10 from the crude reaction mixture involved exposure to ozone at −78 °C (~20 min for 10 g) followed by reductive workup with zinc and acetic acid.
(9) H. O. House, V. Paragamian, R. S. Ro, and D. J. Wluka, *J. Am. Chem. Soc.*, **82**, 1452 (1960).
(10) The ratio of hydrocarbons **22** and **23** was determined by capillary gas chromatography. These compounds were not separated by thin-layer chromatography. Chromic acid oxidation[11] and infrared spectroscopy[12] did not prove to be reliable methods for analyzing mixtures of **22** and **23**.
(11) J. W. Cook, C. L. Hewett, and C. A. Lawrence, *J. Chem. Soc.*, 71 (1936); J. W. Cook, C. L. Hewett and A. M. Robinson, *ibid.*, 168 (1939); J. W. Cook, N. A. McGinnis, and S. Mitchell, *ibid.*, 286 (1944); R. A. Barnes and A. D. Olin, *J. Am. Chem. Soc.*, **78**, 3830 (1956); M. Tada and H. Shinozaki, *Chem. Lett.*, 1111 (1972).
(12) L. A. Paquette, M. J. Kukla, and J. C. Stowell, *J. Am. Chem. Soc.*, **94**, 4920 (1972); H. Christol, A. Gaven, Y. Pietrasanta, and J. L. Vernet, *Bull. Soc. Chim. Fr.*, 4510 (1971).
(13) R. C. Harvey and M. Halonen, *Can. J. Chem.*, **45**, 2630 (1967).
(14) See A. M. Jeffrey and D. M. Jerina, *J. Am. Chem. Soc.*, **94**, 4048 (1972), for the formation of a benzoxepin by air oxidation of dihydronaphthalene. Oxepin **25** also results from the action of air on *cis*-**17**, but is not formed from *trans*-**21**.
(15) W. L. Nelson and D. D. Miller, *J. Med. Chem.*, **13**, 807 (1970). The authors would like to express their gratitude to Professor Nelson for kindly providing copies of the NMR and IR spectra of this olefin.
(16) G. N. Walker, *J. Am. Chem. Soc.*, **79**, 3508 (1957); J. v. Braun and O. Bayer, *Chem. Ber.*, **58**, 2682 (1925).
(17) The isomer of **29** with the carbonyl at the C-4 position has been reported as a colorless solid: G. Haberland, G. Kleinert, and H-J. Siegert, *Chem. Ber.*, **71**, 2623 (1938).
(18) The proportions of ketones **30** and **31** were determined by a combination of thin-layer chromatography and NMR spectroscopy.
(19) See M. Fetizon, G. Moreau, and B. Waegell, *Bull. Soc. Chim. Fr.*, 1229 (1967).
(20) Distillation raises the yield of **10** from ~1.1 to 4.4%.
(21) R. L. Shriner, R. C. Fuson, and D. Y. Curtin, "The Systematic Identification of Organic Compounds", Wiley, New York, p 320.
(22) This semicarbazone derivative may be identical with the unidentified semicarbazone described by Parham and co-workers.[23]
(23) W. E. Parham, E. L. Wheeler, and R. M. Dodson, *J. Am. Chem. Soc.*, **77**, 1166 (1955).

Chiral Spiranes. Optical Activity and Nuclear Magnetic Resonance Spectroscopy as a Proof for Stable Twist Conformations

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The double Michael reaction between 1,3-indandione or 1,3-cyclohexanedione and 1,5-disubstituted pentadien-3-ones gives *cis*- and/or *trans*-spiranes **1–6** depending on the reaction conditions. Use of (−)-quinine as a catalyst gives optically active *trans*-spiranes. The cyclohexanone ring in the *trans*-spiranes was assigned a stable twist conformation as deduced from the symmetry of the ^1H NMR and ^{13}C NMR spectra. The twist conformation was confirmed by an X-ray structure determination. Using the ^{13}C NMR method via diastereoisomer formation with (*S*)-(+)-butane-2,3-dithiol, the enantiomeric purity of *trans*-**4** was found to be 30 ± 5%. Optically pure *trans*-**4**, obtained via crystallization, had $\Delta\epsilon_{max}$ +4.1. Chiroptical properties of *trans*-**3**, *trans*-**4**, and *trans*-**6** were recorded.

Among cyclohexane derivatives stable twist conformations are seldom encountered. This may be due to the fact that in cyclohexane itself the twist conformation has an energy which lies about 5 kcal/mol above the energy of the chair conformation, while the energy of the boat conformation is some 6 kcal/mol higher than the energy of the chair conformation.[1] Thus, the existence of stable twist conformations is ignored in several cases,[2,3a,4] although in the case of cyclohexanone the energy of the twist conformation is only 2.7 kcal/mol higher than the energy of the chair conformation.[1] It has been shown by X-ray analysis that 1,4-cyclohexanedione is a twisted molecule[5] and in some *tert*-butylcyclohexane derivatives a twist conformation is most favorable.[6]

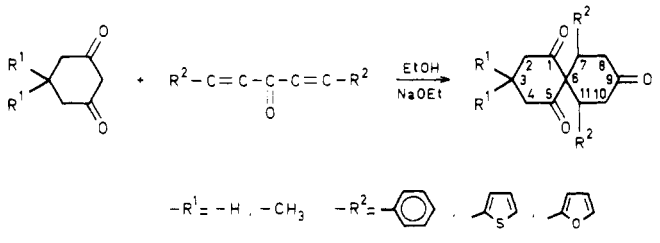
Most cyclohexane derivatives having a stable twist conformation are chiral molecules. For example, cyclohexane (if this molecule existed as a compound with a stable twist conformation),[7] 1,4-cyclohexanedione (if this molecule did not have two interconvertible twist conformations), and twistane are all chiral molecules having D_2 symmetry (see Figure 1).

When we turn to 1,3-disubstituted cyclohexanes, which are chiral in chair or boat form (i.e., the trans isomer), we note that these compounds lack all elements of symmetry but that a C_2 axis is present when the twist conformation is obtained.

Having these facts in hand we turned our attention to several spiranes synthesized in our laboratory some ten years ago by a double Michael reaction between cyclic 1,3-diketones and 1,5-disubstituted pentadien-3-ones[2] (Scheme I).

The cyclohexanone ring in these spiranes was assigned a chair conformation with both R^2 groups being equatorial. As has been pointed out a cyclohexanone ring has only a small energy difference between twist and chair conformation, and because in these spiranes the cyclohexanone moiety is completely rigid (by the presence of the 1,3-cyclohexanedione moiety and the bulky R^2 groups, which do not allow interconversion of axial and equatorial substituents) it should be possible to obtain such spiranes with a stable (and chiral) twist conformation of the cyclohexanone moiety. The possibility of obtaining e,e and e,a isomers of this spiroketone type was demonstrated conclusively by the fact that the double Michael reaction between 1,3-indandione and dibenzalacetone gave rise to two different spiroketones depending on the reaction conditions (sodium ethoxide/ethanol or acetic acid, respectively)[3a] (Scheme II). The two isomers were assigned an e,e (cis) and an a,e (trans) configuration for the two respective phenyl groups with the cyclohexanone moiety having a chair

Scheme I



Scheme II

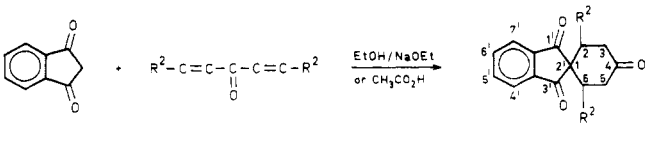


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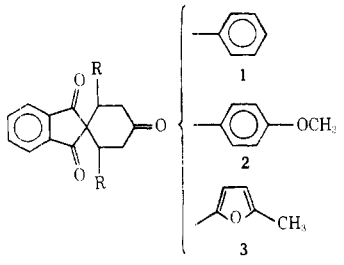
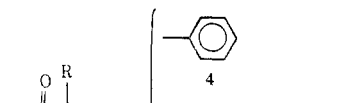
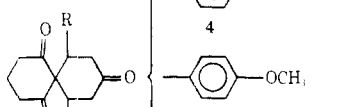
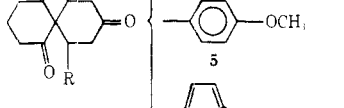
Table I. Synthesis of *cis*- and *trans*-Spiranes by the Double Michael Reaction

R	product and conditions[a] A	B	C	melting points, °C cis	trans	$[\alpha]_{578}$ (RT), deg
 1	trans (30)	cis[b,i] (86)	trans[j] (63)	236–238[3a] (benzene)	206–208[3a] (dioxane/ethanol)	+4.9 (1 cryst.)
2	trans (40, crude)	cis[b,k] (54)	trans[l] (62)	179–180[3a] (ethanol/benzene)	157–158[3a] (ethanol/benzene)	+10 (1 cryst.)
3	trans (25, crude)	cis[b,c,m] (74)	trans[n] (66)	126–127 (ethanol)	187.5–189 (ethanol)	+80 (4 cryst.)
 4	trans[o]/cis (2.5:1)[d,e,f] (50)	cis[p] (46)	cis[h]	146–147[2] (ethanol)	165–166 (ethanol/chloroform, 10:1)	+4.1/+1.5 (0/1 cryst.)
 5	trans[q]/cis (2:1)[f] (54)	cis[r] (50)	cis[h]	178–181 (ethanol/benzene)	202–204 (dioxane)	+3.4 (3 cryst.)
 6	trans[s]/cis (2:1)[d,f] (50)	cis[g] (−)	cis[h,t]		146–149 (ethanol)	−9.6 (3 cryst.)

[a] A = CH_2Cl_2 or CH_2Cl_2/ether, quinine, 40 °C, 3 days; B = NaOH/EtOH or NaOEt/EtOH; C = CH_3CO_2H, 1 h, 100 °C; figures in parentheses represent yields of spirane. [b] Obtained by conversion of trans isomer with $NaOCH_3/CH_3OH$. [c] Also obtained by heating starting compounds in acetic acid for >10 h (68%). [d] Using CCl_4 as solvent (reflux, 20 h) gave a 1:1 ratio. [e] Using L-proline or L-α-phenylethylamine as a catalyst gave the cis isomer. [f] Ratio was determined by integration of appropriate ^1H NMR signals. [g] This isomer could not be obtained crystalline. [h] Product was not isolated. [i–t] Registry no.: [i] 19294-95-2; [j] 69239-04-9; [k] 19294-99-6; [l] 69239-05-0; [m] 69239-06-1; [n] 69239-07-2; [o] 69239-08-3; [p] 69239-09-4; [q] 69239-10-7; [r] 69239-11-8; [s] 69239-12-9; [t] 69239-13-0.

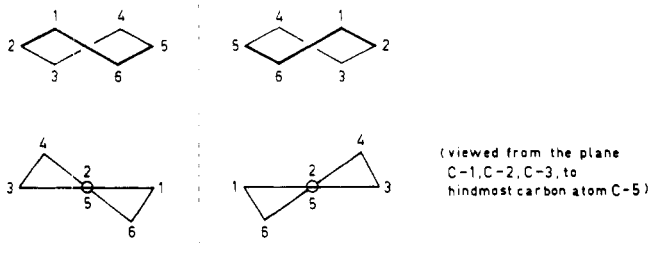


Figure 1.

conformation (see, however, ref 3b,c). It seems unlikely that one of the bulky phenyl groups can adopt an axial position. Thus, the cyclohexanone ring in the trans isomer might be partly or completely twisted; however, the a,e isomer is chiral regardless of its real conformation. It will be shown in this paper that the trans isomer contains a twisted cyclohexanone moiety.

Optically active compounds can be obtained when certain Michael reactions are performed in the presence of (−)-quinine as chiral catalyst.[8] In our case, when an equimolar mixture of dibenzalacetone and 1,3-indandione was refluxed for 3 days in the presence of a catalytic amount of (−)-quinine (solvent CH_2Cl_2/Et_2O), one optically active product, $[\alpha]_{578}$ +4.9°, was isolated. Application of these reaction conditions to other 1,3-diketones and 1,5-disubstituted pentadien-3-ones furnished in all of the cases studied an optically active spirane or one mixed with some nonrotating (i.e., containing a meso carbon atom) isomer. By comparison of ^1H NMR spectra, the spiranes obtained by reactions run in ethanol/sodium ethoxide or in acetic acid were correlated with the optically active isomer (trans isomer) or with the meso isomer (cis isomer). The results are summarized in Table I.

In cases where a mixture of optically active isomer and meso isomer was obtained, the optically active isomer could only be obtained with difficulty because its racemic compound as usual[9] crystallized better in the case of compounds **1**, **2** and **4** (e.g., optically active **1** having $[\alpha]_{578}$ +4.9° after two recrystallizations furnished *trans*-**1** having $[\alpha]_{578}$ ~0°). In the case of compounds **3** and **6**, optical activation was observed after recrystallization; hence, rotations in Table I are of limited value with regard to the amount of asymmetric induction in the (−)-quinine catalyzed double Michael reactions. The exception is compound **4**, for which the absolute rotation and amount of asymmetric induction were determined (see under Chiroptical Properties).

NMR Spectra.[10] ^1H NMR spectra of compounds **1–6**, optically active as well as meso isomers, showed one ABX or AMX pattern for the protons in the cyclohexanone ring (coupling constants were about 12–16 Hz for the geminal and one vicinal (diaxal) interaction and about 2–5 Hz for the other vicinal (axial–equatorial) interaction). The fact that only one ABX (AMX) pattern is observed rules out the possibility of asymmetrical conformations for the cyclohexanone moiety such as a chair, boat, or twist conformation with both an axial and an equatorial R substituent. Hence, the possible conformations are reduced to three if we further assume that conformations with both R groups in an axial position are impossible for steric reasons. In a cyclohexanone ring both the chair and boat conformations have a plane of symmetry (and in our case, contain a meso carbon atom). Therefore, the chair and boat conformations cannot be differentiated; on the basis of energy difference, the boat conformation is discarded. The two possible conformations for compound **1** are shown in Figure 2 (for the sake of convenience, we shall first discuss compounds **1–3**).

The chair conformation has a plane of symmetry (containing a meso carbon atom) and hence is optically inactive. In contrast, the twist isomer has a C_2 axis and so the optically active isomer that was isolated in the (−)-quinine catalyzed reactions must be the twist isomer. This statement is proven by the following facts.

(i) The low-field region of the 100 MHz spectra of both isomers of compound **3** shows a striking difference (Figure 3a). The optically active isomer shows a roughly symmetrical

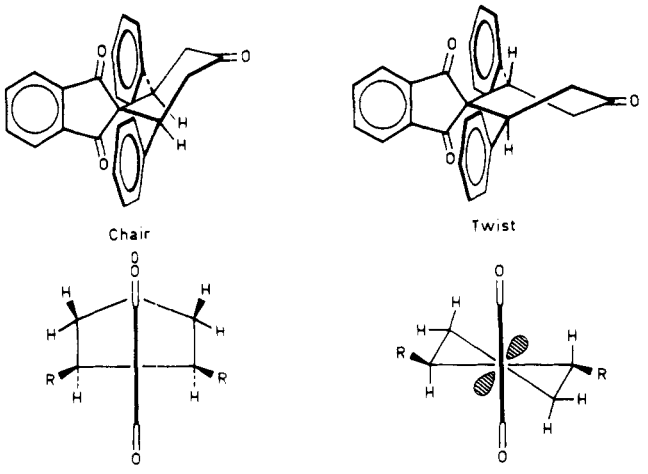


Figure 2.

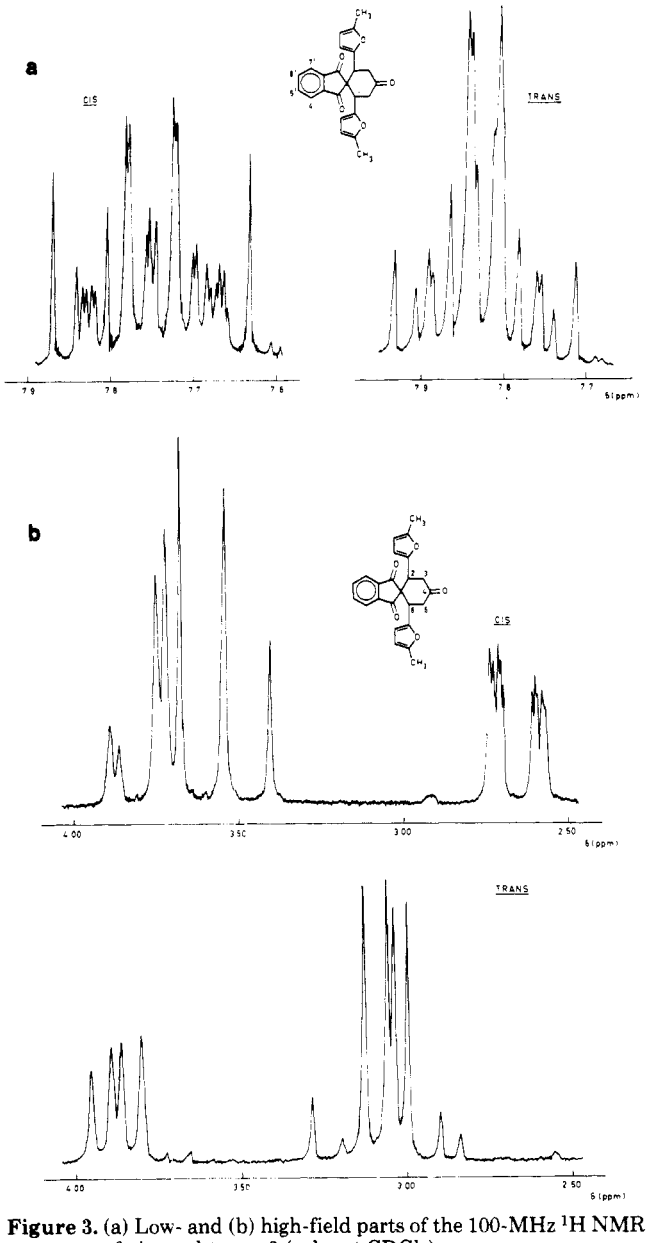


Figure 3. (a) Low- and (b) high-field parts of the 100-MHz ^{1}H NMR spectrum of *cis*- and *trans*-**3** (solvent $CDCl_3$).

AA'BB' system for phenyl protons of the indandione moiety, while the same protons in the meso isomer show an ABCD pattern with lack of symmetry. This is what would be expected; the twist isomer has a C_2 axis, and hence protons at positions 4',7' and 5',6', respectively, are identical. In contrast, the same protons in the meso isomer are all different (see Figure 2) and give rise to the observed ABCD pattern.

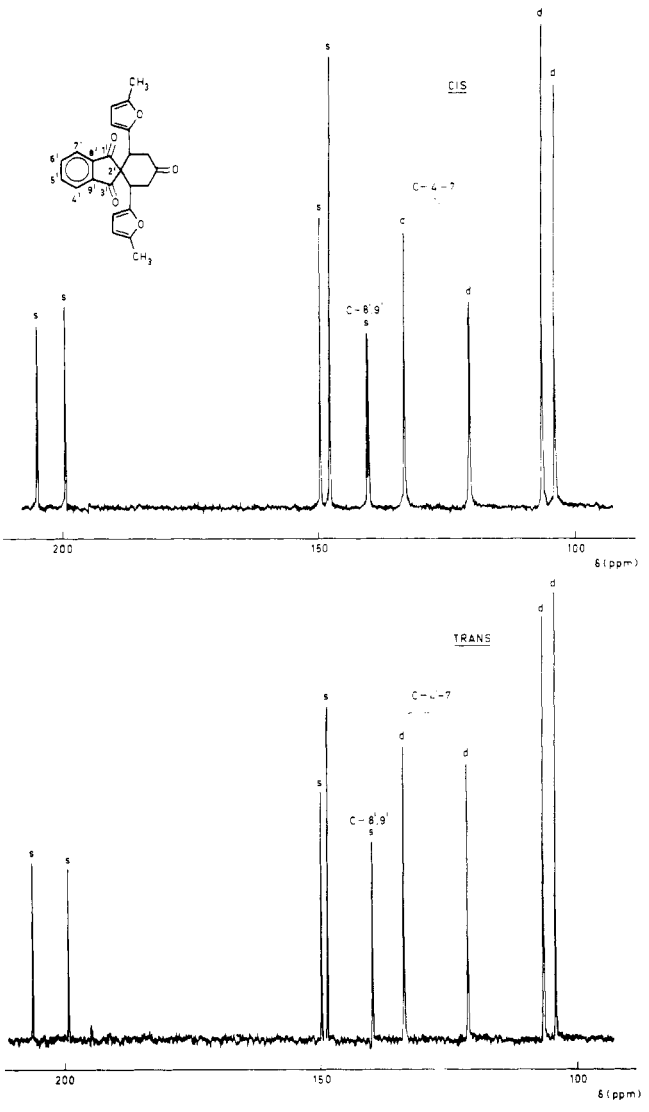


Figure 4. Low-field part of the ^{13}C NMR spectrum of *cis*- and *trans*-**3** (decoupled spectrum, solvent $CDCl_3$).

(ii) Figure 3b shows a higher field part of the isomers of compound **3** descendant from protons at positions 2, 3, 5, and 6. In these ABX patterns protons at positions 2 and 6 will reside in the lower field part, while the equatorial protons at positions 3 and 5 reside in the higher field part of the spectra. Axial protons at positions 3 and 5 will reside in between.[19] As can be seen from Figure 3b, only the meso isomer shows mutual coupling between the equatorial protons ($J \approx 1.7$ Hz) while the optically active isomer shows no mutual coupling. Dreiding models of both isomers account for these facts; the angle between equatorial protons H-3, H-5 in the chair conformation is about 0° (hence, mutual coupling will be observed), while this angle is about 60° in the twist conformation (and hence no mutual coupling will be observed).

(iii) ^{13}C NMR spectra of meso and optically active isomers of **3** are shown in Figure 4 (lower field part, decoupled spectrum). These spectra again show the symmetry/asymmetry of both isomers. Although the meso isomer shows only two carbonyl resonances (while one would expect three), carbon atoms at positions 8',9' and 4',7' (or 5',6') are clearly different (signals at 141.8, 141.5 ppm and 122.0, 121.9 ppm, respectively). In the twist isomer, carbon atoms at these positions

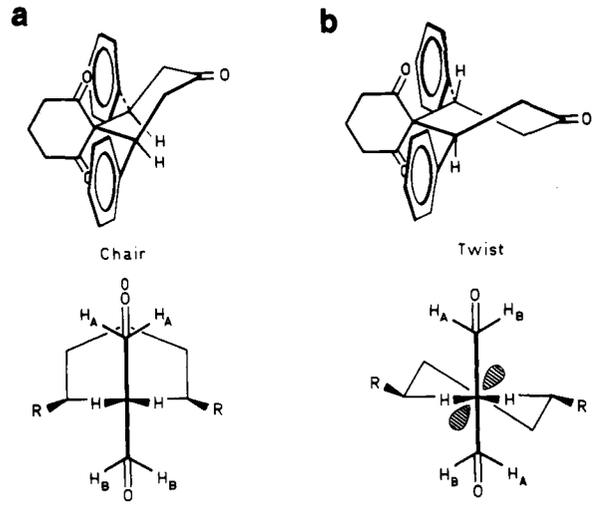


Figure 5.

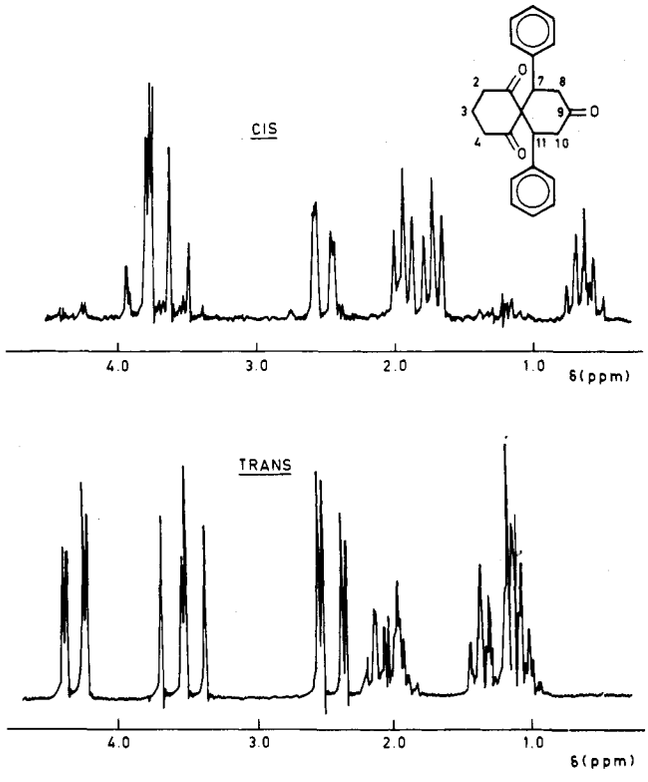


Figure 6. High-field part of the 100-MHz ^1H NMR spectrum of *cis*- and *trans*-4 (solvent $CDCl_3$).

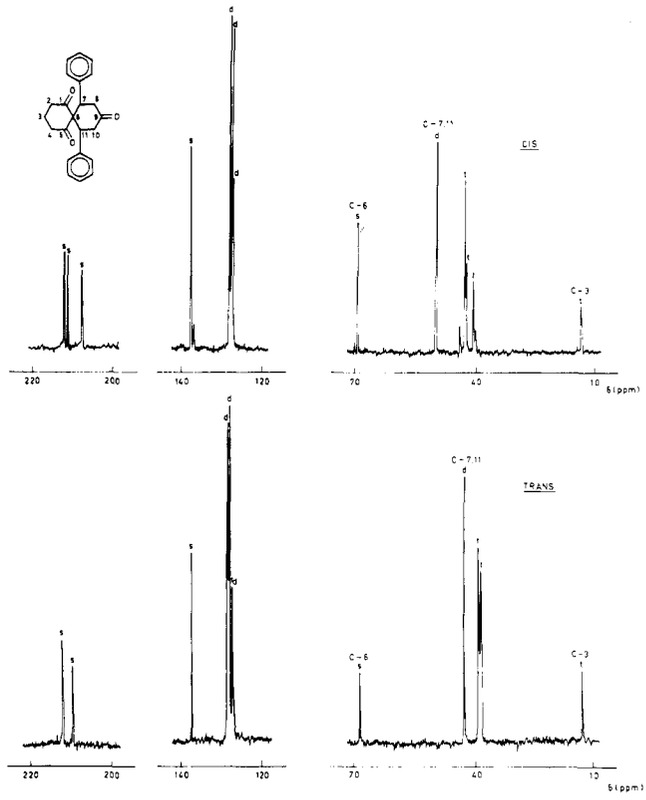


Figure 7. ^{13}C NMR spectrum of *cis*- and *trans*-4 (decoupled spectrum, solvent $CDCl_3$).

are equivalent (signals at 141.3 and 122.8 ppm) and thus prove the symmetry of the twist isomer of compound **3**.

Next let us consider compounds **4–6**. These compounds suffer from the fact that they contain two nonplanar cyclohexane rings. It seems very likely, however, that the cyclohexanedione moiety is rather flexible; so the optically inactive and optically active isomers can be represented by Figures 5a and 5b, respectively, which show the mean cyclohexanedione conformation (this mean conformation may be formed by chair or flattened chair and twist conformations). These structure assignments are proven by three spectroscopic facts.

(i) Owing to the presence of a symmetry plane in the optically inactive isomer, protons at C-2 (and C-4) are enantiotopic, while protons at C-2 are diastereotopic with respect to protons at C-4 (represented by H_A and H_B in Figure 5). The situation is just reversed in the optically active isomer owing to the presence of a C_2 axis; protons at C-2 (and C-4) are diastereotopic, while each proton at C-2 is homotopic with respect to one of the protons at C-4.[11] As a consequence, the ^1H NMR spectrum of the meso isomer should formally show two triplets (for protons at C-2 and C-4) and a nonaplet (for protons at C-3), while the ^1H NMR spectrum of the twist isomer should formally show two sextets (for protons at C-2 and C-4) and a nonaplet (for protons at C-3). The actual situation is represented by Figure 6 (compound **4**), which shows only slight deviations from the expected situation (protons at C-2, C-3, and C-4 reside in the region 0–2.2 ppm).

(ii) The optically inactive isomer of **4** shows mutual coupling of the equatorial protons at C-8 and C-10, while such coupling is absent in the optically active isomer of **4** (Figure 6), as was the case for compound **3**. Hence, equatorial protons at C-8 and C-10 and the carbonyl group are coplanar in the meso isomer, while equatorial protons at C-8 and C-10 and the carbonyl group in the optically active isomer are not (resonances at 2.3–2.7 ppm).

(iii) Figure 7 shows ^{13}C NMR spectra (decoupled) of both isomers of compound **4**. These spectra clearly demonstrate that the meso isomer has three distinct carbonyl groups (C-1, C-5, C-9), while the twist isomer has two equivalent carbonyl groups (C-1 ≡ C-5) due to its C_2 symmetry. Furthermore, C-2 and C-4 are shown to be the same in the twist isomer, while they are not in the meso isomer. Of course, in both isomers C-7, C-11 and C-8, C-10 are equivalent.

Finally, an X-ray structure determination of *trans*-**6** fully proved the twist structure (Figure 8).[12] The torsion angles in the cyclohexanone ring (−64.8, 33.1, 28.0, −63.0, 31.3, 30.5°) are near to the ideal twist torsion angles in cyclohexanone[18] (−60, +29, +29, −60, +29, +29°).

The stability of the twist conformation was assessed by the fact that neither low (−80 °C, CD_2Cl_2) nor high (140 °C, $Cl_2CHCHCl_2$) temperature had any effect on the resonances

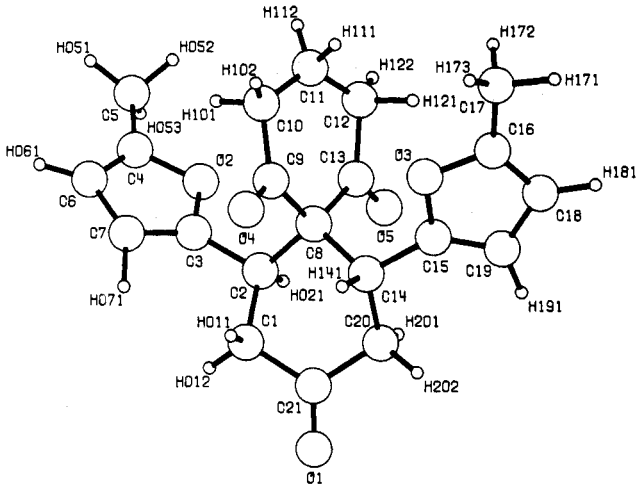


Figure 8. Stereoscopic view of a single molecule of *trans*-**6**.

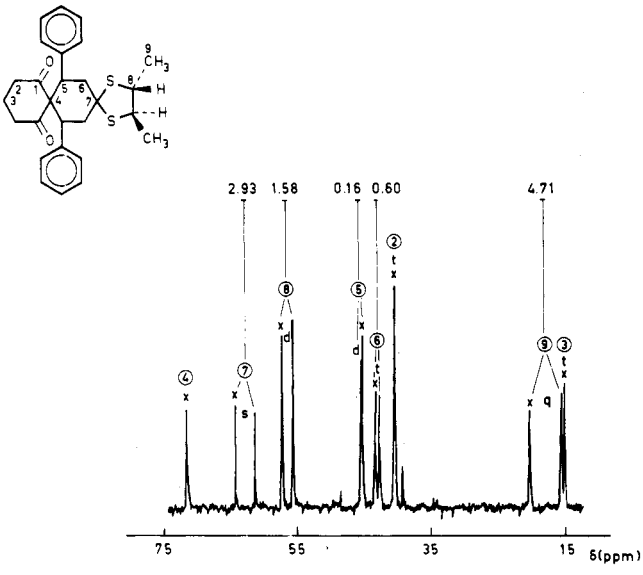


Figure 9. Part of the ^{13}C NMR spectrum of the diastereoisomeric thioacetals from (±)-*trans*-**4** and (*S*)-(+)-2,3-butanedithiol. Figures above the connected lines denote chemical shift differences (in ppm) between corresponding carbon atoms of both diastereoisomers. Lines marked with x represent signals in the ^{13}C NMR spectrum of one pure diastereoisomer. The numbering of **7** is trivial in order to show symmetry relations between carbon atoms.

of the protons in the cyclohexanone moiety of *trans*-**4** (AMX pattern remained unchanged).

These facts taken together with the observed optical activity are a clear proof that the optically active spiranes (trans) must be assigned a stable twist conformation. The meso isomers (cis) are then assigned a stable chair conformation.

Chiroptical Properties. In order to study the chiroptical properties of some of the *trans*-spiranes, optically active material was needed. Only for compounds **3** and **6** could the trans isomers be purified and optically enriched by recrystallization to give compounds whose ORD and CD spectra could be measured. In the case of the *p*-methoxyphenyl derivative **5** ($[\alpha]_{578}$ +3.4° after purification), the absorption in the carbonyl region (at about 290 nm) was too high to measure significant ORD and/or CD effects. Compounds **1**, **2**, and **4** gave only racemic material upon recrystallization of the crude optically active product; furthermore LC separation of *cis*- and *trans*-**4** proved to be unsuccessful. Hence, a better method for obtaining *trans*-spiranes with a higher specific rotation

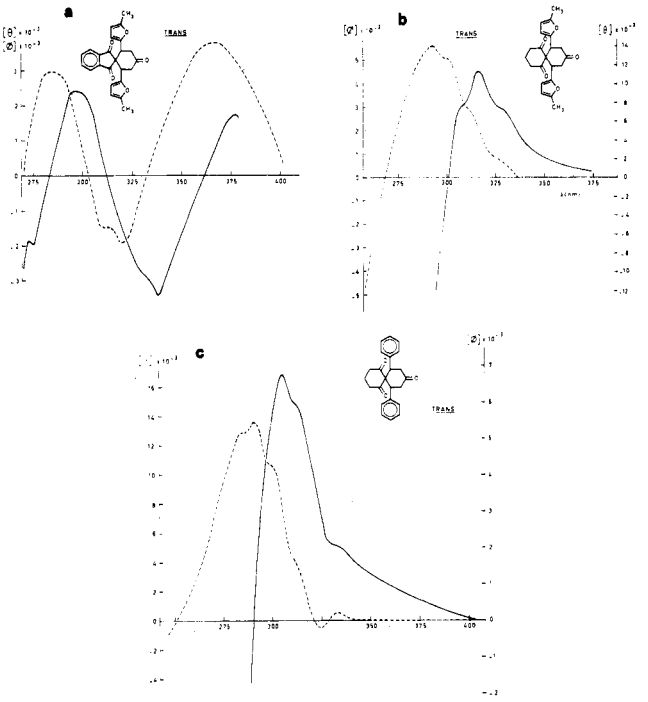


Figure 10. ORD (—) and CD (- - -) spectra of (a) *trans*-**3** (*c* 0.0177, dioxane) with $[\alpha]_{578}$ +80.0°, UV λ_{max} 286 nm sh (ϵ 2300), (b) *trans*-**6** (*c* 0.113, dioxane) with $[\alpha]_{578}$ −9.6°, UV λ_{max} 292 nm sh (ϵ 290), and (c) *trans*-**4** (*c* 0.169, dioxane) with $[\alpha]_{578}$ +21°, UV λ_{max} 292 nm sh (ϵ 180).

had to be sought. This was found by diastereoisomer formation using (*S*)-(+)-butane-2,3-dithiol.[13,14]

Starting with racemic *trans*-**4**, a mixture of equal amounts of thioacetals **7**, mp 82–92 °C, could easily be formed. Both diastereoisomers were seen separately by ^{13}C NMR spectroscopy[16] (Figure 9) or by ^1H NMR spectroscopy (giving CH_3 signals at 1.26, 1.36 ppm and 1.36, 1.46 ppm, respectively). Recrystallization from ethanol gave one pure diastereoisomer, mp 187–189 °C, as shown by ^{13}C NMR (Figure 9)[17] and ^1H NMR (only CH_3 signals at 1.36 and 1.46 ppm were present).

Dethioacetalization was best accomplished using HgO/$HgCl_2$ in methanol, which gave a mixture of the ketone and the dimethyl acetal. Deacetalization by *p*-TsOH/H_2O/acetone gave the desired optically active ketone **4**, $[\alpha]_{578}$ +21°.

trans-Spiranes **1**, **2**, and **5** easily gave the corresponding thioacetals using (*S*)-(+)-butane-2,3-dithiol. However, in these cases a simple separation of the diastereoisomers by recrystallization was not possible, while LC showed only partial separation. The CD and ORD spectra are shown in Figure 10.

The optical yield for the (−)-quinine catalyzed reaction was determined for compound **4**. The crude reaction mixture (after removal of impurities), containing mostly *cis*- and *trans*-**4** and having $[\alpha]_{578}$ +4.1°, was thioacetalized using (*S*)-(+)-butane-2,3-dithiol. ^{13}C NMR analysis of the mixture of the three thioacetals formed revealed a trans/cis ratio of about 2.3 (stereoselectivity about 40%), while the optical yield was about 30%.

The specific rotation of the crude reaction mixture (+4.1°) is in good accord with these two observations and an absolute rotation of +21° for *trans*-**4**. The molecular ellipticity $[\theta]_{292}$ 13 500° corresponds with $\Delta\epsilon_{max}$ 4.1 for optically pure **4**.

Experimental Section

General. Melting points were taken on a Mettler FP apparatus and are uncorrected. Rotations were measured on a Perkin-Elmer 241

polarimeter. UV spectra were recorded on a Beckman DB-G spectrophotometer. ORD and CD spectra were recorded on a Cary 60 recording spectropolarimeter with a Cary 6002 CD accessory. Microanalyses were performed by the analytical section of our department.

Materials. 5-Methylfurfural (Aldrich) and 1,3-indandione (Aldrich) were used without further purification. 1,3-Cyclohexanedione (Fluka) was recrystallized once from benzene. Dibenzalacetone (mp 106–108 °C) and dianisalacetone (mp 130.5–132.5 °C) were obtained by the usual procedure ("Organic Syntheses", Collect. Vol. 2, Wiley, New York, 1943, p 167) in 85–90% yield after recrystallization from ethyl acetate. Solvents were purified where necessary by standard methods.

1,5-Bis(5-methylfuryl)pentadien-3-one. To a mixture of sodium hydroxide (34 g), water (450 mL), and ethanol (150 mL) kept at about 0 °C was added with good stirring a mixture of 5-methylfurfural (49.7 g, 0.452 mol), acetone (13.5 g, 0.233 mol), and ethanol (20 mL) over a period of 0.5–1 h. The yellow reaction mixture was stirred for an additional hour at 20 °C and then cooled overnight at −15 °C. The crude yellow product was filtered off, washed with water (1 L), dried, and recrystallized from a mixture of benzene and light petroleum (bp 40–60 °C), giving 47.6 g (87% yield) of the orange product: mp 94–96 °C; ^{1}H NMR (CCl_4) δ 2.34 (s, 6 H), 6.04 (d, J = 3 Hz), 6.50 (d, J = 3 Hz), 6.74 (d, J = 15 Hz), 7.30 (d, J = 15 Hz).

Anal. Calcd for $C_{15}H_{14}O_3$: C, 74.36; H, 5.82. Found: C, 74.16, 74.31; H, 5.94, 5.80.

Spiro[cyclohexane-1,2′-indan]-1′,3′,4-triones: 2,6-Diphenyl (1), 2,6-Bis(*p*-methoxyphenyl) (2), and 2,6-Bis(5-methylfuryl) (3). Trans Isomers. A mixture of the appropriate pentadienone, a slight excess (0–5%) of 1,3-indandione, and acetic acid (10–20 mL/g of the pentadienone) was refluxed for 1 h. The resulting solution was evaporated to a small volume, ethanol was added to the residue, and the readily crystallizing spirane was filtered off and washed with ethanol. The product could be purified by recrystallization from an appropriate solvent (Table I).

^{1}H NMR of *trans*-**1** ($CDCl_3$): δ 2.6–3.0 (dd, 2 H), 3.3–4.1 (dd, 2 H), 3.9–4.2 (dd, 2 H), 7.0 (s, 10 H), 7.6 (s, 4 H).

^{1}H NMR of *trans*-**2** ($CDCl_3$): δ 2.5–2.8 (dd, 2 H), 3.3–4.1 (m) and 3.6 (s) (10 H), 6.4–6.9 (AB, 8 H), 7.5 (s, 4 H).

^{1}H NMR of *trans*-**3** ($CDCl_3$): δ 1.9 (s, 6 H), 2.9–3.3 (m, 4 H), 3.8–4.0 (dd, 2 H), 5.7–5.8 (m, 2 H), 5.8–5.9 (dd, 2 H), 7.7–8.0 (m, 4 H). ^{13}C NMR of *trans*-**3** ($CDCl_3$): δ 207.6 (s), 200.6 (s), 151.3 (s), 150.1 (s), 141.3 (s), 135.3 (d), 122.8 (d), 108.2 (d), 105.9 (d), 57.9 (s), 41.0 (t), 38.0 (d), 13.0 (q).

Anal. (*trans*-**3**) Calcd for $C_{24}H_{20}O_5$: C, 74.21; H, 5.19. Found: C, 74.02, 74.34; H, 5.14, 5.09.

Cis Isomers. The trans isomer (1 g) was mixed with methanol (10 mL), sodium methoxide (150 mg) was then added, and the reddish mixture was heated to dissolve all of the spirane (in some cases benzene had to be added). After cooling to 20 °C and standing for 0.5–1 h, water (15 mL) was added and the precipitate was filtered off, washed with ethanol, and further purified by recrystallization from ethanol or ethanol/benzene. *cis*-**3** could also be obtained by refluxing the starting compounds (or *trans*-**3**) for about 10 h or longer in acetic acid, giving a mixture of *cis*-**3** and *trans*-**3** (ca. 9:1) in 68% yield.

^{1}H NMR of *cis*-**1** ($CDCl_3$): δ 2.4–3.0 (m, 4 H), 3.5–4.2 (m, 4 H), 7.0 (s, 10 H), 7.3–7.8 (m, 4 H).

^{1}H NMR of *cis*-**2** ($CDCl_3$): δ 2.3–2.9 (m, 2 H), 3.5–4.1 (m) and 3.6 (s) (10 H), 6.4–7.1 (AB, 8 H), 7.4–7.7 (m, 4 H).

^{1}H NMR of *cis*-**3** ($CDCl_3$): δ 1.8 (s, 6 H), 2.6–2.8 (dd, 2 H), 3.4–3.9 (m, 4 H), 5.5–5.6 (m, 2 H), 5.8–5.9 (dd, 2 H), 7.6–7.9 (m, 4 H). ^{13}C NMR of *cis*-**3** ($CDCl_3$): δ 206.3 (s), 200.7 (s), 150.9 (s), 149.1 (s), 141.8 (s), 141.5 (s), 134.7 (d), 122.0 (d), 121.9 (d), 107.8 (d), 105.4 (d), 58.4 (s), 41.2 (t), 40.8 (d), 12.5 (q).

Anal. (*cis*-**3**) Calcd for $C_{24}H_{20}O_5$: C, 74.21; H, 5.19. Found: C, 74.14, 74.34; H, 5.26, 5.29.

Trans Isomers (Quinine-Catalyzed Reactions). A mixture of the appropriate pentadienone, a slight excess (0–5%) of 1,3-indandione, (−)-quinine (~50 mg/g of the pentadienone), and dichloromethane or dichloromethane/ether (1:1) (~10 mL of solvent/g of the pentadienone) was refluxed in the dark and under nitrogen (3 days). After being cooled, the dark suspension was washed with two portions of dilute (~1 N) hydrochloric acid and with water. The organic layer was dried and evaporated, and the residue was recrystallized from ethanol/dioxane (**1**) or ethanol/benzene (**2, 3**). *trans*-**3** could also be obtained by evaporation of the crude reaction mixture, chromatography of the residue (alumina, activity II, chloroform eluent), and recrystallizing the evaporated eluate.

Rotations: **1** (*c* 4.0, $CHCl_3$) (one crystallization) $[\alpha]_{578}$ +4.9°, $[\alpha]_{546}$ +5.9°, $[\alpha]_{436}$ +15.8°; **2** (*c* 3.0, $CHCl_3$) (one crystallization) $[\alpha]_{578}$ +10.3°, $[\alpha]_{546}$ +12.3°; **3** (*c* 1.5, $CHCl_3$) (four crystallizations) $[\alpha]_{578}$ +80.0°, $[\alpha]_{546}$ +97.7°, $[\alpha]_{436}$ +294.0°.

Spiro[5.5]undecane-1,5,9-triones: 7,11-Diphenyl (4), 7,11-Bis(*p*-methoxyphenyl) (5), and 7,11-Bis(5-methylfuryl) (6). Cis Isomers. A mixture of the appropriate pentadienone, a 10–20% excess of 1,3-cyclohexanedione, sodium hydroxide (~25 mg/g of the pentadienone), and 96% ethanol (5–10 mL/g of the pentadienone) was refluxed for about 5 h. After cooling, *cis*-**4** and *cis*-**5** were readily obtained; *cis*-**6** could not be obtained crystalline, however.

These cis isomers could equally well be obtained by using as catalyst L-proline instead of sodium hydroxide.

The spiranes obtained in these ways contained a trace of the trans isomer which could be removed by recrystallization. In the case of compound **6**, the L-proline catalyzed reaction showed some trans isomer to be present (by ^{1}H NMR spectroscopy, ca. 2:1 cis/trans).

^{1}H NMR of *cis*-**4** ($CDCl_3$): δ 0.4–0.7 (m, 2 H), 1.6–2.0 (dt, 4 H), 2.4–2.6 (dd, 2 H), 3.4–4.0 (m, 4 H), 6.9–7.4 (m, 10 H).

^{1}H NMR of *cis*-**5** ($CDCl_3$): δ 0.5–1.0 (m, 2 H), 1.6–2.1 (m, 4 H), 2.1–2.7 (dd, 2 H), 3.3–4.2 (m) and 3.7 (s) (10 H), 6.6–7.1 (AB, 8 H).

Anal. (*cis*-**5**) Calcd for $C_{25}H_{26}O_5$: C, 73.87; H, 6.45. Found: C, 73.82, 73.90; H, 6.61, 6.65.

^{1}H NMR of *cis*-**6** (CCl_4): δ 0.9–1.4 (m, 2 H), 1.9–2.6 (m) and 2.2 (s) (12 H), 3.0–3.9 (m, 4 H), 5.8 (s, 4 H). ^{13}C NMR of *cis*-**4** ($CDCl_3$): δ 212.6 (s), 211.7 (s), 208.2 (s), 137.9 (s), 128.5 (d), 128.1 (d), 127.8 (d), 127.6 (d), 127.3 (d), 69.4 (s), 50.1 (d), 42.9 (t), 42.7 (t), 40.8 (t), 13.9 (t).

Trans Isomers (Quinine-Catalyzed Reactions). A mixture of the appropriate pentadienone, a 10–20% excess of 1,3-cyclohexanedione, (−)-quinine (~50 mg/g of the pentadienone), and dichloromethane/ether (ca. 1:1) (10–20 mL/g of the pentadienone) was refluxed for 3 days. After being cooled, the reddish reaction mixture was washed with two portions of dilute (~1 N) hydrochloric acid and with water. The organic layer was dried and evaporated, and the residue was recrystallized from ethanol/chloroform (**4**), ethanol/benzene (**5**), and ethanol (**6**) to give the pure trans isomers.

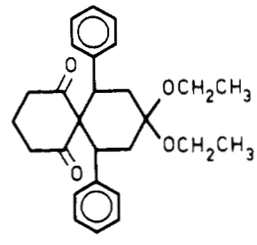
^{1}H NMR of *trans*-**4** ($CDCl_3$): δ 0.9–1 5 (m, 4 H), 1.8–2.2 (m, 2 H), 2.3–2.6 (dd, 2 H), 3.3–3.7 (dd, 2 H), 4.2–4.4 (dd, 2 H), 6.9–7.4 (m, 10 H). ^{13}C NMR of *trans*-**4** ($CDCl_3$): δ 212.0 (s), 209.6 (s), 137.3 (s), 128.4 (d), 128.2 (d), 127.9 (d), 127.6 (d), 127.4 (d), 70.1 (s), 44.1 (d), 40.5 (t), 40.2 (t), 14.9 (t).

^{1}H NMR of *trans*-**5** ($CDCl_3$): δ 1.0–2.1 (m, 6 H), 2.2–2.6 (dd, 2 H), 3.2–3.8 (m) and 3.8 (s) (8 H), 4.1–4.4 (dd, 2 H), 6.6–7.0 (m, 8 H).

^{1}H NMR of *trans*-**6** ($CDCl_3$): δ 1.8–2.7 (m) and 2.2 (s) (14 H), 2.7–3.4 (dd, 2 H), 3.9–4.2 (dd, 2 H), 5.8 (s, 4 H).

Rotations: **4** (*c* 2.0, $CHCl_3$) (one crystallization) $[\alpha]_{578}$ +1.5°, $[\alpha]_{546}$ +2.0°, $[\alpha]_{436}$ +6.2°, $[\alpha]_{365}$ +20.6°; **5** (*c* 1.5, CH_2Cl_2) (three crystallizations) $[\alpha]_{578}$ +3.4°, $[\alpha]_{546}$ +4.2°, $[\alpha]_{436}$ +11.2°, $[\alpha]_{365}$ +33.7°; **6** (*c* 3.2, $CHCl_3$) (three crystallizations) $[\alpha]_{578}$ −9.6°, $[\alpha]_{546}$ −9.8°, $[\alpha]_{436}$ −1.1°, $[\alpha]_{365}$ +79.7°.

In the case of compound **4** recrystallization of the residue from ethanol/chloroform gave *trans*-**4**; the filtrate normally gave *cis*-**4**, but sometimes its diethyl acetal **8** was obtained (**8** could be purified by



8

recrystallization from benzene, giving the acetal with mp 144–146 °C). **8** being stirred overnight with acetone/water/trace *p*-toluenesulfonic acid readily gave *cis*-**4**.

Anal. (*trans*-**4**) Calcd for $C_{23}H_{22}O_3$: C, 79.74; H, 6.40. Found: C, 79.36, 79.30; H, 6.33, 6.30.

Anal. (*trans*-**5**) Calcd for $C_{25}H_{26}O_5$: C, 73.87; H, 6.45. Found: C, 73.63, 73.45; H, 6.48, 6.41.

Anal. (*trans*-**6**) Calcd for $C_{21}H_{22}O_5$: C, 71.17; H, 6.26. Found: C, 71.25, 71.05; H, 6.21, 6.17.

^{13}C NMR of *cis*-**8** ($CDCl_3$): δ 212.9 (s), 211.8 (s), 139.8 (s), 128.3 (d), 128.1 (d), 126.9 (d), 99.5 (s), 70.4 (s), 54.8 (t), 47.4 (d), 42.7 (t), 41.1 (t), 34.2 (t), 15.2 (q), 14.1 (t). ^{1}H NMR of *cis*-**8** ($CDCl_3$): δ 0.3–0.8 (m, 2 H), 1.1–1.4 (2 t, 6 H), 1.6–1.9 (t, 4 H), 1.9–2.2 (dd, 2 H), 2.6–3.0 (t, 2 H), 3.3–3.9 (m, 6 H), 6.9–7.3 (m, 10 H).

Anal. (*cis*-**8**) Calcd for $C_{27}H_{32}O_4$: C, 77.11; H, 7.67. Found: C, 77.28, 77.30; H, 7.67, 7.70.

Thioacetalization of *trans*-4. A mixture of *trans*-spirane **4** (1.01 g, 2.89 mmol), ether (2 mL), (*S*)-(+)-butane-2,3-dithiol (0.37 g, 3.03 mmol), and boron trifluoride etherate (2 mL) was stirred for 3.5 h. Workup by addition of water and ether, separation of the organic layer, washing with sodium bicarbonate solution and water, drying, and evaporation gave the thioacetal, mp 82–92 °C, which was recrystallized from ~20 mL of ethanol to provide 290 mg (22%) of one diastereoisomer, mp 187–189 °C. Another 95 mg could be obtained from the filtrate. The residue was chromatographed over alumina (acidic, activity I, benzene as eluent) to give, after recrystallization from ethanol, the thioacetal, 140 mg. The filtrate, on evaporation, gave 280 mg.

Hydrolysis of Thioacetal 7. A 100-mg amount of thioacetal **7**, mp 187–189 °C, was refluxed for 20–40 h with mercuric chloride (1.5 g), mercuric oxide (0.75 g), 100 mL of methanol, and 2 mL of water. The hot reaction mixture was filtered, the filtrate was evaporated and the residue was taken up in chloroform. This solution was washed with saturated bicarbonate solution (2 × 25 mL), 10% ammonium chloride solution (25 mL), and water (25 mL). The colorless chloroform layer was dried and evaporated to give a residue consisting of the *trans*-spirane **4** and variable amounts of its dimethyl acetal. This residue was stirred overnight with water (1.5 mL), acetone (7.5 mL), and *p*-toluenesulfonic acid (15 mg). Workup gave the crude *trans*-spirane which could be purified by recrystallization from ethanol to give pure *trans*-**4**: $[\alpha]_{578}$ +19.4°, $[\alpha]_{546}$ +24.7°, $[\alpha]_{436}$ +75°, $[\alpha]_{365}$ +246° (*c* 1.4, $CHCl_3$).

From the other fractions of thioacetal mentioned above (95, 140, and 280 mg) there was obtained *trans*-**4** in a similar way having $[\alpha]_{578}$ +21°, −11°, and −13°, respectively. Purification by column chromatography (silica gel, ether as eluent) and subsequent thick-layer chromatography (silica gel, chloroform as eluent) was necessary in the case of the (−) isomers to obtain pure spirane.

Determination of Optical Yield for the (−)-Quinine Catalyzed Reaction between 1,3-Cyclohexanedione and Dibenzalacetone. The crude reaction product obtained after washing with water, 1 N hydrochloric acid, and water was further washed with saturated bicarbonate solution and water and then chromatographed over silica gel (ether as eluent, ~50 g of silica gel/g of product) to give a reasonably pure mixture of *cis*- and *trans*-**4**, $[\alpha]_{578}$ +4.1° (*c* 15.6, $CHCl_3$). This mixture was thioacetalized using a slight excess of (*S*)-(+)-butane-2,3-dithiol to provide a mixture of thioacetals after chromatography over a short alumina column (neutral, activity I, chloroform eluent). The amount of stereoselectivity was determined by the ratio of integrated ^{13}C NMR signals at 70.9 and 70.8 ppm (trans isomer) and 69.3 ppm (cis isomer). The amount of asymmetric induction was determined by the ratio of peak heights of ^{13}C NMR signals at 63.8 and 60.8 ppm (peak at 63.8 ppm was the higher one). Another signal in the region 58 to 75 ppm at 63.3 ppm was assigned to the cis isomer.

Registry No.—(±)-**4**, 69239-16-3; **7** (isomer a), 69307-84-2; **7** (isomer b), 69307-85-3; **8**, 69239-14-1; 1,5-bis(5-methylfuryl)pentadien-3-one, 69239-15-2; 5-methylfurfural, 620-02-0; acetone, 67-64-1; 1,5-diphenylpentadien-3-one, 538-58-9; 1,5-bis(4-methoxyphenyl)-pentadien-3-one, 2051-07-2; 1,3-indandione, 606-23-5; 1,3-cyclohexanedione, 504-02-9; (*S*)-(+)-butane-2,3-dithiol, 69307-86-4.

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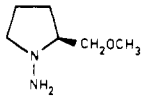

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