Synthesis and Physical Properties of a Series of Optically Active Substituted *trans*-Stilbene Oxides

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A series of substituted *threo*-(*R*,*R*)-diphenylethanediols, prepared by microbial reduction of the appropriate benzil derivatives, was converted to the corresponding *trans*-stilbene oxides. The positive CD bands at 230–235 nm exhibited by these compounds agree in sign and magnitude with those predicted from a model developed by Mason et al. for *trans*-stilbene oxide. Microbial reduction of desyl chloride was shown to yield the *threo*-(*R*,*R*)-chlorohydrin, thus establishing a route for the preparation of optically active *cis*-stilbene oxides. The chemical shifts and coupling constants for the ^{1}H NMR and ^{13}C NMR spectra of several sets of *cis*- and *trans*-stilbene oxides are reported.

In the course of examining the stereoselectivity of microbial reductions in a series of substituted benzil derivatives,[1] we found that these reductions yielded threo-(*R*,*R*) diols which were readily freed of small quantities of accompanying erythro isomers. The threo compounds were important in confirming stereochemical assignments of diols obtained from the enzymatic hydration of substituted *cis*-stilbene oxides.[2] In addition, these diols were also logical starting materials for the preparation of optically active *trans*-stilbene oxides, which were needed in order to test a proposed relation between the sign of the CD band at 230–235 nm in these compounds and their absolute stereochemistries.

Whereas the threo diols could not be readily transformed to cis epoxides, there are a variety of procedures[3] that enable one to interconvert trans and cis oxides. To supplement these chemical methods we have found that microbial reduction of a benzoin derivative yields an optically active *threo*-chlorohydrin, which can be transformed to *cis*-stilbene oxide. As this and earlier studies made several sets of substituted *cis*- and *trans*-stilbene oxides available, the ^{1}H NMR and ^{13}C NMR of these compounds were recorded and assigned.

Results and Discussions

A sample of the *threo*-(*R*,*R*)-diphenylethanediol, **1a**, obtained from microbial reduction of benzil,[1] was converted to an epoxide by Newman's procedure,[4] as shown in Scheme I. The ^{1}H NMR spectrum of the crude epoxide prepared by this sequence showed absorption in the benzylic region for the known trans isomer (**4**); none of the cis compound (**5**) was detected under conditions where 5–10% would readily have been seen. In addition to *threo*-**1a**, *threo*-**1b–f** were subjected to the same reaction sequence; in every case only the corresponding trans oxide was obtained. Dansette et al.[2] observed that erythro dioxolanes yielded significant quantities of *trans*-stilbene oxides in this same sequence of reactions (Scheme II). This observation made it necessary to postulate the existence of an intermediate carbonium ion **6**, which yields a mixture of *erythro*- and *threo*-chlorohydrin acetates on reaction with chlorotrimethylsilane. On treatment with base, the *erythro*-chlorohydrin acetate is transformed to the trans oxide. In order to determine whether the ratio of cis to trans oxide could be varied, we examined the sensitivity of this reaction, for **2f**, to solvent polarity. The results, shown in Table I, indicate that polar solvents favor formation of the trans oxide. This finding is consistent with the expected one, if the trans isomer arises from a carbonium intermediate.[5] Our results show (Scheme II) either that the rate for the isomerization of **7** to **6** is slow or that the threo dioxolane forms a carbonium ion much less readily than does the erythro isomer.

Table I. Relative Ratios of Cis and Trans Epoxides Formed from *erythro*-2-Methyl-2-methoxy-4,5-bis(*p*-methylphenyl)-1,3-dioxolane (2f) in Various Solvents[a]

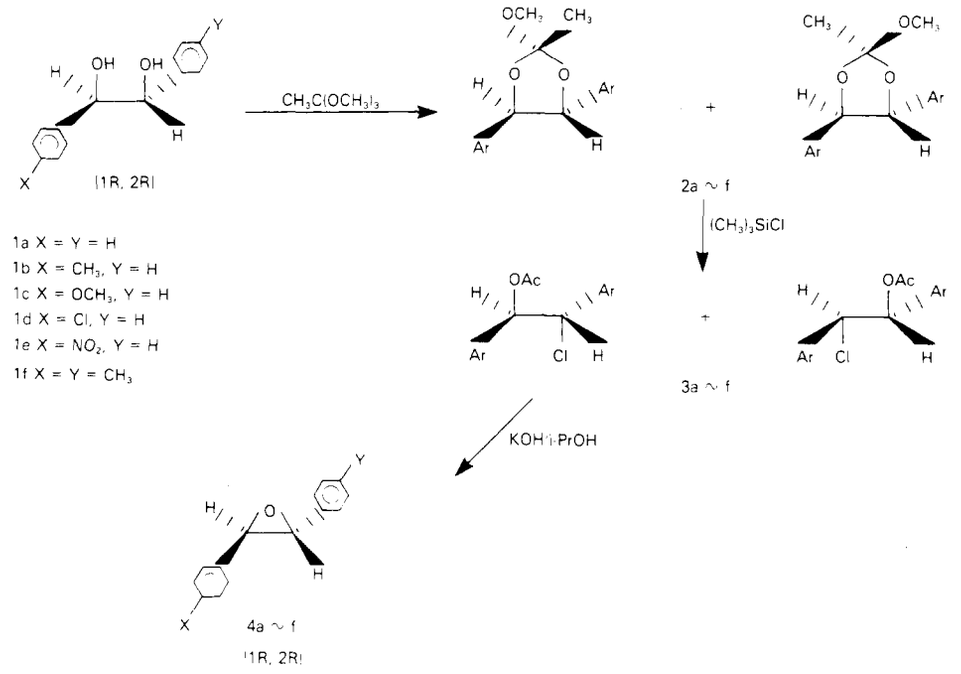
solvent	epoxide[b] cis:trans	solvent	epoxide[b] cis:trans
cyclohexane	69:31	Me_2SO	28:72
benzene	67:33	dioxane–H_2O (1:1)	21:79
dichloromethane	62:38		

[a] All reactions were carried out at 40 °C. [b] Determined by NMR.

The absolute stereochemistries of compounds **4b** and **4d** were previously assigned on the basis of their positive CD bands at 232 nm in conjunction with Mason's model[6] relating the sign of the CD band of **4a** with its configuration. The CD band was postulated to result from exciton coupling of the long-axis transition of the two phenyl rings; however, the only CD data available for extending Mason's model to substituted *trans*-stilbene oxides were those for **4b** and **4d**. The CD spectra of compounds **4a–f** are summarized in Table II. All the epoxides except **4e** gave positive bands with molecular ellipticities between 74 000 and 100 000 deg 10 cm^2/mol. The *p*-nitro substituent present in **4e** profoundly modified its absorption spectrum compared to those for the other substituted *trans*-stilbene oxides and consequently the nature of the short-wavelength band. Synthesis of (*R*,*R*)-**4b** and -**4d** from the threo diols confirmed the previously deduced configuration of these compounds, and the observation that (*R*,*R*)-**4f** also exhibits a positive CD band of the appropriate magnitude provides additional support for this extension of Mason's rule. Synthesis of (*R*,*R*)-**4e** confirmed the previously assigned configuration which was made on the basis of its stereospecific hydration at an (*S*) carbon by the enzyme "hydrase".[2]

(1) M. Imuta and H. Ziffer, *J. Org. Chem.*, **43**, 3319 (1978).
(2) P. M. Dansette, H. Ziffer, and D. M. Jerina, *Tetrahedron*, **32**, 2071 (1976).
(3) (a) J. A. Brewster, *J. Am. Chem. Soc.*, **78**, 4061 (1956); (b) G. Berti and F. Bottari, *J. Org. Chem.*, **25**, 1286 (1960); (c) G. Berti, F. Bottari, P. L. Ferrarini, and B. Macchia, *ibid.*, **30**, 4091 (1965).
(4) M. S. Newman and C. H. Chen, *J. Am. Chem. Soc.*, **94**, 2149 (1972); *ibid.*, **95**, 278 (1973); M. S. Newman and D. R. Olson, *J. Org. Chem.*, **38**, 4203 (1973).
(5) E. S. Gould, "Mechanism and Structure in Organic Chemistry", Holt, Rinehart and Winston, New York, N.Y., 1959, pp 183–184.
(6) G. Gottarelli, S. F. Mason, and G. Wone, *J. Chem. Soc. B*, 1349 (1970).

Scheme I



Scheme II

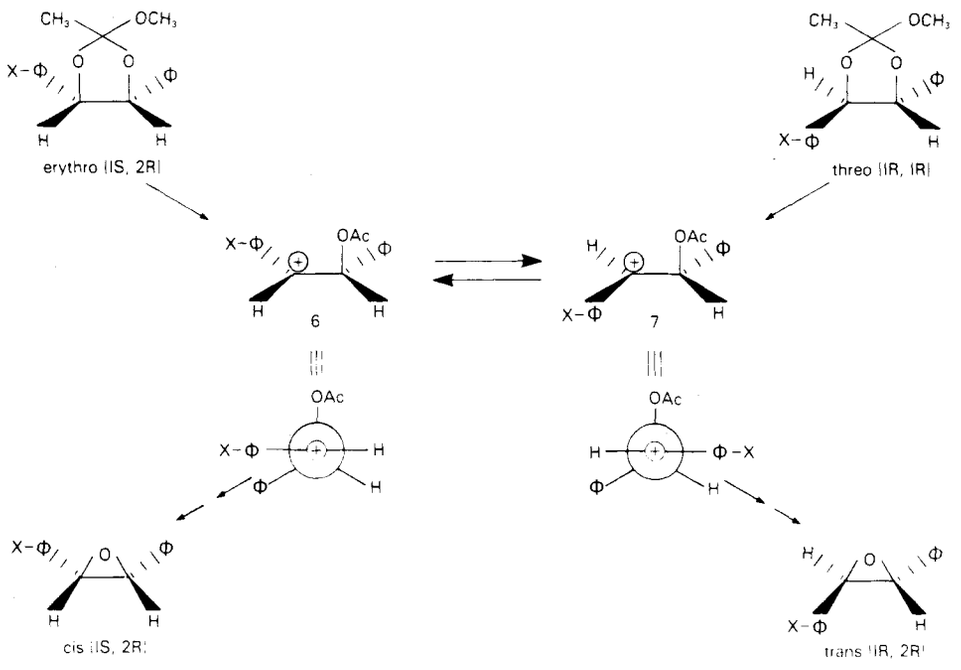


Table II. Optical Properties of the Trans-(*R*,*R*) Epoxides

	$[\alpha]^{25}_{D}$(EtOH)[a]		CD $[\theta]^{b}$ (λ^{c}) (MeOH, 25 °C)	
compd	obsd	reported[2]	obsd	reported[2]
4a	+342 (*c* 1.11)	+360	+78 000 (232)	+80 000 (232)
4b	+351 (*c* 1.14)	−300[d]	+73 700 (233)	−142 500 (232)[d]
4d	+362 (*c* 1.36)	+350	+78 600 (232)	+59 130 (232)
4e	+278 (*c* 1.01)		+12 600 (230)	
4f	+290 (*c* 0.75)		+100 900 (233)	

[a] In degrees. [b] In deg 10 cm²/mol. [c] In nanometers. [d] Reported for (*S*,*S*) enantiomer.

The CD curves of the threo-(*R*,*R*) diols (**1a**, **1b**, **1d**, **1e**) were previously reported[1] to exhibit positive bands at 220–225 nm. While the relation was empirical, i.e., did not depend upon a theoretical model, the similarities in the magnitude and position for the CD bands in the epoxides and diols suggest that the same theoretical treatment can be used to rationalize both sets of results.

Since one important feature of the microbial reductions of substituted benzils was the predominant formation of threo diols,[1] we wanted to determine if the observed stereospecificities could be employed to prepare optically active unsymmetric *cis*-stilbene oxides. The literature on

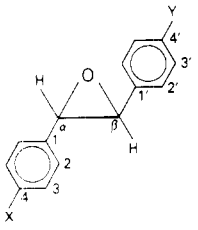
Table III. Comparison of the ^{1}H NMR Spectra of Cis and Trans Epoxides[a]

	δ(H$_{benzylic}$)				δ(H$_{benzylic}$)			
cis	H$_\alpha$	H$_\beta$	J_{AB}	trans	H$_\alpha$	H$_\beta$	J_{AB}	$\bar{\Delta}$(cis/trans)[b]
5a	4.34	4.34		**4a**	3.84	3.84		0.50
5b	4.34	4.30	4.2	**4b**	3.84	3.82	2.0	0.49
5c	4.31	4.27	4.1	**4c**	3.80	3.78	2.0	0.50
5d	4.29	4.34	4.2	**4d**	3.81	3.83	2.0	0.50
5e	4.33	4.49	4.1	**4e**	3.86	3.98	1.9	0.49
5f	4.29	4.29		**4f**	3.82	3.82		0.47

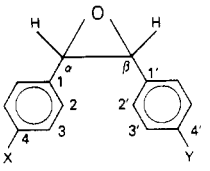
[a] Chemical shifts are reported in parts per million (δ) downfield from Me_4Si in $CDCl_3$, with coupling constants (J) in hertz. [b] Difference between cis and trans isomers.

Table IV

^{13}C chemical shifts of trans epoxides[a]



^{13}C chemical shifts of cis epoxides[a]



carbon	4a[b]	4b[b]	4d[b]	4e[b]	4f[b]	carbon	5a[c]	5b[c]	5d[c]	5e[c]	5f[c]
C$_\alpha$	62.9	62.6	62.2	61.6	62.7	C$_\alpha$	59.9	59.6	59.1	58.4	59.8
C$_\beta$	62.9	62.6	63.0	63.2	62.7	C$_\beta$	59.9	59.6	59.8	59.9	59.8
1	137.2	134.0	135.8	144.3	134.2	1	134.5	131.3	133.1	141.6	131.4
2	125.6	125.4	126.9	126.5	125.4	2	126.9[d]	126.8[d]	128.1[d]	127.8	126.8[d]
3	128.6	129.2	128.9	123.8	129.3	3	127.9[d]	128.5[d]	128.2[d]	123.1	128.5[d]
4	128.4	138.1	134.2	148.4	138.0	4	127.5	137.2	133.5	147.5	137.0
1′	137.2	137.2	136.8	136.9	134.2	1′	134.5	134.5	134.0	134.2	131.4
2′	125.6	125.4	125.6	125.5	125.4	2′	126.9	127.0	126.8	126.6	126.8
3′	128.6	128.5	128.8	128.6	129.3	3′	127.9	127.8	128.0	127.9	128.5
4′	128.4	128.1	128.7	127.8	138.0	4′	127.5	127.5	127.7	127.1	137.0
X (CH$_3$)		21.1			21.2	X (CH$_3$)		20.9			21.1
Y (CH$_3$)					21.2	Y (CH$_3$)					21.1

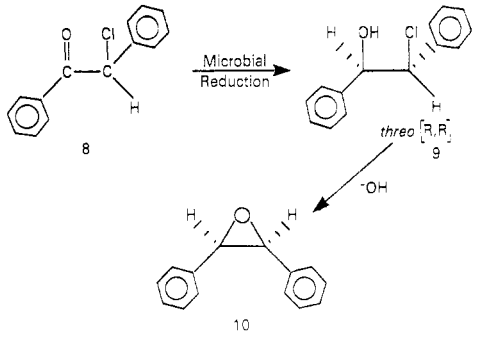
[a] Ppm downfield from Me_4Si in $CDCl_3$. [b] **4a**, X = Y = H; **4b**, X = CH_3, Y = H; **4d**, X = Cl, Y = H; **4e**, X = NO_2, Y = H; **4f**, X = Y = CH_3. [c] **5a**, X = Y = H; **5b**, X = CH_3, Y = H; **5d**, X = Cl, Y = H; **5e**, X = NO_2, Y = H; **5f**, X = Y = CH_3. [d] These assignments may be interchanged.

the acid-catalyzed ring-opening reaction of *cis*- and *trans*-stilbene oxides[3] indicates cis products predominate and therefore that the cis oxides provide an entry to the corresponding erythro diols.

The cis oxides could be prepared from the available trans-(*R*,*R*) oxides by reaction with hydrogen chloride to yield the corresponding *threo*-(*R*,*R*)-halohydrin (retention) followed by treatment with base (inversion). The success of this approach requires that the hydrogen chloride ring-opening reaction be highly *regiospecific* since the optical purity of the cis oxide prepared from the halohydrin is determined in this reaction. While there is precedent for this reaction sequence, we were intrigued by an alternative sequence (Scheme III) that would also test a reaction scheme proposed to account for the formation of threo-(*R*,*R*) diols by microbial reduction of a series of racemic benzoins.[1] This sequence starts with racemic 2-chloro-2-(*p*-substituted phenyl)acetophenone, **8**. Microbial reduction would yield the *threo*-(*R*,*R*)-halohydrin **9** which base treatment will convert to the cis oxide **10**. The critical reduction of **8** to the *threo*-halohydrin was demonstrated by using desyl chloride (X = H), and the corresponding known *threo*-(*R*,*R*)-chlorohydrin (**9**) was obtained. This result established that, in principle, this approach can be used to prepare optically active unsymmetric *cis*-stilbene oxides.

Study of the ^{1}H NMR and ^{13}C NMR spectra of the cis- and trans-substituted stilbene oxides shows that the spectra can be used to establish the stereochemistry of

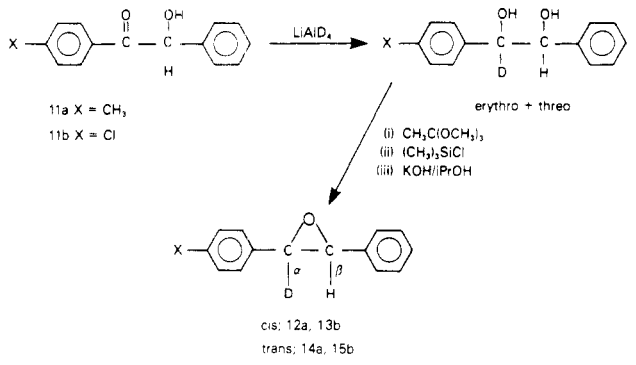
Scheme III



these materials. Ceccarelli et al.[7a] examined the ^{1}H NMR spectra of a series of substituted *cis*- and *trans*-stilbene oxides and found that the vicinal couplings of the trans oxides, with dihedral angles of approximately 155°,[7b] were 1.8–2.0 Hz, while those in the cis isomers were 4.2–4.5 Hz. The values given in Table III are similar. In order to identify the protons on the oxirane ring, Ceccarelli et al. decoupled specific aromatic protons, and from the small

(7) (a) G. Ceccarelli, G. Berti, G. Lippi, and B. Macchia, *Org. Magn. Reson.*, **2**, 379 (1970). (b) Although there are no X-ray data on stilbene oxides, Williams et al. (D. J. Williams, P. Crotti, B. Macchia, and F. Macchia, *Tetrahedron*, **31**, 993 (1975)) have reported the analogous torsion angle in *p*-nitrostyrene oxide. (c) P. Lazzeretti, I. Moretti, F. Taddei, and G. Tone, *Org. Magn. Reson.*, **5**, 385 (1973). (d) G. E. Johnson, Jr., and F. A. Bovey, *J. Chem. Phys.*, **29**, 1012 (1958).

Scheme IV



coupling of the aromatic and oxirane protons, the resonances were assigned. We have, instead, prepared specifically deuterated isomers to assist us in assigning the chemical shifts of the protons H_α and H_β in **4b**, **4d**, **5b**, and **5d** as shown in Scheme IV. The remaining proton on the oxirane ring was then unequivocally identified from its ^1H NMR spectrum.

The only ^{13}C NMR spectra reported in this series are those of the unsubstituted oxides.[8] The ^{13}C NMR spectra of compounds **4a–f** and **5a–f** are summarized in Table IV. In either the cis or trans oxiranes, the largest effect, a "downfield shift" of the oxirane carbons, occurred in derivatives bearing an electron-withdrawing group, i.e., *p*-NO_2 and *p*-Cl. In each set of isomers the oxirane carbon of the cis isomer was consistently ~3 ppm upfield relative to that of the trans compound. Chemical shift differences between C-1 and C-1′ for the two isomers were also ~3 ppm, with C-1 and C-1′ of the cis isomer consistently at higher field. The high-field shift is expected[9] on the basis of steric compression; it is greatest at C-1, falling off for C-2, C-3, and C-4. The difference for C-4, however, is ~1 ppm, i.e., greater than experimental error, but not easily attributable to steric compression.

The aromatic ^{13}C NMR bands of the cis and trans oxides were assigned (Table IV) as follows. The carbon resonances in **4a** assigned by Anet et al.[8b] were used in conjunction with the shielding effects of various substituents on benzene.[10] If it is necessary at any time to interchange assignments of C-2 and C-3 in **4a**, the same change will be required in the substituted cis and trans oxides. The ^{13}C NMR spectrum of **4a** (similarly **5a**) shows the C-2 and C-3 resonances as more intense than those for C-1 and C-4. The observation is consistent with the fact that these resonances arise from twice the number of carbons as those for C-1 and C-4. In addition, the nuclear Overhauser enhancements for C-2 and C-3 are greater than those for C-1 and C-4 (when this carbon bears a substituent). The resonances for C-2 and C-3 in **4a** differ by 3 ppm; therefore analogous carbons in substituted stilbene oxides can be identified by using substituent effects.[10] For example, a methyl substituent is expected to add 8.9 ppm to C-4, +0.7 ppm to C-3, −0.1 ppm to C-2, and −2.9 ppm to C-1.[10] The observed chemical shifts closest to these calculated values were assigned to the carbon in question. The differences between calculated and observed values were small: 0.8, 0.1, 0.1, and 0.3 ppm, respectively. There were no large discrepancies and the assignments were internally consistent. The aromatic carbon resonances in other cis and trans oxides were determined in a similar manner.

In order to identify C_α and C_β in **4d**, **4e**, **5d**, and **5e**, we made use of the C_α deuterio compounds **13b** and **15b** (Scheme IV). The C_α resonances were assigned directly from an examination of the ^{13}C NMR spectra of these compounds. The observed effect of a *p*-chloro substituent was a 0.5–0.7-ppm shift to higher field for C_α, while C_β was not affected. Since the *p*-chloro group is an electron-withdrawing substituent, as is the *p*-nitro group, the two substituents should affect the chemical shift of C_α in the same way. Experimentally one resonance was identical with that in **4a** and **5a**, while the other was shifted 1.3–1.5 ppm to higher field.

Conclusion

Synthesis of several substituted (*R,R*)-*trans*-stilbene oxides from a series of (*R,R*)-diphenylethanediols confirmed stereochemical assignments made from CD measurements. These syntheses, in concert with the CD curve of **4f**, support Mason's model relating a positive CD band at 232 nm with an (*R,R*) configuration. Microbial reduction of desyl chloride yielded the *threo*-(*R,R*)-halohydrin, thus verifying a previously proposed reaction scheme and providing a method for the synthesis of optically active unsymmetric *cis*-stilbene oxides. A comparison of the ^1H NMR and ^{13}C NMR spectra of the cis and trans oxiranes shows that these isomers can be distinguished by their ^{13}C NMR chemical shifts and by an examination of proton–proton couplings on the oxirane ring.

Experimental Section

General Procedure. Melting points were determined by using a hot-stage apparatus; they are uncorrected. Proton magnetic resonance spectra were recorded on a Varian HR-220 MHz instrument with FT technique; chemical shifts are reported in parts per million (δ) downfield from tetramethylsilane as an internal standard, with coupling constants (*J*) in hertz. ^{13}C magnetic resonance spectra were recorded on a JEOL, FX-60 (15.04 MHz) instrument under noise-modulated decoupled conditions; chemical shifts are reported in parts per million (δ) downfield from tetramethylsilane in $CDCl_3$. Optical rotations and circular dichroism spectra were recorded on a Cary 60 spectropolarimeter. Chemical ionization mass spectra were taken with a Hitachi RMS-4 instrument. Microanalyses were performed by the microanalytical section of NIH. Preparative and analytical TLC work was performed on silica gel F-254 plates. Preparation of the erythro diols and threo-(*R,R*) diols (**1a–f**) was previously described.[1]

Preparation of Trans-(*R,R*) Epoxides. A solution of *threo*-(*R,R*)-diphenylethanediol (**1a**) (70 mg) and trimethyl orthoacetate (60 mg) in 10 mL of dry benzene containing a catalytic amount of benzoic acid was refluxed for 2 h. The solvent and excess trimethyl orthoacetate were removed in vacuo, and the residue was dissolved in 10 mL of methylene chloride and heated at 50 °C for 2 h with trimethylsilyl chloride (72 mg). Excess reagent was removed in vacuo to leave a white residue, which was treated with KOH (200 mg) in 2-propanol at 40 °C for 2 h. After dilution with water, the reaction mixture was extracted with ether, washed with water, and dried over sodium sulfate. The proton NMR of this crude reaction mixture showed that the corresponding trans epoxide was produced in ~98% yield without a detectable amount of the cis isomer. The reaction mixture was purified by thick-layer chromatography (silica gel, ethyl acetate–hexane (5:95)) to give 62 mg (95% yield) of (+)-*trans*-(*R,R*)-diphenylethylene oxide (**4a**), which was recrystallized from ligroin, mp 69 °C (reported[2] mp 69 °C). The NMR and mass spectrum of this sample were identical with those of racemic material.

The above procedure was also used to prepare (+)-*trans*-(*R,R*)-**4b** in 91% yield, mp 62 °C (recrystallized from ligroin) (reported[2] mp 61 °C), (+)-*trans*-(*R,R*)-**4d** in 92% yield, mp 100

(8) (a) S. G. Davies and G. H. Whitham, *J. Chem. Soc., Perkin Trans. 2*, 861 (1975); (b) N. R. Easton, Jr., F. A. L. Anet, P. A. Burns, and C. S. Foote, *J. Am. Chem. Soc.*, **96**, 3945 (1974).

(9) F. W. Wehrli and T. Wirthlin, "Interpretation of Carbon-13 NMR Spectra", Heyden and Son Ltd., London, 1976, pp 27–29.

(10) G. L. Nelson, G. C. Levy, and J. D. Gargioli, *J. Am. Chem. Soc.*, **94**, 3089 (1972).

Table V. Relative Ratio of Cis and Trans Epoxides Prepared from Erythro Diols

starting diol	epoxide[a] cis:trans	overall yield,[b] % (cis and trans)
erythro-(1a)	54:46	95
erythro-(1b)	61:39	85
erythro-(1c)	57:43	*c*
erythro-(1d)	59:41	87
erythro-(1e)	60:40	69
erythro-(1f)	62:38	91

[a] Determined by NMR. [b] Determined by isolation. [c] Because of their instability in the isolation process, the isomers were not separated.

°C (recrystallized from ligroin) (reported[11] mp 99 °C), (+)-*trans*-(*R*,*R*)-**4e** in 67% yield, mp 127 °C (recrystallized from ligroin) (reported[2] mp 126–127 °C), and (+)-*trans*-(*R*,*R*)-**4f** in 89% yield, mp 104 °C (recrystallized from ligroin). Anal. Calcd for $C_{16}H_{16}O$: C, 85.71; H, 7.14. Found: C, 85.42; H, 7.20. The NMR spectra of these epoxides are summarized in Tables III and IV. Optical properties ($[\alpha]^{25}_D$ and CD) are given in Table II.

Preparation of (±)-Trans and Cis Epoxides. Conversion of each erythro diol to the epoxide was carried out by essentially the same procedure as described above. In these cases, after treatment of the corresponding chlorohydrin acetate with base, the NMR spectrum of the crude reaction mixture showed it to be a mixture of cis and trans oxides. The mixtures were separated by thick-layer chromatography (silica gel, ethyl acetate–hexane (5:95)). The relative ratios of cis and trans epoxides prepared from erythro diols and the overall yields (%) are summarized in Table V.

Conversion of *erythro*-2-Methyl-2-methoxy-4,5-bis-(*p*-methylphenyl)-1,3-dioxolane (2f) to the Cis and Trans Epoxides in Various Solvents. A solution of *erythro*-*p*,*p*'-dimethyldiphenylethanediol (121 mg) and trimethyl orthoacetate (90 mg) in 10 mL of dry benzene containing 5 mg of benzoic acid was refluxed for 2 h. Excess trimethyl orthoacetate was removed in vacuo to leave a white residue, which was recrystallized from benzene to give the corresponding *erythro*-1,3-dioxolane (**2f**), 141 mg (97% yield), mp 102–106 °C. The resulting product consists of a mixture of two stereoisomers (**2fa**, **2fb**) at C-2 (**2fa**:**2fb**, 5:4). NMR (in $CDCl_3$): **2fa**, δ 1.69 (s, 3 H), 2.09 (s, 6 H), 3.59 (s, 3 H), 4.90 (s, 2 H); **2fb**, δ 1.86 (s, 3 H), 2.08 (s, 6 H), 3.36 (s, 3 H), 4.98 (s, 2 H).

The reaction of **2f** with trimethylsilyl chloride was carried out at 40 °C in the following solvents: cyclohexane, benzene, dichloromethane, dimethyl sulfoxide, dioxane–water (1:1). The resulting reaction mixture was subsequently hydrolyzed with KOH in 2-propanol. The crude reaction mixture was analyzed by NMR to determine the ratio of the cis and trans epoxides. The results are summarized in Table I.

(11) A. Feldstein and C. A. Vanderverf, *J. Am. Chem. Soc.*, **76**, 1626 (1954).

Microbial Reduction of Desyl Chloride (8). A sample of desyl chloride was reduced by using *Cryptococcus macerans* as previously described.[1] *threo*-(*R*,*R*)-2-Chloro-1,2-diphenylethanol was produced in 95% yield: mp 67–68 °C (reported[3c] mp 66–67 °C); $[\alpha]^{25}_D$ −19.8° (*c* 4.80, ethanol), reported[3c] $[\alpha]^{25}_D$ −20.2° (*c* 5.20, ethanol). The optical purity of the microbially derived product was 98%. The NMR spectrum of this sample was identical with that of racemic material prepared from *trans*-stilbene oxide by treatment with HCl in chloroform. NMR ($CDCl_3$): δ 3.16 (1 H, d, J = 3.0 Hz, OH), 4.89 (1 H, dd, J = 8.0, J = 3.0 Hz), 4.98 (1 H, d, J = 8.0 Hz), 7.02–7.23 (1 H, mult).

Preparation of α-Deuterio(*cis* and *trans*-*p*-substituted)diphenylethylene Oxides. To a slurry of $LiAlD_4$ (40 mg) in 10 mL of dry ether was added *p*-chlorobenzoin (**11b**) (62 mg), and the solution was stirred overnight. The reaction mixture was decomposed with 10% NaOH and worked up as usual to yield 59 mg of a product whose NMR spectrum indicated that it consisted of the erythro diol and threo diol in a 75:25 ratio. The resulting reaction mixture was converted to the corresponding epoxides by the procedure described above. The cis epoxide (**13b**) and trans isomer (**15b**) were separated by thick-layer chromatography (silica gel, ethyl acetate–hexane (5:95)).

Cis epoxide (**13b**): 39 mg (70% yield), colorless oil; mass spectrum m/e 231 (M^+); ^1H NMR ($CDCl_3$) δ 4.33 (s, 1 H), 7.09–7.15 (mult, 9 H); ^{13}C NMR ($CDCl_3$) δ 59.0 (C_α, $J_{C\text{-}D}$ = 27.8 Hz), 59.8 (C_β).

Trans epoxide (**15b**): 14 mg (21% yield); mp 98–100 °C; mass spectrum m/e 231 (M^+); ^1H NMR ($CDCl_3$) δ 3.83 (s, 1 H), 7.10–7.17 (mult, 9 H); ^{13}C NMR ($CDCl_3$) δ 62.1 (C_α, $J_{C\text{-}D}$ = 28.0 Hz), 62.9 (C_β).

α-Deuterio-*cis*- and *trans*-*p*-methyldiphenylethylene oxides (**12a** and **14a**) were prepared from *p*-methylbenzoin (**11a**) by essentially the same sequence of procedures.

Cis epoxide (**12a**): 64% yield, colorless oil; mass spectrum m/e 211 (M^+); ^1H NMR ($CDCl_3$) δ 2.21 (s, 3 H), 4.31 (s, 1 H), 6.94–7.17 (mult, 9 H).

Trans epoxide (**14a**): 25% yield, mp 63–64 °C (recrystallized from ligroin); mass spectrum m/e 211 (M^+); ^1H NMR ($CDCl_3$) δ 2.35 (s, 3 H), 3.82 (s, 1 H), 7.15–7.34 (mult, 9 H).

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Registry No. *threo*-(*R*,*R*)-**1a**, 52340-78-0; *erythro*-**1a**, 579-43-1; *threo*-(*R*,*R*)-**1b**, 62137-63-7; *erythro*-**1b**, 51343-94-3; *threo*-(*R*,*R*)-**1c**, 66768-21-6; *erythro*-**1c**, 66749-65-3; *threo*-(*R*,*R*)-**1d**, 62086-76-4; *erythro*-**1d**, 66768-18-1; *threo*-(*R*,*R*)-**1e**, 62086-77-5; *erythro*-**1e**, 66768-17-0; *threo*-(*R*,*R*)-**1f**, 66768-19-2; *erythro*-**1f**, 5173-29-5; **2a**, 70288-28-7; **2fa**, 70288-29-8; **2fb**, 70288-30-1; **3a**, 70288-31-2; (*R*,*R*)-**4a**, 25144-18-7; (*R*,*R*)-**4b**, 70332-46-6; (*R*,*R*)-**4c**, 70332-47-7; (*R*,*R*)-**4d**, 62137-66-0; (*R*,*R*)-**4e**, 70332-48-8; (*R*,*R*)-**4f**, 70332-49-9; **5a**, 1689-71-0; **5b**, 42730-01-8; **5c**, 70288-32-3; **5d**, 70332-50-2; **5e**, 14802-06-3; **5f**, 70288-33-4; **8**, 70288-34-5; **9**, 70332-51-3; **11a**, 2431-23-4; **11b**, 39774-18-0; **12a**, 70288-35-6; **13b**, 70288-36-7; **14a**, 70288-37-8; **15b**, 70288-38-9; *erythro*-1-deuterio-1-(*p*-chlorophenyl)-2-phenyl-1,2-ethanediol, 70288-39-0; *threo*-1-deuterio-1-(*p*-chlorophenyl)-2-phenyl-1,2-ethanediol, 70288-40-3; trimethyl orthoacetate, 1445-45-0.