Chemistry of Unique Chiral Olefins. 4. Theoretical Studies of the Racemization Mechanism of *trans*- and *cis*-1,1′,2,2′,3,3′,4,4′-Octahydro-4,4′-biphenanthrylidenes

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The minimum energy conformations and racemization barriers for the chiral sterically overcrowded helical alkenes, *trans*- and *cis*-1,1′,2,2′,3,3′,4,4′-octahydro-4,4′-biphenanthrylidenes (**1** and **2**), are reported. The trans-**1** and cis-**2** isomers can each adapt three different conformations, (*P*,*P*) and (*M*,*M*) (an enantiomeric pair) and an achiral (*P*,*M*) meso form, of which only the chiral isomers were obtained by synthesis. The conformations and heats of formation of (*M*,*M*)-(*E*)-**1**, (*P*,*M*)-(*E*)-**1**, (*M*,*M*)-(*Z*)-**2**, and (*P*,*M*)-(*Z*)-**2** isomers were determined by MOPAC AM1 calculations. The racemization process for both the trans- and cis- isomers is postulated to occur via the (*P*,*M*) isomers by two successive inversions of the cyclohexenyl ring; (*M*,*M*) ↔ (*P*,*M*) ↔ (*P*,*P*). The (*M*,*M*) → (*P*,*M*) and reverse (*P*,*M*) → (*M*,*M*) isomerizations were simulated by reaction path calculations, providing the molecular structure and the activation energy of the transition state for each isomerization. For each racemization process, the activation enthalpy ($\Delta H^{\ddagger}$) was calculated as 23.9 and 19.9 kcal mol^{-1} for trans-olefin **1** and cis-olefin **2**, respectively. These values reasonably agree with the experimental values obtained by temperature-dependent circular dichroism, optical rotation, and ^{1}H NMR magnetization transfer measurements: $\Delta H^{\ddagger}$ = 24.6 and 20.8 kcal mol^{-1} for trans-olefin **1** and cis-olefin **2**, respectively. While the racemization of cis-isomer **2** is controlled by the steric interaction of H5 with C4′a and C4′b, the surprisingly high barrier for trans-olefin **1** is due to the severe steric interaction between H5 and H3′α and/or H3′β protons.
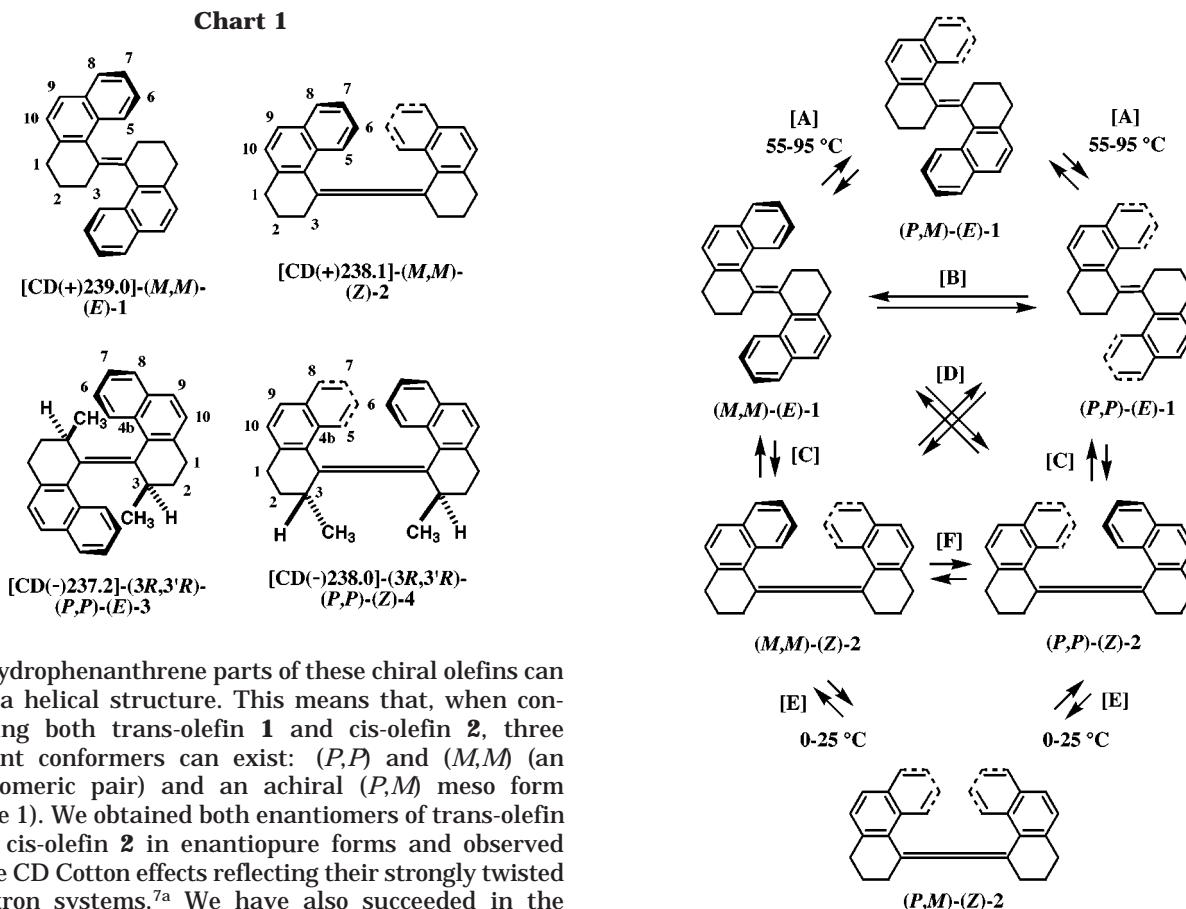
Introduction

Sterically overcrowded ethylenes have attracted considerable attention due to their intriguing conformational behavior as well as the thermo- and photochromic properties associated with several members of this class of compounds.[2] The chirality of bistricyclic alkenes was studied by extensive ^{1}H NMR investigations of disubstituted bifluorenylidenes,[3a,b] biacridanes,[3c] bixanthylidenes,[3d] and bianthrones[3e] and energy barriers ($\Delta G^{\ddagger}$) for their conformational interconversions, ranging from 12 to 22 kcal mol^{-1}, have been reported. The enantioresolution of these alkenes was not achieved. Recently we reported the synthesis, resolution, and remarkable thermal stability toward racemization of thioxanthene-based bistricyclic alkenes[4] and 1,2-benzoannulated bithioxanthylidenes.[5] For these compounds racemization barriers up to $\Delta G^{\ddagger}$ = to 28.6 kcal mol^{-1} have been determined. Employing flexible 1,2,3,4-tetrahydrophenanthrene or 1,2,3-trihydronaphtho[2,1-*b*]thiopyran units instead of a more rigid

linear tricyclic unit, stable enantiomers of photochemically bistable overcrowded alkenes could be synthesized. These molecules are powerful building blocks for so-called chiroptical molecular switches.[6] Detailed knowledge of the dynamic behavior of these chiral overcrowded ethylenes is of prime importance for their further development as new chiroptical materials.

In the previous papers of this series, we reported the chemistry of *trans*- and *cis*-1,1′,2,2′,3,3′,4,4′-octahydro-4,4′-biphenanthrylidenes **1** and **2** (Chart 1) as examples of inherently chiral olefins.[7] Those compounds were the first examples where trans and cis isomers can independently be resolved into enantiomers.[8] The relative structure of **1** and **2** were confirmed by X-ray analysis.[7a,b,9] Inspection of molecular models indicates that the two

(1) (a) University of Groningen. (b) Tohoku University.

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Chart 1

[CD(+)239.0]-(*M,M*)-
(*E*)-**1**

[CD(+)238.1]-(*M,M*)-
(*Z*)-**2**

[CD(-)237.2]-(*3R,3′R*)-
(*P,P*)-(*E*)-**3**

[CD(-)238.0]-(*3R,3′R*)-
(*P,P*)-(*Z*)-**4**

tetrahydrophenanthrene parts of these chiral olefins can adopt a helical structure. This means that, when constructing both trans-olefin **1** and cis-olefin **2**, three different conformers can exist: (*P,P*) and (*M,M*) (an enantiomeric pair) and an achiral (*P,M*) meso form (Figure 1). We obtained both enantiomers of trans-olefin **1** and cis-olefin **2** in enantiopure forms and observed intense CD Cotton effects reflecting their strongly twisted π-electron systems.[7a] We have also succeeded in the theoretical determination of their absolute stereostructures by calculating CD spectra using the π-electron SCF-CI-DV MO method.[7a] To prove their absolute stereochemistry, we synthesized enantiopure *trans-* and *cis-*1,1′,2,2′,3,3′,4,4′-octahydro-3,3′-dimethyl-4,4′-biphenanthrylidenes **3** and **4** starting from (*3R,4R*)-(+)-1,2,3,4-tetrahydro-3-methyl-4-phenanthrenol (Chart 1).[7c] The absolute configurations of chiral dimethyl olefins **3** and **4** were unambiguously determined by X-ray crystallography. Since the CD spectra of olefins **1** and **2** were similar in shape but opposite in sign to those of **3** and **4**, respectively, the absolute stereostructures of chiral olefins **1** and **2** determined theoretically were proved in an experimental manner.[7c]

During those studies, we observed the surprising phenomenon that cis-olefin **2** which looks more sterically hindered easily racemizes at room temperature without formation of trans-olefin **1**; the racemization reaction was thermally accelerated and the activation enthalpy of racemization ($\Delta H^{\ddagger} = 20.8 \pm 0.3$ kcal mol^{-1} for cis-olefin **2**) was determined.[7b] On the other hand, a significantly higher racemization barrier ($\Delta H^{\ddagger} = 24.6 \pm 0.7$ kcal mol^{-1}) was obtained for trans-olefin **1**, which appears sterically less hindered.[7b] These observations pose an intriguing mechanistic problem; how can the sterically more hindered cis-olefin **2** easily racemize at room temperature? Even when considering the fact that aromatic rings can show a large degree of flexibility as shown in a number of studies on chiral helicenes,[10] it would be expected that the less hindered trans-olefin **1** is more likely to racemize

[A]
55-95 °C

[A]
55-95 °C

(*P,M*)-(*E*)-**1**

[B]

(*M,M*)-(*E*)-**1**

(*P,P*)-(*E*)-**1**

[D]

[C]

[C]

[F]

(*M,M*)-(*Z*)-**2**

(*P,P*)-(*Z*)-**2**

[E]
0-25 °C

[E]
0-25 °C

(*P,M*)-(*Z*)-**2**

Figure 1. Possible interconversion pathways between trans-olefin **1** and *cis*-isomer **2**.

at room temperature, since the naphthyl units of **1** are on opposite sides of the molecule.

To solve this challenging problem, we carried out theoretical calculations of molecular conformation and energy along the reaction pathway for racemization of chiral olefins **1** and **2**. We report here the calculation results to clarify the reaction mechanism of their racemization.

Recently, extensive conformational analyses of related dissymmetric aromatic hydrocarbons[11] and overcrowded alkenes[12] have been reported. These reported analyses, performed to find minimal energy conformations, were based on molecular mechanical calculations using MMP2[13] or semiempirical molecular orbital calculations such as AM1,[14] PM3,[15] and MNDO.[16] Most calculations gave

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accurate structures, consistent with experimental data obtained from ^{1}H NMR spectra and X-ray analyses. In many cases the geometry and the relative enthalpy of formation ΔH(form) of the calculated minimum energy conformations could be used to assign NMR spectra of conformational mixtures and to understand geometrical interconversions between different geometrical isomers.

In the studies described in this paper, we employed the AM1 semiempirical molecular orbital method to gain insight into the intriguing static and dynamic conformational behavior of compounds **1** and **2**. Four minimum energy conformations, (M,M)-**1**, (P,M)-**1**, (M,M)-**2**, and (P,M)-**2**, were used as starting geometries for AM1-based reaction path calculations. The calculations simulate the racemization processes of **1** and **2**. A detailed description of these processes, explaining the observed and calculated difference in thermal stability toward racemization of **1** and **2**, is presented.

Setup of Calculations

All possible minimum energy conformations of chiral trans-olefin **1** and cis isomer **2** were automatically generated by the CONFLEX-MM2 conformational space search[17] and then fully optimized by the MOPAC93-AM1 method[14] to reach a sufficiently small gradient norm (<0.1 kcal mol^{-1} Å^{-1}), which in all cases yielded perfect C_2, C_i, and C_s symmetric geometries. Since some energy-minimized conformers found in the MM2 force field merged into identical conformers on the AM1 potential energy surface (PES), those redundant conformers were removed. Furthermore, the AM1 calculations were limited to conformers with (M,M) or (P,M) configuration; the calculation of (P,P) conformers was skipped for reasons of symmetry. The structure of the transition state in each conformational interconversion pathway was obtained by the dynamic reaction coordinate (DRC) and transition state (TS) localization methods in the MOPAC93 package. It was then examined by the intrinsic reaction coordinate (IRC) method to determine whether each transition state was a saddle point between two energy minima. It was finally confirmed that all unique stationary points on the MOPAC AM1 PES have zero (energy minima) or one (saddle points) imaginary frequency in the normal vibration mode analysis. The numerical calculations were carried out on the SGI Power CHALLENGE XL mini-supercomputer in the ICRS, Tohoku University.

Results and Discussion

Structure and Dynamic Behavior of Chiral Olefins 1 and 2. *trans-* and *cis*-1,1′,2,2′,3,3′,4,4′-Octahydro-4,4′-biphenanthrylidenes **1** and **2** were prepared as described previously.[7a,8] Only chiral isomers were obtained for trans-olefin **1** and cis-olefin **2**; no trace of meso isomers (P,M)-**1** and (P,M)-**2** were isolated. Both racemic olefins could be resolved into (P,P) and (M,M) enantiomers by HPLC techniques as described in Part 1 of this series.[7a] A variety of isomerization processes are possible for **1** and **2**, as shown in Figure 1: process A, the racemization of trans-olefin **1** via the meso-form (P,M)-(E)-**1**; process B, the direct racemization of trans-**1** without formation of the meso isomer. When trans-olefin **1** was heated to 55–95 °C in solution, racemization was observed implying that the interconversion proceeds along pathway A and/or B (Figures 1 and 2).[7b,18] Pathways C and D are possible for the cis–trans isomerization
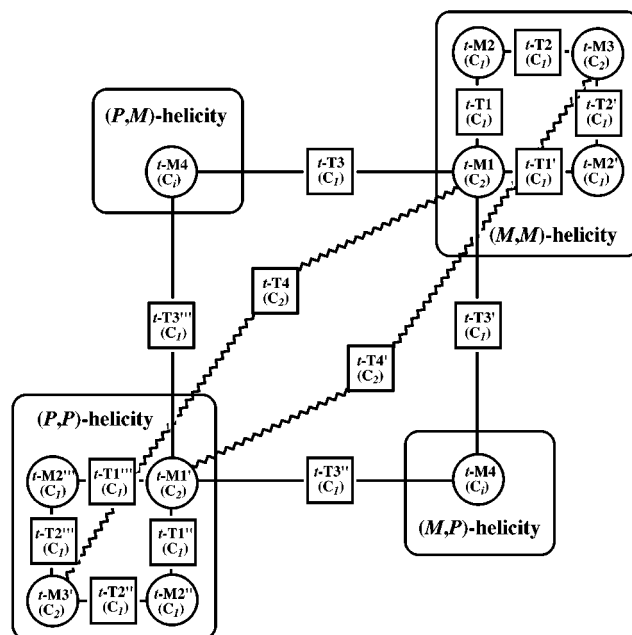

Figure 2. Interconversion pathways for the thermal racemization of trans-olefin **1**. Energy minima are indicated in circles and saddle points in squares. Their point groups are shown parentheses. The ordinate and abscissa are the so-called reaction coordinates, which are approximated by the dihedral angles defining P and M helicities.

of chiral olefins. In process C the helicity of both tetrahydrophenanthrene units is retained, while in process D the cis–trans isomerization is accompanied by a reversal of helicity in both halves of the molecule. These interconversions were observed in their photochemical cis–trans isomerization reaction.[7c,19,20] Pathway E is the racemization of cis-olefin **2** occurring via the meso form (P,M)-(Z)-**2**; this reaction occurred at 0–25 °C.[7b] During the racemization process no thermal cis–trans isomerization has been observed by NMR or HPLC analysis (Figure 1).[18] Process F is the direct racemization of cis-**2** without formation of the meso isomer, but this pathway is unlikely since the two naphthalene rings have to pass through one another as if demonstrating a "tunneling effect".

Surprisingly the racemization barrier for cis-olefin **2** (E_a = 21.5 ± 0.3 kcal mol^{-1}, $\Delta H^{\ddagger}$ = 20.8 ± 0.3 kcal mol^{-1}, $\Delta S^{\ddagger}$ = −8.5 ± 0.8 cal K^{-1} mol^{-1}) as determined by CD and ^{1}H NMR spectroscopy in the temperature range 0–150 °C using hexane and *o*-xylene-d_{10} as solvent, respectively, was strongly decreased compared to that of trans-olefin **1**.[7b] For the racemization of trans-olefin **1**, activation parameters (E_a = 25.2 ± 0.7 kcal mol^{-1}, $\Delta H^{\ddagger}$ = 24.6 ± 0.7 kcal mol^{-1}, and $\Delta S^{\ddagger}$ = −9.1 ± 1.9 cal K^{-1} mol^{-1}) were determined. The fact that the racemization barrier $\Delta H^{\ddagger}$ of cis-olefin **2** is 3.8 kcal mol^{-1} lower than that of trans-olefin **1** is quite unexpected, because at first glance *cis*-isomer **2** appears to be more stable toward

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(18) The central double bond remains intact during this thermal process, which illustrates the fact that the character of this bond is not drastically changed by steric interactions unlike the case of bistricyclic alkenes such as biacridanes, bixanthylidenes, and bianthrones where thermal cis–trans isomerizations readily occurs.[3]

(19) Irradiation experiments (300 nm in hexane at room temperature) revealed a specific (M,M)-(E)-**1** ↔ (P,P)-(Z)-**2** isomerization (process D).

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Table 1. Calculated Energy Minimum Conformations and Transition States of trans-Olefin 1

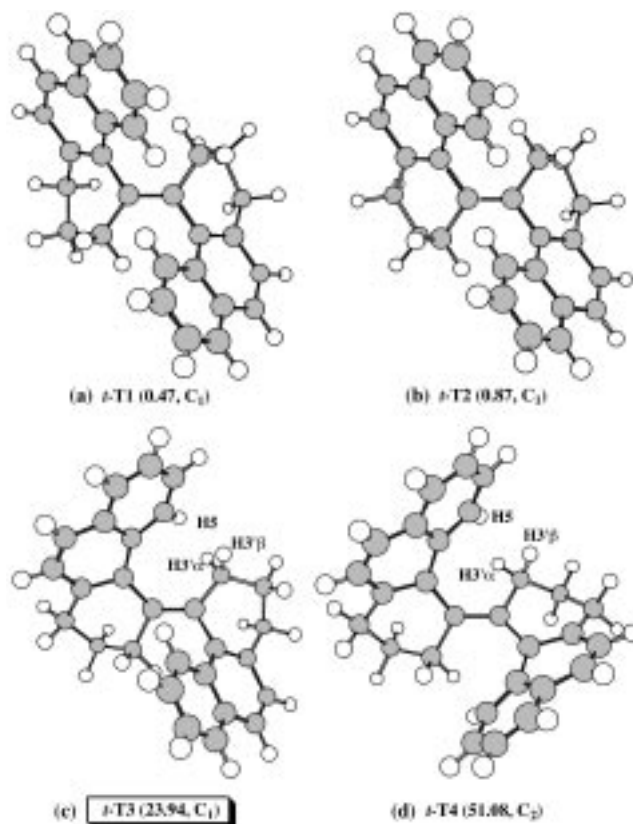| conformation	H_f (kcal mol^{-1})	ΔH_f (kcal mol^{-1})	point group	population[a] (%)	dihedral angle, ϕ (degree)		
					4b−4a−4−4′	4a−4−4′−4′a	4−4′−4′a−4′b
Minimum[b]							
t-M1 (M,M)	81.77	0.00	C_2	43.5	−57	−179	−57
t-M2 (M,M)	82.20	0.43	C_1	41.9	−51	+180	−57
t-M3 (M,M)	82.59	0.82	C_2	10.8	−51	+177	−51
t-M4 (P,M)	83.22	1.44	C_i	3.8	+60	+180	−60
Saddle Point[c]							
t-T1 (M1 ↔ M2)	82.24	0.47	C_1		−56	+180	−55
t-T2 (M2 ↔ M3)	82.64	0.87	C_1		−51	+178	−54
t-T3 (M1 ↔ M4)	105.72	23.94	C_1		−6	+152	−51
t-T4 (M1 ↔ M3′)	132.85	51.08	C_2		−4	+124	−4

[a] Based on the Boltzmann distribution. Numbers listed indicate the total population of stereoisomers with the same energy. For example, the number 43.5% is the total population of t-M1(M,M) and t-M1′(P,P). The multiplicity factors for C_1, C_2, and C_i isomers are 4, 2, and 2, respectively. [b] Absolute configuration in parentheses. [c] Associated with two energy minima in parentheses.

(a) t-M1 (0.00, C_2) (b) t-M2 (0.43, C_1)

(c) t-M3 (0.82, C_2) (d) t-M4 (1.44, C_1)
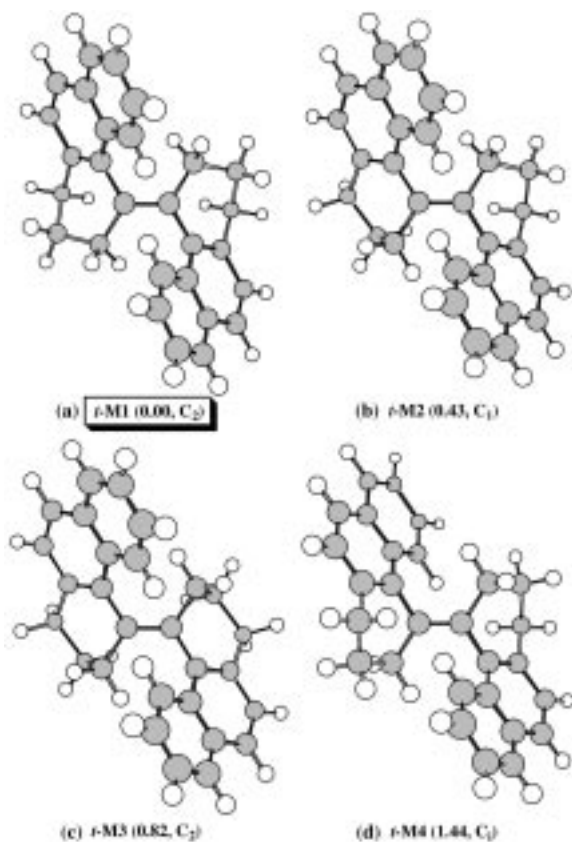
Figure 3. Four energy minima of trans-olefin **1** obtained by the MOPAC-AM1 calculation.

(a) t-T1 (0.47, C_2) (b) t-T2 (0.87, C_1)

(c) t-T3 (23.94, C_1) (d) t-T4 (51.08, C_2)

Figure 4. Four saddle points of trans-olefin **1** obtained by the MOPAC-AM1 calculation.

racemization. Molecular modeling studies indicate that during the racemization of cis-olefin **2** the bulky naphthyl moieties must move along each other, causing severe steric hindrance. For the racemization of trans-olefin **1**, no large steric barrier is apparently present.

Calculation of Minimum Energy Conformations and Transition States of trans-Olefin 1. To clarify the reaction mechanism and pathway of the thermal racemization of trans-olefin (E)-**1**, minimum energy conformations and the transition states between these conformations were searched on the MOPAC AM1 potential energy surface (PES) yielding four energy minima and four saddle points as shown in Table 1 and Figure 2. The stereostructures of these conformations are illustrated in Figures 3 and 4. The most stable conformer, t-M1, has a C_2-symmetrical structure as shown; the cyclohexene ring takes a boat form where C1, C4, C1′,

and C4′ atoms are in the bow positions. In the second-stable conformer, t-M2, one of the cyclohexene rings takes a half-chair conformation in which C2 is down and C3 is up, while the other cyclohexene ring remains in a boat conformation (Figure 3). The half-chair conformation thus raises the energy level of this conformation. The relative energy of the third conformer, t-M3, is almost twice that of t-M2, because t-M3 has two-half-chair cyclohexene moieties: ΔH_f of t-M2 = 0.43 kcal/mol; ΔH_f of t-M3 = 0.82 kcal/mol.

The transition state, t-T1, between minimum energy conformations t-M1 and t-M2 takes an asymmetric conformation, where protons H1′β and H2′β are eclipsed in one cyclohexene ring, and the other cyclohexene ring maintains the boat form (Figures 2 and 4). It is thus reasonable to conclude that t-T1 is the transition state between conformers t-M1 and t-M2. Similarly the conformation of the transition state t-T2 is also reasonable

as the saddle point between *t*-M2 and *t*-M3. Three (*M*,*M*)-*trans*-conformers, *t*-M1, *t*-M2, and *t*-M3, with C_2, C_1, and C_2 symmetry, respectively, exist within 0.8 kcal/mol, and transition states, *t*-T1 and *t*-T2, are also found within 0.9 kcal/mol of the global energy minimum (GEM), *t*-M1. In the stereostructures of *t*-M1, *t*-M2, and *t*-M3, only the conformations of the two cyclohexene parts are different from one another, and therefore fast interconversion between three conformers *t*-M1, *t*-M2, and *t*-M3 via transition states *t*-T1 and *t*-T2 is expected. In fact, the cyclohexene part of (*E*)-**1** can rapidly change its conformation as in the case of the pseudorotation of a cyclohexane in a twist-boat conformation.

Racemization Pathway of *trans*-Olefin (*E*)-1 and Its Transition State. The least stable conformer, *t*-M4, found by calculation has a C_i-symmetrical structure where both cyclohexene rings are in a boat form. However, one tetrahydrophenanthrylidene moiety takes an *M*-helicity, while the other a *P*-helicity as shown in Figure 3. Therefore this conformer is achiral and designated as (*P*,*M*)-*trans*-**1** (meso form). The conformer *t*-M4 is close in energy to the most stable conformer *t*-M1, the energy gap being only 1.4 kcal/mol: ΔH_f of *t*-M4 = 1.44 kcal/mol. The meso conformer *t*-M4 is predicted to be an intermediate on the racemization pathway of trans-**1**. Despite its relatively low energy, however, the meso compound (*P*,*M*)-*trans*-**1** has not been isolated during the synthesis of (±)-(*E*)-**1**.

Saddle point *t*-T3 is the transition state between the most stable conformer *t*-M1 and the meso conformer *t*-M4 (Table 1 and Figure 2), and its stereostructure is depicted in Figure 4. The relative energy of saddle point *t*-T3 was calculated: ΔH_f = 23.94 kcal/mol. This transition state, *t*-T3, is the most significant one in the conformational interconversion of (*E*)-**1**, because the conversion of chiral conformer *t*-M1 to meso conformer *t*-M4 via the transition state *t*-T3 provides the thermal racemization pathway of (*E*)-**1**. Namely, if the reverse conversion from *t*-M4 to *t*-M1 via *t*-T3 occurs thermally, the conversion of *t*-M4 to *t*-M1′ occurs at the same probability because of the symmetrical nature of the conformational interconversion process where conformers *t*-M1 and *t*-M1′ are enantiomers of each other (Figure 2). Therefore, saddle point *t*-T3 was assigned as the transition state of the thermal racemization of trans-olefin **1**.

Transition state *t*-T3 has the following stereochemical features; the naphthalene moiety in the left half of the molecule is just sliding by the side of the cyclohexene ring of the right half (Figure 4c). During the conversion of *t*-M1 to *t*-M4, C5 and H5 atoms move from up to down. On the reverse conversion from *t*-M4 to *t*-M1, those atoms go from down to up. In transition state *t*-T3, the C5 and H5 atoms in the sliding naphthalene are closest to C3′, H3′α, and H3′β atoms as listed in Table 2: C5–C3′, 2.917 Å; H5–H3′α, 1.766 Å; H5–H3′β, 2.171 Å. Those proton–proton distances are less than the corresponding van der Waals distances, r(H–H) = 2.4 Å,[21] indicating that the H5 proton collides with the H3′α and H3′β atoms. This collision raises the energy level of the transition state significantly. It is also interesting to note that, in transition state *t*-T3, the H5 proton is located between the H3′β and H3′α protons. Namely, during the interconversion between *t*-M1 and *t*-M4 and vice versa, the H5 proton moves up and down while being flanked by

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Table 2. Selected Interatomic Distance in the Transition States *t*-T3 (M1 ↔ M4) and *c*-T2 (M2 ↔ M3) as Calculated by the MOPAC-AM1 Method

	distance (Å)	
atoms[a]	trans-**1** (*t*-T3)	cis-**2** (*c*-T2)
C5−C3′	2.917	
H5−H3′α	1.766	
H5−H3′β	2.171	
C5−C4′a		2.928
C5−C4′b		3.184
H5−C4′a		2.305
H5−C4′b		2.192

[a] Atoms in the sliding 1,2,3,4-tetrahydro-4-phenanthrylidene moiety are indicated by regular numbers and others are by numbers with prime.

Table 3. Dihedral Angles (*φ*) Showing Deviation from the Planarity of Naphthalene Moieties in the Transition States *t*-T3 (M1 ↔ M4) and *c*-T2 (M2 ↔ M3) as Calculated by the MOPAC-AM1 Method

	φ (degree)	
carbon atoms	trans-**1** (*t*-T3)	cis-**2** (*c*-T2)
Sliding Naphthalene Moiety		
4a−4b−8a−9	−15.3	−11.4
4a−10a−10−9	+0.8	+1.7
4b−4a−10a−10	−18.9	−16.2
4b−8a−9−10	−3.4	−3.7
8a−4b−4a−10a	+25.9	+20.8
8a−9−10−10a	+10.9	+8.6
4b−5−6−7	−2.6	−1.6
4b−8a−8−7	+7.8	+6.2
5−4b−8a−8	−15.8	−12.0
5−6−7−8	−6.3	−4.8
6−5−4b−8a	+13.4	+9.9
6−7−8−8a	+3.6	+2.5
Remaining Naphthalene Moiety		
4′a−4′b−8′a−9′	+2.0	+0.5
4′a−10′a−10′−9′	−3.4	−3.8
4′b−4′a−10′a−10′	+8.9	+6.9
4′b−8′a−9′−10′	+3.5	+2.6
8′a−4′b−4′a−10′a	−8.9	−5.2
8′a−9′−10′−10′a	−2.9	−1.0
4′b−5′−6′−7′	0.0	−0.3
4′b−8′a−8′−7′	−2.0	−0.5
5′−4′b−8′a−8′	+3.2	+0.4
5′−6′−7′−8′	+1.4	+0.3
6′−5′−4′b−8′a	−2.2	0.0
6′−7′−8′−8′a	−0.3	0.0

these two protons. This motion is partially similar to the geared rotation observed in some atropisomers.[22]

We expected that during the racemization process, the naphthalene moiety would be strongly twisted to release the strain energy between the sliding naphthalene and cyclohexene moieties. The calculation indicates that this naphthalene moiety strongly deviates from a planar aromatic ring as listed in Table 3. For example, the dihedral angle 8a−4b−4a−10a is +25.9°; compare to the corresponding value of the global energy minimum, −6.0°. On the other hand, the other naphthalene moiety is almost planar. In the transition state *t*-T3, to relax the collision between H5 and H3′ protons, the central double bond is also twisted: dihedral angle 4a−4−4′−4′a = +152°. The net deviation from planarity is 28° (compare to the corresponding value of the global energy minimum of 1° (Table 1)). In the transition state *t*-T3 of the racemization, the aromatic ring and the central double bond are thus strongly twisted.

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Table 4. Calculated Energy Minimum Conformations and Transition States of cis-Olefin 2

conformation	H_f (kcal mol^{-1})	ΔH_f (kcal mol^{-1})	point group	population[a] (%)	dihedral angle, ϕ (degree)		
					4b−4a−4−4′	4a−4−4′−4′a	4−4′−4′a−4′b
				Minimum[b]			
c-M1 (M,M)	85.04	0.00	C_2	79.5	−51	−7	−51
c-M2 (M,M)	85.84	0.80	C_2	20.5	−58	2	−58
c-M3 (P,M)	94.50	9.46	C_s	0.0	78	0	−78
				Saddle Point[c]			
c-T1 (M1 ↔ M2)	85.97	0.93	C_1		−51	−2	−58
c-T2 (M2 ↔ M3)	104.96	19.92	C_1		5	−38	−64

[a] Based on the Boltzmann distribution. Numbers listed indicate the total population of stereoisomers with the same energy. The multiplicity factors for C_2, and C_s isomers are 2 and 2, respectively. [b] Absolute configuration in parentheses. [c] Associated with two energy minima in parentheses.
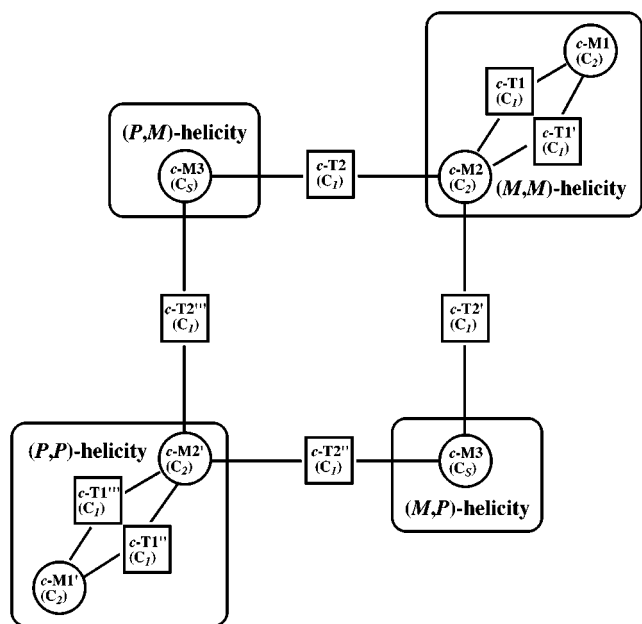
Figure 5. Interconversion pathways for the thermal racemization of cis-olefin **2**. Energy minima are indicated in circles and saddle points in squares. Their point groups are shown parentheses. The ordinate and abscissa are the so-called reaction coordinates, which are approximated by the dihedral angles defining *P* and *M* helicities.

The calculation of the interconversion pathway between the conformers of trans-olefin **1** provided another possible route of racemization. As shown in Figure 2 and Table 1, a route for direct conversion from *t*-M1 to *t*-M3′ via transition state *t*-T4 was found. Since conformers *t*-M1 and *t*-M3′ have (*M,M*) and (*P,P*) helicity, respectively, interconversion along this route leads to the direct racemization of trans-olefin **1** shown as the process B in Figure 1. The stereostructure of transition state *t*-T4 is illustrated in Figure 4d indicating a C_2-symmetrical structure. Two naphthalene moieties simultaneously slip by the sides of the cyclohexene rings, and therefore the relative energy of transition state *t*-T4 is very high: ΔH_f = 51.08 kcal/mol. For this reason, this second racemization route is not feasible.

Calculation of Minimum Energy Conformations and Transition States of cis-Olefin (Z)-2. In the case of cis-olefin (*Z*)-**2**, the MOPAC AM1 PES calculation gave three energy minima and two saddle points as shown in Table 4 and Figure 5. The stereostructures of these conformations are illustrated in Figures 6 and 7. The most stable conformer *c*-M1 has a C_2-symmetrical structure with the cyclohexene rings adopting twist-boat forms. The second-stable conformer, *c*-M2, also has a C_2-
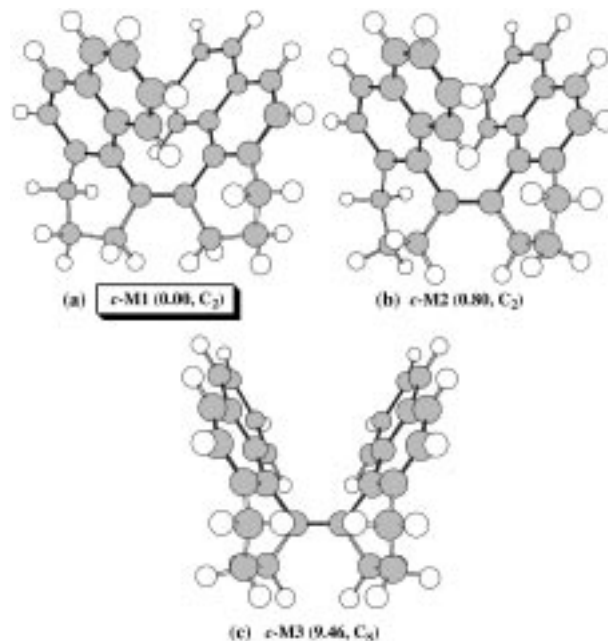

Figure 6. Three energy minima of cis-olefin **2** obtained by the MOPAC-AM1 calculation.
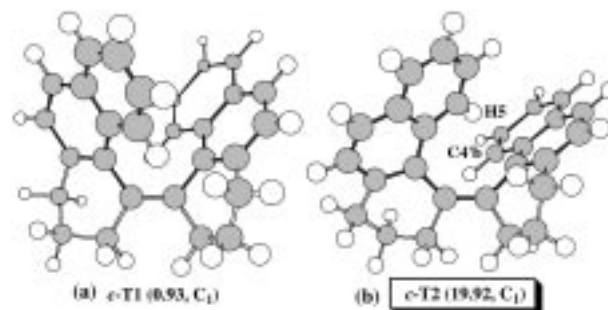

Figure 7. Two saddle points of cis-olefin **2** obtained by the MOPAC-AM1 calculation.

symmetrical structure and is close to the most stable conformer *c*-M1 in energy: ΔH_f = 0.80 kcal/mol. Each cyclohexene ring of *c*-M2 takes a boat form where C1 and C4 atoms are in the bow positions.

Conformation *c*-T1 which has a C_1 stereostructure is the saddle point between two minimum energy conformers, *c*-M1 and *c*-M2 (Figure 5). In transition state *c*-T1, one cyclohexene ring takes a twist-boat form and the other a boat form (Figure 7a). Since the energy level of *c*-T1 is 0.93 kcal/mol (Table 4), rapid interconversion between conformers *c*-M1 and *c*-M2 is possible. The cyclohexene parts of cis-olefin **2** thus can change their
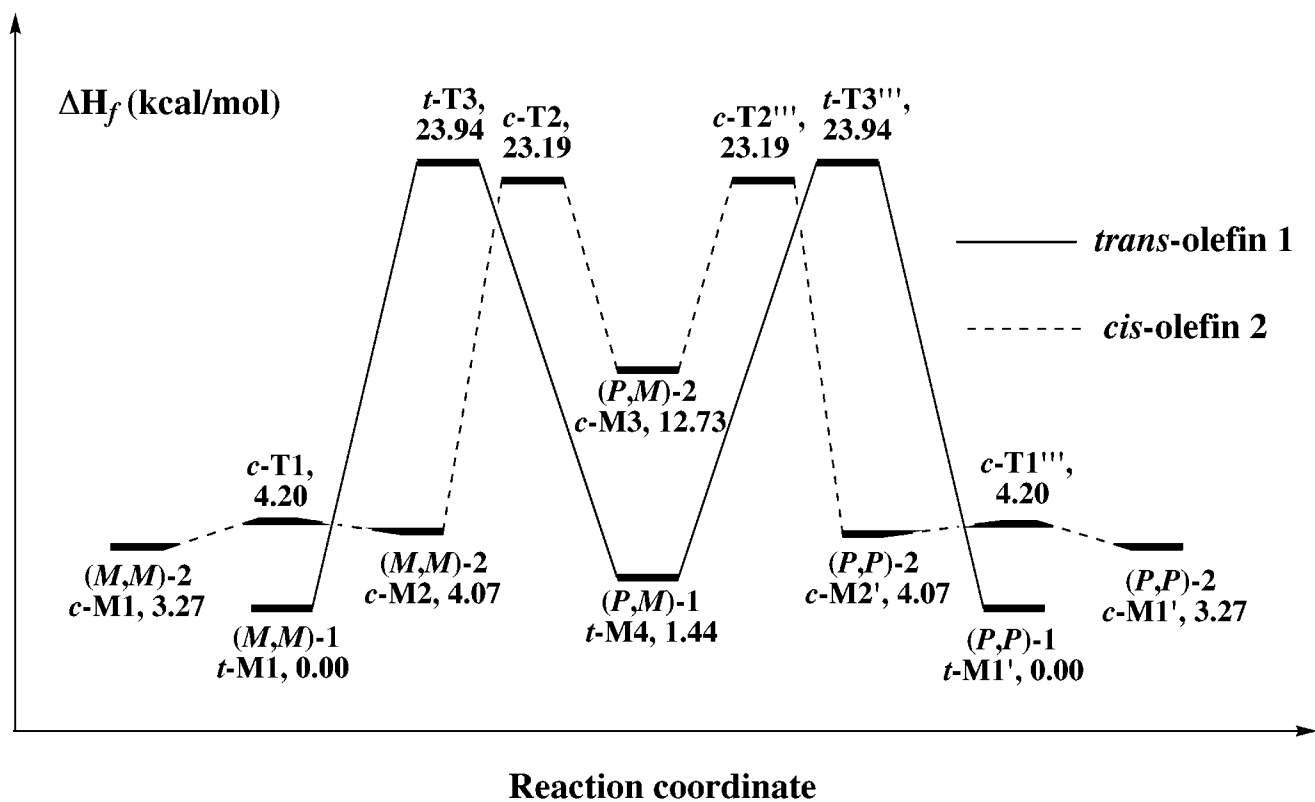
Figure 8. Reaction pathways for the racemization of chiral olefin trans-**1** (solid line) and cis-olefin **2** (dotted line). For the symbols of conformations, see Tables 1 and 4. Numerical values are the relative energies to the global energy minimum (*t*-M1) of trans-**1**.

conformations (Figure 5). However, this interconversion is not directly relevant to the racemization of (*Z*)-**2**, because the molecular helicity remains unchanged.

Racemization Pathway of cis-Olefin 2 and Its Transition State. The least stable conformer, *c*-M3, has a C_s-symmetrical structure (Figures 5 and 6c); both cyclohexene rings take boat forms, where atoms C1, C4, C1′, and C4′ are located in the bow positions. The calculated structure of *c*-M3 showed a butterfly-shaped molecule with both naphthyl moieties almost perpendicularly oriented toward the central double bond. This extraordinary structure is a consequence of the proximity of the sterically demanding naphthyl units oriented cis toward each other. A strong deformation of the bond angles around C4 (e.g., C3−C4−C4a = 108°) and a very large fold angle of C4b−C4a−C4−C4′ (=78°) compared to the corresponding angle (51−58°) in conformers *c*-M1 and *c*-M2 are remarkable (Table 4). No twist of the central double bond was observed. As is easily seen in Figure 6c, the *c*-M3 conformer is achiral, because one tetrahydrophenanthrylidene moiety takes *M*-helicity, while the other adopts *P*-helicity. Therefore this conformer is designated as (*P,M*)-cis-**2** (meso form). Due to the severe steric hindrance, the relative energy of *c*-M3 is much higher than the others: $\Delta H_f = 9.46$ kcal/mol. As in the case of trans-olefin **1**, the meso conformer *c*-M3 is predicted to be an intermediate on the racemization pathway of cis-**2** (Figure 1).

Saddle point *c*-T2 was found as the transition state between the second-stable conformer *c*-M2 and the meso conformer *c*-M3 (Table 4 and Figure 5), and its stereostructure is illustrated in Figure 7b. The relative energy of saddle point *c*-T2 was calculated as $\Delta H_f = 19.92$ kcal/mol. The transition state *c*-T2 is the most important

conformation in the thermal racemization of (*Z*)-**2**, because the conversion of chiral conformer *c*-M2 to meso conformer *c*-M3 via transition state *c*-T2 provides the racemization pathway of (*Z*)-**2**. Namely, if the reverse conversion from *c*-M3 to *c*-M2 via *c*-T2 occurs thermally, the conversion of *c*-M3 to *c*-M2′ via *c*-T2‴ must be valid because of the symmetrical nature of the conformational interconversion process, where conformers *c*-M2 and *c*-M2′ are enantiomers (Figure 5). Therefore the saddle point *c*-T2 is assigned as the transition state of the thermal racemization of cis-olefin **2**.

In the transition state *c*-T2 shown in Figure 7b, the naphthalene moiety in the left half of the molecule is just sliding past the naphthalene plane of the right half. During the conversion of *c*-M2 to *c*-M3, the H5 and H6 atoms in the left half move from the front to backside of the naphthalene ring of the right half. For the reverse pathway from *c*-M3 to *c*-M2, those atoms come from the backside to the front. In the transition state *c*-T2, the H5 atom of the sliding naphthalene is close to C4′b and C4′a atoms within the van der Waals distance, r(H−C) = 2.9 Å,[21] as listed in Table 2: H5-C4′b, 2.192 Å; H5−C4′a, 2.305 Å. Some interatomic distances between carbon atoms in *c*-T2 are also shorter than the van der Waals distance, r(C−C) = 3.4 Å:[21] C5−C4′a = 2.928 Å; C5−C4′b = 3.184 Å.

As in the case of trans-olefin **1**, we anticipated that during the racemization process of cis-olefin **2**, each naphthalene moiety has to be strongly twisted to release the strain energy between two naphthalene moieties which are facing with each other. The congested naphthalene moiety strongly deviates from a planar structure as listed in Table 3, e.g., the dihedral angle 8a−4b−4a−10a is +20.8°, while the other naphthalene moiety

remains almost untwisted (compare to the corresponding value of the global energy minimum of −6.2°). It should be emphasized that most dihedral angle values of the transition state *c*-T2 are smaller than those of *t*-T3, as listed in Table 3. Namely, the naphthalene parts in the transition state *c*-T2 are less strained implying that the energy barrier for racemization of cis-olefin **2** is lower than that of trans-olefin **1**. On the other hand, the central double bond of *c*-T2 is more largely twisted (dihedral angle 4a−4−4′−4′a, −38°) than that of *t*-T3 (the net deviation angle from planarity 4a−4−4′−4′a, 28°) (Tables 1 and 4). In the cis-olefin **2**, strong twist of the central double bond thus assists switching of two naphthalene rings. The calculation described here clarified the mechanism of thermal racemization of trans- and cis-olefins. Despite the fact that cis-olefin **2** appears more sterically hindered, it easily racemizes at room temperature, while trans-olefin **1** racemizes at higher temperature.

Reaction Pathways of the Thermal Racemization of trans- and cis-Olefins. The reaction pathways of both olefins are depicted in Figure 8, where the relative energy levels of conformers and transition states are plotted relative to the energy of the global energy minimum of trans-olefin **1** (*t*-M1). For the racemization of trans-olefin, enantiomer (*M,M*)-**1**, *t*-M1 climbs uphill to reach saddle point *t*-T3 with an activation energy of 23.94 kcal/mol and then goes downhill to arrive at the intermediate meso form (*P,M*)-**1**, *t*-M4, releasing excess energy of 22.5 kcal/mol. The meso intermediate *t*-M4 climbs uphill again reaching transition state *t*-T3‴ and subsequently goes down to conformer *t*-M1′ with opposite (*P,P*) helicity. The net activation energy of the racemization of trans-olefin **1** is thus 23.94 kcal/mol.

In the case of cis-olefin enantiomer (*M,M*)-**2**, the global energy minimum (*c*-M1) is transformed into the second-stable conformer (*M,M*)-**2** (*c*-M2) with the small activation energy of 0.93 kcal/mol. As in the case of trans-olefin **1**, the conformer *c*-M2 climbs uphill reaching the saddle point *c*-T2 with an activation energy of 19.12 kcal/mol and then goes downhill arriving at the intermediate meso form (*P,M*)-**2**, *c*-M3. The meso intermediate *c*-M3 climbs up again reaching transition state *c*-T2‴ and goes down to arrive at the other enantiomer *c*-M2′ with (*P,P*) helicity. This conformer is transformed into the (*P,P*) enantiomer *c*-M1′, which is equivalent in energy to the global energy minimum. From these results, the net activation energy of the racemization of cis-olefin **2** is calculated as 19.92 kcal/mol.[23]

The experimental activation enthalpy ($\Delta H^{\ddagger}$) values of trans-olefin **1** and cis-olefin **2** were reported as 24.6 and 20.8 kcal mol^{-1}, respectively.[7b] Therefore, the activation enthalpy values theoretically calculated are in excellent agreement with the experimental values. In conclusion, the phenomenon that cis-olefin **2** racemizes thermally more easily than trans-olefin **1** was well reproduced by theoretical calculation using the AM1 method as implemented in MOPAC. The proposed reaction mechanism for the racemization of both unique chiral olefins is thus strongly supported by theoretical calculations.

(23) A similar mechanism has been proposed for the racemization of helicenes; see ref 10a.