

moved and the mixture was cooled and extracted with methylene chloride. The methylene chloride in turn was extracted thoroughly with 1 *N* sodium hydroxide to remove the acidic component, washed with water and evaporated to dryness. After removal of the solvent, the residue, constituting the neutral fraction, was triturated with ethanol to yield 0.77 g. of yellow prisms of 2,2-diphenyl-1,3-indandione, m.p. and mixed m.p. after recrystallization from ethanol 122–123°. The infrared spectrum of this compound was identical to that of an authentic sample.

The aqueous sodium hydroxide extract upon acidification with 6 *N* hydrochloric acid yielded 1.07 g. of 2-phenyl-1,3-indandione, m.p. and mixed m.p., after recrystallization from benzene-petroleum ether, 147–148°. The infrared spectrum was identical to that of an authentic sample.

Determination of Benzene Formed in the Phenylation Reactions.—The phenylations of 2-phenyl-1,3-indandione, 1,3-indandione and the sodium salt of ethyl 1,3-indandione-2-carboxylate were carried out under identical conditions to the ones described above on a 1-gram scale. After the proper reaction time the *t*-butyl alcohol was distilled through a fractionating column and the amount of benzene in the distillate was determined by ultraviolet spectroscopy from the optical density at 254 μ . The amount of benzene found was 20, 12 and 8%, respectively. It was established by control experiments that the benzene detected in these reactions was not due to the decomposition of the iodobenzene present, but rather arose from intermediates formed during the phenylation (probably phenyl free radicals).

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY OF STANFORD UNIVERSITY, STANFORD, CALIFORNIA, THE DEPARTMENT OF CHEMISTRY OF NEW YORK UNIVERSITY, NEW YORK 53, NEW YORK AND THE DEPARTMENT OF PHYSICAL CHEMISTRY OF THE UNIVERSITY OF COPENHAGEN, DENMARK]

Inherently Dissymmetric Chromophores and Circular Dichroism

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Ultraviolet circular dichroism (C.D.) curves have been measured for a group of optically active substances possessing inherently dissymmetric chromophores (β,γ -unsaturated ketones and twisted biaryls) and compared with their ultraviolet absorption spectra and optical rotatory dispersion (O.R.D.) curves. The correspondence between these three spectral properties is discussed and confirms the earlier enunciated deductions of the relationship between absolute configuration and optical rotatory power of such inherently dissymmetric chromophores. Circular dichroism has been found particularly useful in this instance for defining the optical rotatory contribution of each individual optically active transition.

The Cotton effect associated with a particular electronic transition manifests itself in two complementary phenomena: *circular dichroism* (C.D.)⁴ and *anomalous optical rotatory dispersion* (O.R.D.). For reasons of instrumentation, it is the latter which has received virtually exclusive attention in recent years.⁵ However, the same structural information is contained in the measurement of either phenomenon, since the shape of the partial C.D. curve and its signed intensity (a measure of the rotational strength) can be related in a known way to the shape of the associated partial O.R.D. curve and its signed amplitude.⁶

In the case of inherently dissymmetric chromophores,^{6,7} the C.D. is particularly interesting. Not only does the sign of the C.D. reflect the chirality of the chromophore, but, subject to certain as-

sumptions, theory also predicts that the partial C.D. curve and partial absorption are proportional, i.e., are of the same shape to within a scale factor.^{6,8} The relationship between the absolute configuration and O.R.D. of inherently dissymmetric chromophores (as represented by conjugated and homoconjugated π -systems) has recently been the subject of intensive study.⁹ In the present paper we wish to report results bearing on the utility of C.D. in studies of absolute configuration and optical rotatory power of such inherently dissymmetric chromophores.

The β,γ -unsaturated ketones constitute a class of compounds for which the optical rotatory phenomena have been successfully discussed in terms of a twisted composite chromophore formed from carbonyl and olefinic moieties,^{10–13} i.e., in terms of an inherently dissymmetric chromophore. The C.D. curves of selected key substances in this group are reported (solid lines) in Fig. 1 (parasantonide, I), Fig. 2 (dehydronorcamphor, II), Fig. 3 (bicyclo-octenone, III), and Fig. 4 (dimethyldibenzuberone, IV (R-configuration) and V (S-configuration)) along with the absorption curves (dashed lines). The high rotational strengths of the dissymmetric chromophores find expression in the large values of

(1) In view of the intimate connection between circular dichroism and optical rotatory dispersion, all circular dichroism studies from the Stanford laboratories will be considered part of our series "Optical Rotatory Dispersion Studies." The present paper represents part LXXVI; for part LXXV see, C. Djerassi and W. Klyne, *Proc. Natl. Acad. Sci., U. S. A.*, **48**, June (1962). The work at Stanford University has been supported by the National Science Foundation (Grant No. G-19905).

(2) Fellow of the Alfred P. Sloan Foundation.

(3) On leave from the Department of Chemistry, University of Minnesota, Minneapolis 14, Minnesota.

(4) For some examples of previous measurements of circular dichroism see: W. Kuhn and E. Braun, *Z. physik. Chem. (Leipzig)*, (B) **8**, 445 (1930); J.-P. Mathieu, *J. chim. phys.*, **33**, 78 (1936); S. Mitchell and K. Schwarzwald, *J. Chem. Soc.*, 889 (1939); and further references cited by W. Kuhn, *Ann. Rev. Phys. Chem.*, **9**, 417 (1958). For more recent studies see J. Badoz, M. Billardon and J.-P. Mathieu, *Compt. rend.*, **251**, 1477 (1960); L. Velluz and M. Legrand, *Angew. Chem.*, **73**, 603 (1961); R. Deen, D.Sc. Thesis, Leiden, 1961.

(5) C. Djerassi, "Optical Rotatory Dispersion: Applications to Organic Chemistry," McGraw-Hill Book Co., New York, N. Y., 1960.

(6) (a) W. Moffitt and A. Moscowitz, *J. Chem. Phys.*, **30**, 648 (1959); (b) A. Moscowitz, Chapter 12 in reference 5.

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(10) K. Mislow, M. A. W. Glass, A. Moscowitz and C. Djerassi, *J. Am. Chem. Soc.*, **83**, 2771 (1961).

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(13) K. Mislow, M. A. W. Glass, R. E. O'Brien, P. Rutkin, D. H. Steinberg, J. Weiss and C. Djerassi, *J. Am. Chem. Soc.*, **84**, 1453 (1962).

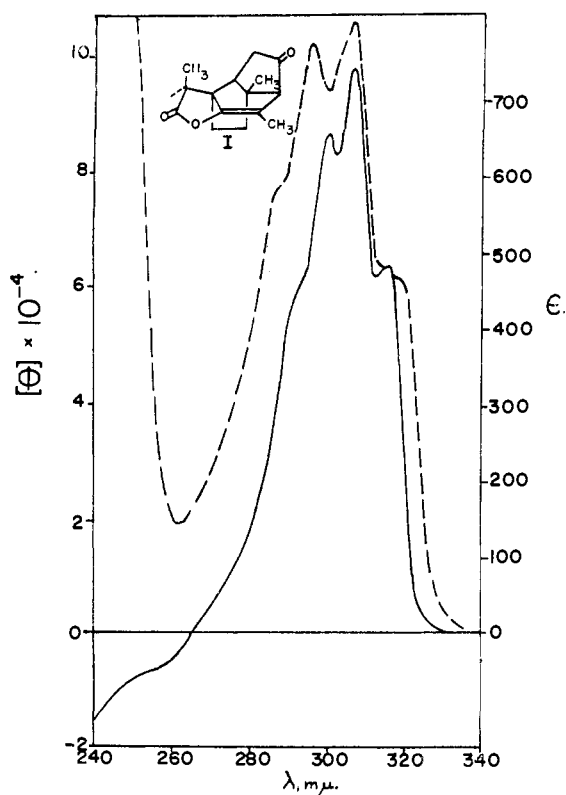


Fig. 1.

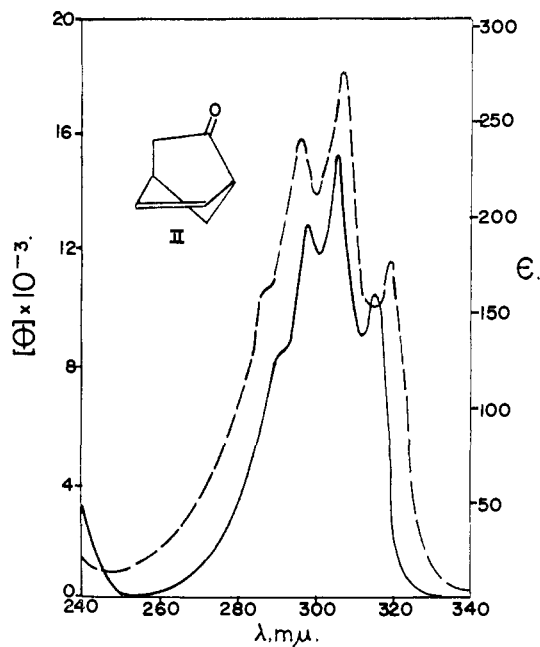


Fig. 2.

the molecular ellipticity $[\theta]^{14}([\theta]_{\max} \text{ ca. } 3 - 10 \times 10^4)$ as they did in the correspondingly high amplitudes of O.R.D. curves and high ϵ_{\max} values (relative to saturated ketones) previously discussed¹⁰⁻¹³ (see Table I). The sign of the long-wave length C.D. curves, like the sign of the corresponding partial O.R.D. curves, reflects the absolute configura-

(14) For definition, see p. 155 in reference 5.

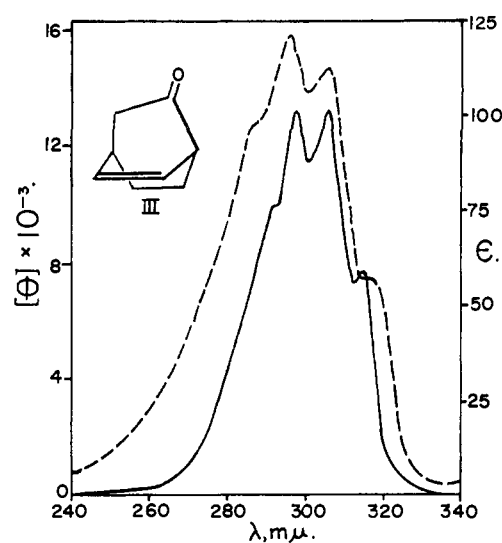


Fig. 3.

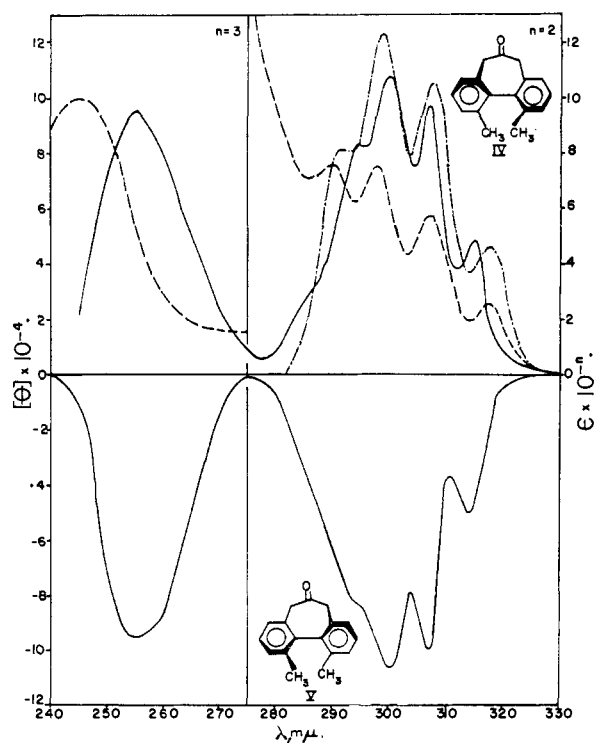


Fig. 4.

tion (or conformation) of the composite chromophore. A positive sign corresponds to the absolute stereochemistry indicated in Figs. 1-4, in accord with the generalized octant rule.^{10, 11}

In all of the cases (except IV below 300 mμ) the shape of the long-wave length C.D. curve closely follows the vibrational contour of the absorption curve, although the latter is uniformly broader. This discrepancy can be attributed to the fact that, although the transition in question is electronically allowed, it is only *weakly* allowed ($\epsilon_{\max} < 1000$), so that a non-negligible portion of the observed intensity of absorption still comes from vibrational-electronic interactions of the type that account for

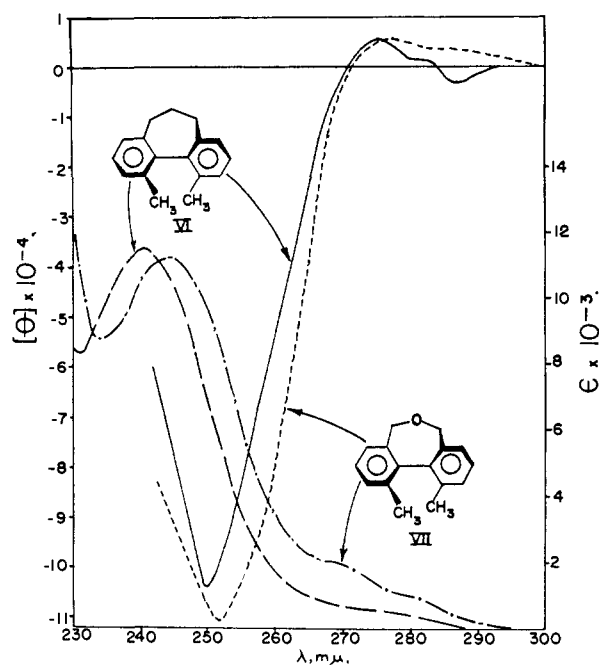


Fig. 5.

the bulk of the absorption intensity in transitions forbidden by symmetry (*e.g.*, the $n-\pi^*$ transition in formaldehyde and the 260 $m\mu$ band in benzene). To a first approximation, vibrational-electronic transitions of this sort can contribute to the absorption but not to the rotatory power.

It has been pointed out^{10,11} that the symmetry of dimethyldibenzuberone IV requires that the electric dipole transition moment $\bar{\mu}_e$ and the magnetic dipole transition moment $\bar{\mu}_m$ be parallel for the long-wave length transition, and hence that both the scale and shape factors for the rotatory quantities are obtainable from the partial absorption curve, if it is further assumed that $\bar{\mu}_m$ may be taken as one Bohr magneton for the carbonyl $n-\pi^*$ transition. On this basis, a satisfactory approximation to the experimental rotatory dispersion curve was calculated.^{10,11} The same approach permits a prediction of the C.D. curve, and the results are shown in Fig. 4. Agreement between the experimental (solid line) and calculated (dot-dash line) curves is fairly good, although not wholly satisfactory. The discrepancies can be attributed to a slightly high estimate of the value of $\bar{\mu}_m$, the presence of some vibrationally allowed intensity in the experimental absorption band, and the necessity of estimating the shape of the partial long-wave length absorption band in the presence of the overlapping biphenyl conjugation band.¹⁵

The shorter wave length C.D. in IV and V corresponds to the above-mentioned biphenyl conju-

(15) The shape of the long-wave length partial absorption band was estimated by subtracting a Gaussian continuation of the biphenyl conjugation band.¹¹ The resulting partial absorption curve was then approximated by a sum of four Gaussians as: $\epsilon = 255 \exp[-(\lambda - 317.8)^2/(4.3)^2] + 570 \exp[-(\lambda - 307.6)^2/(4.6)^2] + 645 \exp[-(\lambda - 298.5)^2/(4.4)^2] + 405 \exp[-(\lambda - 290.6)^2/(4.4)^2]$. With the assumptions mentioned in the text, this leads to an expression for the difference ($\epsilon_L - \epsilon_R$) in the molar absorption coefficients for left and right circularly polarized light plotted in units of Θ in Fig. 4: $(\epsilon_L - \epsilon_R) = 14.1 \exp[-(\lambda - 317.8)^2/(4.3)^2] + 31.5 \exp[-(\lambda - 307.6)^2/(4.6)^2] + 35.7 \exp[-(\lambda - 298.5)^2/(4.4)^2] + 22.4 \exp[-(\lambda - 290.6)^2/(4.4)^2]$.

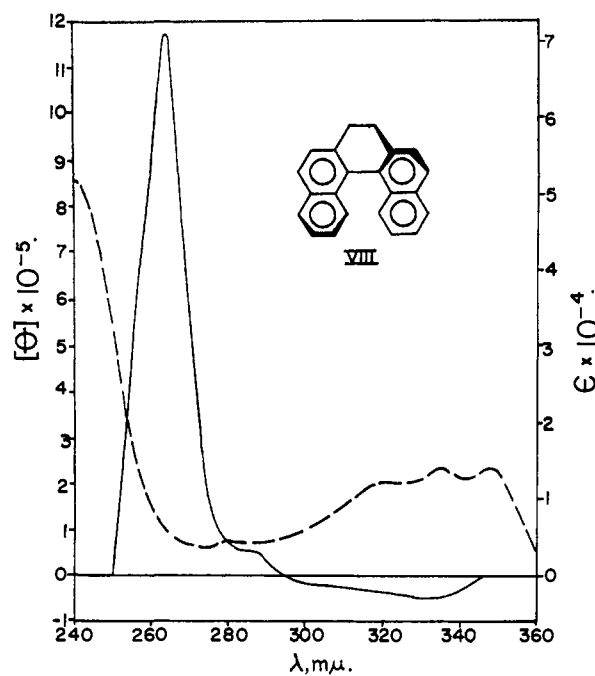


Fig. 6.

gation band which lies near 245 $m\mu$. This transition has previously been shown¹³ to give rise to high amplitude Cotton effects whose sign depends upon the absolute sense of twist of the biphenyl moiety (an excellent example of an inherently dissymmetric chromophore). Signs and magnitudes of the C.D. and O.R.D. curves again show the expected correspondence (Table I).

A few other selected examples of C.D. in twisted biphenyls of known absolute configuration are presented in Figs. 5 and 6 (solid and crossed lines) along with the corresponding absorption curves; *cf.* also Table 1. In Fig. 5, the relative displacement of the biphenyl conjugation band in VI and VII is faithfully mirrored in the relative displacement of the C.D. curves. However, it will be noted that the C.D. maxima are red-shifted relative to their corresponding ultraviolet maxima. This can be understood in terms of an overlapping intense transition lying toward the blue and which contributes strongly to both the absorption and the C.D. (An intense, higher energy transition is in fact visible in Fig. 5.) If this transition exhibits C.D. of opposite sign to that of the biphenyl conjugation band, then the effect of the overlapping is to shift the ultraviolet maximum (where the superposed bands have the same sign) toward the blue and to shift the C.D. maximum (where the bands are of opposite sign and tend to cancel) toward the red. It might also be mentioned here that differences in the shapes of the C.D. and ultraviolet spectra may be expected in the regions of the onset of partial absorption bands (*cf.* Fig. 4 in the vicinity of 280 $m\mu$). Although the intensity culled from vibrational-electronic interactions is negligible for the total intensity of a strong band, it may nevertheless be comparable to the electronically allowed intensity in the tails of the band where the allowed intensity is very small.

TABLE I^a

Fig.	Compound (solvent)	Long-wave length region			Short-wave length region		
		$[a]_D \times 10^{-4}$	$[\theta]_{\max} \times 10^{-4}$	$\epsilon_{\max} \times 10^{-2}$	$[\alpha]_D \times 10^{-4}$	$[\theta]_{\max} \times 10^{-4}$	$\epsilon_{\max} \times 10^{-2}$
1	I (isoöctane)	+14.2 (304) ^c	+ 9.85 (307)	8.05 (308) ^c	...	Negative below 260 m μ	66 (228)
2	II (isoöctane)	+ 7.8 (302) ^{d,e}	+ 3.18 (306) ^e	2.77 (307.5) ^c	...	Positive below 250 m μ	...
3	III (isoöctane)	+ 5.2 (298) ^{d,f}	+ 3.35 (298) ^f	1.22 (296) ^c
4	IV (isoöctane)	+13.7 (297) ^g	+10.8 (300)	6.70 (297.5) ⁱ	...	+ 9.65 (255)	98 (245) ^g
4	V (isoöctane)	-15.2 (301) ^{g,h}	-10.6 (300)	6.70 (297.5) ⁱ	- 16.2 (243) ^{g,h}	- 9.5 (255)	98 (245) ^g
5	VI (isoöctane)	...	- 0.33 (287)	6.0 (274) ^{g,i}	- 13.0 (242) ^g	- 10.4 (250)	115 (240.5) ^g
			+ 0.60 (275)				
5	VII (dioxane)	...	+ 0.59 (276)	8.90 (281) ^{g,i}	- 9.8 (241) ^g	- 11.1 (252)	111 (244.5) ^g
				19.3 (270) ^g			
6	VIII (dioxane)	...	- 4.15 (330)	142 (348) ^g	+157 (253) ^g	+118 (264)	519 (240) ^g

^a Values in parentheses are wave lengths in m μ . ^b Molecular amplitude of O.R.D. curves with wave lengths taken half-way between extrema. ^c A. Moscowitz, K. Mislow, M. A. W. Glass and C. Djerassi, *J. Am. Chem. Soc.*, **84**, 1945 (1962). ^d K. Mislow and J. G. Berger, *ibid.*, **84**, 1956 (1962). ^e After correction to optical purity assuming 48% optical purity for the sample (ref. *d*). ^f After correction to optical purity assuming 40% optical purity for the sample (ref. *d*). ^g K. Mislow, M. A. W. Glass, R. E. O'Brien, P. Rutkin, D. H. Steinberg, J. Weiss and C. Djerassi, *J. Am. Chem. Soc.*, **84**, 1455 (1962). ^h Refers to solvent dioxane. ⁱ Shoulder. ^j After subtraction of the aromatic absorption band (ref. *c*).

A particularly instructive feature may be found in the C.D. behavior of VI and VII in the long-wave length region. It had previously been remarked¹³ that in numerous seven-membered ring bridged biphenyls a long-wave length Cotton effect of low amplitude accompanies the conjugation band Cotton effect, and that the two effects are of the same sign. It was also pointed out that the oxepin VII is exceptional in not exhibiting the long-wave length Cotton effect. The C.D. curves in Fig. 5 clearly substantiate these observations and in addition imply the presence of a heretofore unsuspected Cotton effect of opposite sign which is hidden by the tail of the high amplitude Cotton effect centered near 245 m μ .

The O.R.D. of the binaphthyl VIII also has been discussed¹³ and Fig. 6 shows the C.D. associated with each group of absorption bands. The negative long-wave length and positive short-wave length C.D. curves correspond to the negative and positive Cotton effects previously demonstrated. The value of $[\theta]_{\max}$ (Table 1) is extremely high, but in accord with the comparably intense O.R.D. curve.

The present work verifies the major conclusions concerning the relationship between absolute configuration and optical rotatory power that had previously been arrived at from O.R.D. data for the group of inherently dissymmetric chromophores herein considered. At the same time it demon-

strates the anticipated advantage of C.D. over O.R.D., namely, that the marked reduction of overlapping tails in the C.D. curves, as compared to the O.R.D. curves, greatly facilitates individual study of the rotatory power of each separate optically active transition, and indeed can be of aid in rendering the identification of the relevant electronic transition more secure.

Experimental¹⁶

Circular dichroism measurements were conducted in isoöctane or dioxane solution (see Table 1) using a Baird-Atomic/Jouan Dichrograph (Model JO-1). The concentrations employed (*c*, 0.001-0.01 for β,γ -unsaturated ketones I-III; *c*, 0.001-0.0002 for twisted biaryls in region below 280 m μ and *c*, 0.01-0.001 above 280 m μ) were such as to maintain the slit width below 1.3 mm. in the region of the circular dichroism maximum. Both the solvent and racemic IV gave a straight line over the spectral range covered in Figs. 1-6. The molecular ellipticity $[\theta]$ is expressed¹⁵ as $[\theta] = 2.303 (4500/\pi)(\epsilon_L - \epsilon_R)$ with $(\epsilon_L - \epsilon_R) = (d \times \text{sensitivity} \times 10^{-4} \times \text{mol. wt.}) / c \times l$ where *d* is the recorder deflection (in mm.) at the particular sensitivity setting (1.5, 2 or 3) of the instrument, *c* is the concentration in g./l. and *l* the cell path length in cm.

(16) We are greatly indebted to Mrs. Ruth Records for her skillful technical assistance.