[\text{C}_4\text{H}_7\text{O}]^+$ five-membered ions

Structure	3-21G//3-21G	4-31G//3-21G	CI/4-31G//3-21G	4-31G*///3-21G
<i>a</i>	-228.862360	-229.797859	-230.268022	-229.921309
<i>d</i>	-228.853607	-229.789645	-230.256661	-229.884371
<i>c</i>	-228.846489	-229.780739	-230.250048	-229.875176
<i>b</i>	-228.793664	-229.735742	-230.190795	-229.852277

Table 4. Calculated relative energies (kJ mol⁻¹) of [C₄H₇O]⁺ cations of structures a–d^a

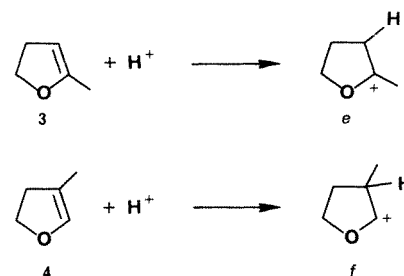
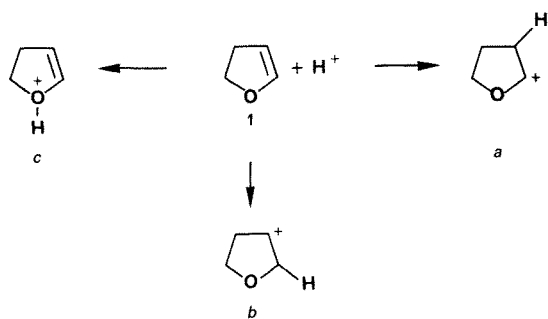
Structure	4-31G	CI/4-31G*	4-31G*	CI/4-31G* ^b
a 	0	0	0	0
d 	22	30	97	105
c 	45	47	121	123
b 	163	203	181	221

^a *Ab initio* 3-21G optimized geometries (see Fig. 1).

^b Estimated assuming additivity of correlation and polarization effects (see text).

simplest case is vinyl alcohol, CH₂=CHOH, where it is established that the most stable adduct (CH₂CHOH + H⁺) is the [CH₃CHOH]⁺ ion.^{9a,10} *Ab-initio* MO calculations predict that the protonation of CH₂=CHOH on the β-carbon atom is favoured by 90 kJ mol⁻¹ over that of the hydroxyl groups^{9a} and by 215 kJ mol⁻¹ over that of the α-carbon atom.¹⁰ Our present calculations are in good agreement with these investigations, although the latter were conducted at a higher level of theory and on a simpler system.

Several experimental arguments confirm the preferred formation, under equilibrium conditions, of a structure like *a* in which the π-donating effect of the oxygen atom stabilizes the adjacent cationic centre. First, Table 1 reveals identical *GB* values for the three conjugated ethers, **1**, **4** and **5** (837 kJ mol⁻¹). If protonation of **5** occurs on the β-carbon atom, the adduct ion is [CH₃CH₂OCHCH₃]⁺. For the latter Lossing proposed a Δ*H*_f^o value of *c.* 500 kJ mol⁻¹ on the basis of appearance energies measurements with monoenergetic electrons.¹¹ The Δ*H*_f^o of [5H]⁺ presented in Table 2 and deduced from the *GB* determinations is 513 kJ mol⁻¹, in agreement with Lossing's expectation and thus confirming the site of protonation to be the β-carbon atom for **5** and consequently for **1** and **4**.



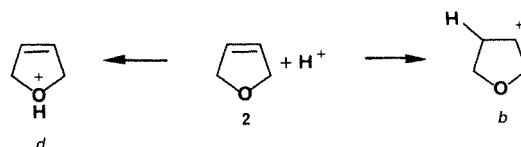
Second, all the conjugated ethers **1** and **3–6** are more basic than the saturated analogues: *GB*(tetrahydrofuran) = 805 kJ mol⁻¹, *GB*(diethyl ether) = 808 kJ mol⁻¹.¹ This is not predicted if protonation occurs at the oxygen atom. On the contrary, the π electron-releasing effect of the oxygen atom should decrease its basicity and, subsequently, orient protonation towards the olefinic system.

Third, the incidence of the position of the methyl group on the *GB* values of **3** and **4** is noteworthy and can be only interpreted by a β-protonation process (Scheme 2). In this instance, the following experimental data are explained: (i) *GB*(**1**) = *GB*(**4**) and (ii) *GB*(**3**) > *GB*(**1**). To illustrate those two points, one may consider the substituent effect on enthalpic quantities (Table 2). The identity *PA*(**1**) = *PA*(**4**) indicates that the differences in heats of formation between **1** and **4** and between their protonated counterparts [1H]⁺ and [4H]⁺ are equal. This common difference, Δ*H*_f^o = 35 kJ mol⁻¹, compares well with Δ*H*_f^o(CH₃CHOH) – Δ*H*_f^o(CH₃CH₂CHOH) = 29 kJ mol⁻¹,¹¹ where the two secondary carbocations differ only by the addition of a methyl group in the β position to the oxygen atom. This is exactly the expectation if protonation of **1** and **4** gives oxycarbonium ions *a* and *f*.

The introduction of a methyl group in position 2 is accompanied by an increase in *PA*, *PA*(**3**) – *PA*(**1**), equal to 34 kJ mol⁻¹. The difference in heats of formation between the neutral is again 35 kJ mol⁻¹; thus [3H]⁺ is more stable than [1H]⁺ by 69 kJ mol⁻¹. This enthalpy difference compares well with: Δ*H*_f^o([CH₃CHOH]⁺) – Δ*H*_f^o([(CH₃)₂COH]⁺) = 79 ± 8 kJ mol⁻¹ and Δ*H*_f^o([CH₃CHOH₃]⁺) – Δ*H*_f^o([(CH₃)₂COCH₃]⁺) = 75 ± 8 kJ mol⁻¹,¹¹ thus confirming that protonation of **3** yields the tertiary carbocation *e*.

Protonation of β,γ-unsaturated ethers

The two possibilities for protonating 2,5-dihydrofuran (**2**) are summarized in Scheme 3. An energy difference of 116 kJ mol⁻¹ is predicted by MO calculation favouring the oxygen-protonated species *d* over *b*.



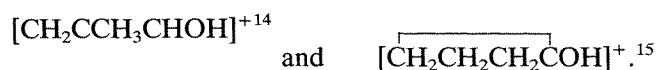
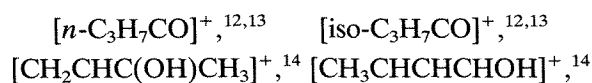
Consequently, in equilibrium proton transfer experiments, protonation of β,γ -unsaturated ethers should occur on the oxygen atom.

Once again, the experimental data confirm the expectations based on molecular orbital studies. The GB values for **2** and **7**, respectively 802 and 812 kJ mol⁻¹ (Table 1), are very close to that of saturated cyclic or linear ethers ($GB(\text{tetrahydrofuran}) = 805 \text{ kJ mol}^{-1}$, $GB(\text{diethyl ether}) = 808 \text{ kJ mol}^{-1}$).¹ Moreover these values are far from the GB of cyclopentene (703 kJ mol⁻¹) and propene (774 kJ mol⁻¹).¹ The difference in GB of c 100 kJ mol⁻¹ between unconjugated ethers and olefinic compounds is in good agreement with the calculated energy difference between d and b noted above.

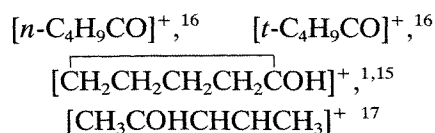
These conclusions confirm the intuitive idea that **2** and **5** contain two non-interacting functional groups and that the most basic site is provided by the ether function.

Thermochemistry of the $[\text{C}_4\text{H}_7\text{O}]^+$ and $[\text{C}_5\text{H}_9\text{O}]^+$ systems

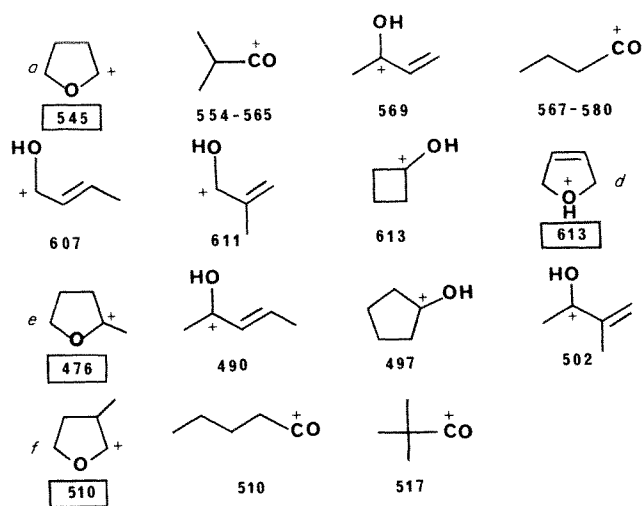
The experimentally derived thermochemical data for $[\text{C}_4\text{H}_7\text{O}]^+$ ions have been, until now, limited to ΔH_f° values for six structures:



Five experimental ΔH_f° ($[\text{C}_5\text{H}_9\text{O}]^+$) have been available, for the following structures:



and



Scheme 4

These heats of formation, expressed in kJ mol⁻¹ are shown in Scheme 4 together with the new experimental values attributed to ions a , d , e and f (Table 2).

The major observation concerning these two systems $[\text{C}_n\text{H}_{2n-1}\text{O}]^+$ is that the presently determined ΔH_f° values for structures a and e are the lowest in each series. Their participation in the description of low-energy dissociation processes of oxygenated cations is thus to be expected.

EXPERIMENTAL

4-Methyl-2,3-dihydrofuran (**4**) was synthesized by the procedure described by Zenk and Wiley.¹⁸ First, 3-methyl-2-oxotetrahydrofuran was reduced by diisobutylaluminum hydride in hexane. The resulting lactol was added rapidly to a stirred solution of *p*-toluenesulphonic acid in isoquinoline, and the product **4** was simultaneously distilled. Boiling point (64 °C) and NMR characteristics were identical to the literature data.¹⁹

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