arations were combined (7.1 g, 12.4 mmol) and after three recrystallizations from benzene–cyclohexane had mp 135–139°; $[\alpha]^{25}_{578}$ +13.4°, $[\alpha]^{25}_{546}$ +15.3°, and $[\alpha]^{26}_{D}$ (calcd) +12.7° (*c* 2.54, methylene chloride).

Fractional crystallization of this material from carbon tetrachloride–cyclohexane afforded as the less soluble fraction (−)-*trans*-dichloro(*trans*-bicyclo[8.2.2]tetradeca-5,10,12,13-tetraene)(α-methylbenzylamine)platinum(II) (**4a**) as yellow crystals having mp 140.5–141.5°; $[\alpha]^{25}_{578}$ −38.7°, $[\alpha]^{25}_{546}$ −53.6°, and $[\alpha]^{25}_{D}$ (calcd) −35.1° (*c* 1.11, methylene chloride) after seven recrystallizations.[10]

Anal. Calcd for $C_{22}H_{29}Cl_2NPt$: C, 46.07; H, 5.10; Cl, 12.38; N, 2.44; Pt, 34.00. Found: C, 46.56; H, 5.33; Cl, 12.30; N, 2.53; Pt, 34.26.

(+)-*trans*-Dichloro(*trans*-bicyclo[8.2.2]tetradeca-5,10,12,13-tetraene)(α-methylbenzylamine)platinum(II) (4b). The olefin **1** (0.90 g, 4.8 mmol) in pentane solution was added to a stirred methylene chloride solution of 1.99 g (4.8 mmol) of (−)-*trans*-dichloro(ethylene)(α-methylbenzylamine)platinum(II).[4a,24] The mixture was treated as described above for the complex with (*R*)-(+)-α-methylbenzylamine. Three such preparations were combined (7.0 g, 12.1 mmol) and after three recrystallizations from benzene–cyclohexane had $[\alpha]^{25}_{578}$ −13.1°, $[\alpha]^{25}_{546}$ −15.3°, and $[\alpha]^{25}_{D}$ (calcd) −12.3° (*c* 1.53, methylene chloride).

Fractional crystallization of this material from carbon tetrachloride–cyclohexane afforded as the less soluble fraction (+)-*trans*-dichloro(*trans*-bicyclo[8.2.2]tetradeca-5,10,12,13-tetraene)(α-methylbenzylamine)platinum(II) (**4b**) as yellow crystals having mp 141.5–143.0°; $[\alpha]^{25}_{578}$ +41.3°, $[\alpha]^{25}_{546}$ +55.3°, and $[\alpha]^{26}_{D}$ (calcd) +37.7° (*c* 1.04, methylene chloride) after eight recrystallizations.[10]

Anal. Calcd for $C_{22}H_{29}Cl_2NPt$: C, 46.07; H, 5.10; Cl, 12.38; N, 2.44; Pt, 34.00. Found: C, 46.69; H, 5.24; Cl, 12.97; N, 2.42; Pt, 32.69.

Liberation of the Olefin 1 from Partially Resolved Complex 4a. Partially resolved complex **4a** (81 mg, 0.14 mmol) having $[\alpha]^{25}_{578}$ −19.7°, $[\alpha]^{25}_{546}$ −29.6°, $[\alpha]^{25}_{D}$ (calcd) −17.6° (*c* 1.01, methylene chloride), in a few milliliters of methylene chloride at 0° was shaken with a cold (0°) solution of 15% (by wt) aqueous sodium cyanide.[4a] After separation of the methylene chloride layer, the aqueous phase was washed with three 20-ml portions of olefin-free pentane. The combined pentane–methylene chloride extracts were washed with 10 ml of cold 10% hydrochloric acid, with water, with three 20-ml portions of saturated sodium bicarbonate, and finally with three 10-ml portions of water. The solution was dried with anhydrous magnesium sulfate and the solvent was removed at reduced pressure on the rotary evaporator. The resulting olefin (23 mg, 88%) in cyclohexane solution showed no optical activity. The vapor phase chromatographic retention time and infrared and mass spectra established the identity of this material as olefin **1**.

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(24) The (*S*)-(−)-α-methylbenzylamine used in the preparation of this complex had $[\alpha]^{25}_{D}$ −38.87° (neat, d^{25}_{4} 0.9528).

Hindered Rotation in Substituted Paracyclophanes[1]

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Contribution from the Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139. *Received June 30, 1967*

Abstract: The rates and activation parameters describing the interconversion of enantiomers of 15-oxatricyclo-[8.2.2.1^{4,7}]pentadeca-4,6,10,12,13-pentaene-11,13-d_2 (**3**) (E_a = 11.1 ± 0.3 kcal/mol, $A = 10^{12.5\pm0.3}$ sec^{-1}), bicyclo-[8.2.2]tetradeca-10,12,13-triene-4,7-dione-3,3,5,5,6,6,8,8,11,13-d_{10} (**4**) (E_a = 9.3 ± 0.7 kcal/mol, $A = 10^{11.7\pm0.7}$ sec^{-1}), *trans*-bicyclo[8.2.2]tetradeca-5,10,12,13-tetraene-4,7-dione-3,3,8,8,11,13-d_6 (**5**) (E_a = 11.2 ± 0.5 kcal/mol, $A = 10^{12.1\pm0.5}$ sec^{-1}), and *trans*-bicyclo[8.2.2]tetradeca-5,10,12,13-tetraene-3,3,5,6,8,8,11,13-d_8 (**7**) (E_a = 13.4 ± 0.7 kcal/mol, $A = 10^{12.7\pm0.5}$ sec^{-1}) have been measured using nmr spectroscopy. These data provide an instructive example of the influence of structural variation on the rates of medium-ring conformational isomerization and a practical check on the precision of kinetic analysis of spin-coupled nmr spectra.

The conformational analysis of medium-ring cycloalkanes has contributed extensive and useful information to the study of the influence of nonbonded interactions and bond-angle deformations on the properties of organic molecules.[3] Of the available spectroscopic techniques, nuclear magnetic resonance has proved to be the best suited for the direct examination of the conformations of this class of compounds in solution. The nmr spectra of these materials are usually very complicated, and in many instances it has been more convenient to investigate the simpler spectra of appropriately substituted medium-ring compounds than the more complex spectra of their unsubstituted parents. In consequence, a number of recent investigations have relied in part on nmr measurements of the rates of interconversion between conformers of substituted cyclic hydrocarbons to provide detailed information concerning not only the structures of these materials themselves, but also by inference information concerning the structures of their unsubstituted analogs.[4,5] The interpretation of these studies has been complicated by difficulties in isolating the effects of the substituents on the rates, and by uncertainty concerning the extent to which the substituents are capable of influencing the geometry of the con-

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(1) This research was supported by the National Science Foundation (GP 2018) and the Army Research Office (Durham) (DA-ARO(D)-31-124-G-404 and DA-ARO(D)-31-124-435). Calculations were carried out in part at the Massachusetts Institute of Technology Computation Center, Cambridge, Mass.

(2) (a) National Institutes of Health Predoctoral Fellow, 1963–1966; (b) deceased June 4, 1966.

(3) For recent examples and references see (a) J. B. Hendrickson, *J. Amer. Chem. Soc.*, **86**, 4854 (1964); (b) K. B. Wiberg, *ibid.*, **87**, 1070 (1965); (c) M. Saunders, *Tetrahedron*, **23**, 2105 (1967); (d) M. Bixon, H. Dekker, J. D. Dunitz, H. Eser, S. Lifson, C. Mosselman, J. Sicher, and M. Svoboda, *Chem. Commun.*, 360 (1967), and references therein; (e) A. C. Cope, M. M. Martin, and M. A. McKervey, *Quart. Rev.* (London), **20**, 119 (1966); (f) J. Sicher, *Progr. Stereochem.*, **3**, 202 (1962); (g) M. Hanack, "Conformation Theory," Academic Press Inc., New York, N. Y., 1965, p 164 ff; (h) J. Dale, *Angew. Chem. Intern. Ed. Engl.*, **5**, 1000 (1966).

(4) For examples, see (a) J. E. Anderson, *Quart. Rev.* (London), **20**, 426 (1965); F. A. L. Anet and M. St. Jacques, *J. Amer. Chem. Soc.*, **88**, 2586 (1966); (c) S. L. Spassov, D. L. Griffith, E. S. Glazer, K. Nagarajan, and J. D. Roberts, *ibid.*, **89**, 88 (1967); (d) J. D. Roberts, *Chem. Brit.*, **2**, 529 (1966).

(5) G. Binsch and J. D. Roberts, *J. Amer. Chem. Soc.*, **87**, 5157 (1965).

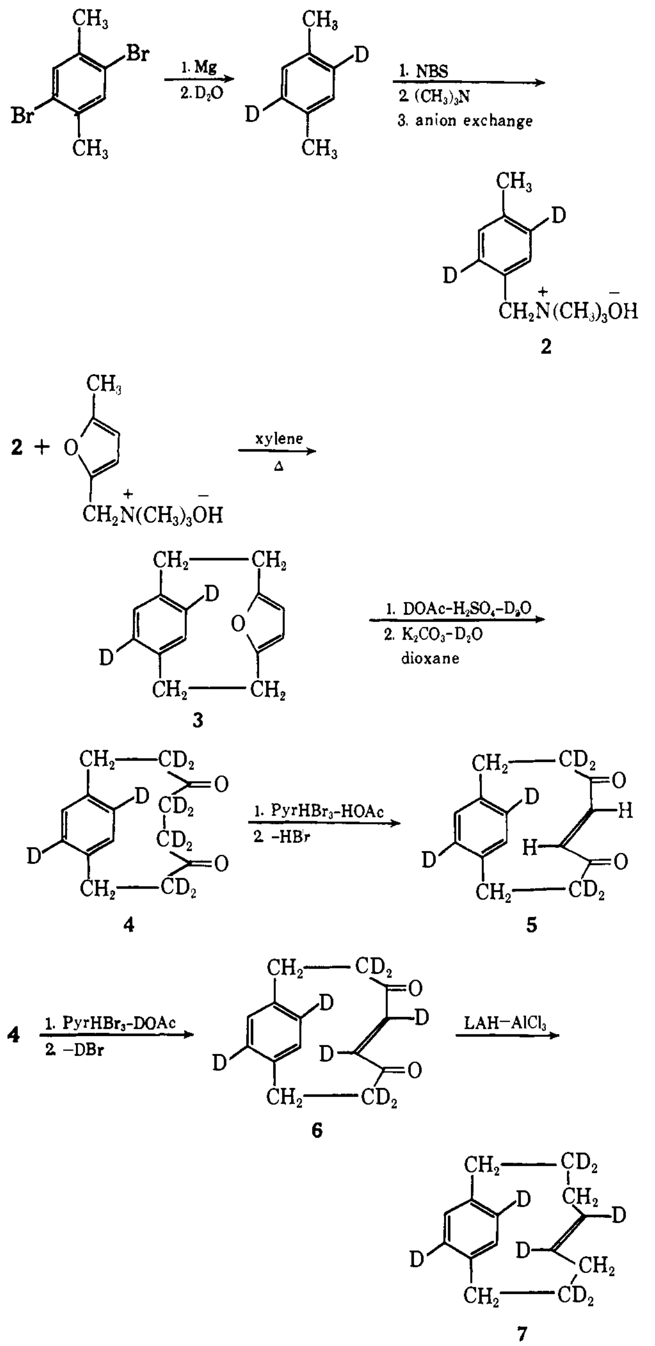
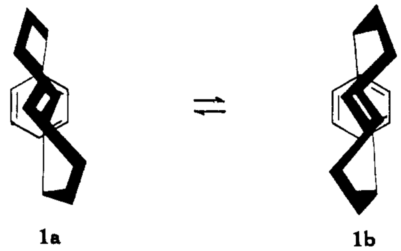


Figure 1. Synthesis of deuterated paracyclophanes.

formers. In this paper we report an examination of the rates of interconversion of the enantiomers of four inherently dissymmetric paracyclophanes. Our intent in this work was to investigate qualitatively the effect of simple changes in structure on the rates of conformational interconversion in a related group of medium-ring hydrocarbons of relatively well-defined geometry, in the hope that these studies would prove useful in estimating the magnitudes of similar substituent effects on the rates of analogous interconversions in more complicated compounds.

Results

A previous examination of *trans*-bicyclo[8.2.2]tetradeca-5,10,12,13-tetraene (4-[8]paracyclophene) (**1**) had demonstrated that although the platinum complex of **1**, formed by displacement of ethylene from *trans*-dichloro(ethylene)((*R*)-(+)-α-methylbenzylamine)platinum(II), could be resolved, no optical activity could be detected in the olefin liberated from the resolved complex with cyanide ion at room temperature.[6] This observation suggested that racemization of the optically active hydrocarbon, due to rotation of the olefinic bond through the loop of the ring (**1a** ⇌ **1b**), was occurring with a half-life time of less than approximately 1 min at this temperature. Examination of the temperature dependence of the nmr spectrum of **1** confirmed this conclusion qualitatively and further indicated that the rate of rotation was such as to be amenable to quantitative examination using nmr techniques. In order to simplify the spectrum sufficiently to make analysis of the spectral line shapes practical, an appropriately deuterated derivative **7** was prepared, using the method outlined in Figure 1.[7]



1a **1b**

α-Bromo-*p*-xylene-2,5-d_2, prepared by bromination of *p*-xylene-2,5-d_2 with N-bromosuccinimide, was converted to the corresponding quaternary ammonium bromide by treatment with trimethylamine. Ion-exchange chromatography of the ammonium bromide afforded the quaternary ammonium hydroxide **2** which was converted to the benzene–furan dimer **3** by cross-dimerization with N,N,N-trimethyl-5-methylfurfurylammonium hydroxide, using the procedure described previously by Cram and coworkers.[8] Hydrolysis[8] of the furan ring of **3** in deuterium oxide containing acetic acid-1-*d* and sulfuric acid afforded bicyclo-[8.2.2]tetradeca-10,12,13-triene-4,7-dione-d_6. The deuteration of the methylene groups adjacent to the carbonyl groups in this compound was completed by three successive treatments with potassium carbonate in 1:1 dioxane–deuterium oxide, to give bicyclo[8.2.2]tetradeca-10,12,13-triene-4,7-dione-d_{10} (**4**). Bromination of **4** with pyridinium hydrobromide perbromide in glacial acetic acid-1-*d*, followed by dehydrobromination with collidine, afforded *trans*-bicyclo[8.2.2]tetradeca-5,10,-12,13-tetraene-4,7-dione-d_8 (**6**). Reduction of **6** with lithium aluminum hydride–aluminum chloride[9] afforded *trans*-bicyclo[8.2.2]tetradeca-5,10,12,13-tetraene-3,3,5,6,8,8,11,13-d_8 (**7**).

The deuterium-decoupled low-temperature nmr spectrum of **7** (Figure 2) is composed of a doublet[10] centered at 6.75 ppm for the aromatic protons, an AB spectrum

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[6] A. C. Cope and B. A. Pawson, *J. Am. Chem. Soc.*, **90**, 636 (1968).

[7] This pattern of deuteration is modeled on that used by Binsch and Roberts in their similar study of the rates of interconversion of the diastereoisomers of *trans*-cyclodecene-d_6.[5]

[8] (a) D. J. Cram and G. R. Knox, *J. Amer. Chem. Soc.*, **83**, 2204 (1961); (b) D. J. Cram, C. S. Montgomery, and G. R. Knox, *ibid.*, **88**, 515 (1966).

[9] Reduction of the undeuterated analog of enedione **5** with lithium aluminum deuteride–aluminum chloride was found to yield olefin **1** containing 90% d_4 at the allylic positions.[6]

[10] This doublet is complicated by a superimposed AB spectrum resulting from incomplete isotopic substitution in the aryl group.

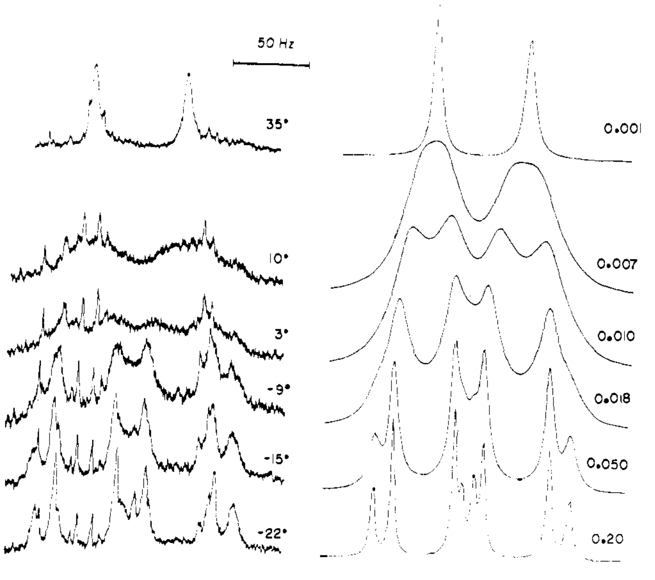

Figure 2. Deuterium-decoupled spectra of the aliphatic region of *trans*-bicyclo[8.2.2]tetradeca-5,10,12,13-tetraene-3,3,5,6,8,8,11,13-d_8 (**7**) as a function of temperature (left). Calculated spectra, with corresponding values of τ in seconds (right). The sharp temperature-independent peaks in the observed spectra are due to impurities.

centered at 2.49 ppm due to the benzylic methylene protons, and an AA'BB' spectrum centered at 1.45 ppm for the allylic methylene protons.[11] On warming the sample, each of these patterns collapsed to a single sharp line. Determination of the rate of interchange of protons leading to this collapse was carried out separately for the aliphatic and aromatic regions at each temperature by visual comparison of the observed spectra with calculated spectra generated for a range of values of the preexchange lifetime τ using the density matrix procedure.[12] Typical observed and calculated spectra are compared in Figures 2 and 3. The chemical shift differences and coupling constants used in these calculations are given in Table I.

Table I. Coupling Constants and Chemical Shifts Used in Variable-Temperature Analysis

Compd	Proton type	J_{AB}, Hz	$\Delta\nu$, Hz	Band center,[a] ppm
3	Aromatic	<1	57.7	6.90
4	Aromatic	7.5	25.2	7.00
4	Benzylic	13.0	23.3	2.90
5	Aromatic	7.5	30.8	6.97
5	Benzylic	12.7	29.3	2.85
7	Aromatic	7.4	13.7	6.75
7	Benzylic	13.0	52.4	2.49
7	Allylic	14.0	56.3	1.45

[a] This number is the chemical shift of the sharp collapsed line obtained in the fast exchange limit, taken at 33° with TMS as internal standard.

No effort was made to treat the AA'BB' part of this spectrum exactly[13] in these calculations. Instead, the line shape in the slow exchange limit was approximated by assigning an "effective" relaxation time T_2 to the allylic protons which was shorter than the one actually determined from the widths of the individual components of the spectrum. Consequently, the line shapes calculated for larger values of the preexchange lifetime τ are in error for this group of lines; however since $J_{AA'}$ and $J_{BB'}$ are much less than J_{AB}, and since the line broadening resulting from this artifice is much less than the total observed line widths in the intermediate exchange region, the calculated rates of exchange will not be significantly in error over most of the exchange-broadened region.

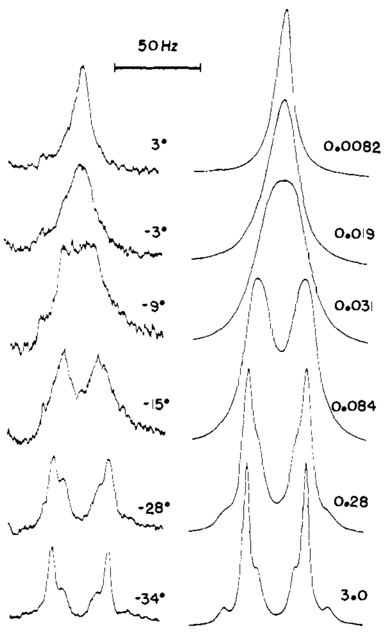

Figure 3. Deuterium-decoupled observed spectra (left) and calculated spectra (right) for the aromatic protons of **7**.

Similar studies were carried out for the temperature dependence of the deuterium-decoupled spectra of the aryl protons of the related paracyclophanes **3**, **4**, and **5**, and of the benzylic protons of **4** and **5**. The fit of observed to calculated spectra in these compounds was comparable to that obtained for **7**; these spectra are not reproduced here. Table I gives the coupling constants and chemical shifts observed at the slow exchange limit for each of these compounds.

Arrhenius activation parameters describing the conformational interconversions for each of these compounds are listed in Table II. The corresponding

Table II. Arrhenius Parameters for Interconversion of Paracyclophane Enantiomers

Compd	E_a,[a] kcal/mol	A,[a] sec^{-1}	C[b]	Rel rate at 0°
3	11.1 ± 0.3	$10^{12.6\pm0.3}$	0.995	50
4	9.3 ± 0.7	$10^{11.7\pm0.7}$	0.973	200
5	11.2 ± 0.5	$10^{12.1\pm0.5}$	0.980	10
7	13.4 ± 0.7	$10^{12.7\pm0.5}$	0.978	1

[a] Errors are rms errors: see H. Margenau and G. M. Murphy, "The Mathematics of Physics and Chemistry," D. Van Nostrand Co., Inc., Princeton, N. J., 1956, Chapter 13. [b] Correlation coefficients for the Arrhenius plots in Figure 4.

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[11] The assignment of benzylic and allylic protons is based on the premise that the five-bond coupling across the olefinic bond will be greater than any coupling of the methylene groups across the benzene ring: S. Sternhell, *Rev. Pure Appl. Chem.*, **14**, 15 (1964).

[12] (a) S. Alexander, *J. Chem. Phys.*, 37, 967, 974 (1962); **38**, 1787 (1963); **40**, 2741 (1964); (b) C. S. Johnson, Jr., *Advan. Magnetic Resonance*, **1**, 33 (1965).

[13] G. M. Whitesides, M. Witanowski, and J. D. Roberts, *J. Amer. Chem. Soc.*, **87**, 2854 (1965).

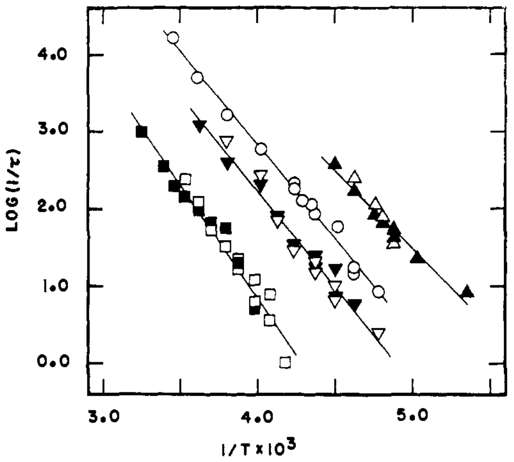


Figure 4. Arrhenius plots for compounds **3** (○), **4** (△), **5** (▽), and **7** (□). Filled points refer to measurements for aliphatic protons; unfilled points to measurements for aromatic protons.

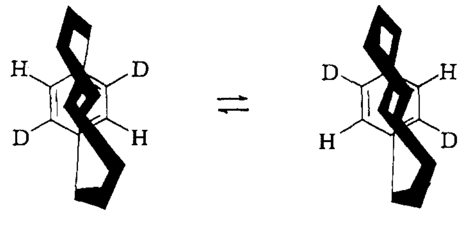
Arrhenius plots are shown in Figure 4. In compounds **4**, **5**, and **7** the points corresponding to rates calculated from the aliphatic signals fell on the same straight lines as those derived from the aromatic region. The activation parameters reported in Table II are based on a least-squares analysis of the Arrhenius equation for *all* of the available points for each compound.

Discussion

In order to interpret the data in Table II, it is first necessary to define for each compound the nature of the conformational changes which are influencing the spectra. Examination of molecular models indicates that the only reasonable conformations for the cyclophanes examined in this work are those analogous to **1**; that is, conformations in which the four bridging atoms C_3–C_8 roughly define a plane parallel to the plane of the benzene ring. The length of the bridging chain in these compounds is sufficiently short that more complicated conformations, involving folding of the chain, need not be considered. In conformations similar to **1** the two protons of each benzylic or allylic methylene group are expected (and observed) to be magnetically nonequivalent by virtue of their distinct geometries relative to the unsaturated groups in the molecules. Only conversion of one enantiomer into the other by rotation of the bridging carbon chain through the loop of the ring (**1a** $\rightleftharpoons$ **1b**) can completely average the environments of these methylenic protons.[5] Hence, examination of the shapes of the methylene resonances in the temperature region in which these lines undergo exchange broadening permits a determination of the rate of interconversion of enantiomers.

The two aromatic protons are also magnetically nonequivalent in each enantiomer. However, averaging of the nonequivalence of these protons can in principle occur by either of two processes: interconversion of enantiomers or rotation of the phenyl group itself through the loop of the bridging chain (**8a** $\rightleftharpoons$ **8b**).

A comparison of the rates of interchange of the phenyl and methylene protons should permit a determination of the rate of rotation of the phenyl group through the loop of the ring relative to the rate of the corresponding rotation of the bridging alkyl chain.



8a **8b**

The observation that the rates obtained from independent line-shape measurements of the aliphatic and aromatic regions of the spectra of compounds **4**, **5**, and **7** fall on the same straight line (Figure 4) indicates immediately that the rate of rotation of the phenyl group is slow compared to the corresponding rotation for the aliphatic part of these compounds. If the rates of the two processes had been comparable, then the phenyl protons would have appeared to be exchanging more rapidly than their aliphatic counterparts, because both types of conformational interconversion can contribute to the line shapes for the phenyl hydrogens, but only interconversion of enantiomers can contribute to the broadening of the aliphatic resonances.

The conclusion that the phenyl group of compounds **4**, **5**, and **7** effectively does not rotate can plausibly be extended to the benzene–furan dimer **3**, for which no independent measurement of the rate of interchange of the methylene protons was carried out. Thus, the relative rates given in Table II are taken to be the relative rates for the interconversion of enantiomers for each of the compounds examined.

The relative rates reported in Table II are difficult to rationalize in terms of the detailed structures of the compounds involved and suggest that no single structural parameter is of predominant importance in determining the ease with which these interconversions take place. The most obvious structural requirement in the high-energy intermediate conformations involved in the interconversion of enantiomers is that of minimizing the nonbonded repulsions between the aromatic ring and the atoms directly opposed to it. These interactions are sufficiently unfavorable to distort the aromatic moiety from planarity in structurally related compounds,[8b,14] and will undoubtedly be more unfavorable when the bridging group is rotated so that its hydrogen atoms are directed toward the ring. The strain introduced in rotating the alkyl chain could plausibly be partially relieved by spreading the C–C–C bond angles at C_3, C_4, C_7, and C_8. The tenfold rate increase observed on replacing the allylic methylene groups of **7** with ketone groups (**5**), with the attendant increase in the C_4 and C_7 bond angles, is in qualitative agreement with the idea that angle strain at these atoms may have an important influence on the rates of the interconversions. However, it is clear that other structural features are at least as important in determining the rates as angle strain. For example, saturation of the double bond of **5** increases the rate by a factor of 20. Apparently, the increased bulk of the central methylene groups in **4** is compensated by an increase in the flexibility of the chain. Even shortening the length of the bridging chain (**7** → **3**) does not *per se* increase the barrier to rotation.[15] In short, although

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(14) B. H. Smith, "Bridged Aromatic Compounds," Academic Press Inc., New York, N. Y., 1964, p 393 ff.

it is possible to rationalize the relative rates of Table II after the fact, it would have been difficult to predict them beforehand. Relatively small changes in structure clearly produce significant changes in the rates of conformational interconversion.

The colinearity of the rate plots from the analysis of the aromatic and aliphatic regions serves another useful purpose. It permits an empirical comparison of the accuracy of kinetic analysis of a spin-coupled AB-type spectrum with that of an uncoupled AB spectrum.[16] With the ready availability of computers and associated curve plotters kinetic analysis of spin-coupled AB spectra has become commonplace. However, the observed line-shape changes in the intermediate exchange region in this type of spectrum are more complicated than those in an uncoupled system, and it is not clear whether line-shape analysis in these two types of spin systems can in practice be carried out with comparable accuracy. In the present example, the fact that the spectra of the aromatic regions (approximately uncoupled spectra) and the aliphatic regions (coupled spectra) of compounds **4**, **5**, and **7** are simultaneously influenced by the same conformational processes provides an opportunity to compare the results of independent kinetic analysis of the two types of spectra. This comparison is unfortunately less clear-cut than it might ideally be, because the isotopic impurities in the aromatic regions of these compounds complicate their line shapes appreciably. Nonetheless, the two types of analyses do lead to very similar results as evinced by the agreement obtained from the two spectral regions at the common temperatures examined (Figure 4).[17] Moreover, the close similarity between the values of A obtained for these compounds and the high correlation coefficients for the corresponding Arrhenius plots indicate that these data are at least internally consistent and suggest that kinetic analyses of line shapes in coupled spectra are of comparable accuracy to those of uncoupled spectra.

Experimental Section[18]

Nmr spectra were taken of approximately 10% solutions in carbon disulfide. Theoretical spectra were calculated using a modification of Alexander's equations.[12] For an AB spin system with eigenfunctions

$$\psi_1 = \alpha\alpha$$

$$\psi_2 = p\beta\alpha - r\alpha\beta$$

$$\psi_3 = p\alpha\beta + r\beta\alpha$$

$$\psi_4 = \beta\beta$$

The line-shape function $I(\omega)$ can be shown as in eq 1 where as usual[12]

$$I(\omega) \propto Re((p-r)^2, (p+r)^2, (p+r)^2, (p-r)^2) \times \begin{pmatrix} -\alpha_1 - (p+r)^2/\tau & (p^2-r^2)/\tau & 0 & 0 \\ (p^2-r^2)/\tau & -\alpha_3 - (p-r)^2/\tau & 0 & 0 \\ 0 & 0 & -\alpha_2 - (p-r)^2/\tau & (p^2-r^2)/\tau \\ 0 & 0 & (p^2-r^2)/\tau & -\alpha_4 - (p+r)^2/\tau \end{pmatrix}^{-1} \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} \quad (1)$$

$\alpha_k = i(\omega_k - \omega) + 1/T_{2k}$ and the subscript k refers to the observed lines in the AB spectrum. Here, τ is the preexchange lifetime in sec, ω_k is the frequency of the kth observed line in radians/sec, and T_{2k} is the relaxation time characterizing that line. The lines are numbered consecutively in order of increasing frequency.[19]

Calculation of the aromatic region of compounds **4**, **5**, and **7** are carried out by superimposing an AB spectrum with $J = 0$ and relative area 2.8 on an AB spectrum with the same chemical shifts, having $J \neq 0$ and relative area 1.0. This ratio of areas, derived from the mass spectral analysis of *p*-xylene-2,5-d_2, satisfactorily accounts for the mixture of isotopic species present. No corrections were made for isotopic impurities in the aliphatic region.

***p*-Xylene-2,5-d_2.** 2,5-Dibromo-*p*-xylene was converted in 64% yield into *p*-xylene-2,5-d_2 by the Grignard reagent procedure in two successive steps.[21] The nmr spectrum showed a ratio of benzylic to aromatic protons of 2.48:1, or 83% incorporation of deuterium (based on two deuterium atoms per molecule of xylene). Calculation of the deuterium content from the mass spectrum gave 4.0% d_0, 29.3% d_1, and 66.6% d_2.[22]

α-Bromo-*p*-xylene-2,5-d_2. α-Bromo-*p*-xylene-2,5-d_2 was prepared in 69% yield by treatment of *p*-xylene-2,5-d_2 with N-bromosuccinimide[23] in refluxing carbon tetrachloride.

N,N,N-Trimethyl-*p*-methylbenzylammonium-2,5-d_2 bromide was obtained in 93% crude yield by treatment of an ether solution of α-bromo-*p*-xylene-2,5-d_2 with trimethylamine. The product was used in the cross-dimerization without further purification.

15-Oxatricyclo[8.2.2.$1^{4,7}$]pentadeca-4,6,10,12,13-pentaene-11,13-d_2 (3). The preparation and cross-dimerization of N,N,N-trimethyl-*p*-methylbenzylammonium-2,5-d_2 hydroxide and N,N,N-trimethyl-5-methylfurfurylammonium hydroxide were carried out as previously described.[6,8] The product (12.7 g, 20%) had mp 66.5–67.0° (lit.[8b] mp 68–68.5°). The deuterium content, calculated from the mass spectrum, was 3.6% d_0, 30.2% d_1, and 66.2% d_2.[22]

Bicyclo[8.2.2]tetradeca-10,12,13-triene-4,7-dione-d_{10} (4). The benzene–furan dimer **3** (10 g) was treated as described previously[8b] with acetic acid-1-*d*, sulfuric acid, and deuterium oxide. Recrystallization of the crude product from 95% ethanol afforded 7.2 g (68%) of colorless crystals, mp 160–161° (lit.[8b] mp 154–154.5°);

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(15) In **3**, the oxygen atom rather than the CH=CH group is almost certainly the part of the furan moiety which actually passes through the loop of the ring. Hence, elimination of the nonbonded repulsions between the hydrogen atoms of the alkyl chain and the benzene ring is probably important in explaining the relatively low barrier. Note also that in this compound, the two conformations involved in the equilibration are enantiomeric only by virtue of the deuterium substitution on the aromatic ring.

(16) For a discussion of the accuracy of this simpler type of kinetic analysis, see A. Allerhand, H. S. Gutowsky, J. Jonas, and R. A. Meinzer, *J. Amer. Chem. Soc.*, **88**, 3185 (1966); F. A. L. Anet and A. J. R. Bourn, *ibid.*, **89**, 760 (1967).

(17) Independent least-squares analysis of the data from the aliphatic and aromatic regions of **5** and **7** gave values for E_a differing by approximately 0.5 kcal/mol from those given in Table II. The correlation coefficients for the Arrhenius plots were approximately the same as those in the table.

(18) Melting points were taken on a Kofler hot stage; boiling points are uncorrected. Infrared spectra were recorded on a Perkin-Elmer Model 237B grating spectrophotometer. Mass spectra were measured on a Hitachi Perkin-Elmer Model RMU-6D mass spectrometer. Vapor phase chromatographic analyses were performed on an F & M Model 720 gas chromatograph with helium as carrier gas using a flow rate of 1 cc/sec. Nmr spectra were taken at 60 MHz on a Varian A-60 spectrometer, equipped with a V-6040 variable-temperature probe and controller. Sweep widths were calibrated using a Krohn-Hite Model 450 pushbutton oscillator. Deuterium-decoupling experiments were carried out using an NMR Specialties Model HD-60A decoupler. Calibration of the temperature controller was accomplished by measuring peak separations in a methanol or ethylene glycol sample.

(19) This method is not the most efficient in terms of computer time for calculating AB special line shapes; however in this instance it fit conveniently into the format of a program normally used for a somewhat different type of calculation.[20]

(20) R. Kubo, *Nuovo Cimento Suppl.*, **6**, 1063 (1957); R. A. Sack, *Mol. Phys.* **1**, 163 (1958). For examples see G. M. Whitesides and J. S. Fleming, *J. Amer. Chem. Soc.*, **89**, 2855 (1967), and references therein.

(21) L. H. P. Weldon and C. L. Wilson, *J. Chem. Soc.*, 235 (1946).

(22) K. Biemann, "Mass Spectrometry—Organic Chemical Applications," McGraw-Hill Book Co., Inc., New York, N. Y., 1962, p 223 ff. Mass spectra reported here were taken at 9-eV ionizing voltage. At this potential the M − 1 peak was negligible.

(23) W. Qvist, *Acta Acad. Aboensis Math. Phys.*, **18**, 7 (1952).

$\nu_{\max}^{\mathrm{CHCl_3}}$ 2430, 2730, 2130, 1695, and 1325 cm^{-1}. The vapor phase chromatographic retention time (2 ft × 0.25 in. 20% silicone rubber column, 195°) was equal to that of an undeuterated sample. The deuterium content, calculated from the mass spectrum, was 0.3% d_0, 0.5% d_1, 2.4% d_2, 8.3% d_3, 19.4% d_4, 28.8% d_5, 25.3% d_6, 11.6% d_7, 3.0% d_8, and 0.5% d_9.[22]

To this diketone (6.07 g) in 100 ml of deuterium oxide and 100 ml of dioxane was added sufficient potassium carbonate to give a solution having pH 10. The mixture was heated to reflux for 18 hr. After the mixture had cooled, extraction with methylene chloride and removal of solvent from the dried extract yielded 6.0 g of product. After three successive exchanges, the colorless crystals (6.0 g) showed only two absorptions in the nmr spectrum for benzylic and aromatic protons in a ratio of 1.76:1 (in agreement with 82% d_2 incorporation in the benzene ring). The deuterium content, calculated from the mass spectrum, was 0.4% d_3, 0.9% d_4, 2.4% d_5, 6.9% d_6, 16.7% d_7, 29.1% d_8, 29.5% d_9, 13.9% d_{10}, and 0.3% d_{11}.[22] The infrared spectrum showed $\nu_{\max}^{\mathrm{CHCl_3}}$ 2380, 2210, 2130, and 1695 cm,$^{-1}$.

***trans*-Bicyclo[8.2.2]tetradeca-5,10,12,13-tetraene-3,3,5,6,8,8,11,13-d_8 (7).** The diketone **4** (744 mg, 3.28 mmol) was dissolved in 30.5 g of glacial acetic acid-1-*d* and warmed to 50°. Pyridinium hydrobromide perbromide[24,25] (1.05 g, 3.3 mmol) was added with stirring. The reaction mixture was maintained at 60° for 10 min. The cooled mixture was extracted with chloroform and the chloroform extracts were washed with two portions of deuterium oxide and four portions of saturated sodium bicarbonate, and finally with saturated sodium chloride. Evaporation of the solvent from the dried extract gave 601 mg of residue. Freshly distilled γ-collidine (2.2 ml) was added to the bromination product, and the resulting mixture was heated to 160° for 45 min. The cooled reaction mixture was diluted with chloroform and washed with cold 3% sulfuric acid until the washings were strongly acidic, then with water, saturated sodium bicarbonate, and water again. The dried chloroform extract was evaporated to dryness, and the residue was purified by sublimation at 120° (0.4 mm). The product (220 mg) was shown by its vapor phase chromatogram and infrared spectrum to be a mixture of the desired enedione 6 and the starting diketone **4**.

This mixture was treated with lithium aluminum hydride–aluminum chloride as described previously.[5] Following the work-up, 66 mg of olefin **1** was obtained, which had $\nu_{\max}^{\mathrm{CS_2}}$ 3010, 2915, 2870, 2850, 2820, 900, and 700 cm^{-1}. The deuterium content, calculated from the mass spectrum, was 0.4% d_4, 1.4% d_5, 6.2% d_6, 31.0% d_7, 60.2% d_8, and 0.8% d_9.[22]

***trans*-Bicyclo[8.2.2]tetradeca-5,10,12,13-tetraene-4,7-dione-3,3,8,8,11,13-d_6 (5).** Treatment of the diketone **4** (5.0 g) with pyridinium hydrobromide perbromide in glacial acetic acid as described above afforded, after dehydrobromination with collidine, product having $\nu_{\max}^{\mathrm{CHCl_3}}$ 2220, 2150, 1695, 1675, and 970 cm^{-1}, which was purified by sublimation at 120° (0.4 mm). The deuterium content, calculated from the mass spectrum, was 0.2% d_1, 0.8% d_2, 4.0% d_3, 14.1% d_4, 30.9% d_5, 33.1% d_6, 9.7% d_7, 5.1% d_8, 1.7% d_9, and 0.4% d_{10}.[22] The use of undeuterated acetic acid in this bromination apparently resulted in essentially complete exchange of the deuterium atoms at C_5 and C_6 for hydrogen atoms.

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(24) L. F. Fieser, "Experiments in Organic Chemistry," 3rd ed, D. C. Heath and Co., Boston, Mass., 1957, p 65.

(25) C. Djerassi and C. R. Scholz, *J. Amer. Chem. Soc.*, 70, 417 (1948).

Acidity of Hydrocarbons. XXVII. Proton Exchange Rates of Fluorobenzene with Lithium Cyclohexylamide[1,2]

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Abstract: Deuterium and tritium exchange in aryl positions of fluorobenzene and benzotrifluoride were studied with lithium cyclohexylamide in cyclohexylamine at 25°. Rates for D and *T* exchange relative to benzene are: fluorobenzene −2, 6.3×10^5, *3.4×10^5*; −3, 107, *86*; −4, 11.2, *9.1*; benzotrifluoride −3, 580, *390*. These rates are in only qualitative agreement with previous work and are interpreted with a field effect model for inductive effects. 2,5-Difluorotoluene-α-*d* is found to exchange 350 times faster than toluene-α-*d*.

A fluorine substituent has a powerful effect on the kinetic acidity of an aryl hydrogen. Pentafluorobenzene undergoes rapid hydrogen isotope exchange even with sodium methoxide in methanol at room temperature.[4] Hall, Piccolini, and Roberts[5] found the *o*-hydrogen of fluorobenzene to be about 10^6 more reactive than a benzene hydrogen toward potassium amide in liquid ammonia.[5] However, in this latter deuterium exchange work, experimental difficulties allowed the determination of only approximate rate constants for these reactions. Even for the slower *meta* and *para* positions, the kinetics of the reactions were not determined and rate constants were calculated from the amount of exchange at two times only. In order to obtain more precise values for these kinetic acidities, we undertook the present more detailed study of the fluorobenzene positions using the lithium cyclohexylamide–cyclohexylamine (LiCHA–CHA) system. Relative rates in this system have been shown previously to correspond closely to potassium amide–liquid ammonia results.[6] The *meta* position of benzotrifluoride and the α position of 2,5-difluorotoluene were included in the present study for additional comparisons.

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(3) On leave from the Institute of Chemical Process Fundamentals, Prague, Suchdol 2, Czechoslovakia.

(4) A. Streitwieser, Jr., J. Hudson, and F. Mares, *ibid.*, 90, 648 (1968).

(5) G. E. Hall, R. Piccolini, and J. D. Roberts, *ibid.*, 77, 4540 (1955).

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