region was taken in a 0.1-cm sample holder: $\Delta\epsilon_{314}$ −23.6; $\Delta\epsilon_{288}$ +11.4.

Case 3. (2*S*,3*S*)-3-Phenylpropane-2-amine-1,3-diol, 0.63 mg (entry **19**; K & K), was dissolved in a 5.0×10^{-5} *M* solution of $Ni(acac)_2$ in 0.2 *M* *t*-BuOH–CCl_4. A CD taken in a 1-cm sample holder resulted in $\Delta\epsilon_{315}$ +7.1.

References and Notes

(1) R. E. Reeves, *Adv. Carbohydr. Chem.*, **6**, 107 (1971); S. T. K. Bukhari, R. D. Wrixon, A. I. Scott, and A. D. Wrixon, *Chem. Commun.*, 1580 (1968); *Tetrahedron*, **26**, 3653 (1970).
(2) E. Bunnenberg and C. Djerassi, *J. Am. Chem. Soc.*, **82**, 5953 (1960); see also A. I. Scott and A. D. Wrixon, *Chem. Commun.*, 1184 (1969).
(3) A. H. Haines and C. S. P. Jenkins, *Chem. Commun.*, 350 (1969).
(4) N. Harada and K. Nakanishi, *J. Am. Chem. Soc.*, **91**, 3789 (1969).
(5) N. Harada and K. Nakanishi, *Acc. Chem. Res.*, **5**, 257 (1972), and references cited therein.
(6) S. L. Chen, N. Harada, and K. Nakanishi, *J. Am. Chem. Soc.*, **96**, 7352 (1974).
(7) M. Koreeda, N. Harada, and K. Nakanishi, *J. Am. Chem. Soc.*, **96**, 266 (1974).
(8) V. Delaroff and R. Viennet, *Bull. Soc. Chim. Fr.*, 277 (1972).
(9) Preliminary accounts have been published: (a) K. Nakanishi and J. Dillon, *J. Am. Chem. Soc.*, **93**, 4058 (1971); (b) K. Nakanishi, D. A. Schooley, M. Koreeda, and J. Dillon, *Chem. Commun.*, 1235 (1971); (c) J. Dillon and K. Nakanishi, *J. Am. Chem. Soc.*, **96**, 4057, 4059 (1974).
(10) J. Dillon and K. Nakanishi, *J. Am. Chem. Soc.* **97**, following paper in this issue.
(11) G. J. Bullen, R. Mason, and P. Pauling, *Inorg. Chem.*, **4**, 456 (1965).
(12) D. P. Graddon and E. C. Watten, *Nature (London)*, **190**, 906 (1961).
(13) F. A. Cotton and J. P. Fackler, Jr., *J. Am. Chem. Soc.*, **83**, 2818 (1961).
(14) J. P. Fackler, Jr., *J. Am. Chem. Soc.*, **84**, 24 (1962).
(15) J. P. Fackler and F. A. Cotton, *J. Am. Chem. Soc.*, **83**, 3775 (1961).
(16) J. T. Hashagen and J. P. Fackler, Jr., *J. Am. Chem. Soc.*, **87**, 2821 (1965).
(17) For reviews of this and other topics concerning the chemistry of β-ketoenolate transition metal complexes, see: D. P. Graddon, *Coord. Chem. Rev.*, **4**, 1 (1969).
(18) T. S. Kannan and A. Chakravorty, *Inorg. Chem.*, **9**, 1153 (1970).
(19) See, for example: A. B. P. Leven, "Inorganic Electronic Spectroscopy", Elsevier, New York, N.Y., 1968, p. 134.
(20) E. J. Corey and J. C. Bailar, Jr., *J. Am. Chem. Soc.*, **61**, 2620 (1959).
(21) (a) J. R. Gollogly and C. J. Hawkins, *Inorg. Chem.*, **8**, 1168 (1968); (b) C. J. Hawkins, "Absolute Configuration of Metal Complexes", Wiley-Interscience, New York, N.Y., 1971.
(22) W. De W. Horrocks, Jr., D. H. Templeton, and A. Zalkin, *Inorg. Chem.*, **7**, 1552 (1968).
(23) A. J. McCaffery, S. F. Mason, B. J. Norman, and A. M. Sargeson, *J. Chem. Soc. A*, 1304 (1968); B. Bosnich and J. MacB. Harrowfield, **94**, 3425 (1972).
(24) M. J. Harding, S. F. Mason, and B. J. Peart, *J. Chem. Soc.*, 955 (1973).
(25) B. Bosnich, *Acc. Chem. Res.*, **2**, 266 (1969).
(26) L. J. Boucher, *Inorg. Chem.*, **9**, 1202 (1970).
(27) J. P. Fackler, Jr., *J. Am. Chem. Soc.*, **84**, 24 (1962).
(28) D. P. Graddon, *Nature (London)*, **195**, 891 (1961).
(29) J. P. Fackler, Jr., and F. A. Cotton, *J. Am. Chem. Soc.*, **82**, 5005 (1960).
(30) J. Dillon and K. Nakanishi, *J. Am. Chem. Soc.*, **96**, 4055 (1974).
(31) D. R. Eaton and W. D. Phillips, *Adv. Magn. Reson.*, **1**, 103 (1965).
(32) W. De W. Horrocks, Jr., J. P. Sipe, III, and D. Sudnick, "Nuclear Magnetic Shift Reagents", R. E. Sievers, Ed., Academic Press, New York, N.Y., 1973.
(33) T. C. McMorris and M. Anchel, *J. Am. Chem. Soc.*, **85**, 831 (1963).
(34) H. Ziffer, D. M. Jerina, D. T. Gibson, and V. M. Kobal, *J. Am. Chem. Soc.*, **95**, 4048 (1973).
(35) Supported by NSF GP 40087.

Absolute Configurational Studies of Vicinal Glycols and Amino Alcohols. II. With $Pr(dpm)_3$

James Dillon and Koji Nakanishi*

Contribution from the Department of Chemistry, Columbia University, New York, New York 10027.

Received January 29, 1975

Abstract: A spectroscopic method requiring no substrate derivatization has been developed for absolute configurational studies of glycols and amino alcohols. The substrates which are suited for studies by the $Pr(dpm)_3$ method are complementary to those suited for study by the $Ni(acac)_2$ method, and are cyclic (**1–11**) and hindered acyclic secondary/tertiary (**15–19**) vicinal glycols. The method consists of measuring the CD of substrate and $Pr(dpm)_3$ dissolved in a dry nonpolar solvent. The solution shows an induced split Cotton effect consisting of two peaks of opposite sign and near equal intensity centered at ca. 300 nm. The longer wavelength extremum is positive for cyclic α-glycols of positive chirality and negative for glycols of negative chirality. Studies indicate that the size of the Cotton effect amplitude varies with concentration, time, and temperature. These data suggest that the observed CD results from formation of an unstable bidentate adduct between the glycol and $Pr(dpm)_3$. Several examples of the application of this method to compounds of unknown absolute configuration are presented.

In our previous papers,[1,2] we discussed the general usefulness of $Ni(acac)_2$ as a structural probe. Here we will present the scope and limitations of $Pr(dpm)_3$. We have reported its application to cyclic glycols,[3] and this was extended in a limited way to acyclic secondary/tertiary (sec/tert) α-glycols during the course of absolute configurational studies of the insect juvenile hormone.[4] More recently, it was shown that $Pr(dpm)_3$ can be used for cyclic α-hydroxyamines and certain monofunctional amines.[5] Studies carried out on a variety of substrates and at different concentrations show that the $Pr(dpm)_3$ reagent is complementary to the $Ni(acac)_2$ reagent and is more suited for cyclic vicinal glycols and hindered sec/tert vicinal glycols. In contrast to $Ni(acac)_2$, the solvent should be vigorously dried and nonpolar.

Results and Discussion

A split CD curve centered at ca. 300 nm is observed immediately upon addition of an optically active glycol or amino alcohol to a solution of $Pr(dpm)_3$ (dpm = dipivalomethanato; sometimes called thd = 2,2,6,6-tetramethyl-3,5-heptadionato). A typical curve, a 1:1 mixture of cholest-5-ene-3β,4β-diol and $Pr(dpm)_3$ in CCl_4 is depicted in Figure 1. The observed Cotton effect consists of two extrema of opposite signs and near equal intensities. The amplitudes of these extrema are concentration dependent as shown in Figure 2 for a cyclic case and Figure 3 for an acyclic case.

Tables I and II give the results obtained for a series of cyclic and acyclic glycols and amino alcohols. The chirality of a cyclic glycol moiety is defined as being negative or posi-

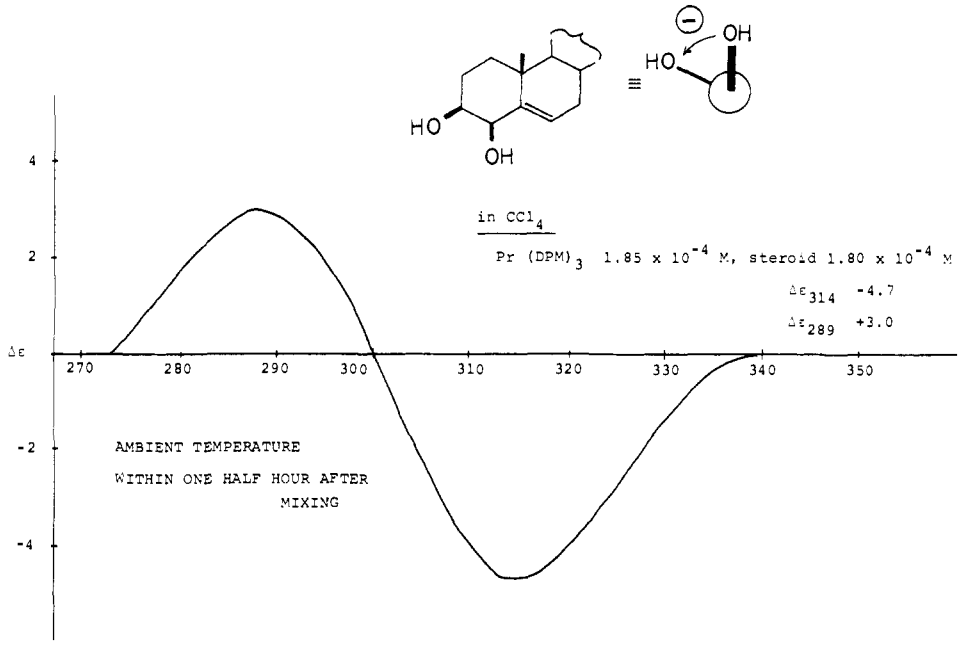


Figure 1. CD of a mixture of 1.85×10^{-4} *M* $Pr(dpm)_3$ and 1.80×10^{-4} *M* cholest-5-ene-3β,4β-diol in CCl_4.

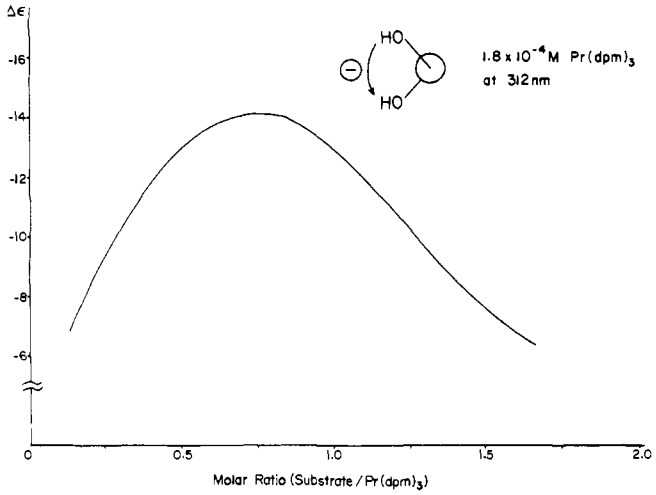


Figure 2. The change in $\Delta\epsilon$ at 312 nm for a mixture of 1.8×10^{-4} *M* $Pr(dpm)_3$ and various concentrations of cholest-5-ene-3β,4β-diol in CCl_4.

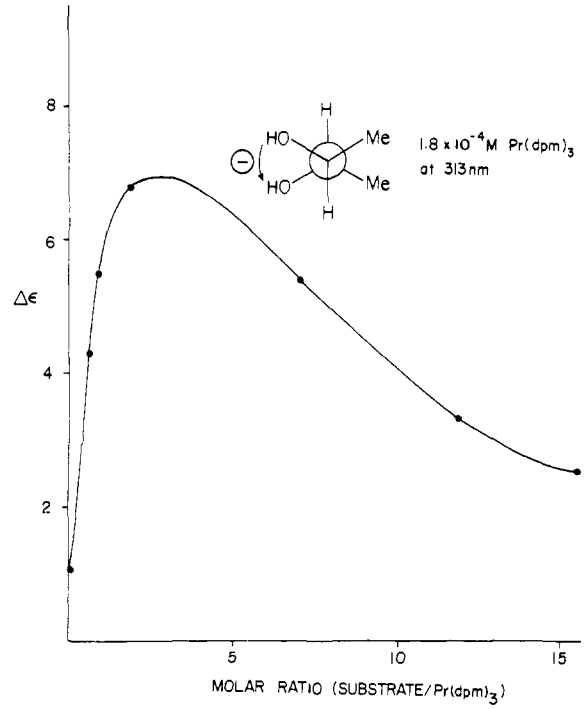
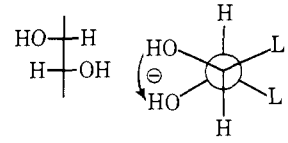


Figure 3. The change in $\Delta\epsilon$ at 313 nm for a mixture of 1.8×10^{-4} *M* $Pr(dpm)_3$ and various concentrations of (2*R*,3*R*)-butane-2,3-diol in CCl_4.

tive, respectively, when the Newman projection represents a counterclockwise or clockwise rotation from one hydroxyl or amino group to the other. In the case of acyclic compounds, there exist three rotamers; for reasons given in the previous paper,[1] conformer I where the bulkier groups are pseudo-equatorial (in the complex) is the one assumed to be involved in complex conformation.



I, L = bulkier groups

Only the signs of Cotton effects corresponding to the longer wavelength extrema are given in the tables. This is due to the fact that the high absorbance in the region of the shorter wavelength CD extremum resulted in a low signal to noise ratio, and this reduced the reliability of their measurements.

The observed Cotton effects show that, for hindered cyclic and sec/tert acyclic compounds, the signs coincide with the glycol chirality whereas for acyclic prim/sec and sec/sec compounds, the signs are opposite to the glycol chirality of the conformer having the large groups to the rear (e.g., conformer I).

Origin of the CD. Osmometric studies indicate that $Ln(dpm)_3$ (Ln = Pr, Eu) are monomeric in CCl_4.[6] When lanthanides are exposed to nucleophiles, they can expand their coordination to eight and accommodate two additional monodentate ligands,[7] establishing an equilibrium between free $Ln(dpm)_3$, and a seven- and eight-coordinate complex,[8]

Table I. Cyclic and Secondary/Tertiary Acyclic Glycols.

Entry	Compd	Chirality[a]	Molar ratio (sub/Pr)	Δε, nm[b]	Solvent
1	Cholest-5-ene-3β,4β-diol	(−)	1:1	−12.6 (312)	CCl_4
2	Cholest-5-ene-3β,4β-diol 3-acetate	(−)	1:1 7:1	−1.8 (305) −6.5 (315)	CCl_4
3	Cholest-5-ene-3β,4β-diol 3,4-diacetate	(−)	1:1	−0.47 (314)	CCl_4
4	5α-Cholestane-2β,3β-diol	(+)	1:1	+9.7 (311)	CCl_4
5	5α-Cholestane-2α,3α-diol	(+)	1:1	+6.0 (305)	CCl_4
6	Ponasterone A 20,22-acetonide[h]	(−)	1:1	−5.3 (312)	CCl_4
7	Ponasterone A 20,22-acetonide 3-acetate	(−)	1:1	−1.0 (307)	CCl_4
8	Cholestane-3β,5α,6α-triol	(−)	1:1	−5.6 (315)	CCl_4
9	Cholestane-3β,5α,6α-diol 3-acetate[c]	(−)	1:1	−6.0 (314)	CCl_4
10	5α-Androstane-3β,16α,-17α-triol	(+)	1.5:1	+5.8 (313)	$CHCl_3$
11	1,3,5(10)-Estratriene-3,-16α,17α-triol[c]	(+)	1.5:1	+7.6 (315)	CCl_4
12	(1*S*,2*S*)-1,2-Dihydroxy-1,2,3,4-tetrahydronaphthalene[d]	(+)	1:1	−4.5 (313)	CCl_4
13	Methyl arjunolate[e]		6:1	+1.5 (313)	CCl_4
14	(2*S*)-3-Methylbutane-2,3-diol[f]	(+)	9:1	−1.0 (315)	CCl_4
15	(3*S*)-2,5-Dimethylhexane-2,3-diol[g]	(+)	9:1	+4.5 (314)	*n*-hexane
16	(3*R*)-2,5-Dimethylhexane-2,3-diol[g]	(−)	17:1	−3.2 (314)	*n*-hexane
17	(4*S*)-2-Methyl-5-ethylheptane-4,5-diol[g]	(+)	6:1	+1.0 (308)	*n*-hexane
18	(4*R*)-2-Methyl-5-ethylheptane-4,5-diol[g]	(−)	5:1	−1.6 (308)	*n*-hexane
19	See entry 18, ref 1	(−)	*h*	−8.2 (303)	*n*-hexane

[a] The conformer with the bulkier groups to the rear is used to define the chirality of acyclic glycols. [b] The Δε is based on the concentration of $Pr(dpm)_3$. [c] Gift of Dr. J. Fried, Syntex Corporation. [d] Gift of Professor M. Nakazaki, Osaka University. [e] See entry 28, ref 1. [f] Gift of Professor A. Kjaer, Copenhagen, and Dr. R. Paul, Lederle Laboratories. [g] See ref 4. [h] A saturated solution of the glyeol was used.

Table II. Acyclic Primary/Secondary and Secondary/Secondary Compounds

Entry	Compd	Chirality[a]	Molar ratio (sub/Pr)	Δε, nm[b]	Solvent
20	(2*S*)-3-Chloropropane-2-hydroxy-1-amine[c]	(+)	5:1	−1.2 (312)	CCl_4
21	(2*R*)-Butane-1-hydroxy-2-amine	(−)	8:1	+3.4 (315)	CCl_4
22	(2*S*)-4-Methylpentane-1,-2-diol[d]	(+)	3:1	−2.2 (315)	CCl_4
23	(2*R*)-4-Methylpentane-1-hydroxy-2-amine[d]	(−)	3:1	+1.6 (313)	CCl_4
24	(2*S*)-4-Methylpentane-1-hydroxy-2-amine[d]	(+)	5:1	−2.2 (313)	CCl_4
25	(2*S*)-3-Phenylpropane-1-hydroxy-2-amine[d]	(+)	2:1	−3.5 (313)	CCl_4
26	(2*S*)-3-Methylpentane-1-hydroxy-2-amine[d]	(+)	6:1	−1.8 (315)	CCl_4
27	(2*S*)-2-Phenylethane-1,2-diol[d]	(+)	2:1	−0.9 (315)	CCl_4
28	(2*R*,2*R*)-Butane-2,3-diol	(−)	3:1	+7.0 (313)	CCl_4
29	(2*R*,3*S*)-3-Phenylpropane-3-hydroxy-2-amine	(+)	6:1	−4.8 (313)	CCl_4
30	(2*S*,3*S*)-3-Phenylpropane-2-amine-1,3-diol	(−)	2:1	−3.1 (312)	CCl_4
31	(2*S*)-Butane-1,2,4-triol[b,e]	(+)	3:1	+1.3 (314)	CCl_4
32	(2*S*)-Butane-4-methoxy-1,2-diol	(+)	4:1	−1.4 (315)	CCl_4

[a] The conformer with the bulkier groups to the rear is used to define the chirality of acyclic glycols. [b] The Δε is based on the concentration of $Pr(dpm)_3$. [c] Gift of Dr. R. Paul, Lederle Laboratories. [d] Prepared by the reduction of the corresponding acids. [e] See ref 18.

the equilibrium constants being dependent on the basicity of the nucleophile.[9]

In this work, various experiments were carried out to determine the origin of the CD and to define the limits of this technique. These include variation in the nature of the substrate and concentration and time dependence studies.

Substrate Variation. The addition of monofunctional alcohols to $Pr(dpm)_3$ resulted in a small CD, e.g., a 1:1 mixture of $Pr(dpm)_3$ and cholesterol gives $\Delta\epsilon_{300} < 0.01$.[10] This is also true for diaxial glycols, e.g., cholestane-2β,3α-diol and cholestane-3β,5α,6β-triol, and rigid nonadjacent glycols, cholestane-3β,6β-diol and the 6-oxo-3β,5α-diol derived from diosgenin. Conversely, all of the α-glycols and α-amino alcohols presented in Tables I and II give relatively large CD's.

A likely explanation, then, for the CD's observed immediately upon addition of a glycol to $Pr(dpm)_3$ is the following: the bidentate glycol binds to $Pr(dpm)_3$ forming an eight coordinate complex, which has a greater rotational strength than that formed by one or two monodentate ligands. It can also be seen that the formation of this bidentate adduct depends on the O–O distance of the substrate, a condition generally found in inorganic complexes.

Alternative explanations for the appearance of this induced CD are that it results from exchange, where the glycol displaces dpm preferentially from one of the $Pr(dpm)_3$ enantiomers, or that it is due to a hydrogen-bonded interaction. Exchange does occur to some degree, but it is difficult to assess the role it plays in the formation of the optical active species. On the other hand, hydrogen bonding cannot account for the inversion of the sign of the Cotton effect when the structure of the glycol is changed from a cyclic or secondary/tertiary to a secondary/secondary or primary/secondary (Tables I and II). Indeed, whether the observed sign of the Cotton effect agrees or disagrees with the predicted chirality depends on even more subtle structural changes in the glycol. The cyclic glycol entry **12** and the acyclic secondary/tertiary glycol entry **14**, the two cases which do not conform to generalities, differ from the other glycols in their class in that the overall bulk of one of the α-carbons is small.

In conclusion then, the CD's seen here are most probably due to expansion of the $Pr(dpm)_3$ coordination sphere to eight and the fact that the structure of this absorbing species is intimately related to the structure of the incoming glycol or amino alcohol.

Concentration Dependence. Figure 2 reproduces the change in Δε with increasing concentrations of a cyclic glycol, while Figure 3 is a graph for an acyclic case. As can be seen for the cyclic case, the Δε increases to a maximum at a substrate–$Pr(dpm)_3$ ratio of 1.6/1 and then decreases with increased substrate concentration. This reflects a competition between bidentate and monodentate complexation. At higher substrate concentrations, the formation of bismonodentate complexes is favored, because hydroxyl groups from different compounds can compete for sights in the same $Pr(dpm)_3$ molecule; since complexes formed from mono-

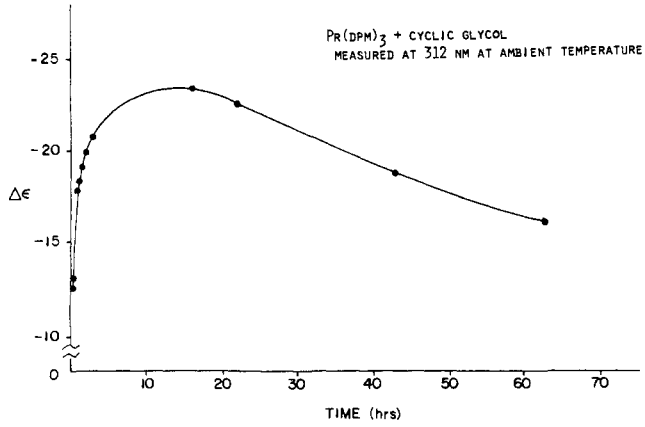


Figure 4. The change in $\Delta\epsilon$ at 312 nm with time for a mixture of 1.7×10^{-4} *M* $Pr(dpm)_3$ and 1.7×10^{-4} *M* cholest-5-ene-3β,4β-diol, in CCl_4, ambient temperature.

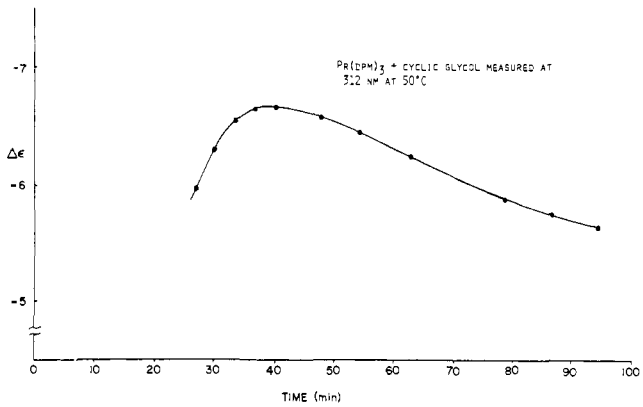


Figure 5. The change in $\Delta\epsilon$ at 312 nm with time for a mixture of 1.1×10^{-4} *M* $Pr(dpm)_3$ and 2.8×10^{-4} *M* cholest-5-ene-3β,4β-diol, in CCl_4, 50°.

dentate adducts have a low rotational strength, the size of the $\Delta\epsilon$ decreases.

It can be seen from Table I that acetylation (compare entries **1** and **2**) reduces the $\Delta\epsilon$. This agrees qualitatively with NMR shift reagent data,[9] where ketones and esters are shifted less than hydroxyl compounds at the same relative concentrations. As expected, at higher substrate–$Pr(dpm)_3$ concentrations, the observed $\Delta\epsilon$ approaches that for the nonacetylated glycol; e.g., for entry **2**, a 7:1 substrate to $Pr(dpm)_3$ ratio produced a $\Delta\epsilon$ of −6.5.

Time Dependence. The $\Delta\epsilon$ presented in Tables I and II are those recorded a few minutes after mixing the solutions of $Pr(dpm)_3$ and the substrate. However, the Cotton effect magnitudes are not constant with time, as shown in Figures 4 and 5 for a 1:1 solution of cholest-5-ene-3β,4β-diol and $Pr(dpm)_3$ at ambient temperature and a 2:1 solution at 50°; the change is much faster at the higher temperature. Both the initial gain and subsequent loss of ellipticity also occur more rapidly for unhindered acyclic glycols than for the cyclic glycol shown here. For example, a 1:1 mixture of (2*R*,3*R*)-butane-2,3-diol and $Pr(dpm)_3$ is decreased by 60% in approximately 1 hr at ambient temperature. The uv also changes with time as exemplified in Figure 6 for a 10:1 mixture of cholestenediol and $Pr(dpm)_3$ at ambient temperature. These observations indicate that the substrate–$Pr(dpm)_3$ equilibrium is quite dynamic. Namely, it consists of (i) an instantaneous CD, which we have hypothesized as resulting from an expansion of $Pr(dpm)_3$ to eight coordination, followed by (ii) further asymmetric synthesis and (iii) an eventual loss of ellipticity.

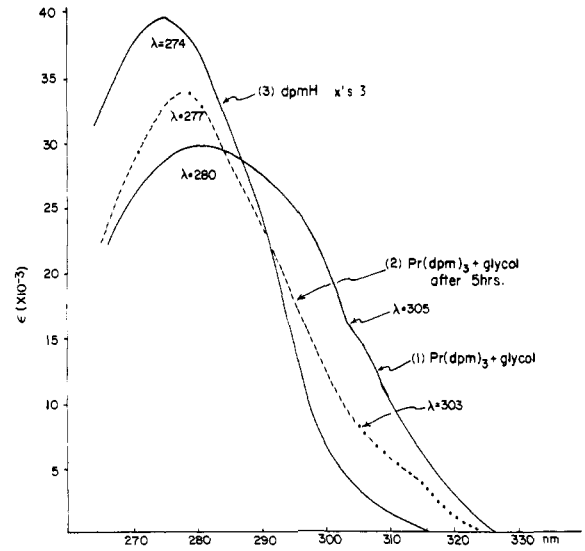


Figure 6. Curve 1: uv of a mixture of 1.73×10^{-5} *M* $Pr(dpm)_3$ and 1.73×10^{-4} *M* cholest-5-ene-3β,4β-diol in CCl_4, ambient temperature. Curve 2: the same mixture 5 hr later. Curve 3: uv of dpmH × 3.

Asymmetric synthesis has been observed in other systems. One such example is the transformation of *trans*-$[Co(en)_2ClOH]Cl{\cdot}H_2O$ to optically active *cis*-$[Co(en)_2ClOH]^+$ when the former was dissolved in warm (2*R*,3*R*)-butane-2,3-diol.[11] Since Co is a transitional metal, coordinations of greater than six are not expected. Thus a five-coordinate transition state was hypothesized to explain the transformation. In the present work, an attractive rationalization for the observed asymmetric synthesis is to suggest that it occurs through an eight-coordinate complex.

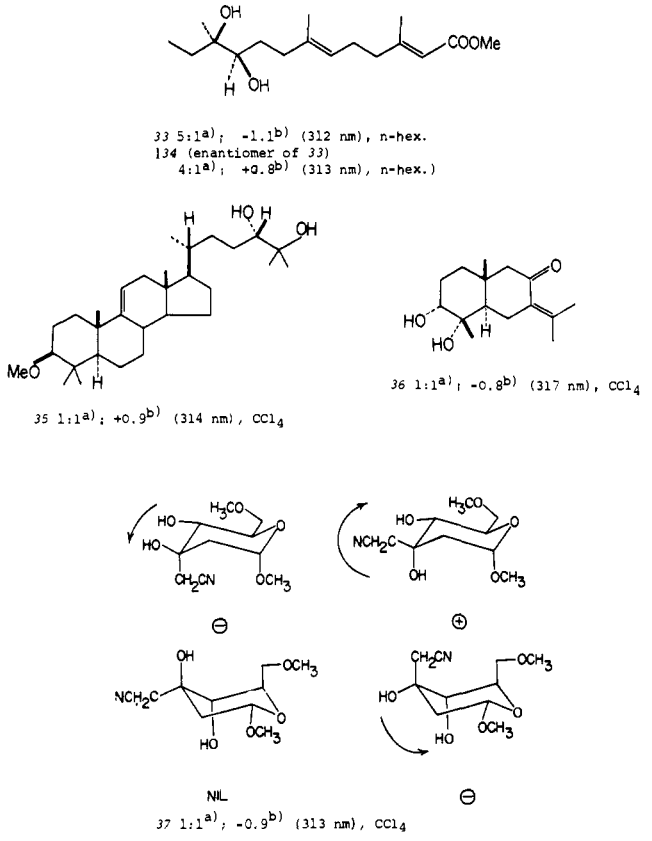
As can be seen in Figure 6, after a period of time, the uv of a $Pr(dpm)_3$–cholestenediol mixture appears to take on the shape of dpmH itself. This suggests that there is some exchange between the glycol and dpm, releasing dpmH into solution. There is also a decrease in the size of $\Delta\epsilon$ with time (Figure 4), and this occurs faster at higher temperatures (Figure 5) and at higher concentrations; thus, a 10/1 cholestenediol–$Pr(dpm)_3$ mixture at 50° loses 60% of its ellipticity after only 2 hr.

Although the origin of the induced CD is far from clear, a possible rationalization of the mentioned observations would be as follows: (i) upon dissolving a glycol (G) an equilibrium mixture is formed in which G interacts with both enantiomers of $Pr(dpm)_3$, one to a greater extent than the other (for the sake of argument, we will call the predominant species G·Δ); (ii) the expansion of Λ in G·Λ causes it to transform to Δ over a period of time; and (iii) while this is going on, the G can exchange with dpmH with a concomitant loss in ellipticity. This mechanism, of course, assumes that the sign of the Cotton effects of G·Δ and Δ are the same.

Actual Measurements and Interpretation. The relative concentrations used are taken from the studies shown in Figures 2 and 3. The optimum conditions are a 1:1 mixture for cyclic compounds, and a 1:4–7 mixture for acyclic compounds. The concentration of $Pr(dpm)_3$ (1×10^{-4} *M*) was selected since a greater concentration resulted in instrument noise with concomitant operational and interpretive difficulties.

The $\Delta\epsilon$ value is adversely affected by competing nucleophiles such as ethanol and water. Therefore in actual measurements it is essential that the solvent used is dry (see Experimental Section). This also holds for the substrate glycol. It is suggested that the compound be kept in a vacuum overnight over P_2O_5.

Table III.



[a] Molar ratio of substrate/Pr(dpm)$_3$. [b] $\Delta\epsilon$ values.

Dry *n*-hexane and carbon tetrachloride appear to be the most suitable solvents for this method. Chloroform may also be used, but it is essential to free it from ethanol (stabilizer) immediately prior to use. Substrates not soluble in aprotic solvents can be handled by the Ni(acac)$_2$ method.

The correlation of the induced CD with structure has several pitfalls which should be noted. Isolated amines and bifunctional groups other than glycols and amino alcohols (e.g., α-hydroxy ketones and α-hydroxy esters) exhibit induced CD's with Pr(dpm)$_3$. Therefore, compounds containing both an α-glycol and the mentioned functionalities should be interpreted with care. However, the $\Delta\epsilon$ values of these other alcohol functions (entries **2** and **3**) are smaller than those due to α-glycol or α-amino alcohol functions. There may also be a problem with bidentate amino alcohols where the amine is sterically much less hindered than the hydroxyl group, e.g., entries **20** and **29.** Here amines themselves can induce a CD, and it is not known whether the observed CD is due to a mono- or bidentate interaction, the result of which is unpredictable at this time.

Trifunctionality, in which three groups are in close proximity, also causes a problem. In entry **13,** the observed chirality is that for the 1,3-glycol rather than the 1,2-glycol. This may be due to the closer approach of the O–O distance in the 1,3 case, which would be expected to complex better than the rigid 1,2-glycol. On the other hand, this result may just be fortuitous. Entries **30** and **31** present a more interesting problem. Here the observed Cotton effects are opposite to those expected for general prim/sec α-glycols or amino alcohols. There are several possible explanations for this: (i) the sec/sec complex (entry **30**) and/or the 1,3 complex (entries **30** and **31**) are more stable than the corresponding 1,2 prim/sec complex; (ii) a bidentate complex is being formed in which the additional hydroxyl is hydrogen bonded; (iii) an intriguing possibility is that the CD's are the result of nonacoordination of the Pr(dpm)$_3$. It is as yet not clear which of these explanations is correct (it is conceivable that there may be other possible rationalizations for these results) but, as entry **32** shows, O-methylation of **31** at position 4 effectively blocks the interfering interaction.

Table IV. A Comparison of the Ni(acac)$_2$ and Pr(dpm)$_3$ Method

Conditions	Ni(acac)$_2$	Pr(dpm)$_3$
(1) Solvents	Dry *n*-hexane, CCl_4, $CHCl_3$, *t*-BuOH, CH_3CN	Dry *n*-hexane, CCl_4, $CHCl_3$
(2) Concentrations, *M*	Solvent: 5×10^{-5} Substrate: 5×10^{-4}	1×10^{-4} 1×10^{-4}
(3) Intensities, $\Delta\epsilon$	5–50	1–10
(4) Compd class	(a) Acyclic α-glycols: prim/sec, sec/sec, unhindered sec/tert[a]; (b) acyclic vicinal prim/sec hydroxyamines; (c) some 1,3-glycols	(a) Cyclic α-glycols; (b) hindered acyclic sec/tert α-glycols

[a] Sterically crowded acyclic secondary/tertiary α-glycols give no induced CD with Ni(acac)$_2$; acyclic primary/tertiary glycols are not included because of lack of authentic cases.

To summarize, this method is applicable to hindered cyclic and sec/tert acyclic cases. Table I demonstrates its utility. Entry **8** is a cyclic sec/tert glycol, and thus it would have been difficult to carry out configurational studies due to lack of carbinyl proton and difficulty in derivatization. Entry **6** shows the application of this method to a compound already possessing strong CD Cotton effects, i.e., at 327 ($\Delta\epsilon$ +1.8) and 248 nm ($\Delta\epsilon$ −3.9) (in ethanol). This measurement was carried out by taking a spectrum of entry **6** with and without Pr(dpm)$_3$; the $\Delta\epsilon$ listed in Table II is the resultant differential CD.

Table III lists a few compounds in which the Pr(dpm)$_3$ method was used to determine their absolute configurations. Glycol **33** was obtained by epoxide cleavage of the natural insect juvenile hormone and glycol **34** from its enantiomer. The application of this method established the absolute configuration of the epoxide as 10*R*/11*S*;[4] the same conclusion was arrived at by independent studies.[12]

The use of this method for entry **35** gave $\Delta\epsilon$ +0.9 in CCl_4, which established the absolute configuration of C-24 as being *S*.[13] Compound **36** is the sesquiterpene cuauhtemone, where flexibility of the enone group prevented application of the various rules proposed for determining the enone chirality. NMR studies showed that the 3-hydroxyl function adopts an equatorial conformation. A differential CD curve before and after the addition of Pr(dpm)$_3$ to a CCl_4 solution of compound **36** showed a negative peak at 317 nm ($\Delta\epsilon$ −0.8), and this led to the absolute configuration depicted.[14]

The configuration of sugar **37** was deduced to be α on the basis of ir data and the failure to form an acetonide[15] (hence a *trans*-3,4-glycol). This was corroborated by a negative peak at 313 nm ($\Delta\epsilon$ −0.9), thus top-left expression.

Finally, Table IV presents a comparison of experimental conditions and utilities of the Pr(dpm)$_3$ and Ni(acac)$_2$ methods. In general, Ni(acac)$_2$ is more stable, gives higher $\Delta\epsilon$'s, and can be used in a broader range of solvents than Pr(dpm)$_3$. On the other hand, Pr(dpm)$_3$ is more useful for hindered compounds, and smaller molar ratios can be used.[19]

Experimental Section

The CD measurements were made on a Cary-6001 attachment on a Cary-60 spectropolarimeter and uv measurements on a Cary 16 spectrophotometer. The solvents used were spectrograde and were dried over molecular sieves type 4A overnight.

Chloroform was made ethanol free by shaking four times in a separatory funnel with water, drying over sodium sulfate, and passing through a column of aluminum oxide (Wöhrlm, neutral). All measurements were performed by taking volumetric samples from a premixed stock solution and mixing them immediately prior to measurements of spectra. It was found that atmospheric moisture has deleterious effects on the intensity of the spectra and hence, if more than one sample is to be mixed and measured, it is advantageous to do so in a nitrogen atmosphere.

The concentration studies were also mixed under a stream of dry nitrogen.

Pr(dpm)$_3$. Pr(dpm)$_3$ was prepared according to the literature:[16] yield 82%; mp 219–222° (uncorr); sublim 183° (0.1 mm).

The following are two examples of typical measurements. Case 1: 5α-Cholestane-2β,3β-diol (0.2 mg, entry **4**) was dissolved in 5 ml of a 1.0 × 10^{-4} M solution of Pr(dpm)$_3$ in dry CCl_4, $\Delta\epsilon_{311}$ +9.7. Case 2: Ponasterone A 20,22-acetonide (0.5 mg) was dissolved in 5 ml of dry CCl_4; 2.5 ml of this was diluted to 5 ml with CCl_4, and the spectrum was taken. The remaining sample was diluted to 5 ml by the addition of 2.5 ml of a 2.0 x 10^{-4} M solution of Pr(dpm)$_3$ in dry CCl_4, and the spectrum was taken. The difference of the two curves gave the induced CD, $\Delta\epsilon_{312}$ −5.3.

References and Notes

(1) J. Dillon and K. Nakanishi, *J. Am. Chem. Soc.*, **97**, preceding paper in this issue.
(2) Preliminary communications: J. Dillon and K. Nakanishi, *J. Am. Chem. Soc.*, **96**, 4057, 4059 (1974).
(3) K. Nakanishi and J. Dillon, *J. Am. Chem. Soc.*, **93**, 4058 (1971).
(4) K. Nakanishi, D. A. Schooley, M. Koreeda, and J. Dillon, *J. Chem. Soc., Chem. Commun.*, 1235 (1971).
(5) G. N. Mitchell and F. I. Caroll, *J. Am. Chem. Soc.*, **95**, 7912 (1973).
(6) J. S. Ghotra, F. A. Hart, G. P. Moss, and M. L. Stamforth, *J. Chem. Soc., Chem. Commun.*, 113 (1973).
(7) For an X-ray crystallographic study of Eu(dpm)$_3$·Py$_2$, see: R. E. Cramer and K. Seef, *J. Chem. Soc., Chem. Commun.*, 400 (1972).
(8) Evidence for eight coordination is limited, see, for example: C. C. Hinkley, W. A. Boyd, G. V. Smith, and F. Behbahany, "Nuclear Magnetic Resonance Shift Reagents", R. E. Sievers, Ed., Academic Press, New York, N.Y., 1973, Chapter 1.
(9) C. C. Hinckley, et al., ref 8 p 5.
(10) The addition of mono-ols to Eu also gives very small CD's in the uv region. See: N. H. Anderson, B. J. Bottino, and S. E. Emith, *J. Chem. Soc., Chem. Commun.*, 1193 (1973).
(11) B. Bosnich, *J. Am. Chem. Soc.*, **89**, 6143 (1967).
(12) D. J. Faulkner and M. R. Petersen, *J. Am. Chem. Soc.*, **93**, 3766 (1971).
(13) J. P. Kutney, G. Eigendorf, R. B. Swingle, G. D. Knowles, J. W. Rowe, and B. A. Nagasampagi, *Tetrahedron, Lett.*, 3115 (1973).
(14) K. Nakanishi, R. Crouch, I. Miura, X. Dominguez, A. Zamudio, and R. Villarreal, *J. Am. Chem. Soc.*, **96**, 609 (1974).
(15) A. Rosenthal and G. Scholinhammer, *Can. J. Chem.*, **52**, 51 (1974).
(16) K. J. Eisentraut and R. E. Sievers, *J. Am. Chem. Soc.*, **87**, 5254 (1965).
(17) K. Nakanishi, M. Koreeda, S. Sasaki, M. L. Chang, and H. Y. Hsu, *Chem. Commun.*, 915 (1966).
(18) H. Hayashi, K. Nakanishi, C. Brandon, and J. Marmur, *J. Am. Chem. Soc.*, **95**, 8749 (1973).
(19) Supported by NSF GP 40087.

Oscillations in Chemical Systems. IX.[1] Reactions of Cerium(IV) with Malonic Acid and Its Derivatives

Jing-Jer Jwo[2] and Richard M. Noyes*

Contribution from the Department of Chemistry, University of Oregon, Eugene, Oregon Eugene, Oregon 97403.

Received November 12, 1974

Abstract: Cerium(IV) in 0.8 M H_2SO_4 will oxidize malonic (MA), tartronic (TTA), and glyoxylic (GOA) acids to produce one molecule of formic acid (FA) per molecule of acid. Mesoxalic (MOA) and oxalic (OA) acids are oxidized entirely to carbon dioxide. The sequence of oxidation of malonic acid is apparently MA → TTA → GOA → FA; mesoxalic, oxalic, and glycolic (GCA) acids are not formed as intermediates in significant amounts. Mesoxalic, glyoxylic, and oxalic acids have carbonyl groups adjacent to carboxyl groups and can form five-member chelate rings; they are oxidized within a couple of minutes or less at 25°. Malonic, bromomalonic (BrMA), and tartronic acids have two carboxyl groups separated by an incompletely oxidized carbon atom and can form six-member chelate rings; they are oxidized at 25° at rates approximately consistent with second-order kinetics and rate constants of the order of 1 M^{-1} sec^{-1}. Glycolic and formic acids and formaldehyde are inert to oxidation by cerium(IV) in sulfuric acid even though such oxidation is thermodynamically favored. Bromide ion catalyzes the oxidation of formic acid by cerium(IV); the mechanism involves oxidation of the formic acid by Br_2 or by HOBr. When bromomalonic acid is oxidized by cerium(IV), the rate of consumption of oxidant during a specific run will increase virtually discontinuously by a factor that is often of the order of 2 to 3 and may be as great as 7; production of bromide ion follows a smooth curve through this break point in Ce(IV) consumption. Radicals formed by Ce(IV) attack on several of these molecules are more likely to disproportionate with other radicals than to react with additional Ce(IV) ions. Radicals from the initial oxidation of bromomalonic acid are hydrolyzed to produce bromide ion before they react further. Malonic acid is not significantly attacked by radicals from other organic species, but malonyl radicals can abstract hydrogen from bromomalonic, tartronic, and perhaps glyoxylic acids. Radicals from oxidation of other species can also attack bromomalonic acid thereby initiating liberation of bromide ion. In the presence of bromide ion and cerium(IV), malonyl radicals are converted to bromomalonic acid. In the Ce(IV) + MA + BrMA and Ce(IV) + MA + Br^- systems, concentrations of bromide ion can go through peculiar maxima, minima, and stationary conditions that are not entirely explained. The combination of all of these observations permits an unexpectedly complete description of the complicated sequence of events during the cerium(IV) oxidation of malonic and bromomalonic acids.

The best established examples of homogenous chemical oscillators belong to a reaction type first reported by Belousov.[3] Zhabotinskii[4] has subsequently shown that oscillations take place in many solutions containing sulfuric acid, bromate ion, a one-equivalent redox couple with a reduction potential of about 1.0 to 1.5 V, and an organic compound that can be brominated by an enolization mechanism. Many of the subsequent studies have used the Ce(III)–Ce(IV) couple and malonic acid.

The principal features of the mechanism have been eluci-