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Ethylene glycol to acetaldehyde-dehydration or a concerted mechanism

William B. Smith*

Department of Chemistry, Texas Christian University, Fort Worth, TX 76129, USA

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Abstract—Two possible mechanisms have been proposed to account for the rearrangement of ethylene glycol to acetaldehyde. The first is a rearrangement with a hydride shift occurring in concert with the loss of a water molecule. The second is an acid catalyzed dehydration reaction proceeding through the enol to yield acetaldehyde. DFT calculations are presented which show the first postulation to be the lower energy pathway by a considerable margin. © 2002 Elsevier Science Ltd. All rights reserved.

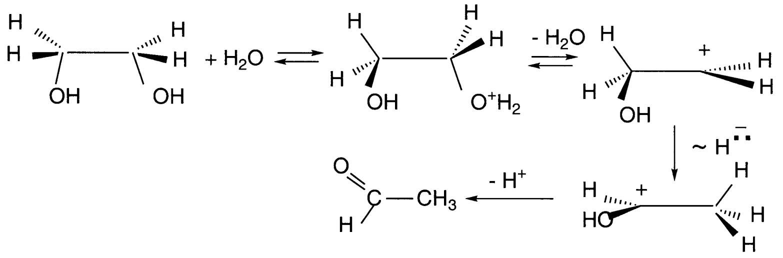
1. Introduction

The indices collected earlier by Beilstein[1] gave a number of examples of the conversion of ethylene glycol to acetaldehyde. In his 1949 textbook, Wheland[2] extensively reviewed the pinacol rearrangement. Applying the carbocation mechanism first suggested by Whitmore,[3] he was able to correlate a vast body of experimental data. Applying the Whitmore mechanism to ethylene glycol, the reaction path to acetaldehyde may be written as in Scheme 1.

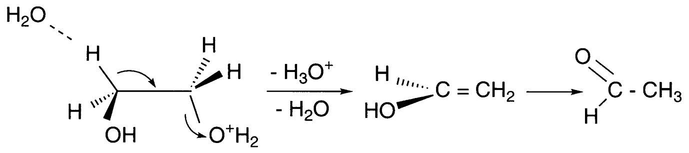
Ingold[4] pointed out that when hydrogen is the migrating group in a pinacol rearrangement one could equally well explain the rearrangement by evoking an acid catalyzed loss of water with enol formation proceeding on to the carbonyl product. Since an E1 elimination seems unlikely in forming a primary carbocation, the mechanism (Scheme 2) is shown here as a E2 process.[5]

While considering the Whitmore mechanism for pinacol itself, the Fiesers[6] considered only the dehydration mechanism for ethylene glycol.

The issue of enol vs a 1,2-shift mechanism involving hydrogen migration has been addressed for a limited set of structures. Ley and Vernon[7] rearranged 1,2-dimethyoxy-2-



Scheme 1. The Whitmore mechanism.



Scheme 2.

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* Fax: +1-817-257-5851; e-mail: w.b.smith@tcu.edu

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methylpropane in DOMe and concluded that the isotopic enrichment in the 1,1-dimethoxy-2-methylpropane product was consistent with an internal migration of the hydrogen. Based on deuterium isotope and carbon-14 studies, Collins and co-workers[8] showed that 1,1,2-triphenylethylene glycol-2-D followed very closely upon the classical carbocation mechanism. Examination of the benzhydryl phenyl ketone by infrared and NMR indicated an internal migration of hydrogen. In a parallel study with 1,1,2-trimethylethylene-2-D glycol Smith and students[9] found infrared evidence for the retention of a substantial portion of the migrating deuterium.

Each of the studies considered above represent pinacol rearrangements with a tertiary hydroxyl or methoxyl group at the migration origin and a primary or secondary hydroxyl (methoxyl) group at the migration terminus. These reactions all occur under conditions that are milder than those associated with the rearrangement of ethylene glycol. Consequently, the dehydration mechanism cannot be summarily dismissed in this case.

At least two computational studies of the pinacol rearrangement have appeared in recent years.[10,11] Nakamura and Osamura[10] published an ab initio study of the pinacol rearrangements of ethylene, propylene and isobutylene glycols at the HF/6-31G**//HF/6-31G* level. They reported the first formed β-hydroxycations for the first two examples to spontaneously rearrange to the protonated carbonyl products. The *tertiary* cation formed first from the isobutylene glycol acted as a stable intermediate. They favored hydrogen-bridged transition structures (TSs) as energetically the more favored pathways to products.

Subsequent work in These Laboratories[11] employed the B3LYP/6-31G* methodology to study the rearrangements of ethylene glycol and 1,1-dimethyl- and 1,1,2-trimethylethylene glycols, respectively. It was shown that the spontaneous rearrangement of the β-hydroxycation of ethylene glycol occurred only when one C–H bond was specifically anti periplanar to the departing water molecule. The work supported the mechanism of a concerted hydrogen migration with the loss of water though not the concept of bridged hydrogen cations as intermediates. Experimental deuterium isotope effects were reproduced by these calculations.

The proposal of the dehydration mechanism for ethylene glycol seems amenable to a decision by computational methods. The B3LYP methodology seemed an appropriate method for the current determination. The results of such a study are given below.

2. Computational methods

All calculations were carried out with Gaussian 98.[12] Schleyer and co-workers[13] have established that the B3LYP/6-31G* method produces satisfactory results for carbocation processes including those reactions which involve bridged or nonclassical structures. This method was employed throughout here. Synchronous transit-guided quasi-Newton methods were employed in searching for TSs.[14,15] In the fastest of these, QST2, a TS is approximated from input structures for the starting material and the product(s). This structure may then require refinement by the QST3 method in which these structures are augmented by the approximate TS, the result leading to new TS that may be optimized to give a structure exhibiting a single imaginary frequency corresponding to motion along the reaction coordinate. These methods failed with respect to the dehydration reaction forming only the concerted TS. A series of relaxed potential energy scans were employed to find a reasonable TS for the dehydration procedure. All structures were subjected to frequency calculations to determine zero point and thermal energy corrections as well as for an examination of vibrational modes. Visualizations were carried out with the graphics program GaussView 2.[16] All energies were also corrected for the solvent effects of water using the polarized continuum model of Miertius and Tomasi.[17] All stable structures were optimized in vacuo as well as in the solvent cavity. The software does not provide the required analytical gradients for the optimization of TSs using the polarized continuum models. The solvent corrections for these were carried out as single point calculations based on the vacuum calculated structures. Energies for all pertinent structures are given in Table 1.

3. Results and discussion

All structures were optimized by means of the Gaussian 98 program at the B3LYP/6-31G* level. To avoid the hazards of basis set superposition error all calculations were carried out with the same size basis sets, i.e. the same number and atom types in all calculations for a given set of conditions.

Initially the reasonable assumption was made that the TS for the dehydration reaction approximated an E2 process. The

Table 1. B3LYP/6-31G* total electronic energies (hartrees), ZPE corrections and thermal corrections to 25°C

	$C_2H_9O_3$ series[a]	$C_2H_{13}O_5$ series[a]
$CH_2(OH)CH_2(OH_2^+)$	−306.869975	−459.716801
TS (dehydration)	−306.787408, ΔH^*=51.8[b]	−459.603807, ΔH^*=70.9[b]
TS (concerted)	−306.828445, ΔH^*=26.1	−459.715049, ΔH^*=1.1
Acetaldehyde	−306.918289, ΔH=−30.3	−459.794289, ΔH=−48.6

1 hartree=627.51 kcal/mol.

[a] The $C_2H_9O_3$ series consists of the structure plus one water molecule calculated in vacuo. The $C_2H_{13}O_5$ series includes a total of three waters corrected in energy to the dielectric constant of water.

[b] Activation and reaction enthalpies are given in kcal/mol.

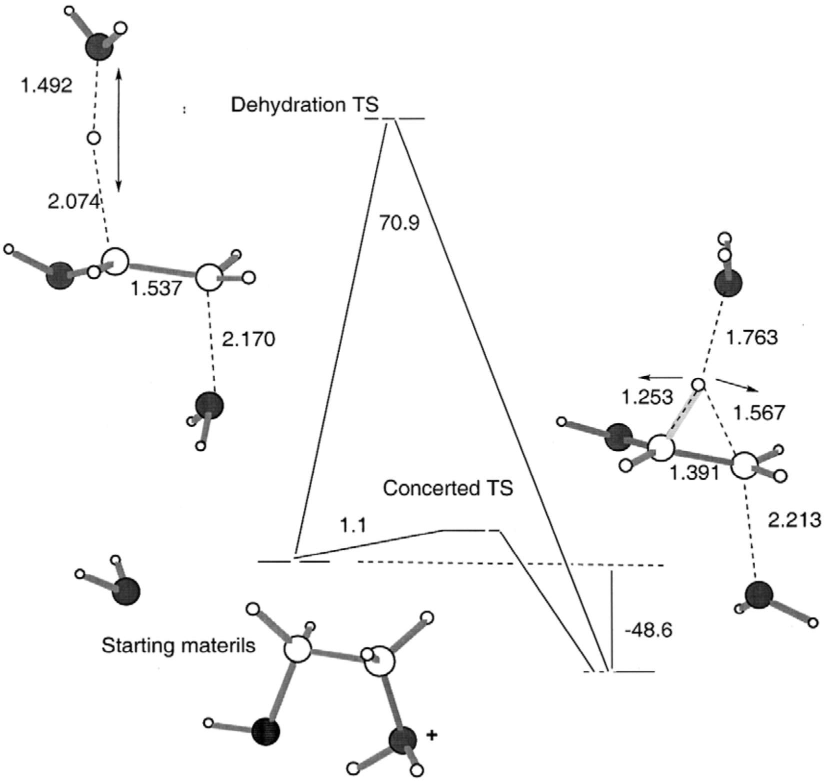

Figure 1. Reaction and activation enthalpies (kcal/mol) for the dehydration and concerted mechanisms with the structures for the appropriate TSs. The sense of the vibrations along the reaction coordinate is given by the arrows. The two additional water molecules are not shown.

loss of the protonated hydroxyl group would produce a high-energy primary carbocation if the process were E1 in nature. Nakamura and Osamura[10] established that such a carbocation would spontaneously rearrange to the 1-hydroxyethyl cation in the computational process of optimization (see Ref. 11 for comments on this observation). For the E2 process, the loss of the proton attached to the β-carbon must be stabilized by solvation with one water at least. For the initial calculations in vacuo all species then were $C_2H_9O_3$ for basis set consistency.

The TS for this process is shown in Fig. 1. The arrows illustrate the sense of the imaginary vibrations along the reaction coordinate. The calculated enthalpy of reaction was −30.3 kcal/mol and the activation enthalpy was 51.8 kcal/mol.

The TS for the concerted pinacol rearrangement converting ethylene glycol to acetaldehyde was modeled by the QST2 method and refined by a QST3 calculation. Assuming the migrating proton would take on some positive charge and for direct comparisons of the energies for the two TSs a water molecule was allowed to interact with the migrating hydrogen which was found to carry a charge of +0.2*e*. The frequency calculation confirmed the TS as having one imaginary frequency with appropriate vibrational mode. The data for the energies are given in Table 1. The structure of the TS is detailed in Fig. 1. The activation enthalpy for the concerted process is 26.1 kcal/mol. The geometry of the TS closely resembles that found previously.[11]

The Gaussian 98 program contains four variations of the polarized continuum model for solvent energy corrections. The simplest method is that of Miertius and Tomasi[17] that was employed here to correct the energies to the dielectric constant of water. A reviewer suggested that additional water molecules included in the solvent cavity would enhance the accuracy of the solvent corrections. A total of three waters were included in these calculations (the $C_2H_{13}O_5$ series, Table 1). The effect of the solvent correction was to spread the difference of activation enthalpies for the two mechanisms reinforcing the choice of the concerted mechanism over the dehydration pathway. It is clear from both sets of calculations that the concerted pathway is significantly the more favored pathway.

In summary, standard density functional techniques at the 6-31G* level have been applied to answer the question of whether the pinacol rearrangement of ethylene glycol proceeds through a dehydration to the enol then forming acetaldehyde or by a concerted migration of a hydride with the loss of water. The latter process was shown to proceed at a substantially lower activation enthalpy than the route through the enol intermediate.

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