although the values are small compared to the Φ_d^{intra} values. The Φ_d^{inter} values for the samples from $n = 5$ to 12 are larger than those for the samples $n \leq 4$ and $n \geq 14$. The Φ_d^{inter} is expressed by the following equation.

$$\Phi_d^{inter} = (k_d^{inter}[DBA]/(k_n + k^{intra} + k^{inter}[DBA]))\Phi(triplet) \quad (12)$$

For the samples from $n = 5$ to 12, the k^{intra} values [$k^{intra} = (1-1.5) \times 10^4$ s^{-1}] are smaller than those for other compounds [$k^{intra} = (2-7) \times 10^4$ s^{-1}] as shown in Figure 6. Hence, the triplet lifetimes for the samples $5 \leq n \leq 12$ are longer than those for other compounds. Because of the longer lifetime, these samples $5 \leq n \leq 12$ have more chance to react with other DBA molecules intermolecularly than the other samples, and the Φ_d^{inter} values are higher in this region of chain lengths. The k_d^{inter} values estimated by eq 12 are almost constant: $(5-7) \times 10^6$ M^{-1} s^{-1} irrespective of the chain length. The chain length dependence of Φ_d^{inter} is a reflection of the triplet lifetime of these bichromophoric compounds.

In the present work, the highest ring-closure probability was estimated to be $n = 18$ by laser photolysis. This experimental fact was explained without taking into consideration the direction of the terminal bonds. On the other hand, the maximum quantum yield for the ring-closure reaction appears at a longer chain length, $n = 26$, because the terminal bonds must point in opposite directions to each other in order to take anti configuration. The chain length that yields the maximum quantum yield for the intrachain reaction shifts to chains longer than "the second peak" reported for other polymethylene systems. In the present reaction system, the steric factor of a pair of terminal groups must be considered in the examination of intramolecular reaction probability. It is concluded that the reaction yield of the intramolecular ring-closure reaction is determined by the equilibrium ring-closure probability of a molecular chain with a certain direction of terminal bonds.

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Binding Sites of Pyrene and Related Compounds and Chiral Excimer Formation in the Cavities of Cyclodextrins and Branched Cyclodextrins

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Abstract: Circular dichroism (CD) and circularly polarized fluorescence (CPF) spectra reveal the formation of the intermolecular dimer of pyrene having left-handed chirality and intramolecular dimers of 1,3-dinaphthylpropanes having right-handed chiralities in the γ-cyclodextrin cavity. These guest molecules are estimated to be bound to the relatively hydrophobic primary hydroxyl group side of the γ-cyclodextrin cavity, while the more hydrophilic secondary hydroxyl group side is the binding site of the chiral pyrene dimer in the 6-*O*-α-maltosyl-γ-cyclodextrin cavity because the narrower side of the cavity is capped by the maltosyl group. The pyrene dimer in the branched γ-cyclodextrin exhibits right-handed chirality.

One of the recent topics of cyclodextrin chemistry is utilization of cyclodextrins for chiral recognition,[1-4] enantioselective reactions,[5,6] asymmetric syntheses,[7-10] and separation of stereoisomers, diastereomers, and enantiomers.[11,12] Such research subjects are very interesting from the viewpoint of enzyme models and are important for developing the use of the cyclodextrins into new enzyme-mimetic reactions. In a previous paper, we reported the asymmetric formation of the pyrene excimer (or dimer) in cyclooctaamylose (γ-cyclodextrin, γ-CDx) cavity.[13] The present paper reports the formation of the chiral dimers of the achiral arenes as well as the binding sites of these arenes in the cyclodextrin cavities in greater detail.

It is known that a pyrene molecule binds to a cycloheptaamylose (β-cyclodextrin, β-CDx) molecule to form a 1:1 complex that exhibits only the pyrene monomer fluorescence,[14-21] while γ-CDx, with a larger cavity size, organizes the pyrene molecules in its cavity resulting in the observation of excimerlike fluorescence.[22-24] The stoichiometry of the pyrene–γ-CDx complex has not been clarified as yet.[25,26] Most of the studies concerning the pyrene–cyclodextrin complexes do not deal with the structures of the inclusion complexes in water. In order to understand the mechanism for formation of the chiral pyrene excimer in γ-CDx cavity, we have to know, at least, the binding site of the pyrene molecules in the cavity. In the present study, we first evaluated the binding

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sites of pyrene in the β- and γ-CDx cavities using circular dichroism (CD) spectroscopy and a fluorescence quenching technique. 6-*O*-α-Maltosylcycloheptaamylose (G2-β) and 6-*O*-α-maltosylcyclooctaamylose (G2-γ) played important roles in determination of the binding sites. In the second step, we studied the asymmetric formation of the arene dimers in the cyclodextrin cavities by means of CD, fluorescence-detected CD (FDCD), and circularly polarized fluorescence (CPF) spectroscopy.

Experimental Section

β- and γ-CDxs (Nakarai) were purchased and used without further purification. 6-*O*-α-Glucosylcycloheptaamylose (G1-β), G2-β, and G2-γ were prepared by the reactions of α-glucosyl fluoride and/or α-maltosyl fluoride with the corresponding cyclodextrins in the presence of pullulanase.[27] The sources and purification of pyrene,[16] 1,3-di-1-pyrenylpropane (P3P),[28] naphthalene,[16] and acenaphthene[29] were previously described. 1,3-Di-1-naththylpropane (α,α-DNP) and 1-(1-naphthyl)-3-(2-naphthyl)propane (α,β-DNP) were prepared according to the procedures described in the literature.[30] 1-Ethylpyrene (mp 94.7–95.3 °C) was prepared by the Wolf–Kishner reduction of 1-acetylpyrene.

The absorption and fluorescence spectra were measured with a Shimadzu UV-200S spectrophotometer and a Hitachi 650-60 spectrofluorometer (excitation and emission bandwidths, 2 nm). The CD and FDCD spectra were taken on a Jasco J-500A spectropolarimeter with a data processor. The optical arrangement and the filter system for measuring the FDCD spectra of the pyrene excimer were the same as those employed by Egusa et al.[31] A Jasco FCD-1F instrument was used to take the CPF spectra. The fluorescence decay curves were obtained by an Ortec-PRA single-photon counting apparatus and were analyzed by a Simplex method with an NEC 9801 microcomputer. The 400-MHz ^{1}H NMR spectra in D_2O were measured by a JEOL GX-400 spectrometer at 23 ± 0.5 °C. Sodium 3-(trimethylsilyl)-1-propanesulfonate (Merck) was used as an external standard for determining chemical shifts. Spectroscopic measurements were carried out at room temperature under aerobic conditions unless otherwise noted.

Results and Discussion

Binding Sites of Pyrene in the β-CDx and G2-β Cavities. Theoretical considerations predict the signs of the induced CD (ICD) of an achiral guest molecule in a chiral cyclodextrin cavity;[32,33] i.e., a positive ICD is observed when a transition dipole moment of the guest molecule is parallel to the C_n symmetric axis of cyclodextrin (axial complex), while a guest molecule having a perpendicular orientation (equatorial complex) shows a negative ICD. Pyrene shows an absorption spectrum including the ^1B_a, ^1B_b, ^1L_a, and ^1L_b transition bands. It is known that the ^1B_b transition of pyrene is polarized along the short axis, and the ^1L_a transition is the long-axis-polarized band.[34] An aqueous solution of pyrene (2×10^{-6} M) in the presence of β-CDx (1×10^{-2} M) showed a positive ICD at the ^1L_a transition ($[\theta] = 2.5 \times 10^3$ at 341 nm) and a negative one at the ^1B_b transition ($[\theta] = -5.8 \times 10^3$ at 272 nm), suggesting that the long axis of the pyrene molecule coincides with the C_7 symmetry axis of β-CDx. The Corey–Pauling–Koltum (CPK) molecular model suggests that the inner diameters of the narrower (primary OH side) and wider (secondary OH side) rings of a β-CDx toroid are 5.5–5.9 and 6.2–7.2 Å, respectively. Since a molecular dimension of pyrene is 9 Å × 11 Å, pyrene should be bound shallowly to the rim of the cyclodextrin cavity. The question is whether pyrene is located at the primary OH or the secondary OH side of the cyclodextrin molecule.

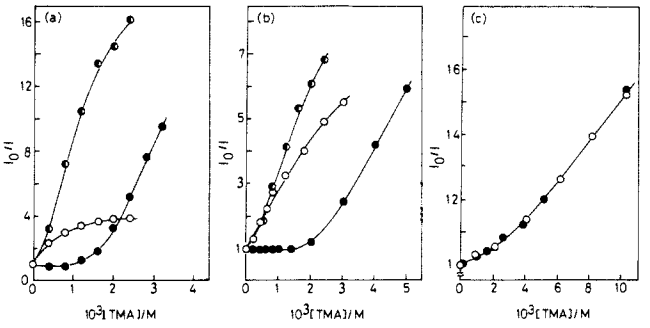

Figure 1. Stern–Volmer plots for the fluorescence quenching of (a) pyrene (2×10^{-6} M), (b) acenaphthene (1×10^{-5} M), and (c) naphthalene (1×10^{-5} M) by TMA in water containing β-CDx (○), G2-β (●), and G1-β (◐) (1×10^{-2} M).

The oppositely signed Cotton effects were measured for the pyrene–G2-β inclusion complex ($[\theta] = -3.8 \times 10^3$ at 337 nm, -2.8×10^3 at 322 nm, and $+2.2 \times 10^3$ at 276 nm). If the effect of the maltosyl group of G2-β on ICD is ignored, pyrene (2×10^{-5} M) is included in the G2-β (1×10^{-2} M) cavity to form an equatorial complex. In order to determine the effect of the maltosyl group, ICD was measured for acridine, which should be included completely into the β-CDx and G2-β cavities to form axial complexes, in a pH 9.0 Britton–Robinson buffer (0.04 M). Both acridine solutions of β-CDx and G2-β showed exactly the same ICD spectra at the wavelengths corresponding to the ^1L_a ($[\theta] = 910$ at 357 nm) and ^1L_b ($[\theta] = -720$ at 382 nm) transitions. It can be concluded, therefore, that the ICD of a guest molecule tightly included into the G2-β cavity is not affected by the maltosyl group. It may be reasonable to consider that the maltosyl group also does not affect the ICD of the guest molecule bound to the secondary OH side of G2-β. If pyrene is located in the vicinity of the maltosyl group, however, one cannot ignore a perturbation due to this substituent. Another approach is needed in order to estimate the structure of the pyrene–G2-β complex. We applied the fluorescence-quenching technique to solve this problem.

Significant acceleration effects by β-CDx have been known for the fluorescence quenching of pyrene, 1-methylnaphthalene, and acenaphthene by trimethylamine (TMA) in water, but not as effective for naphthalene.[16,29] The catalytic effect by β-CDx is realized for those complexes where the fluorescent guest molecules are bound shallowly to the β-CDx cavity, because an additional guest molecule such as TMA can penetrate into the remaining space in the cavity. Static quenching takes place for such fluorophore–quencher–β-CDx three-component complexes. When the guest molecule is included completely into the β-CDx cavity, however, no empty space remains in the cavity leading to inhibition or less effective acceleration or the fluorescence quenching by β-CDx. This is the case observed for naphthalene.[29]

Figure 1 shows the effects of β-CDx, G1-β, and G2-β on the fluorescence quenching of pyrene, acenaphthene, and naphthalene by TMA. The fluorescence quenching behaviors of the pyrene- and acenaphthene–G2-β systems are markedly different from that observed with β-CDx. Although the saturation-type Stern–Volmer plots were observed for β-CDx, the quenching reaction was completely inhibited by G2-β up to TMA concentrations of $(1–2) \times 10^{-3}$ M and, above these TMA concentrations, the quenching is dramatically accelerated by G2-β. In the case of naphthalene, however, no difference was observed between β-CDx and G2-β in the relatively slower fluorescence quenching. It is noteworthy that the novel effect of G2-β is realized in the fluorescence

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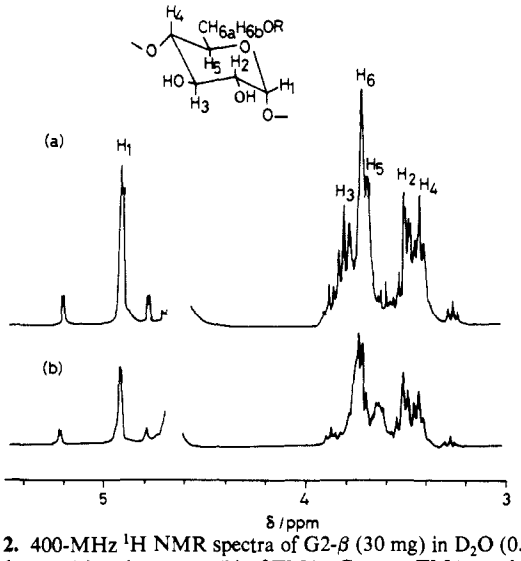

Figure 2. 400-MHz ^1H NMR spectra of G2-β (30 mg) in D_2O (0.9 mL) in the absence (a) and presence (b) of TMA. Gaseous TMA was bubbled into the D_2O solution of G2-β, and the concentration of TMA was not determined.

quenching of the guest molecules whose molecular sizes are too large to be included completely into the cavity. In order to explain the difference between β-CDx and G2-β on the fluorescence quenching of pyrene and acenaphthene, we presume that these guest molecules are bound preferentially to the more hydrophobic primary OH side of β-CDx, whereas they are present at the more hydrophilic secondary OH side of G2-β because the maltosyl group caps the ring of the primary OH side through hydrogen bonding. The CPK molecular model suggests several points where the hydrogen bonds between the G2-β ring and the maltosyl group are plausible. G1-β seems to be a key host molecule to evaluate such assumption. The interaction of the G1-β ring with the glucosyl group should be much weaker than is the case with G2-β. Indeed, no marked inhibition of the fluorescence quenching by G1-β was found at lower TMA concentrations, and G1-β was the most effective catalyst among three cyclodextrins (see Figure 1). The negative ICD signal at the wavelength corresponding to the ^1B_b transition of pyrene ($[\theta] = -1.9 \times 10^3$ at 272 nm) suggests the axial complex of pyrene and G1-β.

On the basis of the results of ICD and the fluorescence quenching studies, we can discuss the binding sites of pyrene in the β-CDx and G2-β cavities. The hydrophobic pyrene molecule seems to be bound to the primary OH side of β-CDx to form the axial complex. TMA can penetrate into the β-CDx cavity from the secondary OH side, giving the pyrene–TMA–β-CDx complex in which a static fluorescence quenching takes place. Meanwhile, since the primary OH side of G2-β is capped by the maltosyl group, pyrene is forced to bind to the more hydrophilic secondary OH side, giving the equatorial complex. Since the primary and secondary OH sides of the G2-β cavity are capped by the maltosyl group and pyrene, respectively, TMA cannot penetrate into the cavity of the pyrene-bearing G2-β at lower TMA concentrations. Under such circumstances, G2-β inhibits the fluorescence quenching. At higher TMA concentrations, however, the TMA molecules start to interact with the hydroxyl groups of the maltosyl group leading to cleavage of the hydrogen bond(s) between the maltosyl group and the cyclodextrin ring. The catalytic effect of an open form of G2-β thus generated seems to be the same as that of G1-β. The TMA molecules bound to the maltosyl or glucosyl group may participate in the acceleration of the fluorescence quenching via a proximity effect.

The 400-MHz ^1H NMR spectra were taken in D_2O to verify the conformational change of G2-β upon addition of TMA (Figure 2). The assignment of the NMR signals was performed by comparing the spectrum with that of β-CDx. The protons due to the maltosyl group of G2-β appeared at 3.5–4.0 ppm. In the absence of TMA, the H_6 protons of the glucopyranose residue of the cyclodextrin ring show a singlet signal. Of course, the doublet signal due to the H_6 protons was observed for β-CDx. The coalescence of the H_6 signals suggests the interaction of the primary OH group of the G2-β ring with the maltosyl group. Upon addition of TMA, all signals slightly shifted to lower magnetic fields and the H_6 protons appeared as the doublet line, suggesting that the interaction between the maltosyl group and the G2-β ring is weakened by TMA. Capping by the maltosyl group seems to be released by the addition of TMA. The signals due to the H_3 protons became obscure upon addition of TMA. The TMA molecules may be concentrated around the rim of the wider ring of G2-β by hydrogen bonding. The results of ^1H NMR are consistent with those of ICD and fluorescence quenching.

Binding Sites of Pyrene and Diarylpropanes in the γ-CDx and G2-γ Cavities. As in the case of γ-CDx,[13,22] pyrene (1×10^{-5} M) was solubilized in water by using G2-γ (5×10^{-3} M). The pyrene solution showed an excimerlike fluorescence with a maximum intensity at 470 nm along with the monomer fluorescence (λ_{max}^f = 372, 378, 382, 392, 414 nm). Although the fluorescence excitation spectrum of the pyrene–G2-γ complex solution followed at 470 nm was much broader than that of the pyrene–γ-CDx complex, no microcrystals were detected in this solution. As was previously described, the rise of the intensity of the excimerlike fluorescence is observed in the fluorescence decay curve of the pyrene–γ-CDx complex.[13] For the pyrene–G2-γ complex, however, no rise of the excimerlike fluorescence was detected by nanosecond time-resolved fluorometry. The structure of the pyrene dimer in the γ-CDx cavity seems to be somewhat looser than that in the G2-γ cavity.

P3P in organic solvents can form an intramolecular excimer whose fluorescence maximum is observed at 485 nm. P3P is so hydrophobic that it is insoluble in water and disperses as microcrystals.[35] The microcrystals of P3P show a broad fluorescence band around 482 nm. γ-CDx (1×10^{-2} M) could solubilize P3P (1×10^{-6} M) in water, and the fluorescence maximum shifted to 492 nm. The characteristic intense absorption band due to a stacked form of P3P was observed at 333 nm. The fluorescence emission and excitation spectra of P3P in aqueous G2-γ were completely different from that in the γ-CDx solution and were in good agreement with that in water. Filtration (0.5-μm pore size) caused the disappearance of the fluorescence, indicating no interaction of P3P with G2-γ. Similarly, α,α- and α,β-DNPs were not bound to G2-γ while these dinaphthylpropanes are included into the γ-CDx cavity in their stacked forms (vide supra). These inclusion phenomena can be explained by using the conclusion obtained for the β-CDx– and G2-β–pyrene complexes. The relatively more hydrophobic side of the γ-CDx cavity (primary OH side) prefers to include the very hydrophobic diarylpropanes. Only the secondary OH side of G2-γ, however, is a possible binding site because the narrower side of G2-γ is capped by the maltosyl group. Since the secondary OH side is too hydrophilic to interact with the diarylpropanes, these guest molecules disperse in water as microcrystals.

Chiral Excimers of Pyrene and 1-Ethylpyrene in the γ-CDx and G2-γ Cavities. In the previous communication,[13] we reported the formation of a chiral pyrene excimer in the γ-CDx cavity, which is detected by CPF measurement. CPF can detect the difference in intensities between left-handed circularly polarized fluorescence (I_L) and right polarized component (I_R).[36-39] Kuhn's dissymmetry factor g_{em} is defined as

$$g_{em} = 2(I_L - I_R)/(I_L + I_R)$$

Although there are numerous studies on CPF of chiral metal complexes,[36-39] few results have been reported on CPF of organic systems because of very weak CPF signals. Brittain has reported

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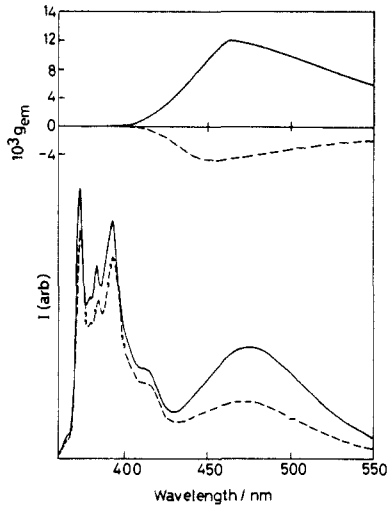

Figure 3. Fluorescence (bottom) and CPF spectra of pyrene in water containing γ-CDx (1×10^{-2} M, —) and G2-γ (5×10^{-3} M, ---). Pyrene was excited at the wavelength corresponding to the ^1L_a transition band. The concentrations of pyrene were 2×10^{-6} and 1×10^{-5} M for the γ-CDx and G2-γ systems, respectively.

the cyclodextrin-induced CPF of an achiral dye, fluorescein, the g_{em} value being quite small (ca. 6×10^{-4}).[40] One has to pay careful attention to possible artifacts due to partially linearly polarized fluorescence for high-sensitivity CPF measurements.[39] Relatively intense CPF signals ($|g_{em}| < 4 \times 10^{-3}$) have been measured for the excimer fluorescence of (+)- and (−)-1-(1-hydroxyhexyl)pyrenes in methanol.[41] The pyrene excimer formed in the γ-CDx cavity exhibits an extremely large g_{em} value (1.2×10^{-2}), while no detectable signal is observed at the wavelengths corresponding to the pyrene–monomer fluorescence.[13] Of course, CD spectroscopy can provide essentially important information on chiral complex formation in the cyclodextrin cavities. If two chromophores are simultaneously included in a cyclodextrin cavity to form a chiral complex, an exciton-coupling interaction causes a bisignated CD Cotton effect. The exciton-coupling theory predicts the chiralities of bichromophoric compounds. A compound having a left-handed chirality (*S* chirality) shows a bisignated CD with a negative sign at a longer wavelength region and a positive sign at a shorter wavelength region. An enantiomer having an *R* chirality shows an oppositely signed CD. Kobayashi et al. have reported briefly the bisignated Cotton effects for the dimers of acridine orange and pyrene in the γ-CDx cavity.[24,42] These dimers have the *S* chiralities. Recently, Lightner et al. measured the bisignated CD spectra of bilirubin IX_α in water containing α-, β-, and γ-CDxs and found that an enantiomer with the *S* chirality is preferentially bound to CDxs.[4] In the system were a chiral molecular complex is bound to cyclodextrin, the CD spectrum is expected to be considerably complex because of overlap of bisignated CD with normal ICD. This is the case for the pyrene–γ-CDx system. In the present study, we measured CD, FDCD, and CPF spectra to investigate the formation of the chiral dimers of pyrene.

Figure 3 shows the fluorescence and CPF spectra of the pyrene solutions in water containing γ-CDx and G2-γ. For CPF measurements, 1×10^{-5} M P3P in 1×10^{-2} M hexadecyltrimethylammonium chloride (HTAC) micellar solution was employed to take a base line, which was subtracted from the CPF signal of the sample. The fluorescence spectrum of P3P in the micellar solution was very similar to those of pyrene in the γ-CDx and G2-γ solutions.[43] In the HTAC micellar solution of P3P, no detectable CPF signal was observed at both wavelength regions corresponding

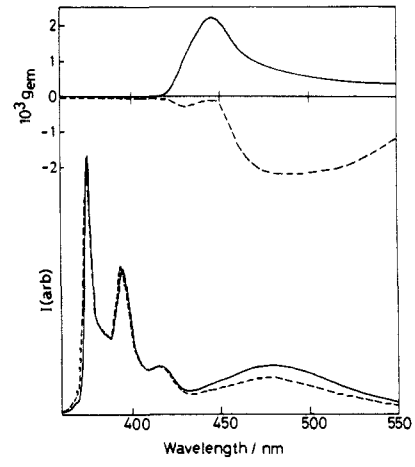

Figure 4. Fluorescence (bottom) and CPF spectra of 1-ethylpyrene in water containing γ-CDx (1×10^{-2} M, —) and G2-γ (5×10^{-3} M, ---). The concentrations of 1-ethylpyrene were 2×10^{-6} and 1×10^{-5} M for the γ-CDx and G2-γ systems, respectively.

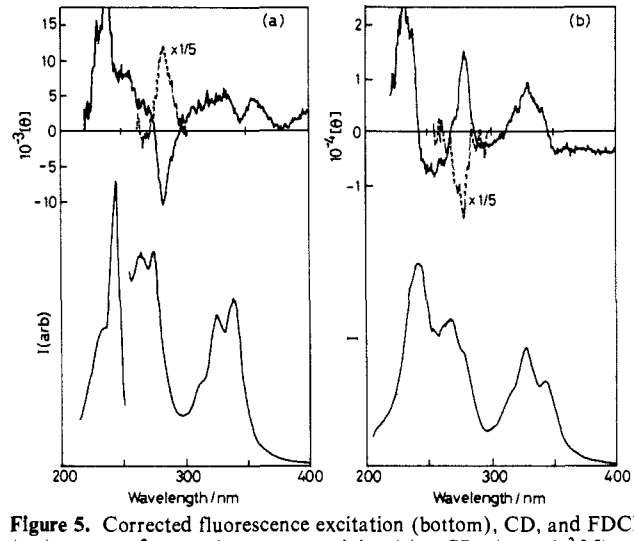

Figure 5. Corrected fluorescence excitation (bottom), CD, and FDCD (---) spectra of pyrene in water containing (a) γ-CDx (1×10^{-2} M) and (b) G2-γ (5×10^{-3} M). The concentrations of pyrene were 2×10^{-6} and 1×10^{-5} M for the γ-CDx and G2-γ systems, respectively. The excitation and FDCD spectra were taken by following the excimer fluorescence intensities.

to the monomer and intramolecular excimer emissions. As was reported previously,[3] the excimer fluorescence of pyrene in the γ-CDx solution is greatly polarized ($g_{em} = 1.2 \times 10^{-2}$). Very similar but considerably weak CPF spectra have been reported for *N*-acetyl-L-pyrenylalanine methyl ester (g_{em} = ca. 5×10^{-4}) in toluene and poly(L-pyrenylalanine) (g_{em} = ca. 1.5×10^{-3}) in dimethylformamide.[31] The g_{em} values for these inter- and intramolecular excimers of pyrene attached to the chiral amino acid and polyamino acid are much smaller than that for the γ-CDx system. Interestingly, an oppositely signed CPF signal was detected for the aqueous pyrene solution containing G2-γ ($g_{em} = -4 \times 10^{-3}$) (Figure 3). This CPF spectrum resembles that of *N*-acetyl-D-pyrenylalanine methyl ester in toluene.[31] The CPF spectra clearly indicate that the pyrene excimers formed in the γ-CDx and G2-γ cavities have opposite chiralities. Similar results were obtained for 1-ethylpyrene (Figure 4). In the case of 1-ethylpyrene–γ-CDx complex, however, the g_{em} value markedly decreased as longer wavelength. Presumably, an achiral dimer having its fluorescence maximum at longer wavelength is also included in the γ-CDx cavity. The fluorescence decay curve of the 1-ethylpyrene excimer is composed of three components: i.e., very fast rise ($\tau_1 < 1.5$ ns, 77%), slower rise ($\tau_2 = 15.3$ ns, 23%), and decay ($\tau_3 = 106.5$ ns). As in the case of the pyrene–γ-CDx complex,[13] most of the pyrene–dimer component forms the ex-

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cimerlike state immediately after excitation. Part of the dimer component, however, changes its configuration in the excited state to yield the excimer.

Unfortunately, the absolute configuration of the chiral pyrene dimer cannot be determined from CPF. Next, we measured the CD and FDCD spectra, which were compared with the corrected fluorescence excitation spectra followed at the wavelengths corresponding to the excimer emission. The results are shown in Figure 5. The excitation spectra correspond to the absorption spectra of the pyrene dimers in the γ-CDx and G2-γ cavities, in which the monomer component is excluded. The FDCD spectra were followed at wavelengths corresponding to the excimer fluorescence by using a solution filter (saturated aqueous $NaNO_2$ in a quartz cell with a 10-cm optical length). In both γ-CDx and G2-γ systems, no obvious bisignated Cotton effect was observed. In the pyrene–γ-CDx system, however, the wavelength (284 nm) at which the CD and FDCD peaks are observed does not fit with that of the excitation maximum (280 nm). We considered, therefore, that the pyrene dimer in the γ-CDx cavity exhibits the bisignated CD and FDCD Cotton effects that indicate the left-handed chirality. Analyses of CD and FDCD spectra of the pyrene–G2-γ complex were more difficult because the structures of the excitation spectral bands were much broader than those of the pyrene–γ-CDx complex. Since the shape of the CD spectra around at 330 nm (^1L_a) is the same as that of the excitation spectrum, this positive Cotton effect seems to be ascribed to the normal ICD of the pyrene dimer in the G2-γ cavity. Strictly speaking, we could not distinguish the bisignated Cotton effect from the CD and/or FDCD signals around 280 nm. The chirality of the pyrene dimer in the G2-γ cavity, however, can be determined unequivocally to be *R* from the result of CPF so far as the absolute configuration in the γ-CDx cavity is correct.

Summarizing the results, we can conclude the following. Pyrene forms a dimer at the primary OH side of the γ-CDx cavity, and the formation of the achiral face-to-face dimer is prohibited by the steric factor, resulting in the asymmetric formation of the pyrene dimer with the *S* chirality. Meanwhile, since the primary OH side of the G2-γ cavity is capped by the maltosyl group, the pyrene dimer having the *R* chirality is formed at the secondary OH side of the G2-γ cavity.

Chiral Intramolecular Dimers of Dinaphthylpropanes in the γ-CDx Cavity. It was considerably more difficult to measure the obviously bisignated CD spectra for the γ-CDx– and G2-γ–pyrene dimer complexes. This may be ascribed to the CD signals at the ^1B_a transition band in the vicinity of the ^1B_b transition band. Naphthalene is expected to be a good chromophore for CD measurements because the intense ^1B_b transition band is well isolated from other absorption bands. We tried to include naphthalene in the γ-CDx cavity. Very weak excimer emission, however, was observed for this system. Then we chose α,α- and α,β-DNPs as the guest molecules. It is known that α,α-, α,β-, and β,β-DNPs are bound to γ-CDx in their stacked forms, which emit the intramolecular excimerlike fluorescence.[44,45] Analogous fluorescence studies of dinaphthyl compounds have been reported.[46,47] The asymmetric nature of these guest molecules in a cyclodextrin cavity has not been known.

α,α-DNP in hexane showed the monomer fluorescence band with the structures at 324, 334, and ca. 350 nm (sh) and the intramolecular excimer fluorescence band with its maximum intensity at 415 nm. Meanwhile, only monomer fluorescence was observed at 320, 327, 334, 339, and 350 nm for the hexane solution of α,β-DNP. The CPK molecular model indicates that α,α-DNP can form a face-to-face dimer in its excited singlet state, whereas two naphthalene moieties of α,β-DNP can partially overlap each other. In water containing γ-CDx, however, only excimerlike emissions were detected for both α,α- and α,β-DNPs, which is

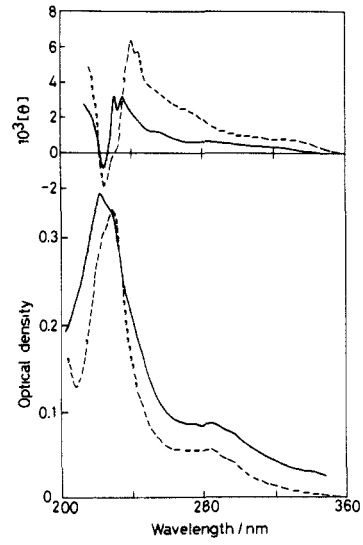

Figure 6. Absorption (bottom) and CD spectra of 3×10^{-6} M α,α- (—) and α,β-DNPs (---) in water containing γ-CDx (1×10^{-2} M).

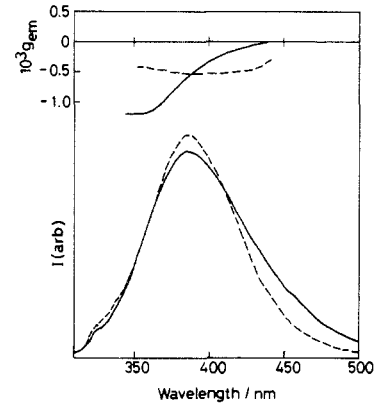

Figure 7. Fluorescence (bottom) and CPF spectra of 3×10^{-6} M α,α- (—) and α,β-DNPs (---) in water containing γ-CDx (1×10^{-2} M). DNPs were excited at the wavelengths corresponding to their ^1L_a bands.

in good agreement with the results reported previously.[44,45] Such systems are favorable for CD measurements because the contribution of the monomer components can be neglected.

The absorption and CD spectra of the aqueous γ-CDx solutions of α,α- and α,β-DNPs are shown in Figure 6. In both cases, the obvious bisignated CD Cotton effects were observed at the wavelength regions corresponding to the ^1B_b transitions, indicating the right-handed chiralities of the intramolecular dimers of these dinaphthylpropanes in the γ-CDx cavity. We checked that the 1:1 complexes of 1- and 2-ethylnaphthalenes and γ-CDx show only simple Cotton effects with positive ellipticity at the ^1B_b transition bands. The wavelength-dependent negative g_{em} value was measured on the CPF spectrum of the α,α-DNP–γ-CDx complex (Figure 7). For CPF measurements, 1×10^{-5} M α,α-DNP in aqueous 1×10^{-2} M HTAC solution was used for taking a base line. The fact that the $|g_{em}|$ value decreases at longer wavelength can be reasonably interpreted in terms of the inclusion of both chiral partially overlapped dimer and achiral face-to-face dimer of α,α-DNP. The fluorescence decay curve of the α,α-DNP–γ-CDx complex was composed of two exponential components without a rise of the intensity of the excimer fluorescence. The lifetimes of the fluorescence followed at 375 nm were 12.9 (40%) and 84.5 ns (60%), while the ratio of the short component decreased [τ_1 = 13.7 ns (25%) and τ_2 = 81.4 ns (75%)] when the fluorescence decay was monitored at longer wavelength (450 nm). These results suggest that the chiral α,α-DNP dimer has a fluorescence maximum at shorter wavelength and a shorter lifetime compared with the achiral face-to-face dimer. Meanwhile, the g_{em} values of the α,β-DNP–γ-CDx complex were almost constant over the wavelengths where the appreciable CPF signals were

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detected (see Figure 7). As is described above, α,β-DNP can form only the partially overlapped dimer. An enantiomer with the *R* chirality seems to be bound preferentially to the primary OH side of the γ-CDx cavity.

Summary

The present study reveals that the hydrophobic guest molecules having molecular sizes larger than the cyclodextrin cavity size tend to be bound to the relatively hydrophobic part (primary OH side) of the cavity unless the primary OH side is capped. The intermolecular pyrene dimer as well as the intramolecular dinaphthylpropane dimers are included in the primary OH side of the γ-CDx cavity, which recognizes the enantiomers of these guest molecules. The *S* chiral pyrene dimer is preferentially bound to γ-CDx, whereas the *R* chiral stacked dimers of α,α- and α,β-DNPs are recognized as the preferable guests by γ-CDx. Extension of the present study may allow designation of the appropriate systems for asymmetric syntheses and chiral recognition using cyclodextrins.

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Reaction of Dicarbomethoxycarbene with Acetaldehyde and Simple Ketones[1]

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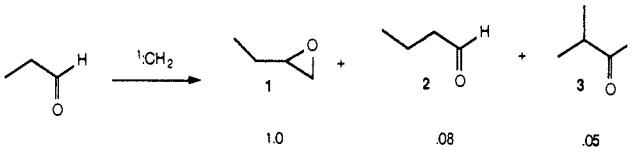
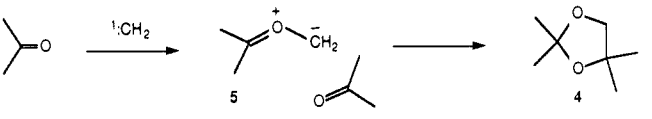
Abstract: Singlet dicarbomethoxycarbene reacts with acetaldehyde to give dioxolane **8**, the ultimate product of formation of ylide **10** and subsequent addition of a second molecule of aldehyde. Photosensitized generation of the carbene gives increased hydrogen abstraction and decreased products derived from the ylide. Replacement of the aldehyde with a ketone changes the course of the reaction and dioxolanones (**11**, **20**, and **26**) become the major products. Suggestions are made for the mechanisms of the singlet and triplet reactions and for the peculiar behavior of acetone in which generation of singlet and triplet carbene gives the same product slate.

The addition to the carbon–carbon double bond is surely the most familiar reaction of divalent carbon.[2] Given that a significant portion of organic chemistry is concerned with reactions of the carbonyl group, it is striking how little investigated is the reaction of carbenes with the carbon–oxygen double bond. Kirmse's famous book[2a] devotes but three pages to the subject, and relatively little has been published since. Important exceptions include the report by Rose and Fuqua of the reactions of methylene with propionaldehyde in the gas phase[3] and Huisgen and de March's relatively recent and thorough description of the reaction of dicarbomethoxycarbene with aromatic aldehydes.[4]

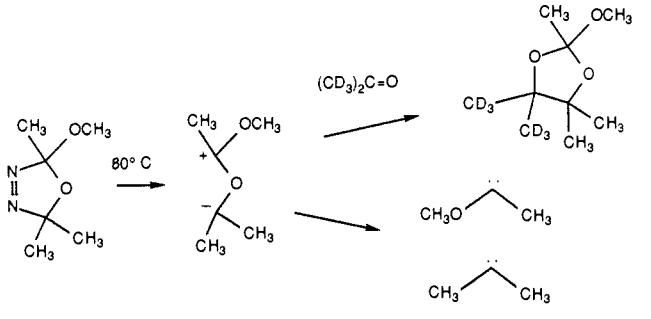
Methylene reacts with propionaldehyde to give three main products, epoxybutane (**1**), *n*-butyraldehyde (**2**), and isobutyraldehyde (**3**). The major product is **1**, and Rose and Fuqua



estimated that the carbonyl group is 13–18 times as reactive as the α and β carbon–hydrogen bonds, respectively. This observation supported an earlier report of Bradley and Ledwith,[5] who found that in solution the carbonyl group of acetone was ca. 15 times as reactive toward methylene as was the carbon–hydrogen bond. These workers found that the dominant product in solution was the dioxolane **4**, and proposed a sensible mechanism involving capture of the ylide **5** by a second molecule of acetone.



In 1983 it was noted by Bēkhazi and Warkentin that oxadiazolines lost nitrogen on heating to generate carbonyl ylides.[6] These ylides both fragmented to carbenes and were trapped by acetone. The daughter carbenes reacted with acetone to give new ylides which also could be trapped by acetone.



Reactions of carboalkoxycarbenes with aldehydes had been described as early as 1885,[7] and the structure of the dioxolane products proposed in 1910,[8] but it remained for Huisgen and de March[4] to describe the reaction in detail and to trap the ylide **6** with a number of reagents, including the aldehyde itself to give dioxolane **7**.

In recent years carbonyl ylides have been detected spectroscopically from the reactions of a variety of carbenes, usually

(1) Support for this work by the National Science Foundation through Grant CHE 83 18345 is gratefully acknowledged. Portions are taken from the A. B. Thesis of T.M.F., Princeton University, 1974.

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