

has a profound effect on the kinetics and dynamics of the dissociations. This has been demonstrated here for hydrogen-bridged complexes, as well as previously⁵⁵ for ion/dipole complexes. The complexes need not reside in deep potential energy wells. The hydrogen-bridged complex treated here resides in a very shallow well. It has already been suggested previously^{14,17} that transition structure switching^{56,57} can lead to "entropic wells" in which the system tends to linger. A species is considered an ion/neutral complex if it exists long enough between the points at which covalent bond-breaking and the overcoming of long-range attractive forces take place so that a chemical reaction other than dissociation has time to occur.¹⁷ In ionized acetone, dissociation leads to methyl loss, but the methyl is attracted by an ion-induced dipole attraction to the acetyl cation below its dissociation limit. It is free to move to the other methyl group within the "entropic well" and to abstract a hydrogen atom. This hydrogen abstraction reaction can only take place below its activation barrier and dominate at energies beneath the methyl dissociation limit if tunneling through a genuine barrier is allowed. Previous examples for tunneling in ionic fragmentations are scarce. The most con-

vincing one involves tunneling through a rotational barrier in the case of the fragmentation of metastable CH_4^{*+} ions.^{58,59}

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Registry No. $\text{C}_3\text{H}_6\text{O}^{*+}$, 34484-11-2; D_2 , 7782-39-0.

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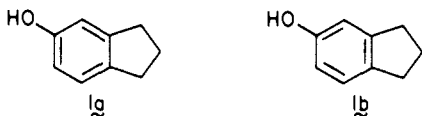
Dynamic Behavior of 1,2-Annulated Cyclooctatetraenes. Kinetic Analysis of Transition-State Steric Congestion Involving Neighboring Alicyclic Substituents

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Abstract: The 1,2-tetramethylene annulated cyclooctatetraene **4** has been prepared in optically active condition by three methods. When treated analogously, the 1,2-trimethylene analogue **6** has been observed to racemize too readily at room temperature and below for it to display an optical rotation. The first-order rate constants for racemization of (+)-**4** at 30.0, 40.0, and 50.0 °C were determined. When compared to the rates of bond shifting in the 1,8-tetramethylene isomer **5** (at 40–60 °C), appropriate processing of which also gives the k_{BS} rates for **4**, the rates of racemization of (+)-**4** are found to be dominated by dynamical ring inversion. Not only were the consequences of the Mills–Nixon effect quantified, but the basis for recognizing [8]annulenes as passing through planar, alternate transition states during ring inversion was further extended. The likely source of the greater conformational flexibility of **6** relative to **4** is discussed.

The long-standing preoccupation of organic chemists with the possible stabilization of one Kekulé form of a benzene derivative relative to the other was formally enunciated in 1930¹ and the stabilization has become known as the Mills–Nixon effect.² The suspicion at that time was that fusion of a five-membered ring to phenol as in **1** would, for geometric reasons, cause **1a**, with two of its double bonds exo to the annulated cycle, to be preferred over **1b**. Of course, no rigid fixation of double bonds is operative



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in indans, nor in the lower homologous benzocyclobutenes³ and benzocyclopropenes.⁴ Several theoretical treatments of the subject have appeared,^{5–8} the most compelling being due to Streitwieser and to Finnegan. They concluded that annulation can serve to

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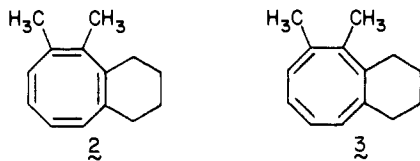
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increase the effective electronegativity of the bridgehead carbons but cannot serve to induce substantial localization of the benzenoid π bonds.⁹ Angular distortions have been measured in certain cases,¹⁰ but bond localization within the aromatic ring has not been witnessed even in tris-annulated examples.¹¹

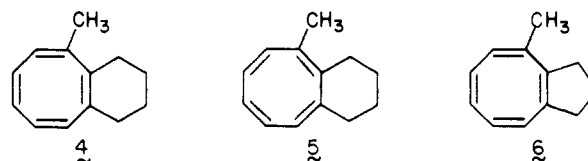
Several years ago, *shelf-stable* pairs of cyclooctatetraene bond-shift isomers typified by **2** and **3** were shown to be capable of isolation.¹² These [8]annulene valence tautomers were the first



of their kind to become available¹³ and provided an unrivaled opportunity for examining the direction of equilibrium and the energetic costs associated with the π -bond-shifting process.^{14,15} Further, the chirality of these tub-shaped molecules has lent itself to the resolution of a number of substituted cyclooctatetraenes and to the quantitative assessment of the energy barriers to mechanical ring inversion in certain cases.^{12,14a,b}

More recently, it has proven possible to gain access to the three annulated cyclooctatetraenes **4–6**.¹⁶ Two important structurally related issues emerged from this particular investigation. First, bond-shift isomers **4** and **6** are the more stable tautomers of each subset. Whereas **5** proved to be isolable, no evidence for the existence of its cyclopentannulated counterpart could be found despite intensive probing for this compound. *By all indicators, the double bonds in 6 are "frozen" in the anti-Mills–Nixon sense!*

Clearly, the more stable double bond arrangement in these cyclooctatetraenes is that where the π linkage is central to both



rings, and the effect is significantly stronger in **6** than in **4**. This observation goes contrary to the Brown–Brewster–Shechter rule¹⁷ where the generalization is made that five-membered rings favor the formation or retention of *exocyclic* double bonds. This nonconformity can be explained by simple consideration of the rather unusual external angles forced upon the five-membered ring by the adjacent cyclooctatetraene framework.

Secondly, detailed ¹H NMR analysis and molecular mechanics calculations revealed **6** to possess a less-folded tub shape than **4** and the cyclobutane-fused lower homologue to have a still more shallow low-energy conformation.¹⁶

These unusually distinctive characteristics have prompted us to obtain kinetic and thermodynamic information relating to the dynamic behavior of the **4–6** triad. With the present analysis of these data, the weight of evidence has become sufficient to provide an exceptionally clear description of steric effects at play in the planar-alternate transition states that intervene during tub-to-tub ring inversion. The accompanying and future papers¹⁸ delve into the more complex mechanistic details of the bond-shift isomerization.

Results

Since the ¹H NMR features of **4** and **5** are distinctively different, this spectroscopic tool was to be relied upon for kinetic analysis of their interconversion. Quantitation of ring inversion is, however, greatly facilitated if the cyclooctatetraenes are available in optically active condition. In the case of those [8]-annulenes that enter into Diels–Alder cycloaddition via their bicyclo[4.2.0]octatriene forms, (–)-*endo*-bornyl-1,2,4-triazoline-3,5-dione¹⁹ has proven particularly useful. Fractional crystallization or chromatographic separation of the resulting diastereomeric urazoles followed by individual alkaline hydrolysis and oxidation then provides the resolved polyolefins.¹² However, whereas **4** has earlier been found to enter into customary [4 + 2] cycloaddition with the simpler *N*-phenyltriazolinedione, cyclopentannulation as in **6** introduces considerable resistance to related adduct formation, even under forcing conditions.¹⁶ This dramatic departure from the norm required that alternative methods of resolution be uncovered.

Resolution of 4. The separation of **4** into its enantiomers was first examined by the now classical procedure involving condensation with (–)-*endo*-bornyltriazolinedione. The partial separation of **7** from **8** was achieved with some difficulty by preparative-scale HPLC. The more powerfully rotating adduct (–)-**7** was then carried forward. To gain information on diastereomeric purity, a sample of **7** exhibiting $[\alpha]_D^{25} -10.7^\circ$ was subjected to lanthanide-induced shifting with tris[3-[(trifluoromethyl)hydroxymethylene]-*d*-camphorato]europium(III). Since diastereomers and not enantiomers are involved, a chiral shift reagent is not required in principle. However, advantage was taken of the fact that the presence of 0.1 molar equiv of the europium(III) additive caused the signals due to the two pairs of olefinic protons at δ 6.21 and 6.02 to be distinctly doubled. Integration of the two more dominant peaks relative to the less intense ones showed this particular sample of **7** to possess 15% de.

The hydrolysis of (–)-**7** enriched to this level was achieved by heating with sodium hydroxide in isopropyl alcohol. Following appropriate dilution with water and pH adjustment, oxidation was

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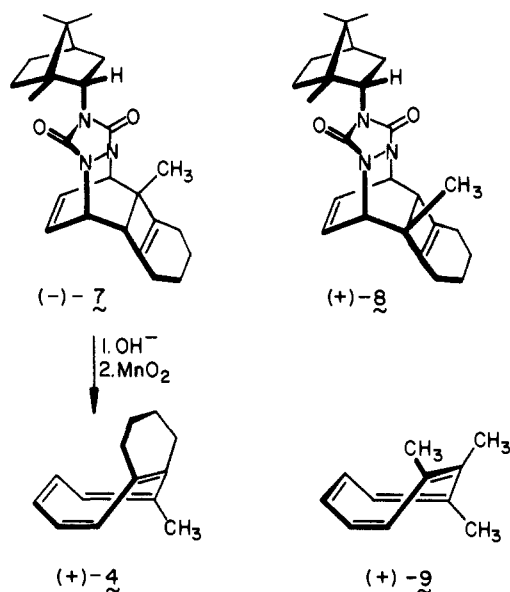
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accomplished with somewhat more than 10 molar equiv of manganese dioxide. The resultant sample of **4** proved to be dextrorotatory, $[\alpha]_D +43.6^\circ$. Its absolute configuration is considered to be as illustrated in the formula, principally on the strength of direct correlation with the structurally related (+)-**9**, whose three-dimensional features have been established unequivocally.^{12d,f} Since our subsequent experience in the handling



of (+)-**4** showed it to be subject to loss of optical activity at room temperature, the above-cited $[\alpha]_D$ value should be considered a lower limit for material having 15% ee. With passage of enough time, the optical rotation of **4** eventually fell to zero, thereby indicating the sample to be essentially free of optically active impurities.

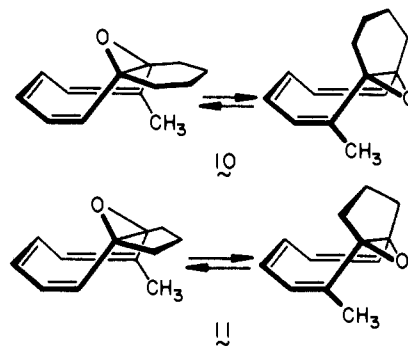
In 1964, Brown, Ayyangar, and Zweifel demonstrated that it was possible to achieve kinetic resolution of a chiral olefin by partial hydroboration with (+)-tetra-3-pinanyldiborane.²⁰ The isolation of optically active olefins in this manner has since received modest attention.²¹ Particularly striking to us was the efficacy with which multiply unsaturated molecules such as trimethylcyclododecatriene,²² 1,3-dimethylallene,^{23,24} and 1,2-cyclononadiene²⁴ could be obtained in optically enriched condition. In accordance with our objectives, **4** was treated with slightly less than 0.5 equiv of the α -pinene-derived reagent in anhydrous tetrahydrofuran at -25°C . An elapsed time of 24 h was necessary to achieve nearly complete hydroboration.²⁵ The unreacted **4** subsequently recovered proved to be dextrorotatory. The $[\alpha]_D$ of a given sample ($+6.3^\circ$) suggested it to possess approximately 2% ee. Although the level of optical purity was low, the high rotatory power of the polyolefin permitted its use in the kinetic experiments that follow.

Kinetic Resolution Studies Involving 6. When **6** was allowed to react with $\text{Pn}_4\text{B}_2\text{H}_2$ under comparable conditions, the recovered unreacted [8]annulene proved invariably to be racemic. Was **6** being consumed with a selectivity substantially below that seen with **4**? Or was **6** sufficiently more prone to racemization that any induced optical activity was lost during the course of reaction

and workup? While we were not successful in obtaining experimentally based answers to these questions via hydroboration technology, the succeeding results clearly show that **6** does racemize rapidly relative to **4**.

At this point, our attention turned to an evaluation of the feasibility of utilizing monoperoxy camphoric acid (MPCA) for kinetic resolution. Previously, this reagent has proven effective for the asymmetric synthesis of chiral sulfoxides,²⁶⁻²⁸ epoxides,²⁸⁻³¹ and oxaziridines.^{28,32-34} In most of these cases, however, the degree of asymmetric induction happened to be low, presumably because the MPCA had been generated in solution and not purified.³⁵ To our knowledge, recrystallized MPCA had not previously been examined for its ability to achieve the kinetic resolution of a chiral olefin. Consequently, **4** was treated with 0.59 equiv of freshly prepared, recrystallized MPCA in dichloromethane at -15°C until no peracid remained (40 h). Flash chromatographic purification gave **4** exhibiting $[\alpha]_D -5.3^\circ$. Thus, the enantiomeric excess happens to be slightly lower than that achieved via chiral hydroboration, but in the opposite direction. In addition, the epoxide concomitantly produced, i.e. **10**, was also optically active, $[\alpha]_D +4.2^\circ$.

These results raised the possibility that **6** could be resolved in this fashion. The viability of this hypothesis was tested by means of a rather large number of experiments where stoichiometry, temperature, and workup conditions were varied. In every instance, the epoxide **11** that was isolated proved to be optically active and dextrorotatory, as was **10**. However, the annulated



cyclooctatetraene **6** failed to give a polarimetric reading under all circumstances. Of course, the isolation of **11** in optically active condition, $[\alpha]_D +7.3^\circ$, is necessarily dependent on the operation of a kinetic resolution. While the enantiomeric forms of **6** necessarily react with MPCA at different rates and consequently partially deplete the reaction mixture of one antipode, the [8]-annulene had already racemized when reisolated. The implication is that **6** loses optical activity at a rate considerably in excess of **4**. Quantification of this accelerated kinetic behavior is presented below.

Bond-Shifting Energetics Associated with the 4 \rightleftharpoons 5 Equilibrium. The availability of **12** and **13** and the readiness with which these urazoles can be denitrogenated to provide individual racemic samples of **4** and **5**, respectively,¹⁶ permitted kinetic analysis of their interconversion. Because the equilibrium is heavily dominated by **4**, it was necessary to follow the rate at which bond-shift isomer **5** was converted into **4**. In keeping with precedent,¹² the

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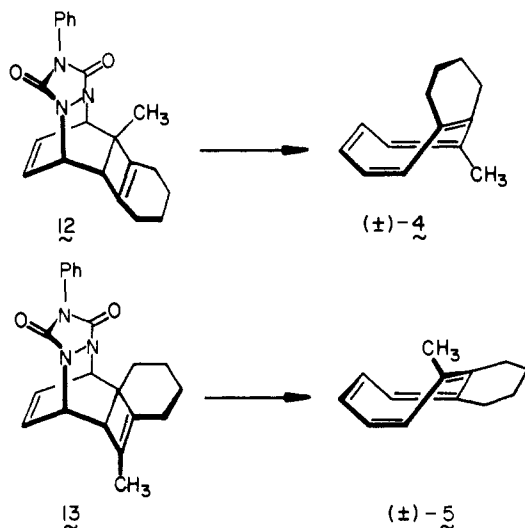
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overall kinetic situation with which we are dealing is defined as



where k_2 and k_{-2} are the relevant first-order bond-shifting rate constants.

For the acquisition of kinetic data, sealed NMR tubes containing (\pm)-5 in degassed dioxane- d_8 solution were heated for various time intervals at 40, 50, and 60 °C in a thermostated oil bath and expanded-scale ^1H NMR spectra were recorded at 300 MHz. To obtain the relative ratios of 5:4 as a function of time, the well-separated proton signals at δ 2.0 and 2.2, stemming from a single allylic proton in each isomer, were integrated. Rate constants were obtained by plotting $\ln \left[\frac{[4]_e}{[4]_t} - \frac{[5]_t}{[5]_e} \right]$ versus time according to the equation

$$\ln \left[\frac{[4]_e}{[4]_t} - \frac{[5]_t}{[5]_e} \right] = (k_2 + k_{-2})t + A$$

where $[4]_e$ represents the concentration of 4 at equilibrium.

The finalized rate data for bond shifting, together with activation parameters, are collected in Table I. Since K is defined as k_2/k_{-2} , it follows directly that 4 is significantly more stable than 5:

$$\Delta(\Delta G^\circ_{25}) = -RT \ln K = 1.6 \text{ kcal/mol}$$

Dynamics of Ring Inversion for 4. Samples of (+)-4 were immediately dissolved in purified dioxane and placed in a 1-dm polarimeter cell maintained at 30.0, 40.0, and 50.0 °C by means of a circulating constant-temperature bath. Optical rotations were recorded at 436 nm as a function of time, and plots of $-\ln \alpha$ vs time afforded excellent straight lines whose slopes (k_{rac}) were equal to $2(k_1 + 2k_{-2})$.^{12f} A sample data set is provided in Table II, and the rate constants for ring inversion, together with the activation parameters, are collected in Table III.

The overall kinetic profile for 4 is illustrated in Figure 1. Therein, allowance is made specifically for the incursion of ring inversion *with* bond shifting (diagonal arrows). However, the overall kinetic profile for 4 is so overwhelmingly dominated by k_1 , the ring-inversion rate constant, that the extent to which k_{-2} is folded in has little impact on the overall racemization rate constant.

Discussion

Since our intent is to discuss the bond-shift (BS) phenomenon at length in later papers,^{18c,d} comments here are restricted only to a comparative analysis with other substituted cyclooctatetraenes (Table IV). The enthalpies of activation associated with BS in 4 and 5, when calculated at 25 °C, amount to 24.9 and 20.8 kcal/mol, respectively. Strikingly, these data place 5 ahead of the 1,3-di-*tert*-butyl derivative in terms of its innate ability to experience double bond translocation. However, entropic influences in these two systems are rather divergent (-11.8 eu vs -2.9

Table I. Rate Data for Bond Shifting in 4 and 5 and Activation Parameters for k_{-2} in 4 and k_2 in 5

t , °C	K	slope, s^{-1}	k_2 , s^{-1}	k_{-2} , s^{-1}
40	10.49	2.26×10^{-5}	2.06×10^{-5}	1.96×10^{-6}
		2.29×10^{-5}	2.09×10^{-5}	1.99×10^{-6}
		6.85×10^{-5}	6.10×10^{-5}	7.53×10^{-6}
50	8.10	6.62×10^{-5}	5.89×10^{-5}	7.27×10^{-6}
		6.85×10^{-5}	6.10×10^{-5}	7.53×10^{-6}
60	6.81	1.97×10^{-4}	1.72×10^{-4}	2.53×10^{-5}
		1.87×10^{-4}	1.63×10^{-4}	2.39×10^{-5}
30 ^a			6.3×10^{-6}	5.16×10^{-7}

For Bond Shifting in 4
 $E_{\text{act}} = 25.5 \text{ kcal/mol}$ $\Delta S^\ddagger (25 \text{ }^\circ\text{C}) = -3.3 \text{ eu}$
 $\ln A = 27.8$ $\Delta G^\ddagger (25 \text{ }^\circ\text{C}) = 25.9 \text{ kcal/mol}$
 $\Delta H^\ddagger (25 \text{ }^\circ\text{C}) = 24.9 \text{ kcal/mol}$

For Bond Shifting in 5
 $E_{\text{act}} = 21.4 \text{ kcal/mol}$ $\Delta S^\ddagger (25 \text{ }^\circ\text{C}) = -11.8 \text{ eu}$
 $\ln A = 23.5$ $\Delta G^\ddagger (25 \text{ }^\circ\text{C}) = 24.3 \text{ kcal/mol}$
 $\Delta H^\ddagger (25 \text{ }^\circ\text{C}) = 20.8 \text{ kcal/mol}$

Table II. Exemplary Rate Data for Racemization of (+)-4 (40.0 \pm 0.2 °C)

time, s	α_{436} , deg	$\ln \alpha_{436}$
0	+0.739	-0.302
1200	+0.663	-0.411
2400	+0.596	-0.518
3600	+0.534	-0.627
4800	+0.481	-0.732
6000	+0.431	-0.842
7200	+0.387	-0.949
9600	+0.310	-1.171
10800	+0.279	-1.277
12000	+0.250	-1.386

slope = $9.02 \times 10^{-5} \text{ s}^{-1}$
 $r = 0.99999$

Table III. Racemization and Ring-Inversion Rate Data for 4: Activation Parameters for k_1 in 4

t , °C	measd rate constants for racemization of 4, s^{-1}	rate constants for k_1 in 4, s^{-1}
30	2.38×10^{-5}	1.16×10^{-5}
	2.67×10^{-5}	
40	9.02×10^{-5}	4.90×10^{-5}
	8.93×10^{-5}	
50	2.84×10^{-5}	1.27×10^{-4}
	2.82×10^{-4}	

For Ring Inversion in 4
 $E_{\text{act}} = 22.8 \text{ kcal/mol}$ $\Delta S^\ddagger (25 \text{ }^\circ\text{C}) = -4.4 \text{ eu}$
 $\ln A = 27.2$ $\Delta G^\ddagger (25 \text{ }^\circ\text{C}) = 23.5 \text{ kcal/mol}$
 $\Delta H^\ddagger (25 \text{ }^\circ\text{C}) = 22.2 \text{ kcal/mol}$

Table IV. Comparison of Enthalpies of Activation for Bond Shifting in Selected Di-, Tri-, and Tetrasubstituted Cyclooctatetraenes

cyclooctatetraene	$\Delta H^\ddagger (25 \text{ }^\circ\text{C})$, kcal/mol
5	20.8
1,3-(<i>tert</i> -Bu) ₂	22.7
1,2,3-Me ₃	22.9
4	24.9
1,2,3,4-Me ₄	28.1
1,4-Me ₂ -2,3-Ph ₂	32.4
3,8-Me ₂ -1,2-Ph ₂	34.8

eu). When specific consideration is given to 4, its barrier to bond shifting is seen to be higher than that of the 1,2,3-Me₃ example. Thus, the greater ground-state energy of 5 relative to that of 4 surfaces clearly under such comparative scrutiny.

Since 4 can be isolated in optically active condition, the magnitude of its barrier to ring inversion (RI) must be adequately high to restrict the molecule from readily attaining a planar alternate conformation. At 23.5 kcal/mol, the free energy for

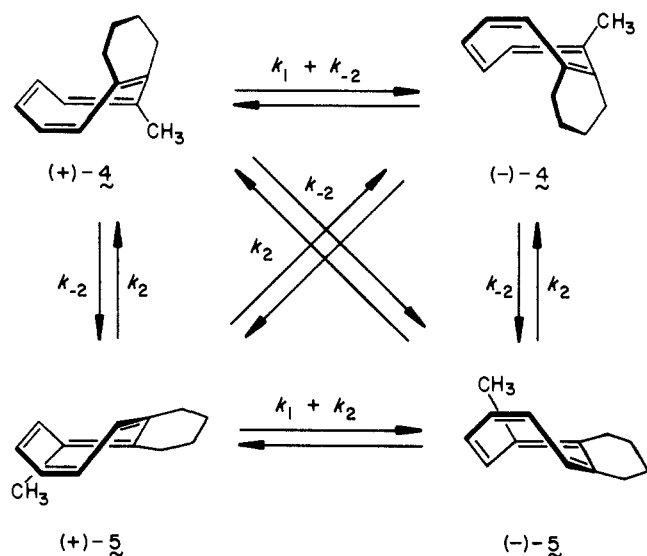
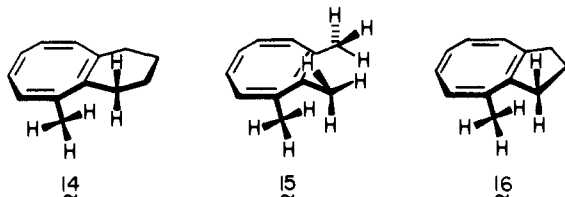


Figure 1.

ring inversion within **4** remains below the value for bond shifting, in agreement with the ordering customarily encountered with alkyl-substituted cyclooctatetraenes.¹⁵ The $\Delta\Delta G^\ddagger$ gap between BS and RI is 2.4 kcal/mol, a value quite similar to that determined for 1,2,3- Me_3COT (1.8 kcal/mol).^{12f} Molecular models suggest that the generally accepted geometry for RI transition states will in these two cases not engender grossly divergent nonbonded peripheral steric crowding (see **14** and **15**). Nonetheless, distinctions of a more subtle nature are now capable of being recognized.



Allinger and co-workers have previously estimated that a total energy cost of 15.1 kcal/mol is necessary to achieve flattening of the unsubstituted cyclooctatetraene into an optimized D_{4h} planar geometry.³⁶ This barrier, which materializes as a consequence of increases in van der Waals and angular-bending energies, can be considered to be a common element in the ring inversion of all cyclooctatetraenes. Consequently, the differences which are manifested in the $\Delta G^\ddagger_{\text{RI}}$ values arise chiefly from changes in steric compression between the peripheral substituents in the transition state. In **15**, the level of nonbonded steric interaction involving the three contiguous methyl groups is unquestionably larger than that contained within **14**. The advantage associated with incorporation of two pendant methyl groups into a six-membered ring amounts to a 1.2 kcal/mol differential for **4**. This value is somewhat less than one-half of the usual methyl-methyl butressing contribution (ca. 3.1 kcal/mol).^{14b,37}

Our inability to resolve **6** by means of the earlier described protocols requires that $\Delta G^\ddagger_{\text{RI}}$ in this instance be at or below 18 kcal/mol. The calculated k_1 for **6** at -15°C is at least $4.5 \times 10^{-5} \text{ s}^{-1}$. The differences in free energies of activation between **4** and **6** can be regarded as the direct result of reduced intramolecular steric crowding in **16**. Several comparative studies between indans and tetralins have been reported over the years. Of these, the lines of investigation pursued by Arnold and co-workers are the most exhaustive.³⁸ Their conclusions that the methylene groups in the

differently sized alicyclic rings exert quite different steric influences on ortho substituents attached to the arene segment and that the methylene groups in the five-membered examples have the smaller effect has direct applicability to the present investigation. The larger internal [8]annulene angles in **14**–**16** serve to exacerbate further the peripheral crowding.

Clearly, the steric screening contributed by the cyclopentenyl methylene group in **16** cannot be constant to that in its homologue **14** and must offer less impedance to the adjoining methyl substituent as these groups strive to become coplanar. The differences in $\Delta G^\ddagger_{\text{RI}}$ between **14** and **16** is significant, amounting to 5 kcal/mol or more. This value appears to be somewhat higher than that expected solely on the basis of decreased van der Waals and bending repulsions between these substituents. The somewhat more elevated ground-state strain in **6** likely also contributes to its greater ease of racemization.

In conclusion, the varied level of steric interference purposefully introduced to probe the fascinating dynamical process of ring inversion has proven to be very revealing. The experimental rate constants, in particular, are remarkably consistent with the intervention of **14**–**16** within the limits of confidence imposed by this mechanistic model.

Experimental Section

Resolution of 4 Using (-)-endo-Bornyltriazolinedione. A solution of **4** (1.34 g, 7.8 mmol) in 25 mL of ethyl acetate was treated with freshly sublimed (-)-endo-bornyltriazolinedione (2.05 g, 8.7 mmol) and refluxed for 2 h. The cooled reaction mixture was evaporated and the residue was chromatographed on silica gel (elution with 10% ethyl acetate in petroleum ether) to give 1.43 g (45%) of diastereomeric urazoles. Diastereomer separation was achieved on a Waters Prep 500 HPLC by making use of peak-shaving techniques and recycling. The eluent was 8% ethyl acetate in petroleum ether. This process afforded 0.60 g of white solid, which was recrystallized from ethyl acetate–petroleum ether to give 0.18 g of colorless crystals: mp 200 – 201.5°C ; $[\alpha]_{\text{D}}^{25} -10.7^\circ$, $[\alpha]_{436}^{25} -19.3^\circ$ (c 1.65, CHCl_3); $^1\text{H NMR}$ (300 MHz, CDCl_3) δ 6.21 (m, 1 H), 6.02 (m, 1 H), 4.86 (m, 1 H), 4.48 (m, 1 H), 4.23 (m, 1 H), 2.71 (br s, 1 H), 2.38 (m, 1 H), 1.83–1.24 (series of m, 14 H), 1.40 (s, 3 H), 0.95 (s, 3 H), 0.87 (s, 3 H), 0.79 (s, 3 H); MS, m/z (M^+) calcd 407.2573, obsd 407.2594. Anal. Calcd for $\text{C}_{25}\text{H}_{33}\text{N}_3\text{O}_2$: C, 73.68; H, 8.16. Found: C, 73.75; H, 8.22.

A solution of (-)-**7** (21 mg, 0.05 mmol) and sodium hydroxide (80 mg, 2.0 mmol) in isopropyl alcohol (3 mL) was refluxed under argon for 13 h. The mixture was cooled to room temperature, acidified with 5% hydrochloric acid (1.5 mL), neutralized with 3 N ammonium hydroxide to pH 9 (4 mL), and treated with pentane (4 mL) and activated manganese dioxide (57 mg, 0.66 mmol). The slurry was stirred at room temperature for 20 min and the pentane layer was separated, dried, and evaporated at 20°C . Without delay, the residual oil was purified by filtration through a short silica gel column (elution with pentane). There was isolated 9 mg (100%) of (+)-**4**, $[\alpha]_{\text{D}}^{25} +124.8^\circ$ (c 0.75, dioxane). The spectral properties of the hydrocarbon are identical with those reported earlier.¹⁶

Kinetic Resolution of 4 by Hydroboration. A solution of the borane-dimethyl sulfide complex (58 μL of a 2 M solution in THF, 0.12 mmol) in 0.25 mL of anhydrous tetrahydrofuran was cooled to 0°C and treated with 38 mg (0.28 mmol) of α -pinene, $[\alpha]_{\text{D}}^{25} +43.56^\circ$ (neat). The reaction mixture was stirred in the cold for 50 min, deposited in a refrigerator overnight, and cooled to -25°C . A 40-mg (0.25-mmol) sample of **4** was introduced and stirring at -25°C was maintained for 24 h. The excess hydroborating agent was destroyed by the addition of a few drops of water. The mixture was diluted with pentane and the organic phase was washed with water, dried, and concentrated (no heat!). Without delay, the oily residue was filtered through a short column of silica gel (elution with pentane). There was obtained 14 mg of **4**, $[\alpha]_{\text{D}}^{25} +6.3^\circ$ and $[\alpha]_{436}^{25} +18.1^\circ$ (c 1.2, dioxane).

Kinetic Resolution of 4 by Asymmetric Epoxidation. A magnetically stirred solution of **4** (30 mg, 0.17 mmol) in dry dichloromethane (2 mL) was cooled to -15°C and crystalline monoperoxyacemphoric acid (21.6 mg, 0.10 mmol) dissolved in 2 mL of the same solvent was added. The reaction mixture was stirred at -15°C for 40 h, the solvent was removed on a rotary evaporator, and the residue was taken up in pentane. The

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organic solution was washed with water and dried. This solution was passed down a short column of silica gel (pentane elution) and 10 mg of **4** was recovered, $[\alpha]^{23}_D -5.3^\circ$, $[\alpha]^{23}_{436} -15.0^\circ$ (*c* 0.8, dioxane). An increase in solvent polarity to 3% ethyl acetate in petroleum ether furnished 6 mg (30%) of epoxide **10**, $[\alpha]^{23}_D +4.2^\circ$ (*c* 0.6, dioxane).

Chiral Epoxidation of 6. A 38-mg (0.24-mmol) sample of **6** was allowed to react with 35 mg (0.16 mmol) of crystalline monoperoxy-

camphoric acid exactly as described above. The recovered cyclooctatetraene (11 mg) proved to be optically inactive. The more polar epoxide **11** (12 mg, 43%) exhibited $[\alpha]^{23}_D +7.3^\circ$ and $[\alpha]^{23}_{436} +19.4^\circ$ (*c* 1.0, dioxane). This result proved consistent over several runs.

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Dynamic Properties of Chiral Cyclooctatetraenes. Total Inhibition of the Racemization Process by 1,4-Annulation

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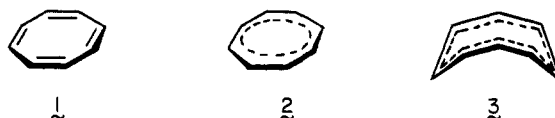
Contribution from the Evans Chemical Laboratories, The Ohio State University, Columbus, Ohio 43210. Received April 21, 1988

Abstract: The chiral cyclooctatetraene **15** has been prepared in 10 steps from cycloheptene-1,2-dicarboxylic anhydride (**8**). Following Diels-Alder cycloaddition to isoprene, the anhydride functionality was transformed into a cyclobutene ring by Ramberg-Bäcklund ring contraction of the derived α -chloro sulfone. To introduce added unsaturation in the cyclohexene ring, it proved most expedient to isomerize the double bond in **13** first and to brominate **14** allylically as a prelude to dehydrobromination. The resulting triene underwent spontaneous isomerization to give (\pm)-**15**, which was resolved through formation and partial chromatographic separation of the diastereomeric urazoles **16** and **17**. The optically active [8]annulene did not experience racemization when heated extensively. The dynamic conformational potential of **15** has consequently been seriously inhibited by the 1,4-pentamethylene chain such that its homotopicity is maintained until thermal destruction.

In earlier work from this laboratory, a number of optically active cyclooctatetraenes were prepared, and the energetics of their ring inversion and bond shifting, both of which result in racemization, were quantified.² The combination of these and still earlier experiments^{3,4} provide substantive credence to the proposition that mechanical tub-to-tub interconversion is mediated by planar alternate transition states typified by the parent D_{4h} structure **1**. This reaction manifold is particularly well-accommodated by the kinetic consequences of varied 1,2-annulation.⁵

When the tool of proximal peripheral substitution is applied to evaluation of the actual pathway followed during π -bond alternation, the incremental increases in the free energies of activation can be interpreted as being compatible with the involvement of planar delocalized species related to **2**.⁶ The energetic costs of bond shifting (BS) are usually higher than those associated with ring inversion (RI),⁷ but are they high enough to be compatible with the antiaromatic character of **2**?⁸ As a direct consequence

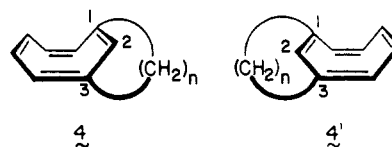
of the associated potential energy surface, this pathway can be viewed as unattractive since the second-derivative matrix of force constants should have more negative eigenvalues than the single one required for a transition state (**3**) linking two equivalent nonplanar boat minima of the cyclooctatetraene.⁹



The latter reasonable option involves a pseudorotation scheme where existing π bonds are simultaneously uncoupled with one set of neighboring carbons and formed with the other. Should this interconversion proceed along a path not bound by precise S_4 symmetry (for the parent system), then a transition state resembling **3** and not the crown conformation proposed by Dewar¹⁰ would become a suitable descriptor.

In order to shed light on this delicate mechanistic distinction, additional studies of a highly refined nature become necessary. In pursuit of these objectives, we have set out to examine the dynamic behavior of three classes of annulated cyclooctatetraenes.

As concerns the enantiomeric 1,3-bridged systems **4**, racemization according to classical thinking will be dictated by the ease with which C_2-H can proceed into the interior of the polymethylene chain as planarization of the eight-membered ring occurs. With



short chains, this pathway cannot, of course, be operative. On the other hand, pseudorotation does not demand planarization, and loss of optical activity can consequently be achieved without C_2 and its associated hydrogen ever entering the intraannular zone.^{7b}

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