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Theoretical study of the thermolysis reaction of methyl β-hydroxycarboxylates in the gas phase

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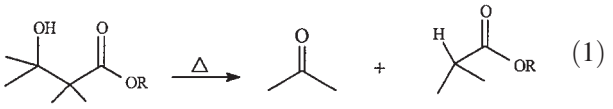
ABSTRACT: Theoretical studies on the thermolysis in the gas phase of three methyl β-hydroxycarboxylates $RR'C(OH)CH_2COOCH_3$, methyl 3-hydroxypropanoate (primary alcohol, **I**), methyl 3-hydroxybutanoate (secondary alcohol, **II**) and methyl 3-hydroxy-3-methylbutanoate (tertiary alcohol, **III**), were carried out using *ab initio* theoretical methods at the MP2/6–31G(d) and MP2/6–311+G(d,p) levels of theory. The pathways describe a mechanism via a six-membered cyclic transition state, with the formation of an aldehyde or a ketone and an enol intermediate, followed by the tautomerization of this intermediate to methyl acetate. The progress of the reactions was followed by means of the Wiberg bond indices. The results indicate that the transition states are late, and the proton transfer is the more advanced process. The kinetic parameters calculated for the reactions studied agree well with the available experimental results. A theoretical study on the kinetic deuterium isotope primary and α- and β-secondary effects was also carried out. Copyright © 2004 John Wiley & Sons, Ltd.

KEYWORDS: methyl β-hydroxycarboxylates; thermolysis; gas phase; *ab initio* theoretical methods; kinetics

INTRODUCTION

The thermolysis of β-hydroxy esters [Eqn (1)] has been little studied either experimentally or theoretically, although this functionality is a structural unit of interest. For example, optically active hydroxy esters have application as chiral synthons and monomers for the synthesis of biodegradable polymers.[1]



(1)

In previous work,[2] we carried out a theoretical study of the thermolysis reaction of ethyl β-hydroxycarboxylates $RR'C(OH)CH_2COOCH_2CH_3$. We considered two competitive reaction pathways (see Fig. 1). The first pathway describes a two-step mechanism, the first step being a concerted process in which an aldehyde or a ketone and an enol intermediate are formed via a six-membered cyclic transition state; the second is the tautomerization of the enol intermediate to ethyl acetate via a four-membered cyclic transition state. The second pathway is a one-step concerted process in which ethylene and a carboxylic acid are formed via a six-membered cyclic transition state.

In this paper, we present a theoretical study on the thermolysis reaction of three methyl β-hydroxycarboxylates $RR'C(OH)CH_2COOCH_3$, methyl 3-hydroxypropanoate (primary alcohol, **I**), methyl 3-hydroxybutanoate (secondary alcohol, **II**) and methyl 3-hydroxy-3-methylbutanoate (tertiary alcohol, **III**). In the thermolysis of these compounds, only one pathway is possible.

These reactions were studied experimentally by August *et al.*[3] in 1987. The experimental data show that they are homogeneous, unimolecular and follow a first-order rate law. The products formed were methyl acetate and an aldehyde or ketone (Fig. 2). It was proposed that the reactions involve a cyclic six-membered transition state similar to that of first pathway in Fig. 1.

The temperature dependence of the rate constants for the formation of these products in their corresponding Arrhenius equations, obtained in Ref. 3, is given by

$$\log k(s^{-1}) = 11.11 - 178.0\,\text{kJ mol}^{-1}(2.303\,RT)^{-1} \quad (2)$$

for **I**,

$$\log k(s^{-1}) = 10.90 - 164.4\,\text{kJ mol}^{-1}(2.303\,RT)^{-1} \quad (3)$$

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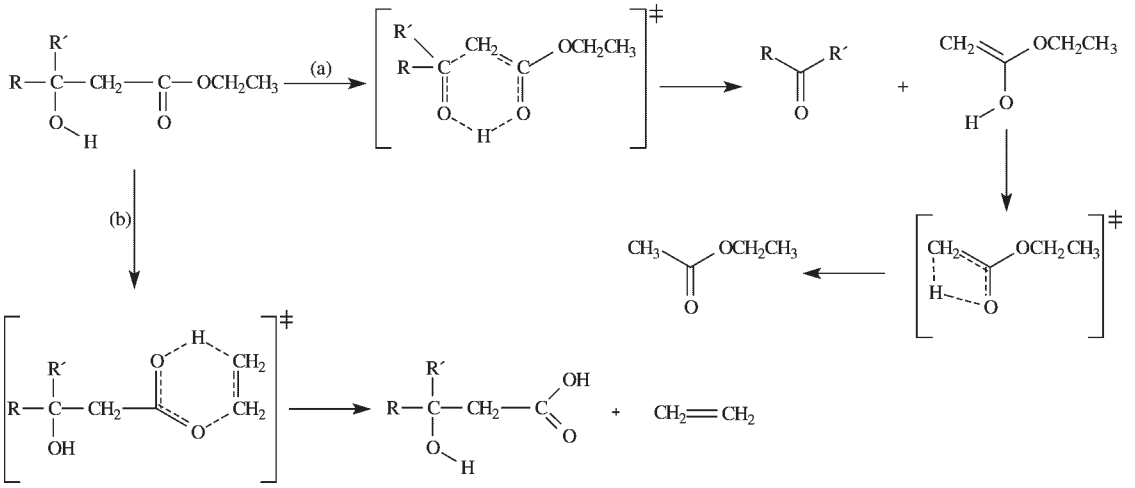


Figure 1. The two possible pathways in the thermolysis of ethyl β-hydroxycarboxylates

for **II** and

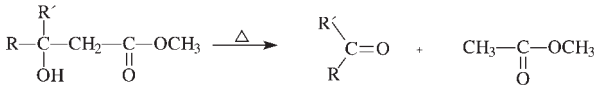
$$\log k(\mathrm{s}^{-1}) = 11.18 - 159.9\,\mathrm{kJ\,mol}^{-1}(2.303\,RT)^{-1} \quad (4)$$

for **III**.

To our knowledge, there are two previous theoretical calculations on some of these reactions but only at semi-empirical levels. Kao,[4] in 1988, studied the thermolysis of methyl β-hydroxypropanoate at the MNDO level, and Lee *et al.*,[5] in 1991, carried out a theoretical study on the pyrolysis of some carbonate esters, β-hydroxy ketones and α- and β-hydroxy esters, including the three studied in this work, at the AM1 level. However, in both studies only the activation barriers were calculated, and the values obtained were far from the experimental ones. This prompted us to carry out this work, at high *ab initio* levels.

COMPUTATIONAL DETAILS

All calculations were carried out using the Gaussian 98 computational package.[6] The geometric parameters for all the reactants, the transition states (TSs) and the products of the reactions studied were fully optimized using *ab initio* analytical gradients at the MP2 level[7] with the 6–31G(d) basis set.[8] Each stationary structure was characterized as a minimum or a saddle point of first order by analytical frequency calculations. A scaling factor[9] of 0.9670 for the zero-point vibrational energies



I R,R′ = H
II R = H; R′ = CH_3
III R,R′ = CH_3

Figure 2. The three reactions studied in this work

was used. Thermal corrections to enthalpy and entropy values were evaluated at the experimental temperature of 600.15 K. To calculate enthalpy and entropy values at a temperature T, the difference between the values at that temperature and 0 K was evaluated according to standard thermodynamics.[10]

Transition vectors,[11] the eigenvectors associated with the unique negative eigenvalue of the force constant matrix, were obtained for all the transition states. Intrinsic reaction coordinate (IRC) calculations[12] were performed in all cases to verify that the localized TS structures connect with the corresponding minimum stationary points associated with reactants and products. All the optimized structures were fully reoptimized at the MP2/6–311+G(d,p) level.[13]

The bonding characteristics of the different reactants, transition states and products were investigated using a population partition technique, the natural bond orbital (NBO) analysis of Reed and co-workers.[14,15] The NBO formalism provides values for the atomic natural total charges and also provides the Wiberg bond indices[16] used to follow the progress of the reactions. The NBO analysis was performed using the NBO program,[17] implemented in the Gaussian 98 package,[6] and was carried out on the MP2 charge densities in order to include explicitly electron correlation effects.

We selected the classical transition-state theory (TST)[18,19] to calculate the kinetic parameters. The rate constant, $k(T)$, for each elementary step of the kinetic scheme was computed using this theory assuming that the transmission coefficient is equal to unity, as expressed by the following relation:

$$k(T) = k_{\mathrm{B}}T/h\,\exp[-\Delta G^{\neq}/RT] \quad (5)$$

where k_{B}, h and R are the Boltzmann constant, Planck's constant and the universal gas constant, respectively, and $\Delta G^{\neq}(T)$ is the standard-state free energy of activation at the absolute temperature T.

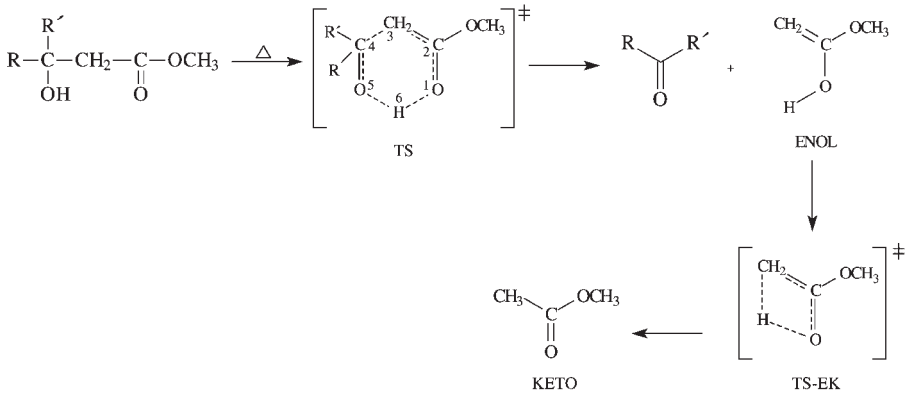


Figure 3. Mechanism of the decomposition of methyl β-hydroxycarboxylates suggested from experiments

The activation energies, E_a, and the Arrhenius A factors were calculated using Eqns (6) and (7), respectively, derived from the TST theory:

$$E_a = \Delta H^{\neq}(T) + RT \quad (6)$$

$$A = ek_B T/h \exp[\Delta S^{\neq}(T)/R] \quad (7)$$

RESULTS AND DISCUSSION

Theoretical calculations at the MP2/6–311+G(d,p) level of theory were carried out in order to explore the nature of the reaction mechanism for the unimolecular decomposition of methyl β-hydroxycarboxylates in the gas phase. The pathway proposed for these reactions describes a two-step mechanism (Fig. 3). The first step is a concerted process in which an aldehyde or a ketone and an enol intermediate are formed via a six-membered cyclic TS where the hydrogen atom of the hydroxylic group is migrating to the oxygen atom of the carbonyl group. The second step is the tautomerization of the enol intermediate to methyl acetate, through a 1,3-hydrogen shift process via a four-membered cyclic TS.

Since in the gas phase the thermal decomposition step is not reversible and the activation free energy for the thermal decomposition is higher than that for the tautomerization, it is expected that the experimental Arrhenius equations depend mainly on the free activation energy associated with the first and irreversible process. Hence the first step is the rate-limiting step of the global process.

Electronic energies, zero-point vibrational energies, thermal correction to enthalpies and entropies for all the reactants, TSs and products involved in the two steps of the three reactions studied are given in Table 1.

Free energy profiles for the decomposition processes of the three methyl β-hydroxycarboxylates are presented in Fig. 4.

The calculated activation free energies for the first step of the process are 201.7, 194.3 and 184.9 kJ mol^{-1}, for reactions I, II and III, respectively, while the calculated activation free energy of the second step is 176.1 kJ mol^{-1}, the same in the three processes because the enol intermediate is the same.

The overall processes are exergonic, with reaction free energies of −37.8, −59.9 and −78.4 kJ mol^{-1} for reactions I, II and III, respectively. These energies are less negative than those obtained[2] for the decomposition processes of the corresponding ethyl β-hydroxycarboxylates of −62.8, −86.9 and −106.8 kJ mol^{-1}, respectively.

We carried out a detailed study of the two steps of the reactions. The first step is the rate-limiting step, as indicated above. There is one and only one imaginary vibrational frequency in the TSs for this first step of the studied thermal decomposition reactions [417.7i 505.5i and 584.2i cm^{-1} for **TS-I**, **TS-II** and **TS-III**, respectively, evaluated at the MP2/6–31G(d) level of theory, with the lowest real frequency being 78.1, 75.4 and 71.4 cm^{-1} for **TS-I**, **TS-II** and **TS-III**, respectively]. The optimized structures for these TSs and the reactants are shown in Fig. 5.

The studied β-hydroxy esters present intramolecular hydrogen-bonded conformations, with hydrogen bonding

Table 1. Electronic energies evaluated at the MP2/6–311 + G(d,p) level, zero-point vibrational energies (*ZPE*) and thermal corrections to enthalpies (*TCH*) in hartree and entropies (*S*) in cal mol^{-1} K^{-1}, for all the reactants, transition states and products involved in the reactions studied

Species	MP2/6–311 + G(d,p)	*ZPE*[a]	*TCH*[a]	*S*[a]
I	−382.018041	0.127365	0.154644	113.127
TS-I	−381.936781	0.121617	0.148585	111.626
ENOL	−267.694321	0.090935	0.111891	95.634
H_2CO	−114.241609	0.027283	0.035779	58.957
TS-EK	−267.625011	0.086370	0.105907	91.901
KETO	−267.745024	0.092174	0.112541	95.736
II	−421.220327	0.155921	0.188185	124.867
TS-II	−421.141953	0.150274	0.182083	123.241
MeCHO	−153.449434	0.056956	0.069873	74.215
III	−460.422739	0.184446	0.221692	135.331
TS-III	−460.347981	0.178601	0.215488	133.584
Me_2CO	−192.655280	0.085926	0.103937	89.049

[a] Evaluated at the MP2/6–31G(d) level.

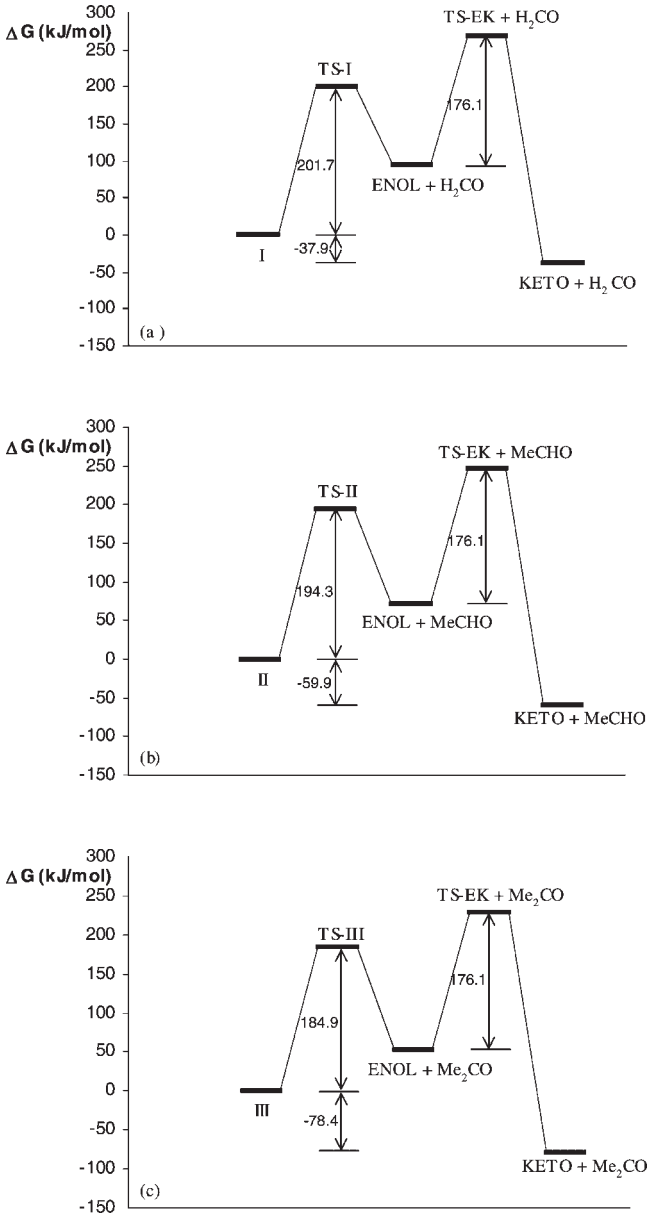


Figure 4. Free energy profiles at 600.15 K, evaluated at the MP2/6–311 + G(d,p) level, for the decomposition processes. (a) Relative free energy values (to reactant **I**, in kJ mol^{-1}) of the stationary points found are as follows: **TS-I**, 201.7; **ENOL** + H_2CO, 93.9; **TS-EK** + H_2CO, 270.0; **KETO** + H_2CO, CO, −37.9. (b) Relative free energy values (to reactant **II**, in kJ mol^{-1}) of the stationary points found are as follows: **TS-II**, 194.3; **ENOL** + MeCHO, 71.9; **TS-EK** + MeCHO, 248.0; **KETO** + MeCHO, −59.9. (c) Relative free energy values (to reactant **III**, in kJ mol^{-1}) of the stationary points found are as follows: **TS-III**, 184.9; **ENOL** + Me_2CO, 53.4; **TS-EK** + Me_2CO, 229.5; **KETO** + Me_2CO, —78.4

to the acyl oxygen predominating. This behavior was revealed by careful examination of their IR spectra in CCl_4.[20] Table 2 shows the distances between the atoms involved in the reaction center for each optimized reactant and TS. During the thermolysis process, when the reactant is being transformed into its TS, the O_1—C_2, C_3—C_4 and O_5—H_6 distances are increasing, whereas the C_2—C_3, C_4—O_5 and H_6—O_1 distances are decreasing. Comparing distances in the TSs, following the order **TS-I**, **TS-II** and **TS-III**, the values calculated at the MP2/6–311+G(d,p) level show that the C_4—O_5 distance increases from 1.256 to 1.270 Å, the O_5—H_6 distance decreases from 1.503 to 1.417 Å and the H_6—O_1 distance increases from 1.027 to 1.055 Å. The electron-releasing effect of the methyl groups attached to C_4 indicates that the hydrogen migration from O_5 to O_1 and the C_4—O_5 double-bond formation are delayed along the reaction pathway.

The transition vectors, TV, associated with the unique negative eigenvalue of the Hessian matrix for the TSs of the studied reactions are shown in Table 3. The main components of the TV are the O_5—H_6, C_4—O_5 and H_6—O_1 distances, the O_5—H_6—O_1 and C_2—O_1—H_6 bond angles and the dihedral angles related with the breaking of the C_3—C_4 bond (it should be pointed that the C_3—C_4 bond is not defined at the corresponding *z*-matrix). The largest component (around 27–29%) of TV corresponds to the O_5—H_6 distance, associated with the hydrogen migration process from O_5 to O_1.

As in other theoretical studies on reaction mechanisms carried out by us,[2,21–23] the progress of the reactions was followed by means of the Wiberg bond indices,[16] B_i, to avoid the subjective aspects associated with geometric analysis of the TSs. A very precise image of the timing and extent of the bond-breaking and bond-forming processes along the reaction path can be achieved[24] by analyzing the evolution of the bond indices corresponding to the bonds being broken or made in a chemical reaction.

The Wiberg bond indices corresponding to the bonds involved in the reaction center of the first step of the three studied reactions, for all the reactants, TSs and products, are given in Table 4.

Moyano *et al.*[24] defined a relative variation of the bond index at the TS, δB_i, for every bond, i, involved in a chemical reaction as:

$$\delta B_i = \frac{(B_i^{TS} - B_i^{R})}{(B_i^{P} - B_i^{R})} \tag{8}$$

where the superscripts R, TS and P, refer to reactants, transition states and products, respectively. Hence it is possible to calculate the percentage of evolution of the bond order through the chemical step by means of[25]

$$\%EV = 100\delta B_i \tag{9}$$

The calculated percentages of evolution of the bonds involved in the reaction center area are given in Table 4. As can be seen, the H_6 displacements from O_5 to O_1 are very advanced. The O_5—H_6 bonds are almost broken (77–83%) while the H_6—O_1 bonds are almost formed (68–74%). The O_1—C_2 double bond breaking is also very advanced (76–80%). The C_3—C_4 bond breaking is advanced (68–69%). The less advanced processes are the C_2—C_3 and C_4—O_5 double bond formation (56–60 and 52–58%, respectively).

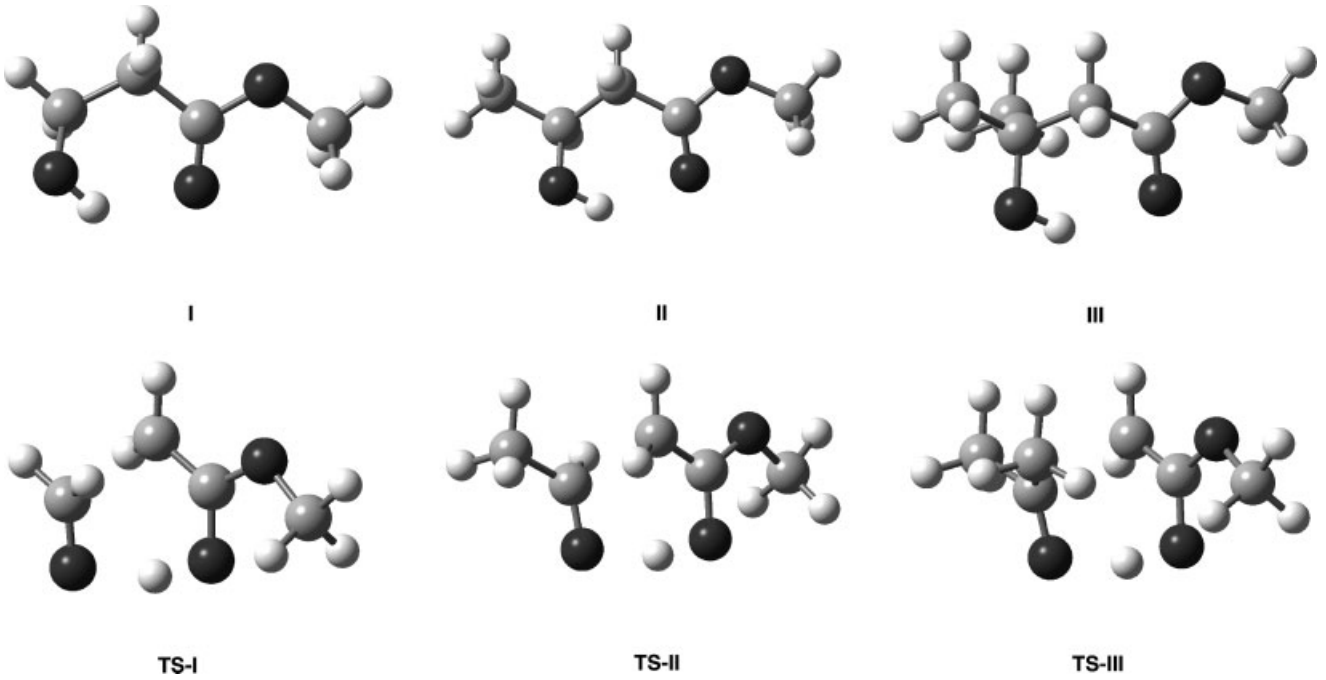


Figure 5. Structures of reactants and transition states for the first step of the decomposition of methyl β-hydroxycarboxylates, optimized at the MP2/6–311 + G(d,p) level of theory

The elongation of the O_1—C_2 bond with the initial migration of H_6 from O_5 to O_1 is the driving force for the reactions studied.

The average value, δB_{av}, calculated as[24]

$$\delta B_{av} = \frac{1}{n}\sum \delta B_i \qquad (10)$$

where n is the number of bonds involved in the reaction, measures the degree of advancement of the TS along the reaction path. Calculated δB_{av} values for the first step of the studied reactions are shown in Table 4. As can be seen, the δB_{av} values show that the TSs have a 'late' character, nearer to the products than to the reactants. The primary alcohol has the latest TS. Comparing the decomposition reactions of methyl and ethyl β-hydroxycarboxylates, the TSs of the decomposition of the methyl derivatives are slightly more advanced (δB_{av} values of 0.708, 0.673 and 0.662, for the primary, secondary and tertiary alcohol, respectively) than those corresponding to the decomposition of ethyl derivatives (δB_{av} values of 0.675, 0.652 and 0.637, respectively).[2]

The synchronicity, *Sy*, of a chemical reaction can be calculated as

$$Sy = 1 - A \qquad (11)$$

Table 2. Main distances, in ångstroms, in reactants, transition states and products, optimized at the MP2/6–311 + G(d,p) level

	O_1—C_2	C_2—C_3	C_3—C_4	C_4—O_5	O_5—H_6	H_6—O_1
First step of the pathway—						
Reaction I						
I	1.218	1.510	1.525	1.418	0.964	2.151
TS-I	1.316	1.378	2.180	1.256	1.503	1.027
Products	1.366	1.343	—	1.213	—	0.963
Reaction II						
II	1.218	1.509	1.529	1.423	0.966	2.092
TS-II	1.311	1.381	2.170	1.263	1.452	1.042
Products	1.366	1.343	—	1.215	—	0.963
Reaction III						
III	1.219	1.508	1.541	1.427	0.968	2.037
TS-III	1.308	1.383	2.179	1.270	1.417	1.055
Products	1.366	1.343	—	1.220	—	0.963
Second step of the pathway—						
ENOL	1.366	1.343	—	—	—	0.963
TS-EK	1.296	1.424	—	—	—	1.242
KETO	1.212	1.507	—	—	—	—

Table 3. Hessian unique negative eigenvalue and main components of the transition vectors for the transition states of the first step of the studied reactions, calculated at the MP2/6–311 + G(d,p) level (all values in arbitrary units)

	TS-I	TS-II	TS-III
Eigenvalue	−0.08945	−0.09531	−0.08934
O_1—C_2	0.159	0.159	0.156
C_2—C_3	−0.122	−0.125	−0.123
C_4—O_5	−0.219	−0.214	−0.207
O_5—H_6	0.522	0.524	0.538
H_6—O_1	−0.246	−0.277	−0.304
C_2—O_1—H_6	0.176	0.180	0.161
O_5—H_6—O_1	0.185	0.186	0.142
O_1—C_2—C_3—H	0.264	0.245	0.246
C—C_4—O_5—H_6	−0.395	−0.181	−0.168
C′—C_4—O_5—H_6	0.359	0.226	0.132

Where A is the asynchronicity, calculated using the expression proposed by Moyano *et al*.:[24]

$$A = \frac{1}{(2N-2)} \sum \frac{|\delta B_i - \delta B_{av}|}{\delta B_{av}} \qquad (12)$$

Synchronicities vary between zero and one, which is the case when all of the bonds implicated in the reaction center have broken or formed at exactly the same extent in the TS. The *Sy* values obtained in this way are, in principle, independent of the degree of advancement of the TS. The *Sy* values calculated for the studied reactions are shown in Table 4. The synchronicities are 0.93 in all cases, indicating that the mechanisms correspond to concerted and highly synchronous processes, the synchronicities increasing in the order primary <secondary <tertiary alcohol. In comparison with the decomposition reactions of ethyl β-hydroxycarboxylates, these present slightly lower *Sy* values (0.918, 0.924 and 0.926, for the decomposition of the primary, secondary, and tertiary alcohol, respectively).[2] However, from the analysis of the main distances (Table 2), transition vectors (Table 3) and Wiberg bond indices (Table 4), it is clear that the proton transfer process from O_5 to O_1 is more advanced that the C_3—C_4 breaking bond. Therefore, the two chemical processes, proton transfer and C—C bond breaking, are asynchronous. It seems that Moyano *et al*.'s equation[24] [Eqn (12)] does not give a good chemical representation of the asynchronicity of the processes studied.

Another aspect to be taken into account is the relative asynchronicity of the bond-breaking and the bond-forming processes that measures the'bond deficiency' along the reaction path. In the studied reactions, the bond-breaking processes are more advanced (74–77%) than the bond-forming processes (59–64%), indicating a bond deficiency in the TSs.

The charge distribution in reactants and TSs was analyzed by means of the NBO analysis of Reed and coworkers.[14,15] In Table 5, the natural atomic charges at the atoms involved in the reaction center are given. There is an important positive charge developed on H_6 (0.48–0.49 at reactants, and 0.54 at TSs) and on C_4 (0.06–0.31 at

Table 4. Wiberg bond indices (B_i) of reactants, transition states and products of the studied reactions, percentage of evolution (%EV) through the chemical process of the bond indices at the transition states, degree of advancement of the transition states (δB_{av}) and absolute synchronicities (*Sy*) (values calculated at the MP2/6–311 + G(d,p) level)

	O_1—C_2	C_2—C_3	C_3—C_4	C_4—O_5	O_5—H_6	H_6—O_1
First step of the pathway—						
Reaction I						
B_i^R	1.672	0.995	1.007	0.932	0.750	0.006
B_i^{TS}	1.102	1.498	0.314	1.449	0.127	0.562
B_i^P	0.963	1.830	0.000	1.882	0.000	0.753
%EV	80.4	60.2	68.8	58.3	83.0	74.4
		$\delta B_{av} = 0.709$	$Sy = 0.929$			
Reaction II						
B_i^R	1.669	0.996	0.997	0.915	0.743	0.008
B_i^{TS}	1.119	1.477	0.319	1.400	0.153	0.535
B_i^P	0.963	1.830	0.000	1.825	0.000	0.753
%EV	77.9	57.6	67.9	53.2	79.4	70.7
		$\delta B_{av} = 0.678$	$Sy = 0.927$			
Reaction III						
B_i^R	1.662	0.994	0.979	0.903	0.737	0.011
B_i^{TS}	1.130	1.465	0.316	1.359	0.171	0.514
B_i^P	0.963	1.830	0.000	1.778	0.000	0.753
%EV	76.1	56.4	67.7	52.1	76.8	67.8
		$\delta B_{av} = 0.662$	$Sy = 0.928$			
Second step of the pathway—						
B_i^R	0.963	1.830	—	—	0.001[a]	0.753
B_i^{TS}	1.272	1.271	—	—	0.351[a]	0.317
B_i^P	1.714	1.005	—	—	0.948[a]	0.002
%EV	41.1	67.8	—	—	37.0	58.1
		$\delta B_{av} = 0.510$	$Sy = 0.844$			

[a] This value correspond to the C_3—H_6 bond.

Table 5. NBO charges, calculated at the MP2/6–311 + G(d,p) level, at the atoms involved in the reactions

Species	O_1	C_2	C_3	C_4	O_5	H_6
First step of the pathway—						
I	−0.729	0.982	−0.468	0.057	−0.782	0.484
TS-I	−0.783	0.885	−0.646	0.378	−0.813	0.541
II	−0.729	0.987	−0.466	0.184	−0.796	0.489
TS-II	−0.787	0.901	−0.658	0.522	−0.833	0.542
III	−0.735	0.991	−0.468	0.305	−0.806	0.490
TS-III	−0.792	0.907	−0.660	0.668	−0.854	0.542
Second step of the pathway—						
ENOL	−0.755	0.743	−0.591	—	—	0.485
TS-EK	−0.814	0.950	−0.878	—	—	0.508

reactants, that increases to 0.38–0.67 at TSs), whereas the electronic excess is supported by the two oxygens [−(0.73–0.74) at reactants and −(0.78–0.79) at TSs, for O_1; and −(0.78–0.81) at reactants and −(0.81–0.85) at TSs, for O_5], and by C_3 [−0.47 at reactants and −(0.65–0.66) at TSs]. The negative character of O_1 allows it to attract the H_6 in the TS.

The most significant feature that can be obtained from the NBO charges is the large positive charge developed on the C_4 atom in the TSs, which increases with the methyl substitution on this carbon atom. The stabilization of this incipient carbocationic carbon can explain the lowering of the activation enthalpy for the first step with the methyl substitution on C_4. This explanation was pointed by Domingo *et al*.[26] in a theoretical study of the gas-phase decomposition of three α-hydroxycarboxylic acids.

The kinetic parameters for the three reactions studied here were calculated at the MP2/6–311+G(d,p) level at the same temperature as used in the experiments, 600.15 K. These data are compared with the experimental results in Table 6. The calculated rate constants agree very well with the experimentally determined values. The primary: secondary:tertiary rate ratio, obtained from calculated rate constants, is 1:4.4:28.9, in agreement with the experimental ratio of 1:9.3:44.7, and it is very similar to that obtained[2] for ethyl β-hydroxycarboxylates, 1:6.4:24.5. These ratios are according to the stabilization of the incipient carbocationic carbon pointed above.

In the second step of the pathway, the enol intermediate initially formed tautomerizes to its keto form, methyl acetate. Keto–enol equilibrium has been in the mainstream of physical organic chemistry for many decades.[27,28] The thermodynamic stabilities of the keto–enol tautomeric isomers have been the main subjects of many experimental and theoretical investigation, but some studies on the kinetic aspects of the tautomeric equilibria in solution have also been carried out, principally by Kresge's group.[29–34] Andrés *et al*.[35] carried out a theoretical study of transition structures, barrier heights and reaction energies for the intramolecular tautomerization in the acetaldehyde–vinyl alcohol system.

The optimized structures of the enol and keto forms of methyl acetate and the TS associated with them are shown in Fig. 6. The enol prefers an almost planar *syn* conformation in the gas phase. This behavior of enols is known from experiment[36–38] and has been confirmed by theory.[39] **TS-EK** has a four-membered cyclic structure. It presents one and only one imaginary vibrational frequency, 2164.0i cm^{-1}, with the lowest real frequency being 132.7 cm^{-1}. An analysis of the Wiberg bond indices (see Table 4) indicates that the TS of this second step of the studied reactions has an intermediate character between reactant and product, and it is asynchronous, the C_2—C_3 double bond breaking is very advanced (68%) whereas the formation of the O_1—C_2 and C_3—H_6 bonds is delayed (percentages of evolution of 41 and 37%, respectively). The NBO charge distribution (see Table 5) indicates that the methylene carbon C_3 carries the most negative charge, and the carbonyl carbon C_2 is the most positively charged center.

Table 6. Calculated[a] and experimental[b] kinetic and activation parameters for the studied reactions

	10^4k (s^{-1})		E_a(kJ mol^{-1})		Log A		$\Delta H^{\neq}$(kJ mol^{-1})		$\Delta G^{\neq}$(kJ mol^{-1})		$\Delta S^{\neq}$ (J mol^{-1} K^{-1})	
Reaction	Calc.	Exp.	Calc.	Exp.	Calc.	Exp.	Calc.	Exp.	Calc.	Exp.	Calc.	Exp.
First step of the pathway—												
I	0.349	0.412	202.9	178.0	13.2	11.11	197.9	176.8	201.7	194.8	−6.3	−30.0
II	1.54	3.84	195.2	164.4	13.2	10.90	190.2	163.2	194.3	183.6	−6.8	−34.0
III	10.1	18.4	185.5	159.9	13.2	11.18	180.5	158.7	184.9	175.8	−7.3	−28.6
Second step of the pathway—												
	60.1		171.7		12.7		166.7		176.0		−15.6	

[a] At the MP2/6–311 + G(d,p) level of theory. Values calculated at 600.15 K.
[b] Values taken from Ref. 3.

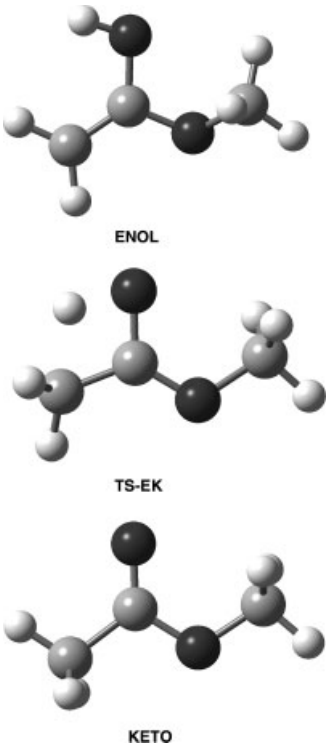


Figure 6. Structures of enol and keto forms, and the corresponding transition state, **TS-EK**, optimized at the MP2/6–311 + G(d,p) level of theory

This second step of the reactions is a more rapid process than the first step, with an activation free energy of 176.1 kJ mol^{-1}, so it is not the rate-limiting step of the reactions. Wu and Lien[40] obtained a correlation between the activation free energies corresponding to the tautomerization X—C(OH)═CH_2 ↔ X—C(O)—CH_3, and the Hammett substituent resonance parameters, σ_R^+, for proton transfer in the gas phase compiled by Taft and co-workers:[41,42]

$$\Delta G^{\neq}(\text{kcal mol}^{-1}) = 55.79 + 30.95\sigma_R^+ \qquad (13)$$

Table 7. Kinetic deuterium isotope effects (k_H/k_D) in the pyrolysis of methyl and ethyl β-hydroxycarboxylates in the gas phase

Reaction	Effect	Methyl compounds[a]	Ethyl compounds[b]
I	Primary	1.42	1.49
	α-Secondary	1.20	1.28
II	Primary	1.53	1.70
	α-Secondary	1.13	1.13
	β-Secondary	1.03	1.03
III	Primary	1.63	1.78
	α-Secondary	1.04	1.11
	β-Secondary	1.05	1.11

[a] Values calculated in this work, at 600.15 K, at the MP2/6–311 + G(d,p) level of theory.
[b] Values taken from Ref. 2, calculated at 479.15 K, at the MP2/6–311++G(2d,p)//MP2/6–31G(d) level of theory.

Using this equation and the σ_R^+ value[43] for the OCH_3 group, −0.42, a value of the free energy of activation for the tautomerization of the enol form of methyl acetate of 179.0 kJ mol^{-1} is obtained, in very good agreement with the value calculated in this work.

The calculated rate constant of the tautomerization of the enol intermediate to methyl acetate is 6.01×10^{-3} s^{-1}, evaluated at the MP2/6–311+G(d,p) level of theory. The reaction is exergonic, the keto form being 131.8 kJ mol^{-1} more stable than enol form.

We also carried out a theoretical study on the kinetic deuterium isotope effects in the thermal decomposition of the studied methyl β-hydroxycarboxylates, and compared the results with those calculated previously[2] for ethyl β-hydroxycarboxylates. To our knowledge, there has not been any experimental study on kinetic isotope effects in the thermal decomposition of methyl β-hydroxycarboxylates.

The kinetic isotope effects, k_H/k_D, obtained at the MP2/6–311+G(d,p) level of theory, are shown in Table 7. As can be observed, the primary isotope effects are lower in methyl than in ethyl esters. It is known that the magnitude of the primary isotope effect in a hydrogen-transfer reaction varies with the symmetry of the TS and it is maximum when the hydrogen is symmetrically bonded to the atoms between which it is being transferred. The small value of this effect is a consequence of the fact that transfer of hydrogen, partially bonded to the oxygen of the carbonyl and hydroxyl groups in the TS, is not linear, and the TS is late. The O—H bond is not stretched to its breaking point, but it does bend, so the hydrogen atom may become attached to another part of the molecule. It is the bending rather than the stretching which is connected to translational motion.[44–47] Because vibrational frequencies for bending are much lower than those for stretching, the zero-point energy lost in the TS will be small and therefore the primary kinetic deuterium isotope effect should be small. As can be seen in Table 7, the primary effect increases in the order primary alcohol < secondary alcohol < tertiary alcohol.

The α-secondary deuterium isotope effects that occur when deuterium atoms are attached to a center that is undergoing a hybridization change are small but >1. These results are a consequence of the fact that in the proposed mechanism the C_3 and C_4 atoms change their hybridization from sp^3 to sp^2 in the TSs. According to the Streitweiser model,[48] the α-isotope effect is predominantly due to the change of a tetrahedral C–H bending vibration to an 'out-of-plane' deformation in the TS. The α- and β-secondary effects are cumulative and depend on the number of H_α and H_β in the molecules. Hence the α-secondary effect increases in the order reaction III < reaction II < reaction I, in the same order as the number of H_α increases (two in reactant **III**, three in **II** and four in **I**), whereas the β-secondary effect is small but slightly higher in reaction III (six H_β in reactant **III**) than in reaction II (only three H_β in **II**), and there is no β-secondary effect in reaction I (there is no H_β in reactant **I**).

CONCLUSIONS

A theoretical study on the thermal decomposition in the gas phase of three methyl β-hydroxycarboxylates has been carried out at the MP2/6–311 + G(d,p) level of theory. The reactions take place via a six-membered cyclic TS. The progress of the reactions was followed by means of the Wiberg bond indices. The TSs are late, nearer to the products than to the reactants. The analysis of the main distances, transition vectors and Wiberg bond indices indicates that the proton transfer is the most advanced process.

The kinetic parameters for the studied reactions, evaluated at the MP2/6–311 + G(d,p) level of theory, agree well with the available experimental data. There is a large positive charge developed on the C_4 atom at the TSs, which increases with the methyl substitution on this carbon atom. The stabilization of this incipient carbocationic carbon can explain the lowering of the activation enthalpy for the first step with the methyl substitution on C_4 and, therefore, the order of the experimental and calculated rate constants: primary alcohol < secondary alcohol < tertiary alcohol.

A theoretical study on the kinetic deuterium isotope effects was also carried out, comparing the results with those corresponding to ethyl β-hydroxycarboxylates.

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