Bond Fixation in Annulenes. 8. Assessment of the Ring Inversion and Bond Shifting Barriers in 1,2,3-Trimethylcyclooctatetraene. Resolution, Absolute Configuration, and Circular Dichroic Behavior of an [8]Annulene Hydrocarbon[1]

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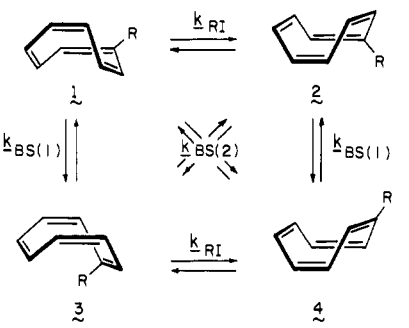
Abstract: A synthesis of racemic 1,2,3-trimethylcyclooctatetraene (**13**) based upon the expectation that 1,7,8-trimethylbicyclo[4.2.0]octa-2,4,7-triene (**12**) would open disrotatorily under orbital symmetry control was realized. This [8]annulene demonstrated a ready propensity for two-electron reduction as shown by electrochemical methods and direct reduction with K in ND_3. The latter study permitted direct spectral examination of the dianion (**16**) which was clearly planar on the ^1H NMR time scale. Since the previous synthesis of **13** did not cause perturbation of that asymmetry introduced in the first step, complete resolution of the starting material was accomplished and optical activity was carried through the entire sequence to deliver levorotatory **13***, $[\alpha]_D$ −148°. X-ray analysis of an intermediate in this scheme (to which the (*R*)-(+)-α-methylbenzylamine moiety had been bonded for internal reference purposes) permitted the assignment of absolute configuration to (−)-**13***. A method for the direct resolution of (±)-**13** without involving destructive loss of the COT was also developed. The rates of racemization of (−)-**13*** were determined. By means of (±)-1,2-bis(trideuteriomethyl)-3-methylcyclooctatetraene, it proved possible to measure the rates and energetics of π-bond shifting. These combined kinetic studies permitted indirect assessment of the rates and activation parameters for ring inversion. The complete kinetic profile of the dynamic behavior of **13** was thereby obtained. The chiroptical properties of (−)-**13*** are also presented.

Electron diffraction[3] and X-ray crystallographic studies[4] of cyclooctatetraene (COT) have established its ground state to comprise a rigid tub-shaped structure of D_{2d} symmetry (e.g., **1**, R = H). By application of ^1H NMR techniques to suitable monosubstituted derivatives, Anet,[5] Oth,[6] and others[7] subsequently showed the nonplanar [8]annulene ring system to be capable of ring inversion (RI) and bond shifting (BS). As Scheme I illustrates, the four resultant structures for COT itself (R = H) are superimposable, while in the case of a monosubstituted derivative (R ≠ H) formulas **1**/**2** and **3**/**4** comprise enantiomeric representations.[8] Accordingly, both processes are isodynamic.[9]

On the basis of the several early experiments designed to elucidate the thermodynamics of these fundamental changes, it has become clear that conformational ring inversion ($\Delta G^{\ddagger}$ = 12.5–14.8 kcal/mol) is less energy demanding than bond shifting ($\Delta G^{\ddagger}$ = 14.9–17.4 kcal/mol). The following transition-state descriptions were advanced in explanation. As concerns ring inversion, the framework is considered to experience progressive flattening until the planar D_{4h} symmetric form **5** is attained. At this point, the van der Waals and angular bending energies presumably exert their maximum destabilizing effects. With regard to bond shifting, the gradual acquisition of a planar or nearly planar conformation

Scheme I. Isodynamical Ring Inversion (k_{RI}) and Bond Shifting ($k_{BS(1)}$, $k_{BS(2)}$) in COT (R = H) and Its Monosubstituted Derivatives



is assumed to be accompanied by bond-length equalization to produce the D_{8h} symmetric species **6**. Since the difference in

energy between **5** and **6** largely corresponds to the delocalization energy of COT, the planar [8]annulene structures **5** and **6** constitute prototypes of central importance to our detailed understanding of nonbenzenoid conjugated systems.

Theoretical interest in this subject has understandably been intense. In general, the COT ring inversion barrier has been closely approximated by calculation.[10-14] However, Dewar and his coworkers computed the energy difference between **5** and **6** to be

(1) For part 7, see: Gardlik, J. M.; Paquette, L. A., *Tetrahedron Lett.* **1979**, 3597.
(2) The Ohio State University Dissertatioin Fellow, 1977–1978.
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(4) Bordner, J.; Parker, R. G.; Stanford, R. H. *Acta Crystallogr., Sect B* **1972**, *28*, 1069.
(5) Anet, F. A. L. *J. Am. Chem. Soc.* **1962**, *84*, 671. Anet, F. A. L.; Brown, A. J. R.; Lin, Y. S. *Ibid.* **1964**, *86*, 3576.
(6) Oth, J. F. M.; Merenyi, R.; Martini, Th.; Schröder, G. *Tetrahedron Lett.* **1966**, 3087.
(7) Gwynn, D. E.; Whitesides, G. M.; Roberts, J. D. *J. Am. Chem. Soc.* **1965**, *87*, 2862. Buchanan, G. W. *Tetrahedron Lett.* **1972**, 665. Luz, Z.; Meiboom, S. *J. Chem. Phys.* **1973**, *59*, 1077.
(8) Of course, if the side chain possesses a chiral center, ring inversion produces a diastereoisomer. See: Anet, F. A. L.; Bock, L. A. *J. Am. Chem. Soc.* **1968**, *90*, 7130.
(9) Oth, J. F. M. *Pure Appl. Chem.* **1971**, *25*, 573.
(10) Allinger, N. L. *J. Org. Chem.* **1962**, *27*, 443.
(11) Snyder, L. C. *J. Phys. Chem.* **1962**, *66*, 2299.
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(13) Wipff, G.; Wahlgren, U.; Kochanski, E.; Lehn, J. M. *Chem. Phys. Lett.* **1971**, *11*, 350.
(14) Allinger, N. L.; Sprague, J. T.; Finder, C. J. *Tetrahedron* **1973**, *29*, 2519.

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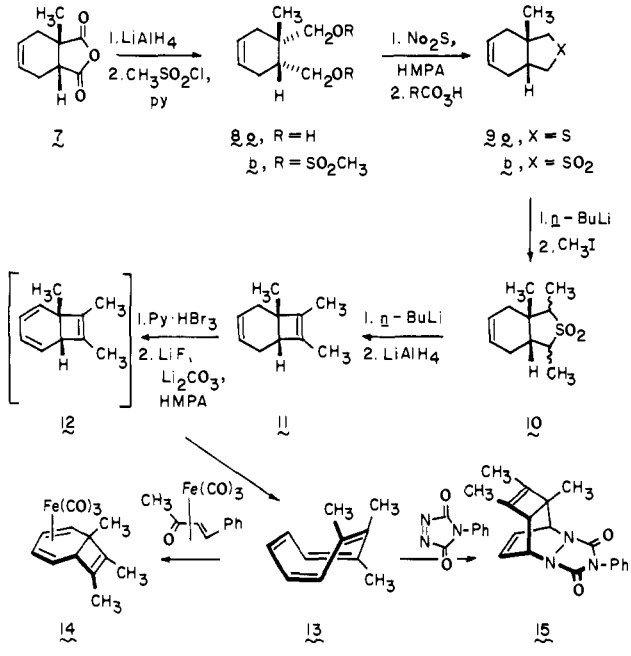
Scheme II. Synthesis of Racemic 1,2,3-Me_3COT



13.9 (MINDO/2) or 15.4 kcal/mol (π approximation),[15] values substantially in excess of those obtained by experiment ($\Delta\Delta G^{\ddagger} \approx 2.5$–$3.5$ kcal/mol). As a result, they concluded that **6** could not be involved during bond shifting and that a nonplanar structure, probably of crown geometry, was likely involved. Although Allinger has regarded this conclusion as improbable[14] and the suggestion has received little additional support, a final resolution of this question has not materialized. New experimental evidence in support of **6** would prove invaluable in guiding our expectations concerning the energetics of antiaromatic ($4n$) delocalization.

Accordingly, we have been concerned with obtaining additional information on the RI and BS processes in cyclooctatetraene derivatives. Our approach, which differs intrinsically from the techniques utilized in previous investigations, is founded upon the preparation of optically active [8]annulenes and analysis of racemization and other kinetic data. This paper describes in detail two methods of resolving 1,2,3-Me_3COT, the assignment of absolute configuration, and the complete analysis of its dynamic behavior.[16] A companion contribution deals with the optically active 1,2,3,4-Me_4COT example.[17a] Such incremental introduction of steric and buttressing effects has provided thermodynamic evidence most cogently accommodated by transition-state structures **5** and **6**.[17b]

Synthesis and Chemical Behavior of Racemic 1,2,3-Me_3COT. Past attempts to prepare polysubstituted COT derivatives by introduction of groups onto a preexisting [8]annulene framework have invariably yielded complex mixtures of products.[18] For this reason, the approach selected for the synthesis of **13** focused on first obtaining bicyclo[4.2.0]octatriene **12**, whose thermodynamically favored[19] valence isomerization to **13** was expected to proceed

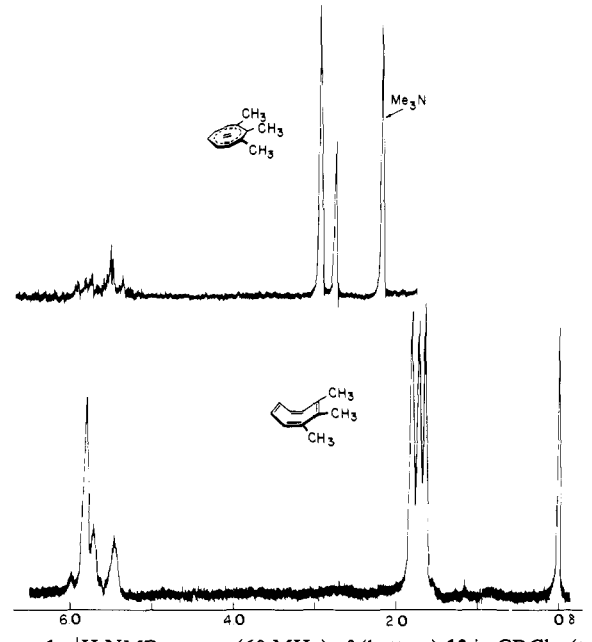


Figure 1. ^1H NMR spectra (60 MHz) of (bottom) **13** in $CDCl_3$; (top) dipotassio-1,2,3-trimethylcyclooctatetraenide (**16**) in ND_3 at −55 °C (Me_3N present as internal standard, δ_{Me_4Si} 2.135).

via opening of the 1,3-cyclohexadiene moiety under orbital symmetry control,[20] as noted previously.[21] In view of the anticipated accessibility of **12** by controlled bromination–dehydrobromination[21,22] of **11**, the expeditious elaboration of this bicyclic diene became our first goal.

Synthesized by Diels–Alder addition of citraconic anhydride to 1,3-butadiene,[23] **7** was efficiently converted in turn to diol **8a**, dimesylate **8b**, and cyclic sulfide **9a** (Scheme II). As a consequence of the neopentyl nature of one leaving group in **8b**, best results (88% yield) were achieved by use of anhydrous sodium sulfide in hexamethylphosphoramide (HMPA).[21] α,α'-Dimethylation of derived sulfone **9b** was accomplished by sequential treatment with 2 equiv of *n*-butyllithium at −78 °C and quenching of the resulting dianion with excess methyl iodide at the same temperature. When the anion of **10** was subjected to lithium aluminum hydride reduction,[21,24] ring-contracted diene **11** was isolated in 28% yield. Regioselective bromination of **11** with pyridinium hydrobromide perbromide and dehydrobromination with a stirred slurry of lithium fluoride, lithium carbonate, and powdered glass in HMPA[22] afforded the desired COT in 61% overall yield from **11**.

1,2,3-Me_3COT is a distillable, colorless liquid which is stable for extended periods of time if stored in the cold and protected from light and oxygen. Although the process is undetectable by NMR, **13** is in equilibrium with a small amount of bicyclic isomer **12**. The presence of **12** was revealed through trapping experiments with reagents reactive toward planar 1,3-diene units. For example, the complex **14** was isolated in 62% yield upon treating **13** with excess benzylidenacetoneiron tricarbonyl.[25] Additionally, adduct

(15) Dewar, M. J. S.; Harget, A.; Haselbach, E. *J. Am. Chem. Soc.* **1969**, *91*, 7521. Internally conflicting results appear to exist relative to an earlier report: Dewar, M. J. S.; Gleicher, G. J. *Ibid.* **1965**, *87*, 685.

(16) Preliminary reports on various aspects of the present study have previously been published: (a) Paquette, L. A.; Gardlik, J. M.; Photis, J. M. *J. Am. Chem. Soc.* **1976**, *98*, 7096. (b) Gardlik, J. M.; Johnson, L. K.; Paquette, L. A.; Solheim, B. A.; Springer, J. P.; Clardy, J. *Ibid.* **1979**, *101*, 1615. (c) Gardlik, J. M.; Paquette, L. A.; Gleiter, R. *Ibid.* **1979**, *101*, 1617. (d) Reference 1.

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(18) Reviews: (a) Schröder, G. "Cyclooctatetraen"; Verlag Chemie: Weinheim/Bergstr., West Germany, 1965. (b) Paquette, L. A. *Tetrahedron* **1975**, *31*, 2855. (c) Fray, G. I.; Saxton, R. G. "The Chemistry of Cyclooctatetraene and Its Derivatives"; Cambridge University Press: New York, 1978.

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(20) Woodward, R. B.; Hoffmann, R. "The Conservation of Orbital Symmetry"; Verlag Chemie: Weinheim/Bergstr., West Germany, 1971.

(21) (a) Paquette, L. A.; Photis, J. M.; Ewing, G. D. *J. Am. Chem. Soc.* **1975**, *97*, 3538. (b) Paquette, L. A.; Photis, J. M. *Ibid.* **1976**, *98*, 4936.

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(23) Bloomfield, J. J.; Lee, S. L. *J. Org. Chem.* **1967**, *32*, 3919. Subsequent to the completion of our work, Dr. John Buckingham (Westfield College, University of London) called our attention to an earlier synthesis of (+)-**13**, $[\alpha]^{25}_D$ +14.1° [Dixon, J.; Lythgoe, B.; Siddiqui, I. A.; Tideswell, J. *J. Chem. Soc. C* **1971**, 1301]. These workers also elucidated the correct absolute configuration of the acid ester.

(24) (a) Photis, J. M.; Paquette, L. A. *J. Am. Chem. Soc.* **1974**, *96*, 4715. (b) Paquette, L. A.; Photis, J. M. *Org. Synth.* **1977**, *57*, 53.

(25) Howell, J. A. S.; Johnson, B. F. G.; Josty, P. L.; Lewis, J. *J. Organomet. Chem.* **1972**, *39*, 330. Scholes, G.; Graham, C. R.; Brookhart, M. *J. Am. Chem. Soc.* **1974**, *96*, 5665.

Table I. Reduction Potentials of Substituted Cyclooctatetraenes in Anhydrous HMPA[a]

compd	$E_{1/2}$, V vs. SCE[b]	$\Delta E_{1/2}$[c]
COT	−1.61	
MeCOT	−1.73	0.12
1,2-Me_2COT	−1.95	0.22
1,2,3-Me_3COT	−2.20	0.25
1,2,3,4-Me_4COT	−2.54	0.34

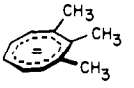
[a] Literature values taken from ref 21b. [b] The $E_{1/2}$ values were obtained vs. $Ag/AgClO_4$ and corrected to SCE by adding 0.36 V. The measurements were conducted in the presence of 0.1 M tetra-*n*-butylammonium perchlorate as the supporting electrolyte. [c] $\Delta E_{1/2} = E_{1/2} - E_{1/2}(n-1)$ where n = number of adjacent methyl groups.

15 was produced in 51% yield when **13** was heated to 50 °C under nitrogen in hexane–ethyl acetate solution with 1.1 equiv of *N*-phenyltriazolinedione. Hydrolysis–oxidation of **15** returned **13**. These observations do not rule out the presence of low-level equilibrium concentrations of other bicyclo[4.2.0]octatriene isomers; rather, they establish only the high reactivity of **12** which presumably results from the unsubstituted nature of its 1,3-diene moiety.

The room temperature 60-MHz ^1H NMR spectrum (in $CDCl_3$) of **13** (Figure 1) consists of three distinct methyl singlets at δ 1.80, 1.72, and 1.64, in addition to a vinyl proton multiplet of area 5 at δ 6.00–5.35. At 90 MHz in Me_2SO-d_6 solution, the methyl signals are shifted downfield to δ 2.80, 2.71, and 2.63, respectively. As the temperature of such solutions was gradually increased to 185 °C, no coalescence of the singlets due to the outer methyl groups was observed, although slight broadening was evident. Therefore, the environments of these two substituents are not experiencing meaningful exchange *on the NMR time scale* at this temperature as they must be if BS were occurring (see below). A lower barrier for this interconversion of $\Delta G^{\ddagger} \approx 25$ kcal/mol can thereby be estimated.[26]

The polarographic reduction potential of **13** was determined in anhydrous HMPA solution, using a vacuum-line cell designed for total exclusion of moisture and oxygen.[27] In the presence of 0.1 M tetra-*n*-butylammonium perchlorate as background electrolyte, **13** underwent smooth two-electron reduction to the dianion at $E_{1/2} = -2.20$ V vs. SCE.[28] The reduction potential can be viewed as a measure of the difficulty experienced in the attainment of planarity in the dianionic species. The value for **13** can be related to the $E_{1/2}$'s obtained for its lower and higher homologues (Table I). A direct quantitative correlation between the facility of reduction and anticipated ease of ring flattening is clearly evident.

The affinity of **13** for two electrons was also revealed by its ready reduction to dianion **16** with potassium in ND_3. The



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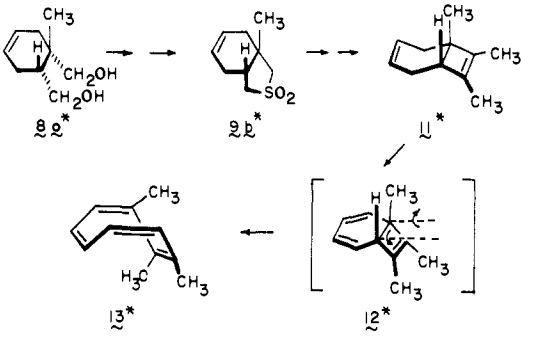
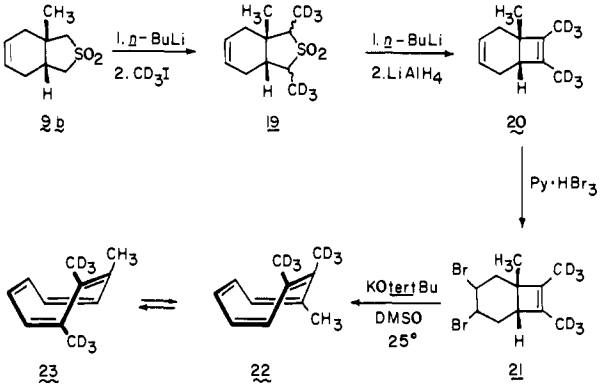
symmetry of the resultant species as revealed by its ^1H NMR spectrum (Figure 1) is consistent with an essentially planar conformation on the NMR time frame. Thus, the aromaticity inherent in the 10π-electron dianion is adequate to offset the prevailing steric destabilization of the three adjacent methyl groups in the planar topology.

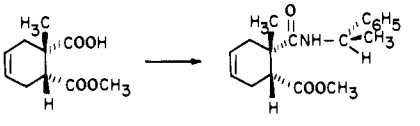
Incorporation of Optical Activity Early in the Synthetic Scheme. The Absolute Configurational Assignment. No reaction utilized in the preparation of **11** affects the asymmetry introduced at the [4 + 2] cycloaddition step which delivers **7**. Therefore, any optical activity generated in a derivative of this anhydride would be expected to be observed in **13**, barring any loss attributable to ring inversion or bond shifting during isolation of the cyclooctatetraene, or to inadequate orbital symmetry control during electrocyclic ring opening of **12**. The derivative selected for resolution, half-acid ester **17**,[23] was obtained in 50% yield by heating **7** in methanol.

Scheme III. Preparation of Levorotatory 1,2,3-Me_3COT



Scheme IV. Synthesis of 1,2,3-Me_3COT-d_6





17 **18**

Two recrystallizations of the *endo*-bornylamine[29] salt of **17** from absolute ethanol afforded a highly crystalline material, mp 159–161 °C and $[\alpha]_D$ +3.4°, whose melting point and rotation could not be improved by subsequent recrystallization. Liberation of **17***, $[\alpha]_D$ −13.8°, was followed by conversion to its acid chloride with oxalyl chloride and condensation with (*R*)-(+)-α-methylbenzylamine. Amide **18*** so produced displayed a single methyl ester absorption at δ 3.59 in its ^1H NMR spectrum. When racemic **17** was treated under identical conditions, the unpurified amide exhibited two methyl singlets of equal intensity at δ 3.59 and 3.66. The diastereomeric purity of **18*** having thus been ascertained, the substance was submitted to single-crystal X-ray structure analysis in Professor Clardy's laboratory.[16b] With knowledge of the absolute configuration of the amide nitrogen portion of the molecule, the absolute configurations of the other chiral centers could be assigned with certainty as 1*S*,6*R* and as depicted in the formulas.

Following lithium aluminum hydride reduction of fully resolved **17***, $[\alpha]_D$ −13.8°, to the diol, optically active sulfone **9b***, $[\alpha]_D$ +45.2°, was arrived at as before (Scheme III). Alkylative ring contraction in the precedented manner furnished **11***, whose absolute configuration must also be 1*S*,6*R*. Bromination–dehydrobromination (LiF, Li_2CO_3, HMPA, 55 °C) of **11*** under the conditions used to prepare racemic **13** provided samples of the

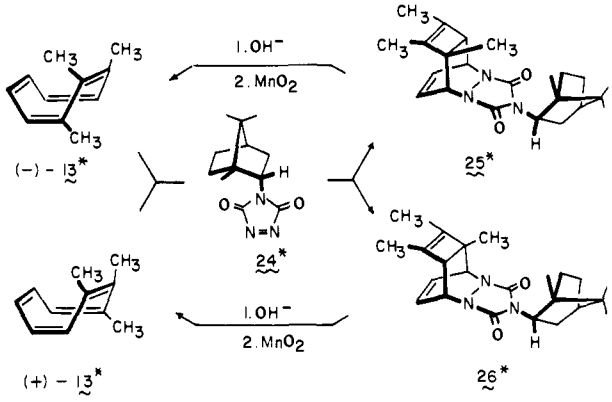
(26) (a) Binsch, G. *Top. Stereochem.* **1968**, *3*, 97. (b) Anet, F. A. L.; Anet, R. "Determination of Organic Structures by Physical Methods", Vol. 3; Academic Press: New York, 1971; pp 344–353. (c) Johnson, C. S., Jr. *Adv. Magn. Reson.* **1965**, *1*, 33–102.

(27) Mills, J. L.; Nelson, R.; Shore, S. G.; Anderson, L. B. *Anal. Chem.* **1971**, *43*, 157.

(28) Taggart, D. L. Ph.D. Thesis, The Ohio State University, 1976.

(29) (a) von Auwers, K. *Chem. Ber.* **1889**, *22*, 605. (b) Forster, M. O. *J. Chem. Soc.* **1898**, *73*, 386. (c) Hückel, W.; Rieckmann, P. *Justus Liebigs Ann. Chem.* **1959**, *625*, 1.

Scheme V. Direct Resolution of 1,2,3-Me_3COT



COT with $[\alpha]_D$'s whose magnitudes were very low. Since racemization was thought to be occurring under these reaction conditions, a search was undertaken for a less stringent means of effecting this formal dehydrogenation.

To facilitate this study and because the compound was required for kinetic studies, our attention was turned to the racemic bis(trideuteriomethyl) derivative **22**. With knowledge of the level of bond shifting to **23** operative during its formation, a reasonable estimate of optical purity of **13*** was thought feasible. Requisite bicyclooctadiene **20** was easily prepared according to Scheme IV. When **20** was brominated and dehydrobrominated as before, a 1:1 mixture of the deuterated COTs **22** and **23** was obtained as judged by ^1H NMR analysis of diglyme-d_{14} solutions. After much investigation, it was found that the action of potassium *tert*-butoxide in Me_2SO on dibromide **21** (25 °C, 1 h) gave rise to a crude product mixture containing **22** and **23** in an approximate ratio of 4:1. However, purification of this product by careful column chromatography lowered the ratio to 2:1. When **13*** was similarly treated and the resultant hydrocarbon was purified without delay by chromatography on Florisil (pentane elution), a sample exhibiting $[\alpha]_D$ −148° and whose absolute configuration must be as depicted in Scheme III was isolated in 14% yield. Since our experience showed this reaction to be difficultly reproducible in terms of the optical rotation of the 1,2,3-Me_3COT, a reliable estimate of the enantiomeric purity of **13*** prepared in this fashion cannot be made.

Direct Resolution of Racemic 1,2,3-Trimethylcyclooctatetraene. As a consequence of the complications outlined in the preceding section, alternative methodology was sought whereby optical activity could be incorporated cleanly at the cyclooctatetraene level of structural elaboration. The new technique would undeniably gain added merit if it were simple to apply and, most importantly, nondestructive of the [8]annulene substrate. These self-imposed restrictions immediately removed from further consideration the type of kinetic resolution introduced by Brown in the form of (+)-tetra-3-pinanyldiborane[30] and used successfully, for example, by Moore in the preparation of a series of chiral allenes,[31] since success could only be achieved at the expense of valuable polyolefin.

In a second approach, the racemic COT might be converted to a mixture of diastereomeric derivatives, suitable separation of which by physical methods and subsequent retrograde chemical synthesis would liberate chiral hydrocarbon. Chiral platinum complexes have previously been used for such purposes,[32] but the cost of this method is prohibitive on a preparative scale and success in this particular instance, as gauged from existing precedent, did not appear at all promising. However, we had previously demonstrated that **13** enters into cycloaddition with *N*-phenyltriazolinedione to give the chiral adduct **15**, whose hydrolysis–oxidation efficiently returned the COT. Hence, racemic 1,2,3-Me_3COT was heated with enantiomerically pure (−)-*endo*-bornyl-1,2,4-triazoline-3,5-dione (**24***, prepared from *d*-camphor[33]) in ethyl acetate solution and converted to the diastereomeric adducts **25*** and **26*** (Scheme V). This colorless, crystalline mixture of urazoles expectedly melted over a rather wide range and gave indication of being homogeneous on thin layer chromatography (silica gel). Its ^1H and ^{13}C NMR spectra gave no indication of the ability to distinguish the two diastereomers. However, repeated recrystallization from ethyl acetate–hexane served to improve both the melting range and optical rotation. With a selection of various diastereoisomeric mixtures in hand, it proved possible to assess their composition through admixture with 0.2 molar equiv or tris(3-(trifluoromethylhydroxymethylene)-*d*-camphorato)europium(III).[34] With the appearance of the bridgehead methyl group originally at δ 1.37 as two peaks, a linear correlation of $[\alpha]_D$ vs. percent levorotatory isomer was developed (Figure 2). From such data, it could be determined that our purest sample of adduct, mp 219–221 °C, $[\alpha]_D$ +34.6°, contained 92% of the dextrorotatory and 8% of the levorotatory diastereoisomers. Hydrolysis–oxidation of this sample afforded the levorotatory enantiomer of **13***, $[\alpha]_D$ −161°, after isolation by Florisil chromatography at −25 to −35 °C. Since a sample of this material completely racemized when heated at 50 °C for 24 h, it was considered to be essentially free of optically active impurities.

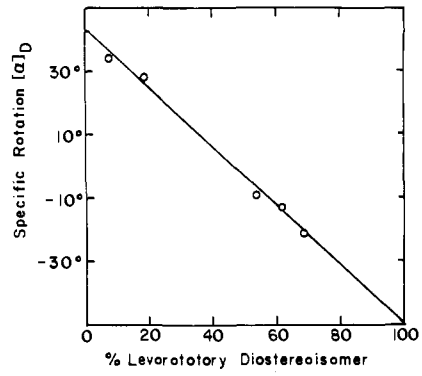


Figure 2. Plot of specific rotation, $[\alpha]_D$, vs. percent of the levorotatory diastereoisomer present in adducts **25*** and **26***.

The absolute configuration of the levorotatory enantiomer of **13*** having been determined previously, definitive stereochemical assignments to urazoles **25*** and **26*** follow unambiguously. Thus, the dextrorotatory form must have the stereochemistry indicated by **25*** (Scheme V). As expected from such considerations, hydrolysis–oxidation of a sample of **26***, $[\alpha]_D$ −21.3°, afforded 1,2,3-Me_3COT having $[\alpha]_D$ +24.4° which also completely racemized after heating at 50 °C for 24 h.

An additional point of interest is that a reasonable prediction concerning the rotation of an optically pure sample of **13*** can now be made. If no optical activity is lost during workup and isolation, then pure **13*** should then possess an $[\alpha]_D$ of −192 or +192°. More realistically, this value should be regarded as a lower limit of the maximum rotation that this particular hydrocarbon can exhibit.

Since (−)-*endo*-bornyl-1,2,4-triazoline-3,5-dione (**24***) proved capable of resolving **13** by diastereomer separation, what then can be said about the possibility of observing asymmetric induction in the cycloaddition reaction proper?[35] This question was briefly

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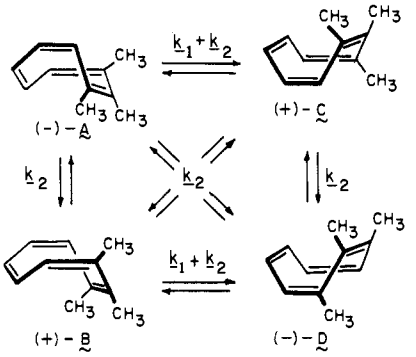
Scheme VI. Summary of Isodynamical Processes in Optically Active 1,2,3-Me_3COT



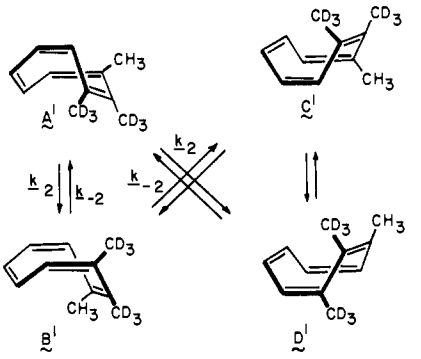
addressed in conducting the Diels–Alder reaction under conditions where competition for **24** would be maximized. A hexane solution of racemic **13** was heated at 50 °C under nitrogen while a solution of **24*** in ethyl acetate was added slowly (1 mL/h) by means of a syringe pump. The adduct, isolated as a white solid, $[\alpha]_D$ −4.12° after Florisil chromatography, was treated with 0.2 molar equiv of tris(3-(trifluoromethylhydroxymethylene)-*d*-camphorato)europium(III) as described above. Integration of the bridgehead methyl singlets showed that a 1:1 ratio of diastereoisomers was present within the limits of experimental error. Clearly, no meaningful asymmetric induction had occurred, but this is not to say that such phenomena will not be observed in other situations where much lower temperatures can be utilized.[36] Unfortunately, in the case of **13**, adduct formation proceeds too slowly at 25 °C and below to be practical.[37]

Isodynamical Processes in 1,2,3-Trimethylcyclooctatetraene. Since 1,2,3-Me_3COT can be expected to undergo the same pair of dynamic processes as its lower homologues, four isodynamical structures are required to completely define the mutual interconversion profile (Scheme VI). The faster ring inversion corresponds to the process (−)-A ⇄ (+)-C or (+)-B ⇄ (−)-D and clearly illustrates the racemization which must ensue. The less energetically accessible π-bond shifting is defined most simply by the changes (−)-A ⇄ (+)-B and (+)-C ⇄ (−)-D, also with loss of optical activity. However, if the transition state considered for bond shifting (i.e., **28**) is the true one, then this reactive planar

delocalized structure must also allow for the incursion of ring inversion *with* bond shifting. In structural terms, this assumption requires that the changes (−)-A ⇄ (−)-D and (+)-B ⇄ (+)-C also be considered kinetically. Furthermore, it signifies that attainment of the energy level demanded by **28** should allow any given species to return to any of the other three isodynamical forms as well as to itself.

Herein, we define k_1 as the rate of low-energy passage through **27** which results in ring inversion without bond shifting; k_2 is considered to be the rate associated with passage through a higher energy transition state which results in ring inversion and/or bond

Scheme VII. Summary of Bond-Shifting Processes Interconnecting 22 and 23



shifting. In these terms, the overall kinetic scheme which can be derived is

$$-d[A]/dt = (k_1 + 3k_2)[A] - (k_1 + k_2)[C] - k_2[B] - k_2[D]$$

$$-d[B]/dt = (k_1 + 3k_2)[B] - (k_1 + k_2)[D] - k_2[A] - k_2[C]$$

$$-d[C]/dt = (k_1 + 3k_2)[C] - (k_1 + k_2)[A] - k_2[D] - k_2[B]$$

$$-d[D]/dt = (k_1 + 3k_2)[D] - (k_1 + k_2)[B] - k_2[C] - k_2[A]$$

The rate at which the levorotatory enantiomer decreases in concentration can therefore be expressed as

$$-d[A + D]/dt = (k_1 + 2k_2)\{[A + D] - [B + C]\}$$

An analogous expression relates to the return of the dextrorotatory enantiomer:

$$-d[B + C]/dt = (k_1 + 2k_2)\{[B + C] - [A + D]\}$$

In the particular case of optically active 1,2,3-Me_3COT, ring inversion and bond shifting both result in racemization. Accordingly, the overall loss of optical activity can be defined as

$$\alpha = C([A + D] - [B + C])$$

$$-d\alpha/dt = -d[A + D]/dt + d[B + C]/dt$$

$$-\frac{d([A + D] - [B + C])}{dt} = 2(k_1 + 2k_2)[A + D] - 2(k_1 + 2k_2)[C + D]$$

$$= 2(k_1 + 2k_2)([A + D] - [C + D]) - d\alpha/dt = 2(k_1 + 2k_2)\alpha$$

Integration between the limits of $t = 0$ and $t = t$ yields the integrated rate law

$$-\ln \alpha = 2(k_1 + 2k_2)t - \ln \alpha_0$$

The factor 2 is obligatory because enantiomer production not only causes loss of the molecule undergoing dynamic change, but also negates the rotatory power of a second.

The kinetic profile for bond shifting involving **22** and **23**, as observed by ^1H NMR experiments and described in Scheme VII, is simplified because A′/C′ and B′/D′ are now identical. Furthermore, since all forms are approximately of the same ground-state energy (neglecting steric deuterium isotope effects), we set $k_2 \approx k_{-2}$. On this basis

$$d[B']/dt = k_2[A'] + k_2[C'] - 2k_2[B']$$

$$d[D']/dt = k_2[A'] + k_2[C'] - 2k_2[D']$$

$$d[B' + D']/dt = 2k_2[A' + C'] - 2k_2[B' + D']$$

For simplification, we set $[A' + C'] = x$ and $[B' + D'] = y$. Since $x + y$ must equal 1

$$dy/dt = 2k_2x - 2k_2y = 2k_2(x - y) = 2k_2(1 - 2y)$$

The integrated form of this expression is

$$\ln (1 - 2y) = -4k_2t + \ln (1 - 2y_0)$$

(35) For examples of asymmetric induction of the Diels–Alder reaction, see: (a) Walborsky, H. M.; Borash, L.; Davis, T. C. *Tetrahedron* **1963**, *19*, 2333. (b) Sauer, J.; Kredel, J. *Angew. Chem., Int. Ed. Engl.* **1965**, *4*, 989. *Tetrahedron Lett.* **1966**, 731, 6359. (c) Farmer, R. F.; Hamer, J. *J. Org. Chem.* **1966**, *31*, 2418. (d) Ensley, H. E.; Parnell, C. A.; Corey, E. J. *Ibid.* **1978**, *43*, 1610. (e) Corey, E. J.; Ensley, H. E. *J. Am. Chem. Soc.* **1975**, *97*, 6908.

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Table II. Rate Data for Bond Shifting in 22 and 23 and Activation Parameters for k_2 in 13

t, °C	measd rate constants for k_2 in 22 and 23, s^{-1}	calcd rate constants for k_2 in 13 assuming $k_H/k_D = 0.83$, s^{-1}
50	5.62×10^{-6}	4.66×10^{-6}
	5.55×10^{-6}	4.61×10^{-6}
70	6.27×10^{-5}	5.20×10^{-5}
	6.12×10^{-5}	5.08×10^{-5}
90	3.61×10^{-4}	3.00×10^{-4}
	2.69×10^{-4}	2.23×10^{-4}

For Bond Shifting in 13
E_{act} = 23.5 kcal/mol
ln A = 24.4
$\Delta H^{\ddagger}$(25 °C) = 22.9 kcal/mol
$\Delta S^{\ddagger}$(25 °C) = −12 eu
$\Delta G^{\ddagger}$(25 °C) = 26.5 kcal/mol

Table III. Racemization and Ring Inversion Rate Data for 13. Activation Parameters for k_1 in 1,2,3-Me_3COT

t, °C	slope $[=2(k_1 + 2k_2)]$, s^{-1}	extrapolated rate constants for k_2 in 13, s^{-1}	rate constants for k_1 in 13, s^{-1}
34.0	3.09×10^{-5}	7.51×10^{-7}	1.43×10^{-5}
	3.21×10^{-5}		
42.3	9.36×10^{-5}	2.07×10^{-6}	3.99×10^{-5}
	8.23×10^{-5}		
50.6	2.22×10^{-4}	5.35×10^{-6}	0.97×10^{-4}
	2.10×10^{-4}		

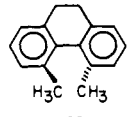
For Ring Inversion in 13
E_{act} = 23.0 kcal/mol
ln A = 26.6
$\Delta H^{\ddagger}$(25 °C) = 22.4 kcal/mol
$\Delta S^{\ddagger}$(25 °C) = −7.7 eu
$\Delta G^{\ddagger}$(25 °C) = 24.7 kcal/mol

and, therefore, plotting ln $(1 - 2y)$ vs. t gives a slope equal to $-4k_2$.

Acquisition of Kinetic Data. When solutions of (−)-**13*** in purified diglyme were placed in a 1-dm polarimeter cell maintained at 34.0, 42.3, and 50.6 °C by means of a circulating constant-temperature bath, and the rotations at 436 nm were recorded as a function of time, plots of $-\ln \alpha$ vs. time afforded excellent straight lines whose slopes were equal to $2(k_1 + 2k_2)$. A sample data set is provided in Table IV.

In order to extract the rate constants for RI from this composite expression, it becomes necessary to determine independently the rate constants for BS at these same temperatures. For this purpose, solutions of a 2:1 mixture of the deuterium-labeled COTs **22** and **23** (see above) in diglyme-d_{14} were placed in an NMR probe at selected constant temperatures and expanded-scale spectra were recorded at suitable time intervals. Planimetric integration of the methyl signals characteristic of **22** and **23** provided quantities that were proportional to the concentrations of each isomer present.

Prior to the utilization of these rate constants in conjunction with eq 8 to interpret the racemization data, correction must be made for the steric deuterium isotope effect.[39] Because of the smaller vibrational amplitudes of C–D bonds relative to C–H bonds, reactions proceeding through transition states involving H–H nonbonded steric interactions will proceed more rapidly if these hydrogens are replaced by deuterium.[40] A particularly relevant earlier study by Mislow and co-workers concerned the racemization of **29** and **30** where a pair of methyl groups was



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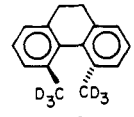

30

replaced by trideuteriomethyl counterparts.[41] In this example, the observed fractionation factor (k_H/k_D) was 0.83. For the present purposes, we have assumed that bond shifting in **22** and **23** occurs with a deuterium steric isotope effect of comparable magnitude. These adjusted rate constants as well as the activation parameters for BS in **13** appear in Table II. The entire kinetic and thermodynamic profiles for RI in **13** follow in Table III.

The energetics associated with RI and BS in 1,2,3-Me_3COT have thus been revealed to be ordered as in less substituted cyclooctatetraene analogues. Although RI still requires a lower energy barrier, the existing gap relative to BS has measurably decreased. At 25 °C, $\Delta\Delta G^{\ddagger}$ is 1.8 kcal/mol and $\Delta\Delta H^{\ddagger}$ merely 0.5 kcal/mol. This compression of the energy demands for the two processes is considered to be significant and is discussed in detail in a companion paper.[17b]

Table IV. Exemplary Rate Data for Racemization of (−)-**13*** (34.0 ± 0.1 °C)

time, s	α_{436}, deg	ln α_{436}
0	−1.228	0.2054
1800	−1.1645	0.1523
3600	−1.100	0.0953
5400	−1.042	0.0411
7200	−0.986	−0.0141
9000	−0.931	−0.0715
10 800	−0.883	−0.1244
12 600	−0.833	−0.1827
14 400	−0.789	−0.2370
16 200	−0.746	−0.2930
18 000	−0.703	−0.3524

slope = 3.09 (±0.01) × 10^{-5} s^{-1}
y intercept = 0.2074 (±0.009)
r = 0.099 966

Table V. Exemplary Rate Data for Interconversion of 22 and 23 (50.0 ± 1.0 °C)

$$X = [23] = \frac{\text{area of methyl singlet at } \delta\ 1.50}{\text{total area of } \delta\ 1.75 \text{ and } 1.50 \text{ singlets}}$$

time, s	area of peak at δ 1.75	area of peak at δ 1.50	X	ln $[X_{eq}/(X_{eq} - X)]$
0	608	309	0.337	1.121
1800	576	313	0.352	1.217
3600	549	306	0.358	1.259
5400	558	315	0.361	1.280
7200	537	319	0.373	1.370
9000	538	323	0.375	1.386
10 800	537	333	0.383	1.452
12 600	517	327	0.387	1.487
14 400	522	330	0.387	1.487
18 000	517	336	0.394	1.551
21 600	505	342	0.404	1.650
23 400	507	353	0.410	1.715
25 200	511	355	0.410	1.715
172 800 (eq)	462	456	0.497	

slope = 2.25 (±0.11) × 10^{-5} s^{-1}
y intercept = 1.173 (±0.030)
r = 0.990 312

Chiroptical Properties of (−)-1,2,3-Me_3COT. Through placement of methyl groups on three contiguous carbon atoms of the cyclooctatetraene nucleus, it has proven possible to inhibit adequately the high susceptibility of the COT frame for ring inversion and π-bond alternation and permit maintenance of optical activity. This property is not shared by the smaller annulene rings (cyclobutadiene and benzene), which are too planar to support optical

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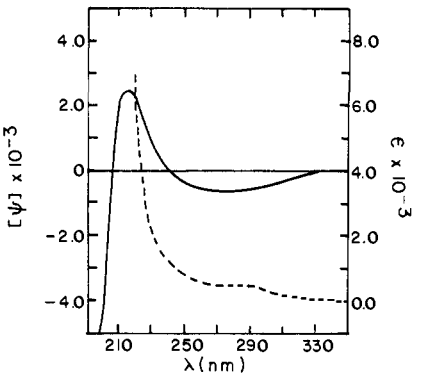

Figure 3. The CD (—) and UV (---) spectra of (−)-1,2,3-trimethylcyclooctatetraene (**13***) recorded in *n*-hexane solution.

activity,[42] and the larger annulenes, which are too flexible to maintain chirality.[9] In practice, therefore, the medium-sized COT ring system is ideally suited for probing the interaction of light with a cyclic conjugated polyolefin network.

The absolute configurational assignment to (−)-**13*** represents the first example of a chiral [8]annulene whose three-dimensional structure is known with precision. Since **13** belongs to the C_1 point group, it follows that the molecule is asymmetric. Because the parent COT ring system is achiral (D_{2d} symmetry), none of its chiral derivatives can be characterized as "inherently dissymmetric" chromophores.[43] Such a designation would be appropriate only under conditions where the substituents caused the [8]annulene framework to distort significantly to a chiral geometry or if the pendant groups participated so significantly in the electronic transitions under consideration that they would have to be considered an integral part of the chromophore. Neither phenomenon is anticipated in the present instance.

Consequently, neither the homoannular diene helicity rule[44] nor the allylic chirality rule[45] applies. Twisting about individual double bonds[46] similarly cannot be playing a significant role.

The ultraviolet spectrum of (−)-**13*** (Figure 3) clearly reveals that a "conjugated" polyene system is not being dealt with; no distinct near-UV absorption maximum is apparent. In tandem with the CD curve, it is revealed that the COT ring can best be viewed as consisting essentially of four virtually unconjugated ethylene chromophores coupled principally by the electrostatic potential between the $\pi \rightarrow \pi^*$ transition dipoles. As a result, it becomes difficult to know *which* CD band is pertinent for a given analysis. Additional information in the form of several differently substituted examples is required and research in this direction is being continued.

Experimental Section

Melting points and boiling points are uncorrected. Proton magnetic resonance spectra were obtained with Varian T-60, Varian EM-360, and Bruker HX-90 spectrometers; apparent splittings are given in all cases. Infrared spectra were determined on a Perkin-Elmer Model 467 instrument. Mass spectra were recorded on an AEI-MS9 spectrometer at an ionization potential of 70 eV. Optical rotations were measured on Perkin-Elmer Model 141 and 241 polarimeters. Elemental analyses were performed by the Scandinavian Microanalytical Laboratory, Herlev, Denmark.

***cis*-4-Methyl-4,5-bis(methanesulfonyloxymethyl)cyclohexene (8b).** To a mechanically stirred refluxing slurry of 45.0 g (1.18 mol) of lithium aluminum hydride in 2.5 L of anhydrous tetrahydrofuran was added dropwise under nitrogen a solution containing 166.0 g (1.0 mol) of **7**[23] in 500 mL of the same solvent. The reaction mixture was refluxed for 10 h, cooled, quenched by the careful addition of a saturated sodium sulfate solution, and stirred until the salts were white. The insoluble material was removed by vacuum filtration, the solid was rinsed with dichloromethane, and the combined filtrates were dried and evaporated to yield diol **8a** as a nearly colorless oil which solidified on standing.

The diol was dissolved in 400 mL of pyridine and added dropwise to a mechanically stirred solution of 320 g (2.62 mol) of methanesulfonyl chloride in 1.5 L of pyridine at −10 °C. After the addition was complete, the reaction mixture was allowed to come to room temperature, stirred for an additional 4 h, recooled in an ice bath, treated carefully with 1 L of 10% hydrochloric acid while stirring, and extracted with dichloromethane (4 × 500 mL). The combined organic layers were washed with 10% hydrochloric acid until the aqueous layer remained acidic and water (500 mL) before drying. Removal of the solvent in vacuo afforded 259.0 g (83%) of dimesylate **8b** as a viscous, yellow oil: ν_{max} (neat) 1350 and 1175 cm^{-1}; ^{1}H NMR (δ, $CDCl_3$) 5.65 (m, 2 H), 4.55–3.85 (m, 4 H), 3.00 (s, 6 H), 2.17 and 1.95 (br m's, 5 H), and 1.17 (s, 3 H, methyl). This racemic material was used for the next step without further purification.

Comparable reduction of 32.1 g (0.162 mol) of **17***, $[\alpha]_D$ −13.8°, yielded 24.35 g (97%) of optically active diol **8a** as a white, crystalline solid, mp 90–93 °C, $[\alpha]_D$ −33.6° (*c* 10.2, C_2H_5OH).

A cold solution of sulfene was prepared by adding 44.6 g (0.390 mol) of methanesulfonyl chloride to 250 mL of pyridine at −23 °C. To this cold solution was added with stirring a solution of 24.35 g (0.156 mol) of the optically active diol in 60 mL of pyridine. After the addition was complete, the reaction mixture was allowed to come to room temperature, stirred for an additional 2 h, poured carefully onto 200 mL of ice-cold 10% hydrochloric acid, and extracted with dichloromethane (4 × 100 mL). The combined organic phases were washed with 10% hydrochloric acid until the aqueous layer remained acidic, 5% sodium bicarbonate solution (300 mL), and water (300 mL) before drying. The solvent was removed in vacuo to give 43.5 g (86%) of optically active dimesylate as a viscous oil whose spectral characteritics were identical with those of the racemic compound. A small amount of material was chromatographed on silica gel. Elution with ether yielded purified **8b*** as a colorless oil, $[\alpha]_D$ −18.3° (*c* 46.7, C_2H_5OH).

***cis*-Methyl-8-thiabicyclo[4.3.0]non-3-ene (9a).** An anhydrous slurry of sodium sulfide in HMPA was prepared by distillation of the water–HMPA fraction (bp 36–132 °C, 30 mm) from a mixture of 540 g (2.25 mol) of $Na_2S{\cdot}9H_2O$ and 2.5 L of HMPA. Oily dimesylate **8b** (220 g, 0.705 mol) was added to the cooled slurry in one portion and the reaction mixture was stirred and heated at 120 °C for 32 h under nitrogen. The reaction mixture was cooled, poured onto 2.5 L of ice–water, and extracted with pentane (4 × 1 L). The combined organic layers were washed with water (10 × 1 L) and saturated salt solution (1 L) prior to drying. The solvent was removed in vacuo and the residue was distilled to yield 95.0 g (88%) of sulfide **9a** as a colorless liquid: bp 63–71 °C (1.5 mm); ν_{max} (neat) 2950–2830, 1450, and 1524 cm^{-1}; ^{1}H NMR (δ, $CDCl_3$) 5.55 (m, 2 H), 3.00–2.58 (m, 4 H), 2.30–1.50 (m, 5 H), and 1.10 (s, 3 H, methyl); calcd *m/e* 154.098161, obsd 154.081 84.

Reaction of the unpurified optically active dimesylate **8b*** (43.5 g, 0.139 mol) under comparable conditions provided a yellow oil which was chromatographed on 200 g of alumina (neutral, activity I). Elution with pentane afforded a colorless liquid which was distilled to yield 17.44 g (82%) of optically active sulfide **9a**, bp 69–71 °C (1.5 mm), $[\alpha]_D$ +63.5° (*c* 10.1, pentane).

***cis*-1-Methyl-9-thiabicyclo[4.3.0]non-3-ene 8,8-Dioxide (9b).** To a mechanically stirred solution of 90.0 g (0.60 mol) of **9a** in 500 mL of ether cooled to 0 °C was added 2.5 L of 0.5 M ethereal monoperphthalic acid (1.25 mol). After the addition was complete, the reaction mixture was stirred at room temperature for 6 h and allowed to stand for 12 h. The precipitated phthalic acid was removed by vacuum filtration and the

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filtrate was concentrated in vacuo to a thick paste. Methylene chloride (2 L) was added and the resulting solution was washed with 0.5 N sodium hydroxide solution (2 × 1 L) and water (1 L) before drying. The solvent was removed in vacuo to yield 101.0 g (98%) of **9b** as a nearly colorless oil: ν_{max} (neat) 3020–2840, 1440–1380, 1290, and 1230–1080 cm^{-1}; ^{1}H NMR (δ, $CDCl_3$) 5.67 (m, 2 H), 3.30–3.00 (m, 4 H), 2.85–1.67 (m, 5 H), and 1.21 (s, 3 H, methyl); *m/e* calcd 186.071 43, obsd 186.071 73.

The analytical sample was prepared by chromatography on silica gel (ether elution) and double molecular distillation (bath temperature ~60 °C, 0.1 mm).

Anal. Calcd for $C_9H_{14}O_2S$: C, 58.03; H, 7.58; S, 17.22. Found: C, 58.11; H, 7.62; S, 16.90.

Analogous oxidation of **9a***, $[\alpha]_D$ +63.5° (17.42 g, 0.113 mol), delivered a viscous oil which crystallized on standing. The material was recrystallized from ether–hexane to give 17.95 g (85%) of crystalline **9b***, mp 72–73 °C, $[\alpha]_D$ +45.2° (*c* 12.5, CH_2Cl_2).

1,7,8-Trimethylbicyclo[4.2.0]octa-3,7-diene (11). To a magnetically stirred solution containing 41.13 g (0.221 mol) of **9b** in 600 mL of dry tetrahydrofuran was added 276 mL of a 1.6 M solution of *n*-butyllithium in hexane (0.442 mol) via cannula at −78 °C under nitrogen. The reaction mixture was stirred at −78 °C for 0.5 h and a solution of 94 g (0.663 mol) of methyl iodide in 50 mL of dry tetrahydrofuran was added dropwise over a period of about 30 min. After the addition was complete, the mixture was stirred at −78 °C for 1 h, allowed to come to room temperature, and stirred for an additional 4 h. Water (50 mL) was added and most of the tetrahydrofuran was removed in vacuo. The residue was taken up in dichloromethane (1 L) and the organic phase was washed with water (2 × 1 L) and dried. The solvent was removed in vacuo to yield 50.84 g (100%) of **10** as a viscous, yellow oil.

The trimethyl sulfone was dissolved in 280 mL of dry dioxane and treated with 138 mL of a 1.6 M solution of *n*-butyllithium in hexane (0.221 mol) via cannula with external cooling (ice bath) under nitrogen. The orange solution was allowed to come to room temperature, transferred via cannula to a pressure-equalized addition funnel, added dropwise over a period of 20 min to a refluxing slurry of 42.0 g (1.105 mol) of lithium aluminum hydride in 2800 mL of dry dioxane under nitrogen, and refluxed for 20 h. The reaction mixture was cooled, quenched by careful addition of Glauber's salt, and stirred until the salts were white. The solids were removed by vacuum filtration and washed with pentane (2 × 300 mL). The filtrate was divided in half and each half was poured onto water (2 L) and extracted with pentane (3 × 600 mL). The combined extracts were washed with water (5 × 2 L) and saturated salt solution (2 L) prior to drying. The solvent was removed in vacuo and the residue was chromatographed on 770 g of alumina (neutral, activity I). Elution with pentane and distillation of the eluate yielded 9.11 g (28%) of **11** as a colorless liquid: bp 30–35 °C (0.1 mm); ν_{max} (neat) 3030–2820 cm^{-1}; ^{1}H NMR (δ, CCl_4) 5.85–5.45 (br m, 2 H), 2.40–1.70 (m, 5 H), 1.70–1.32 (m, 6 H), and 1.17 (s, 3 H); calcd *m/e* 148.125 19, obsd 148.125 37.

Anal. Calcd for $C_{11}H_{16}$: C, 89.12; H, 10.88. Found: C, 88.80; H, 10.95.

Submission of 17.95 g (0.0965 mol) of optically active **9b***, $[\alpha]_D$ +45.2°, to the predescribed conditions afforded a yellow oil which was chromatographed on 100 g of alumina (neutral, activity I). Pentane elution (fraction size 20 mL) afforded in fractions 4, 5, and 6 a colorless oil which was distilled to yield 800 mg (29%) of optically active **11**, bp 30–35 °C (0.1 mm), as a colorless liquid. A sample was further purified by preparative VPC (6 ft × 0.25 in. 5% SE-30 on 60/80 Chromosorb W, 50 °C), $[\alpha]_D$ +141° (*c* 12.7, hexane).

1,2,3-Trimethylcyclooctatetraene (13). To a magnetically stirred solution of **11** (9.11 g, 0.0616 mol) in 350 mL of carbon tetrachloride and 350 mL of glacial acetic acid was added 19.71 g (0.0616 mol) of pyridinium hydrobromide perbromide in one portion and the reaction mixture was stirred at room temperature until all the solid had dissolved (ca. 2 h). The mixture was poured onto water (700 mL), the layers were separated, and the aqueous layer was extracted with carbon tetrachloride (2 × 350 mL). The combined extracts were washed with water (500 mL), 5% sodium bicarbonate solution (500 mL), and water (500 mL) prior to drying. The solvent was removed in vacuo to yield 17.8 g (94%) of dibromide as a yellow oil.

The dibromide was added in one portion to a mechanically stirred slurry of 15.0 g (0.577 mol) of lithium fluoride, 42.4 g (0.577 mol) of lithium carbonate, and 0.5 g of powdered glass in 900 mL of dry HMPA. The reaction mixture was stirred and heated at 50–55 °C under nitrogen for 24 h, cooled, poured onto ice water (1 L), and extracted with pentane (3 × 1 L). The extract was washed with water (10 × 1 L) and saturated salt solution (1 L) before drying. The solvent was removed in vacuo to yield a green oil which was chromatographed on 300 g of Florisil. Elution with pentane (fraction size 150 mL) afforded in fractions 4–7 a nearly colorless liquid which was distilled to yield 5.41 g (61%) of **13**: bp 35–37 °C (1.0 mm); ν_{max} (neat) 3000–2920 cm^{-1}; ^{1}H NMR (δ, CCl_4) 6.05–5.32 (m, 5 H), 1.95, 1.72, and 1.55 (s's, 3 H each); *m/e* calcd 146.109 54, obsd 146.109 92.

The analytical sample was obtained by preparative VPC (10 ft × 0.25 in. 10% Carbowax M on 60/80 Chromosorb W, 50 °C).

Anal. Calcd for $C_{11}H_{14}$: C, 90.35; H, 9.65. Found: C, 90.06; H, 9.90.

The optically active hydrocarbon was obtained in highest optical purity by making recourse to the following procedure. To a magnetically stirred solution of 500 mg (3.25 mmol) of optically active **11***, $[\alpha]_D$ +141°, in 20 mL of carbon tetrachloride and 20 mL of glacial acetic acid was added 1.18 g (3.74 mmol) of pyridinium hydrobromide perbromide in one portion. The reaction mixture was stirred at room temperature for 2 h. Water (40 mL) was added, the layers were separated, and the aqueous layer was extracted with carbon tetrachloride (2 × 20 mL). The combined organic layers were washed with water (40 mL), 10% sodium bicarbonate solution (40 mL), and water (40 mL) prior to drying. The solvent was removed in vacuo to yield a yellow oil which was chromatographed on 10 g of Florisil. Elution with pentane yielded 980 mg (96%) of optically active dibromide as a colorless oil.

To a magnetically stirred solution of 1.05 g (9.36 mmol) of potassium *tert*-butoxide in 30 mL of dry dimethyl sulfoxide was added dropwise with external cooling (ice bath) a solution of 980 mg (3.12 mmol) of the optically active dibromide in 10 mL of pentane under an atmosphere of nitrogen. After the addition was complete, the cooling bath was removed and the solution was stirred at room temperature for 1 h, recooled in an ice bath, and treated with a few pieces of ice to hydrolyze any remaining *tert*-butoxide. The reaction mixture was poured onto ice water and extracted with pentane (3 × 20 mL). The combined extracts were washed with ice water (3 × 40 mL) and saturated salt solution (40 mL) before drying. The solvent was removed in vacuo to yield 500 mg of a brown oil which was filtered through 10 g of Florisil. Elution with pentane afforded 200 mg of a colorless oil which was carefully rechromatographed on 25 g of Florisil. Elution with pentane (fraction size 10 mL) yielded in fractions 10–20 63.4 g (14%) of optically active **13*** as a colorless oil: ^{1}H NMR (δ, CCl_4) 6.05–5.32 (m, 5 H) and 1.95, 1.72, and 1.55 (m, 3 H each); $[\alpha]_D$ −148° (*c* 21.1, diglyme). The CD spectrum and kinetic data were obtained using this sample.

1,7,8-Trimethylbicyclo[4.2.0]octatrieneiron Tricarbonyl (14). A solution of 82 mg (0.562 mmol) of **13** and 983 mg (3.44 mmol) of freshly recrystallized benzylidinacetoneiron tricarbonyl in 10 mL of dry benzene was heated at 60 °C under nitrogen for 48 h. The reaction mixture was concentrated in vacuo and chromatographed on 10 g of silica gel. Elution with pentane and molecular distillation (bath temperature 30–35 °C, 0.1 mm) of the concentrated eluate afforded 100 mg (62%) of **14** as a greenish oil: ν_{max} (neat) 2050 and 1975 cm^{-1}; ^{1}H NMR (δ, $CDCl_3$) 5.77–5.50 (m, 2 H), 3.66–3.12 (m, 2 H), 2.62 (br m, 1 H), 1.63 (m, 6 H), and 1.42 (s, 3 H); *m/e* calcd 286.029 18, obsd 286.029 78.

Anal. Calcd for $C_{14}H_{14}FeO_3$: C, 58.77; H, 4.93. Found: C, 58.93; H, 4.95.

***N*-Phenyltriazolinedione Adduct of 1,2,3-Trimethylcyclooctatetraene (15).** To a magnetically stirred solution of 3.52 g (0.0242 mol) of **13** in 75 mL of hexane heated at 50 °C under nitrogen was added a solution of 4.65 g (0.0266 mol) of freshly sublimed *N*-phenyltriazolinedione in 100 mL of ethyl acetate over a period of 1 h. After the addition was complete, the solution was stirred and heated at 65 °C for 40 h under nitrogen. The cooled reaction mixture was poured onto 15 g of Florisil and freed of solvent in a stream of air. The Florisil containing the product was placed atop a column of 250 g of Florisil; elution with 10% ethyl acetate in hexane (1000 mL) yielded only hydrocarbon impurities. Elution with 50% ethyl acetate in hexane (1000 mL) afforded 4.0 g (51%) of white solid which was recrystallized from ethyl acetate–hexane to yield 2.77 g (39%) of highly crystalline material: mp 148–150 °C; ν_{max} (KBr) 1770, 1710, and 1505–1025 cm^{-1}; ^{1}H NMR (δ, $CDCl_3$) 7.38 (s, 5 H), 6.15 (t of d, J = 6.0 and 2.0 Hz, 2 H), 4.95 (t of d, J = 6.0 and 2.0 Hz, 1 H), 4.55 (d of d, J = 6.0 and 2.0 Hz, 1 H), 2.55 (br d, J = 4.0 Hz, 1 H), 1.43 (s, 6 H), and 1.37 (s, 3 H); *m/e* calcd 321.147 69, obsd 321.148 22.

Anal. Calcd for $C_{19}H_{19}N_3O_2$: C, 71.01; H, 5.96; N, 13.08. Found: C, 70.93; H, 6.03; N, 13.11.

Hydrolysis–Oxidation of 15. A slurry of 500 mg (1.56 mmol) of **15** and 500 mg of sodium hydroxide in 30 mL of isopropyl alcohol was refluxed for 2 h under an atmosphere of nitrogen. The solution was cooled, made acidic (pH 1) by the careful addition of 3 N hydrochloric acid, and then made basic (pH 9) by the careful addition of 3 N ammonium hydroxide. Pentane (30 mL) and 1.5 g (17.2 mmol) of manganese dioxide were added. The reaction mixture was stirred at room temperature for 1 h under nitrogen, poured onto cold water (30 mL), and separated into layers. The aqueous layer was extracted with pentane (2

× 20 mL). The combined organic phases were washed with water (5 × 50 mL) and saturated salt solution (50 mL) prior to drying. The solvent was removed in vacuo and the residue was chromatographed on 6 g of Florisil. Elution with pentane afforded 170 mg (74%) of pure 1,2,3-trimethylcyclooctatetraene (**13**) which was identical in all respects with an original sample.

Resolution of 17 Using (−)-*endo*-Bornylamine. (−)-*endo*-Bornylamine hydrochloride (186.6 g, 0.995 mol) was dissolved in 1000 mL of water and the solution was made basic by the addition of a 10% sodium hydroxide solution. This alkaline solution was extracted with ether (3 × 700 mL). The combined organic layers were washed with water (1000 mL) and saturated salt solution (1000 mL) prior to drying. The ether solution was concentrated in vacuo until a volume of about 500 mL was obtained.

The half-acid ester **17**[23] (197.0 g, 0.995 mol) was dissolved in 1000 mL of ether and the above ethereal solution of the amine was added with stirring. The salt immediately precipitated and was collected by vacuum filtration, washed with ether, and dried in vacuo (293.8 g, 0.836 mol). This solid was recrystallized three times from decreasing amounts of warm absolute ethanol (the first recrystallization required 2000 mL of solvent) to yield 64.0 g (18%) of large, colorless needles, mp 159–161 °C, $[\alpha]_D$ +3.4° (*c* 10.8, C_2H_5OH), whose melting point and rotation could not be improved by subsequent recrystallizations.

Anal. Calcd for $C_{28}H_{33}NO_4$: C, 68.34; H, 9.46; N, 3.99. Found: C, 68.46; H, 9.48; N, 3.99.

The above salt (64.0 g, 0.182 mol) was treated with 1000 mL of a 10% hydrochloric acid solution and extracted with ether (5 × 200 mL). The combined organic layers were washed with water (500 mL) and saturated salt solution (500 mL) before drying. The solvent was removed in vacuo and the residue was recrystallized from ether–hexane to yield 32.7 g (91%) of crystalline **17***, mp 78–79 °C, $[\alpha]_D$ −13.8° (*c* 10.8, C_2H_5OH).

Diastereoisomeric Amides 18. Determination of the Optical Purity of 17* Using ^{1}H NMR. A solution of 128 mg (6.44 mmol) of optically active **17***, mp 78–79 °C, $[\alpha]_D$ −13.8° (*c* 10.8, C_2H_5OH), in 5 mL of dry benzene was stirred with excess freshly distilled oxalyl chloride at 0 °C for 0.5 h. All of the volatiles were removed in vacuo to yield the acid chloride as a nearly colorless liquid.

The acid chloride was stirred with a solution of 2.34 g (19.3 mmol) of (*R*)-(+)-α-methylbenzylamine in 10 mL of dry benzene at room temperature for 0.5 h. The reaction mixture was poured onto an ice-cold 10% hydrochloric acid solution (30 mL) and extracted with ether (3 × 10 mL). The extract was washed with water (20 mL) and saturated salt solution (20 mL) before drying. The solvent was removed in vacuo to yield 182 mg (94%) of white solid whose ^{1}H NMR showed only one methyl ester resonance at δ 3.59, indicating that the half-acid ester is greater than 95% optically pure: ^{1}H NMR (δ, $CDCl_3$) 7.28 (s, 5 H), 5.66 (m, 2 H), 5.4–5.0 (m, 1 H), 3.59 (s, 3 H), 3.20–1.65 (m, 6 H), 1.47 (d, *J* = 6.0 Hz, 3 H), and 1.22 (s, 3 H). This material was recrystallized three times from ether–hexane to yield 76 mg (25%) of large, needle-like crystals suitable for X-ray crystal structure determination, mp 95–97 °C, $[\alpha]_D$ +66.5° (*c* 18.8, C_2H_5OH).

Anal. Calcd for $C_{18}H_{23}NO_3$: C, 71.73; H, 7.69; N, 4.65. Found: C, 71.82; H, 7.88; N, 4.74.

When a 52-mg sample (2.62 mmol) of optically active half-acid ester **17**, mp 79–105 °C, $[\alpha]_D$ +9.6° (*c* 10, C_2H_5OH), was treated with excess oxalyl chloride and excess (*R*)-(+)-methylbenzylamine under identical conditions, 79 mg (87%) of white solid was obtained whose ^{1}H NMR showed a large methyl ester resonance at δ 3.66 and a much smaller methyl ester resonance at δ 3.59 (ratio 8.5:1.5), indicating that the half-acid ester is approximately 85% optically pure. This material was recrystallized from ether–hexane to yield 40 mg (44%) of fine, white, needle-like crystals, mp 96–98 °C, $[\alpha]_D$ +67.4° (*c* 1.9, C_2H_5OH).

When a 1.0-g sample of racemic half-acid ester **17** was treated with excess oxalyl chloride and excess (*R*)-(+)-α-methylbenzylamine under identical conditions, 1.0 g of white solid was obtained whose ^{1}H NMR showed two methyl ester resonances at δ 3.66 and 3.59 in a one to one ratio. This material was recrystallized from ether–hexane to yield 700 mg of a white powder, mp 65–77 °C, $[\alpha]_D$ +80.9° (*c* 8.5, C_2H_5OH).

***cis*-1-Methyl-7,9-bis(trideuteriomethyl)-8-thiabicyclo[4.3.0]non-3-ene 8,8-Dioxide (19).** To a magnetically stirred solution of 11.5 g (0.062 mol) of **9b** in 150 mL of dry tetrahydrofuran was added via syringe at −78 °C under nitrogen 81 mL of a 1.53 m solution of *n*-butyllithium in hexane (0.124 mol). The yellow solution was stirred at −78 °C for 0.75 h and 20.0 g (0.138 mol) of trideuteriomethyl iodide in 50 mL of dry tetrahydrofuran was added dropwise over a period of about 0.5 h. The reaction mixture was stirred at −78 °C for 4 h, allowed to come slowly to room temperature, and stirred overnight. Water (50 mL) was added and most of the tetrahydrofuran was removed in vacuo. The residue was taken up in 200 mL of water and extracted with dichloromethane (3 × 70 mL). The combined extracts were washed with water (2 × 100 mL) and dried. The solvent was removed in vacuo to yield 13.93 g (100%) of **19** as a yellow oil. This material was used for the next step without further purification.

***cis*-Methyl-7,8-bis(trideuteriomethyl)bicyclo[4.2.0]octa-3,7-diene (20).** To a magnetically stirred solution of 13.93 g (0.062 mol) of **19** in 80 mL of dry dioxane cooled in an ice bath was added under nitrogen 41 mL of a 1.53 M solution of *n*-butyllithium in hexane (0.062 mol) via syringe. The orange solution was stirred at 0 °C for 20 min, allowed to come to room temperature, and transferred via syringe to a nitrogen-filled pressure-equalized addition funnel. The orange solution was added dropwise to a refluxing slurry of 11.8 g (0.310 mol) of lithium aluminum hydride in 800 mL of dry dioxane over a period of 30 min and the reaction mixture was refluxed for 20 h. The slurry was cooled and excess hydride was decomposed by the careful addition of Glauber's salt with stirring until the salts were white. The salts were removed by vacuum filtration. Water (1000 mL) was added to the filtrate and the aqueous solution was extracted with pentane (3 × 300 mL). The combined extracts were washed with water (5 × 1000 mL) and saturated salt solution (1000 mL) before drying. The solvent was removed in vacuo to yield a yellow oil which was chromatographed on 200 g of alumina (neutral, activity I). Elution with pentane (fraction size 60 mL) afforded in fractions 3–5 the bicyclooctadiene **20** as a colorless oil. The material was distilled to yield 2.73 g (29%) of hydrocarbon: bp 30–35 °C (0.1 mm); ^{1}H NMR (δ, CCl_4) 5.67–5.46 (m, 2 H), 2.37–1.71 (m, 5 H), and 1.08 (s, 3 H); calcd *m/e* 154.167 86, obsd 154.168 06.

1,2-Bis(trideuteriomethyl)-3-methylcyclooctatetraene (22) and Bond Shift Isomer (23). To a magnetically stirred solution of 500 mg (3.25 mmol) of **20** in 20 mL of carbon tetrachloride and 20 mL of glacial acetic acid was added 1.18 g (3.74 mmol) of pyridinium hydrobromide perbromide in one portion. The reaction mixture was stirred at room temperature for 2 h. Water (40 mL) was added, the layers were separated, and the aqueous layer was extracted with carbon tetrachloride (2 × 20 mL). The combined organic extracts were washed with water (40 mL), 5% sodium bicarbonate solution (40 mL), and water (40 mL) before drying. The solvent was removed in vacuo to yield a yellow oil which was chromatographed on 10 g of Florisil. Elution with pentane afforded 980 mg (96%) of dibromide **21** as a colorless oil.

To a magnetically stirred slurry of 1.05 g (9.35 mmol) of potassium *tert*-butoxide in 30 mL of dry dimethyl sulfoxide was added dropwise with external cooling (ice bath) a solution of 980 mg (3.12 mmol) of **21** in 10 mL of dry dimethyl sulfoxide under nitrogen. After the addition was complete, the cooling bath was removed and the mixture was stirred at room temperature for 1 h prior to cooling in an ice bath and treatment with a few pieces of ice to hydrolyze any remaining *tert*-butoxide. The reaction mixture was poured onto ice water and extracted with pentane (3 × 20 mL). The extract was washed with ice water (3 × 40 mL) and saturated salt solution (40 mL) before drying. The solvent was removed in vacuo to yield a brown oil which was filtered through 10 g of Florisil. Elution with pentane yielded 200 mg of a colorless oil which was carefully chromatographed on 25 g of Florisil. Elution with pentane (fraction size 10 mL) afforded in fractions 10–20 50 mg (10%) of a colorless oil which was judged to be a 2:1 mixture of **22** and **23** by ^{1}H NMR (δ, diglyme-d_{14}): 5.86–5.36 (m, 5 H), 1.76–1.74 (m, 2 H), and 1.50 (s, 1 H). After the sealed NMR tube was heated at 90 °C for 24 h in an oil bath, a 1:1 ratio of isomers **22** and **23** was obtained as indicated by the identical integration of the methyl resonances.

Note: It is thought that bond shifting does occur during the purification of this compound because the ^{1}H NMR of the crude product showed only a small peak at δ 1.59. After chromatography this peak had become substantially larger.

Direct Resolution of 1,2,3-Trimethylcyclooctatetraene Using (−)-*endo*-Bornyltriazolinedione. A solution of 1.89 g (0.0129 mol) of **13** in 75 mL of hexane was heated at 50 °C under nitrogen and a solution of 3.16 g (0.0142 mol) of freshly sublimed (−)-*endo*-bornyltriazolinedione (**24**) in 75 mL of ethyl acetate was added over a period of 1 h with stirring. After the addition was complete, the solution was heated at 65 °C for 40 h, allowed to cool, and freed of solvent in vacuo. The residual yellow solid was recrystallized from hexane–ethyl acetate (6:1) to yield 2.21 g (45%) of white crystals, mp 196–205 °C, $[\alpha]_D$ +4.51° (*c* 12.2, C_2H_5OH).

This material was crystallized six times from ethyl acetate–hexane to yield 110 mg of the partially resolved adduct **25**: mp 219–221 °C; $[\alpha]_D$ +34.6° (*c* 9.6, C_2H_5OH); ν_{max} (KBr) 2990–2900, 1760, 1695, 1410, and 1380 cm^{-1}; ^{1}H NMR (δ, $CDCl_3$) 6.14 (q of d, *J* = 2.5 and 1.0 Hz, 1 H), 6.01 (t of d, *J* = 3.2 and 1.0 Hz, 1 H), 4.82 (t of d, *J* = 2.5 and 1.0 Hz, 1 H), 4.43 (d of d, *J* = 3.0 and 1.0 Hz, 1 H), 2.60–2.40 (m, 1 H), 2.04–1.56 (m, 7 H), 1.43 (s, 6 H), 1.34 (s, 3 H), 0.94, 0.85, and 0.78 (s's, 3 H each); calcd *m/e* 381.241 61, obsd 381.241 99.

Anal. Calcd for $C_{23}H_{31}N_3O_2$: C, 72.41; H, 8.19; N, 11.02. Found: C, 72.36; H, 8.14; N, 10.97.

Table VI

$[\alpha]_D$, deg	% 25 present	% 26 present
+34.6	92	8
+28.9	81	19
−8.5	46	54
−12.5	38	62
−21.3	30	70

This material was shown to contain 92% of diastereoisomer **25** and 8% of diastereoisomer **26** by the addition of 0.21 molar equiv of tris(3-(trifluoromethylhydroxymethylene)-*d*-camphorato)europium(III) according to the procedure described in the next experiment.

The mother liquor from the first recrystallization of the yellow solid material was deposited on 2.0 g of Florisil and placed atop a column of 50 g of Florisil. Elution with hexane (300 mL) afforded hydrocarbon impurities. Elution with 10% ethyl acetate in hexane (600 mL) afforded 1.51 g of white solid, mp 178–200 °C, $[\alpha]_D$ −18.5° (*c* 11.5, C_2H_5OH).

This material was recrystallized two times from ethyl acetate–hexane to yield 650 mg of white, needle-like crystals, mp 197–205 °C, $[\alpha]_D$ −21.3° (*c* 10.6, C_2H_5OH), whose IR, NMR, and mass spectra were identical with those of the other diastereoisomer. Subsequent recrystallizations did not improve the melting point or optical rotation.

This solid was shown to contain 30% of diastereoisomer **25** and 70% of diastereoisomer **26** by the addition of 0.21 molar equiv of tris(3-(trifluoromethylhydroxymethylene)-*d*-camphorato)europium(III) according to the procedure described in the next experiment.

Determination of Diastereoisomeric Purity of Adducts 25 and 26. A 61.7-mg sample (0.16 mmol) of adduct, $[\alpha]_D$ −8.5° (*c* 6.0, C_2H_5OH), was dissolved in 0.3 mL of $CDCl_3$ containing 1% Me_4Si and the ^1H NMR spectrum was recorded. Particular attention was given to the singlet assigned to the bridgehead methyl group at δ 1.34. To this sample was added 14.5 mg (0.016 mmol, 0.1 molar equiv) of tris(3-(trifluoromethylhydroxymethylene)-*d*-camphorato)europium(III) and the NMR spectrum was recorded. The singlet originally at δ 1.34 now appeared as two peaks at δ 1.17 and 1.20. In similar fashion, an additional 15.7 mg (30.2 mg total, 0.034 mmol, 0.21 molar equiv) of shift reagent was added to the sample which resulted in the appearance of the above peaks at δ 1.57 and 1.62. Two further additions of the europium complex such that 0.32 and 0.46 molar equiv of shift reagent were present resulted in the appearance of the above peaks at δ 2.00, 2.12, 2.52, and 2.68, respectively. From the appearance of the spectra, it was thought that the addition of 0.21 molar equiv of shift reagent produced the spectrum that was most suitable for expansion and integration for determination of the relative proportion of diastereoisomers present.

A series of samples of different rotations was prepared in the above fashion containing 0.21 molar equiv of shift reagent and their NMR spectra were recorded using an expanded scale. Integration of the bridgehead methyl peaks was carried out using a planimeter and the data in Table VI were obtained.

When the specific rotation was plotted as a function of the percent of diastereoisomer **26** present, a linear correlation within the estimated accuracy of the experiment was obtained (Figure 2).

Hydrolysis–Oxidation of *endo*-Bornyltriazolinedione Adducts 25 and 26. A slurry of 100 mg (0.262 mmol) of an adduct sample enriched in **25** (mp 219–221 °C, $[\alpha]_D$ +34.6° (*c* 9.6, C_2H_5OH)) and 400 mg of sodium hydroxide in 12 mL of isopropyl alcohol was refluxed for 16 h under nitrogen. The reaction mixture was cooled, made acidic (pH 1) by the careful addition of 3 N hydrochloric acid, and then made basic (pH 9) by the careful addition of 3 N ammonium hydroxide. Pentane (10 mL) and 300 mg (3.44 mmol) of manganese dioxide were added, and the reaction mixture was stirred at room temperature for 20 min under nitrogen before being poured onto cold water. The layers were separated and the aqueous layer was extracted with pentane (2 × 10 mL). The combined extracts were washed with water (5 × 30 mL) and saturated salt solution (30 mL) before drying. The solvent was removed in vacuo and the residue was chromatographed at −30 °C on 2.5 g of Florisil (cold methanol was circulated through a jacketed chromatography column). Elution with pentane (fraction size 50 mL) yielded in fraction 2 18.2 mg (47%) of a colorless oil whose ^1H NMR spectrum (CCl_4) indicated it to be pure **13**. The carbon tetrachloride was removed in vacuo, the residue (12.4 mg) was dissolved in 1.0 mL of hexane, and the following rotations were recorded: $[\alpha]_D$ −133.2, $[\alpha]_{578}$ −139.4, $[\alpha]_{546}$ −165.3, and $[\alpha]_{436}$ −369.4°. The hexane was removed in vacuo, the residue (8.8 mg) was dissolved in 1.0 mL of diglyme, and the following rotations were recorded: $[\alpha]_D$ −161.1, $[\alpha]_{578}$ −170.7, $[\alpha]_{546}$ −201.4, and $[\alpha]_{436}$ −455.5°.

The diglyme sample was sealed in a glass ampule and heated at 50 °C in an oil bath for 24 h. The cooled solution showed no optical activity at any of the above wavelengths.

A 100-mg sample of adduct enriched in **26** (mp 190–205 °C, $[\alpha]_D$ −20.4° (*c* 14.5, C_2H_5OH)) was subjected to the identical reaction and workup conditions to yield optically active **13** [$[\alpha]_D$ +22.6, $[\alpha]_{578}$ +24.0, $[\alpha]_{546}$ +28.3, and $[\alpha]_{436}$ +63.0° (*c* 10.5, hexane); $[\alpha]_D$ +24.2, $[\alpha]_{578}$ +25.8, $[\alpha]_{546}$ +30.5, and $[\alpha]_{436}$ +68.8° (*c* 8.2, diglyme)] which racemized completely upon heating at 50 °C in a sealed glass ampule for 24 h.

Determination of the Rate of Racemization of Optically Active 13. A 63.4-mg sample of optically active **13** was dissolved in 3.0 mL of purified diglyme (distilled from Na/K alloy) and a portion of this solution was placed in a thermally equilibrated polarimeter cell heated by a circulating constant-temperature bath. The solution was allowed to equilibrate for a few minutes and then an accurate timer was started and readings were taken at appropriate time intervals. The resulting −ln α data were plotted vs. time and accurate slopes of the straight lines were determined by the method of least squares.

Determination of Rate of Bond Shifting in 1,2-Bis(trideuteriomethyl)-3-methylcyclooctatetraene (22). A small amount (about 10 mg) of **22** was dissolved in purified pentane and transferred to a thin-walled NMR tube. The pentane was removed under high vacuum and diglyme-d_{14} was distilled onto the sample from Na/K alloy under high vacuum. The solution was degassed by three freeze–thaw cycles, sealed under vacuum, and placed in the thermally equilibrated constant-temperature probe of a Bruker HX-90 NMR spectrometer. After allowance was made for thermal equilibration (a few minutes), FT spectra (four scans) were taken at appropriate time intervals. The methyl region was recorded on a fully expanded scale and the peaks were integrated with respect to an internal standard (benzene) with the use of a planimeter. The data were processed as described in the text and refined through use of the method of least squares.

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