

Fundamentals of Theoretical Organic Chemistry

Lecture 10

2.3 Elimination reactions

Introduction

Elimination:

in broader sense, any reaction where a small part of a molecule is excised or the whole molecule is fragmented

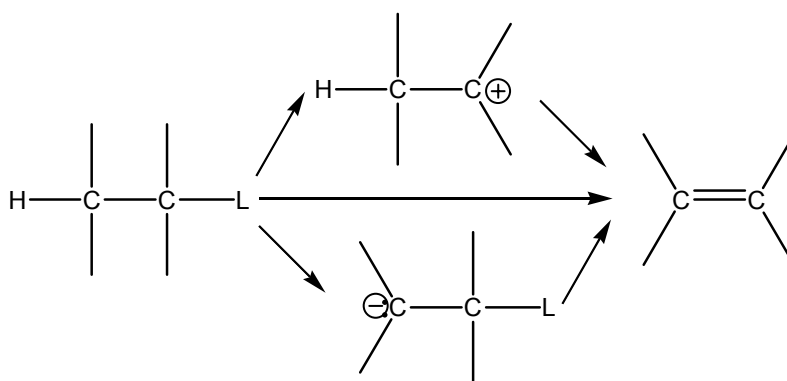
more strictly, elimination occurs when two atoms (or groups of atoms) leave the molecule without being substituted

Mechanisms

E1: leaving group (X or L in general) is excised first

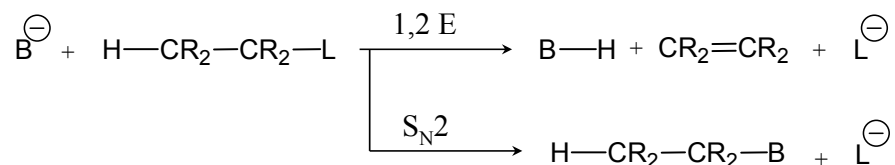
E1cb: H is the first atom to leave (cb stands for conjugated base)

E2: X and H leave in a coordinated but not necessarily concerted manner

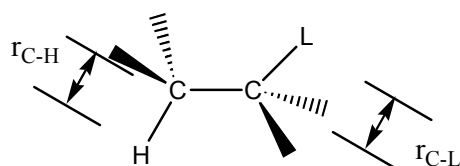


Mechanism occurring in nature are generally not 'pure', i.e. they represent an intermediate between E1 and E2. As E (elimination) is often coupled to nucleophilic substitution, these two reaction types are investigated together both by theory and experiment.

A common example



For all the mechanisms the following pair of bond lengths may be singled out as those internal coordinates that change the most during the elimination.



A schematic (PES) for the elimination reaction.

Three reaction mechanisms correspond to three routes on the (PES). Of course the molecular structure, the nature of leaving group, the basicity and concentration of nucleophile as well as the polarity of the solvent will influence which route will be the most favourable energetically.

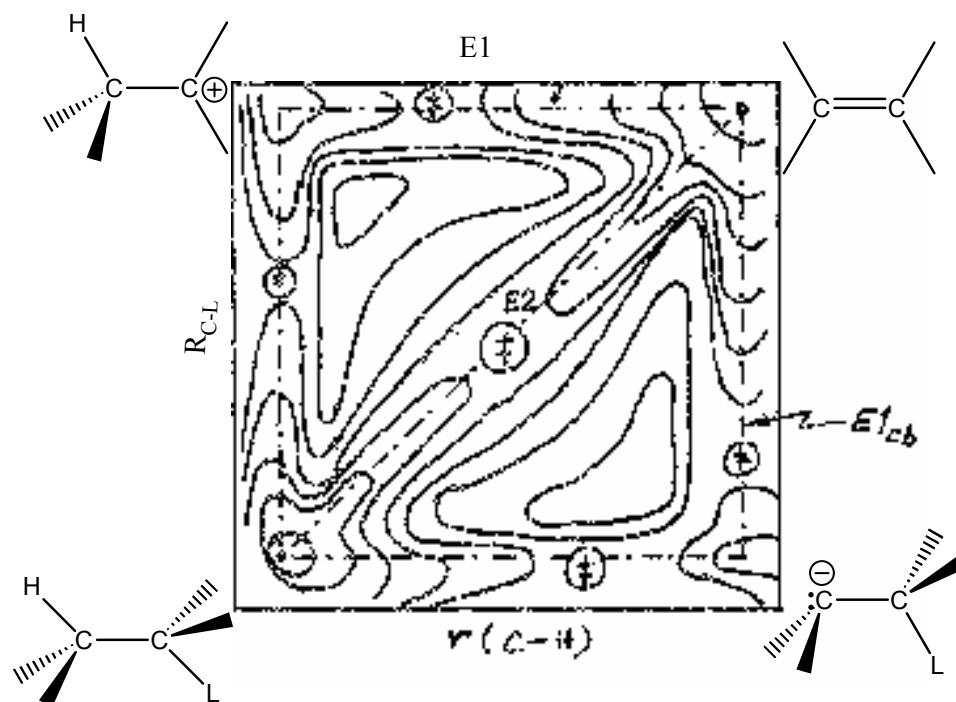
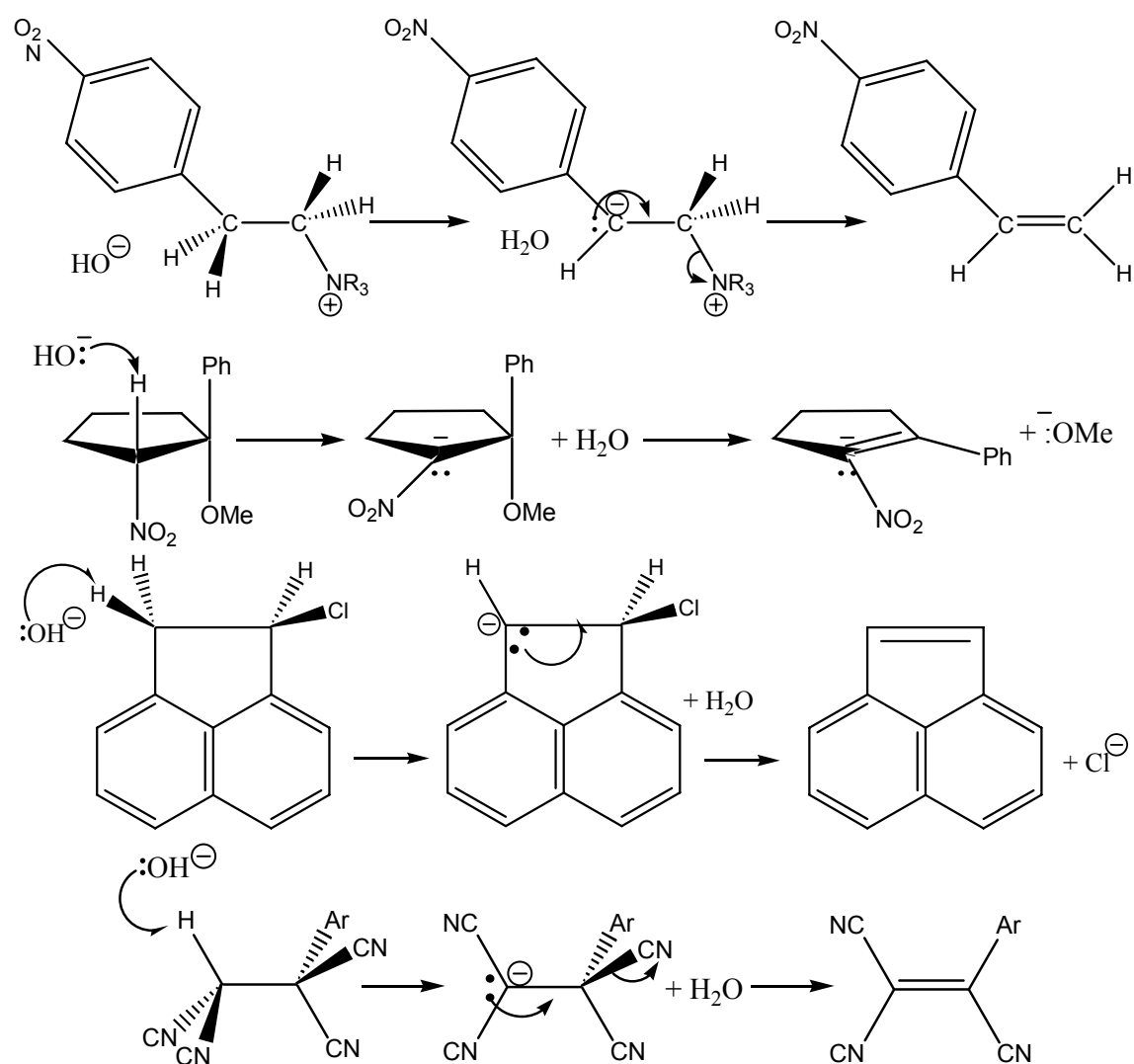


Figure 2.3.1—1 A schematic (PES) of a 1, 2 - elimination reaction.

There are rare molecular structures that favor $E1_{cb}$ mechanisms and some of examples are shown below:



However, in most cases either the E2 or the E1 mechanisms represent the lowest energy path. These two alternatives are illustrated schematically in Figure 6.14. It is assumed here that under these rather ordinary conditions the E1_{cb} mechanism is the least favoured one.

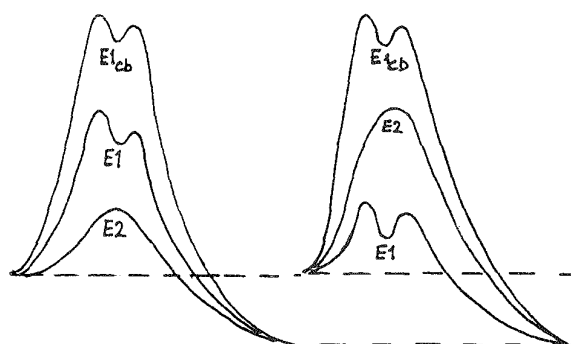


Figure 2.3.1—2 A schematic illustration of two extreme cases: E2 is favoured over E1 (left hand side) and E1 is favoured over E2 (right hand side). It is assumed that under ordinary circumstances $E1_{cb}$ is the least favoured mechanism.

Thermodynamic and kinetic control

In most cases of parallel reactions the thermodynamic stability of the products formed and the kinetic stability of the transition states leading to product formation are parallel (c.f. Figure 6.15A). In contrast to this, the potential energy surfaces may cross, leading to transition state stabilities which are different from product stabilities (c.f. Figure 6.15B).

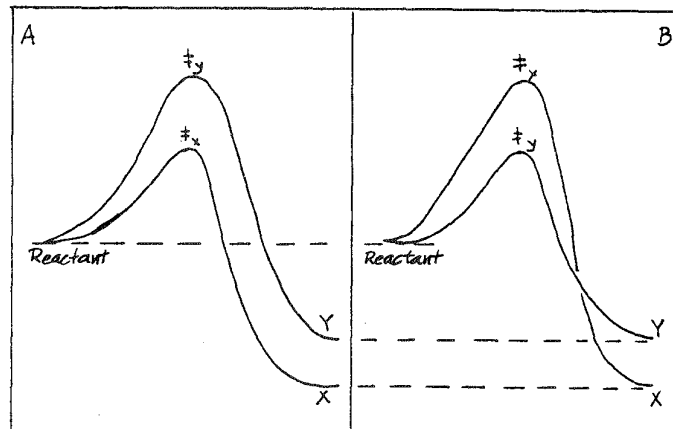
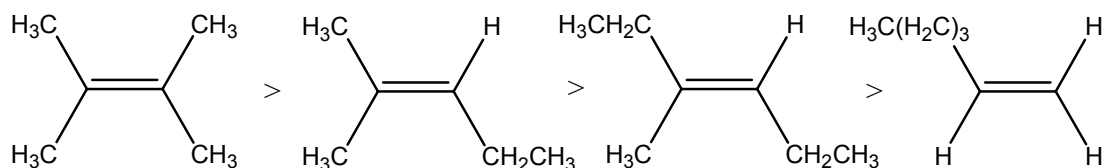


Figure 2.3.1—3 A schematic illustration of nearly parallel (A) and crossing (B) (PES) for competing reaction mechanism.

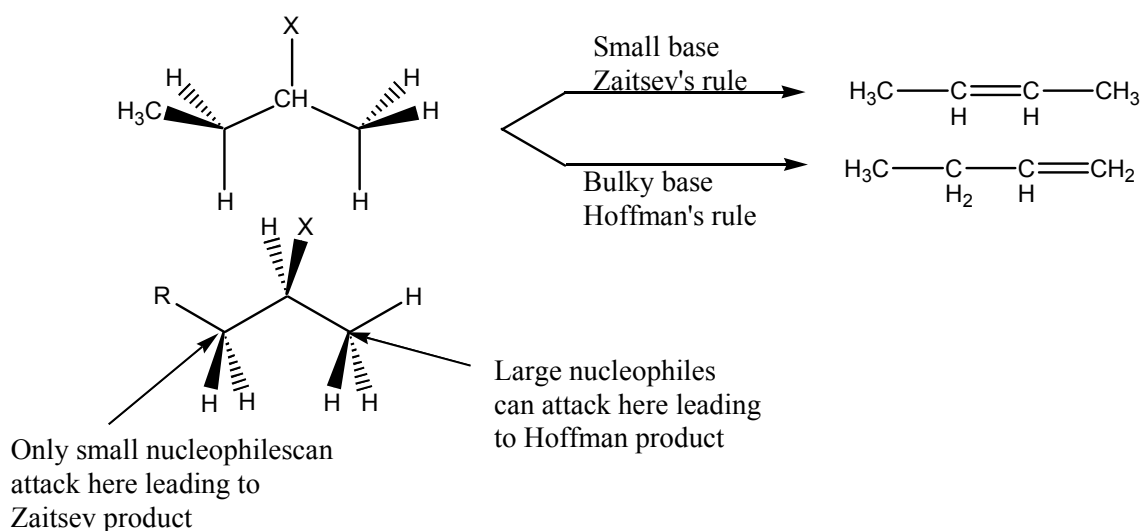
In the case shown in Figure 6.15A both product stability and transition state stability would predetermine compound X to be the major product. However, the case shown in Figure 6.15B is not all that clear. A lower barrier implies a larger rate constant and therefore a faster rate. If the rate is faster, more products is formed per unit time; thus, the relative rates would predetermine the product ratio. The situation presented in Figure 6.15B is such that the thermodynamically least stable Y will be the major product.

The more heavily an olefin is substituted, the greater its stability:



Thus it is easy to predict which isomer is to be formed in parallel elimination reactions. The Zaitsev rule presented in [6.59a] corresponds to the situation of Figure 6.14A while the Hofmann rule [6.59b] represents the case shown in Figure 6.15B. We may say therefore, that the Hofmann product is under kinetic control while the Zaitsev product follows the thermodynamic stability of the product.

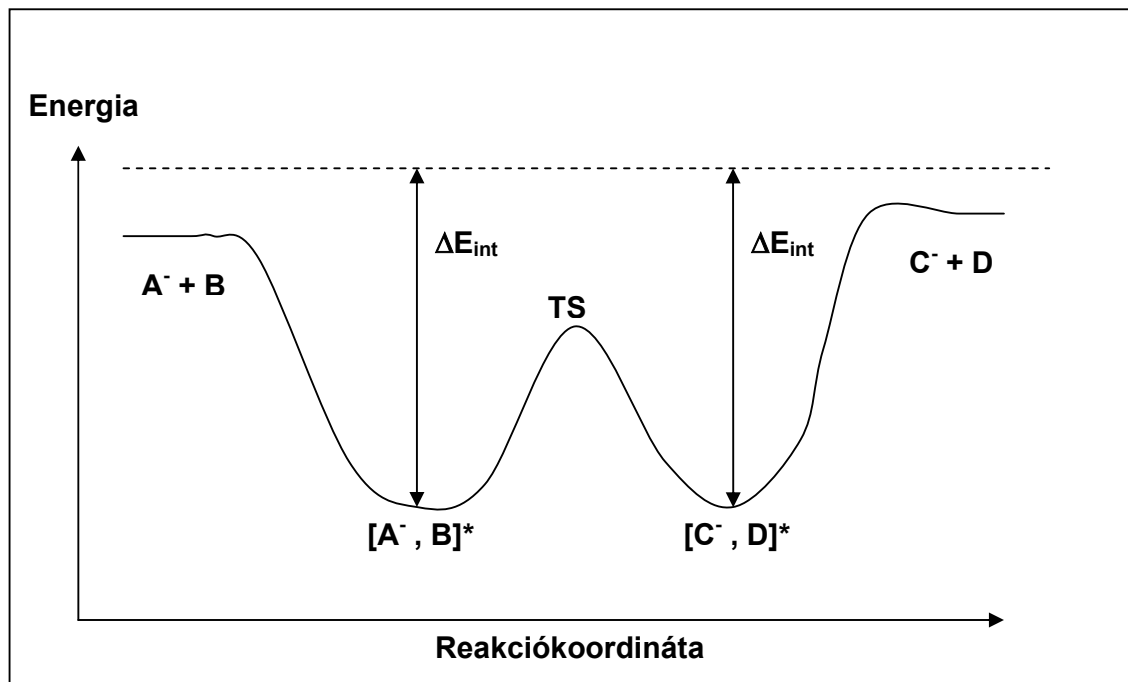
The size of the nucleophile plays a dominant role in determining whether the Zaitsev or the Hofmann product is formed thus, constitutional isomer may also be formed.



The elimination reaction can sometimes lead to cis and trans-geometrical isomers. Usually the more stable trans product dominates the product mixture.

2.3.1 Base catalysed Elimination Mechanisms

Gas phase ionic reactions



In contrast to reactions in solution, gas phase reactions can be described by a double-well potential energy curve (double-well means that it has two minima): the energies of the assembled ion+molecule complexes is lower than that of the reactants and products (in other words, the reaction partners are stabilized by 'solvating' each other). Moreover, energy of the transition state (TS) can also be lower than these.

Nevertheless, the reaction may not proceed spontaneously in all cases as it can be hindered by factors such as statistical or entropic ones, e.g. when the number of available quantum states is limited in the course of complex formation.

An experimental system: FT-ICR mass spectrometry

FT-ICR MS = Fourier Transform Ion Cyclotron Resonance Mass Spectroscopy

A mass spectroscopic method with a mode of detection called FT-ICR: the ions produced are directed into a magnetic field where they will exercise circular motion with a frequency characteristic of their mass/charge ratio. The ions should be 'swept together' by a pulse in order to establish coherence. The advantage of the method is that frequency is one of the most precisely detectable physical quantities.

There is vacuum in the reaction cell (where the ions circulate), thus the probability of thermolecular reactions is negligible, the emerging complexes can not dissipate their excess energy by collisions but only by photon emission (the excess energy is due to association). Thus, the excess energy is stored as rovibrational (rotational + vibrational) energy and is

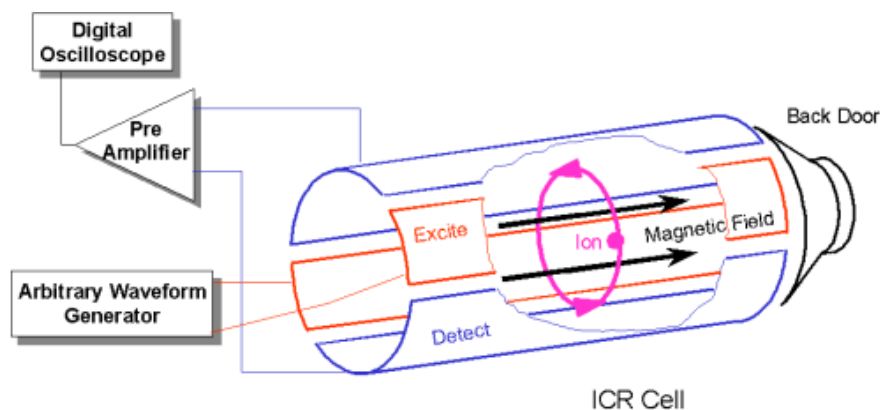
available for the separation of the complex or for driving the reaction. Typically, the lifetime of such a complex is in the microsecond regime.

$$F = z_i V \times B_0 \quad \omega_c = \frac{z_i B_0}{2\pi m_i} \quad \frac{m_i}{z_i} = - \frac{B_0}{2\pi \omega_c}$$

B_0 a mágneses térerő, ω az adott ion körfrekvenciája, F az ionra ható erő, V az ion sebessége, z a töltése

Being isolated, energy gain of the complex is also excluded, allowing only exothermic or thermoneutral reactions. Slightly endothermic (1-5 kcal/mol) reactions may occur provided there can be energy uptake during the operation of the FT-ICR device (during the ion selection procedure).

An unparalleled advantage of the FT-ICR method is to provide excellent basis for comparing gas phase theoretical and experimental data.



Examples

General considerations

α -Hydroxy-propionic acid $RRC(OH)COOH$ where R,R is H and their homologons derivates(eg lacticid where R,R is H,Me) have 4 unique conformations in which the two OH groups assume special conformational relationships with respect to each other. These involve two internal rotations(dihedrals) associated with the two/OH groups with a unique carbnyl orientations.

Conformation D is sufficiently destabilized so only A, B and C are expected to show decarbonylation reaction

The following 3 families of mechanisms may be anticipated

A: Unimolecular Internal S_N2 type reaction mechanism (S_Ni) with α-lactone formation

B: Unimolecular Internal Addition/elimination mechanism with α-lactone formation

C: Bimolecular elimination (E2) reaction mechanism with the involvement of a base catalyst

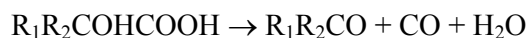
1. Gas phase decomposition of hydroxycarboxylic acids

(Domingo et al., J. Am. Chem. Soc. 1997, 119: 6415-6422).

Background:

These gas phase reactions are homogeneous, unimolecular and of first order (Chuciani et al, J. Chem. Kinet. 1989, 21: 367, J. Chem. Kinet. 1991, 23: 779, J. Phys. Org. Chem. 1993, 6: 54, J. Phys. Org. Chem. 1995, 8: 133).

Reaction scheme:



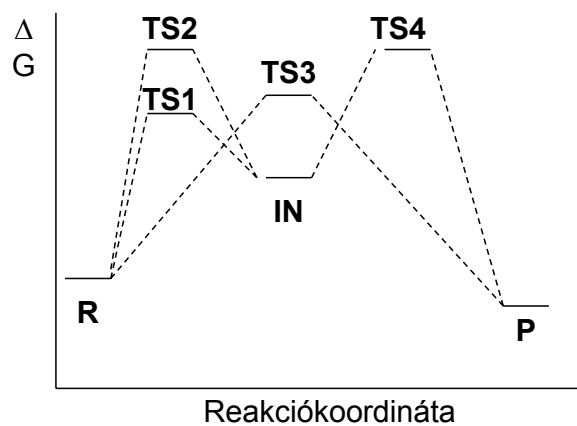
N ^o	Substituent	Name
I.	R ₁ =R ₂ =H	Glycolic acid
II.	R ₁ =H, R ₂ =CH ₃	Lactic Acid
III.	R ₁ , R ₂ =CH ₃	α-hydroxyiso-butiric acid

Purpose:

Determination of dominant reaction path, including transition states (TS) and reaction intermediate (IN)

Approach:

Three different reaction mechanisms were investigated

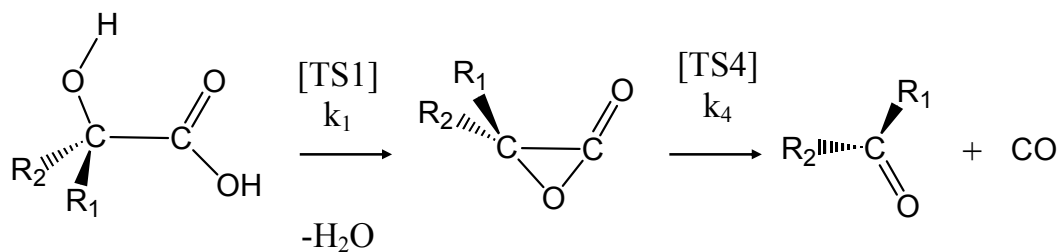


Methods:

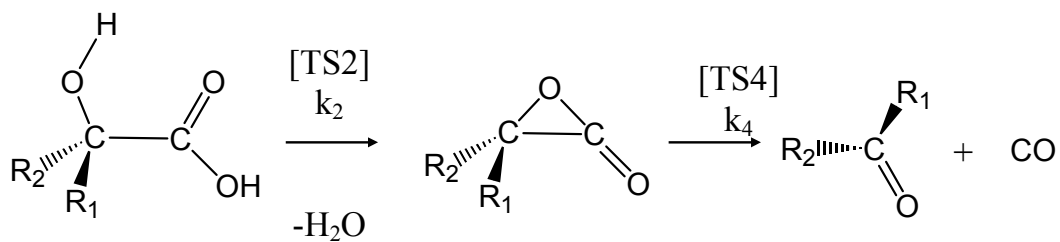
MP2/6-31G**, MP2/6-31++G** szinten, Gaussian 92 és 94 programokkal

Investigated reaction paths

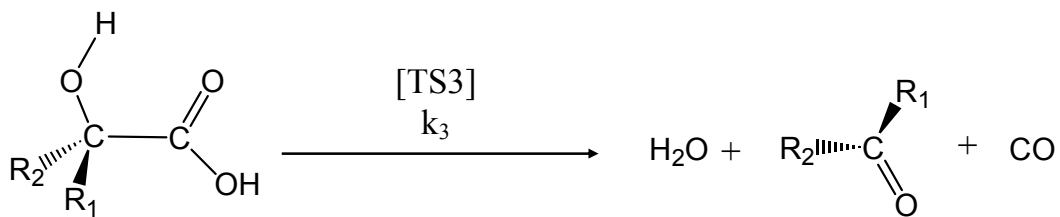
First reaction path



Second reaction path

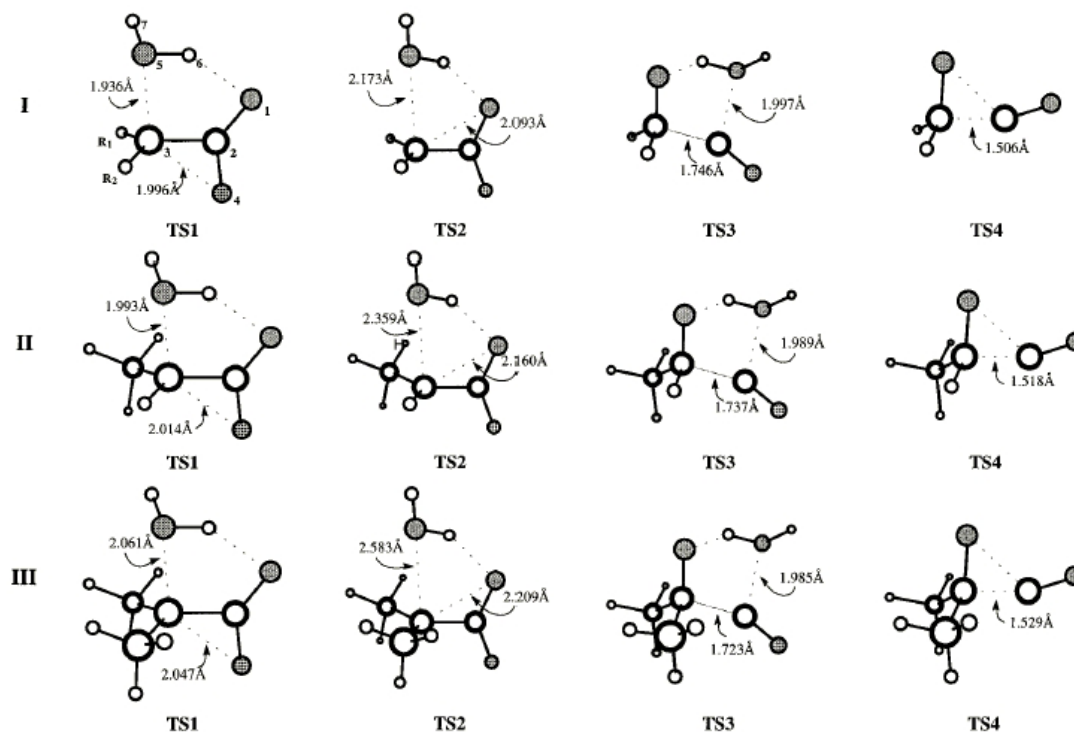


Third reaction path



The first and second reaction paths differ in the side from which the alpha-carbon is attacked. While the transition states are not equivalent, the intermediates are, more precisely, in the case of $R_1=R_2$ they are the same species and in general they are enantiomers. In the third case there is no intermediate, the reaction proceeds in one step.

Results:



Explanation of structures and reaction courses: in the case of TS1 and TS2, the hydroxyl group is leaving while acquiring the proton of the carboxylic group to form water. TS1 and TS2 differ in the identity of the attacking carbonyl oxygen (the side of the attack). In TS3, the proton and one of the oxygens of the carboxyl group forms water with the hydrogen of the hydroxyl group. Note that in this case there is no nucleophilic attack but a proton transfer.

Energies

	MP2/6-31G**		MP2/6-31++G**	
	ΔH	ΔS	ΔH	ΔS
		I		
TS1	222.53	13.92	213.26	13.52
TS2	304.36	31.91	289.42	34.83
IN	165.53	166.64	155.88	165.07
TS3	247.63	32.25	240.73	32.01
TS4	300.08	168.69	278.20	167.11
P	114.57	320.23		
		II		
TS1	207.41	-8.17	198.46	-3.03
TS2	273.01	15.93	251.88	39.47
IN	154.36	146.47	143.96	149.59
TS3	234.68	9.95	228.19	12.99
TS4	284.07	145.59	262.19	148.92
P	94.29	310.36		
		III		
TS1	185.22	-0.17	176.46	4.10
TS2	232.18	30.04	202.87	29.71
IN	138.02	153.26	128.12	155.51
TS3	220.26	11.42	214.17	14.48
TS4	265.16	150.50	244.20	151.75
P	76.79	332.80		

For the calculation of the energy of each state all species were considered. Data are corrected for zero point energy (ZPVE) and temperature. All intermediates are considerably less stable than the reactants or products.

Which way is dominant?

The answer lies in kinetic considerations, as k_2 is large, the apparent rate constant (k_{ap}) was calculated as follows:

$$k_{ap}=k_1+k_2+k_3$$

	<i>k</i>	
	MP2/6-31G**	MP2/6-31++G**
I		
k_1	7.51×10^{-6}	4.41×10^{-5}
k_2	6.99×10^{-12}	1.86×10^{-10}
k_3	4.95×10^{-7}	1.86×10^{-6}
k_4	5.64×10^1	6.20×10^2
k_{ap}	8.01×10^{-6}	4.60×10^{-5}
k_{obsd}	in the range 6.83×10^{-5} to 3.71×10^{-4}	
II		
k_1	1.02×10^{-5}	1.10×10^{-4}
k_2	4.80×10^{-10}	5.14×10^{-7}
k_3	4.30×10^{-7}	2.21×10^{-6}
k_4	1.02×10^2	9.98×10^2
k_{ap}	1.07×10^{-5}	1.13×10^{-4}
k_{obsd}	in the range 2.81×10^{-4} to 7.78×10^{-4}	
III		
k_1	2.08×10^{-3}	1.94×10^{-2}
k_2	7.88×10^{-6}	2.38×10^{-3}
k_3	8.69×10^{-6}	4.14×10^{-5}
k_4	1.35×10^2	1.05×10^3
k_{ap}	2.10×10^{-3}	2.18×10^{-2}
k_{obsd}	in the range 5.92×10^{-3} to 1.94×10^{-2}	

Data calculated at higher level of theory (MP2/6-31++G**) are closer to experimental values. Experimental rate constants are close to the calculated k_1 values: the first reaction course is dominant.

Detailed analysis of the reaction mechanism: bond orders

Bond orders can be calculated as follows:

$$BO = \exp[(R(1) - R(SP))/0.3]$$

Where BO is the bond order, R(SP) is the bond length at a given reaction coordinate, R(1) is a properly chosen reference point. It may be more convenient to use the relative alteration of the absolute bond order at the given reaction step (the bond order itself may be > 2):

$$\%Ev = \frac{BO(TS) - BO(R)}{BO(P) - BO(R)} * 100$$

Results show that in TS1 and TS2 the breaking of the C-O and O-H bonds is faster than the nucleophilic attack resulting in the closure of the lacton ring. Similarly, in the TS3 pathway the elimination of water is more advanced than the formation of the carbonyl species. In TS4, the formation of the double bond is faster than the departure of CO. These results show that although the breaking and formin of certain bonds is a coordinated process they are not necessarily concerted (see also the definition of mechansim E2).

Summary

The elimination proceeds in two steps

The first, arte-limiting step is is the elimination of water during alpha-lacton formation by nucleophilic attack of the carbonyl oxygen

This step proceeds with polarization of the C-OH bond, dehydration occurs with the help of the acidic H of the COOH group.

Water elimination is faster than lacton formation

Methyl substituents stabilize the emerging carbocation-like structure thereby accelerating the elimination. Moreover, the basicity of the OH group grows in the primer -> terciar direction. In agreement with this, the reactivity order of the molecules is as follows: 2-hydroxybutiric acid > lactic acid > glycolic acid

Using MP2, 6-31++G** is more accurate than 6-31G** with respect to experimental data

III. Investigation of E2 model systems to characterize kinetic isotope effects

(Schröder és Jensen (1997), J. Org. Chem. 62, 253-260.)

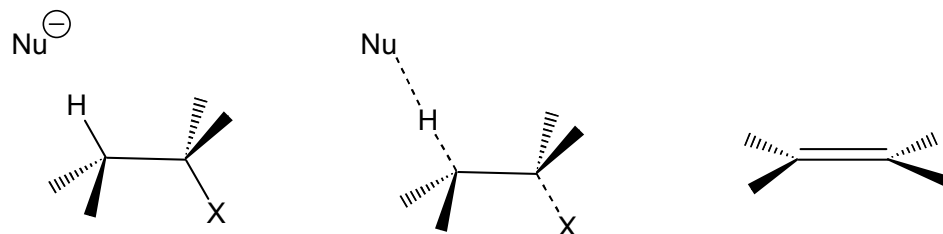
Bakground

Kinetic isotope effects (KIE; alterations in the kinetics of a reaction upon replacing an atom with an isotope) may give information about the mechanism of a given reaction: provided that several useful relationships can be established by calculation, a powerful tool can be given to experimentists. Calculation of KIE for a H-D replacement:

$$k_H / k_D = \exp((\Delta G_D - \Delta G_H) / RT)$$

Where $\Delta G = G^\ddagger - G^0$; using G^P instead of G^\ddagger , the equilibrium isotope effect (EIE) is obtained (G^0 , G^\ddagger and G^P are the Gibbs free energy of the reactants, the transition state and the products, respectively).

Reaction scheme:



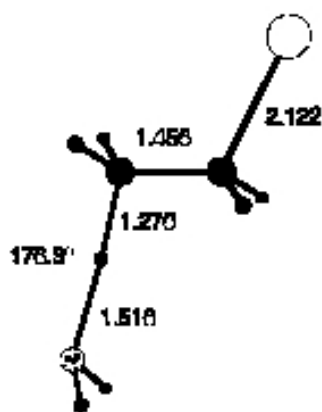
Methods:

MP2/631+G* level of theory, programs used are Gaussian92 and 94.

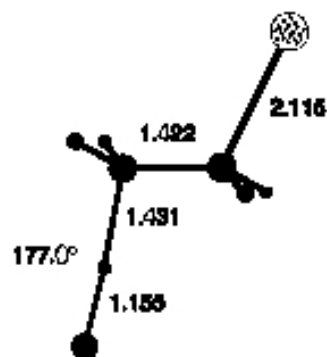
Reactions studied: 5 leaving groups (NH₃, Br⁻, Cl⁻, F⁻, SH⁻) and 6 nucleophiles (NH₂⁻, OH⁻, F⁻, PH₂⁻, SH⁻, Cl⁻) giving 30 combinations altogether.

Results

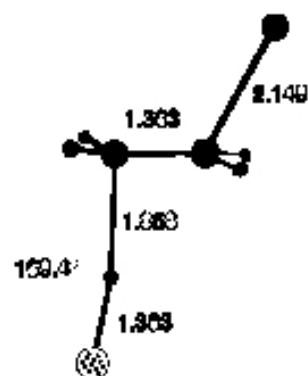
Three types of transition states can be distinguished: reactant- and productlike as well as the type E2 corresponding to a transition between the two. Distinguishing these is possible on the basis of bond lengths in TS structures.



Br-/NH₂-
reactant like



Cl-/F-
E2
transition state (TS)



F-/Cl-
product-like

The proton transfer occurs along a linear in most cases, only two structures deviate from 180 degrees (both of them are reactant-like with NH₃ leaving group. The departure of the leaving group and the proton transfer are coordinated but not coincident, the former depends on the initial compound, the latter on the nucleophile.

Kinetic isotope effects

Replacing the transferred H with D causes a primary KIE (PKIE) and also gives rise to EIE. If the TS is fully reactant-like, PKIE=0, when it is fully product-like, PKIE=EIE. Thus it is advantageous to correct the value of PKIE according to EIE, this requires the introduction of a hypothetical relationship like:

$$\ln(\text{PKIE}_0) = \ln(\text{PKIE}) - (1 - n_{\text{CH}}) \ln(\text{EIE})$$

where n_{CH} is the bond order of the C-H bond and $1 - n_{\text{CH}}$ is the reaction coordinate chosen. According to the corrected data, the difference obtained between nucleophiles of the first and second period is largely due to EIE.

Secondary KIE (SKIE) is the effect measured when a H other than the transferred one (e.g. on the C1 or C2 carbon atom). C1-SKIEs correlate acceptably with the structures of the transition states (the torsion of C1 hydrogens relative to the CC axis).

Summary

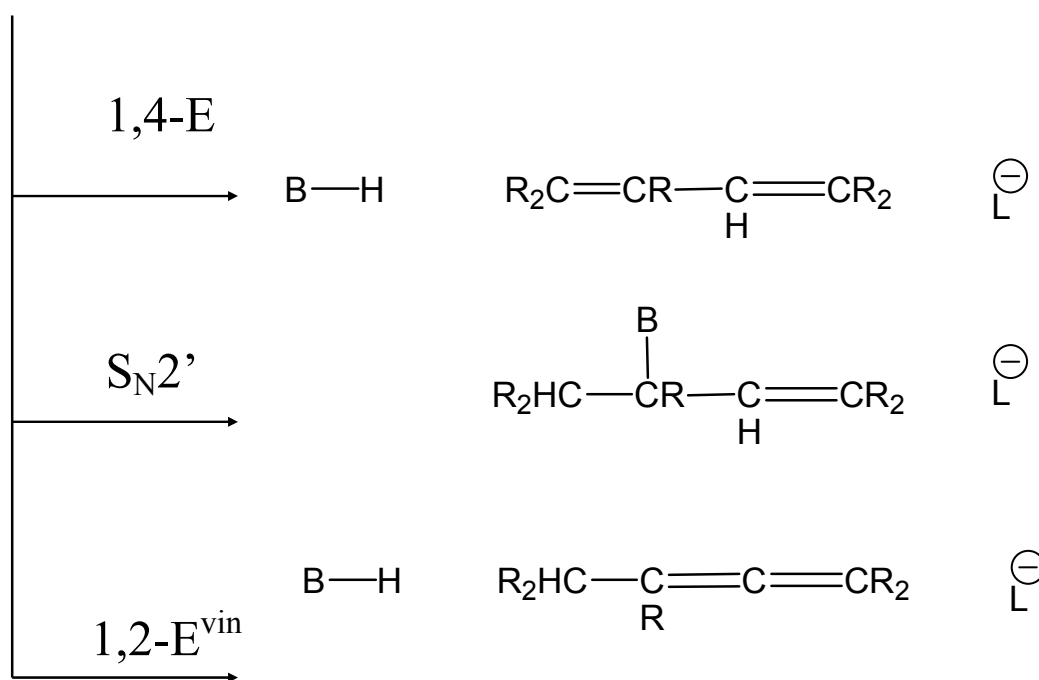
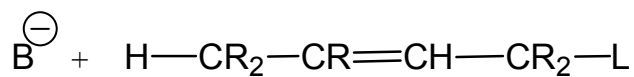
In general, TS structures can not be predicted from KIEs. C1-SKIE can be used but only for a rough estimate. Several C2-SKIE values greater than the corresponding EIE indicate that not all features of a TS can be obtained by interpolating between the start and end point of the reaction.

Base-induced 1,4-elimination

(Bickelhaupt (2001) Mass Spectrom. Rev.. 20, 347-361.)

Background:

Competing reaction pathways



Using different reaction systems, 1,4-elimination dominates over 1,2 E. The real competitor is SN2: the greater the electronegativity of the leaving group, the more likely SN2 is (the LUMO of the substrate localizes more on C α).

Aims:

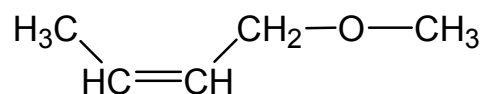
Deciphering reaction mechanisms

Methods:

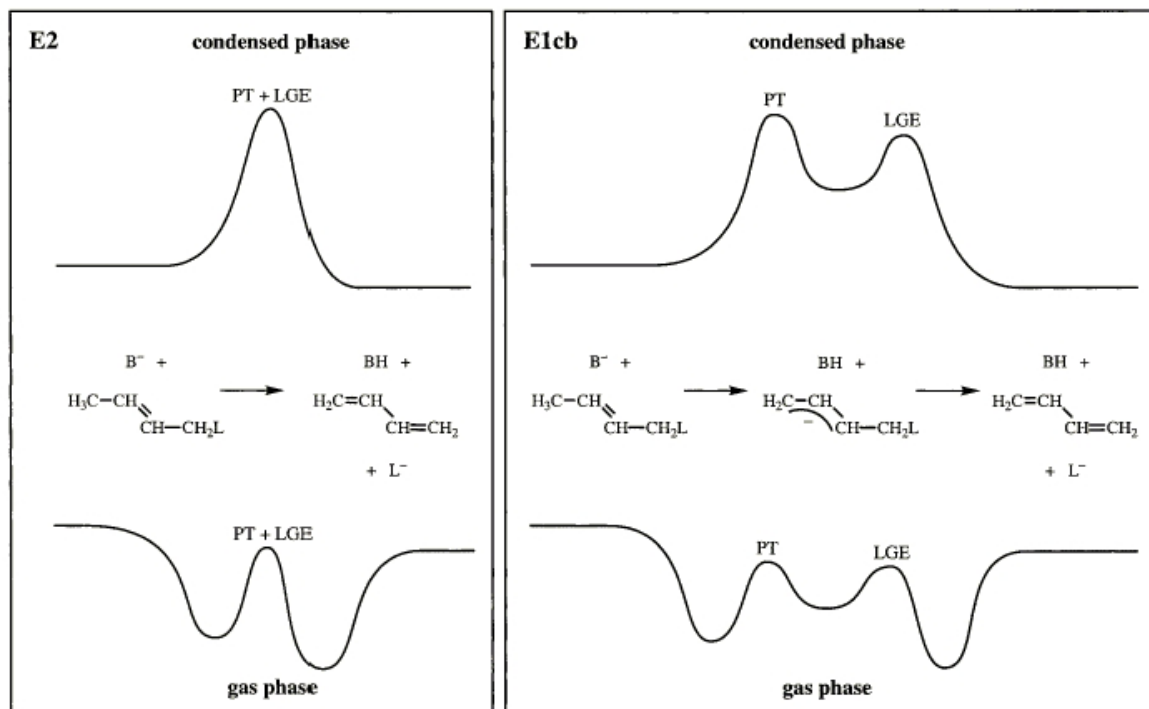
E.g. BP86/TZ2P and DFT calculations with an in-house program (Amsterdam Density Functional, ADF).

Reaction mechanisms

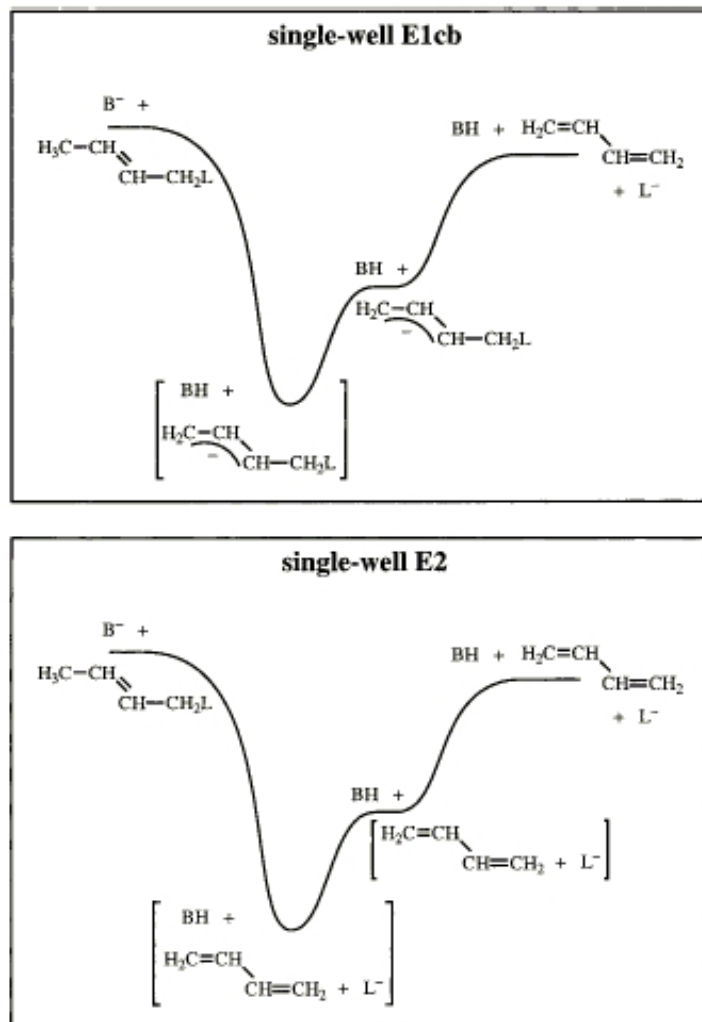
In the case of 1-alkoxy-2-butenes (Bickelhaupt et al., 1995, J. Am. Chem. Soc. 117: 9889) the reaction mechanism is E1cb with the formation of S-H⁻ ions (S=CH₃CHCHCH₂O₂t, CH₃CHCHCH₂OMe).



With cis-methoxy substrates, F^- and OH^- yields a barrierless proton transfer, moreover, the allyl cation is stable after dissociation of the BH conjugated acid. The bond between $C\alpha$ and the leaving group is intact and only slightly longer than in the reactant.

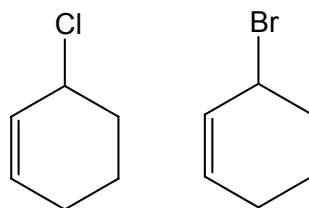


(Fig.) Double-well E2 and E1cb mechanisms



(Fig.) Single-well E1cb and E2 mechanisms

F^- -induced 1,4-elimination of halogenated cyclohexanes investigated at MP2/6-31G** level of theory (Gronert and Kass, 1997, J. Org. Chem. 62:7991).



In the case $R=Cl$ the mechanism is E2, for $R=F$ it is E1cb-like E2 with practically completed proton transfer but without stable E1cb intermediate. The leaving group departs from both the solvated and free allyl cation: no 'clear' mechanism.

OH-induced 1,4-elimination of halogenated cyclohexanes (te Velde *et al.*, 2001, J. Comp. Chem. 22:931): for chloro-, fluoro- and hydroxycyclohexanes, E-2 and Z-2-butenes the proton transfer is barrierless. In the case of Cl as leaving group the first stable species is the product itself: single-well E2 mechanism, exothermic reaction. For leaving groups fluorine and hydroxide the mechanism is E1cb, these are slightly endothermic reactions. Fluorine represents the boundary line between E2 and E1cb: while the cyclohexane scaffold yields an unstable allyl cation, a stable one corresponds to the linear compound. Steric factors should be considered: for Z isomers the reaction is 2 kcal/mol 'more endothermic' than for E isomers. The attacking water does not form a hydrogen bond with the leaving OH unlike in the case of OMe as leaving group.

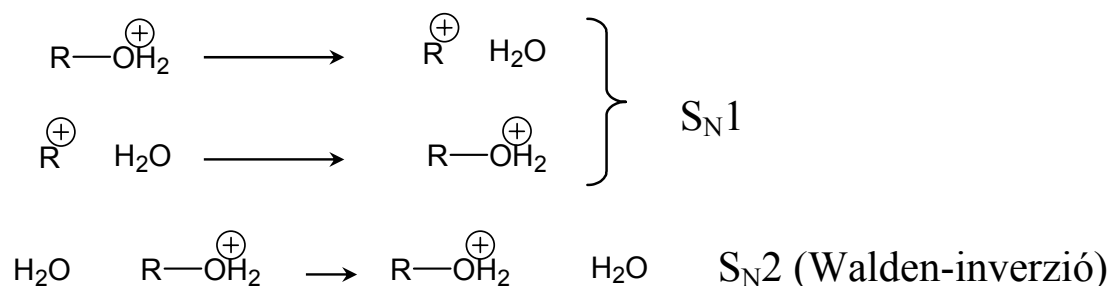
Reaction of protonated alcohols with water

(Uggerud és Bache-Andreassen (1999), Chem. Eur. J. 5, 1917-1930.)

Background:

Alcohols in acidic water solution can either reform by water exchange or yield an alkene with water elimination. This research group focused primarily on the substitution reaction, elimination came into focus as competing (thus unavoidable) reaction. The article even is hard to read and interpret, however, a selection of their results can be worth examining.

Reaction schemes:



Methods:

Experiments: FT-ICR

Theoretical methods: HF/6-31G(d) optimization and MP2/6-31G(d) energy calculation for each critical point (reactants, transition states, intermediates, products). Geometry

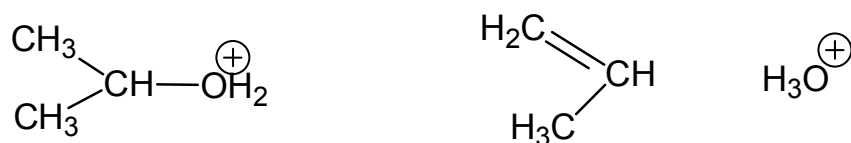
optimization at MP2/6-31G(d) and B3LYP/6-31G(d) level of theory was performed for all reactions but those including water clusters (see below). Zero-point energy correction was performed. reaction rates were calculated with the method 'microcanonical variation Rice-Ramsperger-Kassel-Marcus' (RRKM).

Results

Proton affinity of water clusters (aggregates of several water molecules, not really great clusters) increases with their size (MP2 calculations tend to overestimate it). The reaction takes place only if it is exothermic or only slightly endothermic. This means that the proton affinity of water involved should be greater than that of alkenes.



The ethanol → ethene reaction pathway is energetically favoured. However, the bound water molecule increases the activation barrier. The reaction is observable experimentally but very slow.



The isopropanol → propene reaction is observable experimentally in spite of being slightly less favoured thermodynamically than the former as the energy barrier is lower.



The tert-butanol → isobutene reaction is endothermic and less favoured energetically than the substitution. In spite of these this is the dominant reaction. It is explained on the basis of the unfavoured formation of the butyl cation (in the case of the elimination TS is intramolecular (???)). It is not clear from the article whether they have actually calculated anything for carbocations but they reason using their stability.

The slightly endothermic reactions do not agree well with expectations but are explainable. The covibrational energy of the reactant was possibly underestimated and the experimental heats of formation bear also some uncertainty.

To investigate reactions in water, the authors performed calculations involving water cluster models. In these reactions the proton affinity of the medium is an important factor (the water in the medium does not participate in the reaction but has a catalytic role by promoting water excision from the protonated alcohol). Naturally, the solvation of the species is also important.

Proton affinities (literature data vs. MP2 calculations): H₂O (691, 704), (H₂O)₂ (806, 839), (H₂O)₃ (871, 888), valamint CH₂CH₂ (681, 681), CH₃CHCH₂ (752, 748), (CH₃)₂CCH₂ (796, 806)

Structures correspondig to TSs are solvated less well tah reactants and products. Even considering this, the order of activation energies is the reverse of that for nucleophilic substitution: CH₃CH₂ > (CH₃)₂ > (CH₃)₃C.

Summary

While for S_N2 the reactivity order is reversed when shifting from the gas phase to water, this does not occur in the case of elimination (this is not emphasised by the authors but this is what they got).

2.4 Acid catalysed elimination

Dehydration of carbohydrates [2]

Models:

alcohols (ethanol, isopropanol, ethylene-glycol)

Methods:

1. B3LYP/6-311G(d,p) and CBS-QB3 (the authors state that the latter is more suitable for energy calculations of transition states)
2. Estimation of reaction rates with TST (transition state theory) method

Aims:

1. Determination of activation energies for the alcohols and comparing the obtained values. Conclusions for carbohydrates.
2. Investigation of the effects of alkali metals and protons.

Table 1

Calculated reaction enthalpies, $\Delta_{\text{react}}H_{298}$, and relative energies, ΔE_0^a , for transition states

Reaction		B3LYP ^b (kcal mol ⁻¹)	CBS-QB3 (kcal mol ⁻¹)	Exptl (kcal mol ⁻¹)
<i>Neat alcohols</i>				
(CH ₃) ₃ COH →				
(CH ₃) ₂ CCH ₂ + H ₂ O ($\Delta_{\text{react}}H_{298}$)	(2)	13.6	13.7	12.6 ± 0.3
TS2 (ΔE_0)		59.6	65.9	66.2
(CH ₃) ₂ COHCH(CH ₃) ₂ →				
(CH ₃) ₂ CC(CH ₃) ₂ + H ₂ O ($\Delta_{\text{react}}H_{298}$)	(3)	10.8	13.0	10.7 ± 0.4
TS3 (ΔE_0)		60.4	66.8	64.7
CH ₃ CH ₂ OH →				
CH ₂ CH ₂ + H ₂ O ($\Delta_{\text{react}}H_{298}$)	(8)	13.5	11.6	11.0
TS8 (ΔE_0)		62.7	67.4	
(CH ₃) ₂ CHOH →				
CH ₂ CHCH ₃ + H ₂ O ($\Delta_{\text{react}}H_{298}$)	(16)	14.0	13.3	12.2
TS16 (ΔE_0)		61.5	67.0	
HOCH ₂ CH ₂ OH →				
CH ₂ CHOH + H ₂ O ($\Delta_{\text{react}}H_{298}$)	(21)	8.5	7.9	6.7 ± 2.1
TS21 (ΔE_0)		63.4	69.6	
Levogluconan →				
1 + H ₂ O ($\Delta_{\text{react}}H_{298}$)	(25)	13.4		
TS27 (ΔE_0)		68.3		

Alkali metal complexes

$\text{CH}_3\text{CH}_2\text{OH} \cdot \text{Li}^+ \rightarrow$			
$\text{CH}_2\text{CH}_2 \cdot (\text{H}_2\text{O} \cdot \text{Li}^+) (\Delta_{\text{react}}H_{298})$		8.9	9.9
$\text{CH}_2\text{CH}_2 + \text{H}_2\text{O} \cdot \text{Li}^+ (\Delta_{\text{react}}H_{298})$	(10)	17.1	17.5
TS10 (ΔE_0)		48.2	55.3
$\text{CH}_3\text{CH}_2^+ + \text{LiOH} (\Delta_{\text{react}}H_{298})$	(12)	92.8	94.5
$\text{CH}_3\text{CH}_2\text{OH} \cdot \text{Na}^+ \rightarrow$			
$\text{CH}_2\text{CH}_2 \cdot (\text{H}_2\text{O} \cdot \text{Na}^+) (\Delta_{\text{react}}H_{298})$		8.0	9.7
$\text{CH}_2\text{CH}_2 + \text{H}_2\text{O} \cdot \text{Na}^+ (\Delta_{\text{react}}H_{298})$	(11)	15.2	18.1
TS11 (ΔE_0)		53.1	60.0
$\text{CH}_3\text{CH}_2^+ + \text{NaOH} (\Delta_{\text{react}}H_{298})$	(13)	110.3	114.1
$(\text{CH}_3)_2\text{CHOH} \cdot \text{Li}^+ \rightarrow$			
$\text{CH}_3\text{CHCH}_2 \cdot (\text{H}_2\text{O} \cdot \text{Li}^+) (\Delta_{\text{react}}H_{298})$		9.3	11.6
$\text{CH}_3\text{CHCH}_2 + \text{H}_2\text{O} \cdot \text{Li}^+ (\Delta_{\text{react}}H_{298})$	(17)	19.0	20.8
TS17 (ΔE_0)		40.4	49.5
$\text{CH}_3\text{CHCH}_3^+ + \text{LiOH} (\Delta_{\text{react}}H_{298})$	(18)	75.3	82.7
$\text{HOCH}_2\text{CH}_2\text{OH} \cdot \text{Li}^+ \rightarrow$			
$\text{CH}_2\text{CHOH} \cdot (\text{H}_2\text{O} \cdot \text{Li}^+) (\Delta_{\text{react}}H_{298})$		1.3	3.4
$\text{CH}_2\text{CHOH} + \text{H}_2\text{O} \cdot \text{Li}^+ (\Delta_{\text{react}}H_{298})$	(22)	31.9	30.7
TS22 (ΔE_0)		69.1	74.2
$\text{CH}_3\text{CHOH}^+ + \text{LiOH} (\Delta_{\text{react}}H_{298})$	(23)	72.1	74.5

Calculated reaction enthalpies, $\Delta_{\text{react}}H_{298}$, and relative energies, ΔE_0^a , for transition states

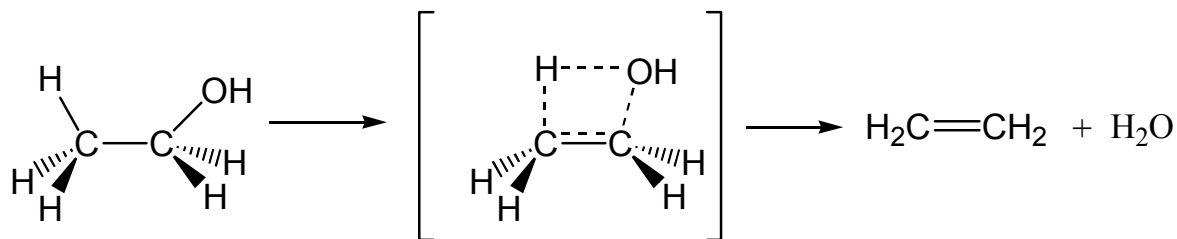
Reaction		B3LYP ^b (kcal mol ⁻¹)	CBS-QB3 (kcal mol ⁻¹)	Exptl (kcal mol ⁻¹)
<i>Protonated alcohols</i>				
$\text{CH}_3\text{CH}_2\text{OH}_2^+ \rightarrow$				
$\text{CH}_2\text{CH}_2 \cdot \text{H}_3\text{O}^+ (\Delta_{\text{react}}H_{298})$		10.8	12.1	
$\text{CH}_2\text{CH}_2 + \text{H}_3\text{O}^+ (\Delta_{\text{react}}H_{298})$	(14)	32.5	32.1	31.6
TS14(ΔE_0)		18.6	20.7	
$\text{CH}_3\text{CH}_2^+ + \text{H}_2\text{O} (\Delta_{\text{react}}H_{298})$	(15)	38.5	34.2	33.7
$(\text{CH}_3)_2\text{CHOH}_2^+ \rightarrow$				
$\text{CH}_3\text{CHCH}_2 \cdot \text{H}_3\text{O}^+ (\Delta_{\text{react}}H_{298})$		10.3	14.0	
$\text{CH}_3\text{CHCH}_2 + \text{H}_3\text{O}^+ (\Delta_{\text{react}}H_{298})$	(19)	37.6	38.1	36.7
TS19 (ΔE_0)		7.7	11.8	
$\text{CH}_3\text{CHCH}_3^+ \cdot \text{H}_2\text{O} (\Delta_{\text{react}}H_{298})$		7.7	13.5	
$\text{CH}_3\text{CHCH}_3^+ + \text{H}_2\text{O} (\Delta_{\text{react}}H_{298})$	(20)	24.3	25.1	22.9
$\text{HOCH}_2\text{CH}_2\text{OH} \cdot \text{H}^+ \rightarrow$				
$\text{CH}_3\text{CHOH}^+ \cdot \text{H}_2\text{O} (\Delta_{\text{react}}H_{298})$		-13.7	-11.4	
$\text{CH}_3\text{CHOH}^+ + \text{H}_2\text{O} (\Delta_{\text{react}}H_{298})$	(24)	3.5	1.6	7.0
TS24		24.4	27.6	

Calculated activation energy for each alcohol and reaction rates for neutral and protonated states and in the presence of alkali metals.

Reaction		E_a (kcal mol ⁻¹) ^a	A (s ⁻¹)	$k(250\text{ }^\circ\text{C})$ (s ⁻¹)	$k(500\text{ }^\circ\text{C})$ (s ⁻¹)
(CH ₃) ₂ COHCH(CH ₃) ₂ → (CH ₃) ₂ CC(CH ₃) ₂ + H ₂ O	(2)	66.8	6.6 × 10 ¹³		
(CH ₃) ₃ COH → (CH ₃) ₂ CCH ₂ + H ₂ O	(3)	65.9	1.3 × 10 ¹⁴		
CH ₃ CH ₂ OH → CH ₂ CH ₂ + H ₂ O	(8)	67.4	2.7 × 10 ¹³	1.8 × 10 ⁻¹⁵	2.4 × 10 ⁻⁶
CH ₃ CH ₂ OH · Li ⁺ → CH ₂ CH ₂ + H ₂ O · Li ⁺	(10)	55.3	4.5 × 10 ¹³	3.5 × 10 ⁻¹⁰	1.0 × 10 ⁻²
CH ₃ CH ₂ OH · Na ⁺ → CH ₂ CH ₂ + H ₂ O · Na ⁺	(11)	60.0	6.8 × 10 ¹²	5.6 × 10 ⁻¹³	7.2 × 10 ⁻⁵
CH ₃ CH ₂ OH ₂ ⁺ → CH ₂ CH ₂ + H ₃ O ⁺	(14)	30.7	2.8 × 10 ¹⁴	4.1 × 10 ¹	5.8 × 10 ⁵
CH ₃ CH ₂ OH · Li ⁺ → CH ₃ CH ₂ ⁺ + LiOH	(12)	93.5	10 ¹⁶	8.2 × 10 ⁻²⁴	3.6 × 10 ⁻¹¹
CH ₃ CH ₂ OH · Na ⁺ → CH ₃ CH ₂ ⁺ + NaOH	(13)	112.9	10 ¹⁶	6.3 × 10 ⁻³²	3.9 × 10 ⁻¹⁶
CH ₃ CH ₂ OH ₂ ⁺ → CH ₃ CH ₂ ⁺ + H ₂ O	(15)	32.8	10 ¹⁶	2.0 × 10 ²	5.4 × 10 ⁶
(CH ₃) ₂ CHOH → CH ₃ CHCH ₂ + H ₂ O	(16)	67.0	8.2 × 10 ¹³	8.4 × 10 ⁻¹⁵	9.5 × 10 ⁻⁶
(CH ₃) ₂ CHOH · Li ⁺ → CH ₃ CHCH ₂ + H ₂ O · Li ⁺	(17)	49.5	2.2 × 10 ¹⁴	4.6 × 10 ⁻⁷	2.3 × 10 ⁰
(CH ₃) ₂ CHOH ₂ ⁺ → CH ₃ CHCH ₂ + H ₃ O ⁺	(19)	36.9	7.3 × 10 ¹⁴	2.8 × 10 ⁻¹	2.7 × 10 ⁴
(CH ₃) ₂ CHOH · Li ⁺ → CH ₃ CHCH ₃ ⁺ + LiOH	(18)	81.5	10 ¹⁶	9.1 × 10 ⁻¹⁹	3.4 × 10 ⁻⁸
(CH ₃) ₂ CHOH ₂ ⁺ → CH ₃ CHCH ₃ ⁺ + H ₂ O	(20)	22.7	10 ¹⁶	3.4 × 10 ⁶	3.9 × 10 ⁹
HOCH ₂ CH ₂ OH → CH ₂ CHOH + H ₂ O	(21)	69.6	1.2 × 10 ¹⁴	1.0 × 10 ⁻¹⁵	2.6 × 10 ⁻⁶
HOCH ₂ CH ₂ OH · Li ⁺ → CH ₂ CHOH + H ₂ O · Li ⁺	(22)	74.2	8.5 × 10 ¹⁴	8.4 × 10 ⁻¹⁷	8.9 × 10 ⁻⁷
HOCH ₂ CH ₂ OH · H ⁺ → CH ₃ CHOH ⁺ + H ₂ O	(24)	27.6	9.6 × 10 ¹⁴	2.7 × 10 ³	1.5 × 10 ⁷
HOCH ₂ CH ₂ OH · Li ⁺ → CH ₃ CHOH ⁺ + LiOH	(23)	73.2	10 ¹⁶	2.6 × 10 ⁻¹⁵	2.0 × 10 ⁻⁵

Results:

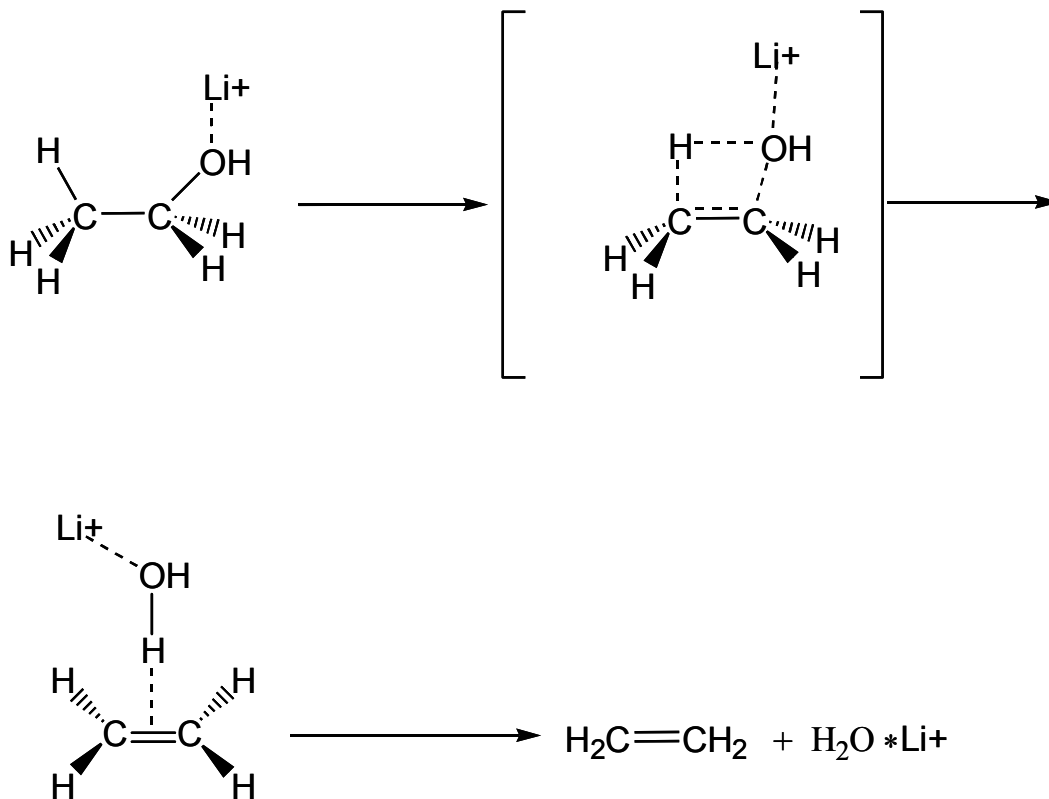
1. Elimination reaction of ethanol (uncatalyzed)



Activation energy is 67.4 kcal/mol which is in agreement with the experimental value. According to bond angles, the four-centered TS is closer to the product than the reactant.

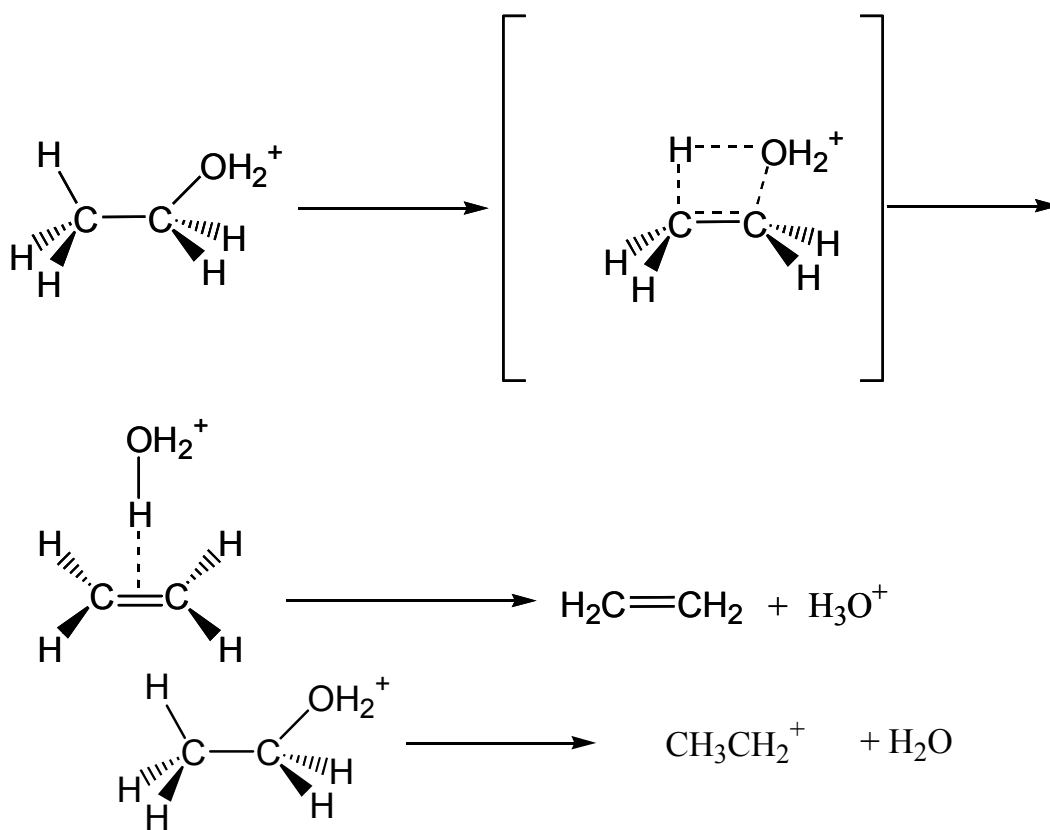
Elimination reaction of ethanol in presence of alkali metals (Lewis acid catalysis)

Li^+ and Na^+ significantly reduce the activation barrier (by 12 and 7 kcal/mol, respectively). Lithium ion is more effective because of the long Na-O bond (the radius of Na is too big). Formation of carbocations may occur as a side reaction, but this is fortunately not significant.

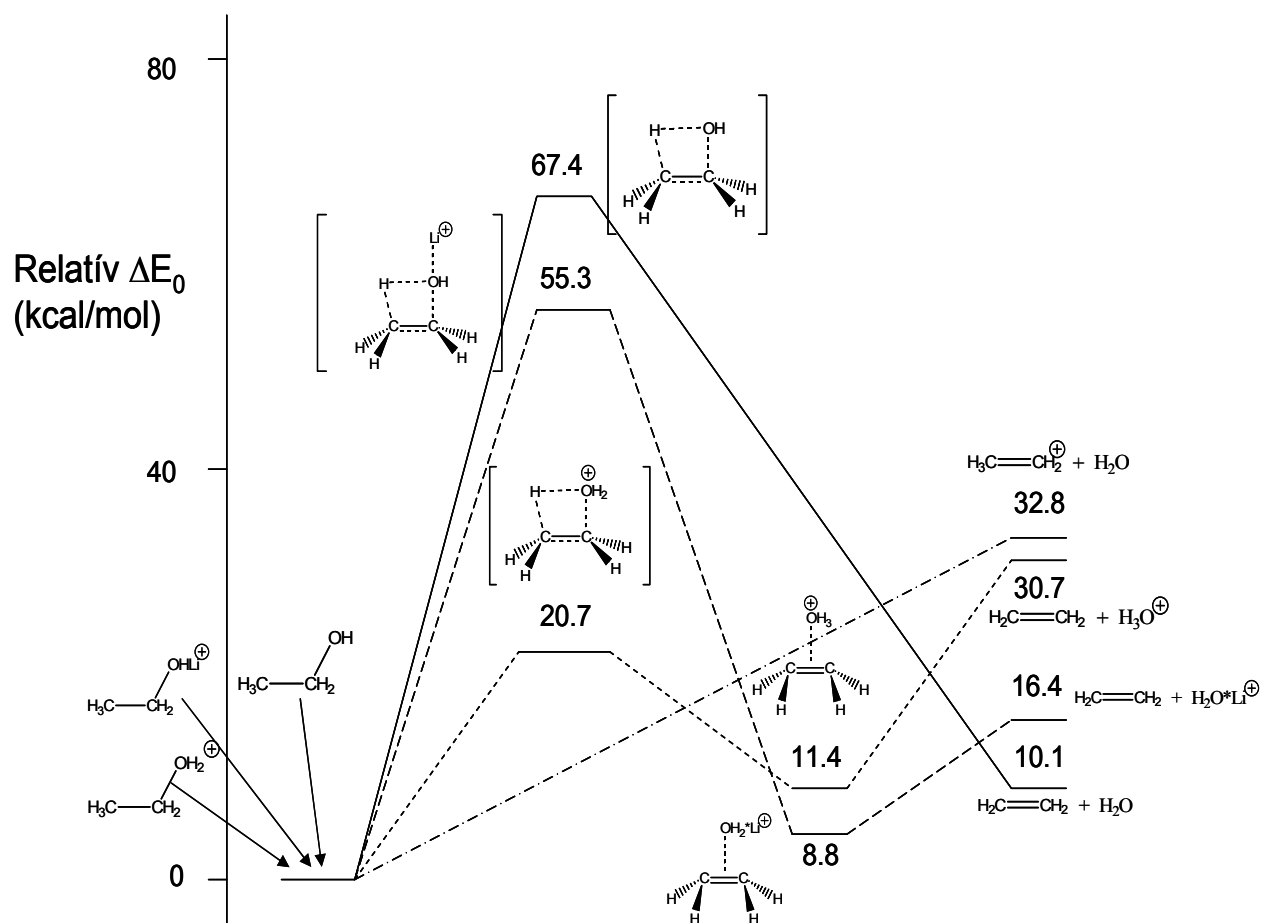


Elimination reaction of protonated ethanol (Brønsted acid catalysis)

Activation E is greatly reduced (20.7 kcal/mol) in the presence of protons, which is in accordance with experimental results. The reaction is endothermic because the proton affinity of the alcohol is greater than that of water. TS is stable and has lower energy than the product. Formation of carbocation occurs as a side reaction.

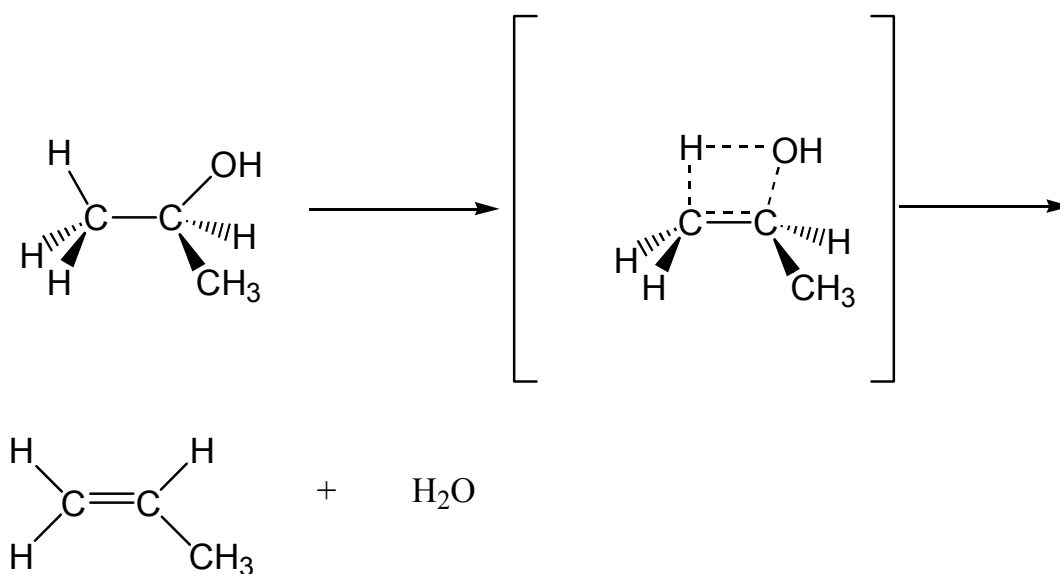


Energy profile of the elimination reaction of ethanol



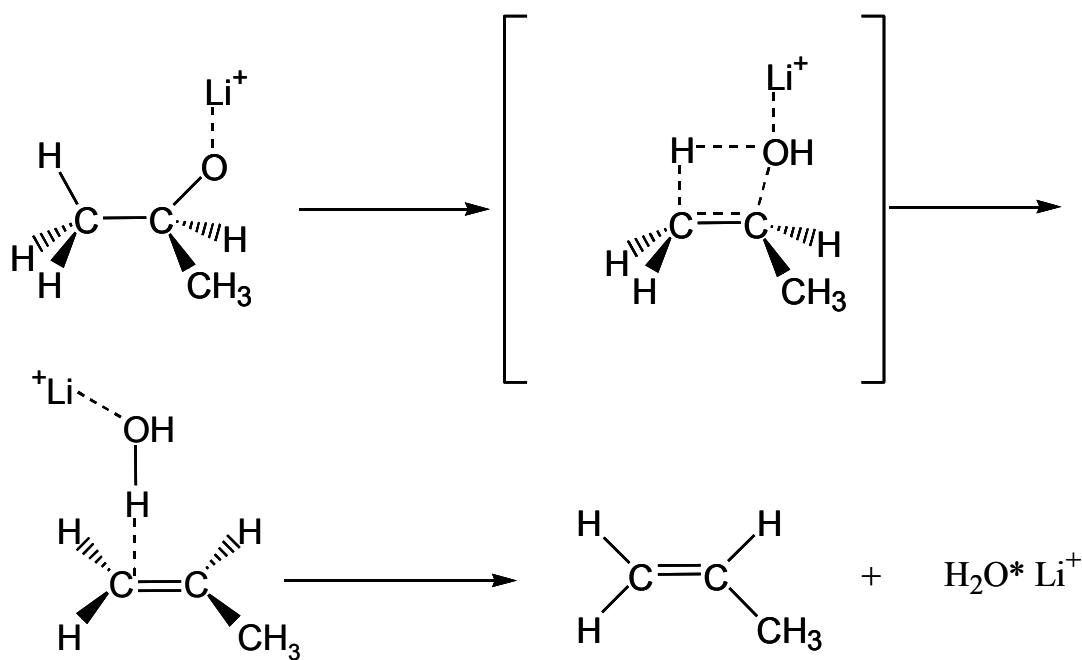
Elimination reaction of isopropanol

Isobutanol is a secunder alcohol, nevertheless, the reaction mechanism is the same as in the case of ethanol with a practically identical activation energy. The only difference is that the TS is more product-like.



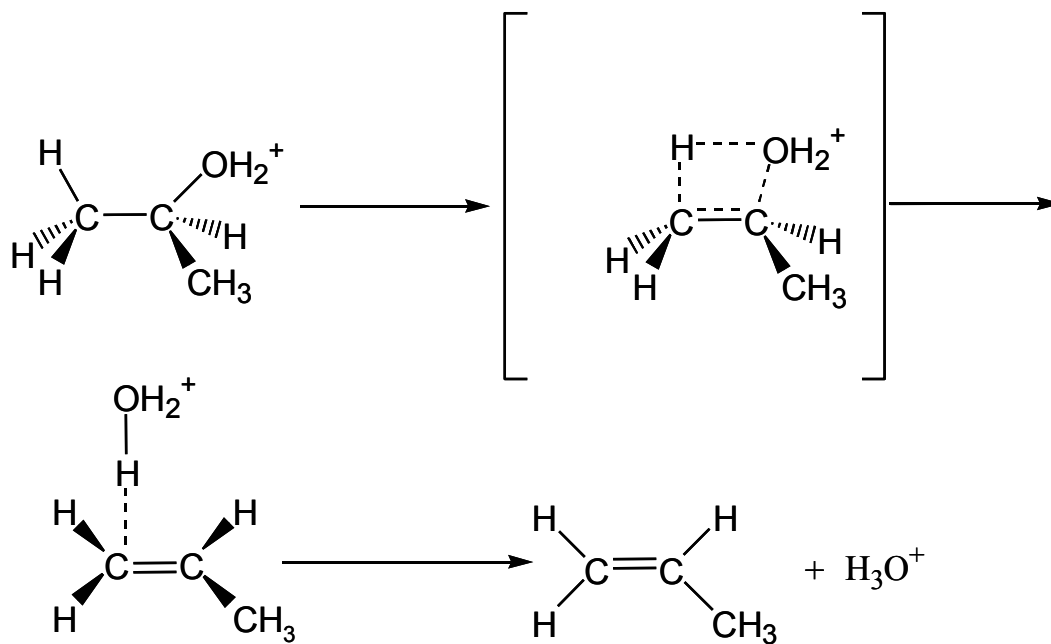
Elimination reaction of isopropanol in the presence of alkali ions

The barrier height decreases more markedly than for ethanol (49,5 kcal/mol). Carbocation formation occurs (a secondary one is more stable) but not in a significant quantity.

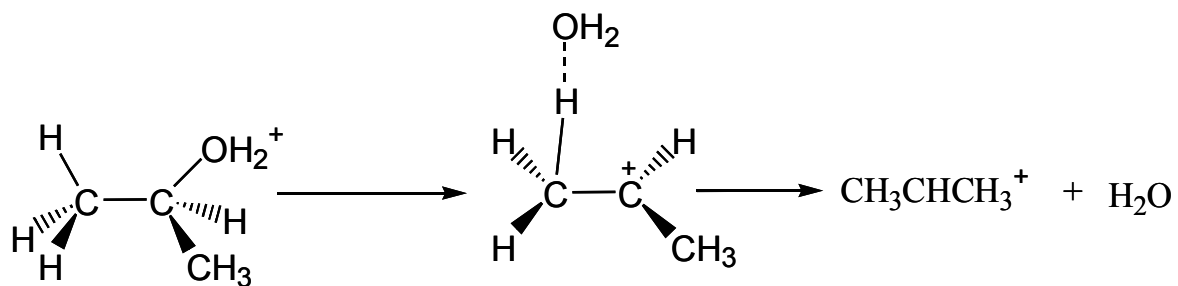


Elimination reaction of protonated isopropanol

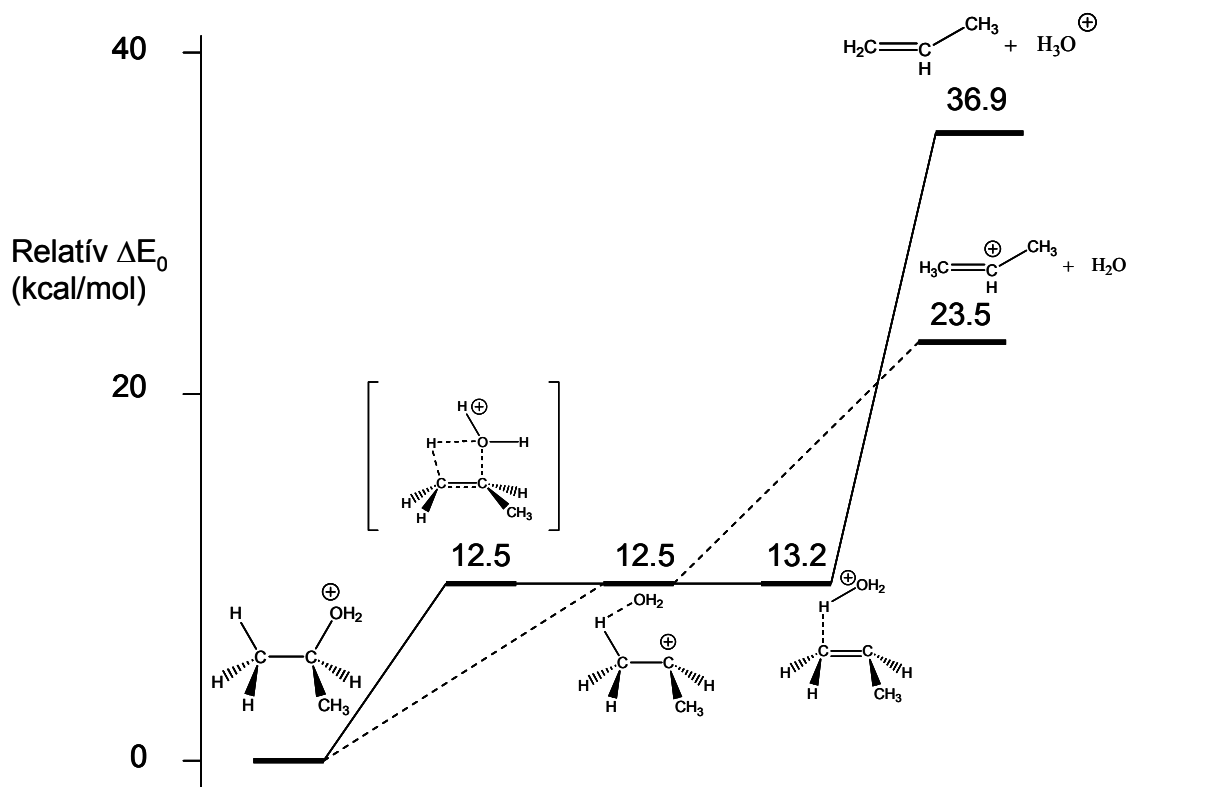
Similarly to alkali field metals, the barrier height decreases more than for ethanol (12.5 kcal/mol). However, the TS is much more than the product (36.9 kcal/mol) thus activation energy should be calculated for the second step. Carbocation is also formed and is thermodynamically more stable than the elimination product.



Carbocation formation



Energy profile of the elimination reaction of protonated isopropanol

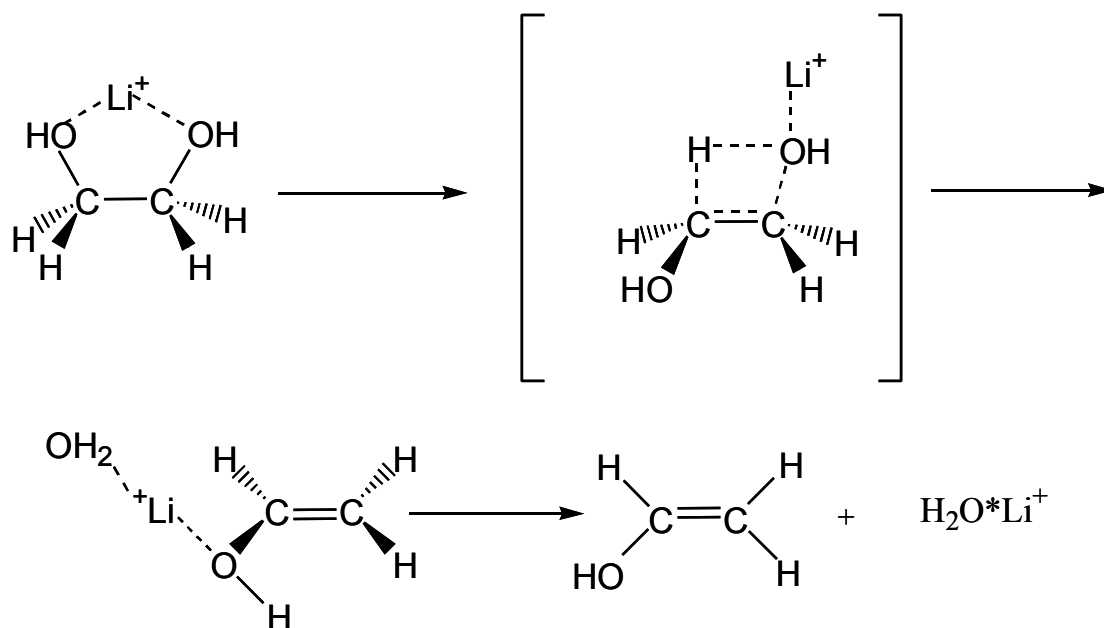


Elimination reaction of ethylene glycol

The barrier height is only slightly altered relative to that of ethanol, thus it can be concluded that it is uniformly 67-69 kcal/mol for all alcohols investigated. This indicates that a similar value for carbohydrates can be expected. This is supported by the investigation of levoglucosan (a sterically hindered carbohydrate).

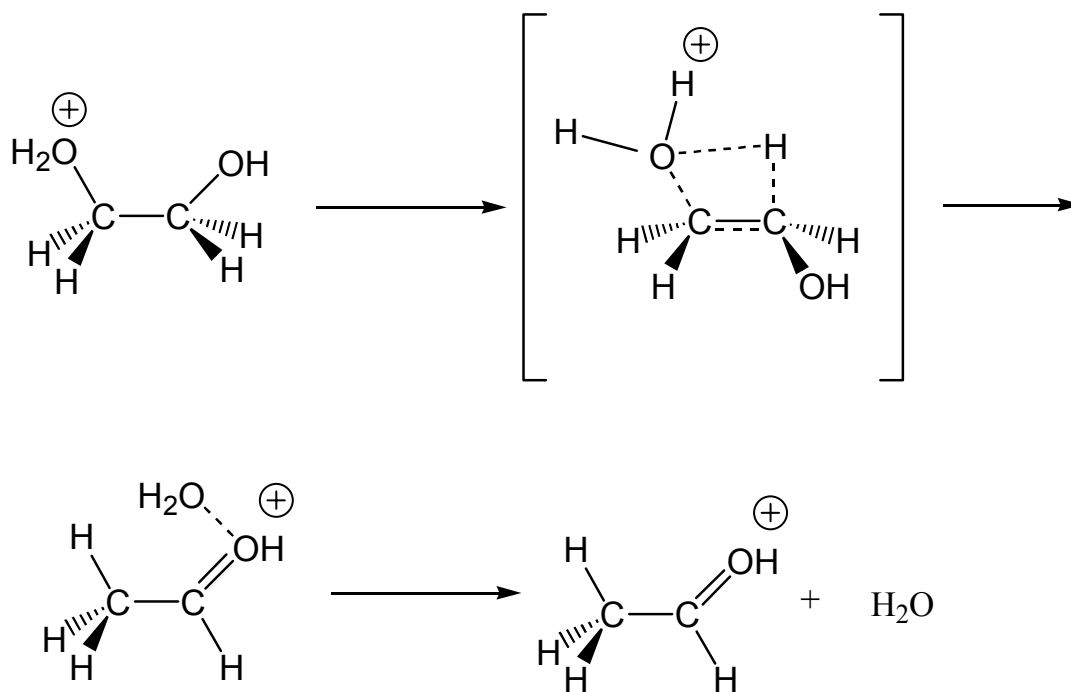
Elimination reaction of ethylene glycol in the presence of alkali metals

As Na^+ and Li^+ form a complex with the compound, the activation energy is high and the reaction is slower than for ethanol.

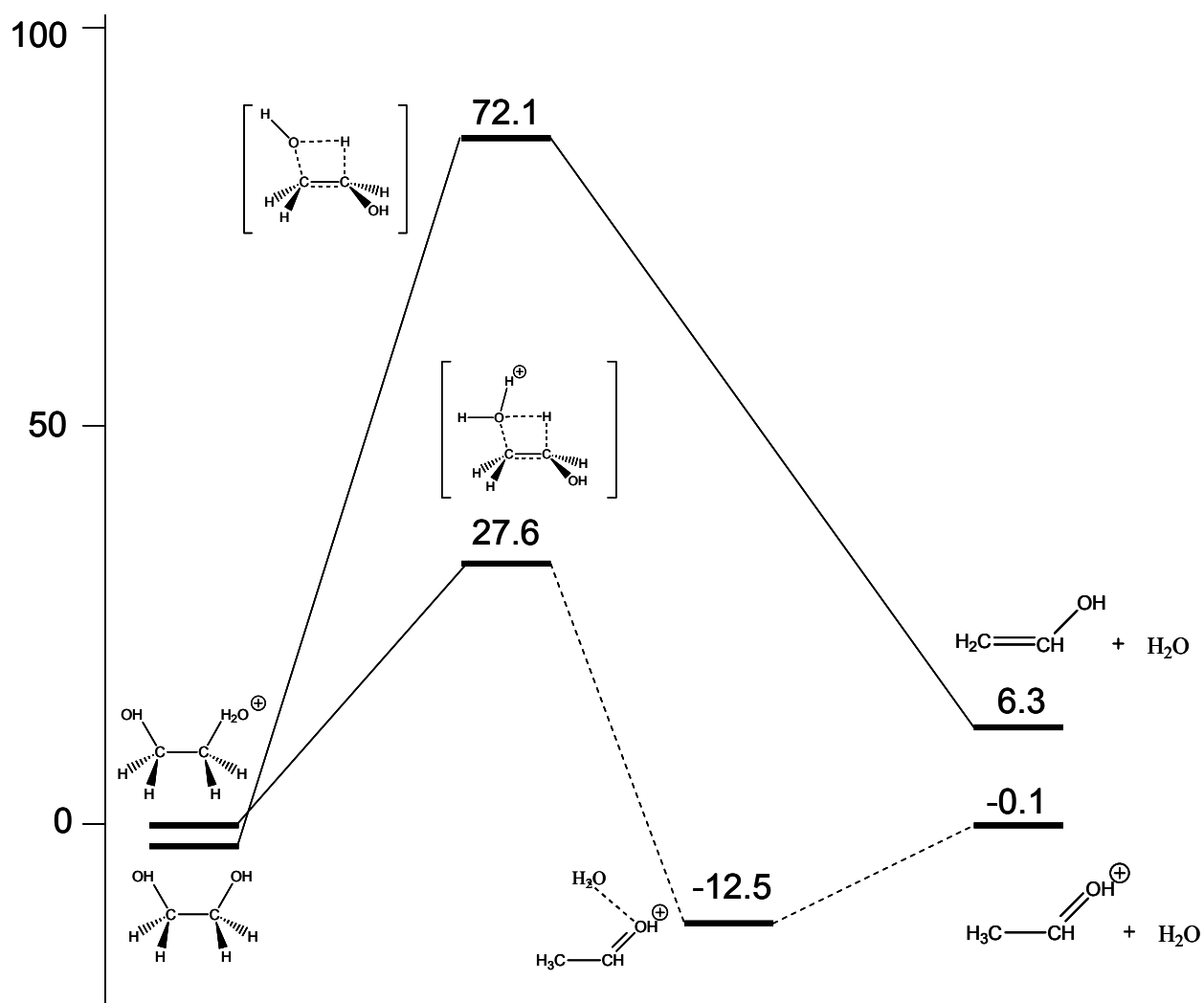


Elimination reaction of protonated ethylene glycol

The barrier height is low, the major product is protonated formaldehyde. Similar oxonium cations may be important in reactions occurring at the pyrolysis of carbohydrates.



Energy profile of the elimination reaction of ethylene glycol



References:

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