[1,3]-Sigmatropic Rearrangements of Divinylcyclopropane Derivatives and Hetero Analogs in Competition with Cope-Type Rearrangements – A DFT Study

Dirk Sperling,[a] **Hans-Ulrich Reißig,**[a] **and Jürgen Fabian***[a]

Dedicated to Professor Achim Mehlhorn on the occasion of his 60th birthday

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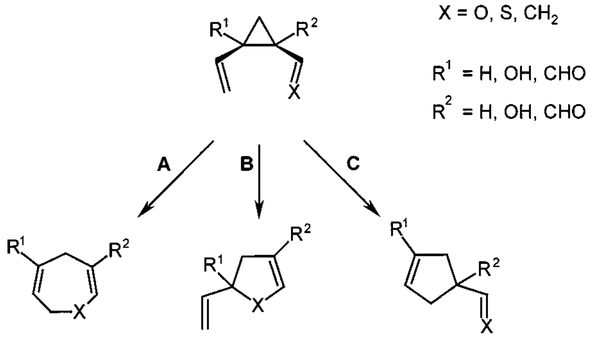
Two possible types of competing [1,3] rearrangements of divinylcyclopropane derivatives and of the hetero-analogous compounds vinylcyclopropanecarbaldehyde and vinylcyclopropanecarbthioaldehyde to five-membered ring compounds have been investigated theoretically by (U)DFT (Becke3LYP/6–31G*) methodology. Although both of the rearrangement pathways correspond to a reaction of the monosubstituted cyclopropane substructure, i.e. a reaction of vinylcyclopropane or of cyclopropanecarb(thio)aldehyde, new features in the reactivity are seen due to the combination of two substituents. Reaction parameters such as reaction and activation energies of the [1,3]-sigmatropic rearrangements have been calculated and compared. Substituent effects of hydroxy and formyl (donor and acceptor) groups in specific positions have also been considered. On the basis of these calculations, the [1,3] rearrangement of vinylcyclopropanecarbaldehydes to dihydrofurans can be expected to be kinetically favored over their conversion to cyclopentenes, while formation of the latter should be favored thermodynamically. This prediction is borne out by the experimental findings. Depending on the substitution pattern, the [1,3]-sigmatropic rearrangement of vinylcyclopropanecarbaldehydes may compete with the [3,3]-sigmatropic rearrangement. For the other investigated structures, the [1,3] rearrangement is strongly disfavored.

Introduction

cis-Divinylcyclopropane derivatives may undergo rearrangement in two different ways. On the one hand, a [3,3]-sigmatropic rearrangement analogous to the Cope reaction may occur, resulting in 1,4-cycloheptadienes (reaction A in Scheme 1).[1] On the other hand, [1,3]-sigmatropic rearrangements may take place with formation of vinyl-substituted cyclopentenes (reaction B, $X = CH_2$).[2] The situation becomes more complex if one of the vinyl groups is replaced by a hetero-analogous group such as carbonyl or thiocarbonyl. In these cases, two possible [1,3]-sigmatropic rearrangements can be envisaged, furnishing either cyclopentenes or five-membered heterocycles. The latter reaction corresponds to reaction B in Scheme 1. Thus, the reactive sites of the [1,3]-rearrangement of the disubstituted cyclopropanes under consideration are either the vinylcyclopropane or cyclopropanecarb(thio)aldehyde fragments.



Scheme 1. [3,3]-sigmatropic rearrangement (A) and [1,3]-sigmatropic rearrangement (B, C) of divinylcyclopropane derivatives and hetero analogs

The [1,3]-sigmatropic rearrangement of the parent cyclopropanecarbaldehyde is known by the reverse reaction of 2,3-dihydrofuran to cyclopropanecarbaldehyde under pyrolytic conditions.[3] The aldehyde is generated on heating 2,3-dihydrofuran to 375°C and is found in detectable amounts in the vapor stream. This result suggests a high activation energy for the rearrangement and a low reaction energy. However, several substituted cyclopropanecarbaldehydes readily undergo [1,3]-sigmatropic rearrangements even at room temperature, as exemplified by Equations 1a and 1b.[4] For further examples of rearrangements of cyclopropyl ketones, see ref.[5]

The [1,3] rearrangement of vinylcyclopropanes to cyclopentenes has attracted much synthetic[2] and theoretical interest.[6] In particular, the mechanism of the rearrangement has been a matter of some controversy. The reaction shows characteristics of both concerted and stepwise processes. Thus, on the one hand, the formation of all four

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[a] Institut für Organische Chemie, Technische Universität Dresden,
Mommsenstraße 13, D-01062 Dresden, Germany
Fax: (internat.) + 49(0)351/463-7030
E-mail: fabian@coch01.chm.tu-dresden.de

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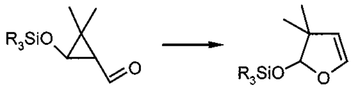
possible stereoisomeric products has been interpreted as evidence for a stepwise reaction involving zwitterionic or biradicaloid intermediates. On the other hand, one major product is formed in all cases. This product stems from the Woodward−Hoffmann-allowed reaction, which proceeds suprafacially with respect to the π system and with inversion at the migrating carbon center (*si* reaction). For the *tert*-butyl-substituted vinylcyclopropane, the stereospecificity exceeds 90% after a correction for stereoisomerization of the starting material.[7] Baldwin has recently contributed an up-to-date review article on the vinylcyclopropane rearrangement.[6]

The [3,3]-sigmatropic rearrangements of vinylcyclopropanecarbaldehyde and of analogous compounds differ from the Cope- or Claisen-type rearrangements of the parent compound only by the additional CH_2 group on the cyclopropane ring in the starting materials (cf. ref.[8]). This rearrangement may be used to prepare 2,5-dihydrooxepins.[4][9] Reaction only takes place if the two unsaturated substituents on the cyclopropane ring are in a *cis* arrangement. In the case of vinylcyclopropanecarbaldehyde ($X = O$; R^1, $R^2 = H$), all three products of the different rearrangement pathways are found experimentally. Vogel obtained cyclopentene-3-carbaldehyde on heating a mixture of both isomers of vinylcyclopropanecarbaldehyde at high temperatures (400 °C).[10] However, on heating the aldehyde to 200−300 °C, only isomerization between the *cis* and *trans* species occurs and the vinyl-substituted dihydrofuran is formed.[11] The [3,3]-sigmatropic rearrangement of *cis*-vinylcyclopropanecarbaldehydes to 2,5-dihydrooxepins does not need such high temperatures and proceeds at room temperature in solution. Under these conditions, the [1,3]-sigmatropic rearrangement of vinylcyclopropanecarbaldehydes is observed only with particular substitution patterns (Equation 2).[4]

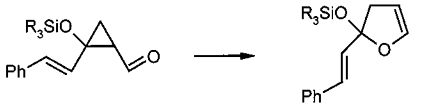
Interestingly, subsequent rearrangement of the product of a [3,3]-sigmatropic rearrangement of a trialkylsiloxy-substituted vinylcyclopropanecarbaldehyde into the product of [1,3] rearrangement was also observed (Equation 3). Therefore, it might seem tempting to assume that the direct isomerization of the dihydrooxepin to the dihydrofuran occurs through [1,3] rearrangement of the corresponding vinylcyclopropanecarbaldehyde, which is in equilibrium to some extent with the seven-membered ring compound. Thus, the experimental findings are suggestive of a variety of competing reactions, which are strongly affected by the substitution pattern.

As detailed in a previous paper,[8] the first step of the theoretical investigation of the sigmatropic rearrangements involved study of the [3,3]-sigmatropic shift. Reaction parameters for the vinylcyclopropanecarbaldehyde to dihydrooxepin rearrangement calculated by DFT were in close agreement with the experimental results. This was also the case for the DFT activation energy of the divinylcyclopropane to 1,4-cycloheptadiene rearrangement. These reactions are predicted to be thermally allowed with activation barriers of 8 and 19 kcal/mol, respectively. The activation energies for the [3,3]-sigmatropic rearrangements of the vinylcyclopropanecarbthioaldehydes were calculated to be very small.[8] The transition structures resemble those of the Cope or hetero Cope reactions. In general, substituents are found to stabilize the seven-membered ring products more strongly than they do the cyclopropane reactants.

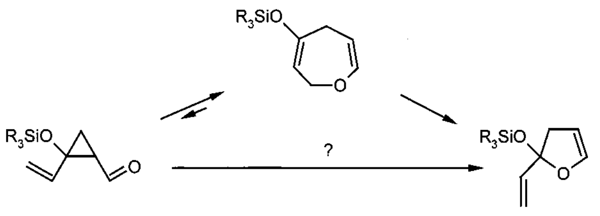
(1a)



(1b)



(2)



(3)

Theoretical investigations of the [1,3]-sigmatropic rearrangement have been largely focused on the parent vinylcyclopropane to cyclopentene rearrangement. Mechanistic aspects of the process have long remained unsolved. Because of the potential formation of biradicaloid intermediates, at first sight it appeared inevitable that we would have to employ multiconfigurational quantum-chemical methods.[12] Fortunately, however, Houk et al. found the computationally less demanding spin-unrestricted version of the density functional theory (UDFT) to be a useful alternative.[13] In more recent studies of reactions proceeding via biradical intermediates, similar reaction parameters were calculated at the (U)DFT and CASPT2 levels.[14] Ab initio CASSCF(4,4) calculations of Gajewski and Davidson[12] and (U)DFT calculations of Houk and co-workers[13] resulted in surprisingly similar geometries for the transition structure of the parent reaction. The UB3LYP/6−31G* activation energy was in better agreement with the experimentally determined value than that derived from the CASSCF(4,4)/6−31G* calculation. Studies of the rearrangement of substituted vinylcyclopropanes using the (U)DFT method have also led to promising results,[15] reproducing the trends in the experimental activation energies. The biradicaloid character of the transition structure of the vinylcyclopropane-cyclopentene rearrangement was established from the occupation numbers of the natural orbitals in the CASSCF(4,4)/6−31G* calculation.[12] Substituent effects on the activation energies for the rearrangement, the singlet-triplet (S_0/T_1) splitting energies, and the expectation values of the S^2 operator were all in accordance with the picture of a biradicaloid transition structure.[16] On the basis of these calculations, the observed product distribution could be rationalized in terms of a concerted reaction proceeding through a biradicaloid transition structure. Theoretical study of the substituent effects revealed the radical-stabilizing effect of the substituents. Geometric and energetic arguments were compatible with a transition structure corresponding to two weakly interacting radical substructures.

Because of the success of spin-unrestricted density functional methods, the competing rearrangements of divinylcyclopropane derivatives and hetero-analogous compounds could be treated on an equal footing. Next, we consider the [1,3]-sigmatropic rearrangements that compete with the [3,3]-sigmatropic rearrangement, and calculate activation and reaction energies for these reactions at the level of density functional theory.

Computational Details and Methodology

All calculations were performed with the GAUSSIAN-94 package.[17] The structures were fully optimized. The Hessian matrix and vibrational frequencies were computed such as to characterize each stationary point as a minimum or transition structure according to the number of imaginary frequencies (zero for minima and one for saddle points, respectively). For all calculations, Becke′s three-parameter exchange functional (B3)[18] was employed, as implemented in GAUSSIAN-94,[19] in conjunction with the Lee−Yang−Parr correlation functional (LYP)[20] and Pople′s 6−31G* split valence basis set. In this DFT method, a generalized gradient approximation (GGA), which includes Hartree−Fock (HF) exchange, is used. The exchange-correlation functional with the acronym B3LYP has been widely used in computational chemistry in calculating reaction parameters. In view of the promising results reported in other studies,[14,16,21,22] the restricted closed-shell DFT procedure was adopted for reactants and products, while the unrestricted open-shell (U)DFT procedure was used for transition structures. Unless specifically noted otherwise, the energies are corrected for zero-point vibrational energies. The relative energies correspond to enthalpies at 0 K (ΔH_0 and $\Delta H^{\neq}{}_0$, respectively).

[1,3]-Sigmatropic Rearrangements of Monosubstituted Cyclopropane Derivatives

Three types of [1,3]-sigmatropic rearrangements have to be considered in this study, namely the rearrangements of vinylcyclopropane, of cyclopropanecarbaldehyde, and of cyclopropanecarbthioaldehyde. For the first case, the reaction parameters as well as the intrinsic reaction coordinates have previously been calculated by Houk and co-workers[13] using the (U)B3LYP/6−31G* method. For comparison, these results are included in Table 1 and Figure 1.

Table 1. Reaction parameters of the [1,3]-sigmatropic rearrangements of vinylcyclopropane, cyclopropanecarbaldehyde, and cyclopropanecarbthioaldehyde in kcal/mol

	$\Delta H_0{}^{\neq}$	ΔH_0
vinylcyclopropane[a]	46.9	−20.8
cyclopropanecarbaldehyde	48.9	−1.2
cyclopropanecarbthioaldehyde	38.7	−16.5

[a] Taken from ref.[13]

The activation enthalpy $\Delta H_0{}^{\neq}$ for the reaction of cyclopropanecarbaldehyde calculated initially in this study was only about 2 kcal/mol higher in energy than that for vinylcyclopropane. The activation enthalpy of the cyclopropanecarbthioaldehyde rearrangement is, however, considerably lower than those of the aforementioned compounds. Reactions of vinylcyclopropane and cyclopropanecarbthioaldehyde are predicted to be strongly exothermic, while that of cyclopropanecarbaldehyde should be almost thermoneutral. Two conflicting energetic effects are operative: Firstly, there is the relief of ring strain, which favors the formation of the five-membered ring compounds, and, secondly, there is the shift of the double bonds. On the other hand, transformation of a carbonyl group into an ether unit in the [1,3] rearrangement of cyclopropanecarbaldehyde is energetically unfavorable, an effect that represents the driving force in the Claisen rearrangement of allyl vinyl ethers to the corresponding carbonyl compounds.[23] For vinylcyclopropane and cyclopropanecarbthioaldehyde, the first effect obviously dominates the reaction enthalpy.

The transition structures are depicted in Figure 1. These structures correspond to reactions that proceed in a suprafacial manner and with inversion at the migrating carbon atom. It should be mentioned that in neither the UB3LYP/6−31G*[13] nor the CASSCF(4,4)/6−31G* calculations[12] a transition structure was derived in a least motion manner with retention at the migrating carbon atom.

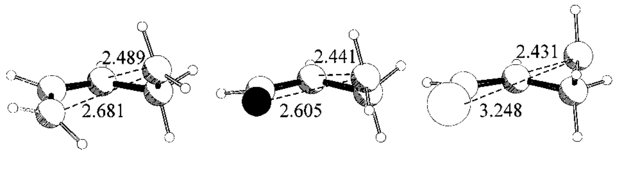


Figure 1. Transition structures for the [1,3]-sigmatropic rearrangement of vinylcyclopropane (from ref.[13]), cyclopropanecarbaldehyde, and cyclopropanecarbthioaldehyde with selected bond lengths in Å

The singlet-triplet gap of the transition structure of the vinylcyclopropane-to-cyclopentene rearrangement was calculated as 5.7 kcal/mol.[16] For the transition structures of the rearrangement of cyclopropanecarbaldehyde and cyclopropanecarbthioaldehyde, vertical singlet-triplet splitting energies of 5.0 and 2.7 kcal/mol, respectively, were determined. These small energy gaps confirm the biradicaloid character of these structures. Calculation of the intrinsic reaction coordinate (IRC), which was started from the geometry of the transition structure of the vinylcyclopropane to cyclopentene rearrangement, led to a broad plateau extending towards the vinylcyclopropane reactant structure. It was shown that low energies may be sufficient to cause rotations, thereby resulting in a loss of stereoselectivity.[13] For the corresponding [1,3]-sigmatropic rearrangement of the cyclopropanecarbaldehyde studied in this paper, a similar dependence of the relative energy on the reaction coordinate was obtained, while the IRC of cyclopropanecarbthioaldehyde was found to exhibit a more marked curvature and a more standard profile (cf. Figure 2).

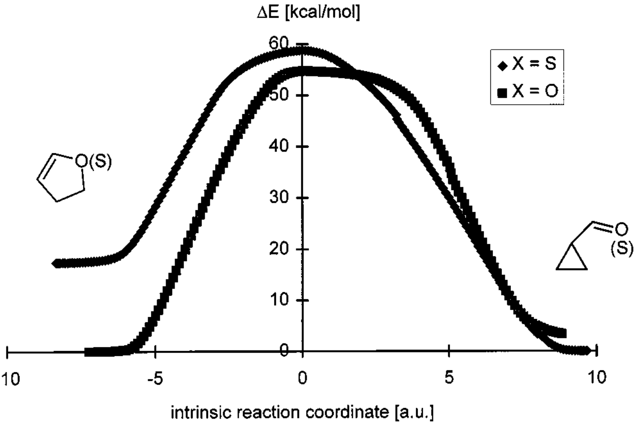


Figure 2. Relative energies (without ZPVE correction) as a function of the intrinsic reaction coordinate of the [1,3]-sigmatropic rearrangement of cyclopropanecarbaldehyde (X = O) and cyclopropanecarbthioaldehyde (X = S)

[1,3]-Sigmatropic Rearrangements of Divinylcyclopropane Derivatives and Hetero-Analogous Compounds

The Search for Intermediates and Additional Transition Structures

In agreement with the findings of Houk,[13] no intermediate could be found for the vinylcyclopropane-to-cyclopentene rearrangement, irrespective of the theoretical model used. This was also the case for the rearrangement of divinylcyclopropanes and their hetero analogs. No intermediates could be found in either the restricted or the unrestricted DFT calculations. A search for transition structures of the isomerization of dihydrooxepins to dihydrofurans was likewise unsuccessful.

Reaction Enthalpies

Relevant reaction enthalpies are collected in Table 2. The substituent effects, as well as the effect of the heteroatom X on the reaction enthalpies of the [1,3] rearrangements, are shown in Figure 3. For the sake of comparison, data for X = CH_2 are given for both reaction types.

The reaction enthalpies for the formation of cyclopentenes are largely independent of the heteroatom X. When R^1 = OH or CHO, the reaction becomes more exothermic. In the cyclopentene, R^1 is attached to the double bond and hence a conjugated system is formed with the formyl or hydroxy group. Since there is no such stabilizing interaction for R^2, the exothermicity either remains of the same order of magnitude (R^2 = OH) as for the unsubstituted system, or it decreases due to steric effects (R^2 = CHO).

For rearrangements of heteroatom-substituted compounds, the reaction enthalpies are low for the formation of 2,3-dihydrofurans. The formation of 2,3-dihydrothiophenes and of cyclopentenes is much more exothermic. Apparently, the same effects are operative as observed in the case of monosubstituted cyclopropanes. Thus, a large difference is found between the reaction enthalpies of the two possible [1,3]-sigmatropic rearrangements of the oxygen-containing compound. The substituent effects on these reactions are found to be similar to those on the rearrangements of the carbaldehydes and carbthioaldehydes. For X = CH_2, there is a deviation from the general trend when R^1 = H and R^2 = OH. This deviation originates from an additional stabilization of the vinylcyclopropanecarb(thio)aldehyde. If the OH substituent is situated adjacent to the formyl or thioformyl group, a hydrogen bond is formed.[8] This kind of stabilization is impossible when X = CH_2. The formation of this hydrogen bond in the cyclopropanes has no great influence on the reaction enthalpies for reaction C leading to cyclopentenes, since the hydrogen bond is also present in the products.

Table 2. Reaction parameters of the [1,3]-sigmatropic rearrangements of divinylcyclopropane derivatives and hetero-analogous compounds in kcal/mol

	reaction B[a]		reaction C[a]	
X; R^1/R^2	ΔH_0	$\Delta H_0^{\neq}$	ΔH_0	$\Delta H_0^{\neq}$
O; H/H	−1.7	32.7	−17.6	36.7
O; OH/H	−7.9	26.3	−20.8	29.0
O; H/OH	1.6	24.9	−19.7	29.8
O; H/CHO	−5.8	25.5	−13.1	34.7
O; CHO/H	−0.4	27.2	−22.9	30.4
S; H/H	−15.9	22.7	−17.7	27.6
S; OH/H	−18.6	–	−23.0	19.1
S; H/OH	−13.8	–	−17.3	
S; H/CHO	−19.1	–	−13.0	27.3
S; CHO/H	−13.8	–	−21.6	20.6
CH_2; H/H	−19.8	33.5	−19.8	33.5
CH_2; OH/H	−20.1	–	−23.1	–
CH_2; H/CHO	−21.4	–	−15.3	–

[a] See Scheme 1.

Transition Structures of the [1,3] Rearrangements

The transition structures for the [1,3]-sigmatropic rearrangements of substituted vinylcyclopropanecarbaldehydes are depicted in Figure 4 (reaction B) and Figure 5 (reaction C). Only in the case of X = O could all transition structures be located. In essence, the search for the transition structures involved the calculation of various conformational geometries. The isomers with the lowest energies are shown. Since the arrangement of substituents in tran-

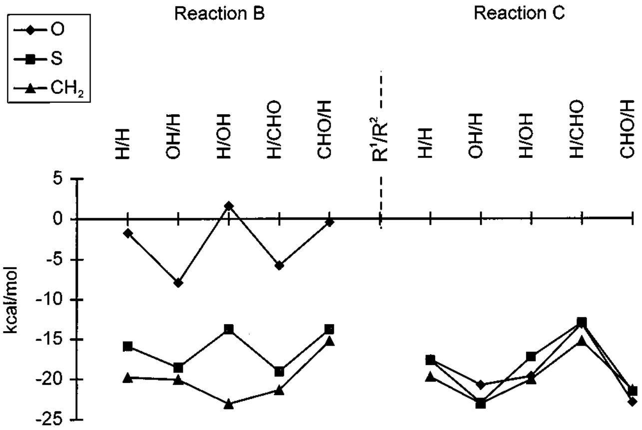
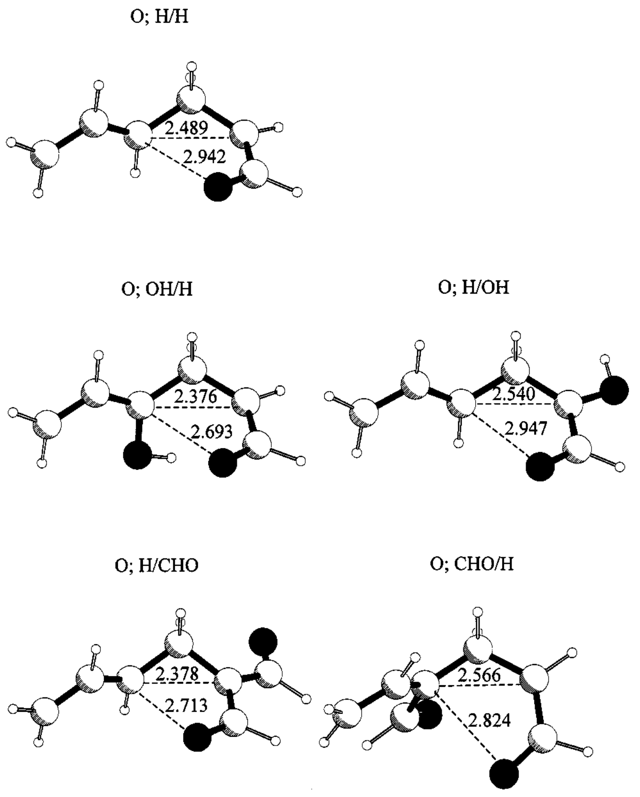


Figure 3. Comparison of the reaction enthalpies of [1,3]-sigmatropic rearrangements (reactions B and C, see Scheme 1) of divinylcyclopropane derivatives and hetero-analogous compounds

sition structures with X ≠ O corresponds to those shown in Figures 4 and 5, they are not depicted separately. The complete geometrical data and the absolute UB3LYP/6−31G* energies are available as Supporting Information. For the vinylcyclopropanecarbaldehyde with $R^1 = H$ and $R^2 =$ CHO, no transition structure could be found with the CHO group similarly arranged in relation to the cyclopropane ring as in the other structures. Since the energies for the other structures change only slightly for the various conformational arrangements, this problem does not affect the overall conclusions.


O; H/H

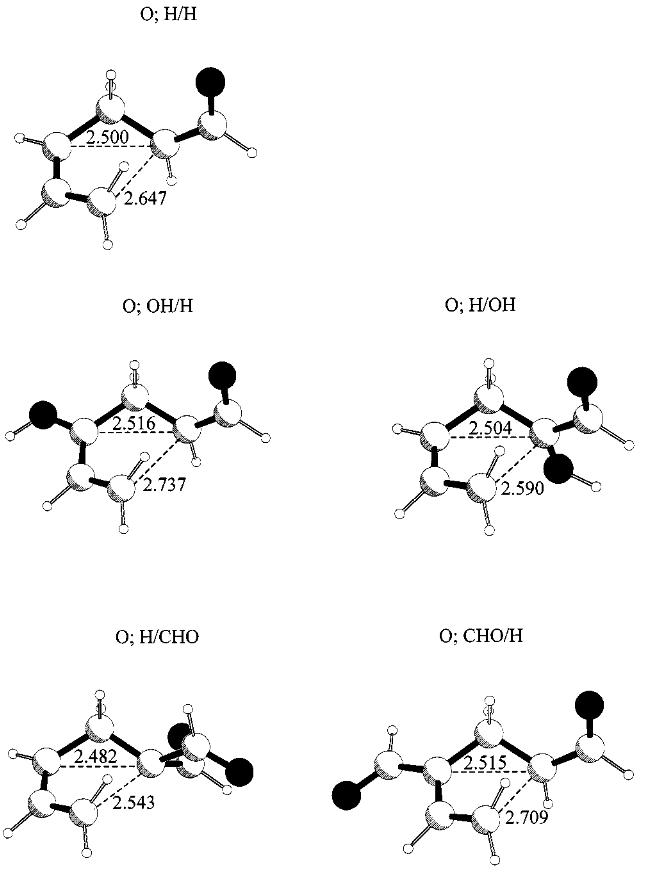
O; OH/H

O; H/OH

O; H/CHO

O; CHO/H

Figure 4. Transition structures of [1,3]-sigmatropic rearrangements of substituted vinylcyclopropanecarbaldehydes involving the formyl group (reaction B)


O; H/H

O; OH/H

O; H/OH

O; H/CHO

O; CHO/H

Figure 5. Transition structures of [1,3]-sigmatropic rearrangements of substituted vinylcyclopropanecarbaldehydes involving the vinyl group (reaction C)

If divinylcyclopropane and vinylcyclopropanecarb(thio)aldehyde are regarded as substituted vinylcyclopropanes, a close relationship between the activation energies of reaction C and the radical-stabilizing properties of the vinyl, carbonyl, and thiocarbonyl groups would be expected on the basis of earlier investigations.[15][16] The radical-stabilizing properties of the three groups were evaluated by means of an isodesmic reaction. The hypothetical reaction of a methyl radical with propene, acetaldehyde, or thioacetaldehyde leads to methane and the corresponding radicals. The reaction energy of this transformation defines the radical stabilization energies ΔH_0(Rad) of the relevant substituted methyl radicals relative to the unsubstituted one. In Figure 6, these stabilization energies are compared with the activation energies of the [1,3]-sigmatropic rearrangements of divinylcyclopropane and vinylcyclopropanecarb(thio)aldehyde. There is clearly a very close correlation, which confirms our expectation.

In Figure 7, the vertical singlet-triplet gaps and the negative expectation values $<S^2>$ of the S^2 operator are compared for all located transition structures of [1,3] rearrangements of substituted divinylcyclopropanes and hetero-analogous compounds. These values are taken as indicators for the biradicaloid character of the transition structures. The biradical character increases with a lowering of the energy gap and an increase in the expectation value $<S^2>$. There-

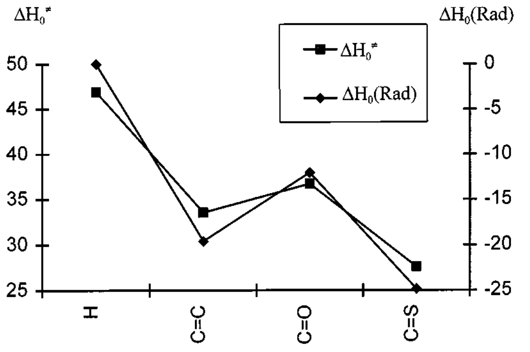


Figure 6. Comparison of the activation energies for reaction C with divinylcyclopropane and vinylcyclopropanecarb(thio)aldehyde and the radical stabilizing energies ΔH_0(Rad) of the C=X group (in kcal/mol)

fore, the negatives of the latter values are compared in Figure 7. The resulting correlation confirms that these criteria are not independent of each other. The correlation is remarkably close and is sensitive to substituent effects. When the (thio)carbonyl group is involved in the rearrangement (reaction B), there is a marked substituent effect on the biradicaloid character of the transition structure. These changes are smaller for reaction C. On comparing the geometries and the biradicaloid character of the transition structures, a close relationship becomes apparent. For rearrangements involving the vinyl group, changes in the interatomic distances of the forming and breaking bonds are small. For reaction B, the processes can be divided into two groups. In the group with the strongest biradicaloid character (H/H, H/OH, CHO/H), the distances between the atoms are clearly longer than in the other group (OH/H, H/CHO).

A second argument supporting the relationship between the biradicaloid character and the strength of the long-distance interactions in the forming and breaking bonds of the transition structures of reaction B may be based on Wiberg's bond indices.[24] These bond indices were evaluated in terms of the natural atomic orbital basis, as implemented in Weinhold's NBO program.[25] For OH/H and H/CHO substitution, significantly larger values were obtained than for the structures with stronger biradicaloid character. Thus, although the distances under consideration are still very large for through-space interactions, the increased delocalization of electrons causes a decrease of the biradicaloid character.

There is a third argument for the particular strength of the biradical character of the transition structures. For reaction B, all transition structures were further optimized at the spin-restricted RB3LYP/6−31G* level of theory. Energies of the transition structures can be expected to be not too dissimilar if the biradical character is low, but to vary more markedly with higher degrees of biradical character. Our results were in fact in agreement with the conclusion drawn from the expectation values of the S^2 operator and the singlet-triplet gaps. For transition structures of reaction B with low biradical character (O; H/CHO) this difference amounts to just 0.7 kcal/mol, while for transition structures with the greatest biradical character, values of 14.6 kcal/mol (O; H/OH) and 14.0 kcal/mol (O; CHO/H) are obtained. The transition structures (O; H/H) and (O; OH/H) have intermediate energy differences of 7.4 and 4.8 kcal/mol, respectively.

Activation Enthalpies

The relevant activation enthalpies are collected in Table 2. The values for the vinylcyclopropanecarbthioaldehyde to cyclopentene rearrangements are 7−9 kcal/mol lower than the corresponding values for the rearrangement of the vin-

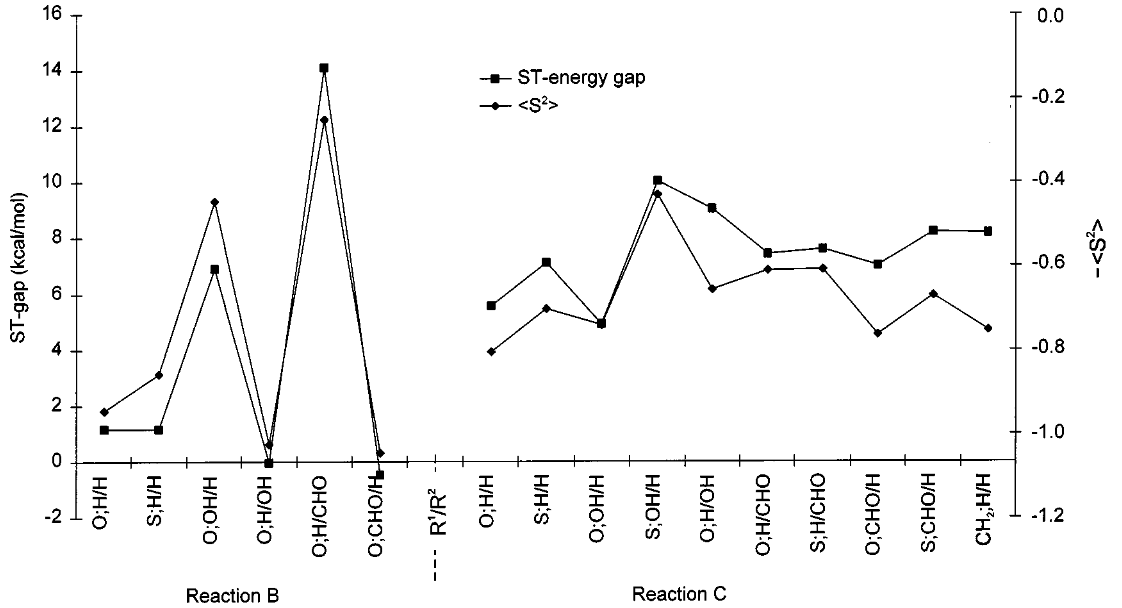


Figure 7. Comparison of the vertical singlet-triplet (S_0/T_1) gap (in kcal/mol) and the negative of the expectation value of the S^2 operator for the spin-contaminated singlet state of the transition structures (see Scheme 1 for reactions B and C)

ylcyclopropanecarbaldehydes. Irrespective of the heteroatom X, the substituents affect the activation enthalpies of the rearrangements involving the vinyl group (reaction C) in a consistent manner. The activation enthalpy strongly decreases relative to the unsubstituted case when R^1 is OH or CHO, while there is negligible effect when R^2 = CHO. The activation enthalpies of rearrangements involving C=X substituents are invariably lower than those for the corresponding reactions involving the vinyl group. While the difference in activation enthalpies for the vinylcyclopropane and cyclopropanecarbaldehyde rearrangements is rather low and no conclusion can be drawn concerning the preferences of the competing [1,3]-sigmatropic rearrangements of vinylcyclopropanecarbaldehyde and vinylcyclopropanecarbthioaldehyde, the situation changes greatly if the complete vinylcyclopropanecarbaldehyde structure is calculated instead of its substructures, and a clear trend becomes apparent. In all cases, the rearrangement to dihydrofurans (reaction B) is kinetically favored relative to the rearrangement leading to cyclopentenes (reaction C). The activation enthalpies for the rearrangements are compared diagramatically in Figure 8. This fact corresponds to the experimental observation that the formation of cyclopentene from vinylcyclopropanecarbaldehyde requires higher temperatures (cf. refs.[3][10]). The largest difference in the activation energy was found with R^2 = CHO (9 kcal/mol). With R^1 = OH, the difference amounts to just 3 kcal/mol. The difference in the activation enthalpies for the two kinds of rearrangements is similar for X = O and X = S in the unsubstituted cases.

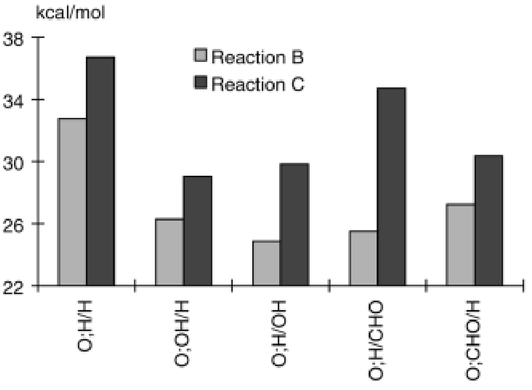


Figure 8. Comparison of the activation enthalpies of [1,3]-sigmatropic rearrangements of substituted vinylcyclopropanecarbaldehydes (see Scheme 1 for reactions A and B)

Stereoisomerizations and Rearrangements of *trans*-Vinylcyclopropanecarbaldehydes

While a *cis* arrangement at the cyclopropane ring is essential for the [3,3]-sigmatropic rearrangement, the [1,3] rearrangement can also occur with derivatives bearing *trans* substituents. The changes in the reaction parameters were evaluated for the vinylcyclopropanecarbaldehyde test case for both types of rearrangements. *trans*-Vinylcyclopropanecarbaldehyde is 1.3 kcal/mol lower in energy than the *cis* isomer. The activation enthalpies of the [1,3]-sigmatropic rearrangements of *trans*-vinylcyclopropanecarbaldehydes involving the vinyl and formyl groups are lower by 1.2 and 1.1 kcal/mol, respectively. Thus, the ratio between the activation energies for [1,3] rearrangements of *cis*- and *trans*-vinylcyclopropanecarbaldehydes remains essentially unchanged.

Selected transition structures for the stereoisomerization of vinylcyclopropanecarbaldehyde are depicted in Figure 9, along with the corresponding relative energies with respect to the transition structure of the [1,3]-sigmatropic rearrangement of *cis*-vinylcyclopropanecarbaldehyde to dihydrofuran.

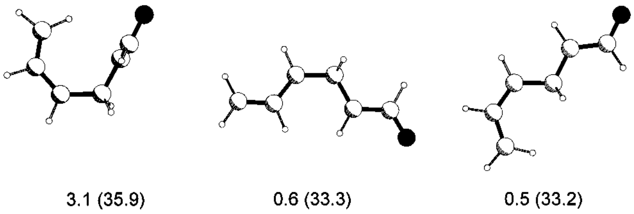


Figure 9. Selected transition structures for the stereoisomerization of vinylcyclopropanecarbaldehyde and their energies relative to the transition structure for reaction B in kcal/mol (values in parentheses are the energies relative to the corresponding cyclopropane)

The activation enthalpies for the stereoisomerization are found to be comparable to those of the [1,3] rearrangement in all considered cases. This suggests that the stereoisomerization and the [1,3]-sigmatropic rearrangement of vinylcyclopropanecarbaldehydes may take place simultaneously. The same behavior has been found experimentally[6] and theoretically[13] for vinylcyclopropane.

Comparison with [3,3]-Sigmatropic Rearrangements

The relevant calculated reaction parameters of the [3,3]-sigmatropic rearrangements of the structures under consideration have been reported previously.[8] The reactions of the vinylcyclopropanecarbaldehyde are compared first. The most stable reaction products are the cyclopentenes. For all substitution patterns investigated, the dihydrofurans are somewhat lower in energy than their seven-membered ring counterparts. The trend in the activation energies runs in the opposite direction. The formation of dihydrooxepins, the products of the [3,3] rearrangement, is favored kinetically compared to the [1,3] rearrangements, while a thermodynamically controlled reaction should lead to cyclopentenes. The experimentally observed formation of dihydrofurans (reaction B) is in accordance with their greater stabilization relative to dihydrooxepins and the lower activation enthalpy relative to that for the formation of cyclopentenes (reaction C). Thus, the theoretical results correspond to the experimental observations for the vinylcyclopropanecarbaldehyde rearrangements. The equilibrium between vinylcyclopropanecarbaldehyde and dihydrooxepin is established at room temperature. If such a mixture is heated up to 200°C, the dihydrofuran is formed. At a temperatures of 400°C, the corresponding cyclopentene is detected as the only product.[10][11]

Furthermore, for the vinylcyclopropanecarbaldehyde with R^1 = H and R^2 = OH, the difference between the activation energies for the [3,3]-sigmatropic rearrangement and the [1,3] rearrangement leading to the dihydrofuran amounts to just 2.4 kcal/mol. This suggests that there will be significant competition between the two reaction paths.

The differences in the reaction enthalpies for the rearrangements of vinylcyclopropanecarbthioaldehydes and divinylcyclopropanes are considerably smaller. These reactions do not show such a marked preference for one specific product as in the case of vinylcyclopropanecarbaldehydes. Furthermore, the differences in the activation energies for the [1,3] and [3,3] rearrangements are larger and, therefore, it can be assumed that the [1,3]-sigmatropic rearrangement is only significant as a competing reaction in the case of vinylcyclopropanecarbaldehydes. Moreover, with X = CH_2 the seven-membered ring compounds are the most stable products and there is no reason for the divinylcyclopropanes to undergo a [1,3] rearrangement if the [3,3] rearrangement is possible, other than in cases where steric constraints prevent adoption of the necessary conformation for this reaction.

Conclusion

Reaction parameters for three types of sigmatropic rearrangements of divinylcyclopropane derivatives and vinylcyclopropanecarb(thio)aldehydes have been calculated by the (U)B3LYP/6−31G* method. The substituent effects and the effects of the heteroatom have been investigated. The transition structures for the [1,3]-sigmatropic rearrangements (reactions B and C) are biradicaloid in nature, as indicated by S_0/T_1 gaps and the expectation values of the S^2 operator. The Claisen-type [3,3]-sigmatropic rearrangement (reaction A) has been found to be kinetically favored for all the compounds under investigation. Nevertheless, in the case of vinylcyclopropanecarbaldehyde, appropriate substitution patterns can minimize the difference in the activation energies of this process and the [1,3] rearrangement to dihydrofurans. For divinylcyclopropane and vinylcyclopropanecarbthioaldehyde derivatives, the differences between the activation energies for the [3,3]- and [1,3]-sigmatropic rearrangements are larger and the [3,3]-sigmatropic rearrangement is strongly favored. The subsequent isomerization of dihydrooxepins to dihydrofurans seems to proceed through the [1,3] rearrangement of the vinylcyclopropanecarbaldehyde, which exists in equilibrium with the dihydrooxepin, as no transition structure for the direct isomerization was found.

All the theoretical results obtained agree quite well with the relatively small amount of experimental data available to date. The DFT method has been shown to be a powerful and economic tool for predicting structure-reactivity relationships of substituted divinylcyclopropane analogs and the relative importance of their [3,3]- and [1,3]-sigmatropic rearrangements.

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