

MO STUDY OF THE POSSIBILITY OF A CONCERTED MECHANISM IN THE PINACOL REARRANGEMENT

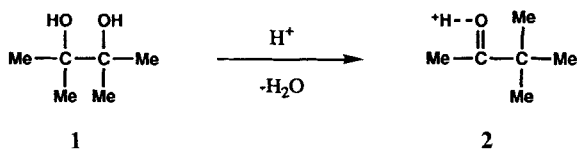
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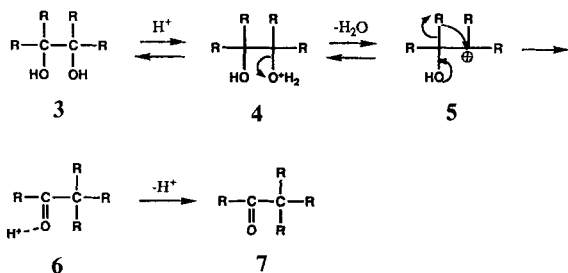
The *ab initio* SCF-MO method was employed to examine the possibility of a reaction pathway without a carbocation intermediate in the pinacol rearrangement. The molecular geometries of the transition states were obtained for the 1,2-hydride shift together with H₂O elimination, starting from the various methyl-substituted protonated 1,2-diols. It was found that the activation energies depend strongly on the substituents. A comparison of the relative energies between β -hydroxycarbonium ions and the transition states of the concerted mechanism suggests that the stepwise mechanism is less favourable than the concerted path in each case.

INTRODUCTION

The pinacol rearrangement reaction is the nucleophilic intramolecular 1,2-shift reaction of 1,2-diols (1) under acidic conditions:



This reaction has been believed to proceed stepwise via a carbonium ion intermediate as similarly to a Wagner–Meerwein rearrangement.^{1,2} In most textbooks on organic chemistry,^{3,4} the mechanism of the pinacol rearrangement is explained as follows:



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According to this mechanism, the pinacol rearrangement proceeds via two steps, first the formation of the β -hydroxycarbonium ion 5 by dehydration of the protonated 1,2-diol 4 and second the formation of the carbonyl compound 6 followed by a 1,2-shift of R in the β -hydroxycarbonium ion 5. The species 5 is thought to exist as an intermediate to explain the racemization of the product.⁵ Although this stepwise mechanism is supported by the experimental observation of mixing of stereochemistry,⁶ there is doubt about the stability of the β -hydroxycarbonium ion, based on our previous theoretical study.⁷ Gas-phase experiment⁸ and the recent observation of a stereospecific pinacol-type rearrangement under mild conditions,⁹ also suggest the concerted mechanism. Considering these facts, the mechanisms of the pinacol rearrangement seems likely to be intrinsically concerted. In this paper, we examine these two mechanisms (stepwise and concerted) more closely in terms of *ab initio* molecular orbital theory.

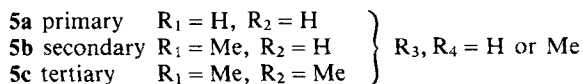
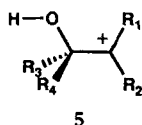
COMPUTATIONAL PROCEDURE

Ab initio molecular orbital calculations were carried out using the GAUSSIAN 82 program package.¹⁰ The geometries of each stationary point were optimized by means of the analytical gradient method at the HF level with the 6-31G basis set. Single-point energy calculations were carried out using the 6-31G** basis set at these geometries, because it is known that a polarization function is necessary to evaluate the energy of a bridged structure such as the transition state of the pinacol rearrangement. Geometry optimization with a

polarization function and the MP2 calculation were performed for the system of the simplest ethane-1,2-diol to test the reliability of the above procedure. All the values cited in the following text are those obtained with the 6-31G** basis set in HF-level calculations unless specified otherwise.

RESULTS AND DISCUSSION

Instability of the β -hydroxycarbonium ion has been discussed in previous molecular orbital studies.^{7,11-13} As a result of our complete examination of the stability of primary, secondary and tertiary β -hydroxycarbonium ions:



we have found that the geometry of 5 is not the equilibrium structure for the primary and secondary cations, and R_3 or R_4 (H or Me) spontaneously migrates without any activation energy to form a protonated aldehyde or ketone.⁷ On the other hand, the formation of an aldehyde by the 1,2-hydride shift of the tertiary β -hydroxycarbonium ion 5c ($R_1 = R_2 = Me$) requires 8 kcal mol⁻¹ of activation energy. While the tertiary carbonium ion 5c seems to be stable enough as an intermediate of the pinacol rearrangement, it is more probable that the rearrangements proceed without forming the β -hydroxycarbonium ion 5 in the case of primary and secondary cations ($R_1 = Me$). In other words, we have to consider the concerted mechanism for the pinacol rearrangement in addition to stepwise mechanism via the β -hydroxycarbonium ion 5.

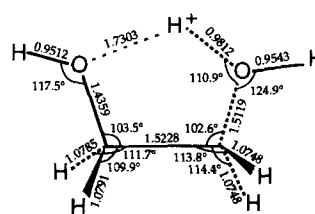
Whether the β -hydroxycarbonium ion is stable or not, it is important to compare the energetic superiority of both the concerted and stepwise mechanisms to discuss the reaction mechanism. In the following sections, we shall discuss the energetics of the stepwise mechanism.

Molecular structures of protonated 1,2-diols and dehydration energies

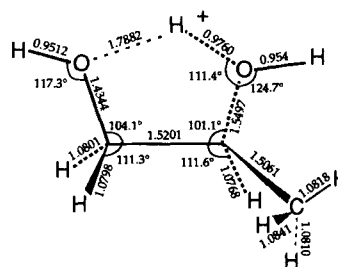
The protonated 1,2-diol 4 may be assumed to be a reactant of the pinacol rearrangement. Optimized geometries of primary (4a), secondary (4b) and tertiary (4c) protonated 1,2-diols are shown in Figure 1. 1,2-Ethanedol is most stable at the conformation where the two hydroxy groups are in a *cis* arrangement because of the intramolecular hydrogen bonding. The *cis* con-

former of protonated 1,2-ethanedol is also substantially stabilized owing to the strong hydrogen bonding between the protonated hydroxy group and the other hydroxy moiety. The energy difference between the *cis* and *trans* conformers of protonated 1,2-ethanedol is calculated to be 12 kcal mol⁻¹.

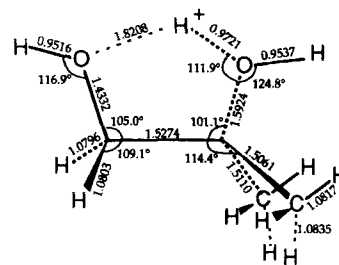
As is shown in Figure 1, protonation prefers the hydroxy group on the side substituted with the methyl group. The proton strongly binds to the oxygen atom on the side substituted with the methyl group. It should be noted that the C—O bond distance of the dimethyl protonated 1,2-diol 4c is 0.08 Å longer than that of protonated ethane-1,2-diol 4a. This suggests the favourable dehydration to produce the tertiary carbonium ion.



protonated ethylene glycol (4a)



protonated 1,2-propanediol (4b)



protonated 2-methyl-1,2-propanediol (4c)

Figure 1. Geometries of protonated 1,2-diols optimized with HF/6-31G

The total energies and relative energies for calculated species are summarized in Table 1. As is shown, the energies required for the formation of primary (5a), secondary (5b) and tertiary (5c) carbonium ions are calculated to be 48.7, 32.4 and 20.4 kcal mol⁻¹, respect-

ively. The large energy differences between primary and secondary and between secondary and tertiary (each about 10 kcal mol⁻¹) are due to the stabilization of the cationic center by hyperconjugation.

Table 1. The energies (hartree) of the reactants, intermediates, transition states, and products of pinacol rearrangement. Relative energies (kcal/mol) are shown in parentheses

	HF/6-31G	HF/6-31G**//HF/6-31G
Primary		
protonated 1,2-ethanediol (4a)	-229.16650 (0.0)	-229.26573 (0.0)
2-hydroxy ethyl cation (5a) + H ₂ O	-229.07416 (57.9)	-229.18806 (48.7)
transition state of concerted mechanism (9a)	-229.10362 (39.4)	-229.22824 (23.6)
protonated acetoaldehyde (6a) + H ₂ O	-229.13698 (18.5)	-229.26007 (3.5)
hydrated protonated acetoaldehyde (12a)	-229.19179 (-19.7)	-229.32227 (-21.7)
Secondary		
protonated 1,2-propane diol (4b)	-268.19818 (0.0)	-268.31590 (0.0)
2-hydroxy-1-methylethylcation (5b) + H ₂ O	-268.13297 (40.9)	-268.26419 (32.4)
transition state of concerted mechanism (9b)	-268.14015 (36.2)	-268.28463 (19.6)
protonated propanal (6b) + H ₂ O	-268.16143 (23.0)	-268.30272 (8.3)
hydrated protonated propanal (12b)	-268.21392 (-9.9)	-268.34401 (-17.6)
Tertiary		
protonated 2-methyl-1,2-propanediol (4c)	-307.22676 (0.0)	-307.36259 (0.0)
2-hydroxy-1,1-dimethylethylcation (5c) + H ₂ O	-307.18090 (28.8)	-307.33010 (20.4)
transition state of concerted mechanism (9c)	-307.17475 (33.4)	-307.33541 (16.7)
transition state of 1,2-shift (8c) + H ₂ O	-307.15105 (47.4)	-307.31777 (28.1)
protonated isobutylaldehyde (6c) + H ₂ O	-307.18372 (26.9)	-307.34465 (11.2)
hydrated protonated isobutylaldehyde (12c)	-307.23481 (-5.1)	-307.38396 (-13.4)

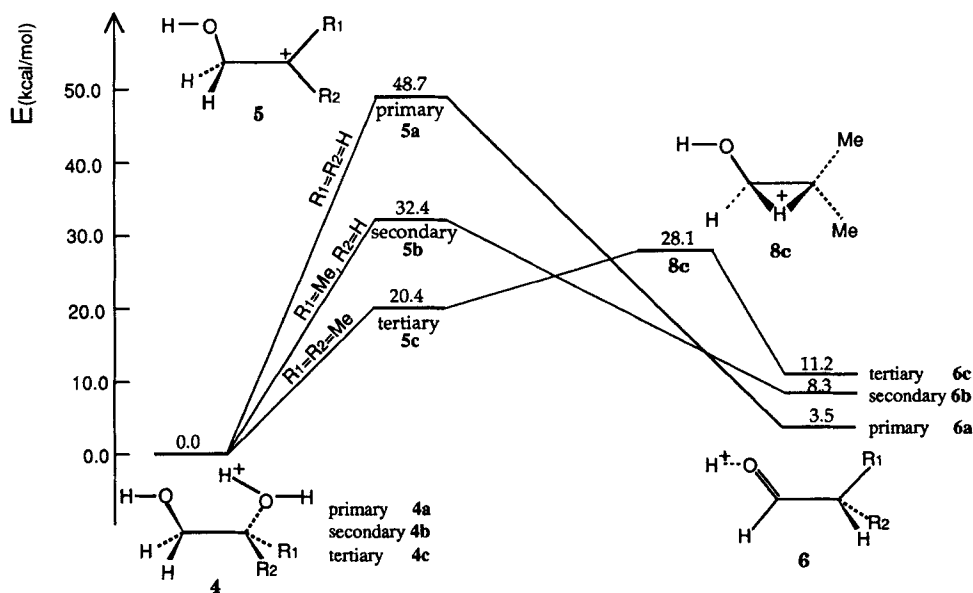


Figure 2. Schematic energy diagram of the stepwise mechanism of the pinacol rearrangement. The relative energies were obtained with the procedure HF/6-31G**//HF/6-31G

Transition state of the stepwise mechanism

Figure 2 summarizes the schematic potential energy surfaces for the stepwise mechanism via β -hydroxycarbonium ions. As we have already concluded previously,⁷ the primary and secondary β -hydroxycarbonium ions (**5a** and **5b**) spontaneously isomerize to the protonated carbonyl compounds. Although the transition state of hydride migration is found in the case of the secondary β -hydroxycarbonium ion **5b**, its energy barrier is extremely small ($0.8 \text{ kcal mol}^{-1}$). In the case of the tertiary β -hydroxycarbonium ion, the transition state of the 1,2-hydride shift (**8c**) was found to be relatively higher

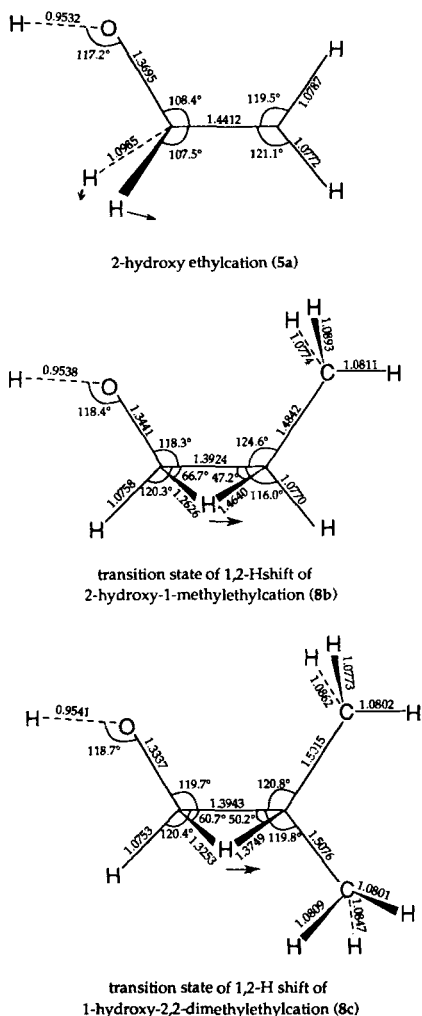


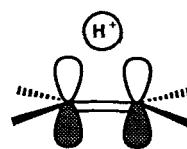
Figure 3. Optimized geometries of the 2-hydroxyethyl cation **5a**, transition states of 1,2-hydride shift of the 2-hydroxy-1-methyl cation **8b** and of the 1-hydroxy-2,2-dimethyl cation **8c** obtained with HF/6-31G

($7.7 \text{ kcal mol}^{-1}$) than the intermediate **5c** as shown in Figure 2. Such a relationship with the stability of the β -hydroxycarbonium ion clearly reflects the structures of the transition state for the 1,2-hydride shift which are illustrated in Figure 3. While the primary β -hydroxycarbonium ion **5a** itself is at the transition state of self-isomerization between two protonated acetoaldehydes, a hydrogen-bridged structure is found to be the transition state of hydrogen-migration in the case of secondary and tertiary carbonium ions (**5b** and **5c**). Noting the difference between the two H-bridged geometries shown in Figure 3, the tertiary β -hydroxycarbonium ion has a late transition state because the cationic centre is stabilized by methyl substitution.

Transition state of the concerted mechanism

Since the primary and secondary β -hydroxycarbonium ions cannot exist as stable species during the dehydration and the 1,2-migration, it is more reasonable to consider the alternative rearrangement pathway, in which the 1,2-shift and water elimination occur simultaneously. It is also worth examining such a concerted reaction mechanism for tertiary diols, which would be an alternative route via the tertiary carbonium ion.

Figure 4 shows the calculated geometries of the transition state of the concerted 1,2-hydride shift starting from the protonated 1,2-ethanediol in *cis* forms. It is clearly shown that the hydride migration occurs in conjunction with the elimination of H_2O . The transition state has a nearly symmetric structure about the migrating hydride. It is notable that the C—C bond length at the transition state (1.38 \AA) is much shorter than the single C—C bond lengths (1.52 \AA and 1.47 \AA) in the reactant and product. One may regard the geometry at the transition state as a so-called non-classical structure protonated on the olefinic π -bond as follows:



When a methyl group is substituted on the carbon atom in 1,2-ethanediol, hydride migration occurs toward the carbon atom substituted with a methyl group. The dehydration prefers the methyl-substituted site, owing to the stability of the carbonium ion formed. The elimination of a water molecule, however, leads to a transition state of the 1,2-hydride shift without forming the β -hydroxycarbonium ion. This situation is clearly shown in unsubstituted ethane-1,2-diol, where the migrating hydride is anti-periplanar to the leaving water molecule.

The transition-state structures shown in Figure 4 are obtained for *trans* elimination of water toward the

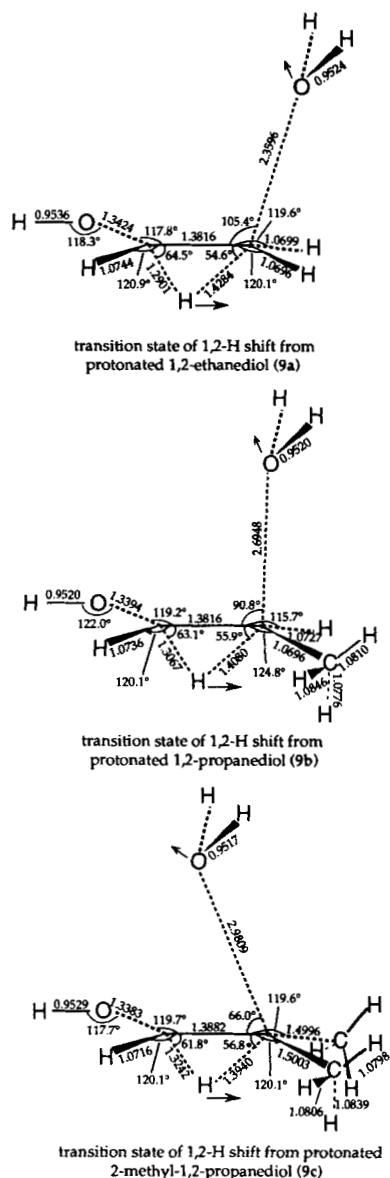


Figure 4. Optimized geometries of the transition states of the concerted mechanism obtained with HF/6-31G

hydride migration starting from the *cis* form of protonated 1,2-ethanediol. In order to examine the non-stereospecificity of the products as experimental evidence, we also calculated the transition state of *cis* elimination starting from the less stable *trans*-protonated 1,2-ethanediol. The geometries of the reactant (10) and transition state (11) are shown in Figure 5. As seen in the transition-state structure 11, the distance between the carbon atom and the leaving water

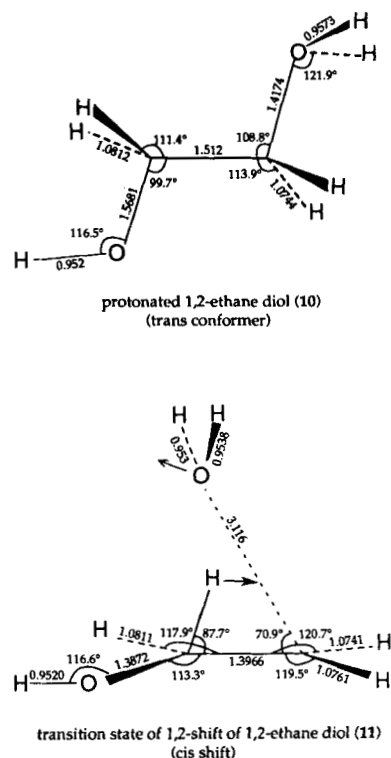


Figure 5. Structure of the reactant and the transition state of the concerted *cis* hydride shift obtained with HF/6-31G

molecule is very large, and the leaving water molecule undergoes a coulombic interaction with the migrating hydrogen atom. Although this energy is found to be almost the same as that obtained for *trans* elimination, *cis* elimination would be unfavourable for a migrating group other than hydride owing to the steric situation. Hence it is difficult to conclude that the *cis* elimination is one of the reasons for the mixing of stereochemistry, except for the case of hydride migration.

It is interesting to consider the geometrical differences among the transition states of hydride migration shown in Figure 4. In the case of monomethyl-substituted ethane-1,2-diol, the C—O bond distance (2.69 Å) at the transition state 9b is much larger than that of non-substituted case 9a (2.36 Å), and the C—C—O angle is found to be almost 90°. Note that the C—C—O angle becomes <90° in the transition state with dimethyl substitution 9c. Since the C—O bond is already cleft (*ca* 3 Å), hydride migration of protonated dimethylethane-1,2-diol seems to occur followed by the formation of a tertiary carbonium ion. The leaving water molecule in the tertiary case is moving toward the hydroxy group showing that the product gains stabilization by further hydration, as will be discussed in the next section.

Noting the charge distributions of the reactants and transition states shown in Figure 6, the positive charge disperses on the hydrogen atoms in any case, but does not localize on a proton. At the transition states, the positive charge distributes equally to the protonated olefinic moiety, although the largest positive charge is on the hydrogen atom which is going to be the proton of the product, the protonated aldehyde.

Energy barriers of the concerted mechanism

In order to obtain more reliable energy barriers for the 1,2-hydride shift in the concerted mechanism, we calculated the total energies with the 6-31G** basis set at the geometries obtained with 6-31G basis set. Energies obtained with both the 6-31G and 6-31G** basis set are summarized in Table 1.

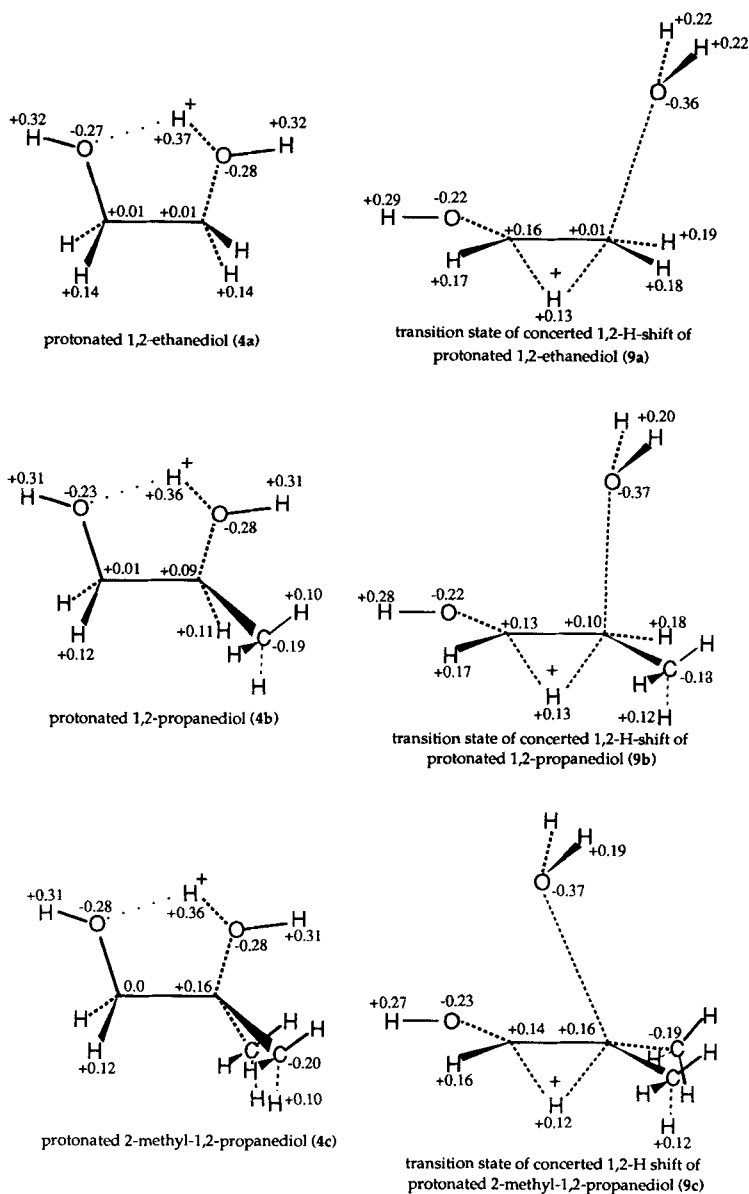
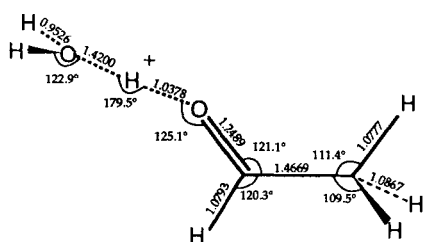
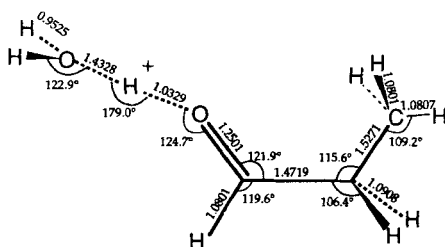


Figure 6. Atomic charge densities for the protonated 1,2-diols and the transition state of the hydride shift. The values were obtained with HF/STO-3G

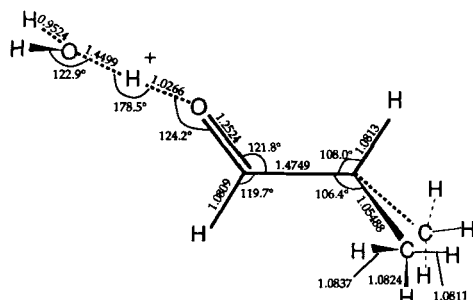
The product of the pinacol rearrangement is reasonably assumed to be the hydrated protonated aldehyde or ketone. As shown in Table 1, however, the protonated aldehyde or ketone is higher in energy than the corresponding reactant, protonated 1,2-diol. One reason is that protonation of the 1,2-diol gives a larger stabilization than that of the aldehyde because a proton can bidentate to two hydroxy groups in 1,2-diol. The other reason is that we are assuming the isolation of the leaving water molecule. Since the pinacol rearrangement is, in fact, normally observed in solution, this reaction would show an enthalpy gain due to the solvation. In the present model calculation, we have there-



hydrated protonated acetoaldehyde (12a)



hydrated protonated propanal (12b)



hydrated protonated isobutyl aldehyde (12c)

Figure 7. Optimized geometries of hydrated protonated aldehydes obtained with HF/6-31G

fore calculated the energies of the hydrated species of the protonated aldehydes as products. Figure 7 shows the molecular structures of products used for the evaluation of reaction energies. As in the transition-state structure shown in Figure 4, the leaving water tends to hydrate to the hydroxy group, especially in the case of a tertiary diol. This automatically leads to the formation of hydrated species of the protonated aldehyde.

Figure 8 illustrates the energy diagrams of the concerted mechanism for the three cases discussed above. The lowering of the barrier heights of 1,2-shift is found to be 4 kcal mol⁻¹ from the primary to secondary and 2.9 kcal mol⁻¹ from secondary to tertiary. It is interesting that the stabilization of the transition state or intermediate due to the methyl substitution is much smaller in the concerted than in the stepwise mechanism. This is because simultaneous nucleophilic migration with dehydration occurs in concerted mechanism. In other words, stabilization of the positive charge by hyperconjugation works more effectively on the β -hydroxycarbonium ion intermediate in the stepwise mechanism than on the transition state in concerted mechanism.

In this study, the effect of the electron correlation was not taken into account. From previous results for the dehydration and 1,2-hydride shift of protonated ethane-1,2-diol,⁷ we have concluded that the contribution of the polarization function is more important than the effect of the electron correlation in order to evaluate the relative energies of these ionic species. The solvent effect would also be important because the actual reaction is performed in solution. An ionic species transition state tends to be less stable than its reactant or product in a polar solvent, because of delocalization of the positive charge. Consequently, the activation energy of the pinacol rearrangement is expected to be higher in a polar solvent, as is known in the S_N2 reaction.¹⁴ The effect of the solvent may be small in an aprotic solvent. Although we have considered the single water molecule as a part of the reactive species in our model calculation, the intrinsic nature of the reaction would not be affected by the solvent. In conclusion, the present results indicate the superiority of the concerted mechanism over the stepwise mechanism, even in the case of the tertiary carbonium ion.

CONCLUSION

We have obtained the geometries of the transition state and the potential energy surfaces for the hydride migration of methyl-substituted 1,2-diols for both stepwise and concerted mechanisms by using the *ab initio* SCF-MO method. In the present model calculation of the pinacol rearrangement, the estimation of the activation energies leads to the result that the concerted mechanism is more favourable than the stepwise

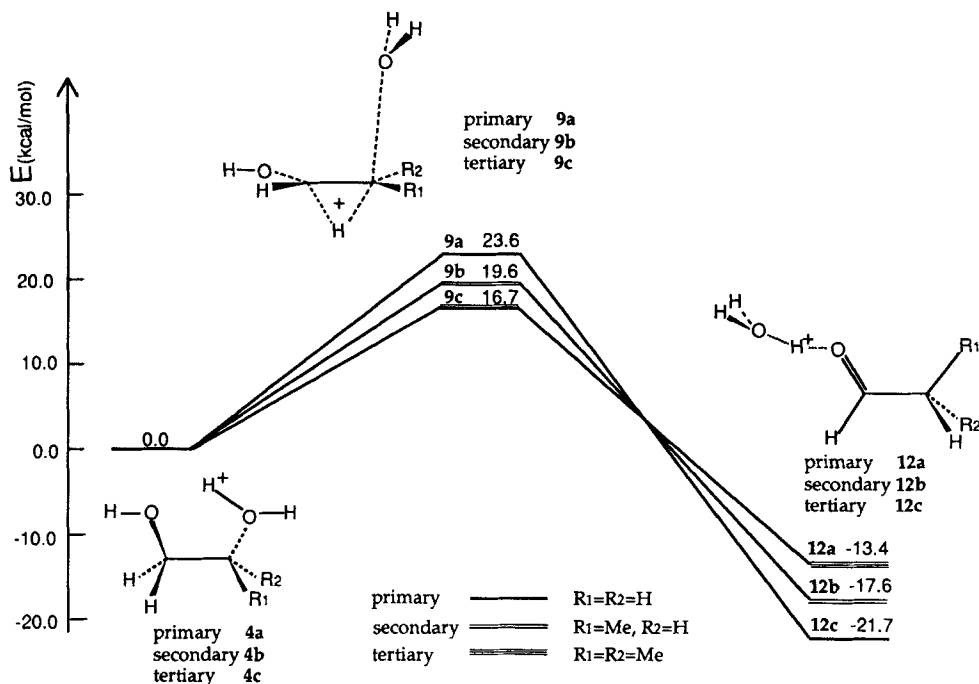


Figure 8. Schematic potential energy diagram of the concerted mechanism of the pinacol rearrangement obtained with HF/6-31G//HF/6-31G**

mechanism. Since the tertiary β -hydroxycarbonium ion can exist as stable intermediate, the stepwise mechanism would also be possible in a polar solvent. We would expect the predominance of the concerted mechanism for the reaction in a non-polar solvent, however. In this respect, the present molecular orbital calculation may be a good model for the recent stereospecific pinacol rearrangement in an aprotic solvent.⁹ Further studies on the substituent effects and migratory aptitude of the pinacol rearrangement will be published elsewhere.¹⁵

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