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Pressure control of enantiodifferentiating photoisomerization of cyclooctenes sensitized by chiral benzenepolycarboxylates. The origin of discontinuous pressure dependence of the optical yield

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Pressure effects on enantiodifferentiating geometrical photoisomerizations of (*Z*)-cyclooctene and (*Z*,*Z*)-cycloocta-1,5-diene sensitized by chiral benzene-1,2,4,5-tetracarboxylate were investigated over a pressure range of 0.1–750 MPa. Enantiomeric excesses (ee's) of the (*E*)- and (*E*,*Z*)-isomers obtained displayed discontinuous pressure dependencies, affording distinctly different differential activation volumes ($\Delta\Delta V^{\ddagger}$) for each range, indicating alteration of the enantiodifferentiation mechanism. The switching of $\Delta\Delta V^{\ddagger}$ occurred at essentially the same pressures of 200 and 400 MPa, which are shared by all the chiral sensitizers, irrespective of the chiral auxiliary employed. Circular dichroism spectral examinations at pressures of up to 400 MPa also revealed that the chiral sensitizers undergo discontinuous conformational changes at 200 MPa, which most likely lead to switching of the enantiodifferentiating sensitization mechanism in the exciplex intermediate.

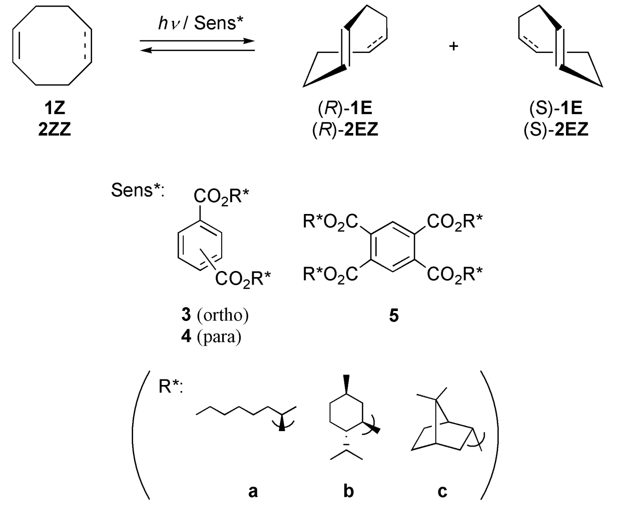
Introduction

Developing novel methodologies for efficiently preparing optically active compounds and also for critically controlling the product chirality and optical yield is a crucial target of current chemistry.[1–3] Among the asymmetric synthetic strategies hitherto proposed, asymmetric photosensitization is particularly unique, attractive and useful in view of the electronic state involved and the chirogen efficiency, as this method necessitates only a catalytic amount of chiral source, yet enabling us to transfer and multiply the molecular chirality of the chiral sensitizer to the prochiral substrate through excited-state interactions, and also to examine the effects of temperature over a much wider range than in thermal asymmetric synthesis.[4] It is noted that, in spite of the short-lived weak interactions in the excited state, fairly high enantiomeric excesses (ee's) of up to 77% were attained in the enantiodifferentiating photoisomerization of C_6–C_8 cycloalkenes sensitized by chiral (poly)alkyl benzene(poly)carboxylates.[5] Furthermore, some unprecedented phenomena unique to photochirogenesis were found to occur. Thus, the chiral sense of product was switched simply by changing the temperature (T),[5d–j] as well as the solvent,[5l] affording the antipodal enantiomers by using a single chiral sensitizer. Such unique chirality-inversion behavior was shown to originate from the critical counterbalance between the enthalpy and entropy factors in the enantiodifferentiation step occurring in the intervening diastereomeric exciplex. At low T's, the product ee, determined by the differential free energy of activation ($\Delta\Delta G^{\ddagger}$), is governed predominantly by the enthalpy term ($\Delta\Delta H^{\ddagger}$), whilst the entropy term ($T\Delta\Delta S^{\ddagger}$) dominates the ee at ambient and higher temperatures, thus rationalizing the temperature switching of the product chirality.[4,5]

We further demonstrated that the product ee is a vital function of pressure (P), which also leads to the switching of product chirality, in the enantiodifferentiating photoisomerization of (*Z*)-cyclooctene (**1*Z***) to the chiral (*E*)-isomer (**1*E***).[6] At least in the applied pressure range of 0.1–200 MPa (occasionally, up to 400 MPa), the pressure dependence of the relative rate constant (k_S/k_R), *i.e.* (100 + %ee)/(100 – %ee), for the formation of (*S*)- and (*R*)-**1*E*** at constant T was successfully analyzed by eqn. (1) to give the differential activation volume ($\Delta\Delta V^{\ddagger}_{S-R} = \Delta V^{\ddagger}_{S} - \Delta V^{\ddagger}_{R}$).

$$\ln(k_S/k_R)T = -(\Delta\Delta V^{\ddagger}_{S-R}/RT)P + \ln(k_S/k_R)_{P=0} \qquad (1)$$

In an attempt to further enhance the product ee and also to test the validity of eqn. (1), we performed the enantiodifferentiating photoisomerizations of **1*Z*** and (*Z*,*Z*)-cycloocta-1,5-diene (**2*ZZ***) at higher P's of up to 750 MPa (Scheme 1), and found an intriguing fact that the pressure dependence profile of the product ee is not uniform over the entire pressure range examined, but is undoubtedly discontinuous at specific pressures, resulting in a bent P–$\ln(k_S/k_R)T$ plot with distinctly different $\Delta\Delta V^{\ddagger}_{S-R}$ values in each pressure region.[7] In this study,



Scheme 1 Enantiodifferentiating photoisomerization of **1*Z*** and **2*ZZ*** sensitized by chiral sensitizers **3b**,**c** and **5a**–**c**.

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Table 1 Enantiodifferentiating photosensitization of **1*Z*** and **2*ZZ*** sensitized by chiral benzenepolycarboxylates **3b**,**c** and **5a**–**c** at various pressures in pentane at 25 °C[a]

Substrate	Sens*	*P*/MPa	Conversion[b] (%)	Yield[c] (%)	*E*/*Z* ratio	Ee[d] (%)	Ref.
1*Z*	**3b**	0.1	[e]	0.2	0.002	+7.9	[f]
		100	[e]	0.3	0.003	+5.5	[f]
		200	[e]	0.4	0.004	+3.0	[f]
		300	[e]	0.6	0.006	+1.5	[f]
		400	[e]	0.6	0.006	+0.3	[f]
	3c	0.1	[e]	0.4	0.004	+13.2	[f]
		100	[e]	0.6	0.006	+8.4	[f]
		200	[e]	0.6	0.006	+5.1	[f]
		300	[e]	1.0	0.009	+1.9	[f]
		350	[e]	0.9	0.009	+1.0	[f]
		400	[e]	1.0	0.009	+0.1	[f]
	5a	0.1	31	15	0.22	−3.8	[g]
		100	37	22	0.35	0.0	[g]
		200	43	26	0.46	+2.1	[g]
		300	[e]	9.7	0.048	+4.3	[f]
		400	[e]	5.5	0.034	+4.4	[f]
		485	[e]	4.8	0.055	+4.4	[f]
	5b	0.1	38	13	0.21	−11.2	[g]
		100	45	18	0.32	−3.6	[g]
		200	41	21	0.36	+5.7	[g]
		300	[e]	2.3	0.020	+12.4	[g]
		400	[e]	2.2	0.050	+17.9	[g]
		400	15.3	12.4	0.146	+19.2	[f]
		450	12.3	9.0	0.105	+19.9	[f]
		500	[e]	[e]	[e]	+18.9	[f]
		525	[e]	6.7	0.055	+21.0	[f]
		650	[e]	7.0	0.052	+23.1	[f]
	5c	0.1	39	19	0.31	+14.2	[g]
		100	41	20	0.34	+14.3	[g]
		200	46	23	0.43	+13.0	[g]
		300	[e]	7.1	0.065	+10.3	[f]
		400	[e]	6.6	0.045	+7.1	[f]
		500	[e]	3.2	0.021	+5.4	[f]
		650	[e]	7.0	0.035	+5.2	[f]
		750	[e]	4.0	0.034	+4.8	[f]
2*ZZ*	**5a**	0.1	16.4	3.6	0.044	−4.4	[f]
		100[h]	17.1	3.9	0.047	−0.7	[f]
		200	15.9	5.0	0.059	+2.3	[f]
		300	16.7	3.5	0.043	+4.2	[f]
	5b	0.1	15.7	3.3	0.039	−8.1	[f]
		100[h]	16.3	3.4	0.041	+3.8	[f]
		200	15.7	3.8	0.044	+13.5	[f]

[a] [**1*Z***] or [**2*ZZ***] = 5 mM; [**3b**,**c**] or [**5a**–**c**] = 1 mM; irradiation time = 60 min, unless noted otherwise. [b] Loss of starting material determined by GC. [c] Chemical yield determined by GC on the basis of the initial concentration of **1*Z*** or **2*ZZ***. [d] Enantiomeric excess determined by chiral GC. [e] Not determined. [f] This work and ref. 7. [g] Ref. 6. [h] Irradiation time = 30 min.

we wish to elucidate the origin of this discontinuous ee pressure dependence through close examination of the relationship between the enantiodifferentiating photosensitization behavior and the ground- and excited-state spectral behavior of chiral sensitizers under high pressure, using electronic absorption, fluorescence and circular dichroism (CD) spectroscopy.

Results and discussion

Photoisomerization

The enantiodifferentiating geometrical photoisomerizations of (*Z*)-cyclooctene (**1*Z***) and (*Z*,*Z*)-cycloocta-1,5-diene (**2*ZZ***) under pressure were effected by chiral polyalkyl *ortho*-benzenepolycarboxylate sensitizers, such as (−)-1-methylheptyl (**a**), (−)-menthyl (**b**), or (−)-bornyl (**c**) phthalates (**3**) and benzene-1,2,4,5-tetracarboxylates (**5**), which are known to give pressure-dependent product ee in the enantiodifferentiating photoisomerization of **1*Z***.[6] A pentane solution of **1*Z*** or **2*ZZ*** (5 mM) and a sensitizer (1 mM) was irradiated at 25 °C under a given *P* ranging from 0.1 to 750 MPa in a temperature-controlled high-pressure vessel. The irradiation period was fixed at 60 min, except for a couple of cases, since the product ee obtained in this enantiodifferentiating photoisomerization was reported to be practically independent of the conversion, at least up to 400 MPa.[6] Results of the enantiodifferentiating photosensitizations of **1*Z*** and **2*ZZ*** with **3b**,**c** and **5a**–**c** at different *P*'s of up to 750 MPa are summarized in Table 1, along with the previous data obtained with a different pressure vessel and a light source.[6]

The major course of the photoreaction was the geometrical isomerization to the chiral (*E*)-isomer, *i.e.* **1*E*** or **2*EZ***, even under high *P*'s, and no appreciable amount of volatile side product was detected by GC analysis. The chemical yields based on the consumed starting material were relatively high (50–80%) for **1*E*** and modest (20–30%) for **2*EZ*** upon sensitization with benzenetetracarboxylates **5a**–**c**. Under similar irradiation conditions, the sensitization of **1*Z*** with phthalate **3b**,**c** gave only low product yields (<1%) and *E*/*Z* ratios (<0.01), as reported earlier.[5] Note that direct comparison of the *E*/*Z* ratios obtained in the present and previous[6] studies could be misleading, since different pressure vessels were used and the irradiation conditions were not exactly the same.

Pressure effects on enantiodifferentiation

As can be seen from Table 1, the product ee is a critical function of the applied *P*. In extreme cases, the sense of product chirality was inverted within the pressure range employed to give the antipodal products. Thus, the photosensitization of **1*Z*** with **5b** gave levorotatory **1*E*** in 11% ee at 0.1 MPa, racemic **1*E*** at *ca.* 130 MPa (the "equipodal" pressure), and ultimately dextrorotatory **1*E*** in 23% ee at 650 MPa. This is not a special, but rather a general case, as the photosensitizations of **2*ZZ*** with **5a** and **5b** also exhibited a quite similar switching of the product chirality of **2*EZ*** within the experimental pressure range (0.1 to 300 MPa). This apparently striking switching behavior is reasonably accounted for in terms of the difference in activation volume between the transition states that lead to the (*S*)- and (*R*)-products. Provided that one of the two diastereomeric transition states (derived from the encounter complex of excited chiral sensitizer with substrate) is unfavorable in activation free energy (and hence gives the minor product at atmospheric *P*) but is more compact in volume than the antipodal one, then the relative contribution of this compact transition state to the final product gradually increases as the pressure increases, eventually switching the product chirality.[6]

As described above, the difference in activation volume ($\Delta\Delta V^{\ddagger}_{S-R}$) is quantitatively assessed from the *P* dependence of ee, by using eqn. (1). We therefore plotted the $\ln(k_S/k_R)$ values, calculated from the data shown in Table 1, as a function of *P* to find an unexpected result. As shown in Fig. 1, the $\ln(k_S/k_R)$ *versus P* plot obtained for each sensitizer–substrate combination does not give a single straight line but affords a bent line composed of two or three straight lines for all of the examined chiral sensitizer–substrate combinations. The $\Delta\Delta V^{\ddagger}_{S-R}$ values obtained for all the sensitizers at different pressure regions are listed in Table 2. This result clearly indicates that the $\Delta\Delta V^{\ddagger}_{S-R}$ value and hence the sensitizing species and enantiodifferentiating mechanism differ in each pressure region, even though the same chiral sensitizer is used. The solvent viscosity is significantly increased at high *P*'s, but the product ee was reported not to be appreciably affected by the solvent viscosity in this enantiodifferentiating photoisomerization, at least at atmospheric pressure.[5] In view of the discontinuity of the ee plot, it is unlikely that the pressure-induced change in viscosity, polarity or diffusion rate constant, each of which is a continuous variable, is responsible for this unusual behavior.

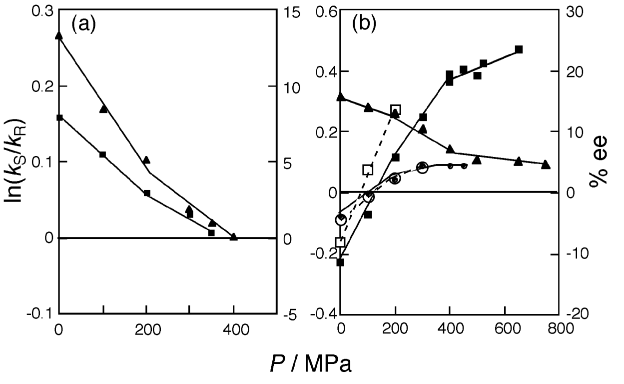

Fig. 1 Pressure dependence of the ee of **1*E*** and **2*EZ*** obtained upon the enantiodifferentiating photoisomerization of **1*Z*** or **2*ZZ*** sensitized by (a) phthalates **3b** (■) and **3c** (▲) and by (b) benzene-1,2,4,5-tetracarboxylates **5a** (●, ○), **5b** (■, □) and **5c** (▲) in pentane at 25 °C.

A close examination of Fig. 1 reveals that the bending points are common to all the chiral sensitizers and substrate employed, occurring at *ca.* 200 and 400 MPa. Hence, the structural variations in the chiral auxiliaries or the substrate structure cannot rationalize the discontinuous changes of product ee, but rather the *ortho*-benzenedicarboxylate moiety, shared by all sensitizers, is more likely to be responsible. In this connection, Slager *et al.* reported in their high-pressure Raman spectroscopic study that the ester moiety of simple alkyl benzoate folds into a compact structure at the transition pressure, accompanying a *discontinuous* change in the C=O stretching vibration.[8] A similar discontinuous structural change is also likely to occur in the benzenepolycarboxylates employed in this study, and could be the origin of the unusual pressure dependence of product ee. Therefore, we carefully investigated the electronic absorption, fluorescence and circular dichroism spectral behavior of the chiral benzenepolycarboxylate sensitizers at various *P*, by using a pressure vessel fitted with sapphire or birefringence-free diamond windows.

Table 2 Differential activation volumes ($\Delta\Delta V^{\ddagger}_{S-R}$) for different pressure regions obtained in the enantiodifferentiating photosensitization of **1*Z*** and **2*ZZ*** sensitized by chiral benzenepolycarboxylates **3b**,**c** and **5a**–**c** in pentane at 25 °C

Substrate	Sensitizer	*P*/MPa	$\Delta\Delta V^{\ddagger}_{S-R}$[a]/cm^3 mol^{-1}
1*Z*	**3b**	0.1–200	+1.22
		200–400	+0.67
	3c	0.1–200	+2.03
		200–400	+1.25
	5a	0.1–200	−1.46
		200–400	−0.57
		400–485	0.0
	5b	0.1–200	−4.20
		200–400	−3.23
		400–650	−1.07
	5c	0.1–200	+0.30
		200–400	+1.48
		400–750	+0.29
2*ZZ*	**5a**	0.1–200	−1.66
		200–300	−0.94
	5b	0.1–200	−5.38

[a] Differential volume of activation: $\Delta V^{\ddagger}_{S} - \Delta V^{\ddagger}_{R}$.

Absorption spectra under high pressure

First, we measured the UV spectra of the chiral sensitizers in pentane at 25 °C at $P = 0.1$ to 400 MPa (the practical limit of the pressure vessel and window materials). As shown in Fig. 2a, the absorbance of a pentane solution of sensitizer **5b** gradually increased on applying pressure, exhibiting a saturating tendency at higher *P*'s. However, this is not a real enhancement of the molar extinction coefficient (ε), but an apparent increase due to a compression of the solution and the accompanying increase of the solute concentration by *P*. The real UV spectra of **5b** at different pressures, which were corrected for the volume changes,[9] are shown in Fig. 2b. Although the pressure does not appear to alter the ε appreciably (particularly at the ^1L_b band around 290 nm), small steady bathochromic peak shifts are induced by applying pressure. This is probably due to the increased dielectric constant of pentane at high pressure.[9]

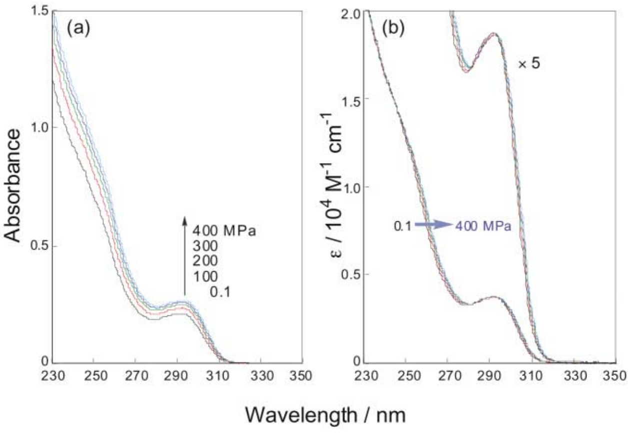

Fig. 2 UV-Vis absorption spectra of **5b** at varying pressures from 0.1 to 400 MPa in pentane at 25 °C; (a) apparent absorbance and (b) corrected molar extinction coefficient for the volume contraction of pentane at elevated pressures.

However, the total shift observed is too small (1.5 nm even at 400 MPa) to confidently discuss the discontinuity of its changing profile. The other benzenepolycarboxylates also gave almost the same ε's with small bathochromic shifts (≤1.5 nm) under pressures of up to 400 MPa. It is concluded therefore that the applied pressure does not cause any significant change in the aromatic–carbonyl conjugation system, at least up to 400 MPa.

Fluorescence spectroscopy under high pressure

Effect of pressure on the fluorescence behavior of the sensitizer was investigated in the presence and absence of substrate in pentane at 25 °C. The quantitative comparison of fluorescence intensity at different pressures is a somewhat tricky task, since the absorbance (A) at the excitation wavelength inherently increases with increasing P due to the volume contraction. In the fluorescence spectral measurements of **5b** at varying P, we employed an approximate correction method; *i.e.*, the fluorescence intensity (F_P) obtained at each P was simply divided by the relative absorbance ($A_P/A_{0.1}$) at the excitation wavelength (290 nm) in order to compensate for the apparent enhancement in A by the pressure-induced volume contraction. This correction seems reasonable, as we used a small cuvette of 2 mm path length and the absorbance of the sample solution was kept low at 290 nm (A = 0.4).[10] The corrected fluorescence spectra of **5b** thus obtained are shown in Fig. 3. The fluorescence maxima show only slight bathochromic shifts of ≤4 nm even at 400 MPa, for which the increase in dielectric constant can be responsible as was the case with the absorption spectra. As can be seen from Fig. 3a, the F_P of **5b** in the absence of **1*Z*** gradually increases with increasing P to give a 35% enhancement at 400 MPa. This enhancement is likely to be caused by the increased viscosities at high pressures as the fluorescence efficiency is enhanced in general in viscous solvents.[11]

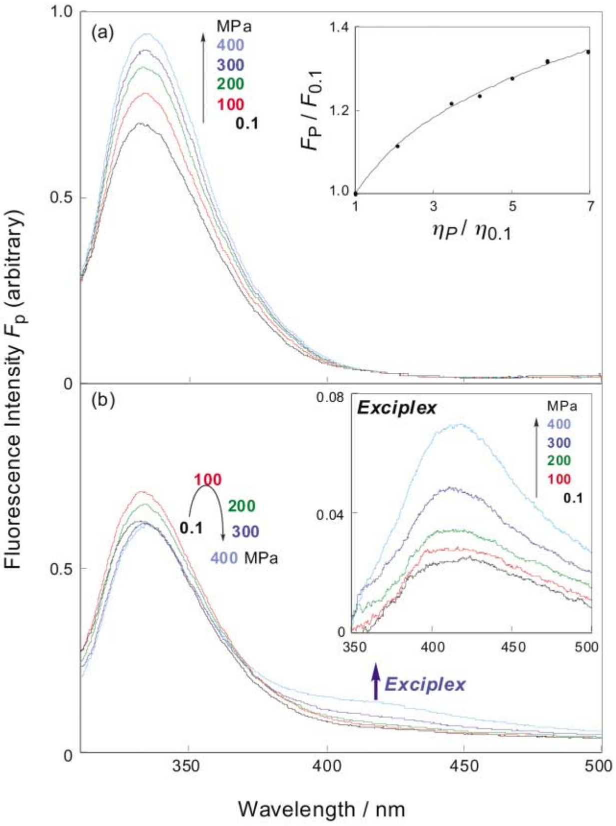

Fig. 3 Fluorescence spectra of **5b** (0.6 mM) excited at 290 nm at varying pressures of 0.1 to 400 MPa in pentane at 25 °C in the presence (lower traces) and absence (upper traces) of **1*Z*** (0.2 M), which are corrected for the volume contraction of pentane at elevated pressures. Plots of the relative intensity of fluorescence maxima *versus* the relative viscosity are shown in the inset of the top figure. Exciplex fluorescence obtained by spectral subtraction is shown in the inset of the bottom figure.

Fluorescence quantum yield (Φ) is related to the solvent viscosity (η) by the following equation:[11b,c]

$$\Phi \cong a\eta^x \qquad (2)$$

where a is a proportional coefficient and x the adjusting parameter specific to the fluorophore examined. Since the present fluorescence enhancement by pressure is considered to originate essentially from the viscosity change, the same relationship [eqn. (2)] was employed in the quantitative analysis. Thus, the fluorescence intensity at P relative to that at the atmospheric pressure is expressed by the following equation:

$$F_P/F_{0.1} = \Phi_P/\Phi_{0.1} = (\eta_P/\eta_{0.1})^x \qquad (3)$$

In Fig. 3a (inset), the $F_P/F_{0.1}$ ratio is plotted against the relative viscosity ($\eta_P/\eta_{0.1}$) calculated from the viscosity data[9] of solvent pentane at each pressure. By fitting the plotted data to eqn. (3), the x value was determined as 0.14. This small value would be rationalized by the large void volume of low-viscosity pentane.

In the presence of **1*Z***, the fluorescence behavior of **5b** under pressure became more complicated. As shown in Fig. 3b, the intensity of sensitizer fluorescence at 330 nm first increased until P = 100 MPa but then gradually decreased at higher P of up to 400 MPa, with an accompanying slight bathochromic shift. Such an apparently extraordinary changing profile of the fluorescence intensity is reasonably accounted for in terms of two conflicting effects. The applied pressure enhances both the sensitizer and exciplex fluorescence through the viscosity change as discussed above, but simultaneously increases the net concentration of **1*Z***, *via* volume contraction, leading to an increased quenching of sensitizer fluorescence and an enhancement of exciplex fluorescence. The net exciplex fluorescence spectrum can be obtained by spectrum subtraction between the normalized fluorescence spectra in the presence and absence of **1*Z*** at each pressure (Fig. 3b, inset). However, further quantitative examinations of the pressure dependence behavior of the sensitizer and exciplex fluorescence seem difficult, since we do not exactly know the pressure effects on the rates and efficiencies of quenching, non-radiative decay, fluorescence and other relevant processes. It is noted however that the fluorescence behavior observed does not display any apparent discontinuity over the entire pressure range examined. The peak shifts of sensitizer and exciplex fluorescence are too small to confidently discuss their discontinuities.

Circular dichroism spectroscopy under high pressure

As described above, the absorption and fluorescence spectral examinations did not give a direct clue as to the discontinuous pressure dependence of product ee. This may not be very surprising or disappointing, since these spectroscopies are less sensitive to the conformational changes in a non-chromophoric part of the molecule. For such a purpose, circular dichroism (CD) spectroscopy is more suitable, as even a minute conformational change at a peripheral position affects the chiroptical property of the chromophore. Hence, we employed a newly developed high-pressure vessel with birefringence-free diamond windows[12] in order to detect such conformational changes in a moiety peripheral to the chromophore, and the chiroptical behavior of the chiral sensitizer under pressure was investigated to elucidate the origin of the discontinuous pressure dependence of product ee.

Fig. 4 illustrates the CD spectral changes of **5b** at P = 0.1 to 400 MPa in pentane at 25 °C, in which the molar circular dichroism ($\Delta\varepsilon$) is corrected for the pressure-induced volume contraction of the solution, as described above. It is noted that

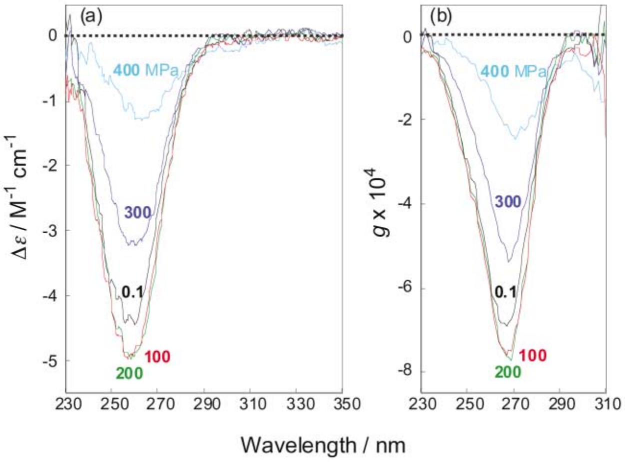

Fig. 4 (a) CD spectra and (b) anisotropy factor ($g = \varepsilon/\Delta\varepsilon$) of **5b** (0.3 mM) at pressures varying from 0.1 to 400 MPa in pentane at 25 °C, which are corrected for the volume contraction of pentane at elevated pressures.

only the major ^1L_a band at *ca.* 260 nm affords moderate CD signals, whilst the low-lying ^1L_b band is almost CD silent at all pressures examined. Intriguingly, the CD extrema ($\Delta\varepsilon_{ext}$) did not display a straightforward pressure dependence, which is obviously discontinuous in the pressure range examined, revealing an initial enhancement up to P = 200 MPa and a subsequent rapid decrease with small bathochromic peak shifts of *ca.* 5 nm at P = 400 MPa. Since the absorption coefficient ε is kept practically constant over the pressure range (Fig. 2), the CD spectral changes accurately reflect the features of the anisotropy factor ($g = \Delta\varepsilon/\varepsilon$) of this transition. Such a sudden change in the pressure dependence of the g factor clearly indicates that the orientation of the chiral auxiliaries towards the chromophore is switched at a transition pressure around 200 MPa.

Crucially, similar switching of the pressure dependence of Δε also occurs with the other chiral benzenetetracarboxylates (**5a**,**c**) and phthalates (**3b**,**c**) *at the same transition pressure*, as shown in Fig. 5. In sharp contrast, the CD spectrum of chiral terephthalate **4b** shows only a slow decrease in Δε, as was the case with **3** and **5** in the low pressure region, but no bending behavior at P = 200 MPa. This contrasting behavior indicates that the adjacent ester groups (not the whole –COOR but the specific –COO– moiety) at the *ortho* positions of **3** and **5** are directly related to the sudden changes of Δε as well as the product ee. Probably, a sudden transition from an extended to a compact folded conformation occurs in the ester moieties of **3** and **5** at the critical pressure, which is the origin of the discontinuous pressure dependencies of Δε and also of the product ee upon photosensitization.

Conclusions

From extensive examinations of the pressure effects on the photosensitized enantiodifferentiating isomerization of **1*Z*** and **2*ZZ*** to the corresponding (*E*)-isomers from 0.1 to 750 MPa, we found the unprecedented dependence of product ee on pressure, which affords an irregular P–$\ln(k_S/k_R)$ plot bent at 200 and 400 MPa. Such a discontinuous pressure dependence of the ee clearly indicates the intervention of distinctly different sensitizer/exciplex structures, as well as enantiodifferentiation mechanisms in the applied pressure range. In order to elucidate the origin of such an unusual pressure dependence of ee, the spectral behavior of the chiral benzenepolycarboxylate sensitizers was investigated at pressures 0.1–400 MPa. Although the electronic absorption and fluorescence spectra of chiral sensitizers/exciplexes showed simple and/or small continuous changes in peak position and intensity over the pressure range examined, the chiroptical properties of *ortho*-benzenepolycarboxylate sensitizers, measured by using the pressure vessel newly developed for CD spectral measurements, displayed clearly discontinuous changes at an identical pressure of 200 MPa for all the *ortho*-esters examined, irrespective of the chiral auxiliaries employed. It is concluded therefore that the chiral *ortho*-benzenepolycarboxylate sensitizers undergo a conformational transition to a more compact structure at the critical pressure, which is the origin of the discontinuous variations in product ee and chiroptical property. This pressure-induced switching behavior is not only new and interesting from the mechanistic point of view but also useful in a more general sense as a tool for controlling the rate and selectivity of photochemical, as well as thermal and enzymatic, enantio- and diastereo-differentiating reactions.

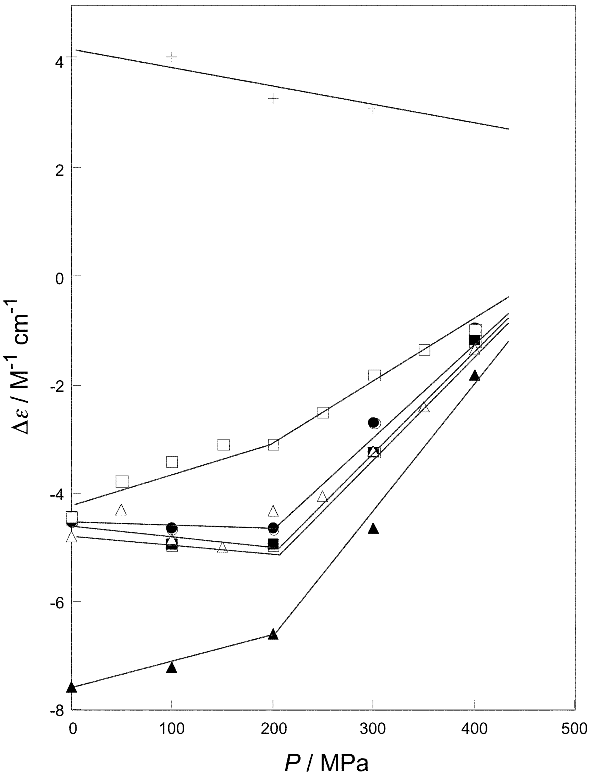

Fig. 5 Pressure dependence of the extreme of **3b** (□), **3c** (△) and **5a** (●), **5b** (■), **5c** (▲) and the maximum of **4b** (+) in CD spectra at varying pressure from 0.1 to 400 MPa in pentane at 25 °C.

Experimental

Materials

Pentane was stirred over concentrated sulfuric acid until the acid layer no longer turned yellow, washed with water, neutralized with aqueous sodium hydrogen carbonate, dried over sodium sulfate, and then fractionally distilled in the presence of sodium. (*Z*)-Cyclooctene **1*Z*** and (*Z*,*Z*)-cycloocta-1,5-diene **2*ZZ*** were purified by fractional distillation, and both were completely free of the (*E*)-isomers.

Optically active phthalates **3**, terephthalate **4** and benzene-1,2,4,5-tetracarboxylates **5** were prepared from the corresponding alcohols and acid chlorides and purified according to the procedures reported previously.[5]

Spectroscopy

Electronic absorption and circular dichroism spectra were recorded on a Shimadzu UV-3100PC spectrophotometer and a JASCO J-720WI spectropolarimeter, respectively. Fluorescence spectra were obtained with a Hitachi F-4500 spectrofluorimeter.

All spectroscopic measurements under high pressure were carried out by using a newly developed high-pressure vessel fitted with three optical windows made of sapphire or diamond with an effective aperture of 7 mm or 1 mm i.d., respectively (the apparatus was designed and manufactured by Teramecs Co., Kyoto). The window materials were sapphire for UV-vis and fluorescence spectroscopy and birefringence-free diamond for CD spectroscopy. A quartz inner cell (inside dimension 3 mm W × 2 mm D × 7 mm H) connected to a short flexible Teflon tube (for adjusting the volume change under pressure) was filled with a sample solution and the top end of the tube was stoppered, and the whole cell was placed inside the pressure vessel. The vessel was fixed in the sample chamber of the spectrometer and a set hydrostatic pressure of up to 400 MPa was applied.

Photolysis

Photosensitization experiments were conducted in a high-pressure vessel HKP-921208 (designed and manufactured by Hikari Koatsu Co., Hiroshima), which was equipped with a sapphire window (5 mm i.d.) for external irradiation and a coolant circulation system in the body of the reactor. A solution (11 cm^3) of **1*Z*** or **2*ZZ*** (5 mM), containing optically active sensitizer **3b**,**c** or **5a**–**c** (1 mM) and cycloheptane (1 mM) added as an internal standard for GC analysis, was introduced to the vessel and pressurized up to 750 MPa with a high-pressure pump KP5B (Hikari Koatsu). The solution was irradiated at wavelengths >220 nm for 30 or 60 min with a 250 W ultra-high pressure mercury lamp (Ushio UI-501C or a similar Wacom lamp for the irradition with **3**) fitted with a Vycor filter and a 5 cm cylindrical quartz vessel filled with water (to eliminate infrared radiation), keeping the vessel temperature at 25 °C. The collimated radiation from the lamp was focused with a quartz lens (f 16.5 cm) just before the front surface of the sapphire window, allowing efficient irradiation.

The irradiated solution was retrieved from the vessel and subjected to capillary GC analysis on a PEG-20M column (0.25 mm Φ × 20 m) for determination of the conversion, chemical yield and *E*/*Z* ratio. The product ee was determined by chiral GC using a Supelco β-DEX 225 column (0.25 mm Φ × 30 m) after selective extraction of **1*E*** or **2*EZ*** from the photolyzate with aqueous silver nitrate solution, as described previously.[5]

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References

1 For the historical background, see: (*a*) H. B. Kagan and J. C. Fiaud, *Top. Stereochem.*, 1978, 10; (*b*) H. Rau, *Chem. Rev.*, 1983, **83**, 535; (*c*) Y. Inoue, *Chem. Rev.*, 1992, **92**, 741.
2 For a more recent review, see: S. R. L. Everitt and Y. Inoue, in *Molecular and Supramolecular Photochemistry*, ed. V. Ramamurthy and K. Schanze, Marcel Dekker, New York, 1999, vol. 3, p. 71.
3 For recent reviews on asymmetric photochemistry in the solid state: (*a*) B. L. Feringa and R. A. van Delden, *Angew. Chem., Int. Ed.*, 1999, **38**, 3418; (*b*) Y. Ito, in *Molecular and Supramolecular Photochemistry*, ed. V. Ramamurthy and K. Schanze, Marcel Dekker, New York, 1999, vol. 3, p. 1.
4 (*a*) Y. Inoue, T. Wada, S. Asaoka, H. Sato and J.-P. Pete, *Chem. Commun.*, 2000, 251; (*b*) Y. Inoue, N. Sugahara and T. Wada, *Pure Appl. Chem.*, 2001, **73**, 475.
5 (*a*) Y. Inoue, Y. Kunitomi, S. Takamuku and H. Sakurai, *J. Chem. Soc., Chem. Commun.*, 1978, 1024; (*b*) Y. Inoue, S. Takamuku, Y. Kunitomi and H. Sakurai, *J. Chem. Soc., Perkin Trans. 2*, 1980, 1672; (*c*) S. Goto, S. Takamuku, H. Sakurai, Y. Inoue and T. Hakushi, *J. Chem. Soc., Perkin Trans. 2*, 1980, 1678; (*d*) Y. Inoue, Yokoyama, N. Yamasaki and A. Tai, *Nature*, 1989, **341**, 225; (*e*) Y. Inoue, T. Yokoyama, N. Yamasaki and A. Tai, *J. Am. Chem. Soc.*, 1989, **111**, 6480; (*f*) Y. Inoue, H. Shimoyama, N. Yamasaki and A. Tai, *Chem. Lett.*, 1991, 593; (*g*) Y. Inoue, N. Yamasaki, T. Yokoyama and A. Tai, *J. Org. Chem.*, 1992, **57**, 1332; (*h*) Y. Inoue, N. Yamasaki, T. Yokoyama and A. Tai, *J. Org. Chem.*, 1993, **58**, 1011; (*i*) Y. Inoue, N. Yamasaki, H. Shimoyama and A. Tai, *J. Org. Chem.*, 1993, **58**, 1785; (*j*) Y. Inoue, H. Tsuneishi, T. Hakushi and A. Tai, *J. Am. Chem. Soc.*, 1997, **119**, 472; (*k*) R. Hoffmann and Y. Inoue, *J. Am. Chem. Soc.*, 1999, **121**, 10702; (*l*) Y. Inoue, H. Ikeda, M. Kaneda, T. Sumimura, S. R. L. Everitt and T. Wada, *J. Am. Chem. Soc.*, 2000, **122**, 406; (*m*) S. Asaoka, H. Horiguchi, T. Wada and Y. Inoue, *J. Chem. Soc., Perkin Trans. 2*, 2000, 737; (*n*) S. Asaoka, M. Ooi, P. Jiang, T. Wada and Y. Inoue, *J. Chem. Soc., Perkin Trans. 2*, 2000, 77; (*o*) R. Saito, M. Kaneda, T. Wada, A. Katoh and Y. Inoue, *Chem. Lett.*, 2002, 860.
6 Y. Inoue, E. Matsushima and T. Wada, *J. Am. Chem. Soc.*, 1998, **120**, 10687.
7 M. Kaneda, S. Asaoka, H. Ikeda, T. Mori, T. Wada and Y. Inoue, *Chem. Commun.*, 2002, 1272.
8 V. L. Slager, H. Chang, Y. J. Kim and J. Jonas, *J. Phys. Chem. B*, 1997, **101**, 9774.
9 D. W. Brazier and G. R. Freeman, *Can. J. Chem.*, 1969, **47**, 893.
10 J. R. Lakowicz, in *Principles of Fluorescence Spectroscopy*, Plenum, New York, NY, 1983, p. 48.
11 (*a*) G. Oster and Y. Nishijima, *J. Am. Chem. Soc.*, 1956, **78**, 1581; (*b*) T. Förster and G. J. Hoffmann, *Z. Phys. Chem.*, 1971, **75**, 63; (*c*) R. O. Loutfy and B. A. Arnold, *J. Phys. Chem.*, 1982, **86**, 4205.
12 R. Hayashi, Y. Kakehi, M. Kato, N. Tanimizu, S. Ozawa, M. Matsumoto, S. Kawai and P. Pudney, *Trends High Pressure Biosci. Biotechnol.*, 2002, **19**, 583.