Articles

Enantiodifferentiating Z-E Photoisomerization of Cyclooctene Sensitized by Chiral Polyalkyl Benzenepolycarboxylates[1]

Yoshihisa Inoue,* Noritsugu Yamasaki, Taizo Yokoyama, and Akira Tai

Department of Material Science, Himeji Institute of Technology, Kamigori, Hyogo 678-12, Japan

Received August 13, 1991

Highly efficient and unique enantiodifferentiating Z-E photoisomerization of cyclooctene (1) was achieved through singlet photosensitization with chiral polyalkyl benzenepolycarboxylates. Conversion dependence of optical yields and an attempted kinetic resolution of racemic (E)-isomer 1E unequivocally showed that the enantiodifferentiating step is not the initial quenching of chiral sensitizer with enantiomeric 1E but the rotational relaxation of planar 1Z to twisted singlet cyclooctene (¹p) within the singlet exciplex with chiral sensitizer. Fluorescence quenching of some benzenetetracarboxylates with 1Z and 1E provides further evidence for the intervention of an exciplex intermediate, showing a new emission at a longer wavelength, and also for the insignificant enantiodifferentiation in the quenching step, affording nearly diffusion-controlled quenching rate constants around 10^{10} s^{-1} for 1E. This novel enantiodifferentiating photosensitizing system via exciplex, in combination with low-temperature irradiation, not only affords the highest optical yields up to 53% but also exhibits unusual temperature-switching behavior of product chirality especially with the o-dicarboxylate sensitizers. The activation parameters obtained in the temperature-dependence study indicate that the temperature-switching phenomenon is attributed to the unequal activation entropies, or frequency factors, for the enantiodifferentiating relaxations of 1Z to (R)- and (S)-¹p within the exciplex, for which the dynamic structural changes in the relaxation process may be responsible.

Asymmetric photochemical reactions in fluid solution have been effected in general through one of the following methodologies:[2a] (1) direct excitation with circularly polarized light, which does not require any material source of chirality but needs special irradiation devices to generate circularly polarized light and merely gives extremely low optical yields around 1%, (2) direct or sensitized photochemical diastereodifferentiation induced by intramolecular chiral substituent, which affords excellent optical yields up to 95% but inevitably demands a stoichiometric amount of chiral source, (3) diastereoselective photochemical reaction of ground-state complex of a prochiral substrate with a chiral reagent,[3] which leads to high optical yields up to 91% (at −55 °C)[3b] and requires a smaller amount of chiral source, (4) photochemical reaction in optically active solvent, which needs an excess amount of chiral source only to give low optical yields (0.5–2%), and, finally, (5) enantiodifferentiating photosensitized reaction, which necessitates only a catalytic amount of chiral sensitizer but, to date, gives low optical yields less than 10% in most cases.[2] The last category is of interest not only from the asymmetric induction but also from the photochemical point of view, since the optical yields obtained by using a variety of chiral sensitizers provides indispensable geometrical insights into the photosensitizing process.

Of these strategies, the enantiodifferentiating photosensitization is particularly attractive and advantageous as a convenient and chirality-efficient method for transferring and multiplying optical activity through photoreaction. The photosensitization systems hitherto surveyed

Scheme I

1Z   (−)-(R)-1E   (+)-(S)-1E
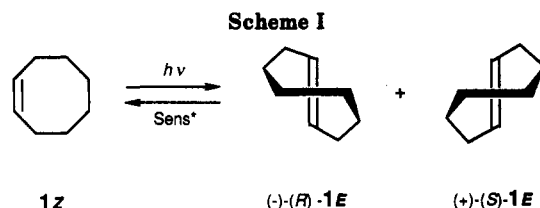
are the geometrical isomerizations of 1,2-diphenylcyclopropane (optical yield: 6.7%),[4] methyl p-tolyl sulfoxide (2.3%),[5] cyclooctene (4.0%),[6] and 1,5-cyclooctadiene (1.6%),[7] the nitrogen elimination of pyrazolines (4.05%),[8] and the di-π-methane rearrangement of cyclic enones (10% at −78 °C).[9] The poor optical yields reported prove the difficulty of achieving efficient enantiodifferentiation in photoreactions. This has long been considered inevitable or inherent to photosensitized reaction,[2a] since the steric interaction between excited sensitizer and substrate is not sufficiently strong or long-lived to induce effectively the chirality in substrate.

We wish now to report our recent results on the highly efficient enantiodifferentiating Z-E photoisomerization of cyclooctene sensitized by several new chiral polyalkyl benzenepolycarboxylates at varied temperatures (Scheme

(1) Preliminary report: Inoue, Y.; Yokoyama, T.; Yamasaki, N.; Tai, A. J. Am. Chem. Soc. 1989, 111, 6480.

(2) For reviews, see: (a) Rau, H. Chem. Rev. 1983, 83, 535. (b) Majima, T. Yuki Gosei Kagaku Kyokaishi (J. Synth. Org. Chem. Jpn.) 1990, 48, 536.

(3) (a) Henin, F.; Mortezaei, R.; Muzart, J.; Pete, J.-P. Tetrahedron Lett. 1985, 26, 4945. (b) Piva, O.; Pete, J.-P. Tetrahedron Lett. 1990, 31, 5157 and references cited therein.

(4) (a) Hammond, G. S.; Cole, R. S. J. Am. Chem. Soc. 1965, 87, 3256. (b) Murov, S. L.; Cole, R. S.; Hammond, G. S. J. Am. Chem. Soc. 1968, 90, 2957. (c) Ouannès, C.; Beugelmans, R.; Roussi, G. J. Am. Chem. Soc. 1973, 95, 8472. (d) Kagan, H. G.; Balavoine, G.; Jugè, S., footnote 9 of ref 4c.

(5) Balavoine, G.; Jugè, S.; Kagan, H. B. Tetrahedron Lett. 1973, 4159.

(6) (a) Inoue, Y.; Kunitomi, Y.; Takamuku, S.; Sakurai, H. J. Chem. Soc., Chem. Commun. 1978, 1024. (b) Inoue, Y.; Takamuku, S.; Kunitomi, Y.; Sakurai, H. J. Chem. Soc., Perkin Trans. 2, 1980, 1672.

(7) Goto, S.; Takamuku, S.; Sakurai, H.; Inoue, Y.; Hakushi, T. J. Chem. Soc., Perkin Trans. 2, 1980, 1678.

(8) Rau, H.; Hörmann, M. J. Photochem. 1981, 16, 231.

(9) (a) Demuth, M.; Raghavan, P. R.; Carter, C.; Nakano, K.; Schaffner, K. Helv. Chim. Acta 1980, 63, 2434. (b) Hoshi, N.; Furukawa, Y.; Hagiwara, H.; Sato, K. Chem. Lett. 1980, 47.

Table I. Geometrical Photoisomerization of (Z)- and (E)-Cyclooctenes (1Z and 1E) Sensitized by Some Chiral, Racemic, and Achiral Benzenepolycarboxylates (2, 5, and 8; R = Methyl or (-)-, (+)-, or (±)-Menthyl) in Pentane

		sensitizer		irradiation					
run	alkene (M)	compd (mM)	R (X)	temp, °C	time, h	conv, %	yield,[a] %	$[\alpha]_D^{25}$ (c, CH$_2$Cl$_2$)	% ee[b]
1	1Z (4.2)	2 (15)	(-)-menthyl (H)	25	0.3	1.9	1.5	-12.1 (4.8)	-2.8[c]
2	1Z (4.2)	2 (17)	(-)-menthyl (H)	25	0.5	2.8	1.9	-13.0 (4.6)	-3.1[c]
3	1Z (4.2)	2 (24)	(-)-menthyl (H)	25	0.8	4.0	3.4	-10.7 (4.2)	-2.5[c]
4	1Z (0.5)	2 (5)	(-)-menthyl (H)	25	9	9.6	9.0	-11.0 (1.1)	-2.6
5	1Z (0.2)	2 (5)	(-)-menthyl (H)	25	28	21[d]	17	-11.6 (1.1)	-2.7
6			(+)-menthyl (H)	25	28	24[d]	17	11.3 (1.0)	2.7
7			(±)-menthyl (H)	25	22	22[d]	17	-0.02 (1.0)	0.0
8			methyl (H)[e]	25	28	22[d]	19	0.00 (1.7)	0.0
9	1Z (4.0)	5 (15)	(-)-menthyl	25	18	3.3	2.9	-25.6 (3.3)	-6.0
10	1Z (0.2)	5 (5)	(-)-menthyl	25	24	25[d]	18	-25.4 (2.6)	-6.0
11	1Z (0.2)	8 (5)	(-)-menthyl	-78	13	11	4.4	90.2 (0.6)	21.2
12					24	12	f	92.2 (2.9)	21.6
13					32	13	9.9	92.1 (3.4)	21.6
14					140	26[d]	21	99.6 (3.1)	23.4
15	1E (0.2)	2 (5)	(-)-menthyl	25	0.4	4.8	4.2 (34)[g]	-0.05 (1.2)	-0.02
16					0.8	10	9.5 (40)[g]	-0.08 (2.0)	-0.01
17	1E (0.1)	8 (5)	(-)-menthyl	-78	8	2.8	2.5 (45)[g]	-4.6 (2.3)	-1.1
18					24	9.4	9.1 (54)[g]	-3.4 (4.0)	-0.8

[a] Chemical yield determined by GC analysis on the basis of starting material, unless noted otherwise. [b] Enantiomeric excess of isolated or recovered 1E, calculated from the specific rotation. [c] Data from ref 5b. [d] Photostationary-state appeared to be established, since the E/Z ratios of 0.23–0.25 obtained for 2 (X = H) and 0.26 for 5 coincides with those obtained previously at lower and/or comparable concentrations of 1 (ref 6b). [e] (-)-Menthol (5 mM) was added to the solution. [f] Yield not determined. [g] Recovery of isolated 1E.
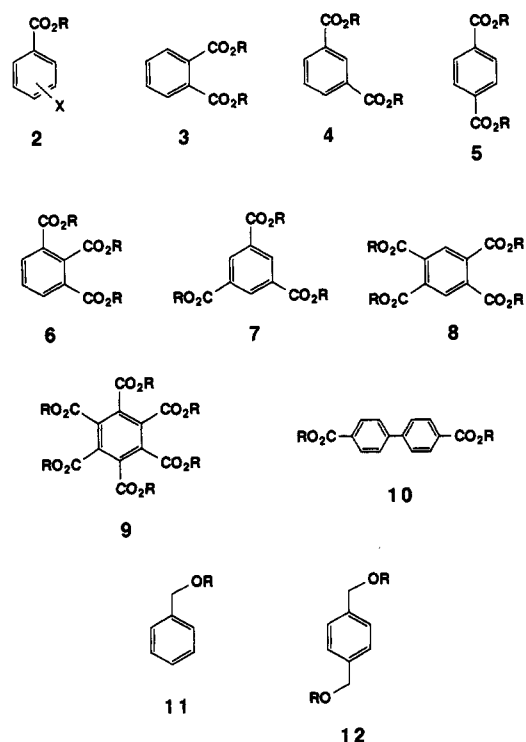
I). This asymmetrically photosensitizing system afforded the highest optical yields ever reported and crucially led to unusual temperature-switching of product chirality. The mechanistic details and implications of this unique photosensitized enantiodifferentiation will be discussed.

Results

Photoisomerization. Enantiodifferentiating photosensitization of (Z)-cyclooctene (1Z) and an attempted photosensitized kinetic resolution of the (E)-isomer (1E) were performed under various irradiation conditions, using a wide variety of chiral alkyl benzenemonocarboxylates to polyalkyl benzenehexacarboxylates shown in Chart I. The major photochemical reaction observed was the Z–E isomerization of cyclooctene in all cases. The (E)-isomer of >98% chemical purity was isolated from the photolyzate through selective extraction of 1E with aqueous silver nitrate.[10] Gas chromatographic analysis indicated that the isolated 1E contained a small amount of pentane but no trace of chiral sensitizers employed or chiral fragments derived therefrom. The purified 1E was more or less optically active, although the optical yield determined as enantiomeric excess (ee) varied dramatically with the factors described below. The circular dichroism spectrum of the optically active (-)-1E, obtained in the enantiodifferentiating photosensitization with 8 (R = (-)-menthyl) accorded in shape and sign with the reported CD spectrum of optically pure 1E.[11]

Chiral Sensitizers. Using some typical (-)-polymenthyl benzenepolycarboxylates, the conversion dependence of the product's optical yield was first examined. Pentane solutions of 1Z were irradiated for varying periods in the presence of (-)-menthyl benzoate (2), (-)-dimenthyl terephthalate (5), or (-)-tetramenthyl 1,2,4,5-benzenetetracarboxylate (R = (-)-menthyl) as chiral sensitizer; X = H, unless noted otherwise. For comparison purposes, the antipodal (+)-menthyl and racemic (±)-menthyl ben-

(10) (a) Cope, A. C.; Bach, R. D. *Organic Syntheses*; Wiley: New York, 1973; Collect Vol. 5, p 315. (b) Inoue, Y.; Takamuku, S.; Sakurai, H. *Synthesis (Stuttgart)* **1977**, 111.

(11) (a) Bach, R. D. *J. Chem. Phys.* **1970**, *52*, 6423. (b) Schnepp, O.; Pearson, E. F.; Sharman, E. *J. Chem. Phys.* **1970**, *52*, 6424. (c) Mason, M. G.; Schnepp, O. *J. Chem. Phys.* **1973**, *59*, 1092.

Chart I

zoates, as well as an equimolar mixture of achiral methyl benzoate and (-)-menthol, were also used as reference sensitizer/additive. Photosensitized kinetic resolution of racemic 1E was attempted at relatively low conversions, employing (-)-menthyl benzoate (2) or (-)-tetramenthyl 1,2,4,5-benzenetetracarboxylate 8 as a sensitizer, and the optical rotation of 1E recovered was measured. The results are listed in Table I; hereafter, the optical yield (% ee) possesses the same sign as the optical rotation of produced/recovered 1E, indicating the product stereochemistry.

As expected, the antipodal sensitizer pair 2 (R = (+)- and (-)-menthyl) gave the respective enantiomer pair (+)- and (-)-1E in identical optical yields; see runs 5 and 6 in Table I. Both the racemic sensitizer 2 (R = (±)-menthyl)

Table II. Enantiodifferentiating Photosensitization of 1Z by Substituted Benzoates and Benzenepolycarboxylates with Various Chiral Alcohol Moieties in Pentane at 25 °C[a]

run	compd	R (X)	E_s[b]	irrad time, h	conv, %	yield,[c] %	$[\alpha]^{25}_D$ (c, CH$_2$Cl$_2$)	% ee[d]
1	2	(−)-menthyl (H)	102.3	28	21	17	−11.6 (1.1)	−2.7
2		(+)-isomenthyl (H)	102.3	29	20	18	4.1 (1.1)	0.96
3		(+)-neomenthyl (H)	102.3	26	19	16	0.69 (3.1)	0.09
4		(−)-bornyl (H)	e	36	27	18	−4.4 (0.5)	−1.0
5		(−)-cholesteryl (H)	e	31	28	17	−0.15 (2.0)	−0.04
6		(−)-1-methyl-1,3-butanediyl (H)[f]	e	30	22	19	−3.6 (0.8)	−0.84
7		(−)-1,3-diphenyl-1,3-propanediyl (H)[f]	e	20	17	13	5.1 (1.9)	1.2
8		(−)-menthyl (2-Me)	100.1	25	15	8	−7.1 (1.5)	−1.7
9		(−)-menthyl (3-Me)	99.6	24	22	12	−18.0 (1.5)	−4.2
10		(−)-menthyl (4-Me)	101.9	22	15	9	−15.7 (1.2)	−3.7
11		(−)-menthyl (4-t-Bu)	102.2	22	13	9	−14.9 (1.5)	−3.5
12		(−)-menthyl (4-F)	105.7	25	21	17	−8.8 (2.7)	−2.1
13		(−)-menthyl (2-CF$_3$)	106.3	26	16	7	−2.8 (3.1)	−0.65
14		(−)-menthyl (3-CF$_3$)	102.9	29	34	24	−11.0 (4.1)	−2.6
15		(−)-menthyl (4-CF$_3$)	101.7	30	30	26	−16.5 (3.0)	−3.9
16		(−)-menthyl (3,5-(CF$_3$)$_2$)	103.4	29	38	29	−10.4 (3.0)	−2.4
17		(−)-menthyl (2-MeO)	98.8	24	10	3	−8.9 (0.8)	−2.1
18		(−)-menthyl (4-MeO)	102.0	19	7	7	−18.3 (1.8)	−4.3
19		(−)-menthyl (2-OH)[g]	95.0	48	9	9	−29.8 (1.0)	−7.0
20		(−)-menthyl (4-CN)	98.5	16	13	7	−13.9 (2.1)	−3.3
21	3	(−)-menthyl	101.6	23	9	5	16.2 (1.4)	3.8
22		(−)-menthyl, methyl[h]	101.6	22	9	5	12.8 (1.0)	3.0
23	4	(−)-menthyl	99.4	31	26	23	−18.8 (0.6)	−4.4
24	5	(−)-menthyl	97.1	24	25	18	−25.4 (2.6)	−6.0
25		(−)-menthyl, methyl[h]	97.1	28	21	17	−12.8 (2.6)	−3.0
26	6	(−)-menthyl	e	20	i	i	−40.0 (2.2)	−9.4
27	7	(−)-menthyl	99.3	27	26	24	−14.4 (1.4)	−3.4
28	8	(−)-menthyl	97.9	29	15	8	−40.9 (1.2)	−9.6
29	9[j]	(−)-menthyl	94.4[k]	20	6	3	−71.6 (0.5)	−16.8
30	10	(−)-menthyl	e	38	10	1	−5.1 (1.1)	−1.2

[a] [1Z] = 0.2 M; [sensitizer] = 5 mM, unless noted otherwise. [b] Singlet energy of sensitizer in kcal/mol, estimated from the absorption 0–0 band in pentane, where available. [c] Chemical yield determined by GC analysis on the basis of the starting material, unless noted otherwise. [d] Enantiomeric excess of isolated 1E, calculated from the specific rotation. [e] Not determined. [f] Dibenzoate of 1,3-diol. [g] [1Z] = 0.6 M. [h] Hemichiral mixed ester. [i] Not determined. [j] [Sensitizer] = 2 mM. [k] Estimated from the onset of absorption spectrum.

and the combination of achiral methyl benzoate and (−)-menthol merely afforded nil optical yield, although the isomerization proceeded similarly (runs 7 and 8).

Importantly, the optical yields of 1E showed little change over a wide range of irradiation periods or conversions, from the initial to nearly photostationary state, irrespective of the varied concentrations of substrate and sensitizer or the different irradiation temperatures; see runs 1–5 and 9–14 in Table I. The attempted photochemical kinetic resolutions of racemic 1E sensitized by chiral 2 or 8 (R = (−)-menthyl) at 25 and −78 °C resulted in extremely low optical yields (≤1%), compared with those obtained in the enantiodifferentiating photoisomerization of 1Z; compare runs 1–5 with 15–16 and 11–14 with 17–18.

The effects of chiral alkyl group and nuclear substituent upon the optical yield were investigated. First examined were some (di)benzoates possessing various chiral alcohol moieties other than (−)-menthol, i.e., (+)-isomenthol, (+)-neomenthol, (−)-borneol, (−)-cholesterol, (−)-(2R,4R)-2,4-pentanediol, and (−)-(1R*,3R*)-1,3-diphenyl-1,3-propanediol. The irradiations were continued for 20–30 h to afford apparent photostationary state mixtures in most cases, since no conversion dependence was seen in the optical yield. The results are shown in Table II (runs 1–7).

Among the chiral benzoates examined, the menthyl ester appeared to be the best choice at least for unsubstituted benzoate 2 (X = H). Hence, the substituent effects were systematically investigated, using (−)-menthyl benzoate as the reference sensitizer; see runs 8–20 in Table II. Obviously, the optical yield is not a simple function of the Hammett σ value, indicating that there is no straightfor-

ward contribution of the electronic effect to % ee. It is noted however that both electron-donating and -withdrawing substituents, introduced at the meta or para position, more or less enhance % ee, while the ortho substituents generally diminish it, except for the salicylate (X = 2-OH), which gave an improved optical yield of 7.0%.

Also examined were the (−)-menthyl esters of benzene- or biphenylpolycarboxylic acids, i.e., phthalate 3, isophthalate 4, and terephthalate 5, 1,2,3- and 1,3,5-benzenetricarboxylates 6 and 7, 1,2,4,5-benzenetetracarboxylate 8, benzenehexacarboxylate 9, and 4,4'-biphenyldicarboxylate 10; runs 21, 23, 24, and 26–30. It is a marked difference that, of all the (−)-menthyl esters examined, only phthalate 3 afforded the antipodal (+)-(S)-1E. Again, the optical yield never correlates with the Hammett σ, but appears to increase with decreasing singlet energy of the sensitizer, except for phthalate 3. Thus, (−)-hexamenthyl benzenehexacarboxylate 9 gave the highest optical yield of 16.8% at 25 °C.

The photosensitizations with mixed esters were also performed in order to get insights into the sensitizer–substrate interaction and the puzzling ortho effect mentioned above. (−)-Menthyl methyl phthalate (3) and (−)-menthyl methyl terephthalate (5) were employed as "hemichiral" sensitizers. As shown in Table II, the hemichiral terephthalate 5 gave 1E in an optical yield of 3.0%, which is exactly half of the value (6.0%) for the dimenthyl analogue; see runs 24 and 25. Quite interestingly, the hemichiral phthalate 3 afforded an optical yield of 3.0%, which is almost comparable with that (3.8%) for the dimenthyl analogue (runs 21 and 22).

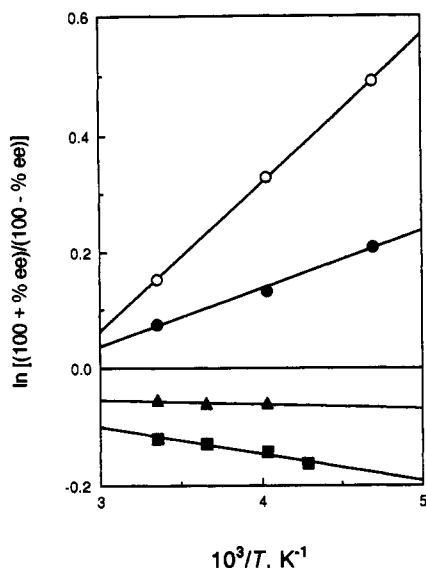**Temperature Effects.** One inherent and distinguished advantage of the photochemical reaction over the thermal

Figure 1. Plots of ln (k_S/k_R), or ln $[(100 + \% \text{ ee})/(100 - \% \text{ ee})]$, as a function of reciprocal temperature $1/T$ for (-)-menthyl benzoate (▲), (-)-dimenthyl (●) and (-)-dibornyl (○) phthalates, and (-)-dimenthyl terephthalate (■).

Figure 2. Plots of ln (k_S/k_R), or ln $[(100 + \% \text{ ee})/(100 - \% \text{ ee})]$, as a function of reciprocal temperature $1/T$ for (-)-tetramenthyl (●), (+)-tetraisomenthyl (△), and (-)-tetrabornyl (○) 1,2,4,5-benzenetetracarboxylates.

one is the much wider range of applicable temperature without influencing the reaction mechanism. Nonetheless, the temperature dependence of enantiodifferentiating photoreactions has scarcely been explored.[9a] In the present photoisomerization, the temperature effects upon optical yield were investigated at temperatures between 50 and –90 °C, employing some benzenepolycarboxylate carrying (-)-menthyl and/or other chiral alkyls; see Table III.

The natural logarithms of the relative rate constants affording (S)- and (R)-1E, i.e., ln (k_S/k_R) are plotted against the reciprocal temperature, $1/T$, in order to analyze the temperature effects more quantitatively; the ln (k_S/k_R) values are calculated as ln $((100 + \% \text{ ee})/(100 - \% \text{ ee}))$. The plots give good straight lines, as shown in Figure 1.

As would be anticipated, the optical yields of (-)-(R)-1E obtained with (-)-menthyl benzoate (2) (X = H) or (-)-dimenthyl terephthalate (5) gradually increase with lowering temperature, while the extrapolation to the infinite temperature gives virtually 0% ee in each case. By contrast, the photosensitization with (-)-menthyl and (-)-bornyl phthalates 3 gave the antipode (+)-(S)-1E. Also noted is that although the optical yield increases with decreasing temperature as is the case with 2 or 5, simple extrapolations to higher temperatures inevitably go across the x-axis (0% ee line) at 91 and 112 °C for the bornyl and menthyl esters 3, respectively, and significantly, beyond that temperature, the product chirality is expected to be inverted.

Indeed, unusual temperature-switching of product chirality was observed with several benzenetetracarboxylates 8 and benzenehexacarboxylates 9. As exemplified in Figure 2, the use of (-)-menthyl or (+)-isomenthyl benzenetetracarboxylates afforded either (R)- or (S)-1E, depending upon the irradiation temperature, and the direction of product's optical rotation was really inverted at a critical point, designated as isoenantiodifferentiating, or simply equipodal, temperature T_0: –17 °C for the menthyl ester and –56 °C for the isomenthyl ester. (-)-Hexamenthyl, (-)-hexabornyl, and (-)-hexakis(1-methylheptyl) benzenehexacarboxylates 9 as photosensitizer also behaved analogously. Eventually, with all ortho-substituted benzene(poly)carboxylates including (-)-menthyl salicylate, analogous temperature-switching phenomena are seen within the examined temperature range or predicted by
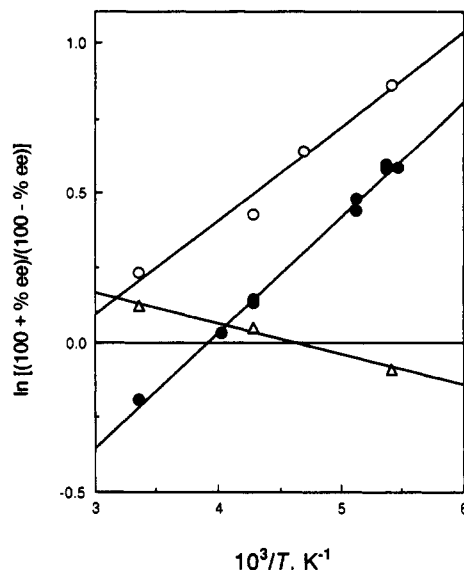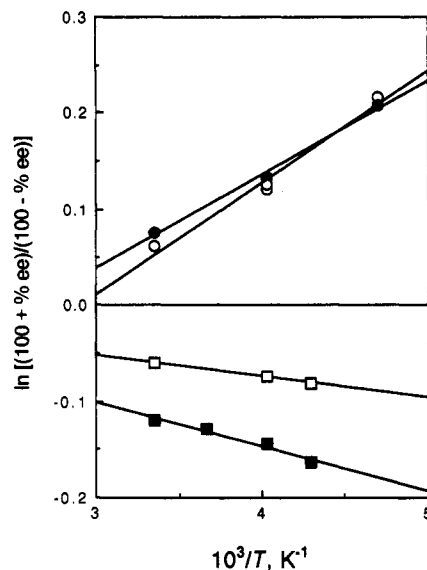

Figure 3. Plots of ln (k_S/k_R), or ln $[(100 + \% \text{ ee})/(100 - \% \text{ ee})]$, as a function of reciprocal temperature $1/T$ for (-)-menthyl methyl (○) and (-)-dimenthyl (●) phthalates and (-)-menthyl methyl (□) and (-)-dimenthyl (■) terephthalates.

simple extension of the straight line. In these cases, below the equipodal temperature T_0, one enantiomer is produced predominantly and the optical yield increases with decreasing temperature, whereas above T_0, the antipode becomes the predominant photoproduct and its optical yield increases as the temperature increases. This unprecedented phenomenon is of much mechanistic as well as synthetic interest, since both enantiomers can be obtained not by employing antipodal sensitizer but by merely changing irradiation temperature.

Mechanistically interesting is the photosensitization with the hemichiral mixed esters, i.e., (-)-menthyl methyl phthalate and terephthalate. The photosensitizations by these mixed esters were carried out under comparable conditions, and the temperature-dependent optical yields are similarly plotted in Figure 3, along with those for the corresponding dimenthyl esters. The use of hemichiral terephthalate led to a halved optical yield at each temperature examined, affording a straight line of exactly half

Table III. Temperature Dependence of Optical Yield in Enantiodifferentiating Photoisomerization of 1Z Sensitized by a Variety of Chiral Polyalkyl Benzenepolycarboxylates in Pentane[a]

run	compd	R (X)	temp, °C	irrad time, h	conv, %	yield,[b] %	$[\alpha]^{25}_{D}$ (c, CH_2Cl_2)	% ee[c]
1	2	(−)-menthyl (H)	25	28	21	17	−11.6 (1.1)	−2.72
2			0	28	25	19	−12.5 (3.2)	−2.92
3			−25	60	20	15	−12.6 (3.1)	−2.97
4			−78[d]	56	17	9	−10.0 (1.0)	−2.34
5			−88[d]	70	21	20	−6.4 (2.5)	−1.50
6		(−)-menthyl (4-CF₃)	25	30	30	25	−16.4 (3.0)	−3.86
7			−60	70	e	e	−18.8 (4.4)	−4.40
8			−88[d]	75	23	22	−13.6 (4.5)	−3.20
9		(−)-menthyl (2-OH)[f]	25	48	9	9	−29.8 (1.0)	−7.04
10			−60	26	3	1	−107.8 (0.6)	−25.3
11	3	(−)-menthyl	25	23	9	5	16.2 (1.4)	3.80
12			−25	70	17	9	28.3 (2.3)	6.63
13			−60	70	18	9	43.7 (2.1)	10.3
14		(−)-menthyl, methyl[g]	25	22	9	5	13.0 (1.0)	3.04
15			−25	61	18	8	25.6 (1.9)	6.00
16				60	e	e	26.9 (1.9)	6.31
17			−60	72	16	9	46.1 (3.0)	10.8
18		(−)-bornyl	25	24	9	6	32.4 (1.2)	7.57
19			−25	70	11	8	69.5 (1.7)	16.3
20			−60	70	12	11	102.1 (2.8)	24.0
21	5	(−)-menthyl	25	24	25	8	−25.4 (2.6)	−5.96
22			0	27	22	12	−27.3 (3.3)	−6.41
23			−25	63	24	19	−30.6 (3.2)	−7.18
24			−40	64	24	18	−34.7 (3.1)	−8.16
25			−88[d]	70	18	12	−18.4 (3.8)	−4.31
26		(−)-menthyl, methyl[g]	25	28	21	17	−12.8 (2.6)	−3.01
27			−25	60	20	14	−15.9 (2.8)	−3.73
28			−40	60	17	13	−17.2 (1.8)	−4.04
29			−60[d]	70	17	13	−16.7 (2.2)	−3.91
30	6	(−)-menthyl	25	24	e	e	−40.0 (2.2)	−9.38
31			−89	48	e	e	−56.9 (0.4)	−13.4
32	8	(−)-menthyl	25	29	15	8	−41.0 (1.2)	−9.60
33			−25	69	19	15	6.30 (3.4)	1.49
34			−40	48	23	15	30.0 (1.8)	7.05
35				66	23	17	28.6 (3.0)	6.71
36			−78	32	13	10	92.1 (3.4)	21.6
37				140	21	21	99.6 (3.1)	23.4
38			−87	48	20	12	119.5 (1.6)	28.1
39				64	22	19	123.2 (1.9)	28.9
40			−90	70	e	e	121.5 (5.2)	28.5
41		(−)-bornyl	25	29	7	6	49.2 (1.0)	11.5
42			−40	48	9	8	116.3 (2.2)	27.3
43			−60	70	16	9	131.7 (2.3)	30.9
46			−88	72	12	9	172.7 (2.3)	40.6
44		(+)-1-methylpropyl	25	25	18	7	−0.05 (1.3)	−0.01
45			−40	70	23	15	−20.2 (2.2)	−4.73
46			−80	70	30	21	−57.0 (3.9)	−13.4
47		(+)-1-methylpentyl	25[h]	24	e	e	7.83 (1.5)	1.84
48			−90[i]	70	e	e	−112.1 (2.4)	−26.3
49		(+)-1-methylheptyl	25	28	20	9	6.4 (1.9)	1.51
50			−40	80	23	16	−27.0 (3.9)	−6.33
51			−85	70	30	21	−103.5 (4.0)	−24.3
52		(+)-1-methylnonyl	25	24	e	e	5.25 (1.6)	1.23
53			−87	70	e	e	−115.2 (3.7)	−27.0
54		(+)-1,2-dimethylpropyl	25	28	15	6	13.2 (1.6)	3.09
55			−40	48	e	e	−13.4 (1.3)	−3.15
56			−87	100	27	17	−68.4 (3.2)	−16.1
57		(+)-1,2,2-trimethylpropyl	25	27	15	8	49.5 (1.7)	11.6
58			−40	70	13	9	204. (1.7)	4.78
59			−86	70	30	23	−66.3 (4.6)	−15.6
60		(+)-isopinocampheyl	25	28	16	3	17.8 (0.9)	4.18
61			−40	36	e	e	17.2 (0.8)	4.03
62			−87	70	15	4	18.7 (1.3)	4.40
63		(−)-fenchyl	25	28	13	3	−3.7 (0.5)	−0.87
64			−40	70	8	5	−25.3 (1.9)	−5.94
65			−86	70	e	e	−34.1 (1.9)	−8.01
66		(+)-isomenthyl	25	28	e	e	30.6 (1.6)	5.95
67			−40	48	e	e	10.8 (1.0)	2.54
68			−88	56	e	e	−19.0 (1.0)	−4.45
69		(+)-neomenthyl	25	24	e	e	−35.9 (1.2)	−8.43
70			−88	55	e	e	−26.6 (2.4)	−6.24
71		(+)-1-cyclohexylethyl	25	24	e	e	7.58 (0.2)	1.78
72			−86	48	e	e	−48.5 (2.3)	−11.4
73		(+)-cedryl	−86	70	18	14	−95.7 (2.3)	−22.5

Table III (Continued)

run	compd	R (X) [sensitizer]	temp, °C	irrad time, h	conv, %	yield,[b] %	$[\alpha]^{25}_D$ (c, CH$_2$Cl$_2$)	% ee[c]
74		(+)-cholesteryl	25	26	18	8	-4.34 (2.2)	-1.02
75	9	(-)-menthyl	25	20	6	3	-71.7 (0.5)	-16.8
76			-25	60	9	5	-3.41 (2.)	-0.80
77			-59	75	8	5	87.6 (1.4)	20.6
78			-86	72	13	10	120.4 (2.3)	28.3
79		(-)-bornyl	25	19	5	2	32.9 (0.6)	7.73
80			-59	66	3	2	147.7 (0.3)	34.7
81			-86	60	3	2	200.2 (1.1)	47.0
82		(-)-1-methylheptyl	25	20	9	6	21.7 (1.7)	5.09
83			-25	24	15	10	112.4 (1.7)	26.4
84			-60	66	12	10	203.6 (1.9)	47.8
85			-85	64	7	4	224.1 (1.5)	52.6
86			-87	24	6	3	224.3 (1.3)	52.7

[a] [1Z] = 0.2 M; [sensitizer] = 5 mM, unless noted otherwise. [b] Chemical yield determined by GC analysis on the basis of the starting material, unless noted otherwise. [c] Enantiomeric excess of isolated 1E, calculated from the specific rotation. [d] Substantial amount of sensitizer (5 mM) precipitated at this temperature, which made the solution opaque. [e] Not determined. [f] [1Z] = 0.6 M. [g] Mixed ester. [h] [Sensitizer] = 4 mM, owing to low solubility. [i] [Sensitizer] = 1.3 mM, owing to low solubility.

Table IV. Activation Parameters (at 25 °C), Extrapolated Optical Yields, and Equipodal Temperatures (T_0) for Enantiodifferentiating Photoisomerization of 1Z Sensitized by a Variety of Chiral Polyalkyl Benzenepolycarboxylates[a]

entry	compd	R (X) [sensitizer]	solvent	data point	$\Delta\Delta H^{\ddagger}_{S-R}$,[b] kcal/mol	$\Delta\Delta S^{\ddagger}_{S-R}$,[c] cal/mol K	A_S/A_R[d]	% ee estimated[e] −200 °C	% ee estimated[e] ∞	T_0,[f] °C
1	2	(-)-menthyl (H)	pentane	3	+0.014	-0.027	0.99	-6.5	-1.5	g
2		(-)-menthyl (4-CF$_3$)	pentane	2	-0.016	-0.043	0.98	-8.0	-2.5	g
3		(-)-menthyl (2-OH)	pentane	2	+0.56	+0.69	1.42	-90.9	38.1	77
4	3	(-)-menthyl	pentane	3	-0.19	-0.22	0.90	49.0	-12.5	112
5		(-)-menthyl, methyl[h]	pentane	4	-0.23	-0.29	0.86	55.6	-16.7	71
6		(-)-bornyl	pentane	3	-0.50	-0.60	0.74	88.0	-33.3	91
7	5	(-)-menthyl	pentane	4	+0.092	+0.033	1.02	-28.9	1.9	930
8		(-)-menthyl, methyl[h]	pentane	3	+0.044	+0.012	1.01	-14.2	0.7	1400
9	8	(-)-menthyl	pentane	9	-0.77	-1.30	0.52	95.5	-63.8	-17
10			heptane	3	-0.80	-1.32	0.51	96.3	-64.4	-10
11			decane	2	-0.83	-1.36	0.50	96.9	-65.8	-8
12			methylcyclohexane	3	-0.34	-0.69	0.71	64.1	-38.1	-61
13			isopentane	2	-0.46	-0.89	0.64	78.4	-47.6	-51
14			isooctane	2	-0.39	-0.81	0.66	69.8	-43.8	-66
15			ether	2	-0.59	-0.99	0.61	89.7	-51.7	-14
16		(-)-bornyl	pentane	4	-0.61	-0.67	0.71	93.5	-37.1	118
17		(+)-1-(methoxycarbonyl)ethyl	CH$_3$CN	2	+0.32	+0.37	1.21	-71.5	21.2	104
18		(+)-1-methylpropyl	pentane	3	+0.29	+0.44	1.25	-63.8	24.9	17
19		(+)-1-methylpentyl	pentane	2	+0.54	+0.82	1.51	-88.4	44.3	14
20		(+)-1-methylheptyl	pentane	3	+0.54	+0.84	1.52	-87.6	44.9	6
21		(-)-1-methylheptyl	pentane	3	-0.52	-0.80	0.67	86.5	-43.2	8
22			CH$_3$CN	3	-0.25	-0.38	0.83	56.9	-21.6	15
23			methanol	3	-0.27	-0.39	0.82	59.8	-22.2	23
24		(+)-1-methylnonyl	pentane	2	+0.57	+0.85	1.54	-89.9	45.7	17
25		(+)-1,2-dimethylpropyl	pentane	3	+0.38	+0.63	1.37	-74.2	34.9	-8
26		(+)-1,2,2-trimethylpropyl	pentane	3	+0.54	+1.02	1.67	-85.1	53.0	-44
27		(-)-fenchyl	pentane	3	+0.14	+0.18	1.10	-36.5	10.4	67
28		(+)-isopinocampheyl	pentane	3	+0.005	+0.064	1.03	5.3	3.7	g
29		(+)-neomenthyl	pentane	2	-0.043	-0.21	0.90	2.7	-12.0	-184
30		(+)-isomenthyl	pentane	3	+0.20	+0.41	1.23	-43.3	23.2	-56
31		(+)-1-cyclohexylethyl	pentane	2	+0.26	+0.42	1.23	-58.4	23.6	3
32	9	(-)-menthyl	pentane	4	-0.96	-1.67	0.43	98.1	-74.9	-24
33		(-)-bornyl	pentane	3	-0.86	-1.13	0.56	98.1	-57.3	60
34		(-)-1-(methoxycarbonyl)ethyl	CH$_3$CN	2	+0.66	+0.87	1.55	-94.2	46.7	54
35		(-)-1-methylheptyl	pentane	4	-1.13	-1.51	0.47	99.5	-70.5	50

[a] All activation parameters obtained by Arrhenius treatment of the optical yields. [b] Differential enthalpy of activation: $\Delta H^{\ddagger}_S - \Delta H^{\ddagger}_R$. [c] Differential entropy of activation: $\Delta S^{\ddagger}_S - \Delta S^{\ddagger}_R$. [d] Relative frequency factor. [e] Enantiomeric excess at -200 °C and the infinite temperature, calculated by extrapolation of Arrhenius plot. [f] Isoenantiodifferentiating, or equipodal, temperature, at which no appreciable enantiodifferentiation occurs. [g] Does not exist. [h] Mixed ester.

slope and almost 0 intercept. On the other hand, the sensitization with the hemichiral phthalate gave almost comparable or even slightly higher optical yields compared with those for the dimenthyl phthalate.

Activation Parameters. The Arrhenius and Eyring treatments of these data, according to the reaction mechanism shown in the Discussion, disclose that this unusual temperature dependence is not specific to the chiral alcohol moiety mentioned above but rather general to the ben-

zenepolycarboxylates possessing ortho substituent(s). The activation parameters, given in relative or differential terms, are calculated from the linear Arrhenius plots. The relative frequency factor (A_S/A_R) and the differential enthalpy and entropy changes of activation ($\Delta\Delta H^{\ddagger}_{S-R}$ and $\Delta\Delta S^{\ddagger}_{S-R}$) are listed in Table IV.

The chiral benzoates 2 and terephthalates 5, lacking ortho substituents, were least enantiodifferentiating, as indicated by very small enthalpy and entropy differences:

Table V. Solvent and Temperature Effects upon Optical Yield in Enantiodifferentiating Photoisomerization of 1Z Sensitized by a Variety of Chiral Polyalkyl Benzenepolycarboxylates at Some Temperatures[a]

run	sensitizer compd	sensitizer R (X)	solvent	temp, °C	irrad time, h	conv, %	yield,[b] %	$[\alpha]^{25}_D$ (c, CH$_2$Cl$_2$)	% ee[c]
1	2	(-)-menthyl (H)	pentane	25	28	21	17	-11.6 (1.1)	-2.72
2			cyclohexane	25	26	25	22	-11.5 (2.2)	-2.70
3	5	(-)-menthyl	pentane	25	24	25	18	-25.4 (2.6)	-5.96
4			cyclohexane	25	26	21	14	-25.2 (2.8)	-5.91
5			acetonitrile	25	26	32	19	-30.2 (3.2)	-7.08
6				25	26	32	24	-30.1 (3.2)	-7.06
7				-25	68	16	14	-36.5 (3.0)	-8.58
8				-40	63	22	16	-36.4 (2.1)	-8.54
9			methanol	25	28	d	d	-24.5 (3.5)	-5.75
10	8	(-)-menthyl	pentane	25	29	15	8	-41.0 (1.2)	-9.35
11			heptane	25	23	9	9	-37.6 (1.9)	-8.83
12				-40	64	23	18	39.5 (1.5)	9.27
13				-87	64	26	25	130.6 (1.9)	30.7
14			decane	25	24	d	d	-37.1 (1.7)	-8.72
15				-30	48	d	d	30.3 (2.2)	7.11
16			cyclohexane	50	15	7	4	-68.5 (1.2)	-16.1
17			methylcyclohexane	25	21	12	8	-54.9 (1.7)	-12.9
18			hexane	-40	64	15	11	-4.90 (1.8)	-1.15
19				-85	64	27	25	16.2 (2.1)	3.80
20			isopentane	25	21	12	8	-55.8 (1.4)	-13.1
21				-87	64	28	23	42.6 (1.4)	9.99
22			isooctane	25	24	11	9	-60.5 (1.4)	-14.2
23				-87	64	27	23	22.9 (1.6)	5.38
24			ether	25	22	10	9	-31.4 (1.7)	-7.38
25				-85	64	31	24	91.2 (1.8)	21.4
26			acetonitrile	25[e]	20	15	8	-35.6 (1.5)	-8.36
27			ethanol	25[e,f]	20	14	6	-30.1 (1.9)	-7.07
28			methanol	25[e,f]	20	8	5	-25.4 (1.8)	-5.97
29		(-)-1-methylheptyl	pentane	25[f]	20	9	6	-5.01 (2.1)	-1.18
30				-40[g]	40	7	5	28.1 (1.3)	6.61
				-86[g]	44	17	13	102.1 (3.0)	24.0
31			acetonitrile	25[f]	21	10	6	-3.18 (2.5)	-0.75
33				-40[f]	22	13	8	24.0 (1.4)	5.63
34			methanol	25[f]	17	9	5	-0.12 (1.3)	-0.03
35				-40[g]	24	7	4	25.0 (1.0)	5.87
36				-86[g]	40	d	d	56.2 (1.2)	13.2
37		(+)-1-(methoxycarbonyl)ethyl	acetonitrile	25	25	36	20	-24.2 (2.0)	-5.68
38				-40	99	36	26	-56.2 (0.9)	-13.2
39	9	(-)-1-(methoxycarbonyl)ethyl	acetonitrile	25[e]	19	17	8	-20.9 (1.3)	-4.91
40				-40[e]	89	15	9	-85.6 (0.8)	-20.1

[a] [1Z] = 0.2 M; [sensitizer] = 5 mM, unless noted otherwise. [b] Chemical yield determined by GC analysis on the basis of the starting material, unless noted otherwise. [c] Enantiomeric excess of isolated 1E, calculated from the specific rotation. [d] Not determined. [e] Sensitizer is slightly insoluble. [f] [Sensitizer] = 2 mM. [g] [Sensitizer] = 1 mM.

$|\Delta\Delta H^{\ddagger}_{S-R}|$ < 0.1 kcal/mol; $|\Delta\Delta S^{\ddagger}_{S-R}|$ < 0.1 cal/mol K. By contrast, much larger $\Delta\Delta H^{\ddagger}_{S-R}$ and $\Delta\Delta S^{\ddagger}_{S-R}$ values (up to 1.13 kcal/mol and 1.67 cal/mol K, respectively) were obtained for most ortho-substituted benzenecarboxylates, i.e., 2 (X = 2-OH), 3, 8, and 9. Consequently, the relative frequency factor A_S/A_R also deviates substantially from unity by a factor of more than 2 in some extreme cases. It is significant that both $\Delta\Delta H^{\ddagger}_{S-R}$ and $\Delta\Delta S^{\ddagger}_{S-R}$ possess the same sign in all, but menthyl benzoate, cases.

Solvent Effects. The photosensitizations with (-)-menthyl benzoate 2, terephthalate 5, and benzenetetracarboxylate 8 were performed in some nonpolar hydrocarbon and polar protic/aprotic solvents; Table V.

In the benzoate and terephthalate sensitizations, the solvent effect was apparently insignificant (runs 1-9 in Table V). The optical yield was affected only slightly by solvent viscosity or polarity at least at 25 °C, although slightly higher optical yields were obtained in acetonitrile; see runs 3-5 (Table V) or compare runs 5-8 (Table V) with runs 21-24 (Table III).

However, this is not the case with tetramenthyl benzenetetracarboxylate. Even at 25 °C, solvents of different viscosity, polarity, or structure gave appreciably different optical yields, varying from 5.97% (methanol) to 14.2% (isooctane). The polar solvents give optical yields between 5.97% (methanol) and 7.38% (ether), which are appreci-

ably lower than that (9.35%) in pentane. Higher solvent viscosity appears to diminish the value slightly, while the branched hydrocarbons like methylcyclohexane, isopentane, and isooctane enhance the optical yield up to 14.2%. Furthermore, the activation parameters differ considerably from those in pentane; Table IV.

Fluorescence Quenching. It has recently been revealed that in contrast to nonfluorescent benzenemono- to benzenetricarboxylates, benzenetetra- and benzenehexacarboxylates emit weak fluorescence in fluid solution.[12] In order to get quantitative information about the quenching process, we carried out the fluorescence quenching of tetramethyl, (-)-tetramenthyl, or (-)-tetrabornyl benzenetetracarboxylate 8 with 1Z or 1E. As exemplified for the (-)-tetramenthyl case in Figure 4, stepwise addition of 1Z or 1E gradually quenched the fluorescence at 331 nm at different efficiency for each isomer. Simultaneously, a new emission emerged at a longer wavelength (410 nm for 1Z and ca. 455 nm for 1E) with an isoemissive point, indicating exciplex formation upon quenching.

(12) (a) Inoue, Y.; Yamasaki, N.; Yokoyama, T.; Tai, A.; Ishida, A.; Takamuku, S. J. Chem. Soc., Chem. Commun. 1989, 1270. (b) Yamasaki, N.; Inoue, Y.; Yokoyama, T.; Tai, A.; Ishida, A.; Takamuku, S. J. Am. Chem. Soc. 1991, 113, 1933.
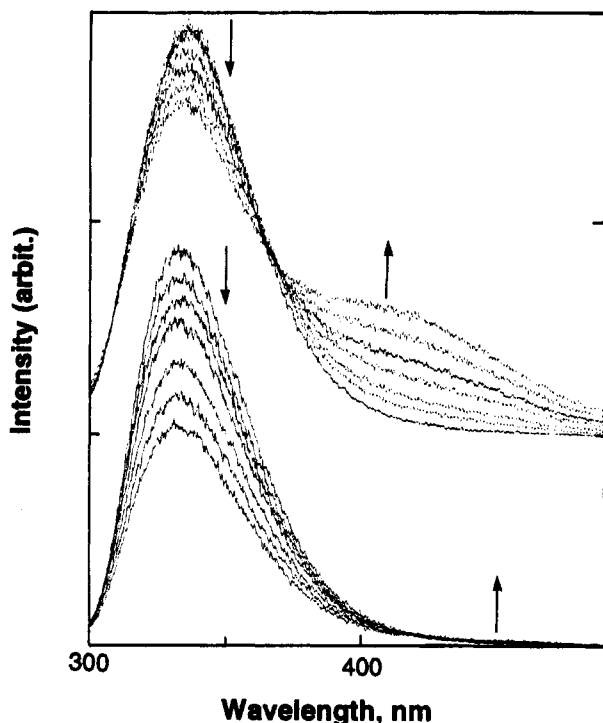
Figure 4. Fluorescence quenching of (-)-tetramenthyl 1,2,4,5-benzenetetracarboxylate 8 (0.2 mM) with 1Z (0-1.07 M; upper traces) and 1E (0-0.35 M; lower traces) in aerated pentane at 20 °C.
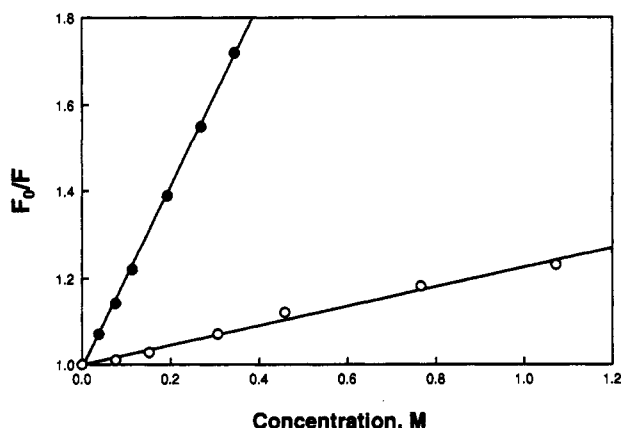

Figure 5. Stern-Volmer plot for the fluorescence quenching of (-)-tetramenthyl benzenetetracarboxylate with 1Z (O) and 1E (●).

According to the conventional Stern-Volmer treatment,[13] relative fluorescence intensity (F_0/F) is plotted as a function of cyclooctene concentration to give good straight lines for both 1Z and 1E, as shown in Figure 5. The slope gives the Stern-Volmer constant $(k_q\tau)$, from which the quenching rate constant (k_q) is calculated by using the sensitizer lifetime (τ) measured with the single photon counting method;[12] the results are summarized in Table VI. The quenching, especially by 1E, is quite efficient, approaching the diffusion-controlled rate in pentane.

Triplet Sensitization. For comparison purposes, triplet-sensitized photoisomerizations were performed in pentane at 25 and -60 °C, employing (-)-menthyl aryl-methyl ethers 11 and 12 as triplet sensitizers. As demonstrated previously,[14] alkylbenzenes act as pure triplet

Table VI. Fluorescence Quenching of Some Tetraalkyl 1,2,4,5-Benzenetetracarboxylates 8 with (Z)- and (E)-Cyclooctene (1Z and 1E)[a]

sensitizer, R	τ,[b] ns	quencher	$k_q\tau$, $M^{-1} s^{-1}$	k_q, $10^9 s^{-1}$	exciplex fluor λ_{max}, nm	rel int[c]
methyl	0.2	1Z	0.65	3.3	415	0.76
		1E	2.70	13.5	445	0.17
(-)-menthyl	0.2	1Z	0.28	1.4	410	≡1.00
		1E	2.08	10.4	~455	0.05
(-)-bornyl	0.2	1Z	0.21	1.1	415	0.89
		1E	1.80	9.0	~455	0.09

[a] Measured with 2.0×10^{-4} M solution of 8 in aerated pentane at 20 °C. [b] Fluorescence lifetime of 8 in aerated pentane at 22-23 °C; ref 14. [c] Intensity of the exciplex emission, relative to that observed in the quenching of the menthyl ester with 1Z under comparable conditions.

sensitizers only at low concentrations of 1 but show mixed behavior of singlet/triplet sensitizers at high concentrations. The critical concentration, at which the singlet starts to participate, is 10-20 mM for toluene and p-xylene.[14a] On the other hand, the singlet sensitization of 1 with aromatic esters[6,15] does not show such concentration dependence, affording steady $(E/Z)_{pss}$ values at 2 to 400 mM.[15] Hence, the photosensitizations with the (-)-menthyl esters 11 and 12 were performed at the 1Z concentrations of 0.63 or 10 to 400 mM. The $(E/Z)_{pss}$ and % ee values obtained are listed in Table VII.

As was the case with the corresponding alkylbenzenes,[14] the $(E/Z)_{pss}$ values obtained in the photosensitizations with 11 and 12 increased with decreasing cyclooctene concentration, approaching the ultimate values of 0.22 and 0.12, respectively. On the contrary, the optical yield for 11 gradually decreased from 1.28% at 40-400 mM to 0.90% at 10 mM and then to 0.44% at 2.5 mM; a smooth extension of the curve would lead to 0% ee. Judging from the $(E/Z)_{pss}$ values at the higher concentrations, it is likely that the singlet sensitization mechanism is operating at least in part and is responsible for the increasing optical yields.

NMR and CD Spectra of Sensitizers at Low Temperatures. The temperature-switching of product chirality observed would be rationalized, if there exist two ground-state conformers for bulky polyalkyl benzene-polycarboxylates, each of which specifically affords one of the enantiomers of 1E upon photosensitization and is equilibrated mutually at the temperature employed. The NMR and CD spectra of (-)-tetramenthyl benzenetetra-carboxylate 8 were recorded at several temperatures ranging from 25 to -90 °C in order to test such possibility. However, no evidence for the equilibrating ground-state conformers was obtained in both NMR and CD spectra, except for the NMR line broadening and the CD intensity enhancement at low temperatures.

Molecular Orbital and Molecular Mechanics Calculations. The MO calculations were performed with the parent compound, i.e., methyl benzoate, in the ground and excited singlet states using the MNDOC program[16,17] in order to elucidate the possible site of sensitizer-substrate

(13) Gilbert, A.; Baggott, J. *Essentials of Molecular Photochemistry*; Blackwell Scientific Publications: London, 1991; p 111.

(14) (a) Inoue, Y.; Kobata, T.; Hakushi, T. *J. Phys. Chem.* **1985**, *89*, 1973. (b) Inoue, Y.; Takamuku, S.; Sakurai, H. *J. Phys. Chem.* **1977**, *81*, 7.

(15) Yamasaki, N.; Inoue, Y.; Yokoyama, T.; Tai, A. *J. Photochem. Photobiol. A* **1989**, *49*, 465.

(16) The MNDOC program, released through QCPE (No. 353), was run on a Fujitsu S-3500 computer.

(17) Attempted calculations on the tetra- and hexacarboxylates, starting with several different initial structures, could not achieve self-consistence on MNDO and MNDOC programs, probably owing to the inappropriate initial excited-state structures used and the severe steric and/or electronic interaction between the ortho substituents.

Table VII. Triplet-Sensitized Enantiodifferentiating Photoisomerization of 1Z with Chiral Alkyl Benzyl Ethers 11 and 12 in Pentane[a]

| | sensitizer | | | | | | | | |
run	compd	R	[1Z], mM	temp, °C	irrad time, h	$(E/Z)_{pss}$[b]	conv, %	yield,[c] %	$[\alpha]^{25}_D$ (c, CH_2Cl_2)	ee[d]
1	11	(−)-menthyl	0.63	25	0.5[e]	0.22				
2					1[e]	0.20				
3			2.5	25	3[f]	0.22	g	g	−1.87 (0.5)	−0.44
4			10	25	4[h]	0.16	g	g	−3.75 (0.7)	−0.88
5					6[i]	0.17	30	11	−3.83 (0.5)	−0.90
6			40	25	10[j]	0.089	19	7	−5.49 (0.6)	−1.29
7			400	25	28[k]	0.013	5	1	−5.46 (0.7)	−1.28
8	12	(−)-menthyl	10	25	6[e]	0.12				
9			400	25	23[k]	0.013	3	1	−7.88 (0.5)	−1.85
10				−60	62[k]	0.008	3	1	−2.39 (0.5)	−0.56

[a] [Sensitizer] = 5 mM. [b] [1E]:[1Z] ratio at the photostationary state. [c] Chemical yield determined by GC analysis on the basis of the starting material, unless noted otherwise. [d] Enantiomeric excess of isolated 1E, calculated from the specific rotation. [e] Irradiation performed with 3-mL solution in a quartz tube only to determine the $(E/Z)_{pss}$ ratio. [f] Irradiation repeated with three portions of 3-L solution in an immersion-well reactor. [g] Not determined owing to the multiple runs. [h] Irradiation repeated with eight portions of 200-mL solution in an annular vessel. [i] Irradiation repeated with four portions of 300-mL solution in an annular vessel. [j] Irradiation repeated with two portions of 300-mL solution in an annular vessel. [k] Irradiation performed with one portion of 300-mL solution in an annular vessel.

interaction. The sign and contribution of each atomic orbital to the HOMO and LUMO in the ground state (S_0) and to the two SOMOs in the excited singlet state (S_1) are illustrated in Figure 6.

The MNDOC-optimized structures indicate that the bond lengths of aromatic C1–C2 and C3–C4 decrease slightly (0.01 Å) in the excited state, while the aromatic C2–C3 and C1—C(=O) bonds are elongated by 0.07 and 0.01 Å, respectively. No significant changes greater than 0.01 Å or 0.2° are seen in the other bond lengths or any bond angles. The MO calculation reveals that the excited benzoate is mostly aromatic π,π^* in nature with partial contribution from carbonyl π,π^*. In the singlet sensitization,[6] the SOMO2 of benzoate may interact with the antibonding π^* orbital of 1. If the exciplex could have a well-defined structure, the vacant π^* orbital of 1 is likely to interact with either the antibonding aromatic C2–C3 or carbonyl C=O of excited benzoate.

The ground-state structure of (−)-menthyl benzoate was estimated by Allinger's MM2 program;[18-20] top and side views of the optimized structure are illustrated in Figure 7. It is noted that the (−)-menthyl moiety creates sidedness in the benzoate chromophore, especially around the carbonyl group; one side of the carboxyl is open, while the other is covered severely with the isopropyl group of the menthyl moiety. Judging from the MNDOC calculations that show little differences in the partial structures around the methoxycarbonyl group of methyl benzoate in the ground and excited states, it is likely that the sidedness observed in the ground state is still effective in the excited benzoate and controls the accessibility of approaching cyclooctene.

Discussion

Singlet versus Triplet Sensitization. Only one enantiodifferentiating photoisomerization system has been surveyed, employing both singlet and triplet sensitizers.[4] In their pioneering work,[4a,b] Hammond and Cole demonstrated that the enantiodifferentiating photoisomerization of 1,2-diphenylcyclopropane can be effected in an optical
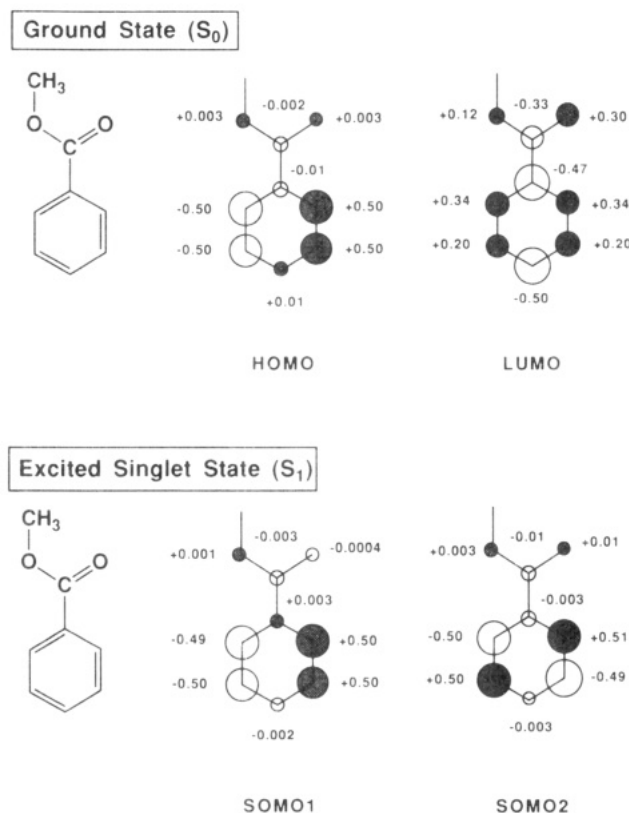

Figure 6. MNDOC calculations on methyl benzoate in its ground and excited singlet states.

yield of 6.7%[21] in the presence of a chiral singlet sensitizer, i.e., (+)-(R)-1-(1-(N-acetylamino)ethyl)naphthalene. Ouannès et al.[4c] and Kagan et al.[4d] later employed chiral aromatic ketones as triplet sensitizers. The use of optically active 3-methyl-1-indanone[4c] and 3- or 4-methyl-1-tetralone[4d] as triplet sensitizers afforded lower optical yields of 3.0 and ca. 1%, respectively. Although the optical yields reported are low and no further systematic efforts were made in these cases, the difference between singlet and triplet sensitizations has not seriously been discussed in general.

We have demonstrated that several benzene(poly)-carboxylates act as singlet sensitizers for simple alkenes.[6] The singlet sensitization of 1 proceeds via the exciplex

(18) The MM2 program used was an NEC PC-9801 version of the original QCMP/004; Allinger, N. L.; Yuh, Y. H.; Chong, D. P. *QCPE Bull.* **1984**, *4*, 113. For the PC-9801 version, see: Osawa, E.; Mochizuki, Y. *Kagaku (Kyoto)* **1985**, *40*, 703; *Manual for MM2 on Personal Computer*; IBM Japan: Tokyo, 1986.

(19) For the MM2 parameters for benzoic acid and other benzene derivatives, see: Tanabe, K.; Suzuki, S.; Uchimaru, T.; Osawa, E. *Chem. Express* **1988**, *3*, 591.

(20) The initial structures were built by using the MOLDA4/GRIMM program modified by Y.I.: Ogawa, K.; Yoshida, H.; Suzuki H. *Modeling of Molecules*; Science House: Tokyo, 1987.

(21) Our experiments under almost comparable conditions employing the same chiral photosensitizer could not reproduce such high optical yield but afforded 3–4%; to be published elsewhere.
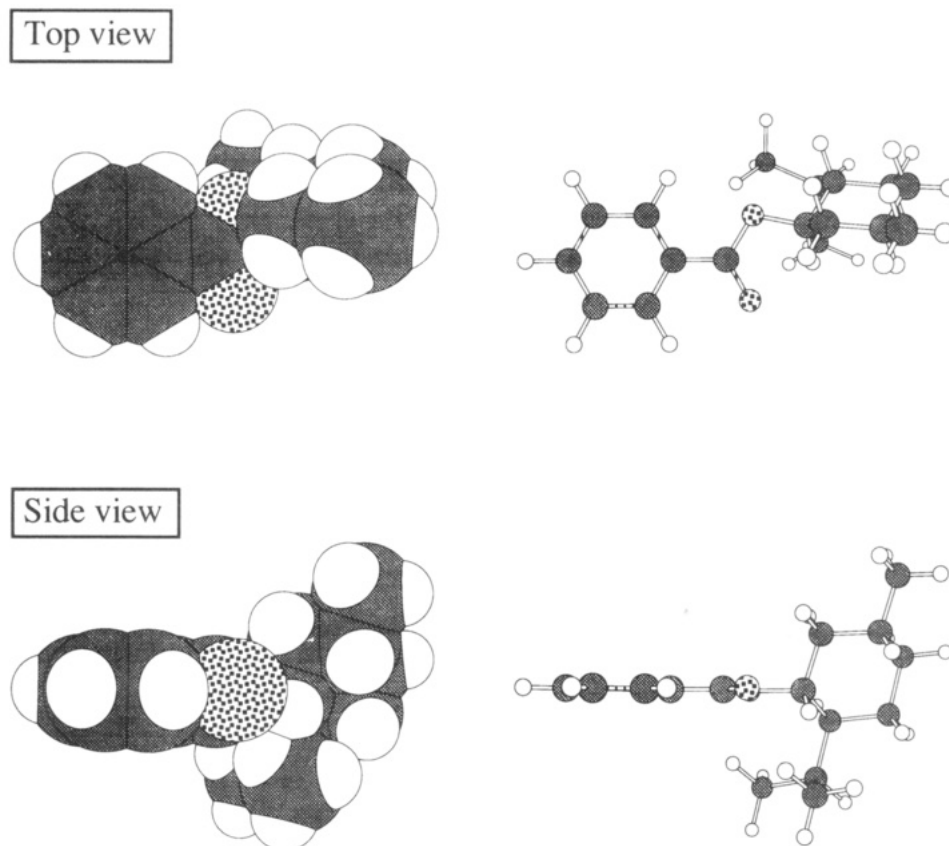
Top view

Side view

Figure 7. Top and side views of (−)-menthyl benzoate structure optimized with MM2 calculation in its ground electronic state.

formation between sensitizer singlet ($^1S^*$) and **1**, followed by the rotational relaxation of **1** within the exciplex, producing perpendicular cyclooctene singlet (^1p).[6] This singlet sensitization mechanism is also applicable to the present enantiodifferentiating photoisomerization, as illustrated in Scheme II.

The concentration-dependent $(E/Z)_{pss}$ and % ee values observed in the formal "triplet" sensitization by **11** and **12** (Table VII) clearly indicate that the use of these aromatic ethers as sensitizer results in the simultaneous operation of both singlet and triplet mechanisms especially at high cyclooctene concentrations and that the pure triplet sensitization, which is dominant at lower concentrations, affords only negligible optical yields below 1%. This observation clearly indicates that no chiral triplet sensitizer is located in close proximity to the isomerizing cyclooctene, even if a triplet exciplex is involved in the photoisomerization. It may be concluded that the triplet sensitization with optically active aromatic hydrocarbons is not advantageous in effecting photochemical enantiodifferentiation.

Another point of interest is the involvement of the Schenck mechanism.[22] In the photosensitized isomerization of alkenes, ketones used as triplet sensitizer often give a 1,4-biradical intermediate, which in turn cyclizes to oxetane or regenerates alkene, accompanying geometrical isomerization.[23] However, such a 1,4-biradical, if formed in the reaction of excited aromatic ester with **1Z** or **1E**, never produces or regenerates **1E** but decays exclusively

Scheme II
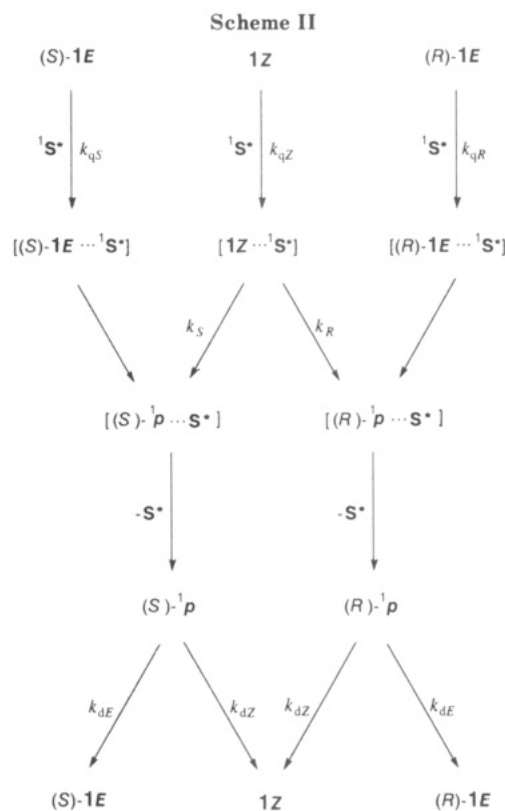
to **1Z**, owing to the much higher strain energy of **1E**,[24] as has been demonstrated by the extremely low $(E/Z)_{pss}$

(22) Schenck, G. S.; Steinmetz, R. *Bull. Soc. Chim. Belg.* **1962**, *71*, 781.

(23) (a) Saltiel, J.; D'Agostino, J.; Megarity, E. D.; Metts, L.; Neuberger, K. R.; Wrighton, M.; Zafirou, O. C. *Organic Photochemistry*; Chapman, O. L., Ed.; Marcel Dekker: New York, 1973; Vol. 3, Chapter 1. (b) Jones, G., II. *Organic Photochemistry*; Padwa, A., Ed.; Marcel Dekker: New York, 1981; Vol. 5, Chapter 1. (c) Carless, H. A. J. *Synthetic Organic Photochemistry*; Horspool, W. M., Ed.; Plenum: London, 1984; Chapter 8.

(24) The strain energy of **1E** is higher by 10 kcal/mol than that of **1Z**: (a) Rogers, D. W.; Von Voithenberg, H.; Allinger, N. L. *J. Org. Chem.* **1978**, *43*, 360. (b) Schleyer, P. v. R.; Williams, J. E.; Blanchard, K. R. *J. Am. Chem. Soc.* **1970**, *92*, 2377.

ratios ($\ll$0.03) in the triplet-sensitized photoisomerization of 1 with aromatic ketones.[14b] On the other hand, our previous kinetic studies on the singlet sensitization of 1 with some achiral alkyl benzenecarboxylates[6b] show that the relative rates of quenching by 1Z and racemic 1E, i.e., k_{qZ}/k_{qE}, are 0.24–0.28 for alkyl benzoates and 0.49 for dimethyl isophthalate, whereas the decay ratio from the twisted cyclooctene singlet, i.e., k_{dE}/k_{dZ}, is 0.76–0.79 and independent of the sensitizer used. These high decay ratios near unity are unrealistic if the 1,4-biradical intervenes in the photoisomerization process.

Enantiodifferentiating Step. No work on asymmetric photosensitization reported so far[2–9] has tried to specify the enantiodifferentiating step in the stream of the photosensitization sequence, which is composed of the initial "physical" quenching and the subsequent "chemical" isomerization process. It has been shown that efficient enantiodifferentiation can be achieved in fluorescence quenching, which, however, leads to exciplex formation with no net reaction[25,26] or results in enantiomerically less-efficient electron-transfer reaction.[27]

The present photoisomerization of 1E/Z sensitized by chiral sensitizer (S*) proceeds through the reaction sequence illustrated in Scheme II.[6] The initial quenching of sensitizer singlet (^{1}S*) by (R)/(S)-1E or 1Z affords the respective Franck–Condon-like exciplex [(R)/(S)-1E/Z···^{1}S*], which fluoresces at different wavelength and intensity specific to 1E and 1Z. The rotational relaxation around the double bond of 1E/Z within this Franck–Condon exciplex gives the relaxed diastereomeric exciplex pair [(R)/(S)-^{1}p···S*]. Judging from the exciplex fluorescence peaks of different wavelength and intensity observed for 1E and 1Z (Figure 4), the rotational relaxation within the exciplex appears to be rate-determining. The relaxed exciplexes thus formed spontaneously fall apart, liberating the corresponding enantiomer of twisted-cyclooctene singlet (R)- or (S)-^{1}p, which in turn decays specifically to (R)- or (S)-1E.

Logically, the quenching by (R)- or (S)-1E and/or the relaxation from the Franck–Condon exciplex [1Z···^{1}S*] may be enantiodifferentiating, and no route is available for the direct conversion between (R)- and (S)-1E. Experimentally, these possibilities can be discriminated unequivocally by observing conversion dependence of the optical yield in the photoisomerization of pure 1Z or by attempting photosensitized kinetic resolution of racemic 1E. Both experiments were carried out; the former experiment gave constant optical yields over a wide range of conversion from initial to photostationary state, and the latter attempt resulted in no appreciable kinetic resolution (Table I). These results jointly manifest that not the quenching of chiral sensitizer but the rotational relaxation in the exciplex is responsible for this highly enantiodifferentiating photoisomerization. The fluorescence quenching study provides the definitive evidence for the mechanism proposed above. As shown in Table VI, the quenching of fluorescence from some benzenetetracarboxylates by 1Z and 1E occurs at nearly diffusion-controlled rate around 10^{10} s^{-1}, which is compatible with the observed negligible enantiodifferentiation in the quenching process.

Enantiodifferentiating Site. It is intriguing to pinpoint the specific site of sensitizer that interacts closely

with the cyclooctene moiety in the encounter complex. The semiempirical MO calculation (Figure 6) indicates that a positive overlap of wave function may occur between the aromatic C2–C3 or, less extensively, the carboxylic C=O bond of excited benzoate and the double bond of 1. The MM2 calculation on (–)-menthyl benzoate in the ground state (Figure 7) indicates that the (–)-menthyl moiety creates sidedness about the benzene-ring plane. If this sidedness is maintained in the excited benzoate at least around the carboxyl moiety as indicated by the MO calculation and if a cyclooctene molecule approaches from the open side to form an exciplex, then the interaction at the carboxylic C=O, rather than aromatic C2–C3, bond with the π bond of 1 appears to assure greater steric interaction between menthyl and cyclooctene moieties, judging from the qualitative examinations with CPK space-filling molecular models. However, no definitive conclusions can be derived from these calculations alone.

The comparative photosensitizations with chiral dimenthyl and hemichiral menthyl methyl esters of phthalic and terephthalic acids offer a more clear-cut basis for the specification of interacting site. As shown in Tables II and III and Figure 3, the replacement of one (–)-menthyl group of dimenthyl terephthalate (5) by an achiral methyl halves the optical yield of 1E at all temperatures examined. Consequently, the differential activation enthalpy ($\Delta\Delta H^*_{S-R}$) is also halved for the hemichiral terephthalate, since the differential activation entropy ($\Delta\Delta S^*_{S-R}$) is very small for both esters; see Table IV. This result reveals that each alkoxycarbonyl group in terephthalate acts as a completely independent site and the carboxylic C=O bond is likely to interact with 1 in the encounter complex. The interaction at the C=O bond may justify the drastic decreases in optical yield caused, for example, by apparently minor structural alteration from menthyl to isomenthyl or neomenthyl in the benzoate series (runs 1–3 in Table II) and the insensitiveness to the bulkiness of the para substituent, i.e., methyl or *tert*-butyl, in the 4-alkylbenzoate series (runs 10 and 11 in Table II).

In contrast, the ortho-substituent effect is most dramatically visualized in the photosensitization with the chiral and hemichiral phthalate 3. Lacking one chiral (–)-menthyl group, the hemichiral mixed phthalate still affords almost comparable or even higher optical yields (Tables II and III) and slightly greater differential activation parameters ($\Delta\Delta H^*_{S-R}$ and $\Delta\Delta S^*_{S-R}$), as compared with dimenthyl phthalate (Figure 3 and Table IV). This indicates that the two alkoxycarbonyl groups at ortho position do not behave as mutually independent chiral sites but rather act cooperatively like a single chiral group as a whole. A similar situation must be encountered with the other o-benzenepolycarboxylates 8 and 9 as well as the ortho-substituted benzoates, and the apparently curious ortho effect may be rationalized by this specific interaction between the neighboring groups.

Temperature-Switching of Product Chirality. In spite of the inherent advantage of photochemical reactions executable in principle at any temperature, the temperature dependence of asymmetric photoreactions has occasionally been examined at a few temperatures only to confirm the tacit understanding: optical yield increases with lowering temperature.[3,28–31] These fragmentary observations imply that the optical yield, or the difference

(25) (a) Irie, M.; Yorozu, T.; Hayashi, K. *J. Am. Chem. Soc.* 1978, *100*, 2236. (b) Yorozu, T.; Hayashi, K.; Irie, M. *J. Am. Chem. Soc.* 1981, *103*, 5480.

(26) Avnir, D.; Wellner, E.; Ottolengi, M. *J. Am. Chem. Soc.* 1989, *111*, 2001.

(27) Rau, H.; Ratz, R. *Angew. Chem., Int. Ed. Engl.* 1983, *22*, 550.

(28) Seebach, D.; Oei, H.-A.; Daum, H. *Chem. Ber.* 1977, *110*, 2316.

(29) Jarosz, S.; Zamojski, A. *Tetrahedron* 1982, *38*, 1447.

(30) Boyd, D. R.; Campbell, R. M.; Coulter, P. B.; Grimshaw, J.; Neill, D. C. *J. Chem. Soc., Perkin Trans. 1* 1985, 849.

(31) Demuth, M.; Palomer, A.; Sluma, H.-D.; Dey, A. K.; Krüger, C.; Tsay, Y.-H. *Angew. Chem.* 1986, *98*, 1093.

in free energy of activation ($\Delta\Delta G^{\ddagger}$) for the asymmetric photoreaction, is governed predominantly by the differential enthalpy change of activation ($\Delta\Delta H^{\ddagger}$), while the differential entropy change of activation ($\Delta\Delta S^{\ddagger}$) plays a minor role. In this context, the present result that the direction of the product's optical rotation is inverted by changing irradiation temperature is unexpected and has no precedent at all.

As clearly proved by the conversion-independent optical yields, the negligible kinetic resolution of 1E, and the diffusion-controlled quenching of sensitizer fluorescence by 1E, the optical yield is determined exclusively by the relative rate of relaxation (k_S/k_R) within the exciplex as shown in Scheme II. According to the Arrhenius and Eyring equations, the relaxation rate constants for (S)- and (R)-isomers are expressed as in eqs 1 and 2. Then the

$$k_S = A_S \exp(-E_S/RT) =$$
$$(\kappa T/h)\exp(-\Delta H^{\ddagger}{}_S/RT + \Delta S^{\ddagger}{}_S/R) \quad (1)$$

$$k_R = A_R \exp(-E_R/RT) =$$
$$(\kappa T/h)\exp(-\Delta H^{\ddagger}{}_R/RT + \Delta S^{\ddagger}{}_R/R) \quad (2)$$

natural logarithm of the relative rate is given by eq 3.

$$\ln(k_S/k_R) = -(E_S - E_R)/RT + \ln(A_S/A_R)$$
$$= -(\Delta H^{\ddagger}{}_S - \Delta H^{\ddagger}{}_R)/RT + (\Delta S^{\ddagger}{}_S - \Delta S^{\ddagger}{}_R)/R \quad (3)$$

As exemplified in Figures 1–3, the plots of $\ln(k_S/k_R)$, or $\ln[(100 + \% \text{ ee})/(100 - \% \text{ ee})]$, against reciprocal temperature give excellent straight lines without showing any sign of bending or curvature over the wide temperature range employed, in spite of the apparent switching of the product chirality in several cases. This means that single mechanism is operative in this enantiodifferentiating photoisomerization throughout the temperature range employed.

The differential activation parameters thus obtained are critical functions of the electronic and stereochemical structures of the chiral sensitizers. The most crucial finding is that, essentially in all cases, the differential entropy change of activation $\Delta\Delta S^{\ddagger}{}_{S-R}$ is not 0 or, synonymously, the relative frequency factor A_S/A_R deviates substantially from unity. As can readily be understood from eq 3 and the plots, these nonzero differential entropies of activation, or unequal frequency factors, are solely responsible for the temperature-switching of product chirality. It is emphasized that the temperature-switching phenomenon is specifically remarkable with the ortho-substituted benzene(poly)carboxylates such as salicylate 2 (R = 2-OH), phthalates 3, 1,2,4,5-benzenetetracarboxylates 8, and benzenehexacarboxylates 9.

The much larger $\Delta\Delta H^{\ddagger}{}_{S-R}$ and $\Delta\Delta S^{\ddagger}{}_{S-R}$ values for the ortho-substituted benzenecarboxylates mean that, in the enantiodifferentiating relaxation from the Franck–Condon exciplex [1Z···1S*] to the diastereomeric exciplex pair [(R)/(S)-1p···S*], the two transition states are differentiated in energy and structure to a much greater extent than those encountered with the chiral sensitizers lacking ortho substituent(s). In elucidating the origin of this specific behavior of ortho-substituted benzenecarboxylates, it may be interesting to review the unusual dual fluorescence behavior of sterically congested benzenehexacarboxylates.[12] Interestingly, bulky hexa-*tert*-butyl, hexamenthyl, hexabornyl, and hexaadamantyl benzenehexacarboxylates 9 exhibit unequivocal dual fluorescence peaks, whereas the least-bulky methyl ester shows ordinary single fluorescence even at −125 °C and the isopropyl ester becomes dual-fluorescent only at low temperatures. This novel steric hindrance-induced dual fluorescence is attributed to the
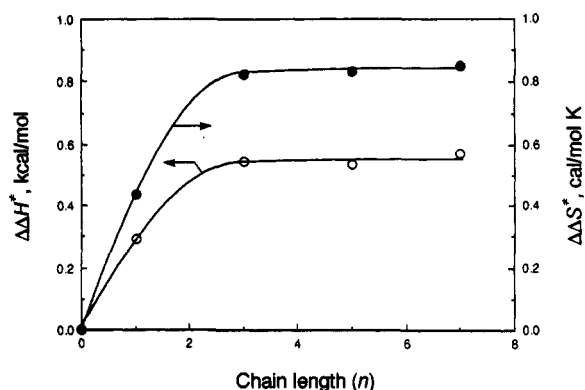

Figure 8. Differential enthalpy (O) and entropy (●) changes of enantiodifferentiating photoisomerization of cyclooctene as functions of methylene chain length (n) in R = $CH_3CH(CH_2)_nCH_3$.

restricted rotational relaxation of the bulky alkoxycarbonyl groups in the excited state.[12b] The corresponding benzenetetracarboxylates 8 never show dual fluorescence, probably because the rotational relaxation in the excited state is much facilitated in less-congested 8. In the present photoisomerization via exciplex, it is likely that the presence of cyclooctene, located in close proximity to the sensitizer in the exciplex, inevitably adds extra barrier to the relaxation of sensitizer, with which the rotational relaxation of cyclooctene-producing (S)/(R)-1p synchronizes. This simultaneous and correlated relaxation, specific to the ortho-substituted benzenecarboxylates, may lead to more dynamic structural changes, differentiating greatly the transition states to (R)- and (S)-1p.

The temperature-dependence study clearly demonstrates that the widespread hypothesis that "lowering temperature leads to higher optical yield" is not always true. This hypothesis holds only when the structural difference between the diastereomeric transition states is insignificant and therefore the entropies of activation, or the frequency factors, are approximately the same, although the optical yield will be low in such cases. It should be emphasized also that the temperature-switching of product chirality is not an anomalous phenomenon but a logical consequence of the nonzero activation entropy difference. Hence, one clever and widely applicable strategy for designing sensitizers of high enantiodifferentiability is to introduce neighboring substituent(s) which interact with each other.

Steric Effects. For a more quantitative view of the sensitizer–substrate interaction in the exciplex, the steric effect was systematically investigated. We employed a series of optically active tetraalkyl benzenetetracarboxylates 8 with varying chain length or bulkiness; two sets of sensitizers with different types of 1-methylalkyl group, i.e., R = $CH_3CH(CH_2)_nCH_3$ (n = 1, 3, 5, and 7) and R = CH_3CHR' (R' = Et, *i*-Pr, and *t*-Bu), were examined to give the activation parameters shown in Table IV (entries 18–20 and 24–26). In Figures 8 and 9, the $\Delta\Delta H^{\ddagger}$ and $\Delta\Delta S^{\ddagger}$ values obtained are plotted against the chain length (n) or the Eliel's A value[32] for R' as a measure of bulkiness.

The activation parameters were critical functions of the chain length and bulkiness and provide valuable insights into the steric interaction in the exciplex and the subsequent relaxation process. As can be seen from Figure 8, both activation parameters behave quite similarly; they show rapid rise with increasing differential chain length up to $n = 3$ and then level off beyond 3, approaching the ultimate values of $\Delta\Delta H^{\ddagger}{}_{S-R}$ = 0.6 kcal/mol and $\Delta\Delta S^{\ddagger}{}_{S-R}$

(32) Eliel, E. L. *J. Chem. Educ.* **1960**, *37*, 126.

= 0.9 cal/mol K. This changing profile clearly indicates that the extra methylene group(s) ($n > 3$) are out of the reach of the cyclooctene moiety during the relaxation in the encounter complex. Since the 1-methylpentyl group possesses the critical differential chain length ($n = 3$), the interacting distance in the exciplex may be estimated as ca. 4 Å from its effective chain length. Hence, in designing more enantiodifferentiating sensitizers, it is important that the simple chain elongation in 1-methylalkyl is a useful strategy only up to $n = 3$.

On the other hand, the bulkiness of the branch R' in 1-methylalkyl (R = CH_3CHR') works in a somewhat different manner. As shown in Figure 9, both activation parameters $\Delta\Delta H^{\ddagger}_{S-R}$ and $\Delta\Delta S^{\ddagger}_{S-R}$ show an abrupt jump for R' = Et and subsequent gradual increases for R' = i-Pr and t-Bu. In contrast to the chain extension discussed above, no apparent saturation is seen in the parameters with increasing bulkiness of the branch R' at least up to *tert*-butyl. However, this result may not particularly be curious, since these bulky branches are regarded as 1- or 1,1-disubstituted ethyls and therefore their formal differential chain length (n) is just one. One promising extension of the present strategies of increasing chain length and bulkiness of branch R' in 1-methylalkyl (R = CH_3CHR') is to design a sensitizer possessing a highly bulky substituent R' with formal chain length (n) of 3: possible candidates for the branch R' include 1-adamantyl and various bulky trialkylmethyl groups.

Enthalpy–Entropy Compensation. Figures 8 and 9 show quite similar profiles for $\Delta\Delta H^{\ddagger}_{S-R}$ and $\Delta\Delta S^{\ddagger}_{S-R}$, indicating a compensatory relationship between them. It is interesting to expand the scope of Leffler's isokinetic relationship, originally proposed for the ground-state chemistry[33,34] to the enantiodiffrentiating photochemical reaction.

In Figure 10, all $T\Delta\Delta S^{\ddagger}$ values obtained ($T = 298$ K) are plotted against the $\Delta\Delta H^{\ddagger}$ values to afford an excellent linear relationship (correlation coefficient 0.987). Judging from the very little deviation from the straight line, no drastic change is expected to occur in the enantiodifferentiation mechanism, although the switching of product chirality is caused by temperature change. The linear relationship means that the change in $T\Delta\Delta S^{\ddagger}$ is proportional to that in $\Delta\Delta H^{\ddagger}$, which leads to empirical expression 4 and its integrated form (eq 5), where γ and $T\Delta\Delta S^{\ddagger}_0$ refer

$$T\delta(\Delta\Delta S^{\ddagger}) = \gamma\delta(\Delta\Delta H^{\ddagger}) \tag{4}$$

$$T\Delta\Delta S^{\ddagger} = \gamma\Delta\Delta H^{\ddagger} + T\Delta\Delta S^{\ddagger}_0 \tag{5}$$

to the slope and the intercept, respectively. Equation 5 indicates that the entropic change consists of two terms, one of which is proportional to the enthalpic change and the other independent of it. Insertion of eq 4 into the differential form of the Gibbs–Helmholtz equation 6 gives eq 7. It is shown that the enthalpy–entropy compensation effect in the enantiodifferentiating photoisomerization is synonymous with the enthalpic control of the optical yield.

$$\delta(\Delta\Delta G^{\ddagger}) = \delta(\Delta\Delta H^{\ddagger}) - T\delta(\Delta\Delta S^{\ddagger}) \tag{6}$$

$$\delta(\Delta\Delta G^{\ddagger}) = (1 - \gamma)\delta(\Delta\Delta H^{\ddagger}) \tag{7}$$

The enthalpy–entropy compensation is not unrealistic in the present case. It is likely that, as the steric hindrance in the encounter complex becomes larger as a consequence

of, for example, the increased bulkiness, the stability difference between the two diastereomeric transition states that afford the corresponding diastereomeric exciplex pair [$(R)/(S)$-^{1}p···S*] increases, while the more stabilized transition state inevitably accompanies more fixed structure. Consequently, the overall change in $\Delta\Delta G^{\ddagger}$ tends to be smaller than might be expected from the change in either $\Delta\Delta H^{\ddagger}$ or $T\Delta\Delta S^{\ddagger}$. As can be seen from eq 7, the slope γ is a quantitative measure of the extent of this entropic canceling effect. The present slope (γ) of 0.45 means that only a proportion (55%) of the increment in $\Delta\Delta H^{\ddagger}$ contributes to raise $\Delta\Delta G^{\ddagger}$ or the optical yield.

Conclusions

The chirality transfer and multiplication through photosensitization has been attempted by several groups in these 25 years but proved to be very difficult in the fluid solution; the optical yields reported are low and the mechanistic details of enantiodifferentiation has not been revealed.[2] In the present study, we have demonstrated that the highly enantiodifferentiating photoisomerization of cyclooctene 1 can be achieved through the singlet photosensitization with chiral polyalkyl benzenepolycarboxylates, whereas the triplet sensitization with the corresponding chiral alkyl benzyl ethers leads only to minimal optical yields. The success of the singlet sensitization is attributed to the intimate sensitizer–olefin interaction in the enantiodifferentiating relaxation process within exciplex. In contrast to the efficient enantiodifferentiation in the fluorescence quenching of chiral 1,1'-binaphthyl with chiral amines,[25] the quenching of excited benzenepolycarboxylate by 1E occurs at the diffusion-controlled rate and is nonenantiodifferentiating in the present case. The exciplex emissions observed at different wavelengths upon fluorescence quenching by 1Z and 1E prove the intervention of an exciplex of different structure for each isomer. It is shown that the enantiodifferentiating photosensitization by hemichiral sensitizer is a useful tool for pinpointing the site of sensitizer–substrate interaction in the exciplex.

The unusual temperature-switching behavior of product chirality is attributed to the unequal frequency factors for the enantiodifferentiating relaxations of 1Z to (R)-^{1}p and to (S)-^{1}p within the exciplex, for which the synchronized and correlated structural changes in the relaxation process may be responsible. The phenomenon provides a unique, apparently paradoxical, approach for enhancing the optical yield by increasing the reaction temperature. It is emphasized that a simple comparison of optical yields at a given temperature is quite precarious in general or even hazardous in some cases, unless their temperature dependence has been examined. Another important consequence is that the frequently-adopted method for deducing/rationalizing the product stereochemistry or enhancing the optical yield, employing molecular models, is not always meaningful, since such kinds of examinations merely take into account the enthalpic factors arising from the steric interaction between substituents, with the entropic contribution being neglected frequently.

Experimental Section

General. Melting points were measured with a YANACO MP-21 apparatus and are uncorrected. Specific rotations were determined by using a Perkin-Elmer 243B polarimeter with a thermostated 10-cm cell. Mass spectra were taken on a JEOL AX-500 instrument. ^{1}H NMR spectra were recorded in chloroform-d or acetone-d_6 at 400 MHz on a JEOL GX-400 spectrometer. IR and UV spectra were obtained on a JASCO IR-810 and Ubest-50 spectrometer, respectively. CD spectra were obtained

(33) (a) Leffler, J. E. *J. Org. Chem.* **1955**, *20*, 1202. (b) Leffler, J. E.; Grunwald, E. *Rates and Equilibria of Organic Reactions*; Wiley: New York, 1963. Reprint edition from Dover Publishing: New York, 1989.

(34) Exner, O. *Correlation Analysis of Chemical Data*; Plenum: New York, 1988.
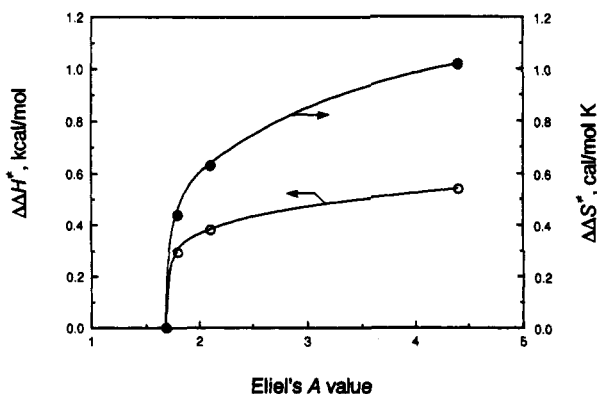
Figure 9. Differential enthalpy (O) and entropy (●) changes of enantiodifferentiating photoisomerization of cyclooctene as functions of Eliel's bulkiness factor (A) of R′ in R = CH_3CHR'.
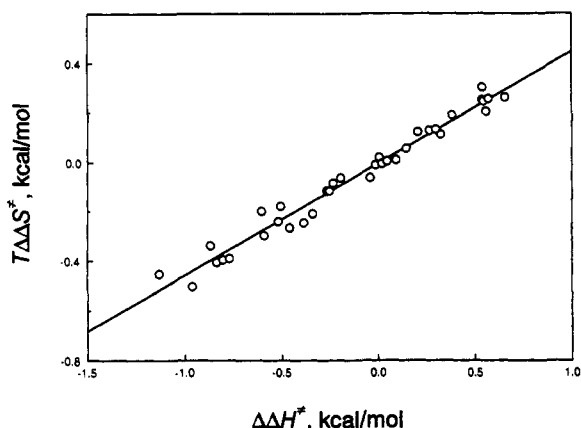

Figure 10. Enthalpy–entropy compensation effect observed in enantiodifferentiating photoisomerization of cyclooctene.

on a JASCO J-500 or J-720 instrument. Low-temperature spectra were taken at 25 to -90 °C in an Oxford cryostat DN-1704. GC analyses were performed on a 3-m packed column of 40% β,β'-oxydipropionitrile at 70 °C.

Materials. Hydrocarbon solvents were purified by treatment with concentrated sulfuric acid and subsequent fractional distillation. Acetonitrile was fractionally distilled from diphosphorus pentaoxide. Methanol was refluxed with magnesium turnings and distilled fractionally.

(Z)-Cyclooctene (Nakarai) was purified by silver nitrate treatment followed by fractional distillation. The purified sample contained 3–4% cyclooctane as the sole detectable impurity, which was employed as an internal standard in GC analysis but was completely free from the (E)-isomer or 1,3- and 1,5-cyclooctadiene. (E)-Cyclooctene of >99.5% purity was prepared by the sensitized photoisomerization of 1Z.[15]

Most optically active alcohols employed were commercially available: (-)-menthol and (+)-isomenthol from Kanto; (-)-borneol, (+)-isopinocamphenol, (+)-neomenthol, (+)-2-butanol, and (+)-2-octanol from Aldrich; (-)-cholesterol and (-)-2-octanol from Nakarai; (+)-cedrol and (+)-fenchol from Fluka; (-)-methyl lactate from Wako. (+)-1-Cyclohexylethanol was prepared by catalytic hydrogenation of (-)-1-phenylethanol (Nakarai) over 5% Rh/C in 1% acetic acid–methanol. (-)-2,4-Pentanediol and (-)-1,3-diphenyl-1,3-propanediol were prepared in asymmetric hydrogenations of the corresponding diketones over asymmetrically modified Raney nickel catalyst.[35] (+)-2-Hexanol and (+)-2-decanol were kindly supplied by T. Harada.[36] Optical resolutions of (+)-3-methyl-2-butanol[37] and (+)-3,3-dimethyl-2-butanol[38] were performed according to the reported procedures.

The chiral polyalkyl benzene(poly)carboxylates 2–8 and 4,4′-biphenyldicarboxylates 10 were prepared from the corresponding acid chlorides and optically pure alcohols in pyridine[12] and purified by distillation or recrystallization from ethanol. (-)-Hexakis-[1-(methoxycarbonyl)ethyl] benzenehexacarboxylate was prepared similarly from (-)-methyl lactate. The highly congested benzenehexacarboxylates 9 were synthesized in reactions of benzene-hexacarbonyl hexachloride with the corresponding potassium alkoxides in the presence of 18-crown-6.[12] The mixed esters 3 and 5 (R = (-)-menthyl, methyl) were synthesized by the esterification in pyridine of acid chlorides of respective hydrogen methyl esters.

Benzyl and p-xylylene (-)-menthyl ethers 11 and 12 were prepared from the corresponding chlorides and (-)-menthol. To a tetrahydrofuran suspension (150 mL) of sodium hydride (0.10 mol) was added (-)-menthol (0.11 mol) with stirring. The mixture was refluxed for 40 h under a nitrogen atmosphere and then cooled, benzyl chloride was added (0.10 mol), and the mixture was stirred for 6 h at room temperature. The residue obtained after workup was distilled in vacuo to give benzyl (-)-menthyl ether (70%): 135–136 °C/4 Torr.

Photolyses. All irradiations were conducted in a thermostated water (+50 to 0 °C) or methanol (-20 to -90 °C) bath. A solution containing 1Z or 1E (200 mM) and an optically active sensitizer (2–5 mM) was irradiated under an argon atmosphere in an annular quartz vessel (200–300 mL) or an immersion-well reactor (3 L), using a 30-W low-pressure mercury lamp fitted with a Vycor sleeve. After irradiation, 1E was extracted from the solution with three portions of 20% aqueous silver nitrate at 0 °C.[10a] The combined aqueous extracts were washed with three portions of pentane and then added dropwise into concentrated ammonium hydroxide at 0 °C to liberate 1E, which was in turn extracted with three portions of pentane. Upon evaporation of the solvent at a reduced pressure >150 Torr, a crude product was obtained and subjected to bulb-to-bulb distillation in vacuo to yield 1E of chemical purity up to 95–99% as determined by GC analyses; the major impurities detected were 1Z and pentane. ^{1}H NMR spectra of the isolated 1E did not show any trace of the chiral sensitizer used or the byproducts derived therefrom. Optical rotation of the isolated 1E was measured in methylene chloride, corrected for the purity, and compared with the literature value: $[\alpha]^{25}{}_D$ -426° (CH_2Cl_2).[39]

As shown in Table III (runs 35–41) as well as Table I, the optical yields were highly reproducible even at the low temperatures and for the different irradiation periods. It should be noted, however, that the suspension of less-soluble sensitizer in chilled solution obviously reduced the optical yield; see runs 4, 5, 8, 25, and 29 in Table III. In such a case, lower sensitizer concentrations were employed.

Supplementary Material Available: NMR and CD spectra of 8 (R = (-)-methyl) at 25 to -90 °C and physical, spectral, and analytical data for the optically active sensitizers (11 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

(35) Ito, K.; Harada, T.; Tai, A. *Bull. Chem. Soc. Jpn.* **1980**, *53*, 3367.
(36) Osawa, T.; Harada, T.; Tai, A. *J. Catalyst* **1990**, *121*, 7.
(37) Newman, P. *Optical Resolution Procedures for Chemical Compounds*; Optical Resolution Information Center, Manhattan College: New York, 1984; Vol. 3, p 68.
(38) Reference 36, p 100.

(39) Cope, A. C.; Ganellin, C. R.; Johnson, H. W., Jr.; Van Auken, T. V.; Winkler, J. S. *J. Am. Chem. Soc.* **1963**, *85*, 3276.