The Stereochemistry of Doubly Bridged Biphenyls: Synthesis, Spectral Properties, and Optical Stability[1,2]
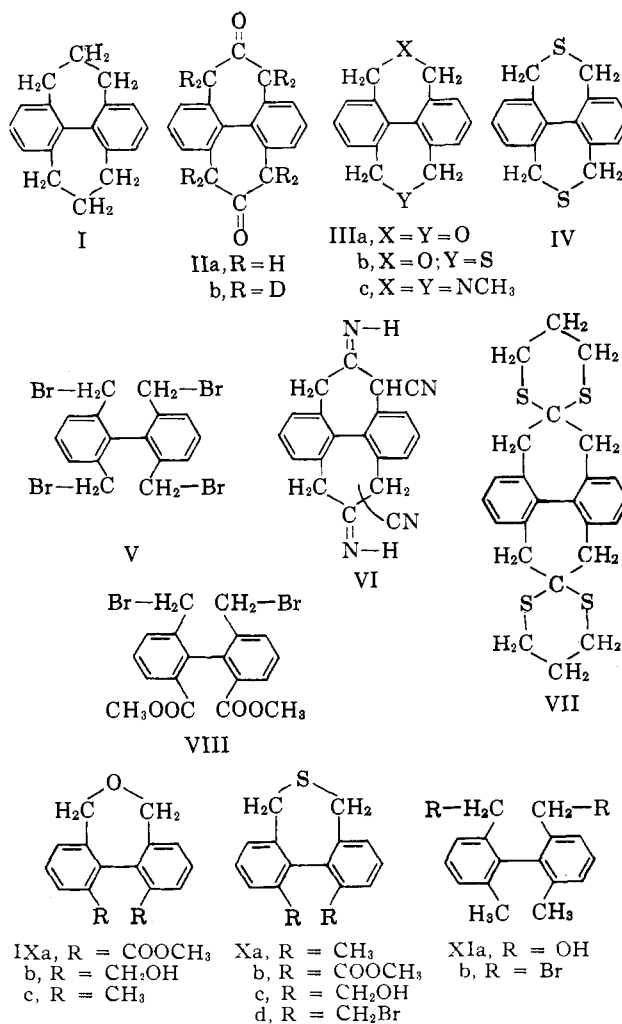
By Kurt Mislow, M. A. W. Glass,[3] Harvey B. Hopps, Edward Simon, and George H. Wahl, Jr.

The doubly bridged biphenyls I–IV have been synthesized. Compounds IIa, IIb, IIIa, IIIb, and IV have been obtained in optically active form; II, IIIa, and IV are the first examples of optically active molecules belonging to point group D_2. Dithiepin IV is formed from thiepin dibromide Xd in a most unusual disproportionation reaction for which a mechanism has been proposed. Since racemic Xd is obtained from solution as a solid while optically pure Xd is obtained as an oil, and since the disproportionation reaction proceeds at a measurable rate only in the undiluted liquid state, the products of the optically active and of the racemic precursors differ chemically. Extensive comparative n.m.r. and ultraviolet studies have led to the conclusion that, for a given type of bridge, the singly bridged o,o'-dimethylbiphenyls have the largest and the doubly bridged biphenyls the smallest biphenyl angle of twist. The n.m.r. study has also shown: (1) the C–CH₃ proton chemical shift in the o,o'-dimethylbiphenyls is a sensitive function of biphenyl dihedral angle; (2) the diastereomeric protons in conformationally rigid bridged biphenyls sometimes give the appearance of magnetic equivalence and the signals are highly solvent dependent. The ultraviolet study has also shown: (1) the long wave length, intensity, and shape of the conjugation band of 4,5,9,10-tetrahydropyrene in combination are taken to mean that the two phenyl rings in that compound are probably more closely coplanar than those of any other unwarped biphenyl heretofore reported; (2) the mixing of the n → π* and π → π* transitions in homoconjugated β,γ-unsaturated ketones such as II is for the first time also revealed in a red shift of both of the instrumentally accessible π → π* transitions; (3) the position of the conjugation band in azepines such as IIIc is strongly suggestive of spectroscopic interaction between the benzene π-electrons and the lone pair of electrons on the nonconjugated nitrogen. The O.R.D. of a synthetic intermediate, the diester IXa, has disclosed a novel dissymmetric chromophore possibly involving twisted methyl benzoate. A simplified quantitative conformational analysis of the racemization process in doubly bridged biphenyls has led to calculated activation energies which are in excellent agreement with the experimental values, though a critical examination of the assumptions and approximations involved in the computations has indicated that this agreement may be to a large extent fortuitous. It has been found that the rate of racemization of the diketone IIa is 6% faster than that of the octadeuterio analog IIb, and the first example of a conformational kinetic isotope effect has thereby been provided.

Optically active biphenyls have been a prime target of investigation in these laboratories for some years.[4] The problem of conformational heterogeneity has been avoided in this work by the device of employing, as key substances, compounds with short chains bridging the 2,2'-positions; this particular structural combination decreases torsional mobility and ensures a high degree of molecular rigidity and conformational homogeneity.

We recently became interested in the possibility of studying *optically active biphenyls in which both the 2,2'- and the 6,6'-positions are symmetrically bridged*, i.e., in which the classical blocking substituents are replaced by two chains linking the four o-positions. It was not to be expected that 4,5,9,10-tetrahydropyrene, the prototype in this series, could be obtained in optically active form, since calculations (see below) suggested an energy barrier of about 7–8 kcal./mole for the interconversion of the twisted enantiomers. We therefore turned our attention to homolog I and to its derivatives II–IV (see formula chart). Since optically active biphenyls have been prepared with three-, four-, and five-carbon 2,2'-bridges and *no* 6,6'-substituents (other than hydrogen),[5] the preparation

I

IIa, R = H
b, R = D

IIIa, X = Y = O
b, X = O; Y = S
c, X = Y = NCH₃

IV

V

VI

VII

VIII

IXa, R = COOCH₃
b, R = CH₂OH
c, R = CH₃

Xa, R = CH₃
b, R = COOCH₃
c, R = CH₂OH
d, R = CH₂Br

XIa, R = OH
b, R = Br

Fig. 1.—Configurational designation of doubly bridged biphenyls in symmetry class D_2.

Fig. 2.—Stepwise reduction of double bridged diketone II ((R)-configuration).

of doubly bridged *and* optically active biphenyls could be anticipated with some confidence.

Doubly bridged biphenyls I–IIIa and IV belong to the rare point group D_2 (or V), *i.e.*, the molecules lack reflection symmetry while possessing three mutually perpendicular twofold axes.[6] Biphenyl itself belongs to this point group in all but two of its conformations. No organic compound belonging to this symmetry class had heretofore been prepared in optically active form and a problem arose in connection with the designation of absolute configuration. The method[7] which had been extensively employed in the biphenyl literature[4] is not directly applicable to the case of compounds I–IV (except IIIb), or for that matter to biphenyl itself in the D_2-conformation, since the four substituents along any of the three C_2-asymmetric reference axes[7] are constitutionally identical. It is, however, possible to overcome this difficulty by *arbitrarily* assigning priority to *either one* of the two bridges. This convenient modification[8] permits normal application of the conversion rule[7] and leads to the designations shown in Fig. 1.

In the following sections will be discussed: (a) the syntheses of I–IV and of related compounds; (b) the ultraviolet absorption, optical rotatory dispersion and nuclear magnetic resonance spectral studies carried out in connection with this work; and (c) racemization studies and problems of optical stability which are related to the peculiar structural feature of double bridging.

Syntheses

The different problems encountered in the preparation of I–IV necessitated different synthetic approaches. It is therefore most convenient to discuss the syntheses under separate headings.

Hydrocarbon I and Diketones IIa and IIb.—Diketone IIa was prepared by the following sequence. 2,2′,6,6′-Tetrakis(bromomethyl)biphenyl (V)[9] was converted, with potassium cyanide, to 2,2′,6,6′-tetrakis(cyanomethyl)biphenyl and thence, by closure with sodium methoxide, to bisiminonitrile VI. No attempt was made to ascertain the precise identity of VI (which can exist in two constitutionally isomeric forms, each of which in turn is capable of *cis–trans* isomerism with respect at least to the cyano groups), since in the subsequent acid hydrolysis to IIa the cyano groups are destroyed. The diketone thus obtained was shown to be homogeneous by g.l.c. and thin layer chromatography, but its melting point behavior

resembled that of a grossly impure substance. In open or sealed capillaries, the melting range was 215–225°, with slight yellowing as the only clue to decomposition. It was eventually found that a sharp melting point, 223–224°, could be obtained only by heating the sample in capillaries sealed under purified nitrogen or under vacuum.

The structure of the diketone was supported not only by the n.m.r. spectrum (see below) but by the exchange of 7.8 hydrogens in IIa by deuterium. The n.m.r. spectrum of the octadeuterio derivative IIb was devoid of proton resonance signals in the methylene region. The infrared spectra of IIa and IIb were unexceptional (λ_{max}^{KBr} 5.85 μ). The ultraviolet spectra of IIa and IIb appeared to be indistinguishable and will be discussed below.

It was found that 90% of the methylene deuterons in IIb were exchanged for protons in a single pass over neutral alumina, activity grade II. Since chromatography over alumina is involved in the procedure for isolating and purifying the diketone, it became necessary to devise means for avoiding this exchange. This end was attained by replacing the water in the alumina with deuterium oxide to give "alumina–D_2O." Chromatography of IIb over alumina–D_2O left the deuterium content unaltered. By the same token, IIb could be *prepared* from IIa by chromatography on alumina–D_2O. Cursory examination of the behavior of some other ketones (Experimental section) indicates that this method of replacing enolizable hydrogen by deuterium may have general applicability.

Diketones IIa and IIb were optically activated by partial asymmetric Meerwein–Ponndorf–Verley reduction with optically active 2-octanol, a method which had previously been employed with success on diverse singly bridged biphenyl ketones.[10–12] However, in contradistinction to the earlier work,[10–12] the present case involves a diketone and a complication is introduced by the fact that *two* discrete reductions of the same molecule may now take place. The reduction of the first carbonyl group yields a ketol, which may then be further reduced to give either one of two diastereomeric diols, as illustrated in Fig. 2 for the (R)-isomer (the mirror image scheme obtains for the (S)-isomer).

Fortunately, for the purposes of the present work the uncertainty in the composition of the reduction product of the intermediate ketol does not introduce a complication. It had previously been demonstrated[10–12] that the stereochemistry of partial asymmetric reductions of this type is essentially independent of the nature of the blocking substituents, and that asymmetric reduction with (+)-2-octanol invariably

(5) K. Mislow, S. Hyden, and H. Schaefer, *J. Am. Chem. Soc.*, **84**, 1449 (1962), and references cited therein.

(6) A further example is provided by "twistane" [H. W. Whitlock, *ibid.*, **84**, 3412 (1962)].

(7) R. S. Cahn, C. K. Ingold, and V. Prelog, *Experientia*, **12**, 81 (1956).

(8) We thank Mr. H. Joshua for this suggestion.

(9) Z. Pelchowicz and E. D. Bergmann, *Bull. Research Council Israel*, **3**, 91 (1953); *Chem. Abstr.*, **49**, 1687 (1955).
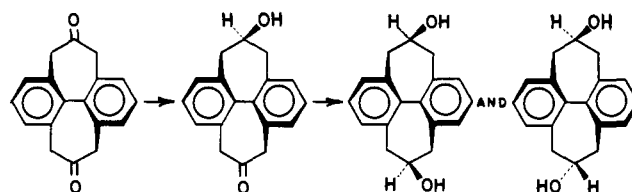
(10) P. Newman, P. Rutkin, and K. Mislow, *J. Am. Chem. Soc.*, **80**, 465 (1958).

(11) K. Mislow and F. A. McGinn, *ibid.*, **80**, 6036 (1958).

(12) K. Mislow, R. E. O'Brien, and H. Schaefer, *ibid.*, **84**, 1940 (1962).

leads to an excess of the (S)-enantiomer in the unreduced (residual) ketone. In the present work it was found that partial asymmetric reduction of racemic diketones IIa and IIb with (+)-2-octanol gives residual (−)-IIa and (−)-IIb, respectively. It is therefore established that (−)-II has the (S)-configuration. Separation of the fractions was effected by chromatography on alumina, from which the ketone was eluted with benzene and the alcohol fractions with ether and methanol. The presence of ketol in the alcohol fractions was indicated by a band at λ_{max}^{KBr} 5.83 μ, but no attempt was made to separate the various reduction products. Instead, the combined alcohol fractions were reoxidized by the two-phase chromic acid procedure of Johnson, Gutsche, and Banerjee[13] as modified by Brown and Garg.[14] In harmony with expectations, the diketone recovered from these oxidations was enriched in the (+)-(R)-enantiomer.

We had hoped that optically active hydrocarbon I could be readily obtained from optically active diketone II. The basis for our optimism was twofold: diketone IIa can be smoothly converted to hydrocarbon I by Raney nickel desulfurization of the bisthioketal VII formed from IIa and 1,3-propanedithiol, and the optical stability of IIa (e.g., $t_{0.5}$ ~2 hr. at 95°) is such as to encourage the belief that racemization of the derived biphenyls might be largely avoided by working at low temperatures. Nevertheless, although the formation of VII from optically active IIa did not require elevated temperatures, both the bisthioketal and the hydrocarbon prepared therefrom were optically inactive in the visible and ultraviolet regions.

This result strongly suggests that VII suffers appreciable racemization even under the mild conditions employed in the above transformations. On the basis of previous studies,[15] it can be safely predicted that a conjugation band Cotton effect with a molecular amplitude of approximately 100,000° is centered at the absorption maximum (255 mμ) of the enantiomerically homogeneous biphenyl VII. Since rotations could therefore have been presumably observed even if the optical purity of the product VII had been as low as 1%, it follows that product VII is essentially racemic.

Dioxepin IIIa.—Cyclization of tetrabromide V with a slurry of silver oxide in aqueous acetone gave the desired dioxepin in 25% yield. The structure of the dioxepin is supported by the n.m.r. spectrum (see below). Although shown to be homogeneous by g.l.c. and thin layer chromatography, dioxepin IIIa exhibited the melting point behavior of a grossly impure substance, and in this respect resembled diketone II. A sharp melting point could be obtained only by heating the sample in capillaries sealed under purified nitrogen or under vacuum (Experimental section).

The extreme air-sensitivity of diketone II and dioxepin IIIa at the melting point was somewhat surprising for, although adequate precedent exists for the autoxidation of ketones and ethers,[16] no similar observations had been recorded previously for bridged biphenyl ethers and ketones. The present compounds do, however, possess an abnormally high proportion of "sensitive" benzyl carbon atoms and the oxidation is expected to be accelerated at the comparatively high temperatures (~200°) of the melting points.

The cyclization of tetrabromide V necessarily affords rac-IIIa, and a method of stepwise ring closure from an optically active precursor was therefore required for the synthesis of optically active IIIa. (−)-6,6'-Dimethyl-2,2'-diphenic acid dimethyl ester, which has the (R)-configuration,[17] was brominated with N-bromosuccinimide to give the dibromo derivative (+)-(R)-VIII. Closure of the oxepin bridge by use of silver oxide in aqueous acetone gave oxepin diester (−)-(R)-IXa, which was reduced with lithium aluminum hydride to oxepin diol (+)-(R)-IXb. Formation of the second oxepin ring by acid-catalyzed ring closure under ordinary conditions or by the use of p-toluenesulfonyl chloride in anhydrous pyridine[18] gave racemic dioxepin IIIa, a result which is readily accounted for by the great optical lability of the product (half-life about 10 min. at room temperature). It was eventually possible to obtain (+)-(R)-IIIa by closure of the second oxepin ring of (+)-(R)-IXb with concentrated sulfuric acid at −20°.

Oxathiepin IIIb.—The synthesis of this compound was analogous to that of IIIa. Again starting with (+)-(R)-VIII, ring closure was effected with sodium sulfide; since the ester groups were saponified under the basic conditions employed in the ring closure, the crude acid was directly re-esterified with diazomethane. The resulting thiepin diester, (−)-(R)-Xb, was reduced with lithium aluminum hydride to thiepin diol, (+)-(R)-Xc, and the oxepin ring was formed by use of p-toluenesulfonyl chloride in pyridine[18] to give (+)-(R)-IIIb. The structure of the oxathiepin is supported by the n.m.r. spectrum (see below). In contrast to dioxepin IIIa, samples of oxathiepin IIIb melt sharply even in open capillaries; there is no evidence of abnormally facile oxidation at the melting point.

Diazepine IIIc.—The racemic modification of this compound was prepared from tetrabromide V and methylamine. No attempt was made to prepare the optically active form.

Dithiepin IV.—In analogy to the syntheses of racemic IIIa and IIIc, rac-IV was readily prepared by treatment of tetrabromide V with sodium sulfide. The structure of IV is supported by the n.m.r. spectrum (see below). A second synthesis started with rac-6,6'-dimethyl-2,2'-diphenic acid dimethyl ester, which was converted, successively, to racemic VIII, Xb, and Xc, as already described for the optically active series in the section dealing with IIIb. Treatment of racemic Xc with phosphorus tribromide in benzene gave the expected thiepin dibromide Xd, which was cyclized to dithiepin IV with sodium sulfide.

It was noted that dibromide Xd melted at 150–151° with partial resolidification and remelting to 210°. Yet the substance appeared to be homogeneous and gave an elemental analysis, including molecular weight, in complete accord with its formulation as Xd; furthermore, the melting process did not appear to be accompanied by signs of gross decomposition,

(13) W. S. Johnson, C. D. Gutsche, and D. K. Banerjee, J. Am. Chem. Soc., 73, 5464 (1951).

(14) H. C. Brown and C. P. Garg, ibid., 83, 2952 (1961).

(15) K. Mislow, M. A. W. Glass, R. E. O'Brien, P. Rutkin, D. H. Steinberg, J. Weiss, and C. Djerassi, ibid., 84, 1455 (1962).

(16) C. Walling, "Free Radicals in Solution," John Wiley and Sons, Inc., New York, N. Y., 1957, pp. 411–414.

(17) M. Siegel and K. Mislow, J. Am. Chem. Soc., 80, 473 (1958).

(18) In this connection, cf. G. A. Haggis and L. N. Owen, J. Chem. Soc., 389 (1953); E. L. Eliel and C. Pillar, J. Am. Chem. Soc., 77, 3600 (1955); C. F. Culberson, J. H. Seward, and P. Wilder, Jr., ibid., 82, 2541 (1960).
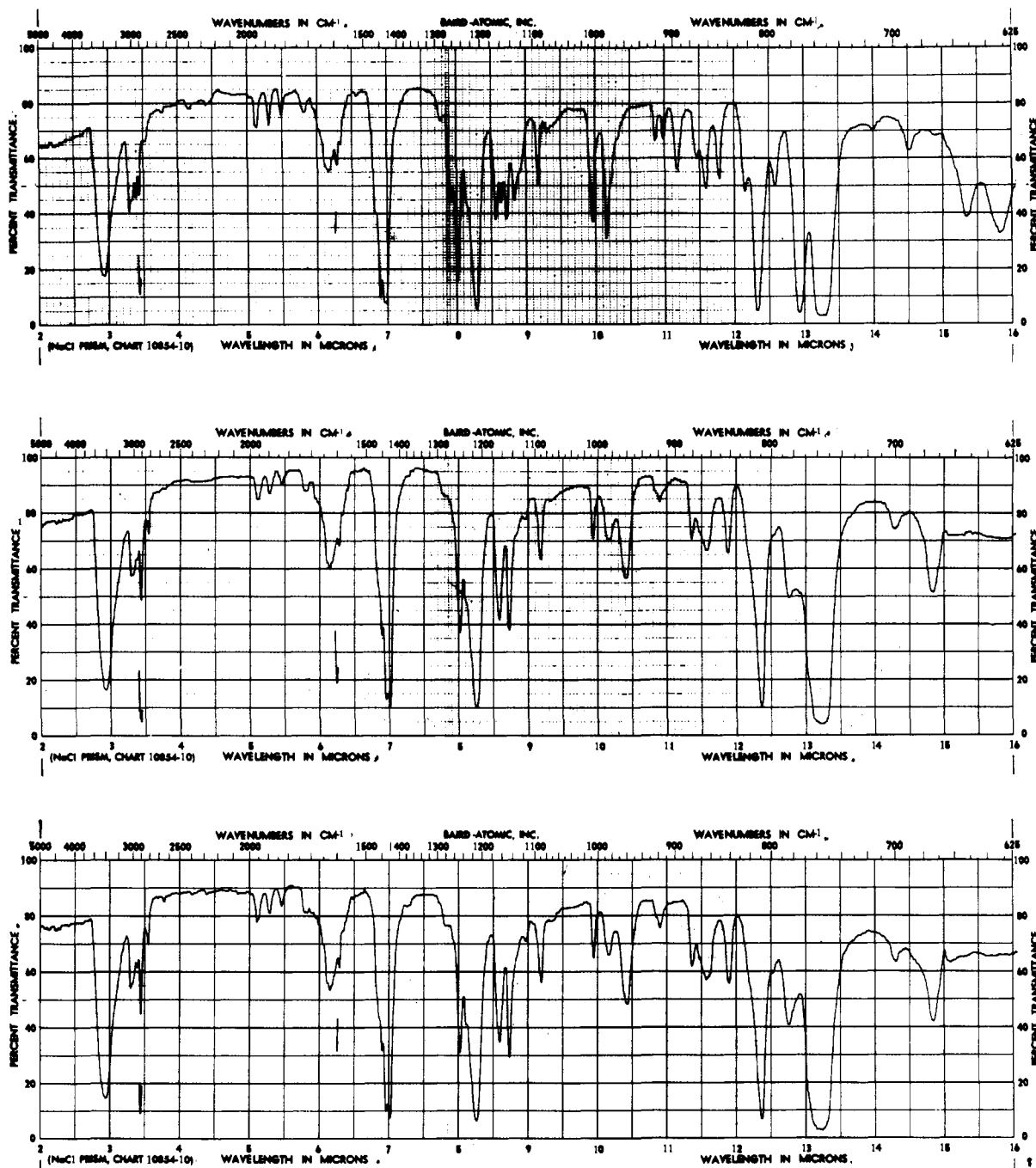
Fig. 3.—Infrared spectra, 5% in potassium bromide: top, racemic thiepin dibromide Xd; middle, same, after heating above the melting point; bottom, equimolar mixture of tetrabromide V and racemic dithiepin IV.

such as decolorization or evolution of gas. However, when a sample of Xd was heated for 4 min. at 150–156°, the infrared spectrum of the resolidified melt was not identical with that of the original substance but was identical instead with that of an equimolar mixture of IV and V (Fig. 3). It follows that racemic thiepin dibromide disproportionates cleanly and quantitatively into dithiepin and tetrabromide at the melting point. On the other hand, a 1.6% solution of Xd in o-xylene remained completely unchanged after heating for the same time at the same temperature; i.e., the rate of disproportionation depends markedly on concentration.

The reaction of optically active thiepin diol Xc with phosphorus tribromide in benzene was expected to yield optically active thiepin dibromide Xd. When

$(+)$-(R)-Xc was treated with phosphorus tribromide under the *identical* conditions employed in the preparation of racemic Xd from racemic Xc, the product obtained was a solid which proved to be an equimolar mixture of $(+)$-(R)-IV and V, as judged by the following evidence. First, fractional crystallization of the solid mixture from acetone and ligroin successfully separated the component parts V and $(+)$-(R)-IV. Second, the infrared spectrum of the solid mixture in chloroform solution differed from the solution spectrum of racemic Xd but was identical with that of an equimolar mixture of V and IV containing 5% of oxathiepin IIIb (strong C–O peak at 1065 cm.$^{-1}$), which is an expected contaminant. Third, chromatography of the solid mixture on alumina afforded $(+)$-(R)-IV. Fourth, treatment of the solid mixture with sodium sulfide
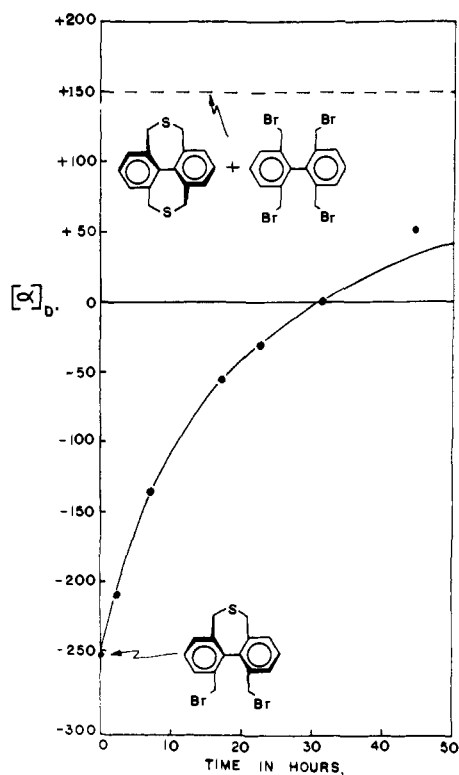
Fig. 4.—Mutarotation of thiepin dibromide Xd. Solid circles are experimental points. The curve was calculated assuming a second-order rate law (see text), and the dashed line represents the rotation of the ultimate product mixture.

resulted in a product which could be separated by fractional crystallization (benzene–ligroin) into approximately equal parts of (+)- and (±)-IV, and which had $[\alpha]_D$ +223° (benzene), corresponding to 51% optical purity based on $[\alpha]_D$ +440° for optically pure (+)-(R)-IV (reaction of an equimolar mixture of V and (+)-(R)-IV would have given 50% optically pure IV). Fifth and last, various preparations of the solid mixture had specific rotations varying from +124 to +144°, in reasonable agreement with the value (+149°) calculated for an equimolar mixture of V and (+)-(R)-IV.

In summary: *The reaction of optically active thiepin diol Xc with phosphorus tribromide affords an equimolar mixture of V and (+)-(R)-IV, whereas, under identical reaction conditions, racemic Xc gives the expected thiepin dibromide Xd which is stable in solution but which disproportionates into an equimolar mixture of V and (±)-IV at the melting point (ca. 150°).*

Preliminary experiments had shown that addition of phosphorus tribromide to thiepin diol Xc gave principally oxathiepin IIIb instead of the desired dithiepin IV. The order of addition was therefore reversed, and thiepin diol was added to phosphorus tribromide in benzene. However, the extreme insolubility of Xc in benzene made it convenient to add Xc as a solid,[2] and the observed difference in the behavior of racemic and optically active Xc was therefore originally believed to be the result of differences in the structure of the respective crystal lattices. This interpretation had to be abandoned when it was subsequently found that the addition of chloroform solutions of Xc to phosphorus tribromide in benzene gave results in no way different from those obtained earlier.

It had been noted that when the benzene or benzene–chloroform extracts of the reaction mixtures from Xc and phosphorus tribromide were evaporated, the product obtained from racemic Xc, viz., Xd, invariably[19] deposited as a *solid*, whereas the product obtained from optically active Xc invariably[19] deposited in the form of an *oil* which crystallized on standing at room temperature. This observation, originally regarded as trivial, proved in the final analysis to be crucial to the solution of our puzzle, for when the oil was examined polarimetrically *immediately upon isolation*, it was found that the substance was *strongly levorotatory* ($[\alpha]_D$ −260° (benzene)), whereas an equimolar mixture of V and (+)-(R)-IV is dextrorotatory. It was observed that on standing at room temperature the oil mutarotated and eventually became dextrorotatory; in the course of the mutarotation crystals deposited until, eventually, the sample had solidified to the final mixture of V and (+)-(R)-IV. However, the levorotation of a 1.8% solution of the oil in o-xylene remained unchanged after heating at 150° for 5 min.

It thus appeared that the oil (but not the solid derived therefrom) was optically active thiepin dibromide Xd. This conclusion was supported by the identity of solution infrared spectra of the freshly prepared oil and of racemic Xd, and by the fact that treatment of the freshly prepared oil with sodium sulfide resulted in optically pure (+)-(R)-IV. The extraordinary difference in behavior of optically active and racemic Xd (as obtained from Xc and phosphorus tribromide) is therefore the consequence of an extravagant concatenation of coincidences: (a) Xd disproportionates in the liquid phase but is stable in the solid phase; (b) the rate of disproportionation is highly concentration dependent; solutions of racemic or optically active Xd are stable toward disproportionation even at elevated temperatures, whereas neat Xd in the liquid (optically active) or molten (racemic) state suffers rapid disproportionation; and (c) the racemic form crystallizes from solution whereas the optically active form condenses as a liquid.[19]

By following the mutarotation of the optically active Xd at room temperature over a period of several days, the order of the reactions was found[20] to be 2.0, with $k_2a = 0.92 \times 10^{-3}$ sec.$^{-1}$ (where a = initial concentration of Xd in the liquid phase), corresponding to a half-life of 18 hr. under these conditions. As shown in Fig. 4, the observed rate of mutarotation is in satisfactory agreement with a second-order law over a period of 30 hr., corresponding to about 60% reaction. Beyond this point the heterogeneity of the sample is pronounced and may account for the divergence of the observed rotations from the calculated values.

A mechanism which is consistent with the above results is outlined in Fig. 5. Bimolecular reaction of Xd (step A) results in a sulfonium salt, which opens (step B) to give an intermediate sulfide in which a sulfur atom forms a link between the two biphenyl systems. Formation of a second sulfonium salt (step C) followed by cleavage into a mixture of IV and V (step D) completes the disproportionation.[21] The

(19) To judge by numerous repeat experiments performed at different times and independently by M. A. W. G., H. B. H., and G. H. W.

(20) According to the method of R. W. Wilkinson [Chem. Ind. (London), 1395 (1961)], taking $[\alpha]_D$ −253° at $t = 0$ and $[\alpha]_D$ +149° at $t = \infty$.

(21) Though the intervention of intermediates such as i cannot be ruled

postulation of sulfonium intermediates which may arise from and in turn may give rise to halides and sulfides follows conventional precedent,[22] though the apparent irreversibility of the events leading to IV and V is remarkable. An interesting complication arises in connection with the stereochemistry of the reaction sequences, since the first sulfonium salt formed in step A can exist in principle in diastereomeric forms while the other intermediates in the proposed mechanistic scheme can exist in principle only in enantiomeric forms. In the reaction of racemic Xd, the possibility is therefore given for the formation of *four* sulfonium salts in step A, *viz.*, $(R)-(R)$, $(S)-(S)$, $(R)-(S)$, $(S)-(R)$, whereas only *one* such salt is possible starting from optically pure Xd, *e.g.*, $(R)-(R)$. Clearly, half of the mechanistic pathways available to racemic Xd in steps A and B involve transition states which are equal in energy to those in the corresponding sequence for optically active Xd, *i.e.*, those which involve the $(R)-(R)$ and $(S)-(S)$ forms. By contrast, steps A and B in the formation and decomposition of the diastereomeric sulfonium salts $(R)-(S)$ and $(S)-(R)$ have transition states which must differ in energy from those in steps A and B of the sequence involving optically active Xd.

Spectral Studies

Nuclear Magnetic Resonance.—In measuring the n.m.r. spectra of the doubly bridged biphenyls, our original purpose had been merely that of confirming the structural identity of these substances. A routine comparison with singly bridged biphenyls, however, revealed certain interesting contrasts and similarities and led to an extensive n.m.r. study of bridged biphenyls as a class. The results of this investigation are reported in this section.

The n.m.r. characteristics of bridged biphenyls in deuteriochloroform at room temperature are collected in Tables I–III.[23] An interpretation of these data is meaningful only in context with a discussion of the molecular conformations, and this aspect must therefore be given first consideration.

In their ground state, all the molecules in Tables I–III are dissymmetrically twisted. This is seen most simply by inspection of molecular models. Calculations based on normal bond angles and distances give values for the angle of torsion (ϕ) about the biphenyl pivotal 1,1'-bond which are listed in Table IV.[5,24] If nonbonding interactions are ignored, these

out, there is at present no experimental evidence which compels their formulation.

i
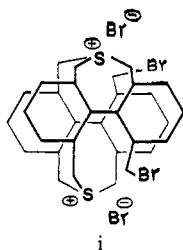
(22) F. E. Ray and I. Levine, *J. Org. Chem.*, **2**, 267 (1937).

(23) Unless otherwise specified, chemical shifts are reported in p.p.m. on the τ-scale and refer to 8–10% (w./v.) solutions with internal tetramethylsilane, as determined on a Varian A-60 spectrometer. Aromatic absorptions are generally complex, and the reported values are estimated centers of the multiplet. Methylene τ-values reported as two numbers separated by a semicolon refer to the centers of gravity obtained by analysis of the AB absorption pattern. Methylene geminal coupling contants (J_{AB}) are given in cycles per second.
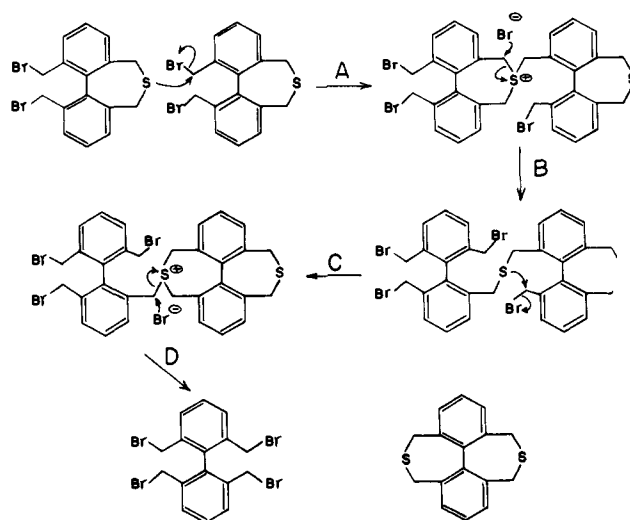
Fig. 5.—Proposed mechanism for the disproportionation of thiepin dibromide Xd into an equimolar mixture of tetrabromide V and dithiepin IV.

values should hold for the singly bridged biphenyls (Table I), the bridged o,o'-dimethylbiphenyls (Table II), and the doubly bridged biphenyls (Table III); and if all interactions are included, the *order* of increasing ϕ given in Table IV should still be maintained in

TABLE I[23]

N.M.R. ABSORPTION OF SINGLY BRIDGED BIPHENYLS AND OF COMPARABLE DIBENZYL DERIVATIVES IN DEUTERIOCHLOROFORM[a]

X	Aromatic protons	Methylene protons	Methylene protons
b	2.31 (6H) 2.80 (2H)	7.18 (4H)	7.07 (4H)
O	2.53 (8H)	5.66 (4H)	5.45 (4H)
NCH$_3$	2.60 (8H)	6.65 (4H)[c]	6.49 (4H)[d]
C=O	2.62 (8H)[e]	6.48 (4H)	6.31 (4H)
S	2.68 (8H)	6.56 6.65 (4H)[f]	6.39 (4H)

[a] The numbers in parentheses refer to the integrated relative number of protons. [b] 9,10-Dihydrophenanthrene. [c] N–CH$_3$ at τ 7.57 (3H). [d] N–CH$_3$ at τ 7.84 (3H). [e] Two complex patterns appear to be centered at τ ~2.53 and ~2.73, but accurate separate integration was not possible. [f] Two broad peaks. The two expected outer peaks could not be detected; at 100 Mc.,[27] an AB pattern with $\Delta\tau$ = 0.22 and J_{AB} 12.5 c./sec.

(24) The following dimensions were used: (a) C–O single bond distance 1.42 Å. and –CH$_2$OCH$_2$– angle 111° (P. H. Kasai and R. J. Myers, *J. Chem. Phys.*, **30**, 1096 (1959); K. Kimura and M. Kubo, *ibid.*, **30**, 151 (1959)). (b) –CH$_2$CH$_2$CH$_2$– angle 112° (R. A. Bonham, L. S. Bartell, and D. A. Kohl, *J. Am. Chem. Soc.*, **81**, 4763 (1959); R. A. Bonham and L. S. Bartell, *ibid.*, **81**, 3491 (1959)). (c) C$_{sp^3}$–C$_{sp^2}$ bond distances 1.51 Å. (M. G. Brown, *Trans. Faraday Soc.*, **55**, 694 (1959); W. Zeil, *Angew. Chem.*, **73**, 171, 751 (1961)). (d) –CH$_2$COCH$_2$– bond angle 120° from the value of ν_{max} ~1710 cm.$^{-1}$ for the carbonyl frequency[15] and application of the Halford equation (J. O. Halford, *J. Chem. Phys.*, **24**, 830 (1956); *cf.* also R. Zbinden and H. K. Hall, Jr., *J. Am. Chem. Soc.*, **82**, 1215 (1960); P. von R. Schleyer and R. D. Nicholas, *ibid.*, **83**, 182 (1961)). We note that the value of the bond angle is the same as for the parent substance 3,4-cycloheptadienone for which a value of λ_{max} 5.84 μ has been reported by O. L. Chapman, D. J. Pasto, and A. A. Griswold, *ibid.*, **84**, 1213 (1962). (e) C–S bond distance 1.81 Å. and –CH$_2$SCH$_2$– bond angle 99° (L. Pierce and M. Hayashi, *J. Chem. Phys.*, **35**, 479 (1961); W. Maier, *Angew. Chem.*, **73**, 120 (1961)). (f) C–N bond distance 1.47 Å., –CH$_2$NCH$_2$ angle 109° (for valence angles of 108, 110, and 111° the angles of torsion are 44.3, 46.2, and 46.6°).

each of the three series. As will be detailed below in the section dealing with racemization studies, conformation stability generally increases with increasing ground state angle of torsion ϕ, and as a matter of convenience in discussion we have followed this order of presentation in all of the n.m.r. and ultraviolet tabulations.

TABLE II[23]
N.m.r. Absorption of Singly Bridged
o,o'-Dimethylbiphenyls in Deuteriochloroform[a]
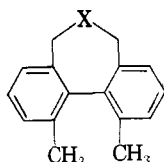
X	Aromatic protons	Methylene protons	J_{AB}	C-Methyl protons
. .[b]	2.89 (6H)	7.37 (4H)[c]	. .	7.75 (6H)
O	2.71 (6H)	5.61; 6.00 (4H)	11.0	7.80 (6H)
NCH₃	2.78 (6H)	6.65; 6.98 (4H)	12.1	7.81 (9H)[d]
CH₂	2.80 (6H)	7.42–8.33 (12H)[e]	Complex	7.86 (12H)[e]
C=O	2.77 (6H)	6.47; 6.68 (4H)	15.2	7.80 (6H)
S	2.81 (6H)	6.75 (4H)	. .	7.92 (6H)

^{a} The numbers in parentheses refer to the integrated relative number of protons. ^{b} 9,10-Dihydro-4,5-dimethylphenanthrene. ^{c} Broad unresolved peak. At 100 Mc.[27] a complex signal consistent with an A_2B_2 pattern is observed. ^{d} Integration includes N–CH₃ at τ 7.72. ^{e} The methylene absorption is very complex and the τ-values give the range of absorption. Separate integration of methylene and methyl signals was not feasible. The spectrum is not significantly simplified at 100 Mc.[27]

TABLE III[23]
N.m.r. Absorption of Doubly Bridged Biphenyls in
Deuteriochloroform[a]
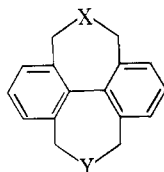
X	Y	Aromatic protons	Methylene protons	J_{AB}
. .	. .[b]	2.95 (6H)	7.15 (8H)	. .
O	O	2.48 (6H)	5.45; 5.82 (8H)	11.5
NCH₃	NCH₃	2.62 (6H)	6.46; 6.78 (8H)	12.5
CH₂	CH₂	2.80 (6H)	7.2–8.1 (12H)[c]	Complex
C=O	C=O	2.70 (6H)	6.43 (8H)[d]	. .
S	S	2.71 (6H)	6.62; 6.71 (8H)[e]	12.7[e]
O	S	2.62 (6H)	5.53; 5.90 (4H)	11.5
			6.47; 6.66 (4H)	12.7

^{a} The numbers in parentheses refer to the integrated relative number of protons. ^{b} 4,5,9,10-Tetrahydropyrene. ^{c} The methylene absorption is very complex and is not significantly simplified at 100 Mc.[27] The τ-values give the range of absorption. ^{d} Unresolved at 100 Mc.[27] ^{e} At 100 Mc.,[27] an AB pattern with $\Delta\tau$ 0.12 and J_{AB} 12.4 c./sec.

TABLE IV
Calculated[5,24] Angles of Torsion (ϕ) in Bridged Biphenyls
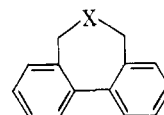
X	. .	O	NCH₃	CH₂	CO	S
ϕ	15.3°	44.1°	45.8°	50.6°	52.4°	56.6°

In most of the singly bridged biphenyls (Table I) the enantiomeric conformations suffer rapid interconversion, and simple calculations (see below) show that only in the case where X = S might there be a possi-

bility of stabilizing the individual enantiomers at room temperature.[25] The n.m.r. data (Table I) are in accord with these views. In the twisted bridged biphenyls the two methylene protons on any one of the benzylic carbon atoms are stereochemically nonequivalent and might also be expected to be magnetically nonequivalent. This point will be discussed in further detail below; in the present context it is sufficient to note that the singly bridged biphenyls with X = single bond (9,10-dihydrophenanthrene), O, NCH₃, and CO display sharp singlets in the methylene region. This is indicative of the rapid conformational interconversion which renders the two methylene protons equivalent on the time average at room temperature,[26] and this conclusion is strengthened by the finding that two of the methylene singlets in Table I (X = O and C=O) remain unresolved even at 100 Mc.[27] On the other hand, the thiepin (X = S) has a poorly defined multiplet which is resolved at 100 Mc.[27] into the expected methylene AB pattern with $\Delta\tau$ 0.22 p.p.m. and J_{AB} 12.5 c.p.s.

The change in ϕ is also reflected in the aromatic portion of the spectrum; specifically, the aromatic protons of 9,10-dihydrophenanthrene show up as two well separated multiplets in the integrated ratio of 2 to 6 (Table I). By analogy with phenanthrene, the former signal is assigned to the 4,5-protons which are each further deshielded by the opposite aromatic ring.[28] Finally, the methylene proton signals of the biphenyls in Table I lie at higher fields than the corresponding signals of the analogous compounds $(C_6H_5CH_2)_2X$. These substances are conceptually derived from the biphenyls by cleavage of the 1,1'-pivot bond and the results suggest shielding by the twisted biphenyl rings; this point will be elaborated on below.

In contrast to the bridged biphenyls in Table I, the bridged o,o'-dimethylbiphenyls (Table II) are conformationally rigid, as shown by the fact that all have been obtained in optically active form in the present and earlier[15,29] studies and that, with the exception of 9,10-dihydro-4,5-dimethylphenanthrene,[29] all have been found to be optically stable at room temperature. In this series, the C-methyl proton signal is a sensitive function of the angle of torsion ϕ. In Fig. 6 are plotted (circles) the methyl proton chemical shifts of Table II against the calculated[24] angles of torsion listed in Table IV; for ϕ = 90° the methyl proton resonance signal of 2,2',6,6'-tetramethylbiphenyl at τ 8.12 was selected

(25) Some evidence to that effect has been advanced in the optical activation of a derived sulfone; unfortunately no information on the optical stability of the compound is available (W. E. Truce and D. D. Emrick, J. Am. Chem. Soc., **78**, 6130 (1956)).

(26) It would be expected that at low enough temperatures and in the absence of special solvent effects (see text) the conformational interconversion would become slow enough to permit resolution of the methylene proton signals. That this is indeed the case has been recently shown by R. J. Kurland for the singly bridged oxepin (Table I, X = O), whose E_{act} of racemization was estimated from the temperature dependence of the AB pattern as ca. 9.6 kcal./mole. Prof. Kurland has similarly found that the corresponding value of E_{act} for the thiepin (Table I, X = S) is ca. 16.2 kcal./mole. We are grateful to Prof. Kurland for disclosing these results to us in advance of publication.

(27) These measurements were kindly performed by Dr. N. S. Bhacca, Varian Associates, Palo Alto, Calif.

(28) J. S. Waugh and R. W. Fessenden, J. Am. Chem. Soc., **79**, 846 (1957); cf. also L. M. Jackman, "Applications of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry," Pergamon Press, London, 1959, pp. 125–129. For a prior, somewhat inconclusive study, cf. S. Brownstein; J. Am. Chem. Soc., **80**, 2300 (1958).

(29) K. Mislow and H. B. Hopps, ibid., **84**, 3018 (1962).

since, to judge by the ultraviolet spectrum,[30] the two phenyl rings in this compound are on the average perpendicular. As expected, the signal moves upfield with increasing angle of torsion ϕ, reflecting the increased shielding of each methyl group by the π-electrons of the distal ring. A theoretical estimate of the change in shielding values with geometry[28,31] is shown by the curve in Fig. 6, and, on the whole, the fit with the semiexperimental points is surprisingly good. However, the τ-value of 7.75 found for 9,10-dihydro-4,5-dimethylphenanthrene is markedly higher than the value of 7.48 which would be calculated on theoretical grounds. There may be several explanations for this result. It is possible to construct Stuart–Briegleb models of 9,10-dihydro-4,5-dimethylphenanthrene and the molecule cannot therefore be considered overcrowded in the conventional sense; nevertheless, the methyl groups are forced into snug contact. Special n.m.r. effects may therefore be operative in which the protons on one methyl group are shielded by the σ-electrons of the other. Alternatively, the nonbonded repulsive interaction between the methyl groups, by causing deformations of the rings which effectively increase the angle ϕ, may give rise to a high methyl proton τ-value. However, this mode of strain relief is contraindicated by the ultraviolet spectral data (below) and it seems much more likely that the molecule relieves any nonbonded strain largely by in-plane and out-of-plane deformations of the methyl groups. The last deformation would also be expected to result in an abnormally high shielding value and we opt for this interpretation of our observations. Nevertheless, it must be pointed out that the general usefulness of the function plotted in Fig. 6 is severely limited, as revealed by the fact that 4-methylbiphenyl, 2-methylbiphenyl, and 2,2'-dimethylbiphenyl, with ϕ^{32} = 0, 58, and 70°, have τ-values[23] of 7.62, 7.72, and 7.97, respectively. These points scatter widely from the theoretical curve, but this result is perhaps not surprising in view of the crudeness of our theoretical treatment.

It was remarked above that the geminal methylene protons in the bridged biphenyls are *stereochemically* nonequivalent. Before turning to a further discussion of the possible *magnetic* nonequivalence, we shall here introduce the term "diastereomeric protons" to describe rigorously the *stereochemical* attribute. This definition may be legitimately applied to geminal protons in dissymmetric molecules such as X–CH_2–Cabc as well as in nondissymmetric molecules[33] such as $(CH_3CH_2O)_2CHCH_3$ and $CH_3CH=CH_2$, and is independent of magnetic equivalence or nonequivalence.

The magnetic nonequivalence of diastereomeric protons has been extensively documented[34,35] and it has
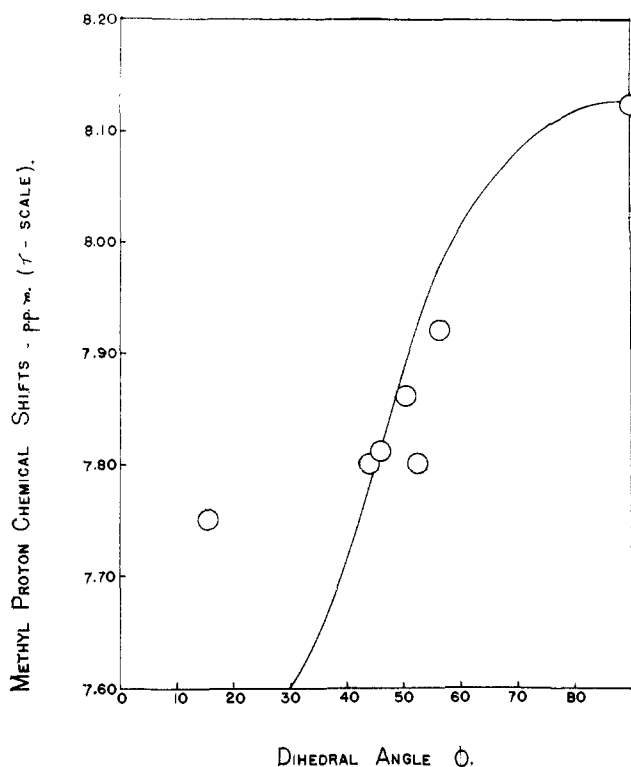

Fig. 6.—Calculated methyl proton chemical shifts (curve) of o,o'-dimethylbiphenyls and observed values (circles) in $CDCl_3$ as functions of calculated biphenyl dihedral angle.

been argued[35] that the difference in chemical shifts of the two geminal protons is a general consequence of the difference in shielding by two diastereomeric environments, a difference which must persist as long as the stereochemical integrity of the environment is maintained. In some circumstances this does not exclude rapid interconversion of conformers (torsional isomers) since even then the *average* diastereoisomerism of the environment may be preserved. Two conditions for the observation of magnetic equivalence of diastereomeric protons are conceivable: (1) rapid conformational interchange of the diastereomeric environments, i.e., the equivalent of rapid interchange of the diastereomeric protons; and/or (2) very small differences in chemical shifts of the two protons, or spin coupling constant effects. Magnetic equivalence of the first kind obtains in most of the bridged biphenyls listed in Table I and in 4,5,9,10-tetrahydropyrene (Table III). However, in the conformationally rigid o,o'-dimethylbiphenyls (Table II) the first condition is not met and the expected simple AB pattern is generally observed,[36] a striking exception being the case of the thiepin Xa; this compound displays a single sharp signal in the methylene region. A similar anomaly is encountered in the series of doubly bridged biphenyls (Table III), where the diketone methylene resonances are collapsed

(30) G. H. Beaven in "Steric Effects in Conjugated Systems," Academic Press, Inc., New York, N. Y., 1958, p. 22 ff. See also G. H. Beaven and E. A. Johnson, in "Conference on Molecular Spectroscopy," ed. by E. Thornton and H. W. Thompson, Pergamon Press, New York, N. Y., 1959, p. 78 ff.

(31) C. E. Johnson, Jr., and F. A. Bovey, J. Chem. Phys., 29, 1012 (1958). In the present computations an "average proton" was taken at the midpoint of the triangle defined by the three methyl protons and distances p and z were estimated using Dreiding models. The value for ϕ = 90° was taken as the anchor point.

(32) H. Suzuki, Bull. Chem. Soc. Japan, 32, 1340, 1350, 1357 (1959).

(33) The idea of the steric nonequivalence of identical substituents X in a molecule with a plane of symmetry Cxyz has been discussed in another connection by P. Schwartz and H. E. Carter, Proc. Natl. Acad. Sci., 40, 499 (1954). Thus the protons in CH_2ClBr might be referred to as "enantiomeric"; these of course are necessarily magnetically equivalent.

(34) See, e.g., P. M. Nair and J. D. Roberts, J. Am. Chem. Soc., 79, 4565 (1957); H. Finegold, Proc. Chem. Soc., 283 (1960); F. Kaplan and J. D. Roberts, J. Am. Chem. Soc., 83, 4666 (1961); P. R. Shafer, D. R. Davis, M. Vogel, K. Nagarajan, and J. D. Roberts, Proc. Natl. Acad. Sci., 47, 49 (1961); G. N. Whitesides, F. Kaplan, K. Nagarajan, and J. D. Roberts, ibid., 48, 1112 (1962).

(35) J. A. Pople, Mol. Phys., 1, 1 (1958); J. G. Pritchard and P. C. Lauterbur, J. Am. Chem. Soc., 83, 2105 (1961); J. S. Waugh and F. A. Cotton, J. Phys. Chem., 65, 562 (1961); H. S. Gutowsky, J. Chem. Phys., 37, 2196 (1962).

(36) We have not analyzed the cases in which the benzylic methylene group is attached to another methylene group since the further spin–spin splitting results in complex absorption patterns.

TABLE V[23]

SOLVENT VARIATION OF METHYLENE PROTON MAGNETIC RESONANCE ABSORPTION OF DIHYDROPHENANTHRENE DERIVATIVES[a]
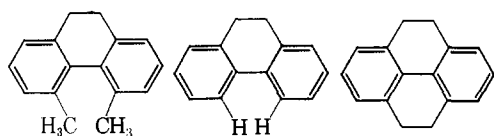
Solvent[b]			
CCl₄	7.41 (3.7)	7.19 (1.5)	7.18 (1.8)
C₆H₆	7.52 (1.7)	7.42 (1.6)	7.37 (1.6)
CS₂	7.44 (3.8)	7.23 (1.7)	7.23 (1.7)
CDCl₃	7.37 (4.8)[c]	7.18 (1.9)	7.15 (1.8)
C₅H₅N	7.41 (4.5)	7.27 (1.8)	7.23 (1.6)
C₆H₅NO₂	7.41[d]	7.23 (1.7)	7.19 (1.7)

[a] Numbers in parentheses are peak widths at half-height given in c.p.s. [b] Solvents are listed in order of increasing dielectric constant. [c] At 100 Mc., the spectrum is resolved into a multiplet indicative of an A₂B₂ pattern. [d] Multiplet; probably an A₂B₂ pattern.

TABLE VI[23]

SOLVENT VARIATION OF METHYLENE PROTON MAGNETIC RESONANCE ABSORPTION OF DIBENZOXEPIN DERIVATIVES[a]
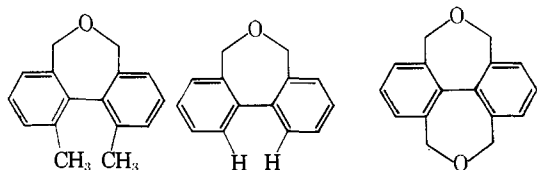
Solvent[b]		J_{AB}			J_{AB}
CCl₄	5.73; 6.10	11.1	5.74 (1.8)	5.53; 5.89	11.5[c]
C₆H₆	5.61; 5.90	11.1	5.67 (1.4)	5.51; 5.81	11.4[d]
CS₂	5.80; 6.16	10.9	5.83 (1.4)	5.59; 5.95	11.5[d]
CDCl₃	5.61; 6.00	11.0	5.66 (1.8)[e]	5.45; 5.82	11.5
C₅H₅N	5.48; 5.88	11.0	5.54 (1.9)	5.30; 5.73	11.1
C₆H₅NO₂	5.57; 6.00	11.2	5.68 (1.5)	5.38; 5.81	11.3[d]

[a] Numbers in parentheses are peak widths at half-height given in c.p.s. Numbers separated by a semicolon are analyzed centers of gravity of an AB pattern. [b] Solvents are listed in order of increasing dielectric constant. [c] Concentration considerably less than 5% (w./v.). [d] Concentration about 4% (w./v.). [e] Singlet at 100 Mc.[27]

into a single sharp signal, in contrast to the other members of the series which generally[36] give the AB pattern.

The sharp methylene proton signal of the diketone in deuteriochloroform is not resolved at 100 Mc.[27] If this compound had not been prepared in optically active and optically stable form, the n.m.r. data might have been incorrectly used as evidence for the first condition of magnetic equivalence, i.e., as evidence for conformational lability. This alternative being eliminated, it was decided to investigate the effect of solvents on the appearance of the methylene proton signal.[37] Our results are summarized in Tables V–XI.

Solvent effects on n.m.r. spectra have been widely studied and interpreted theoretically.[38] In particular,

(37) We are grateful to Prof. J. D. Roberts, whose suggestion of this approach provided the initial impetus for the present solvent study.

(38) A. A. Bothner-By and R. E. Glick, J. Chem. Phys., 26, 1651 (1957); A. D. Buckingham, T. Schaefer, and W. G. Schneider, ibid., 32, 1227 (1960); T. Schaefer and W. G. Schneider, ibid., 32, 1218 (1960); A. D. Buckingham, Can. J. Chem., 38, 300 (1960); G. Slomp and F. MacKellar, J. Am. Chem. Soc., 82, 999 (1960); J. V. Hatton and R. E. Richards, Mol. Phys., 3, 253 (1960); P. Diehl and R. Freeman, ibid., 4, 39 (1961); E. Lustig, J. Phys. Chem., 65, 491 (1961); J. V. Hatton and R. E. Richards, Mol. Phys., 5, 139, 153 (1962); W. G. Schneider, J. Phys. Chem., 66, 2653 (1962); J. V. Hatton and W. G. Schneider, Can. J. Chem., 40, 1285 (1962); R. E. Klinck and J. B. Stothers, ibid., 40, 2329 (1962); O. L. Chapman, H. G. Smith, and R. W. King, J. Am. Chem. Soc., 85, 803 (1963); R. M. Moriarty, J. Org. Chem., 28, 1296 (1963); E. I. Snyder, J. Am. Chem. Soc., 85, 2624 (1963).
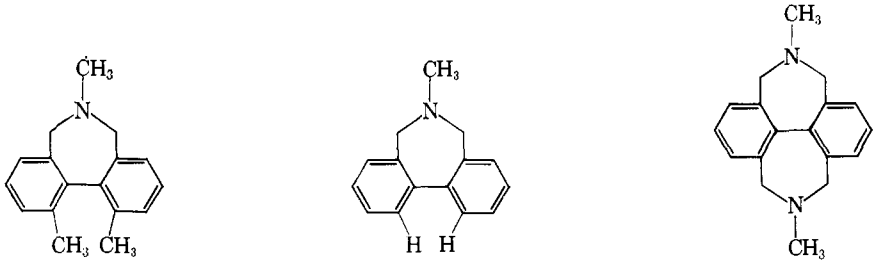
it is now well established that aromatic solvents, in particular benzene, give rise to high-field shifts in the solute. These shifts are related to the large diamagnetic anisotropy of "disk-shaped" solvent molecules in suitable orientations, which has the effect of decreasing the external field in the neighborhood of the solvated solute proton. In the present study this effect is clearly seen in the series of dihydrophenanthrene derivatives (Table V) where, among a variety of solvents covering a wide range of dielectric constants, the chemical shift of the methylene protons in benzene is different from that in the other solvents; this difference amounts to a marked relative shift upfield for each of the three compounds. The same trend is observed in the C-methyl resonances of the bridged o,o'-dimethylbiphenyls which are collected in Table X and of the one unbridged o,o'-dimethylbiphenyl investigated (Table XI).

The salient conclusions which could be derived from the n.m.r. solvent study of the compounds in Tables VI–IX are as follows.

First, the separation of diastereomeric oxepin (Table VI) and azepine (Table VII) proton resonances $\Delta\tau$ (leaving aside cases of magnetic equivalence due to conformational interconversion) increases with dielectric constant except for benzene solutions in which $\Delta\tau$ is abnormally small. Conversely, in the thiepins (Table IX) $\Delta\tau$ appears to decrease with increasing dielectric constant (though the data here are more limited) except again for the benzene solutions which exhibit by far the largest values of $\Delta\tau$; in fact, in the case of the dimethyl compound Xa the AB pattern is revealed only in benzene. Yet a third type of behavior is exhibited by the ketones (Table VIII), where no trend of $\Delta\tau$ with dielectric constant is discernible, but where benzene again plays a unique role: in the case of the diketone IIa the AB pattern is revealed only in benzene. The contrast in solvent behavior is illustrated for Xa in Fig. 7; we stress that the methylene "singlet" at τ 6.81 in carbon tetrachloride is not even resolved at 100 Mc.[27] In other words, diastereomeric methylene protons may display apparent A₂ patterns which remain unresolved even at 100 Mc., even though the protons remain conformationally nonequivalent. This behavior is to a large extent solvent dependent.
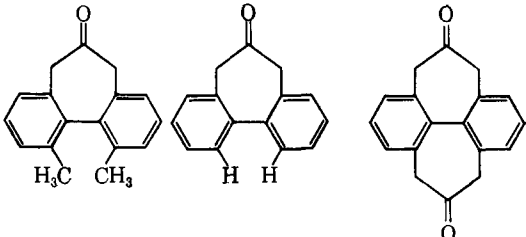
A second observation concerns the average position of the diastereomeric methylene protons, $\bar{\tau} = (\tau_A + \tau_B)/2$. We note that (a) $\bar{\tau}$ has its lowest value in pyridine solutions (all twelve compounds); (b) $\bar{\tau}$ of the three oxepins and of the three azepines has its highest values in carbon disulfide solutions, whereas $\bar{\tau}$ of the three ketones and of the three thiepins has its highest values in benzene solutions.[39] The distinctive behavior in the last respect, which places the oxepins and the azepines in one class and the ketones and the thiepins in another, seems to mirror the distinctive behavior of $\Delta\tau$ discussed above and may be related to changes in ϕ. Of considerable interest are two additional observations. First, for any given solvent, $\bar{\tau}$ of the singly bridged o,o'-dimethylbiphenyls is invariably higher than $\bar{\tau}$ of the analogous singly and doubly bridged biphenyls. Second, for any given

(39) The solvent effect of pyridine and carbon disulfide on chemical shifts has already been discussed.[38]

TABLE VII[23]

SOLVENT VARIATION OF METHYLENE AND N-METHYL PROTON MAGNETIC RESONANCE ABSORPTIONS OF DIBENZAZEPINE DERIVATIVES[a,b]

Solvent[c]	Methylene		N-CH₃	Methylene	N-CH₃	Methylene		N-CH₃
	J_{AB}					J_{AB}		
CCl₄	6.79; 7.07	12.2	7.83	6.74 (1.4)	7.65	6.60; 6.86	12.8	7.67
C₆H₆	6.73; 6.86	12.1	7.82	6.68 (2.0)	7.70	6.57; 6.67	12.6	7.69
CS₂	6.79; 7.08	12.0	7.84	6.79 (1.7)	7.67	6.66; 6.93	12.3	7.68
CDCl₃	6.65; 6.98	12.1	7.72	6.65 (1.6)	7.57	6.46; 6.78	12.5	7.56
C₅H₅N				6.54 (1.5)	7.57	6.42; 6.71	12.5	7.58
C₆H₅NO₂				6.68 (2.0)	7.60	6.45; 6.80	12.4	7.58

[a] Numbers in parentheses are peak widths at half-height given in c.p.s. Numbers separated by a semicolon are analyzed centers of gravity of an AB pattern. [b] These measurements were kindly performed by Miss B. Singer. [c] Solvents are listed in order of increasing dielectric constant.
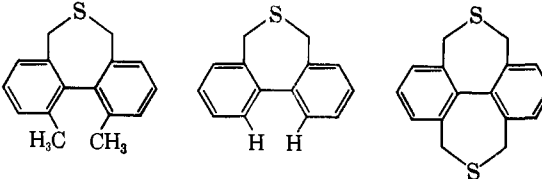
TABLE VIII[23]

SOLVENT VARIATION OF METHYLENE PROTON MAGNETIC RESONANCE ABSORPTION OF DIBENZSUBERONE DERIVATIVES[a]

Solvent[b]	J_{AB}				J_{AB}
CCl₄	6.57; 6.78	14.8	6.54 (2.1)	6.48 (1.9)[c]	..
C₆H₆	6.74 (2.6)[d]	..	6.73 (1.8)	6.69; 6.81	15.5
CS₂	6.62; 6.85	14.5	6.62 (1.6)	6.56 (1.8)[c]	..
CDCl₃	6.47; 6.68	15.2	6.48 (2.1)[e]	6.43 (1.8)[e]	..
C₅H₅N	6.44; 6.56	15.5	6.39 (1.7)	6.39 (1.9)	..
C₆H₅NO₂	6.61 (2.9)	..	6.52 (1.8)	6.42 (2.1)[f]	..

[a] Numbers in parentheses are peak widths at half-height given in c.p.s. Numbers separated by a semicolon are analyzed centers of gravity of an AB pattern. [b] Solvents are listed in order of increasing dielectric constant. [c] Concentration considerably less than 3% (w./v.). [d] AB pattern at 100 Mc.,[27] $\Delta\tau$ 0.09, J_{AB} 15.1 c./sec. [e] Singlet at 100 Mc.[27] [f] Concentration 3.5% (w./v.).
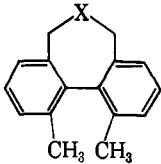
solvent, $\bar{\tau}$ of the singly bridged biphenyls is higher than $\bar{\tau}$ of the analogous doubly bridged biphenyls with the exception of the azepine and thiepin in carbon disulfide and in pyridine, the ketone and the thiepin in benzene, and the thiepin in deuteriochloroform.

Examination of molecular models of o,o'-bridged biphenyls reveals that the diastereomeric environments of the two geminal protons differ markedly; while one proton is essentially in the plane of the near phenyl ring, the other subtends a large angle to the near phenyl ring and also projects into the π-cloud of the far ring. The generally found magnetic nonequivalence is therefore less surprising than are the cases of observed magnetic equivalence. Furthermore, since the magnetic environment of the methylene protons must be a function of biphenyl angle of torsion ϕ, any changes in the methylene chemical shifts should in principle be related, other things being equal, to

TABLE IX[23]

SOLVENT VARIATION OF METHYLENE PROTON MAGNETIC RESONANCE ABSORPTION OF DIBENZTHIEPIN DERIVATIVES[a]

Solvent[b]	J_{AB}			J_{AB}		J_{AB}
CCl₄	6.81 (1.5)[c]	..	6.55; 6.71	12.2	6.58 (5.6)[d]	..
C₆H₆	6.75; 7.00	12.4	6.55; 7.0	11.5	6.73; 7.06	12.7
CS₂	6.88 (2.0)	..	6.66; 6.77[e]	..	6.67; 6.82[d]	12.6
CDCl₃	6.75 (1.8)	..	6.56; 6.65[e,f]	..	6.62; 6.17[g]	12.7
C₅H₅N	6.70 (1.4)	..	6.53; 6.56[e]	..	6.58 (3.9)	..
C₆H₅NO₂	6.78 (2.1)	..	6.70 (3.0)	..	6.67 (2.0)[h]	..

[a] Numbers in parentheses are peak widths at half-height given in c.p.s. Numbers separated by a semicolon are analyzed centers of gravity of an AB pattern. [b] Solvents are listed in order of increasing dielectric constant. [c] Singlet at 100 Mc.[27] [d] Concentration considerably less than 4% (w./v.). [e] Only two peaks detected (position of each given). [f] AB pattern at 100 Mc.,[27] $\Delta\tau$ 0.22, J_{AB} 12.5 c./sec. [g] AB pattern at 100 Mc.,[27] $\Delta\tau$ 0.12, J_{AB} 12.4 c./sec. [h] Concentration 4% (w./v.).

TABLE X[23]

SOLVENT VARIATION OF METHYL PROTON MAGNETIC RESONANCE ABSORPTION OF BRIDGED o,o'-DIMETHYLBIPHENYLS

Solvent[b]	X[a]				
	–[c]	O	N-CH₃[d]	CO	S
CCl₄	7.77	7.80	7.83	7.81	7.92
C₆H₆	7.84	7.97	7.92	7.98	8.06
CS₂	7.81	7.85	7.84	7.85	7.98
CDCl₃	7.75	7.80	7.81	7.80	7.92
C₅H₅N	7.79	7.86		7.87	7.95
C₆H₅NO₂	7.80	7.84		7.86	7.95

[a] Listed from left to right in increasing order of biphenyl angle of torsion (Table IV). [b] Listed in order of increasing dielectric constant. [c] Refers to 9,10-dihydro-4,5-dimethylphenanthrene. [d] This column lists the C-methyl resonances of the N-methylazepine (X = N-CH₃). For N-methyl resonances, see Table VII.
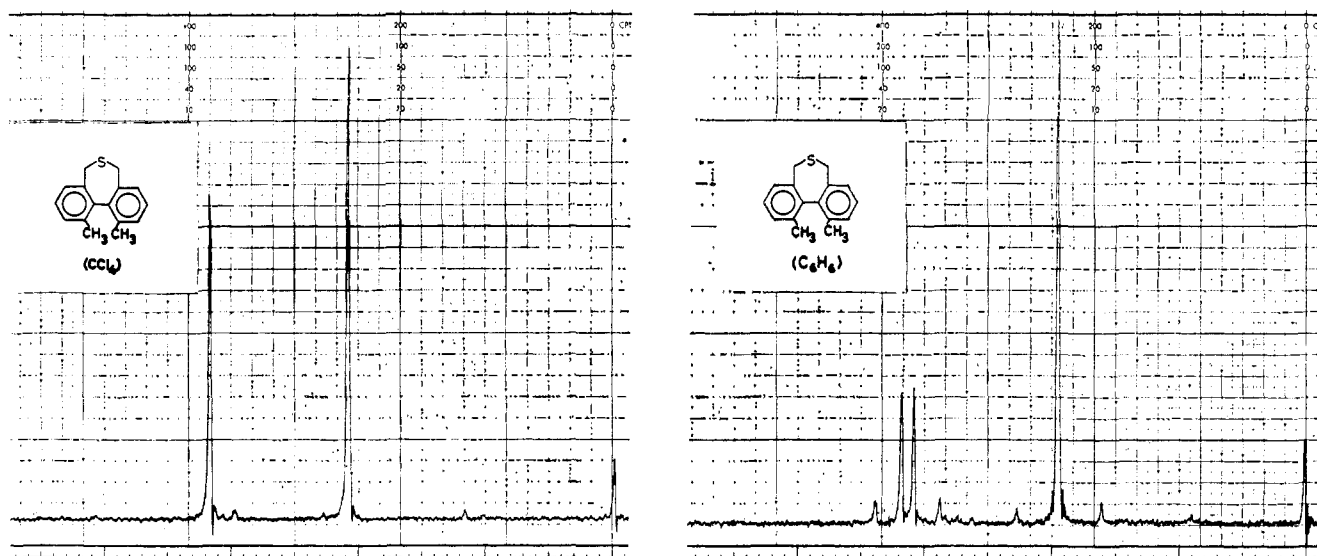
Fig. 7.—N.m.r. spectrum of thiepin Xa (aliphatic region) in carbon tetrachloride and in benzene.

changes in ϕ. The general trend of $\bar\tau$ discussed above, which is also seen in Table V, shows that the average shielding of the methylene protons decreases in the order: bridged o,o'-dimethylbiphenyls, bridged biphenyls, and doubly bridged biphenyls, i.e., from left

TABLE XI[23]

SOLVENT VARIATION OF METHYLENE PROTON MAGNETIC RESONANCE ABSORPTION OF 6,6'-DIMETHYL-2,2'-BIS(BROMOMETHYL)BIPHENYL (XIb)[a]

Solvent	Concn. (% w./v.)	Aromatic	Methylene	Methyl
CCl₄	10	2.70	5.91 (2.0)	8.01
C₆H₆	10		6.06 (1.4)	8.15
CS₂	10	2.73	5.96 (1.5)	8.06
CDCl₃	6	2.64	5.85 (1.8)[b]	8.01
C₆H₅NO₂	10		5.82 (1.5)	8.05
C₁₀H₇Cl[c]	10		6.06 (2.0)	8.30

[a] Absorption positions given in p.p.m. on the τ-scale relative to internal tetramethylsilane. Numbers in parentheses are peak widths at half-height, given in c.p.s. [b] Sharp singlet at 100 Mc.[27] [c] 1-Chloronaphthalene.

to right as listed in Tables V–IX. We take this to be evidence for a change in dihedral angle ϕ (for two of the compounds in Table V, this is an *averaged* change). It seems reasonable to assume that in any given series (Tables V–IX) the bridged o,o'-dimethylbiphenyls have a larger angle of torsion than the analogous compounds which do not have methyl groups in the blocking positions, and this leads to the tentative conclusion that the biphenyl angle of twist in any given row of Tables V–IX decreases in the order of decreasing methylene proton τ-values, with the singly bridged o,o'-dimethylbiphenyls having the largest and the doubly bridged biphenyls the smallest dihedral angle.

The τ-value of the N-methyl group in the azepines (Table VII) is also suggestive of the same trend, since it might be expected that an increase in ϕ would result in a further penetration by the N-methyl group of the shielding portion of the far benzene ring.

The geminal HH spin coupling constants (Tables VI–IX) assume values which lie in ranges characteristic for each series: J_{AB} 10.9–11.5 c.p.s. for the oxepins (Table VI), 12.0–12.8 c.p.s. for the azepines (Table VII), 14.5–15.5 c.p.s. for the ketones (Table VIII), and 12.4–12.7

c.p.s. for the thiepins (Table IX). For any one compound in each series, J_{AB} is solvent independent.[40] Within each series, the doubly bridged biphenyls have J_{AB} values which are on the average larger than those of the corresponding o,o'-dimethylbiphenyls by 0.3–0.4 c.p.s. These results may be rationalized as follows: The characteristic range of values reflects the nature of the substituent attached to the methylene carbon (e.g. oxygen or sulfur) while the small variation within each range reflects the change in ϕ, which may in turn affect the magnitude of the HCH angle.[41]

It is not necessary to bridge the o,o'-positions in order to maintain the diastereoisomerism of the geminal protons in biphenyls.[42] Thus 6,6'-dimethyl-2,2'-bis(hydroxymethyl)biphenyl (XIa) and 6,6'-dimethyl-2,2'-bis(bromomethyl)biphenyl (XIb), both of which have been obtained in optically active and stable form[4] and neither of which is therefore capable of magnetic equivalence of the first kind (see above), would be expected to exhibit methylene AB patterns. This is in fact observed for XIa, whose diastereomeric protons absorb[23] at τ 5.85 and 6.02 with J_{AB} 11.6 c./sec. In contrast to the diol, the dibromide XIb displays a sharp methylene singlet which persists in a wide range of solvents (Table XI) and at 100 Mc.[27]; we can think of no example which better illustrates the danger inherent in drawing stereochemical conclusions from apparent A_2 patterns.

The striking difference in the behavior of XIa and XIb might be related to a difference in the biphenyl angle of torsion ϕ; since the methyl proton resonance signal[23] of XIa occurs at τ 8.16 and that of XIb at 8.01, it may be concluded from Fig. 6, *assuming* the absence of special shielding effects, that the benzene

(40) E. I. Snyder has claimed[38] a solvent dependence of diastereomeric methylene proton coupling constants, *and in this respect his results differ sharply from ours*. On the other hand, he has also interpreted solvent effects on the chemical shifts of diastereomeric methylene protons in terms of intrinsic magnetic nonequivalence of the protons in question, in harmony with our findings; his use of nonrigid systems, however, makes this interpretation less direct. We are grateful to Dr. Snyder for informing us of his results in advance of publication.

(41) H. S. Gutowsky, M. Karplus, and D. M. Grant, *J. Chem. Phys.*, **31**, 1278 (1959); H. J. Bernstein and N. Sheppard, *ibid.*, **37**, 3012 (1962).

(42) W. L. Meyer and R. B. Meyer, *J. Am. Chem. Soc.*, **85**, 2170 (1963). We thank Prof. W. L. Meyer for informing us of his results prior to publication. We also wish to record our indebtedness to Prof. D. G. Farnum, who first brought this possibility to our attention.
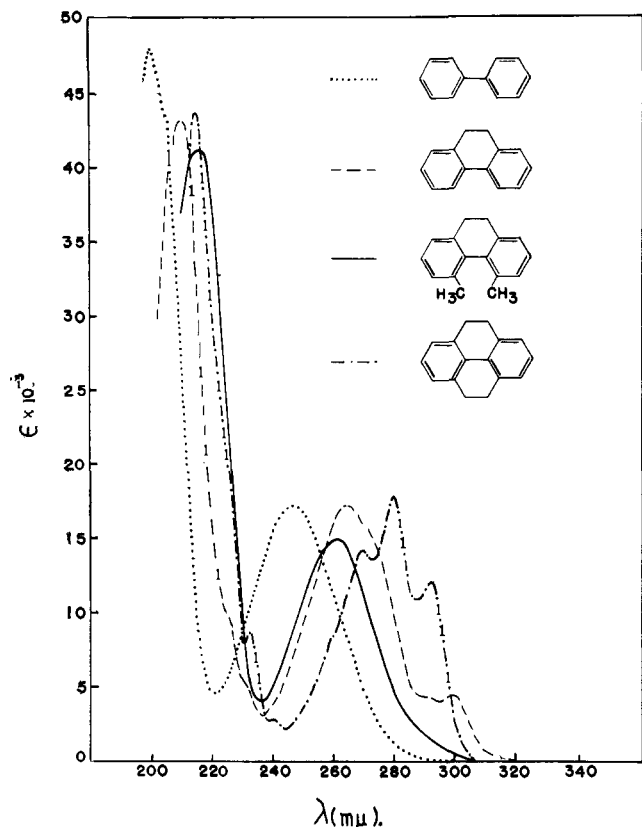
Fig. 8.—Ultraviolet spectra (isooctane) of some six-membered ring bridged biphenyls compared to biphenyl.

Fig. 9 —Ultraviolet spectra of some bridged biphenyl oxepins in isooctane.

rings in the diol XIa are essentially perpendicular while those of the dibromide XIb are inclined at a smaller angle. An alternative explanation might be advanced that hydrogen bonding freezes the conformation of the diol while no such possibility can be envisaged for the dibromide, but recent studies by Meyer and Meyer have cast considerable doubt on the correctness of this view.[43]

Ultraviolet Absorption.—The location of the biphenyl conjugation band depends on the angle of torsion ϕ.[30,32,44,45] We have now compared the ultraviolet spectra (in isooctane) of doubly bridged biphenyls with those of singly bridged biphenyls and the results are recorded in Fig. 8–13. The short wave length features (200–230 mμ) seem to be relatively insensitive to conformation, but we have found unmistakable trends in the location, intensity, and shape of the conjugation bands, all of which can be related to the magnitude of the biphenyl angle of torsion ϕ. To facilitate discussion, the salient data have been collected in Table XII. We shall define by *horizontal series* the series of singly bridged o,o'-dimethylbiphenyls, singly bridged biphenyls, and doubly bridged biphenyls which contain a given bridge substituent X, *e.g.*, the three oxepins (X = O). These series are separately grouped in Fig. 8–13; the order shown in Table XII, from left to right, is the order of increasing angle of torsion ϕ which was established by the n.m.r. study of the methylene and N-methyl proton resonances. By *vertical series* we shall mean the series of variously

(43) Prof. W. L. Meyer, private communication.

(44) H. H. Jaffé and M. Orchin, "Theory and Applications of Ultraviolet Spectroscopy," John Wiley and Sons, Inc., New York, N. Y., 1962, pp. 397–407.

(45) H. Suzuki, *Bull. Chem. Soc. Japan*, **35**, 1715 (1962); see also H. H. Jaffé and O. Chalvet, *J. Am. Chem. Soc.*, **85**, 1561 (1963).
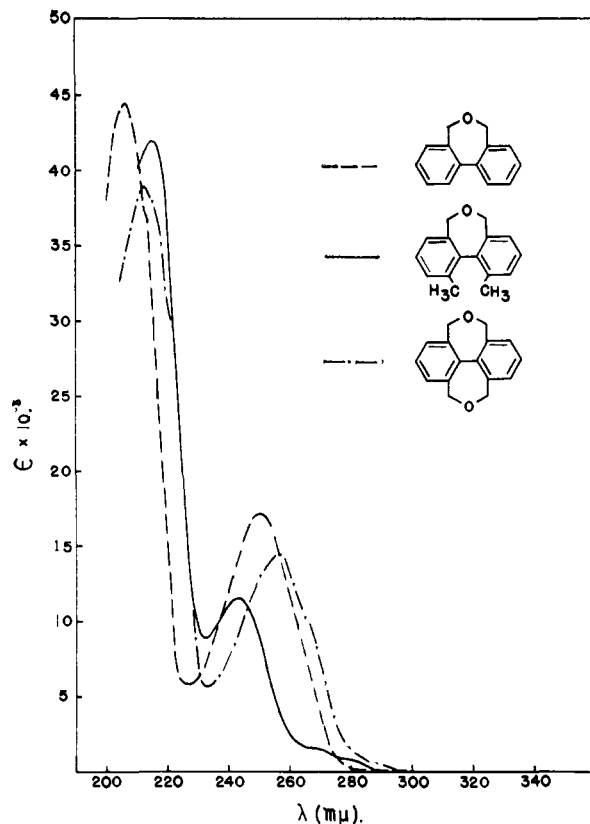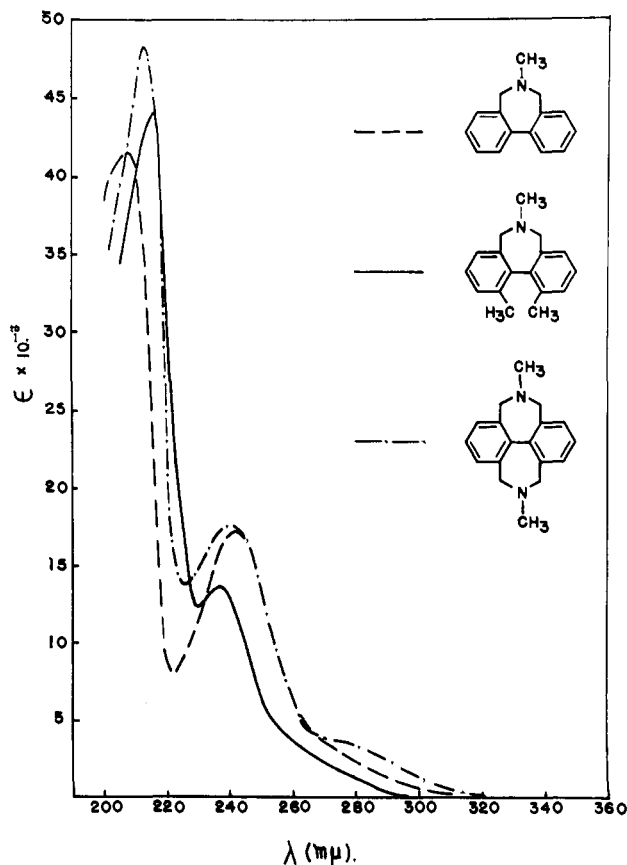
Fig. 10.—Ultraviolet spectra of some bridged biphenyl azepines in isooctane.

bridged biphenyls with constant biphenyl substitution pattern, *i.e.*, the three series separately listed in Tables I–III. The order shown in Table XII, from top
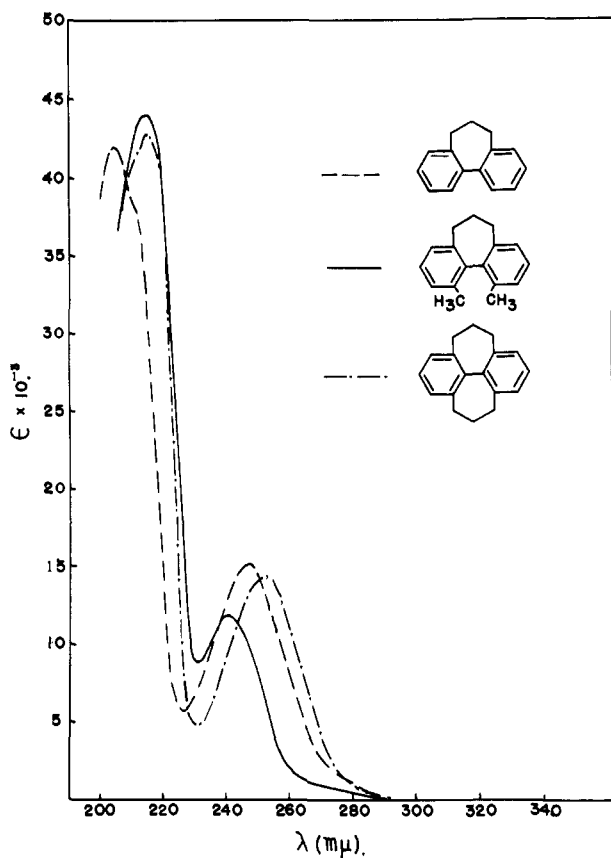
Fig. 11.—Ultraviolet spectra of some seven-membered ring bridged biphenyl hydrocarbons in isooctane.
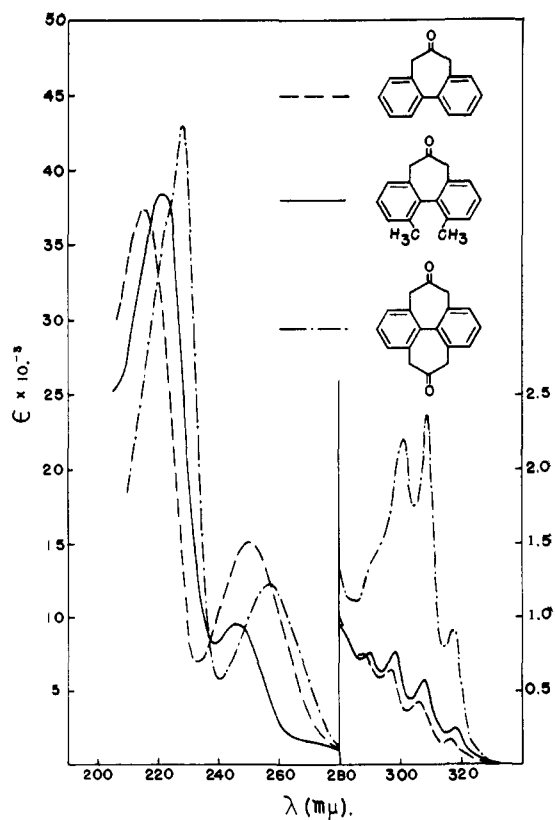

Fig. 12.—Ultraviolet spectra of some bridged biphenyl ketones in isooctane: on the right, n → π* region; on the left, π → π* region.

to bottom, is again the order of increasing angle of torsion as calculated from molecular dimensions
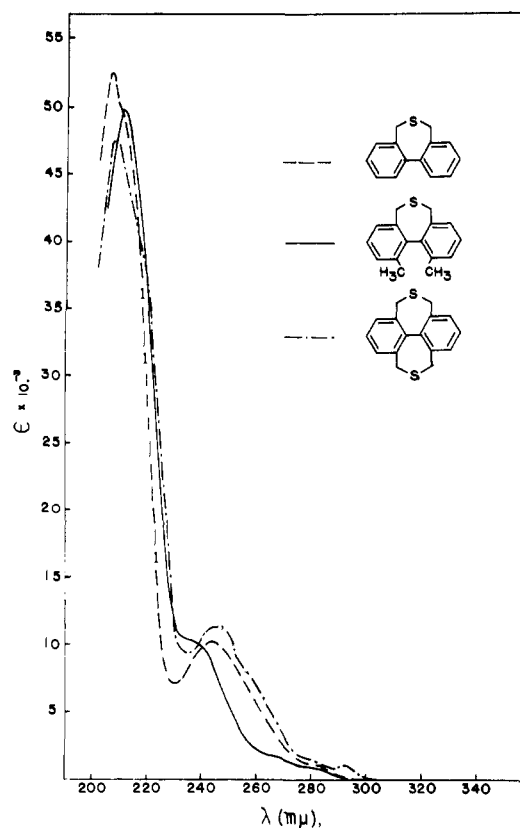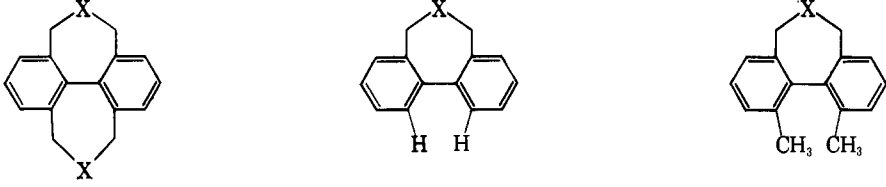

Fig. 13.—Ultraviolet spectra of some bridged biphenyl thiepins in isooctane.

(Table IV) and as established by the n.m.r. study of the C-methyl proton chemical shifts. For comparison purposes we note that biphenyl itself has $\lambda_{max}^{isooctane}$ 247 mμ (ϵ 17,200) and $\Delta\nu$ 5600 cm.$^{-1}$.

It is found that the maximum of the conjugation band (λ_{max}) in all but one (the azepines) of the six horizontal series is shifted to shorter wave lengths as the angle of torsion ϕ increases. Similarly, with the exception of the azepines and of the carbonyl compounds which will be discussed below, λ_{max} in each of the three vertical series is also shifted to shorter wave lengths as ϕ increases. These blue shifts are accompanied in general (though not invariably) by a lowering of the molecular extinction coefficients. Both the blue shifts and the reductions in absorption intensity can be accommodated by Suzuki's model[45] which quantitatively relates changes of λ_{max} and ϵ_{max}[46] to changes in ϕ. The peculiar behavior of the azepines suggests interaction between the nonbonding electrons on nitrogen and the benzene π-electrons. This hypothesis is supported by the observation (Table XII) that spectra of solutions of the salts are normal, in the sense that the positions of the maxima fit the angle-dependent relationship discussed above; the intensities of the maxima, however, are abnormal.

Among the compounds studied in the present work, 4,5,9,10-tetrahydropyrene has the highest value of λ_{max} as well as of ϵ_{max}. Indeed, to our knowledge 280 mμ is the longest wave length maximum thus far reported for the conjugation band of an undistorted

(46) Suzuki's model[45] for the change of ϵ_{max} with ϕ appears to be in conflict with an earlier approach by H. H. Jaffé and M. Orchin, J. Chem. Soc., 1078 (1960). The correspondence of theoretical and experimental oscillator strengths found by Suzuki is fairly satisfactory. In the present treatment, possible complications by hyperconjugative interactions of the substituents are neglected.

TABLE XII

CONJUGATION BAND CHARACTERISTICS OF BRIDGED BIPHENYLS IN ISOOCTANE[a]

X	λmax, mμ	εmax ×10⁻²	Δν, cm⁻¹	λmax, mμ	εmax ×10⁻²	Δν, cm⁻¹	λmax, mμ	εmax ×10⁻²	Δν, cm⁻¹
b	280[c]	176	4530	264	172	4630	261	150	4460
O	256	144	4670	250	171	4670	243	115	d
N–CH₃	241	176	d	241.5	171	5800	236.5	136	d
N–CH₃[e]	255.5	143	4940	248.5	39	5170	242[f]	102	d
CH₂	252	142	4450	247.5	151	4790	240.5	117	d
CO	256.5	122	4150	250	152	4490	246	99	d
S	245.5	114	d	244	102	d	236	103 (sh)	d

[a] Wave lengths have been rounded off to the nearest 0.5 mμ. The half-band width Δν is the measured width of the band at ε = 0.5εmax. [b] From left to right: 4,5,9,10-tetrahydropyrene, 9,10-dihydrophenanthrene, 9,10-dihydro-4,5-dimethylphenanthrene. [c] Satellite peaks at λmax 292.5 mμ (ε 11,800), 269.5 (14,200), and 260 (8430 sh); λ_{max}^{EtOH} 292 mμ (ε 12,000), 280 (17,600), 270 (14,300), 261 (6460 sh). [d] A measurement was precluded by the extensive overlap of the conjugation band with the short wave length band. [e] In 6 N hydrochloric acid. [f] In addition, a pronounced band with λmax 272 mμ (ε 3800).

biphenyl.[47] In this connection we draw attention to the conspicuous *solvent-independent* fine structure in the ultraviolet spectrum of 4,5,9,10-tetrahydropyrene, which contrasts with the essentially structureless spectra of the other compounds listed in Table XII. Suzuki has discussed[45] the dependence of the shape of conjugation bands on the dihedral angle of the interacting π-systems, and he has pointed out that increased fine structure is in general expected to accompany a decrease in φ. If this explanation applies to the present case, the vibrational contour of the conjugation band, which is unique for an undistorted biphenyl,[47] is a consequence of and constitutes further evidence for the virtual planarity of the biphenyl moiety in 4,5,9,10-tetrahydropyrene.

Variations in the half-band width Δν have also been examined, but the data (Table XII) are inconclusive.

It had previously been recognized[15,48] that the spectroscopic coupling of the nonconjugated biphenyl and carbonyl transitions accounts for the exaltation, red shift, and high rotational strength of the long wave length n → π* transition in the bridged ketones and this effect now is seen again in the doubly bridged ketone which displays the intensity and pronounced fine structure (in isooctane) found to be characteristic of the strengthened n → π* transitions.[15,48] As the result of the present comparative ultraviolet study, there is now at hand unequivocal evidence for a red shift also of the near π → π* transitions. As noted before, the conjugation band of the ketones in the three vertical series has been displaced. Since the position of λmax (of the conjugation band) depends on φ, one might have expected λmax of the ketones to be located between λmax of the hydrocarbons and λmax of the thiepins. In fact (Table XII), λmax of the ketones occupies a position nearer λmax of the oxepins, suggesting a 5–10 mμ red shift. Even more remarkable in this respect is the response of the short wave length transitions (Fig. 8–13)

to the presence of a carbonyl group in the bridge; when the ketone is compared with *any* of the other five compounds in the corresponding vertical series, it is found that the intense benzene band near 210 mμ has suffered a 5–10 mμ red shift in the two single bridged series and a 13–20 mμ red shift in the doubly bridged series. The present findings are completely compatible with the views previously expressed,[15,48,49] according to which the interaction of benzene and carbonyl π-systems in the electronically excited state is principally responsible for the lowering of the energy of the separate transitions.

It remains to be reiterated that the ultraviolet spectrum of 9,10-dihydro-4,5-dimethylphenanthrene is normal, in the sense that λmax, εmax, and the shape of the band envelope conform to the general pattern set by the other bridged biphenyls and discussed above in terms of biphenyl angles of torsion φ. There thus appears to be no evidence for a significant distortion of the biphenyl π-system in this compound. It follows that the abnormally high shielding value of the methyl protons (preceding section) is most probably attributable to displacements of the methyl groups out of the plane of the attached benzene rings as a consequence of nonbonded repulsive interactions.

Optical Rotatory Dispersion.—The conjugation band of bridged biphenyls is optically active; the twisted π-system constitutes an inherently dissymmetric chromophore of high rotational strength.[15] The sign of the relevant Cotton effect, which reflects the absolute sense of twist (chirality) of the extended π-system, is positive for the (R)-configuration of symmetrically substituted bridged (φ < 90°) biphenyls.[15] Since the compounds used in the present study were bridged biphenyls of known absolute configuration, we were presented with an opportunity to extend the scope of the earlier investigation.

In accord with expectations, the doubly bridged dithiepin (+)-(R)-IV in dioxane has a positive Cotton effect centered at 253 mμ, near the conjugation band (Fig. 14). The high molecular amplitude of 480,000°

(47) A comparison with the ultraviolet absorption spectra of fluorene and 4,5-ethanofluorene is not meaningful, since the biphenyl system in these strained molecules is not collinear (cf., e.g., G. M. Brown and M. H. Bartner, *Acta Cryst.*, **7**, 139 (1954)).

(48) A. Moscowitz, K. Mislow, M. A. W. Glass, and C. Djerassi, *J. Am. Chem. Soc.*, **84**, 1945 (1962).

(49) L. Labhart and G. Wagnière, *Helv. Chim. Acta*, **42**, 2219 (1959).
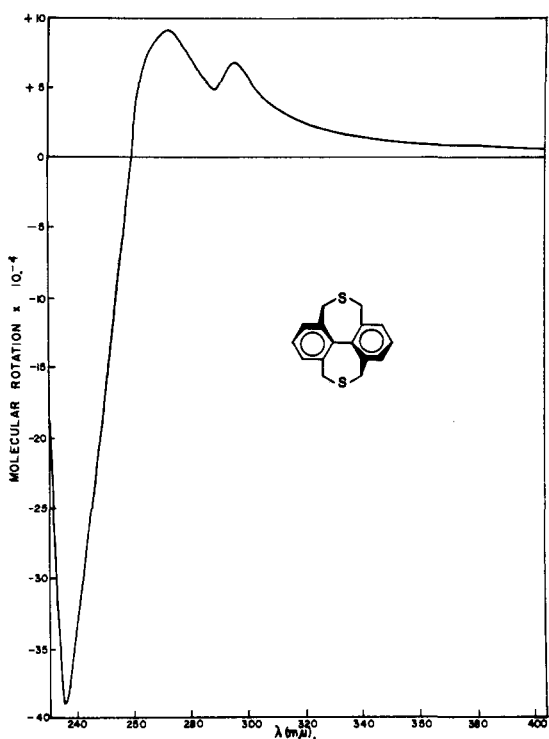
Fig. 14.—Optical rotatory dispersion of dithiepin (R)-IV in dioxane.

Fig. 16.—Optical rotatory dispersion of oxepins IXa,b in dioxane.

Fig. 15.—Optical rotatory dispersion of diketone (S)-IIa in dioxane.
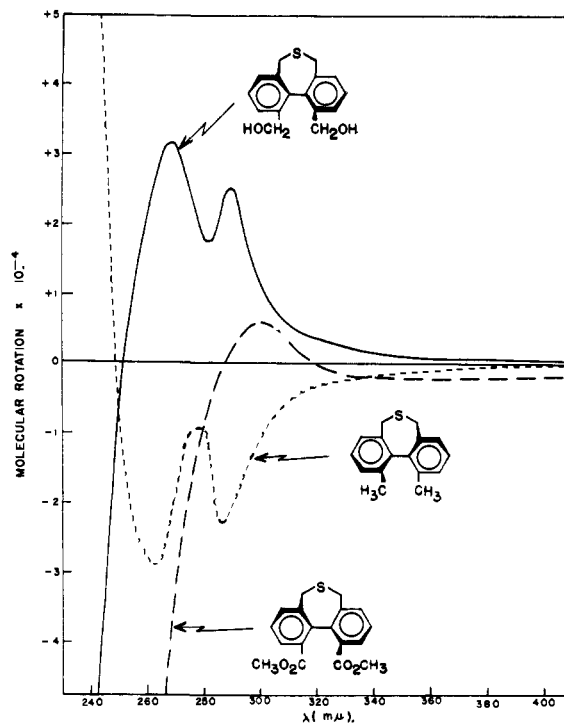
Fig. 17.—Optical rotatory dispersion of thiepins Xa–c in dioxane.

is typical for conjugation band Cotton effects of seven-membered ring bridged biphenyls. Similarly, the strong background rotation whose sign is *opposite* to that of the conjugation band (*i.e.*, in this case negative) and the low-amplitude Cotton effect at longer wave lengths whose sign is the *same* as that of the conjugation band Cotton effect are typical of a bridged biphenyl.[15] The O.R.D. results are confirmed by measurements of the circular dichroism curve[50] of

(R)-IV in dioxane which has positive maxima at 295 and 258 mμ with molecular ellipticity values of 45,300 and 258,000, respectively.

The optical instability of dioxepin IIIa and the unavailability of optically active hydrocarbon I and

TABLE XIII

RACEMIZATION RATES AND ARRHENIUS PARAMETERS OF DOUBLY BRIDGED BIPHENYLS

Compound	Diketone IIa				Dioxepin IIIa		Oxathiepin IIIb			Dithiepin IVc		
Temp., °C.	95.0	105.0	114.8	0.1	10.1	23.3	84.6	104.9	125.3	205.0	215.0	225.0
Concn., g./100 ml.[a]	0.50	0.96	1.45	1.53	1.60	1.75	0.53	0.22	0.19	0.17	0.17	0.17
α_{436} at t_0 (l 2)[b]	+4.58°	+4.14°	−6.90°	+6.90°	+5.03°	+2.73°	+10.79°	+4.64°	+4.06°	+4.79°	+4.52°	+4.11°
$k_1 \times 10^4$, sec.⁻¹	1.01₅	3.10	8.99	0.562	2.12	10.7	0.0605	0.640	4.94	1.54	3.37	6.73
$t_{0.5}$, min.	114	37	13	205	54	11	1902	181	23	75	34	17
Span of observation (in units of $t_{0.5}$)	2.1	3.2	3.5	0.75	1.8	2.7	0.11	1.3	1.4	2.4	3.5	2.6
$E_{act.}$, kcal./mole		31.2			20.4			30.6			35.0	
log A, sec.⁻¹		14.5			12.1			13.5			12.2	

[a] Solvent o-xylene. [b] t_0 was taken as the time of the first measurement, usually about 5 min. after the sample had been placed in the thermostated bath. [c] These figures refer to loss of activity with some decomposition; see text.

azepine IIIc precluded measurement of the O.R.D. of these doubly bridged biphenyls. The O.R.D. curve of diketone (−)-IIa, to which the (S)-configuration had been assigned on mechanistic grounds (see above), displays a carbonyl n → π* Cotton effect (Fig. 15) centered near 305 mμ whose fine structure and high molecular amplitude of 79,200° are characteristic of dissymmetric β,γ-unsaturated ketones.[15,48,51,52] The negative sign of the Cotton effect accords with the chirality of the (S)-configuration.[15,48,51] The C.D. curve[50] of IIa in dioxane has a negative maximum at 305 mμ with a molecular ellipticity of 52,700.[52]

The O.R.D. curves of the singly bridged biphenyls IXa and IXb (Fig. 16) and Xa–c (Fig. 17) were also recorded as part of this study. Oxepin IXb and thiepins Xa and c display positive Cotton effects for the (R)-configuration, and although only the long wave length extremum of the conjugation band Cotton effect was recorded, a related circular dichroism study[50] of the enantiomer (S)-Xa disclosed two negative maxima at 284 and ca. 240 mμ with molecular ellipticities of 22,000 and 162,000, respectively.

The diesters IXa and Xb, however, deviate significantly from the pattern set in this and the preceding[15] O.R.D. study. While the information on Xb is incomplete, oxepin diester IXa is observed to have a very high-amplitude (134,000°) Cotton effect centered at 256 mμ (corresponding to the λmax at 258 mμ (shoulder)) which is negative for the (R)-configuration of the biphenyl. In contrast, the derived diol (R)-IXb has λmax at 245 mμ (the biphenyl conjugation band) and has a positive Cotton effect centered near 240–250 with the long wave length extremum at 254 mμ; it is in all essential respects identical with the closely related dimethyl compound[15] IXc which has λmax at 244 mμ, and which has a positive Cotton effect for the (R)-configuration centered at ca. 240 mμ, with the long wave length extremum situated at 252 mμ. It is therefore apparent that the Cotton effect observed for IXa and probably also for Xb does not correspond simply to the biphenyl conjugation band but is associated with more extensive conjugation which includes the carbomethoxy groups. In support of this conclusion, the O.R.D. curve of the

unbridged analog 6,6′-dimethyl-2,2′-diphenic acid dimethyl ester (λmax 237 mμ (shoulder)) shows a rather similar pattern in what appears to be the extremum of a negative Cotton effect for the (R)-configuration.[15] Inspection of models indicates that the carbomethoxy groups are dissymmetrically twisted relative to the phenyl rings, and that the predominant sense of twist is determined by the absolute conformation of the biphenyl moiety. This in turn suggests that the sign of the observed Cotton effect is a reflection of the absolute chirality of this novel dissymmetric chromophore.[4] In this connection we note that the Cotton effects observed earlier with dinitrobiphenyls[15] may similarly involve dissymmetrically twisted nitrobenzene chromophores; experiments are in progress to clarify this point.

Racemization Studies

Experimental Optical Stabilities.—The rate constants of racemization of the doubly bridged biphenyls were obtained as described in the Experimental part and the results are collected in Table XIII. Several points are worth noting. First, the complete or nearly complete loss of optical activity on heating supports the structures assigned to II–IV. Second, while the products of racemization of optically active II and III had retained their structural identity, the product of racemization of IV had suffered some decomposition and the values reported for IV are therefore less accurate. Finally, we note that the values for log A fall in the range 12.1 to 14.5, which is the range reported for most singly bridged biphenyls.[5,53]

Discussion.—Biphenyls which are substituted in all four o-positions by alkyl groups are conformationally stable even at elevated temperatures. This generalization breaks down in the cases of some singly bridged[29] and most doubly bridged biphenyls. It is of interest to consider the factors which are responsible for this decrease in the activation energy of racemization. Since the symmetrically bridged biphenyls are the subject of the present study, discussion will be limited to the class of compounds exemplified by 4,5,9,10-tetrahydropyrene and by compounds I–IV.

If the biphenyl angle of torsion φ is taken to be zero in the transition state of racemization, it follows that the greater the angle φ in the ground state, the greater will be the change in angle of torsion Δφ, which the molecule must suffer in going from the ground to the transition state. It may now be argued that, within a given series of compound, the magnitude of Δφ will reflect the extent of molecular strain provided (a) that the deformations are equal in number and in kind, and (b) that the various force constants are similar. Since the

(51) K. Mislow and J. G. Berger, J. Am. Chem. Soc., 84, 1956 (1962).

(52) The molecular amplitude and ellipticity are only about half as large as those reported for the singly bridged analogous monoketone, dimethyldibenzsuberone.[15,50] Since the extinction of the diketone in the n → π* region is about four times that of the monoketone (Fig. 12), and since the increased intensity of the transition is reflected in enhanced rotational strength, one would have expected a much higher molecular amplitude for the n → π* Cotton effect in IIa, perhaps close to 500,000°. This suggests that the sample of ketone is, very approximately, 15–20% optically pure, a figure which is not at all unreasonable when compared with the optical yields of similar kinetic resolutions.[10-12] Because of the low optical purity of the sample, we were prevented from recording the expected[15] biphenyl conjugation band Cotton effect at shorter wave lengths (in a spectral region of high optical density), either by O.R.D. or by circular dichroism[50] measurements.

(53) D. M. Hall and M. M. Harris, J. Chem. Soc., 490 (1960).

energy barrier (E_{act}) is expected to parallel the strain, it would therefore seem that for any given *vertical* series in Table XII the values of E_{act} should parallel the values of $\Delta\phi$ and ϕ. This naive view gives a qualitatively correct picture. The calculated effect of variations in bridge substituent on the ground-state angle of torsion ϕ (Table IV) has been qualitatively substantiated by the n.m.r. and ultraviolet studies.[54] The parallelism between E_{act} and ϕ had already been pointed out in the n.m.r. study of the singly bridged biphenyls where it had been found that the thiepin, which has the largest ground-state angle of torsion in the series, is also the compound which shows the greatest conformational stability in the same series. The same trend is evident in the series of doubly bridged biphenyls, where the experimentally determined E_{act} of racemization increases in the order of increasing ϕ, *i.e.*, IIIa < IIa < IV (Tables IV and XIII). Qualitatively this view explains our finding that hydrocarbon I could not be obtained in optically active form. With an optical stability greater than that of dioxepin IIIa but substantially below that of diketone IIa, the complete racemization of I or of the precursor bisthioketal VII under the conditions of preparation can be readily accounted for.

It is not legitimate to extend the parallelism between E_{act} and ϕ to any series of biphenyls in which the deformations are not equal in number and kind, *e.g.*, to members within any horizontal series of Table XII. This point may be illustrated by the example of the oxepins where information happens to be available on the optical stability of all three members of the series. The ultraviolet and n.m.r. studies have clearly revealed that the biphenyl angle of torsion ϕ is greatest for the singly bridged *o,o'*-dimethylbiphenyl and smallest for the doubly bridged biphenyl, with the singly bridged biphenyl occupying an intermediate position. The singly bridged *o,o'*-dimethylbiphenyl is also the most optically stable member of the series (it is not racemized below 100°), but the singly bridged biphenyl, with E_{act} 9.3 kcal./mole,[26] has no optical stability at room temperature while the doubly bridged biphenyl IIIa, with E_{act} 20.4 kcal./mole (Table XIII), occupies an intermediate position. This apparent reversal of the E_{act}–ϕ relationship is readily accounted for (qualitatively) by the fact that the number and the kind of deformations are different in the singly and in the doubly bridged biphenyls.

In order to estimate quantitatively the E_{act} of racemization, it is necessary to compute the difference in enthalpy between the ground-state conformation and the transition-state conformation; this difference is the strain energy E_s. The object is to compute E_s from available molecular dimensions and from a knowledge of the relevant functions which relate the energy of the system to the molecular dimensions.[55] We shall show in the following that the observed E_{act} and the calculated E_s of doubly bridged biphenyls are in excellent agreement.

In connection with an earlier conformational analysis of the singly bridged biphenyls[5] we remarked on the

unsatisfactory state of knowledge of (a) the molecular dimensions of the transition state of racemization and (b) the potential functions and parameters relating energy and geometry. To these comments we now add the opinion that our knowledge of the ground-state geometries is also seriously deficient.

The geometry of a molecule in its ground-state conformation is in principle obtainable by a minimization of the strain energy.[56] This is commonly considered to be a composite of four factors: valence bond stretching, valence angle bending, torsion about dihedral angles, and nonbonded interaction. A fifth factor, lattice forces which constrain the conformation in the crystal structure, must be considered in discussions of conformations in the solid state. The first two energies supposedly follow a Hooke's (quadratic) law, the torsional energies a cosine law, and the nonbonded interaction terms some form of van der Waals potential. The reliability of molecular dimensions thus computed depends in large measure on a proper choice of the relevant force constants, torsional barriers, and van der Waals parameters.

Inspections of molecular models is therefore clearly unsatisfactory for the disclosure of subtle conformational effects. For instance, Dreiding models only respond to gross changes in angle strain and bond stretching and are completely insensitive to torsional and nonbonded strain. It follows that *the spectroscopic evidence for a change of the biphenyl angle of torsion in the horizontal series of singly and doubly bridged biphenyls is acceptable despite the complete lack of corresponding evidence from the examination of Stuart–Briegleb or Dreiding models.*[57] At the same time a new factor of uncertainty has been introduced in the quantitative estimate of E_s, since even the average *ground*-state conformation of the bridged biphenyls is not accurately known. It seems reasonable to assume that the values of ϕ listed in Table IV, which were calculated by neglecting torsional and nonbonded strain, come closest to describing the average dihedral angle in the relatively most rigid singly bridged *o,o'*-dimethylbiphenyls, and that ϕ is somewhat smaller for the singly bridged and smaller yet for the doubly bridged biphenyls in the same horizontal series. However, it is not obvious *why* the angle of twist in the doubly bridged biphenyls should be smaller than that in the corresponding singly bridged biphenyls, nor are the absolute differences between the angles ϕ in each horizontal series known.

The geometry of the transition state is of course even more uncertain. We have assumed that bond lengths remain invariant and that the biphenyl skeleton remains collinear and undistorted. This last assumption is

(56) For some recent examples, see J. B. Hendrickson, *J. Am. Chem. Soc.*, **83**, 4537 (1961); C. A. Coulson and C. W. Haigh, *Tetrahedron*, **19**, 527 (1963).

(57) Confirmation of the order of change of ϕ in the horizontal series comes from an entirely different quarter. It has been observed by Mr. A. J. Gordon in our laboratory that the g.l.c. retention times of 9,10-dihydro-4,5-dimethylphenanthrene, 9,10-dihydrophenanthrene, and 4,5,9,10-tetrahydropyrene (on a 6 ft. × 0.25 in. 10% Dow 710-on-Chromosorb-P column at 225° and 200 cc./min. He carrier flow rate) are, respectively, 12, 15, and 26 min. It has also been pointed out by E. A. Johnson (in "Steric Effects in Conjugated Systems," Academic Press, Inc., New York, N. Y., 1958, Ch. 15) that the retention times or volumes in g.l.c. are rough measures of the degree of interaction with the stationary phase and hence of the degree of planarity in bridged and unbridged alkylbiphenyls. The order of increasing retention times in the present case does in fact parallel the order of decreasing biphenyl angle of torsion as judged from n.m.r. and ultraviolet evidence.

(54) The ultraviolet spectroscopic studies refer to the electronically excited states and the conformations of those states are presumed to be quite similar to those of the ground states, with essentially unchanged angles of torsion (Franck–Condon principle).

(55) F. H. Westheimer in M. S. Newman "Steric Effect in Organic Chemistry," John Wiley and Sons, Inc., New York, N. Y., 1956, Chapter 12.

possibly more valid for the doubly bridged than for the singly bridged biphenyls, by reason of the high degree of constitutional symmetry in the former compounds. The problem of calculating E_s is greatly simplified if nonbonded interactions are neglected, and this seems to be justified in the case of some six-membered ring bridged biphenyls. For 4,5,9,10-tetrahydropyrene a value for E_s ($= E_{act}$) of 7–8 kcal./mole may then be calculated as follows. Since the actual dihedral biphenyl angle is not known, it is assumed that the value of ϕ is that given in Table IV, even though for the singly bridged and doubly bridged biphenyls in each horizontal series this value is believed to be somewhat too high. Assuming $\phi = 15°$, models show that the dihedral angle of the opposing hydrogens in each bridge is about 40°. If V_0 is taken as 2.8 kcal./mole, the total torsional strain resulting from the eclipsing of the ethane-like bonds may then be estimated at 4 kcal./mole. The opening of the internal bridge angles (from 120 to 124° and from 110 to 117°) requires another 4 kcal./mole, if we accept the usual value[55] of 0.8×10^{-11} erg rad^{-2} for the CCC bending force constant. Finally, about 0.5 kcal./mole of π-electron delocalization energy[58] is gained when ϕ changes from the assumed 15 to 0°. Similarly, 9,10-dihydrophenanthrene is calculated to racemize with $E_{act} \approx 4$ kcal./mole.[59] In this case the π-delocalization energy is almost exactly offset by the nonbonded repulsion between the two hydrogen atoms in the 4,5-positions,[58] again assuming a change of ϕ from 15 to 0°.

The treatment of the seven-membered ring bridged biphenyls is far more complex and some estimates were made in earlier work.[5] We have now carried out some calculations using the "buckled bridge" model[5] in which it has been arbitrarily assumed that angle deformations and π-delocalization energies are chiefly responsible in determining the value of E_{act} for the doubly bridged biphenyls. If bending force constants[55,60] of 0.8, 1.27, and 0.98 $\times 10^{-11}$ erg rad^{-2} are taken for CCC, COC, and CSC angles, respectively, and if the previous model[5] is employed, with the additional assumptions (a) that "cis"-buckled and "trans"-buckled transition states differ negligibly in energy and (b) that van der Waals interactions may be neglected, the calculated values of E_s are: for dioxepin IIIa, 22 kcal./mole; for hydrocarbon I, 29 kcal./mole; for diketone IIa, 33 kcal./mole; for dithiepin IV, 37 kcal./mole. The agreement with E_{act} (Table XIII) is remarkably good. Furthermore, the same treatment results in a calculated E_{act} of 9 and 17 kcal./mole for the singly bridged oxepin and thiepin, respectively, in excellent accord with the value found by Kurland.[26] On the other hand, the value calculated for the singly bridged seven-membered ring hydrocarbon (13 kcal./mole) is probably too low.[5]

Considering the many assumptions and approximations which were made in this treatment, the excellent agreement between theory and experiment is probably largely accidental and may be the result of a fortuitous canceling of errors. It should also be pointed out that the best value for the CCC bending force constant[61]

may actually be closer to $1.0–1.2 \times 10^{-11}$ erg rad^{-2}, and this means that a serious absolute error is introduced in the present calculations through use of the most popular figure[55] of 0.8×10^{-11} erg rad^{-2}. Further, the apparent bending force constant is not constant but decreases with increasing bond angle strain,[55,61] though in the present calculations none of the angle deformations exceed 20°, the upper limit of the "crude but useful approximation" of Westheimer.[55] Whatever the objection to our treatment, however, the remarkable agreement between calculated and found strain energies cannot be gainsaid.

A Conformational Kinetic Isotopic Effect.—The availability of the diketone IIa and of its octadeuterio derivative IIb suggested to us the search for a possible isotope effect in the rate of racemization of this biphenyl. When solutions of optically active IIa ($[\alpha]^{25}_{435}$ $-894°$ (CHCl$_3$)) and IIb ($[\alpha]^{26}_{435}$ $-330°$ (CHCl$_3$)) in freshly distilled mesitylene were separately examined in a 2-dm. polarimeter tube maintained at $95.0 \pm 0.1°$ over periods of approximately one half-life (100–155 min.), it was found that $k_H = 1.05 \times 10^{-4}$ sec.$^{-1}$ and $k_D = 0.99 \times 10^{-4}$ sec., so that $k_H/k_D = 1.06$. Enol formation under these conditions was ruled out by an experiment in which a mixture of IIb, n-butyl alcohol, and toluene was heated at $95.0 \pm 0.1°$ for 120 min.; it was found (n.m.r.) that IIb had not exchanged its α-deuterons in the process.

The observed secondary kinetic isotope effect is the first of its kind[62] reported for a purely conformational change.[63] In total magnitude the observed k_H/k_D is comparable to that of more conventional secondary kinetic isotope effects, but $\Delta\Delta G^{\ddagger}$ per deuterium atom is only 5–6 cal./mole. A detailed assessment of the source of such a small effect is unwarranted, the more so because (a) the detailed geometry of the transition state is still a matter of conjecture and (b) the isotope effect is a composite of the different effects contributed by each of the two diastereomeric methylene protons.

Experimental[64,65]

2,2′,6,6′-Tetrakis(bromomethyl)biphenyl (V).—N-Bromosuccinimide (107 g.) and benzoyl peroxide (0.7 g.) were added to

(62) For recent reviews, cf. A. Streitwieser, Jr., Ann. N. Y. Acad. Sci., **84**, 576 (1960), and R. E. Weston, Jr., Ann. Rev. Nucl. Sci., **11**, 439 (1961).

(63) Equilibrium isotope effects for purely conformational changes are known; cf. D. R. Lide, Jr., J. Chem. Phys., **29**, 1426 (1958), for the example of deuterated ethanes.

(64) Melting points are corrected. Elemental analyses and molecular weight determinations were performed by Schwarzkopf Microanalytical Laboratory, Woodside, N. Y. Deuterium analyses were determined by J. Nemeth, Urbana, Ill., by the falling drop method. Ultraviolet absorption spectra were measured on a Cary 15 recording spectrophotometer. Optical rotary dispersion curves were measured on a Rudolph automatic recording spectropolarimeter. Model 260/655/850/810-614. Unless otherwise specified, nuclear magnetic resonance spectra were measured on a Varian A-60 spectrometer and refer to 8–10% solutions in deuteriochloroform with tetramethylsilane serving as internal standard. Infrared spectra were measured on a Baird–Atomic Model 4-55 spectrophotometer equipped with sodium chloride optics.

(65) The nomenclature used to describe doubly bridged biphenyls is based on the dibenzo[ef,kl]heptalene parent system, numbered as shown.
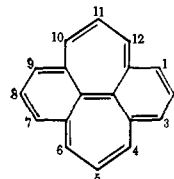
We are grateful to Mr. Leonard T. Capell, Nomenclature Director of the Chemical Abstracts Service, The Ohio State University, Columbus 10, Ohio, for helpful correspondence.

(58) F. J. Adrian, J. Chem. Phys., **28**, 608 (1958).

(59) K. E. Howlett, J. Chem. Soc., 1249 (1955), computes $E_{act} = 1.4$ kcal./mole for 9,10-dihydrophenanthrene but neglects torsional strain.

(60) H. Siebert, Z. anorg. allgem. Chem., **271**, 65 (1952).

(61) Prof. H. J. Dauben, Jr., private communication.

a solution of (±)-6.6'-dimethyl-2,2'-bis(bromomethyl)biphenyl[66] (110 g.) in dry benzene (300 ml.). The mixture was kept under reflux for 12 hr., cooled, and filtered to remove succinimide. The filtrate was evaporated and the residue was triturated with ligroin and methanol. The resulting solid was recrystallized from ligroin–benzene or from n-propyl alcohol to give 45 g. (29%) of crystals, m.p. 172–173.5° (lit.[9] m.p. 167.5–168°).

Anal. Calcd. for $C_{16}H_{14}Br_4$: C, 36.54; H, 2.68; Br, 60.78. Found: C, 36.64; H, 2.79; Br, 60.82.

2,2',6,6'-Tetrakis(cyanomethyl)biphenyl.—A mixture of tetrabromide V (45 g.), potassium cyanide (45 g.), n-propyl alcohol (1 l.), and water (300 ml.) was heated under reflux for 10 min. The mixture was then cooled (ice bath) for 0.5 hr. and filtered. The solid material was suspended in 500 ml. of boiling glacial acetic acid, the insoluble material (1.5 g.) was removed by filtration, and the filtrate was concentrated to a volume of 400 ml. and allowed to stand overnight. The crystalline deposit was collected by filtration and thoroughly washed with hexane. The product thus obtained (15 g., 57%) had m.p. 195–197° after recrystallization from n-propyl alcohol, λ_{max}^{KBr} 4.43 μ (intense, sharp) indicative of C≡N.

Anal. Calcd. for $C_{20}H_{14}N_4$: C, 77.40; H, 4.55; N, 18.06. Found: C, 77.48; H, 4.61; N, 17.90.

4(10 or 12)-Dicyano-4,5,6,10,11,12-hexahydrodibenzo[*ef,kl*]-heptalene-5,11-diimine (VI).—A solution of sodium (1.7 g.) in absolute methanol (50 ml.) was added to a solution of 2,2',6,6'-tetrakis(cyanomethyl)biphenyl (1.0 g.) in absolute methanol (150 ml.). The mixture was refluxed for 30 min., and the precipitated solid (0.66 g., m.p. above 350°) was collected by filtration and was recrystallized from boiling diethylene glycol. There was thus obtained 0.30 g. (30%) of fine, colorless crystals, m.p. *ca.* 390–400° dec. The infrared spectrum exhibited intense bands at λ_{max}^{KBr} 2.92 and 2.99 (=N—H), 4.55 (C≡N), and 6.03 μ (C=N).

Anal. Calcd. for $C_{20}H_{14}N_4$: C, 77.40; H, 4.55; N, 18.06. Found: C, 77.41; H, 4.76; N, 17.95.

(±)-4,5,6,10,11,12-Hexahydrodibenzo[*ef,kl*]heptalene-5,11-dione (IIa).—A mixture of bisiminonitrile VI (1.9 g.), 85% phosphoric acid (55 ml.), and glacial acetic acid (55 ml.) was refluxed for 12 hr. The clear, yellow solution was diluted with water (500 ml.) and extracted with chloroform. The organic layer was washed with water, 5% sodium bicarbonate solution, and evaporated to dryness. The yellow residual solid (0.80 g.) was dissolved in benzene and was chromatographed on 60 g. of neutral alumina, activity grade II. Elution with benzene gave 0.43 g. (27%) of product, which was purified by sublimation at 150° and 0.1 mm. followed by recrystallization from ethanol, methanol, or benzene–hexane to give colorless crystals, m.p. 223–224° (*sealed capillary, under purified nitrogen or under vacuum*), m.p. 215–225° dec. (open capillary, or sealed capillary under air). The diketone was shown to be homogeneous by gas–liquid chromatography (single peak, retention time 12.5 min. at 270° on a 6-ft. × 0.25-in. column of Apiezon L-on-Chromosorb; helium carrier at 30 p.s.i., 150 cc./min.) and by thin layer chromatography (only one spot was brought out with sulfuric acid after elution with benzene, benzene–hexane, and chloroform on Merck alumina G and silica gel G). The infrared spectrum featured a strong peak at λ_{max}^{KBr} 5.85 μ (C=O) and was devoid of imino, nitrile, or amide bands. The ultraviolet spectrum is shown in Fig. 12, and n.m.r. signals are collected in Table III.

Anal. Calcd. for $C_{18}H_{14}O_2$: C, 82.42; H, 5.38; mol. wt., 262. Found: C, 82.61; H, 5.32; N, 0.00; mol. wt., 255 (by osmometry in benzene).

Diketone IIa could also be obtained more directly from tetrabromide V as follows. A mixture of tetrabromide V (12 g.), potassium cyanide (12 g.), n-propyl alcohol (250 ml.), and water (50 ml.) was heated under reflux for 3 hr. The mixture was cooled and the crude bisiminonitrile (4.9 g., 69%) was collected by filtration and hydrolyzed by heating under reflux for 12 hr. in a stirred mixture of 85% phosphoric acid (300 ml.) and diethylene glycol (300 ml.). The mixture was poured onto ice (2 kg.) and extracted with ether. Evaporation of the ether yielded crude diketone, which was purified by chromatography, sublimation, and recrystallization as described above.

Preparation of Diketone IIb by Deuterium Exchange.—Diketone IIa (1.15 g.) was refluxed under nitrogen with 3 ml. of 99.8% deuterium oxide, 10 ml. of dioxane, and 12 mg. of sodium carbonate. After 1 hr. the solution was evaporated to dryness and the

refluxing process was repeated with fresh deuterium oxide and dioxane. This process was repeated for a total of seven exchanges. The product thus obtained was purified by sublimation (150° and 0.1 mm.) to give 0.91 g. of IIb (λ_{max}^{KBr} 5.85 μ), having 7.83 D-atoms per molecule (corresponding to 97.8% exchange). The n.m.r. spectrum was devoid of proton resonance signals in the region above τ 2.8.

Partial Asymmetric Reductions of (±)-Diketone II. A.—Aluminum (+)-2-octoxide (6.30 g.), freshly prepared from 2-octanol with $[\alpha]^{26}D$ +9.64° (neat),[67] was added to a solution of (±)-diketone IIa (0.60 g.) in dioxane (100 ml.), and the mixture was kept at 25.0° for 25 min. The mixture was quenched by the addition of 120 ml. of 0.5 N hydrochloric acid, and the cloudy solution was evaporated to dryness at 40° under reduced pressure. The distillate was collected in a series of Dry Ice traps. The residual solid was leached with benzene (45 ml.) and the extracts were chromatographed on 40 g. of neutral alumina, activity grade II. Elution with benzene afforded 0.27 g. (44% recovery) of unreacted diketone IIa, whose infrared spectrum was identical with that of (±)-IIa and which was optically active; $[\alpha]^{25}_{435}$ −224° (c 2.0, benzene), $[\alpha]^{26}D$ −54° (c 1.6, chloroform); $[\alpha]^{26}_{435}$ −156° (c 1.6, chloroform).

The column was stripped with ether and 0.30 mg. of alcohol ("ketol," λ_{max}^{KBr} 5.83 μ) was isolated, representing *ca.* 50% reduction. This material had $[\alpha]^{26}D$ +38° (c 1.6, chloroform) and $[\alpha]^{26}_{435}$ +108° (c 1.6, chloroform). The "ketol" (0.24 g.) in ether was added to 1.2 ml. of a chromic acid solution prepared by treating 10 g. of sodium dichromate dihydrate with 7.5 ml. of concentrated sulfuric acid and diluting to a volume of 50 ml. with distilled water. The heterogeneous mixture was stirred at 25° for 2 hr. The ether layer was removed, washed with water, and evaporated to dryness. The residue (0.24 g.) was dissolved in benzene and chromatographed on neutral alumina, activity grade II. Elution with benzene afforded 0.14 g. of diketone IIa (identity confirmed by the infrared spectrum), $[\alpha]^{25}_{435}$ +203° (c 1.6, chloroform).

The material collected in the Dry Ice traps during the original concentration step was extracted with ether and the extracts were distilled at atmospheric pressure. The 2-octanol thus recovered had b.p. 174–175°, $n^{27}D$ 1.4225, $[\alpha]^{25}D$ +8.5° (neat), corresponding to 87% retention of optical purity.

B.—A solution of aluminum t-butoxide (0.48 g.) in dioxane (6.3 ml.) was added to a mixture of (±)-IIa (0.50 g.), 2-octanol (9.9 g., $[\alpha]^{26}D$ +9.64° (neat)), and dioxane (13.1 ml.) at 63.0°. The resulting solution was kept at 63.0° for 16.8 min. The reaction mixture was quenched by the addition of 100 ml. of 0.5 N hydrochloric acid. The mixture was evaporated to dryness under reduced pressure. The residual solid was leached with benzene and the extracts were chromatographed as described under A above. Elution with benzene gave 0.15 g. (31% recovery) of IIa, $[\alpha]^{25}_{435}$ −894° (c 1.5, chloroform); O.R.D. in dioxane (c 0.029 (450–330 mμ), c 0.0060 (330–260 mμ), 27°): $[\phi]_{455}$ −1610°, $[\phi]_{317}$ −44,200°, $[\phi]_{312}$ −36,600°, $[\phi]_{308}$ −34,000°, $[\phi]_{290}$ +27,400°, $[\phi]_{280}$ +35,000°, $[\phi]_{260}$ +22,000°; *cf.* also Fig. 15. Elution with ether and methanol gave 0.30 g. of a mixture of "ketol" and "diol" which was oxidized with chromic acid–ether as described under A above. Elution of the products from alumina gave IIa (85 mg.), $[\alpha]^{23}_{435}$ +325° (c 1.2, chloroform).

C.—A partial asymmetric reduction on a larger scale was carried out as described under B above, using 2.10 g. of (±)-IIa, 38.0 g. of (+)-2-octanol, and 2.0 g. of aluminum t-butoxide. There was obtained 1.29 g. (62% recovery) of IIa, $[\alpha]^{25}_{435}$ −278° (c 1.7, chloroform), and 0.61 g. of an alcohol fraction, chromic

(67) L. M. Jackman and A. K. Macbeth, *J. Chem. Soc.*, 3252 (1952), report that 2-octanol with $[\alpha]^{15}D$ +8.10° (neat) affords aluminum octoxide with $[\alpha]^{30}D$ −8.52° (c 12.8, methylcyclohexane). We have found that the presence of traces of 2-octanone suffices to give largely racemic material merely on standing, as shown in the following experiment (by Dr. J. Weiss): 2-Octanol, $[\alpha]^{25}D$ −9.70° (neat), containing 0.3% octanone (by gas-liquid chromatography at 150° on a 6 ft. × 0.25 in. column of Carbowax 1500-on-Chromosorb, helium carrier at 30 p.s.i., 120 cc./min.; retention times: 2-octanol, 16 min.; 2-octanone, 8 min.), was distilled through a Podbielniak Heligrid fractionating column. The alcohol thus obtained contained 0.02% 2-octanone. Aluminum 2-octoxide prepared from this material had $[\alpha]^{24.5}D$ +7.45° (c 10.3, methylcyclohexane) and the 2-octanol immediately liberated from a sample (by acid hydrolysis) had $[\alpha]^{25}D$ −9.24° (neat). After standing for 3 months at room temperature under an atmosphere of nitrogen, the aluminum 2-octoxide had $[\alpha]^{22}D$ +1.99° (c 15.1, methylcyclohexane) and the 2-octanol immediately liberated therefrom had $[\alpha]^{25.5}D$ −2.43° (neat) and contained 0.05% 2-octanone (by g.l.c.).

(66) E. D. Bergmann and Z. Pelchowicz, *J. Am. Chem. Soc.*, **75**, 2663 (1953).

acid oxidation of which afforded 0.34 g. of IIa, $[\alpha]^{25}_{435}$ +487° (c 1.4, chloroform).

The recovered 2-octanol (see A above) had b.p. 177–178°, n^{26}D 1.4236, and $[\alpha]^{27}$D +9.40° (neat), corresponding to 98% retention of optical purity.

Aliquots of optically active IIa from this and preceding preparations were refluxed in o-xylene (144°) for 3 hr. The recovered IIa was optically inactive and identical in every respect with authentic racemic IIa.

D.—A partial asymmetric reduction was carried out as described under B and C above, using 1.66 g. of (±)-IIb, 32.0 g. of (+)-2-octanol, and 1.6 g. of aluminum t-butoxide, with the difference that the quenching operation was carried out with a solution of 4.44 g. of aluminum chloride in 50 ml. of deuterium oxide and that the chromatography was performed on an alumina–D₂O column (see below). There was thus obtained 0.34 g. (20% recovery) of IIb, $[\alpha]^{26}_{435}$ −330° (c 1.7, chloroform), essentially free of IIa (n.m.r.). A sample of this material (10 mg.) in o-xylene (3.0 ml.) had α^{25}_{435} −1.73° (l 2); on heating at 150° for 40 min. the rotation had fallen to zero.

The alcohol fraction (0.31 g.) on oxidation with chromic oxide–ether gave IIb (0.19 g.), isolated by chromatography on alumina–D₂O (see below), whose infrared spectrum was identical with that of (±)-IIb and which had $[\alpha]^{26}_{435}$ +647° (c 1.9, chloroform).

Preparation of Alumina–D₂O.—Woelm neutral alumina, activity grade I (200 g.), was placed in a 500-ml. round-bottomed flask equipped with a thermometer well and a vacuum takeoff. Deuterium oxide (6 ml.) was added and the mixture was stoppered and allowed to stand overnight. The flask was heated under reduced pressure (0.1 mm.) at 200° (internal temperature) until the weight had become constant. The pumped-off water was collected in a Dry Ice trap. The alumina was allowed to cool, 12 ml. of 99+% deuterium oxide was added, and the above process was repeated. Two more exchanges were carried out, using 12 ml. of deuterium oxide each time. The per cent of protium oxide in the pumped-off water following each exchange were determined by n.m.r. The results were

% H₂O	Exchange number
27.0	1
4.3	2
1.2	3
0.9	4

The residual alumina after the fourth exchange was treated with 6.0 ml. to make up neutral alumina–D₂O, activity grade II, or with 12.0 ml. to make up neutral alumina–D₂O, activity grade III. Woelm basic alumina–D₂O, activity grade II, was similarly prepared.
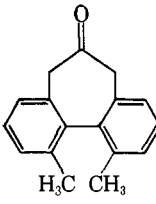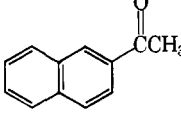
Deuterium Exchanges on Alumina.—Exchanges were carried out by chromatography, employing 100–250 mg. of ketone for 25 g. of alumina. Eluting solvents were benzene or benzene–hexane on neutral alumina, and hexane on basic alumina. Melting points were compared before and after exchange and were found to be unchanged.

A.—A single pass of (±)-diketone IIa over neutral alumina–D₂O, activity grade II, resulted in exchange of 89% of the methylene protons (by n.m.r.). Similarly, a single pass of (±)-diketone IIb over neutral alumina, activity grade II, resulted in exchange of over 90% of the methylene deuterons. Chromatography of IIb on neutral alumina–D₂O, activity grade II, resulted in eluate indistinguishable (by infrared and n.m.r.) from starting material.

B.—Two successive passes over alumina–D₂O, using fresh adsorbent for the second pass, resulted in varying degrees of exchange, as tabulated at the top of the next column.

(±)-**4,5,6,10,11,12-Hexahydrodibenzo[ef,kl]heptalene (I).**—Gaseous hydrogen chloride was passed through a stirred mixture of racemic diketone IIa (0.60 g.), 1,3-propanedithiol (1.49 g.), fused zinc chloride (1.88 g.), and 30 ml. of benzene. The suspension was stirred for 2 hr. at room temperature, poured into water, and extracted with chloroform. The organic layer was washed with water and 5% sodium hydroxide solution, the solvent was removed under reduced pressure, and the residual solid (0.89 g.) was recrystallized from toluene to give the desired **bisthioketal VII**, m.p. 270–302° dec., $\lambda^{dioxane}_{max}$ 289.5 mμ (ε 1050). 255 (14,200). The melting point was not improved on recrystallization.

Anal. Calcd. for C₂₄H₂₆S₄: C, 65.11; H, 5.92; S, 28.97. Found: C, 64.75; H. 6.38; S, 28.86.

Starting ketone	Alumina (activity grade)	Eluate: D-atoms per molecule	Exchange of α-protons, %
	Neutral (III)	3.57	89
	Neutral (III)	1.17	39
(n-C₆H₁₃)₂CO	Neutral (III)	0.10	2.5
(n-C₆H₁₃)₂CO	Basic (II)	0.63	16

A similar preparation of bisthioketal, starting from (−)-IIa ($[\alpha]^{25}_{435}$ −278° (chloroform)), was optically inactive at 435 mμ (c 1.65, l 2, chloroform, sensitivity ±0.01°) and in the 220–250 mμ region (c 0.119, l 0.1, dioxane, sensitivity ±0.001°). Rotations were taken on the residue remaining after removal of the solvent, i.e., prior to recrystallization from toluene.

A suspension of bisthioketal VII (0.80 g.) and Raney nickel catalyst (5.0 g.) in 200 ml. of ethanol was refluxed for 20 hr. The mixture was filtered, the solvent was removed, and the residue was taken up in hexane and chromatographed on neutral alumina, activity grade I. Elution with hexane gave 0.15 g. of waxy solid, which after recrystallization from methanol afforded colorless needles of hydrocarbon 1, m.p. 96–98° (sealed capillary). The ultraviolet spectrum is shown in Fig. 11 and n.m.r. signals are collected in Table III. The hydrocarbon was analytically free of sulfur and was shown to be homogeneous by gas–liquid chromatography (single peak, retention time 7.8 min. at 240° on a 6-ft. × 0.25-in. column of Apiezon L-on-Chromosorb, helium carrier at 30 p.s.i., 150 cc./min.) and by thin layer chromotography (only one spot was brought out with sulfuric acid after elution with benzene, benzene–hexane, and chloroform on Merck alumina and silica gel G).

Anal. Calcd. for C₁₈H₁₈: C, 92.26; H, 7.74. Found: C, 92.18; H, 7.83.

Hydrocarbon 1 similarly obtained from bisthioketal prepared from (−)-IIa was optically inactive in the 230–450 mμ region (c 0.106, l 0.1, dioxane, sensitivity ±0.001°).

(±)- and (+)-**6,6'-Bis(bromomethyl)-2,2'-diphenic Acid Dimethyl Ester (VIII).**—A stirred mixture of (±)-6,6'-dimethyl-2,2'-diphenic acid dimethyl ester[68] (8.0 g.), N-bromosuccinimide (9.6 g.), benzoyl peroxide (0.16 g.), and carbon tetrachloride (40 ml.) was heated under reflux and irradiated with a 275-w. lamp for 1 hr. Succinimide was removed by filtration, the filtrate was evaporated, and the crude product was recrystallized from benzene–ligroin or ligroin to give 8.6 g. (69%) of blocky crystals, m.p. 126–129°. A sample was recrystallized to constant melting point, 130–133°.

Anal. Calcd. for C₁₈H₁₆Br₂O₄: C, 47.39; H, 3.54; Br, 35.04. Found: C, 47.29; H, 3.35; Br, 35.14.

A similar preparation, starting from (−)-6,6'-dimethyl-2,2'-diphenic acid dimethyl ester[68] ($[\alpha]^{24}$D −54° (c 1.6, benzene)), yielded (+)-VIII in 33% yield, m.p. 105–106°, $[\alpha]^{24}$D +21° (c 1.2, benzene).

Anal. Calcd. for C₁₈H₁₆Br₂O₄: C, 47.39; H, 3.54; Br, 35.04. Found: C, 47.19; H, 3.58; Br, 35.14.

(±)- and (−)-**2,7-Dihydro-3,4,5,6-dibenzoxepin-4',1''-dicarboxylic Acid Dimethyl Ester (IXa).**—A solution of (±)-6,6'-bis-(bromomethyl)-2,2'-diphenic acid dimethyl ester (VIII, 4.06 g.) in 125 ml. of warm 5% aqueous acetone was added dropwise, over a 45-min. period, to a stirred suspension of freshly prepared silver oxide (5.8 g.) in 40 ml. of warm 5% aqueous acetone. Following the addition, the mixture was refluxed for 5 hr., filtered, and the filtrate evaporated to dryness. The residue from the evaporation was leached with benzene, and the benzene extracts were evaporated to dryness. The residual crude material was recrystallized twice from methanol to give 1.04 g. (35%) of the desired product, m.p. 185–186°, $\lambda^{chloroform}_{max}$ 5.82 (C=O), 9.46 μ (C—O); $\lambda^{dioxane}_{max}$ 258 mμ (ε 9360 sh), 282 (5500).

(68) G. Wittig and H. Zimmermann, *Chem. Ber.*, **86**, 629 (1953).

Anal. Calcd. for $C_{18}H_{16}O_5$: C, 69.22; H, 5.16; mol. wt., 312. Found: C, 69.36; H, 5.43; mol. wt., 313.

A similar preparation starting from (+)-6,6'-bis(bromomethyl)-2,2'-diphenic acid dimethyl ester gave (−)-IXa in 57% yield, $[\alpha]^{24}D$ −337° (c 1.2, benzene). The infrared spectrum (10% chloroform solution) was identical with that of (±)-IXa; O.R.D. in dioxane (c 0.106 (410–330 mμ), c 0.0348 (330–310 mμ), c 0.0174 (310–290 mμ), c 0.0034 (290–250 mμ), c 0.0014 (250–235 mμ), 24–27°): $[\phi]_{410}$ −3180°, $[\phi]_{309}$ −11,750°, $[\phi]_{297}$ −9,150°, $[\phi]_{272}$ −42,300°, $[\phi]_{240}$ +92,000°, $[\phi]_{235}$ +41,500°: cf. also Fig. 16.

Anal. Calcd. for $C_{18}H_{16}O_5$: C, 69.22; H, 5.16. Found: C, 68.81; H, 5.34.

The melting point of (−)-IXa is above 155° and below 173°, since (a) the observed melting range is ca. 156–186° when the temperature of immersion is below 150° and (b) a sample introduced into the bath at 173° melts sharply to a clear liquid which partially resolidifies at 173° and melts over a range, 173–186°.

A sample of (−)-IXa, maintained for 30 sec. at 187° (melt), had become optically inactive: $\alpha^{23}D$ 0.00° (c 1.05, l 0.05, benzene), corresponding to 99 + % racemization.

(±)- and (+)-4',1''-Bis(hydroxymethyl)-2,7-dihydro-3,4,5,6-dibenzoxepin (IXb).—A solution of (±)-2,7-dihydro-3,4,5,6-dibenzoxepin-4',1''-dicarboxylic acid dimethyl ester (IXa, 0.50 g.) in 120 ml. of 20% benzene–ether was added dropwise, over a 30-min. period, to a stirred suspension of lithium aluminum hydride (1.94 g.) in 40 ml. of 20% benzene–ether at 25°. The mixture was heated under reflux for 3 hr.; excess lithium aluminum hydride was destroyed by the addition of water and 50 ml. of 5% sulfuric acid was added. The organic layer was separated, washed with 5% sodium bicarbonate, and dried. Removal of solvent left IXb as a viscous oil (0.50 g.). The infrared spectrum (10% solution in chloroform) was devoid of carbonyl absorption and featured bands at 9.62 (C–O) and at 2.79 and 2.99 μ (free and hydrogen-bonded OH). Attempts to purify the crude diol by recrystallization from methanol, benzene, benzene–ligroin, and ether–ligroin at 25° and lower temperatures failed. Chromatography of this material on silica gel (100–200 mesh) produced IXb identical (infrared spectrum of a 10% chloroform solution) with the original material.

A similar preparation starting from (−)-2,7-dihydro-3,4,5,6-dibenzoxepin-4',1''-dicarboxylic acid dimethyl ester afforded (+)-IXb in 60% yield. After recrystallization from benzene the product had m.p. 139–140° and $[\alpha]^{23}D$ +32° (c 1.1, chloroform) and its infrared spectrum (10% chloroform solution) was identical with that of racemic IXb.[69] The ultraviolet spectrum had $\lambda_{max}^{dioxane}$ 245.5 mμ (ε 15,100), 285 (600 sh); O.R.D. in dioxane (c 0.096 (450–290 mμ), c 0.0077 (300–270 mμ), c 0.0031 (270–240 mμ), 26°): $[\phi]_{410}$ +693°, $[\phi]_{254}$ +52,300°, $[\phi]_{240}$ −9980°; cf. also Fig. 16.

Anal. Calcd. for $C_{16}H_{16}O_3$: C, 74.98; H, 6.21. Found: C, 75.11; H, 6.45.

(±)-10,12-Dihydro-4H-5,11-dioxadibenzo[ef,kl]heptane (IIIa). **A.**—A solution of (±)-4',1''-bis(hydroxymethyl)-2,7-dihydro-3,4,5,6-dibenzoxepin (IXb, 0.180 g.) and p-toluenesulfonic acid monohydrate (0.010 g.) in 20 ml. of benzene was heated under reflux for 14 hr. in an apparatus which had been fitted with a Dean–Stark water trap. The benzene solution was washed with 5% sodium bicarbonate and the solvent was removed under reduced pressure. The residual solid (0.152 g., 91% yield) was chromatographed on neutral alumina, activity grade I, using ether–benzene as eluent. The product thus obtained melted at 193–194° in a sealed capillary *under purified nitrogen or under vacuum* (the colorless resolidified melt had the same m.p.) but with decomposition (slight yellowing) under other conditions; typically, m.p. 184–190° in sealed capillaries under air, and m.p. 174–190° to 184–190° in open capillaries. Recrystallization from methanol did not alter this behavior, although *freshly* sublimed (0.02 mm., bath temperature 80–100°) material appeared to have shorter m.p. ranges even in open capillaries. The dioxepin IIIa was shown to be homogeneous by gas–liquid chromatography (retention time 15.5 min. at 250° on a 6 ft. × 0.25 in. column of Apiezon L-on-Chromosorb, helium carrier at 20 p.s.i., 120 cc./min.) and by thin layer chromatography (only one spot was brought out with sulfuric acid after elution with benzene, benzene–hexane, and chloroform on Merck alumina or silica gel G). The infrared spectrum featured a pronounced peak at 9.35 μ

---

(69) In another preparation of (+)-IXb, recrystallization from benzene was preceded by chromatography on silica gel (100–200 mesh) using 50% acetone–benzene as eluent.

(C–O) in chloroform or potassium bromide and was devoid of hydroxyl bands. The ultraviolet spectrum is shown in Fig. 9 and n.m.r. signals are collected in Table III.

Anal. Calcd. for $C_{16}H_{14}O_2$: C, 80.64; H, 5.92; mol. wt., 238. Found: C, 80.42; H, 6.04; mol. wt., 235.

B.—*p*-Toluenesulfonyl chloride (0.11 g.) was added to a solution of (±)-IXb (0.14 g.) in anhydrous pyridine (0.5 ml.). After standing at room temperature for 14 hr., the mixture was poured into water. The mixture was made acid to pH 2 with dilute hydrochloric acid and extracted with ether. The ethereal phase was washed with water and dried, the solvent was removed, and the residue was chromatographed on neutral alumina, activity grade I. Elution with 50% ether–hexane afforded dioxepin IIIa, identical in every respect with material prepared by method A.

C.—A warm solution of 2,2',6,6'-tetrakis(bromomethyl)biphenyl (V, 6.0 g.) in 350 ml. of 5% aqueous acetone was added dropwise over a 40-min. period to a mechanically stirred suspension of freshly prepared silver oxide (9.6 g.) in 250 ml. of refluxing 5% aqueous acetone. The heterogeneous mixture was stirred and refluxed for 4 hr. The gray solid was removed by filtration through a mat of Celite, the filtrate was recharged with 9.2 g. of fresh silver oxide, and the mixture was refluxed with stirring for an additional 4 hr. The mixture was filtered, and the filtrate was concentrated at reduced pressure to a yellow oily residue (3.3 g.) which was dissolved in benzene and chromatographed on neutral alumina, activity grade I. Elution with chloroform yielded a solid (0.72 g.) which was recrystallized from methanol to give dioxepin IIIa, identical in every respect with material prepared by method A.

(+)-10,12-Dihydro-4H,6H-5,11-dioxadibenzo[ef,kl]heptalene (IIIa).—(+)-4',1''-Bis(hydroxymethyl)-2,7-dihydro-3,4,5,6-dibenzoxepin (IXb, 0.094 g.) was added in a single portion to 2.0 ml. of concentrated sulfuric acid at −20°. The heterogeneous mixture was stirred at −20° until the solid had dissolved. The solution was poured onto ice water and a flocculent precipitate appeared. The solid was extracted with ice-cold ether, and the organic layer was washed with ice-cold 5% sodium bicarbonate and ice water. Removal of solvent at 20° under aspirator vacuum afforded (+)-IIIa. $[\alpha]^0_{435}$ +230° (c 1.5, o-xylene), infrared spectrum identical with that of racemic IIIa except for two bands at 7.96 and 9.94 μ. After heating at 115° for 20 min., the rotation had fallen to $[\alpha]^0_{435}$ +5° (c 1.5, o-xylene). The additional bands in the infrared spectrum and the small residual rotation gave evidence of slight contamination. The racemized material was chromatographed on neutral alumina, activity grade I. Elution with ether–benzene followed by recrystallization from methanol give racemic dioxepin IIIa, identical in every respect with authentic material.

(±)- and (+)-4',1''-Dimethyl-2,7-dihydro-3,4,5,6-dibenzothiepin (Xa).—A solution of (±)-6,6'-dimethyl-2,2'-bis(bromomethyl)biphenyl[66] (10.0 g.) and sodium sulfide monohydrate (19.6 g.) in 500 ml. of 95% ethanol was refluxed with stirring for 22 hr. The solvent was removed, the residue was extracted with water, and the water-insoluble portion (6.6 g., m.p. 98–101°) was recrystallized from ethanol to give needles, m.p. 102–103°. The ultraviolet spectrum is shown in Fig. 13 and n.m.r. signals are collected in Table II.

Anal. Calcd. for $C_{16}H_{16}S$: C, 79.95; H, 6.71; S, 13.34. Found: C, 79.86; H, 6.47; S, 13.42.

(+)-(S)-6,6'-Dimethyl-2,2'-bis(bromomethyl)biphenyl ([α]²⁰D +51° (benzene)) similarly gave (+)-Xa, m.p. 85.0–85.5°, $[\alpha]^{26}D$ + 142° (c 1.3, benzene); O.R.D. in dioxane (c 1.79 (589–365 mμ), c 0.106 (350–300 mμ), c 0.0094 (300–250 mμ), c 0.0019 (250–230 mμ), 25°): $[\phi]_{589}$ +440°, $[\phi]_{546}$ +1140°, $[\phi]_{257}$ −23,000°, $[\phi]_{279}$ −9200°, $[\phi]_{263}$ −28,600°, $[\phi]_{230}$ +230,000°; cf. also Fig. 17.

Anal. Calcd. for $C_{16}H_{16}S$: C, 79.95; H, 6.71; S, 13.34. Found: C, 79.81; H, 6.97; S, 13.36.

(±)- and (−)-2,7-Dihydro-3,4,5,6-dibenzothiepin-4'1''-dicarboxylic Acid Dimethyl Ester (Xb).—A mixture of (±)-6,6'-bis(bromomethyl)-2,2'-diphenic acid dimethyl ester (VIII, 25.0 g.), sodium sulfide monohydrate (40.0 g.), water (50 ml.), and methanol (1 l.) was heated under reflux and stirred for 0.5 hr. Solvent was removed under reduced pressure. The residual yellow-orange oil was dissolved in 250 ml. of cold water and the solution was made acid to pH ~ 1 with concentrated hydrochloric acid. The resulting precipitate was collected by filtration and slurried with 500 ml. of ether. A solution of 9.0 g. of diazomethane in 310 ml. of ether was added to the ice-cold slurry, the solvent and excess diazomethane were removed under reduced

pressure, and the faintly yellow gummy residue was purified by chromatography on neutral alumina, activity grade II (elution with benzene) followed by recrystallization from methanol. The product thus obtained (in 50–70% yields) had m.p. 172–173°; $\lambda_{shoulder}^{dioxane}$ 295 mμ (ϵ 2800), ϵ_{215} 45,000.

Anal. Calcd. for $C_{18}H_{16}O_4S$: C, 65.84; H, 4.91; S, 9.77. Found: C, 66.03; H, 5.06; S, 9.97.

A similar preparation, starting from (+)-VIII, afforded (−)-Xb, purified by chromatography as described above and by recrystallization from ligroin. The product had m.p. 95–96°, $[\alpha]^{20}D$ −251° (c 1.6, benzene); O.R.D. in dioxane (c 0.765 (4–50 325 mμ), c 0.0227 (325–280 mμ), c 0.0043 (280–242 mμ), 25°): $[\phi]_{450}$ −1400°, $[\phi]_{348}$ −2400°, $[\phi]_{300}$ +6200°, $[\phi]_{242}$ −13,0000°; *cf.* also Fig. 17.

Anal. Calcd. for $C_{18}H_{16}O_4S$: C, 65.84; H, 4.91; S, 9.77. Found: C, 65.74; H, 5.12; S, 10.00.

(±)- and (+)-4′,1″-Bis(hydroxymethyl)-2,7-dihydro-3,4,5,6-dibenzothiepin (Xc).—Solid (±)-2,7-dihydro-3,4,5,6-dibenzothiepin-4′1″-dicarboxylic acid dimethyl ester (Xb, 7.6 g.) was added in portions of 0.5 g. to a stirred suspension of lithium aluminum hydride (10.0 g.) in 30% benzene–ether (1 l.). The reaction mixture was heated under reflux for 3 hr. and cooled. Excess lithium aluminum hydride was destroyed by the addition of water (25 ml.) and 2 N sulfuric acid (500 ml.). The ethereal layer was washed with water and 5% sodium bicarbonate, the solvent was removed by distillation, and the residue (m.p. 144–151°) was recrystallized from aqueous methanol to give 3.4 g. (54%) of the desired product, m.p. 154–155°; $\lambda_{shoulder}^{dioxane}$ 240 mμ (ϵ 10,600), 284 (725).

Anal. Calcd. for $C_{16}H_{16}O_2S$: C, 70.59; H, 5.88; S, 11.78; mol. wt., 272. Found: C, 70.65; H, 6.19; S, 11.86; mol. wt., 260.

A similar preparation starting from (−)-Xb afforded (+)-Xc, m.p. 123–124°, $[\alpha]^{23}D$ +57° (c 1.5, chloroform); O.R.D. in dioxane (c 0.122 (450–290 mμ), c 0.0238 (290–270 mμ), c 0.0082 (270–250 mμ), c 0.00082 (250–230 mμ), 30–32°): $[\phi]_{450}$ +112°, $[\phi]_{289}$ +25,000°, $[\phi]_{282}$ +17,600°, $[\phi]_{268}$ +31,700°, $[\phi]_{230}$ −264,000°; *cf.* also Fig. 17.

Anal. Calcd. for $C_{16}H_{16}O_2S$: C, 70.59; H, 5.88; S, 11.78; mol. wt., 272. Found: C, 70.69; H, 5.80; S, 11.77; mol. wt., 290.

Although the infrared spectra of racemic and optically active Xc in 10% acetone solution are identical, the solid state (potassium bromide) spectra of the two compounds are entirely different in the 7–14 μ region.

(±)-10,12-Dihydro-4H,6H-5-oxa-11-thiadibenzo[ef,kl]heptalene (IIIb).—A solution of (±)-4′,1″-bis(hydroxymethyl)-2,7-dihydro-3,4,5,6-dibenzothiepin (Xc, 0.23 g.) and p-toluenesulfonic acid monohydrate (0.032 g.) in 20 ml. of benzene was heated under reflux for 14 hr. in an apparatus fitted with a Dean–Stark water trap. The benzene solution was washed with water, dried, and chromatographed on neutral alumina, activity grade I. Elution with methylene chloride and chloroform yielded 0.17 g. (80%) of the desired product, m.p. 161–162° after recrystalllization from cyclohexane; $\lambda_{max}^{ethanol}$ 253.5 mμ (ϵ 10,900), 295 (710, shoulder); $\lambda_{max}^{isooctane}$ 250.2 mμ (ϵ 10,300), 255 (ϵ 10,100, sh), 292 (ϵ 650, sh). The n.m.r. signals are collected in Table III.

Anal. Calcd. for $C_{16}H_{14}OS$: C, 75.55; H, 5.55; S, 12.61. Found: C, 75.57; H, 5.70; S, 13.02.

(+)-10,12-Dihydro-4H,6H-5-oxa-11-thiadibenzo[ef,kl]heptalene (IIIb).—A solution of (+)-4′,1″-bis(hydroxymethyl)-2,7-dihydro-3,4,5,6-dibenzothiepin (Xc, 0.21 g.) and p-toluenesulfonyl chloride (0.16 g.) in 0.65 ml. of anhydrous pyridine was allowed to stand at room temperature for 17 hr. Water (10 ml.) was added and the mixture was brought to pH 2 with N hydrochloric acid. The precipitated solid was extracted with benzene, and the benzene solution was chromatographed on neutral alumina, activity grade I. Elution with methylene chloride and chloroform yielded 0.12 g. (63%) of solid, m.p. 158–159°. After one recrystallization from ligroin the product had m.p. 161–162°, $[\alpha]^{27}D$ +333° and $[\alpha]^{26}_{435}$ +1060° (c 0.2, o-xylene).

Anal. Calcd. for $C_{16}H_{14}OS$: C, 75.55; H, 5.55; S, 12.61. Found: C, 75.69; H, 5.81; S, 12.76.

A solution (c 0.24) of (+)-IIIb in o-xylene was heated under reflux for 2 hr. Solvent was removed under reduced pressure. The residue had a small residual rotation ($[\alpha]^{25}_{435}$ +5° (c 5.0, o-xylene), corresponding to 99+% racemization) and was identical in all other respects with authentic (±)-IIIb.

(±)-10,12-Dihydro-4H,6H-5,11-dithiadibenzo[ef,kl]heptalene (IV).—2,2′,6,6′-Tetrakis(bromomethyl)biphenyl (V, 0.81 g.) was

added in 50 mg. portions over a period of 1 hr. to a stirred, warm (ca. 50°) solution of sodium sulfide monohydrate (2.2 g.) and water (1 ml.) in 32 ml. of methanol. The reaction mixture was heated under reflux for 6 hr., concentrated (reduced pressure) to a colorless sludge, and treated with 30 ml. of water and 75 ml. of benzene. The organic layer was separated, washed with water until the washings were neutral to pH Hydrion paper, dried, and evaporated to give colorless crystalline product (0.39 g., 95%) which was further purified by chromatography with benzene on neutral alumina, activity grade I, and recrystallization from benzene–ligroin. The product thus obtained had m.p. 266–267° dec. in either sealed or open capillaries. The dithiepin was shown to be homogeneous by thin layer chromatography (only one spot was brought out with sulfuric acid after elution with benzene, benzene–hexane, and chloroform on Merck alumina and silica gel G). The ultraviolet spectrum is shown in Fig. 13 and n.m.r. signals are collected in Table III.

Anal. Calcd. for $C_{16}H_{14}S_2$: C, 71.07; H, 5.22; S, 23.72; mol. wt., 270. Found: C, 71.16; H, 5.50; S, 23.47; mol. wt., 282.

(±)-4′,1″-Bis(bromomethyl)-2,7-dihydro-3,4,5,6-dibenzothiepin (Xd). A.—(±)-4′,1″-Bis(hydroxymethyl)-2,7-dihydro-3,-4,5,6-dibenzothiepin (Xc, 0.50 g.) was added in 50-mg. portions over a period of 1.5 hr. to a stirred solution of phosphorus tribromide (5.46 g.) in 50 ml. of benzene at 25° to which 3 drops of pyridine had been added. Between additions the reaction mixture was protected from moisture. A further 2.98 g. of phosphorus tribromide was then added to the mixture, followed by the addition of a second portion of 0.50 g. of (±)-Xc, as before. The reaction mixture was stirred at ambient temperature for 24 hr., 30 ml. of benzene was added, and the solution was washed with water and 5% sodium bicarbonate. The organic layer was dried over magnesium sulfate and the solvent was evaporated under reduced pressure (bath temperature ca. 40°) to give a colorless crystalline residue (1.22 g.), m.p. 140–200° dec. Recrystallization of 1.00 g. of this material from ligroin afforded 0.85 g. of colorless elongated prisms, m.p. 150–151°, with partial resolidification and remelting to 210°.

Anal. Calcd. for $C_{16}H_{14}Br_2S$: C, 48.28; H, 3.54; S, 8.05; Br, 40.14; mol. wt., 398. Found: C, 48.38; H, 3.67; S, 8.11; Br, 40.14; mol. wt., 402 (by osmometry in methylene bromide).

B.—A solution of (±)-Xc (0.25 g.) in 10 ml. of chloroform was added dropwise, over a period of 0.5 hr., to a stirred solution of phosphorus tribromide (2.20 g.) in 25 ml. of benzene to which 3 drops of pyridine had been added. Throughout the addition the reaction mixture was blanketed with nitrogen. A further 0.97 g. of phosphorus tribromide was then added to the reaction mixture, followed by the addition of a second portion of (±)-Xc (0.25 g.) in 10 ml. of chloroform. The reaction mixture was stirred at ambient temperature for 24 hr. and worked up as before to give racemic Xd identical with material obtained by method A.

Conversions of Racemic Dibromide Xd into Racemic Dithiepin IV. A.—Racemic dibromide Xd (0.60 g.) was added in 30-mg. portions over a period of 1 hr. to a stirred solution of sodium sulfide monohydrate (1.1 g.) and water (1 ml.) in 30 ml. of methanol heated under reflux. After 14 hr. of refluxing, the reaction mixture was concentrated under reduced pressure and the residual solid was worked up as described in the preparation of racemic IV from V (above). The product, m.p. 265–267°, was obtained in 94% yield and was identical with authentic (±)-IV in every respect.

B.—A sample (22 mg.) of racemic dibromide Xd was heated above its melting point (bath temperature 150–156°) under an atmosphere of nitrogen for 4 min. The sample, withdrawn from the bath, solidified to a colorless, crystalline solid (22 mg.) whose infrared spectrum was different from that of starting dibromide Xd but identical in every detail with that of an equimolar mixture of racemic dithiepin IV and tetrabromide V (Fig. 3). No attempt was made to separate the mixture.

A solution of racemic dibromide Xd in o-xylene (c 1.6) was heated in a sealed tube under nitrogen for 5 min. at 152–155°. The solvent was removed under reduced pressure. The residual solid was identical (infrared spectrum, 4.6% in KBr) with that of starting dibromide Xd.

(−)-4′,1″-Bis(bromomethyl)-2,7-dihydro-3,4,5,6-dibenzothiepin (Xd).—The reaction of (+)-4′,1″-bis(hydroxymethyl)-2,7-dihydro-3,4,5,6-dibenzothiepin (Xc) with phosphorus tribromide was carried out in *precisely* the manner described for the reaction of *racemic* Xc with phosphorus tribromide by procedures A and B (see above). By either procedure, the product (as obtained after evaporation of the solvent under reduced pressure; bath

temperature ca. 40°) was an almost colorless oil, $[\alpha]^{22}$D $-258 \pm 5°$ (c 1.3, benzene), whose infrared spectrum (chloroform solution) was identical with that of racemic dibromide Xd. A solution of this oil in o-xylene ($[\alpha]^{22}$D $-260°$, c 1.8) was heated in a sealed tube under nitrogen for 5 min. at ca. 150° without effecting a change in rotation. In the undiluted state at room temperature the oil rapidly disproportionates (see next section).

Conversions of Active Dibromide (−)-Xd into Active Dithiepin (+)-IV. A.—A solution of (−)-4′,1′′-bis(bromomethyl)-2,7-dihydro-3,4,5,6-dibenzothiepin (Xd, 1.00 g.), freshly prepared and isolated as described in the preceding section, was immediately dissolved in 20 ml. of methylene chloride. The solution was added dropwise over a period of 0.5 hr. to a stirred solution of sodium sulfide monohydrate (2.0 g.) in 1.8 ml. of water and 60 ml. of methanol. The mixture was stirred overnight at room temperature, heated under reflux for 1 hr., and the solvent was removed under reduced pressure. The residual solid was dissolved in a mixture of water (50 ml.) and benzene (75 ml.), the benzene layer was washed with water and dried, and the solution was chromatographed on acid-washed alumina, activity grade II. Elution with benzene gave 0.60 g. (88%) of a white, crystalline product, m.p. 209–217° dec., $[\alpha]^{23}$D $+432°$ (c 1.5, benzene), whose infrared spectrum was virtually identical with that of racemic dithiepin IV. Recrystallization from ligroin afforded (+)-10,12-dihydro-4H,6H-5,11-dithiadibenzo[ef,kl]heptalene (IV), m.p. 213–215° dec., $[\alpha]^{24}$D $+440°$ (c 1.2, benzene), whose infrared spectrum was identical with that of racemic IV; O.R.D. in dioxane (c 0.114 (450–300 mμ), c 0.00845 (300–265 mμ), c 0.0017 (265–230 mμ), 26°): $[\phi]_{450}$ $+3200°$, $[\phi]_{295}$ $+67,800°$, $[\phi]_{289}$ $+47,500°$, $[\phi]_{272}$ $+91,000°$, $[\phi]_{235}$ $-389,000°$, $[\phi]_{230}$ $-201,000°$; cf. also Fig. 14.

Anal. Calcd. for $C_{16}H_{14}S_2$: C, 71.07; H, 5.22; S, 23.72. Found: C, 71.12; H, 5.40; S, 23.76.

A solution of (+)-IV, $[\alpha]^{28}_{435}$ $+1250°$ (c 0.17, o-xylene) was heated (sealed ampoule under nitrogen) at 215° for 3 hr. and at 225° for 6 hr. The rotation was $[\alpha]^{27}_{435}$ $+15°$, corresponding to 99% loss of activity. The product of "racemization" was partially oxidized as judged (a) by the infrared spectrum (KBr wafer), which differed from that of (+)-IV in the appearance of an intense band at 9.65 μ (S–O?), and (b) by the elemental analysis of a sublimed sample which was somewhat low in sulfur.

Anal. Calcd. for $C_{16}H_{14}S_2$: C, 71.07; H, 5.22; S, 23.72. Found: C, 70.85; H, 4.84; S, 22.78.

B.—Freshly prepared and isolated optically active dibromide (−)-Xd was allowed to stand at room temperature (24 ± 3°). At intervals, small aliquots were withdrawn and examined polarimetrically as solutions in benzene. The results are shown in Fig. 4. After 10–20 hr., solid was first noted and after standing for 2–3 days the sample appeared to have completely solidified. Rotations of this and similarly obtained solids varied from $[\alpha]$D $+124$ to $+144°$ (benzene). The solids melted over a range, e.g., 139–165°, and the infrared spectra were essentially identical with the infrared spectrum of an equimolar mixture of optically active dithiepin (+)-IV and tetrabromide V.

A sample of the solid mixture was chromatographed on acid-washed alumina, activity grade I. Elution with benzene and chloroform gave dithiepin (+)-IV, identical with material obtained by method A.

A sample (1.4 g.) of the solid mixture was recrystallized from 24 ml. of acetone. On standing overnight at ambient temperature, colorless blocky crystals (0.61 g.) had deposited from solution. This material was recrystallized from 15 ml. of 1:1 benzene–ligroin. The crystallizate (0.25 g., m.p. 172–173°) was identical with authentic tetrabromide V. The benzene–ligroin mother liquor was diluted to 25 ml. with ligroin, whereupon a crop of needles (0.15 g., m.p. 150–235° dec., $[\alpha]^{25}$D $+325°$ (c 1.6, benzene), positive Beilstein test) precipitated. Sublimation (bath temperature 90–100°, 0.03 mm.) of the mixture, followed by chromatography on acid-washed alumina, activity grade I (30% benzene–ligroin), afforded (+)-IV, identical in every respect with authentic material obtained by method A.

A sample (0.57 g.) of the solid mixture was added to a stirred solution of sodium sulfide nonahydrate (1.05 g.) in 1 ml. of water and 30 ml. of methanol. The mixture was heated under reflux for 6 hr., the solvent was evaporated, and the residual yellowish solid was taken up in a mixture of 40 ml. of water and 60 ml. of benzene. The benzene layer was washed with water and evaporated to give a product (0.36 g., 93%). m.p. 205–259° dec., $[\alpha]^{27}$D $+223°$ (c 1.5, benzene), which gave a negative Beilstein

test and whose infrared spectrum was essentially identical with that of authentic dithiepin IV. The product was chromatographed on neutral alumina, activity grade II, and the eluted (benzene) solid was recrystallized from 2:1 benzene–ligroin to give 0.11 g. of racemic dithiepin IV, m.p. 267–268° dec., α^{20}D 0.00° (c 1.47, l 2, benzene), identical (infrared spectrum) with authentic racemic IV. The mother liquors of the recrystallization on evaporation yielded 0.15 g. of solid. $[\alpha]^{20}$D $+359°$ (c 1.4. benzene). Chromatography of this material on acid-washed alumina, activity grade I, afforded optically active dithiepin IV, $[\alpha]^{24}$D $+440°$ (c 1.2, benzene), whose infrared spectrum was identical with that of authentic (+)-IV.

4,5,9,10-Tetrahydropyrene was prepared from tetrabromide V according to the directions of Pelchowicz and Bergmann.[9] The product after sublimation was homogeneous by g.l.c. (20 ft. silicone gum rubber-on-Chromosorb at 250° and 120 cc./min., helium carrier) and had m.p. 136–138°. The ultraviolet spectrum is shown in Fig. 8 (cf. also Table XII) and the n.m.r. signals are collected in Table III.

Anal. Calcd. for $C_{16}H_{14}$: C, 93.16; H, 6.84; mol. wt., 206. Found: C, 93.15; H, 6.77; mol. wt. by m.s., parent peak m/e 206.

(+)-1,4′,1′′-Trimethyl-2,7-dihydro-3,4,5,6-dibenzazepine (or 1,6,11-trimethyl-6,7-dihydro-5H-dibenz[c,e]azepine) was prepared from (+)-6,6′-dimethyl-2,2′-bis(bromomethyl)biphenyl following the procedure of Wenner[70] for the preparation of the 1-methyl-2,7-dihydro-3,4,5,6-dibenzazepine. The product was obtained in 72% yield after distillation (bath temp. 105–110°, 0.08 mm.) and had m.p. 50.5–52°, $[\alpha]^{21}$D $+87.8°$ (c 1.96, benzene).

Anal. Calcd. for $C_{17}H_{19}N$: C, 86.03; H, 8.07; N, 5.90; mol. wt., 237. Found: C, 85.92; H, 8.31; N, 5.79; mol. wt. by m.s., parent peak m/e 237.

Redistillation did not alter the rotation significantly ($[\alpha]^{24}$D $+86.0°$ (c 1.69, benzene)). The ultraviolet spectrum is shown in Fig. 10 and n.m.r. signals are collected in Table II. The methiodide had m.p. 265° dec., $[\alpha]^{26}$D $+31.7°$ (c 1.06, methanol).

Anal. Calcd. for $C_{18}H_{22}NI$: C, 57.00; H, 5.85; N, 3.69; I, 33.46. Found: C, 57.07; H, 6.03; N, 3.76; I, 33.54.

The N-methobromide had m.p. 287° dec., $[\alpha]^{26}$D $+34.4°$ (c 1.56, methanol); lit.[68] m.p. 278–280°, $[\alpha]^{20}$D $+30.3°$ (c 1.28, methanol). The compound was dried at 110° immediately before elemental analysis.

Anal. Calcd. for $C_{18}H_{22}NBr$: C, 65.06; H, 6.68; N, 4.22; Br, 24.05. Found: C, 65.23; H, 6.79; N, 4.10; Br, 23.83.

1-Methyl-2,7-dihydro-3,4,5,6-dibenzazepine (or 1-methyl-6,7-dihydro-5H-dibenz[c,e]azepine) was prepared according to the procedure of Wenner.[70] The product was isolated by Kugelrohr distillation at 100° (0.08 mm.) and had n^{26}D 1.6183, m/e parent peak 209. It has homogeneous by g.l.c. on a 6 ft. × 0.25 in. column of 20% DC-200-on-Chromosorb (200°, 150 cc. He/min.). The ultraviolet spectrum is shown in Fig. 10 (cf. also Table XII) and the n.m.r. signals are collected in Table III. The methiodide had m.p. 291.5–293° dec., lit.[70] m.p. 288°. The N-methobromide had m.p. 279–282° dec. after recrystallization from ethanol–ether; lit.[70] 276–277°.

Anal. Calcd. for $C_{16}H_{18}NBr$: C, 63.18; H, 5.96; N, 4.61; Br, 26.27. Found: C, 63.00; H, 6.23; N, 4.75; Br, 26.20.

(±)-5,11-Dimethyl-10,12-dihydro-4H,6H-5,11-diazadibenzo-[ef,kl]heptalene (IIIc) was prepared from 2,2′,6,6′-tetrakis(bromomethyl)biphenyl (V) following the procedure of Wenner[70] for the preparation of 1-methyl-2,7-dihydro-3,4,5,6-dibenzazepine, though 55-fold molar excess of methylamine was employed in the present reaction. The product was obtained in 86% yield after one sublimation at 130° (0.09 mm.). The product was analytically pure after two sublimations and had m.p. 130–131.5° (sealed capillary, under vacuum) and m.p. 129–131° (open capillary). The ultraviolet spectrum is shown in Fig. 10 (cf. also Table XII) and the n.m.r. signals are collected in Table III.

Anal. Calcd. for $C_{18}H_{20}N_2$: C, 81.78; H, 7.63; N, 10.60. Found: C, 81.65; H, 7.90; N, 10.56.

Racemization Experiments.—Solutions of optically active doubly bridged biphenyls II, III, and IV in redistilled o-xylene were thermostated (jacketed all-metal polarimeter tube for temperatures below 100° and sealed ampoules under nitrogen for temperatures above 100°) and examined polarimetrically at 435 mμ in a 2-dm. tube. The temperature was constant to within ±0.1°. The results were plotted as log ($\alpha_t - \alpha_\infty$) vs. time; the

(70) W. Wenner, J. Org. Chem., 16, 1475 (1951).

residual "infinity" rotations were obtained by heating to constant rotation and did not exceed 1–2% of the original values, or about 0.05°. Excellent straight-line relationships resulted from each

set of readings. The values of k obtained from the slopes of the curves are listed in Table XIII, along with other information pertaining to the rate measurements.

[Contribution from the Department of Chemistry, New York University, New York 53, N. Y.]

Conformational Kinetic Isotope Effects in the Racemization of 9,10-Dihydro-4,5-dimethylphenanthrene[1,2]

By Kurt Mislow, Rolf Graeve, Arnold J. Gordon, and George H. Wahl, Jr.

Received October 9, 1963

The synthesis of specifically deuterated, optically active derivatives of 9,10-dihydro-4,5-dimethylphenanthrene (II-d_4, II-d_6, and II-d_{10}) is described. It has been demonstrated that small inverse isotope effects accompany the rates of racemization of these hydrocarbons. Since the racemizations are purely conformational changes, and since replacement of protium by deuterium atoms in the 4,5-methyl positions has an accelerating effect, it has therefore been unambiguously demonstrated that in severely overcrowded transition states the deuterium atom has a smaller steric requirement than the protium atom.

Although secondary kinetic isotope effects resulting from the substitution of protium by deuterium have been extensively studied,[3] one outstanding ambiguity has persisted in the interpretation of some of the observed effects.

It is generally accepted that isotope effects arise to a major extent from differences in zero point energy between the isotopic bonds.[4] Since the vibrational level of the heavier isotope is always below that of the lighter one and since ΔE_0 decreases as the bond is stretched and weakened, it follows that $\Delta E_{act}^H < \Delta E_{act}^D$ and that k_H/k_D is greater than unity. This description means in effect that the C–H bond is loosened more easily then the C–D bond, even if the site of isotopic substitution is not directly involved in the reaction. In carbonium ion reactions such effects have been discussed in terms of hyperconjugative interactions.[5] Alternatively, however, the lower zero point energy of deuterium also signifies a smaller amplitude of vibration and, effectively, a smaller van der Waals radius than that of protium.[6] Accordingly, it might be supposed that reactions which involve an increase in bond angles and/or a decrease in coordination number at the reaction center should also exhibit secondary deuterium isotope effects with k_H/k_D greater than unity since relief of nonbonded interactions should be more pronounced in the more congested molecule, i.e., the one containing protium in place of deuterium. Conversely, a decrease in bond angles and/or an increase in the coordination number would imply a k_H/k_D of less than unity. It has been argued[7] that steric acceleration or deceleration accounts for the major portion of many effects which have been discussed heretofore from the point of view of hyperconjugation.[5] However, the relative merit of the two alternative and rival hypotheses has thus far remained undecided.

We have been interested for some time in the possibility of isolating the steric factor and assessing its importance in secondary kinetic isotope effects. The first crucial experiment in this direction[8] involved the partial asymmetric Meerwein–Ponndorf–Verley reduction of ketone I with $(+)$-(S)-2-propanol-d_3. No evidence for the operation of an isotope effect was detected, and it was concluded[8] that methyl and trideuteriomethyl groups appear to have the same size in this particular reaction. It was recognized, however, that more highly crowded transition states might be required for the exhibition of the steric isotope effect.[8] The present paper describes the first unambiguous demonstration of this elusive effect.

9,10-Dihydro-4,5-dimethylphenanthrene (II-d_0) racemizes in benzene with an activation energy of 23.1 kcal./mole.[9] Since the corresponding barrier in 9,10-dihydrophenanthrene is estimated[10] at ca. 4 kcal./mole, the replacement of the hydrogens in the 4,5-positions by methyl groups introduces a 19 kcal./mole increase in activation energy. N.m.r. spectroscopic evidence indicates[10] that the 4,5-methyl groups in II-d_0 are deflected out of the planes of the attached benzene rings, no doubt as a consequence of strain in the ground state. Since the ground-state energy of II-d_0 is therefore raised above that of 9,10-dihydrophenanthrene, it follows that the difference in transition-state energies of the comparison substances must be even greater than 19 kcal./mole. This very large energy increment is unquestionably the result of severe molecular deformations which accompany the extreme congestion of the two methyl groups along the reaction coordinate of racemization. The value of the deformation energy is compatible with the measured strain energy (12.6 ± 1.5 kcal./mole) of 4,5-dimethylphenanthrene.[11a] Since this system has also been obtained in optically active form,[11b] the energy requirement for the transition state of racemization must be even greater.

Introduction of the methyl groups into the 4,5-positions therefore gives rise to the extreme steric

(1) This work was supported in part by a grant from the Alfred P. Sloan Foundation.

(2) Portions of this work have been reported in preliminary form in J. Am. Chem. Soc., **85**, 1199 (1963), and at the 18th National Organic Symposium, Columbus, Ohio, June 19, 1963.

(3) For recent reviews, cf. A. Streitwieser, Jr., Ann. N. Y. Acad. Sci., **84**, 576 (1960), and R. E. Weston, Jr., Ann. Rev. Nuclear Sci., **11**, 439 (1961).

(4) K. B. Wiberg, Chem. Rev., **55**, 713 (1955).

(5) V. Shiner, Tetrahedron, **5**, 243 (1959), and references cited therein.

(6) A. R. Ubbelohde, Trans. Faraday Soc., **32**, 525 (1936).

(7) L. S. Bartell: (a) Tetrahedron Letters, No. **6**, 13 (1960); J. Am. Chem. Soc., **83**, 3567 (1961); (b) Iowa State J. Sci., **36**, 137 (1961). For related discussions, cf., e.g., M. J. S. Dewar, "Hyperconjugation," The Ronald Press Co., New York, N. Y., 1962, pp. 141–143.

(8) K. Mislow, R. E. O'Brien, and H. Schaefer, J. Am. Chem. Soc., **82**, 5512 (1960); **84**, 1940 (1962).

(9) K. Mislow and H. B. Hopps, ibid., **84**, 3018 (1962).

(10) K. Mislow, M. A. W. Glass, H. B. Hopps, E. Simon, and G. W. Wahl, Jr., ibid., **86**, 1710 (1964).

(11) (a) M. A. Frisch, C. Barker, J. L. Margrave, and M. S. Newman, ibid., **85**, 2356 (1963); (b) M. S. Newman and A. S. Hussey. ibid., **69**, 3023 (1947).