perature over several hours. After 5 h, the reaction was poured into saturated $NH_4Cl$ (4 mL) and was extracted with ether (5 × 4 mL). The combined ether layers were dried ($Na_2SO_4$) and concentrated, and the resulting oil was chromatographed (33% EtOAc in hexanes) to provide **36** (52.5 mg, 86%) as a colorless glass.

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# Synthesis and Photochemistry of Some Anthraquinone-Substituted β-Cyclodextrins

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**Abstract:** Anthraquinone-substituted β-cyclodextrins (β-CD) **1-3** have been synthesized by reaction of the corresponding sulfonyl chlorides with β-CD. The anthraquinone-capped β-CD **3** is produced as a mixture of A,C and A,D isomers. Irradiation of **1-3** results in the formation of the corresponding hydroquinones and oxidation of the CD moiety. The main photoproduct from **2** after regeneration of the anthraquinone contains a C6 aldehyde in a hemiacetal or hydrate form. Molecular mechanics suggests that the position of the aldehyde is on the E-glucose ring and that the intramolecular H-abstraction reaction shows some selectivity.

## Introduction

Cyclodextrins (CDs) have received much attention as host molecules in complexation and catalysis studies.[1] They are composed of α-D-glucose residues and possess well-defined cavities. Their relatively small size and ease of functionalization make them ideal substrates for enzyme modeling experiments.[2] Many derivatized cyclodextrins have been synthesized to date, and some show remarkable catalytic activity.[3] More recently, cyclodextrins have been used to modify photochemical reactions.[4] Few photochemically active, derivatized cyclodextrins have been synthesized; for example, benzophenone, rose bengal, and porphyrin moieties have been attached to β-CD resulting in host sensitizer systems for triplet energy transfer,[5] singlet oxygen generation[6] and photoreduction,[7] respectively. This paper describes the synthesis and photochemical properties of β-CD derivatized with anthraquinones and examines their viability as photooxidation sensitizers.

The photochemistry of anthraquinones has been well established.[8] The chemistry of the water-soluble anthraquinonesulfonates and -disulfonates is most relevant to this study since the anthraquinones are bonded to β-CD via a sulfonate ester bond. Anthraquinonesulfonate (AQS) photochemistry is dominated by triplet state reactions due to rapid and efficient intersystem crossing from the singlet state.[9-11] The excited triplet AQS then usually reacts via one of two mechanisms depending on the available substrates: electron transfer or hydrogen abstraction. For example, photolysis of 2-AQS in aqueous NaBr produces $Br_2$ by photooxidation of the bromide anion to atomic bromine.[12,13] This simple and clean reaction can "store" solar energy; indeed, much of the interest in water-soluble anthraquinones stems from their potential use in solar energy conversion schemes. The triplet state can also react through hydrogen abstraction in the presence of certain substrates; for example, 2-propanol is readily oxidized to acetone by reaction with photoexcited anthraquinone-2-sulfonate.[14] Wells and co-workers have demonstrated that the photooxidation mechanism is initiated by a hydrogen abstraction rather than an electron transfer.[14] In the absence of substrates with either low oxidation potentials or abstractable hydrogens, the excited anthraquinonesulfonates will react with water to generate hydroxyanthraquinonesulfonates.[15] This side reaction destroys their utility in most solar energy storage schemes.

## Experimental Section

Commercially available β-cyclodextrin (Amaizo) was used after vacuum drying (0.05 mm) at 100 °C for 12 h with a liquid $N_2$ trap. Pyridine was fractionally distilled, and the fraction between 114 and 115 °C was collected and stored over activated 4-Å molecular sieves until used. $^1H$ and $^{13}C$ NMR spectra were obtained with a GE QE-300 spectrometer. UV/vis spectra were measured on a Beckman DU-70 instrument. TLC was carried out with Baker 0.25-mm precoated silica plates (60F-254); spot detection was done with UV and staining with vanillin. Reverse-phase column chromatography was done with Baker RP-18 silica gel. High-pressure liquid chromatography was performed on a Waters 660 system, equipped with a variable wavelength absorption detector, using a Whatman ODS-3 analytical or a Waters carbohydrate column.

(1) Bender, M. L.; Komiyama, M. *Cyclodextrin Chemistry*; Springer-Verlag: New York, 1978. Saenger, W. *Angew. Chem., Int. Ed. Engl.* **1980**, *19*, 344-362.
(2) Breslow, R. *Science* **1982**, *218*, 532-537. Tabushi, I. *Acc. Chem. Res.* **1982**, *15*, 66-72. D'Souza, V. T.; Bender, M. L. *Acc. Chem. Res.* **1987**, *20*, 146-152.
(3) Croft, A. P.; Bartsch, R. A. *Tetrahedron* **1983**, *39*, 1417-1474.
(4) Ramamurthy, V.; Eaton, D. F. *Acc. Chem. Res.* **1988**, *21*, 300-306. Ramamurthy, V. *Tetrahedron* **1986**, *42*, 5753-5839.
(5) Tabushi, I.; Fujita, K.; Yuan, L. C. *Tetrahedron Lett.* **1977**, 2503-2506.
(6) Neckers, D. C.; Paczkowski, J. *J. Am. Chem. Soc.* **1986**, *108*, 291-292. Neckers, D. C.; Paczkowski, J. *Tetrahedron* **1986**, *42*, 4671-4683.
(7) Gonzalez, M. C.; McIntosh, A. R.; Bolton, J. R.; Weedon, A. C. *J. Chem. Soc., Chem. Commun.* **1984**, 1138-1140.
(8) Bruce, J. M. In *The Chemistry of the Quinoid Compounds*; Patai, S., Ed.; Wiley: New York, 1974.
(9) Moore, J. N.; Phillips, D.; Nakashima, N.; Yoshihara, K. *J. Chem. Soc., Faraday Trans. 2* **1987**, *83*, 1487-1508.
(10) Moore, J. N.; Phillips, D.; Nakashima, N.; Yoshihara, K. *J. Chem. Soc., Faraday Trans. 2* **1986**, *82*, 745-761.
(11) Treinin, A.; Loeff, I.; Linschitz, H. *J. Phys. Chem.* **1983**, *87*, 2536-2544.
(12) Fuchs, B.; Mayer, W. J. W.; Abramson, S. *J. Chem. Soc., Chem. Commun.* **1985**, 1711-1713.
(13) Treinin, A.; Loeff, I.; Linschitz, H. *J. Phys. Chem.* **1984**, *88*, 4931-4937.
(14) Wells, C. F. *Trans. Faraday Soc.* **1961**, *57*, 1703-1718; 1718-1731.
(15) Clark, K. P.; Stonehill, H. I. *J. Chem. Soc., Faraday Trans. 1* **1972**, *68*, 577-590; 1676-1686. Broadbent, A. D.; Newton, R. P. *Can. J. Chem.* **1972**, *50*, 381-387. Broadbent, A. D.; Matheson, H. B.; Newton, R. P. *Can. J. Chem.* **1975**, *53*, 826-830.

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Preparative HPLC was performed on a Waters 224 system, equipped with a UV absorption detector (254 nm), using a Whatman Magnum 20 column packed with ODS. Melting points were taken on a Thomas-Hoover capillary melting point apparatus and are uncorrected. Irradiations were carried out with a Hanovia 450-W medium-pressure lamp with a Pyrex glass filter sleeve.

**Anthraquinone-1-sulfonyl Chloride.**[16] Anthraquinone-1-sulfonic acid sodium salt (5.75 g, 17.5 mmol) was covered with thionyl chloride (20 mL), and the suspension was stirred under $CaSO_4$ drying until gas evolution subsided. It was heated to reflux for 30 min, after which time DMF (1 mL) was added dropwise in several portions. The solution was heated at reflux for 2 h. After the reaction was cooled, it was poured into ice. The resulting yellow solid was collected by filtration and dried in vacuo overnight. The crude material (4.4 g, 82%) was used without further purification. A portion was recrystallized from benzene: mp 211–213 °C (lit. 216–218 °C); $^1$H NMR (DMSO-$d_6$) $\delta$ 8.47 (dd, $J$ = 1.4, 7.8 Hz, 1 H), 8.25 (dd, $J$ = 1.4, 7.7 Hz, 1 H), 8.14 (dd, $J$ = 1.6, 7.5 Hz, 1 H), 8.09 (dd, $J$ = 1.6, 7.6 Hz, 1 H), 7.93 (ddd, $J$ = 1.6, 7.4, 7.5 Hz, 1 H), 7.87 (ddd, $J$ = 1.6, 7.4, 7.5 Hz, 1 H), 7.84 (dd, $J$ = 7.7, 7.8 Hz, 1 H).

**6$^A$-(Anthraquinone-1-sulfonyl)-$\beta$-cyclodextrin (1).** $\beta$-Cyclodextrin (8.17 g, 7.20 mmol) was covered with pyridine (100 mL), and the mixture was sonicated until the $\beta$-CD dissolved completely. The solution was cooled in an ice bath and stirred under $N_2$. Anthraquinone-1-sulfonyl chloride (2.21 g, 7.21 mmol) was added in one portion, and the mixture was stirred for 2 h. The pyridine was removed under high vacuum with warming ($T$ < 44 °C). The residue was dried in vacuo overnight. The solid was ground, washed with acetone, filtered, and dried in vacuo. A portion (2.00 g of 12.60 g) of the solid was purified by reverse-phase chromatography using a gradient elution (0–40% aqueous $CH_3CN$). The fractions containing the desired compound ($R_f$ = 0.60, 5:4:3 $n$-BuOH/EtOH/$H_2O$) were combined and concentrated in vacuo, affording 660 mg (41%). Final purification was accomplished through preparative HPLC using an acetonitrile/water gradient elution (20–26%). Recovery for this step was 45%, and the yield of purified material was 19%: $^1$H NMR (DMSO-$d_6$/$D_2O$) $\delta$ 8.57 (d, $J$ = 7.7 Hz, 1 H), 8.52 (d, $J$ = 7.8 Hz, 1 H), 8.20 (m, 2 H), 8.10 (dd, $J$ = 7.7 and 7.8 Hz, 1 H), 7.96 (m, 2 H), 4.83 (br s, 4 H), 4.74 (br s, 2 H), 4.67 (br s, 1 H), and $\beta$-CD resonances; $^{13}$C NMR (DMSO-$d_6$/$D_2O$) $\delta$ 181.8, 180.8, 136.4, 136.0, 135.7, 135.3, 134.8, 134.5, 134.0, 132.6, 132.4, 132.1, 127.2, 126.8, 102.5, 102.2, 101.9, 81.8, 81.7, 81.5, 73.2, 73.0, 72.5, 72.3, 70.9, 69.1, 60.1, 59.8; UV (1:1 $CH_3CN/H_2O$) $\lambda$ (log $\epsilon$) 257 nm (4.5), 322 nm (3.5).

Anal. Calcd for $C_{56}H_{76}O_{39}S\cdot 2H_2O$: C, 46.67; H, 5.59; S, 2.22. Found: C, 46.48; H, 5.63; S, 2.22.

**Anthraquinone-2-sulfonyl Chloride.**[16] Anthraquinone-2-sulfonic acid sodium salt monohydrate (5.05 g, 15.4 mmol) was reacted with $SOCl_2$ (13.8 g, 116 mmol) and DMF (0.5 g, 7 mmol) as above to afford the sulfonyl chloride (4.57 g, 14.9 mmol, 97%) which was used without further purification. A portion was recrystallized from petroleum ether/$CH_2Cl$: mp 191–192 °C (lit. 197 °C); $^1$H NMR ($CDCl_3$) $\delta$ 8.98 (d, $J$ = 1.5 Hz, 1 H), 8.57 (d, $J$ = 8.3 Hz, 1 H), 8.40 (dd, $J$ = 8.3, 1.5 Hz, 1 H), 8.37 (m, 2 H), 7.90 (m, 2 H); $^{13}$C NMR ($CDCl_3$) $\delta$ 181.3, 180.8, 146.5, 137.2, 135.1, 135.0, 134.5, 133.1, 133.0, 131.3, 129.2, 127.8, 127.7, 126.3.

**6$^A$-(Anthraquinone-2-sulfonyl)-$\beta$-cyclodextrin (2).** $\beta$-Cyclodextrin (8.65 g, 7.62 mmol) was covered with pyridine (100 mL), and the mixture was sonicated until the $\beta$-CD dissolved completely. The solution was cooled in an ice bath and stirred under $N_2$. Anthraquinone-2-sulfonyl chloride (2.36 g, 7.69 mmol) was added in one portion, and the mixture was stirred for 1 h. The pyridine was removed under high vacuum with warming ($T$ < 44 °C). The residue was dried in vacuo overnight. The solid was ground, washed with acetone, filtered, and dried in vacuo. A portion (5.84 g of 12.41 g) of the solid was recrystallized from water (100 mL, $T$ < 80 °C), affording the $\beta$-CD derivative (1.07 g, 0.761 mmol, 21%): $R_f$ 0.59 (5:4:3 $n$-BuOH/EtOH/$H_2O$). Traces of pyridine hydrochloride and anthraquinone-2-sulfonic acid can be removed through preparative HPLC by using an acetonitrile/water gradient elution (28–33%): $^1$H NMR (DMSO-$d_6$) $\delta$ 8.55 (s, 1 H), 8.43 (br s, 2 H), 8.22 (m, 2 H), 8.00 (m, 2 H), and $\beta$-CD resonances; $^{13}$C NMR (DMSO-$d_6$) $\delta$ 181.8, 181.4, 140.2, 136.6, 135.0, 133.9, 133.2, 133.1, 132.8, 128.4, 127.1, 125.9, 102.4, 102.1, 101.6, 81.6, 73.1, 72.9, 72.5, 72.2, 70.8, 68.8, 60.0; UV (1:1 $CH_3CN/H_2O$) $\lambda$ (log $\epsilon$) 256 nm (4.8), 324 nm (3.7).

Anal. Calcd for $C_{56}H_{76}O_{39}S\cdot 6H_2O$: C, 44.45; H, 5.86; S, 2.12. Found: C, 44.25; H, 5.63; S, 2.09.

**Anthraquinone-2,6-disulfonyl Chloride.**[16] Anthraquinone-2,6-disulfonic acid disodium salt (3.00 g, 7.28 mmol) was reacted with $SOCl_2$ (9.00 g, 75.7 mmol) and DMF (0.90 g, 12 mmol) as above to afford the disulfonyl chloride (2.92 g, 7.20 mmol, 97%). The crude disulfonyl chloride was recrystallized from benzene (mp 248–250 °C, lit. mp 250 °C) before being used in the next step: $^1$H NMR ($CDCl_3$/DMSO-$d_6$) $\delta$ 8.94 (d, $J$ = 1.5 Hz, 2 H), 8.68 (d, $J$ = 8.1 Hz, 2 H), 8.56 (dd, $J$ = 8.1, 1.5 Hz, 2 H).

**6$^A$,6$^{C(D)}$-(Anthraquinone-2,6-disulfonyl)-$\beta$-cyclodextrin (3). Warm Capping.** $\beta$-Cyclodextrin (1.02 g, 0.90 mmol) was added slowly to pyridine (300 mL), and the mixture was sonicated until the $\beta$-cyclodextrin dissolved completely. The solution was heated under $N_2$, and pyridine (ca. 25 mL) was distilled to remove traces of $H_2O$. The solution was cooled to room temperature, and anthraquinone-2,6-disulfonyl chloride (0.37 g, 0.90 mol) was added slowly. The mixture was stirred until the solid dissolved completely, and then it was heated to 60 °C for 3 h. The mixture was cooled, and the solution was decanted from viscous oligomeric precipitates. The pyridine was removed by vacuum distillation (0.2 mm, $T$ < 40 °C). The residue was washed with acetone, filtered, and dried in vacuo overnight. Traces of pyridine hydrochloride and anthraquinone-2,6-disulfonic acid were removed by reverse-phase chromatography using a gradient elution (0–30% aqueous $CH_3CN$). Fractions containing the desired compound ($R_f$ = 0.65, 5:4:3 $n$-BuOH/EtOH/$H_2O$) were concentrated in vacuo, affording the capped $\beta$-CD derivative (0.21 g, 0.14 mmol, 15%). Final purification was accomplished through preparative HPLC using an $CH_3CN/H_2O$ gradient elution (20–29%). Approximately 50% of the injected material was recovered on this step, affording an overall yield of 10% HPLC purified material: $^1$H NMR ($CD_3CN/D_2O$) $\delta$ 8.83 (br s, 1 H), 8.81 (br s, 1 H), 8.67 (d, $J$ = 8.2 Hz, 1 H), 8.62 (br d, $J$ = 8.2 Hz, 1 H), 8.55 (d, $J$ = 8.3 Hz, 1 H), 8.51 (br d, $J$ = 8.3 Hz, 1 H), 5.19 (m, 3 H), 5.07 (m, 2 H), 4.95 (m, 1 H), 4.82 (m, 1 H), and $\beta$-CD resonances; $^{13}$C NMR (DMSO-$d_6$) $\delta$ 181.0, 180.5, 180.3, 141.5, 140.5, 140.4, 139.3, 137.2, 136.7, 136.3, 134.7, 134.1, 132.3, 124.9, 102.5, 101.9, 101.6, 82.0, 81.3, 73.2, 72.7, 72.4, 71.1, 70.7, 68.8, 60.0, 59.6; UV (1:1 $CH_3CN/H_2O$) $\lambda$ (log $\epsilon$) 211 nm (4.5), 255 nm (4.7), 323 nm (3.7).

**Cold Capping.** $\beta$-Cyclodextrin (6.0 g, 5.29 mmol), pyridine (300 mL), and anthraquinone-2,6-disulfonyl chloride (2.2 g, 5.42 mmol) were reacted as above except that the reaction was carried out at 0 °C for 3 h. Workup as above gave the $\beta$-CD derivative (1.87 g, 1.27 mmol, 23%). Final purification through preparative HPLC gave a 9% overall yield of HPLC pure material.

Anal. Calcd for $C_{56}H_{84}O_{46}S_2\cdot 5H_2O$: C, 43.19; H, 5.44; S, 4.12. Found: C, 43.08; H, 5.28; S, 4.03 (av of two determinations).

**Regioisomer Ratio Determination.** 4-*tert*-Butylthiophenol (45.3 mg, 0.272 mmol) and NaOMe (15.0 mg, 0.278 mmol) were dissolved in absolute MeOH (0.5 mL) under $N_2$. The MeOH was removed in vacuo, leaving sodium 4-*tert*-butylthiophenolate. Dry DMF (0.865 mL) and **3** (25.0 mg, 0.0175 mmol) were added to the sodium salt, and the resultant solution was heated at 80 °C for 12 h under $N_2$. The solution was cooled, filtered, and concentrated to dryness in vacuo. $H_2O$ (1.5 mL) and aqueous HCl (1 drop) were added to the pale brown residue (pH < 2). The mixture was then extracted with $Et_2O$ (1.6 mL × 4), and the aqueous layer was combined with the insoluble material and concentrated in vacuo. The resulting mixture of 6$^A$,6$^X$-bis[(4-*tert*-butylphenyl)-sulfenyl]-$\beta$-cyclodextrins was dissolved in 78% aqueous $CH_3CN$ solution and analyzed by HPLC using a Waters carbohydrate analysis column (78% aqueous $CH_3CN$, 2 mL/min, 254 nm). Retention times for the A,D- and A,C-derivatives were 12.1 and 13.0 min, respectively (lit.[21] 13.0 and 15.2 min). Treatment of the diphenyl-4,4′-disulfonyl ether capped $\beta$-CDs as above gave peaks with the same retention times, thus confirming the regioisomer assignments. Area ratios were obtained with a less polar eluent (82% aqueous $CH_3CN$, 2 mL/min, $t_R$ = 20.8 and 23.2 min, respectively): warm capping, 80% A,D/20% A,C; cold capping, 58% A,D/42% A,C.

**Photolysis of 1. In Aqueous Acetonitrile.** Compound **1** (4.7 mg, 3.3 $\mu$mol) was dissolved in $D_2O/CD_3CN$ (0.4 and 0.2 mL, respectively), and the solution was transferred to an NMR tube and degassed with $N_2$ for 10 min. The tube was placed into an ice bath which was situated next to a Hanovia 450-W medium-pressure mercury arc lamp in a Pyrex immersion well. Aluminum foil was placed around the immersion well, and an elliptical hole was cut out of the wrap. The solution in the capped NMR tube was irradiated, and the photolysis was monitored periodically by NMR and HPLC (starting material showed a retention time of 8.6 min when eluted with a 23% aqueous $CH_3CN$ solution). The solution was irradiated for 55 min. After the lamp was extinguished, air was bubbled through the solution for 10 min. The NMR spectra were obtained before irradiation, after irradiation, and after bubbling air through the photolysate. The HPLC of the air-sparged product shows four major new peaks with retention times of 5.8, 6.9, 7.4, and 8.3 min with the latter being the largest peak (detection at 320 nm).

**In Aqueous 2-Propanol.** Compound **1** (6.5 mg, 4.6 $\mu$mol) was dissolved in $D_2O$/i-PrOD-$d_7$ (0.5 mL each), and the solution was transferred to

(16) Fierz-David, H. E.; Krebser, A.; Anderau, W. *Helv. Chim. Acta* **1927**, *10*, 197–227.

an NMR tube and degassed with $N_2$ for 10 min. Irradiation (90 min), subsequent sparging with air, and analysis by NMR and HPLC was carried out as above. HPLC of the final solution showed only peaks due to **1** and 1-AQS.

**Preparative Scale.** Compound **1** (860 mg, 0.61 mmol) was dissolved in 40% aqueous $CH_3CN$ (250 mL), and the solution cooled in an ice bath and irradiated for 4.5 h. The solution was concentrated in vacuo ($T$ < 40 °C) until the volume remaining was ca. 40 mL. Flash reverse-phase LC afforded 290 mg of anthraquinone-substituted β-CDs and derivatives. Preparative HPLC (20–30% aqueous $CH_3CN$, flow = 18 mL/min) of this material gave two fractions: mass (retention time), 53.3 mg (12 min), 46.0 (24).

**Photolysis of 2. In Aqueous Acetonitrile.** Compound **2** (16.7 mg, 11.9 μmol) was dissolved in $D_2O/CD_3CN$ (0.5 and 0.4 mL, respectively), the solution was degassed and irradiated (65 min) as above, and the reaction was monitored by NMR and HPLC (**2** showed a retention time of 11.4 min when eluted with 27% aqueous $CH_3CN$) after irradiation and after air sparging for 15 min. The NMR spectra before irradiation, after irradiation, and after bubbling air through the photolysate are shown in Figure 1. The HPLC of the air-sparged product shows three major new peaks (320-nm detection) with retention times of 7.3, 8.4, and 9.3 min with the latter being the largest peak.

**In Aqueous 2-Propanol.** Compound **2** (3.7 mg, 2.6 μmol) was dissolved in $D_2O$/*i*-PrOD-$d_7$ (0.4 mL each), and the solution was transferred to an NMR tube and degassed with $N_2$ for 10 min. Irradiation (70 min), subsequent sparging with air, and analysis by NMR and HPLC was carried out as above (Figure 2). HPLC of the final solution showed only peaks due to **2** and 2-AQS.

**Preparative Scale.** Compound **2** (500 mg, 0.36 mmol) was dissolved in 30% aqueous *t*-BuOH (200 mL), and the solution was cooled in an ice bath and irradiated for 7 h. The solution was concentrated in vacuo ($T$ < 40 °C) until the volume remaining was ca. 20 mL. Preparative HPLC (20–30% aqueous $CH_3CN$, flow = 18 mL/min) of this solution gave four fractions: mass (retention time), 3.8 mg (35 min), 24.9 (42), 43.5 (50), 11.6 (58). The last fraction was identified as **2**. Analytical HPLC showed that the third fraction ($t_R$ = 50 min) was nearly one peak, whereas the first and second peaks were still mixtures of compounds. Fraction 3: $^1$H NMR (DMSO-$d_6$/$D_2O$) δ 8.52 (s, 1 H), 8.38 (m, 2 H), 8.21 (m, 2 H), 8.93 (m, 2 H), 5.74 (br d, $J$ = 18.5 Hz, 1 H), 5.04 (d, $J$ = 7.1 Hz, 1 H), and β-CD resonances; $^{13}$C NMR (DMSO-$d_6$) δ 181.8, 181.4, 140.2, 136.6, 135.0, 134.6, 133.9, 133.3, 133.2, 132.8, 128.4, 127.2, 127.0, 125.9, 102.4, 102.1, 101.6, 87.6, 82.7, 82.0, 81.7, 81.5, 73.2, 73.1, 72.9, 72.5, 72.2, 70.8, 70.7, 68.8, 60.0, 59.8.

**$NaBH_4$ Reduction of Fraction 3.** A 1% aqueous $NaBH_4$ solution (6.3 mL) was added to fraction 3 (5.0 mg), and the mixture was stirred for 1 day. Analysis by HPLC (23% aqueous $CH_3CN$, 1.0 mL/min), showed two peaks at 8.6 min and 18.9 min. The latter was identified as **2** by co-injection, whereas the first peak was coincident with the peak produced by reaction of **2** with $NaBH_4$.

**Taka-amylase Reaction with Fraction 3.** A mixture composed of $H_2O$ (1.3 mL), $CaCl_2$ (1.6 mg), NaOAc (36.5 mg), taka-amylase (12.3 mg), and fraction 3 (5.0 mg) was stirred for 1 day and then analyzed by HPLC as above. The reaction produced two peaks at 32.2 min and 35.1 min. These peaks were also produced when **2** is reacted with the same quantities of reagents.

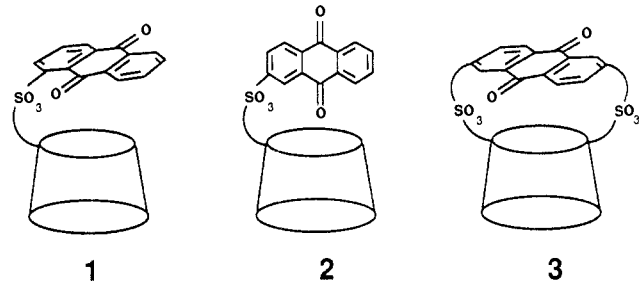
**Photolysis of 3. In Aqueous Acetonitrile.** Compound **3** (7.0 mg, 4.8 μmol) was dissolved in $D_2O/CD_3CN$ (0.6 and 0.3 mL, respectively), the solution was transferred to an NMR tube and degassed with $N_2$ for 10 min. The solution was irradiated as above for 60 min. After the lamp was extinguished, air was bubbled through the solution for 10 min. The HPLC of the air-sparged product shows four major new peaks with retention times of 12.6, 13.3, 15.6, and 17.6 with the latter two being the largest (**3**: $t_R$ = 22.6 min with 20% aqueous $CH_3CN$).

**In Aqueous 2-Propanol.** Compound **3** (7.0 mg, 4.8 μmol) was dissolved in $D_2O$/*i*-PrOD-$d_7$ (0.4 mL each), and the solution was transferred to an NMR tube and degassed with $N_2$ for 10 min. The tube was placed into an ice bath and irradiated as above for 60 min. The solution was sparged with air and analyzed by NMR and HPLC. Both techniques showed that **3** was largely recovered.

**Calculations.** Molecular modeling was carried out with use of Alchemy II (Tripos Associates) and PCMODEL (Serena Software). Molecular mechanics calculations were performed with MMX (Serena Software). Some of the force constants for the H abstraction were taken from those developed by Dorigo and Houk.[17] The V2 torsion constant enforcing the in-plane mode of H abstraction was taken from Sauers.[18] The hydrogen which was abstracted was assigned the Z1 wildcard (no. 58). The carbon atom of the abstraction carbonyl group was designated as a carbon radical (no. 29), and a nonplanar, UHF calculation was employed on the doublet π-system. H bonding was activated for the C3-OH's only, and all lone pairs were included. The electrostatic energy was calculated with use of atomic charge/charge interactions. The structure for β-CD was generated from its crystal structure.[19] The anthraquinone was appended, and H-abstraction geometries were created by twisting about the bonds comprising the tether. Minimizations were performed, the lowest energy structures for abstractions at the different glucose residues were refined by altering the orientations of the hydroxyls to create uniformity between these structures, and they were minimized again. Finally, the lowest energy structures were used to create other structures for H abstraction at different glucose residues, and this process was repeated until further modification did not give a lower energy structure. The effects of the dielectric constant and the planarity of the π-system were also explored.

## Results and Discussion

**Synthesis and Structure of Derivatives.** The preparation of **1–3** was accomplished through condensation of the appropriate sulfonyl chloride derivative of anthraquinone with β-CD. The synthesis of tethered β-CDs was straightforward and gave relatively good yields, whereas the synthesis of the capped β-CD required extensive purification and gave poorer yields. The capping reaction was conducted at 0 °C (cold) and 60 °C (warm), but neither condition was superior with respect to the overall yield. The warm capping produced a waxy precipitate which could be removed from the product solution greatly simplifying the subsequent chromatography. In all cases the yields were very sensitive to the presence of water, and the best yields resulted when water was excluded from the reaction. Compound **2** could be purified by recrystallization in contrast to both **1** and **3**. In most cases the compounds




**1** **2** **3**

were isolated by reverse-phase chromatography followed by preparative HPLC. The evidence for the structures of **1** and **2** follows from NMR and combustion analysis. Integration of the $^1$H NMR spectrum indicates a 1:1 ratio between the anthraquinone and β-CD, whereas the $^{13}$C NMR spectrum shows two shifted glucose resonances between 65 and 70 ppm characteristic for substitution at a glucose C6-OH. The primary hydroxyls are expected to be the site of substitution since they offer a smaller steric barrier to the addition of the electrophile than the secondary OHs.[20,21] The UV spectra of the β-CD sulfonate esters **1–3** are nearly identical with those of the corresponding sulfonic acids indicating that the CD has little effect on the anthraquinone chromophore.[22]

The structure of the capped β-CD is more tenuous. The $^1$H NMR spectrum and combustion analysis both support monoderivatization, and the $^{13}$C NMR spectrum shows shifted glucose peaks indicative of C6 substitution. However, the latter spectrum also shows more resonances that can be accounted for by a single product. The S–S distance in 2,6-anthraquinonedisulfonyl chloride is about 9.9 Å, so a mixture of A,C- and A,D-capped β-CDs is

(17) Dorigo, A. E.; Houk, K. N. *J. Org. Chem.* **1988**, *53*, 1650–1664.
(18) Sauers, R. R. *Tetrahedron Lett.* **1989**, 527–530.
(19) Zabel, V.; Saenger, W.; Mason, S. A. *J. Am. Chem. Soc.* **1986**, *108*, 3664–3671.
(20) Takahashi, K.; Hattori, K.; Toda, F. *Tetrahedron Lett.* **1984**, 3331–3334.
(21) Strong binding of the sulfonating reagent might be expected to yield different regiochemistry (cf. Ueno, A.; Breslow, R. *Tetrahedron Lett.* **1982**, 3451–3454); however, the hydrophobic interactions necessary for this binding are not present when the solvent is pyridine.
(22) UV (1:1 $CH_3CN$/0.01 M $KHSO_3$) λ (log ε); 1-AQS, 256 nm (4.6), 326 nm (3.6); 2-AQS, 256 (4.7), 328 (3.7); 2,6-AQDS, 258 (4.7), 328 (3.7).

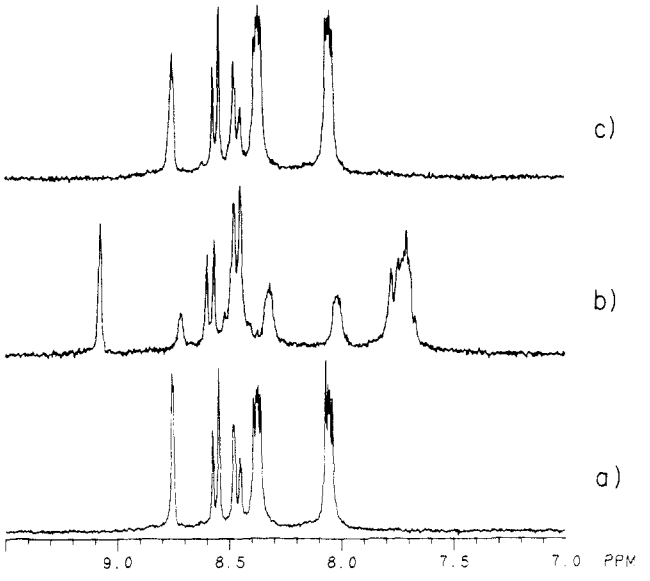



**Figure 1.** $^1H$ NMR spectra of **2** in $CD_3CD/D_2O$ showing the aromatic region (a) before irradiation, (b) after irradiation, and (c) after sparging with air.

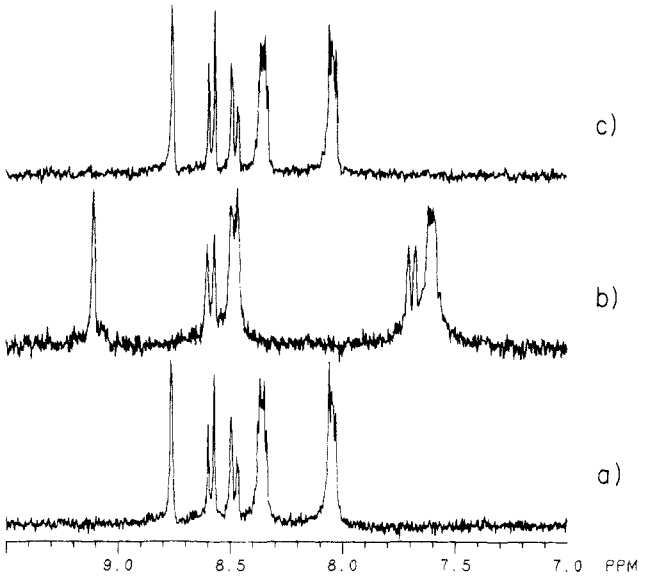
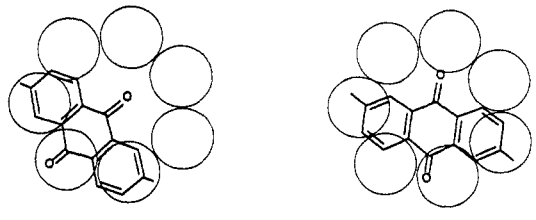



**Figure 2.** $^1H$ NMR spectra of **2** in i-PrOD-$d_7/D_2O$ showing the aromatic region (a) before irradiation, (b) after irradiation, and (c) after sparging with air.

possible.[23] Tabushi and co-workers have developed an assay for determining these regioisomer ratios based on conversion of the capped materials to disubstituted compounds which are separable by HPLC.[24] Accordingly, **3** was converted to the corresponding bis(4-*tert*-butylphenylsulfenyl) derivatives which were analyzed with a carbohydrate column. The chromatogram showed two peaks which had been assigned to the A,C and A,D derivatives.



A,C A,D

This assignment was verified by synthesizing the diphenyl-4,4′-disulfonyl ether capped β-CD and converting it to the bis-sulfenyl compounds. The synthesis of the diphenyl ether capped CD is known to give a roughly equal mixture of A,C and A,D isomers, and HPLC showed two peaks with the same retention times as above. The HPLC results with **3** show that the A,D isomer is favored, especially when the reaction is run at 60 °C. Tabushi also found greater selectivity with higher reaction temperatures.

**Photochemistry.** The photochemical behavior of compounds **1–3** is very similar as judged by HPLC and $^1H$ NMR which were used to monitor the photolysis experiments. Irradiation in $D_2O/CD_3CN$ under deaerated conditions gives rise to formation of new aromatic resonances at the expense of the starting material signals. The original signals could be regenerated (or nearly so) by passing air through the solutions (Figure 1). The same behavior was observed in $D_2O$/i-PrOD-$d_7$ solutions (Figure 2). HPLC analysis of the aerated aqueous $CD_3CN$ solutions indicated that starting material had been destroyed with concomitant formation of several different compounds with shorter retention times. On the other hand, starting material remained relatively intact, and formation of the other products was suppressed in the aqueous i-PrOD-$d_7$ solutions.

These results indicate that the CD moiety suffers oxidation via intramolecular H abstraction by the photoexcited quinone. Hydrogen abstraction is a well known reaction of quinones with certain substrates, especially i-PrOH.[14] Benzoquinone has been postulated to react photochemically with α- and β-CD by H abstraction.[25] It is also known that such reactions generate the corresponding hydroquinones. Since the same aromatic structures are generated in the presence or absence of i-PrOH, we conclude that the hydroquinones are formed in both cases. Reaction of the hydroquinones with $O_2$ regenerates the quinones while reducing $O_2$ to $H_2O_2$. In the i-PrOH solutions the starting materials are regenerated, whereas they are depleted and new products are formed in the absence of i-PrOH. The CD must be the H-atom source in the latter case. The acetonitrile can be ruled out because the same new products appear in aqueous t-BuOH solutions; likewise, the water can be ruled out because photoreactions of sulfonated anthraquinones with $H_2O$ give rise to hydroxylated products. The reaction with $H_2O$ is also inefficient and occurs only in nearly pure aqueous solutions in contrast to the conditions above.

It is difficult to demonstrate rigorously that the hydrogen-abstraction reactions occur via an intramolecular process rather than a bimolecular process. Certainly, remote intramolecular H abstractions have been reported,[26] but derivatized CDs have a propensity towards association, so an intermolecular reaction cannot be ruled out immediately. In the case of **3** where the anthraquinone is strapped to the C6 face of β-CD, intermolecular H abstraction seems unlikely relative to the intramolecular process. One way to approach the question is to examine the conformations leading to H abstraction. If the anthraquinone carbonyl oxygen cannot approach a glucose carbon bound H atom without encountering severe energy barriers, then the intramolecular reaction can be ruled out. On the other hand, if several conformations result in close approach, then it is likely that the intramolecular process accounts for some of the product formation. In the latter scenario the product ratio could be predicted from the relative energies of the transition-state structures leading to H abstraction.[27] Molecular modeling on **2** (vide infra), rotating around the C5–C6, C6–O, O–$SO_2$, and $SO_2$–C bonds, reveals that reasonable conformations can be constructed for H abstraction at each of the glucose rings, and some of these are nearly free from torsional strain. Thus, intramolecular H abstraction appears more

(23) Tabushi, I.; Kuroda, Y.; Yokota, K.; Yuan, L. C. *J. Am. Chem. Soc.* **1981**, *103*, 711–712.
(24) Tabushi, I.; Yamamura, K.; Nabeshima, T. *J. Am. Chem. Soc.* **1984**, *106*, 5267–5270.
(25) Yamada, K.; Kohmoto, S.; Iida, H. *Bull. Chem. Soc. Jpn.* **1976**, *49*, 1171–1172.
(26) Breslow, R.; Baldwin, S.; Flechtner, T.; Kalicky, P.; Liu, S.; Washburn, W. *J. Am. Chem. Soc.* **1973**, *95*, 3251–3262. Winnik, M. A. *Acc. Chem. Res.* **1977**, *10*, 173–179.
(27) Wagner, P. J. *Acc. Chem. Res.* **1983**, *16*, 461–467.

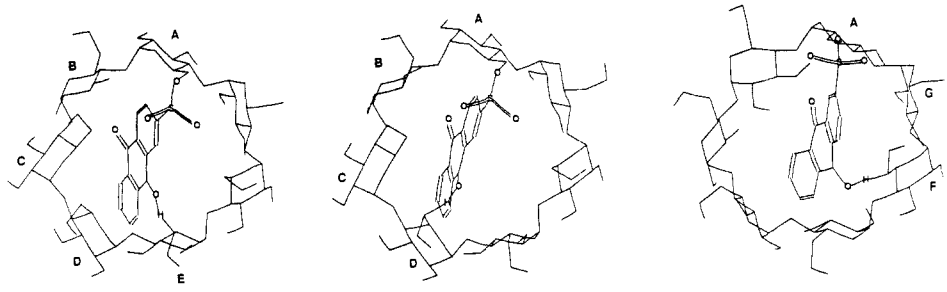



**Figure 3.** Calculated structures for H abstraction at the E-glucose (V2 = 7.5, ε = 1.5), D-glucose (V2 = 7.5, ε = 1.5), and F-glucose (V2 = 7.5, ε = −1) residues.

likely than intermolecular H abstraction.

Several structural features of the main photoproduct (**4**) from the 2-anthraquinone-substituted β-CD (**2**) were elucidated. The photoreactions of **2** were singled out for further study because photoproducts from **1** could not be separated by HPLC, whereas those from **3** suffered hydrolysis during photolysis, work-up, and separation so that sufficient material could not be accumulated. Photoproduct **4** is related to **2** by an oxidation since **4** reacts with $NaBH_4$ to give both **2** and a reduced product of **2**. The oxidation site was confirmed through $^{13}C$ NMR to be the glucose C6 position. Oxidation to a carbonyl produces a carbon bearing one H if a C6–$CH_2$ is attacked, whereas a quaternary carbon results if a C2 or C3–H is abstracted. An attached proton test on the photoproduct shows that the new carbon center (87.6 ppm) has an odd number of hydrogens (emission). The chemical shift for this carbon is not in the carbonyl region, but this shift is reasonable if the carbon exists in a saturated form, i.e. a hydrate or intramolecular hemiacetal. Saturated forms of CD aldehydes have been observed previously.[28] The precise position of the oxidized glucose residue is not easily determined. Results from taka-amylase cleavage reactions rule out abstraction at the B-glucose ring. The reaction of the enzyme with **2** results in cleavage into an A,B fragment which appears as two peaks by HPLC corresponding to the α- and β-forms for the B portion. The reaction of the enzyme with the main photoproduct produces the same two peaks, whereas different peaks are expected if the B-glucose ring were oxidized. Finally, it must be noted that while **4** appears to be a single species, there is the possibility that it is a mixture of regioisomers and that both $^{13}C$ NMR and HPLC are misleading. Mixtures of CD derivatives can be notoriously difficult to detect. The similarity in the photochemical behavior of **1**–**3** suggests that irradiation of **1** and **3** also results in oxidation of a C6–OH and reduction of the anthraquinone.

Molecular mechanics calculations were employed to determine whether the H abstraction in **2** should show some regioselectivity. These calculations determine the enthalpic contribution to the transition-state energies and ignore the entropic contribution. Although entropy might seem important because the reaction occurs between atomic centers which are many bonds apart, there are relatively few degrees of freedom which bring these centers together. These motions are primarily about the bonds tethering the anthraquinone to the β-CD. The various transition states are diastereomeric, so it is valid to consider the strain energy differences provided by the molecular mechanics program. Of the special force constants used for the transition state calculation, the torsion parameters for the C–C–O—H fragment deserve some comment. Two sets of force constants were used: one set consisted of those for an enolic fragment where V2 = 2.7 and the other set used the same V1 and V3 terms but V2 term was increased to 7.5. The higher V2 value was used by Sauers in calculating Norrish II reactions.[18] The large, positive V2 term, which results in an energy maximum with a 90° dihedral angle, is necessary to enforce in-plane H abstraction from the n-π* excited state. The orientation factor in this mechanism is an entropic effect, so calling it torsional "strain" is not really valid. Nevertheless, incorporation of the larger V2 term does model the photochemical Type II reactions successfully.

**Table I.** Differences in Transition-State Enthalpies in **2** for H-Abstraction Reactions at Various Glucose C6 Methylenes

| calculation parameters | | glucose residue[29] | | | | | |
|---|---|---|---|---|---|---|---|
| torsion term (V2) | dielectric constant | B | C | D | E | F | G |
| 2.7 | 59 | 6.7 | 2.5 | 0.1 | 0 | 2.7 | 15.0 |
| 7.5 | 59 | 4.7 | 2.4 | 2.1 | 0 | 3.8 | 14.1 |
| 2.7 | 1.5 | 7.7 | 0.9 | 0.2 | 0 | 2.3 | 15.0 |
| 7.5 | 1.5 | 6.7 | 2.5 | 3.2 | 0 | 3.0 | 13.7 |
| 2.7 | −1 | 9.1 | 0.9 | 4.3 | 2.9 | 0 | 11.4 |
| 7.5 | −1 | 6.9 | 0.5 | 5.5 | 2.2 | 0 | 9.1 |

The differences in the transition state enthalpies are shown in Table I. Using a normal electrostatic calculation with either a low (1.5) or high (59) dielectric constant (the latter is the average of $H_2O$ and $CH_3CN$) results in the smallest transition-state enthalpy for H abstraction at the E-glucose residue. With the smaller V2 term, abstraction of a D-glucose C6-hydrogen is almost as favorable as the E-glucose C6–H abstraction, but the difference between these becomes much larger when the larger V2 term is employed. In the latter case abstraction at the C-glucose is nearly as favorable as at the D-glucose. Abstractions at the C-, D-, and E-rings involve only small variations of the same basic conformation along the tether (Figure 3). On the other hand, when a distance-dependent dielectric calculation is employed, the electrostatic energy term predominates in the total energy, and abstraction at the F ring (Figure 3) becomes most favorable followed closely by reaction at the C ring. In contrast to the conformations above where reaction occurs with the carbonyl *meta* to the sulfonyl group, these structures involve abstraction with the carbonyl *para* to the sulfonyl group. Also, abstraction occurs in-plane directed towards the sulfonyl group, whereas above it occurs in-plane directed away from the tether. In all calculations abstraction at the B or G ring is unfavorable, particularly at the latter.

The calculations indicate that the abstraction reaction shows some selectivity, especially if using the larger V2 term is a valid method for modeling the in-plane H abstraction. But, the results differ depending on the dielectric constant used in the electrostatic calculations. We favor the results which indicate favorable abstraction at the E ring because the calculation methods, i.e. using a high dielectric constant, model the experimental conditions. The photolysis reaction is carried out in a $H_2O/CH_3CN$ mixture, a solvent system which destroys any hydrophobic interactions. The CD derivatives should be completely solvated, so the terms which do not involve charge interactions in molecular mechanics should be most important. Under these reaction conditions it is inappropriate to use a distance-dependent dielectric constant since the charge interaction terms dominate the total energy. Indeed, some verification that the charge terms are less important in structures calculated with use of the high dielectric constant can be seen in

(28) Gibson, A. R.; Melton, L. D.; Slessor, K. N. *Can. J. Chem.* **1974**, *52*, 3905–3912.

(29) Looking down on the primary face of CD, the glucose rings are labeled A through G proceeding in a counterclockwise direction. See Tabushi, I.; Yuan. L. C. *J. Am. Chem. Soc.* **1981**, *103*, 3574–3575 and references therein.

the number of H bonds. Structures generated with the high dielectric constant process fewer H bonds than those which result when a dielectric constant of 1.5 or -1 is used.

## Conclusions

The photoexcited anthraquinone moieties in **1-3** react by rapid H abstraction. In the presence of a good H-atom-donating solvent such as 2-propanol abstraction is a bimolecular process, whereas without such a solvent, the hydrogen-atom source is the CD itself. The latter process appears to be selective in that only the primary alcohols are oxidized. Furthermore, the reaction appears to be regioselective among the six possible C6-OHs. One major product could be isolated from the photolysis of **2**, suggesting that one methylene group was greatly preferred to the others for abstraction. Molecular modeling results suggest that photooxidation of the E-glucose residue is favored. Finally, these molecules would make poor hosts for photoinduced electron transfer (PET) reactions due to this self-destructive reaction which will occur in the absence of a bound guest. We are exploring the selectivity of H abstraction with other pendant groups as well as searching for better groups for PET reactions.

**Acknowledgment.** Acknowledgment is made to the Thomas F. and Kate Miller Jeffress Memorial Trust for the support of this research. We thank Professor R. Sauers for pointing out the importance of the V2 term in n-$\pi^*$ reactions.

# Molecular Mechanics Studies on Inclusion Compounds of Cyanine Dye Monomers and Dimers in Cyclodextrin Cavities

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**Abstract:** Molecular mechanics calculations were applied to monomers and dimers of cyanine dyes (3,3'-diethyloxacarbocyanine iodide (DOC), 3,3'-diethyloxadicarbocyanine iodide (DODC), and 3,3'-diethyloxatricarbocyanine iodide (DOTC)) in $\beta$- and $\gamma$-cyclodextrin (CD) cavities, to explain the experimental findings that DODC and DOTC dimers are included both in $\beta$- and $\gamma$-CD cavities and that the DOC dimer is included only in a $\gamma$-CD cavity. The calculations show that the inclusion of dye dimers into cyclodextrin leads to stabilization of the total system; however, the $(DOC)_2$-$\beta$-CD system is much less stable than the others, in agreement with experimental findings. Except for DOC and $\beta$-CD, the dimer dye $(D_2)$-CD systems are found to be more stable than the corresponding monomer dye (D)-CD systems. This seemingly puzzling result can be rationalized in terms of the important role of the van der Waals stabilization energy in the inclusion compounds. The present study shows the usefulness of molecular mechanics calculations in the investigation of inclusion compounds.

## Introduction

Molecular mechanics (MM) calculations have been widely used in studies of molecular structures and conformational energies.[1] The application of MM calculations to inclusion compounds, however, has been rather limited.[2,4-7] Wipff et al.[2] studied alkali metal ion complexes of 18-crown-6, using the AMBER program.[3] Watson et al.[4] studied the 1:1 and 1:2 complexes formed between benzo-15-crown-5 and dithiooxamide or thioacetamide, respectively. Geue et al.[5] made a conformational analysis of [111] and [222] cryptands. Dharanipragada et al.[6] treated the design of an optically active macrocyclic host composed of diphenylmethane and 4-phenyl-1,2,3,4-tetrahydroisoquinoline units. Imashiro et al.[7] studied the inclusion of *n*-alkanes in urea. These authors used the MM2 program.

Cyclodextrins (CDs) constitute a very important family of compounds which lead to many types of inclusion compounds which are of fundamental scientific interest and also have potential for practical applications.[8-10] In an experimental study of cyanine dyes (D) complexed with $\beta$- or $\gamma$-CD (CD) in aqueous solution,[11,12] we found that dimerization of dyes can be induced by CDs. Examination of 13 cyanine dyes with different end groups and different lengths of the linking chain, including 3,3'-diethyloxacarbocyanine iodide (DOC), 3,3'-diethyloxadicarbocyanine iodide (DODC), and 3,3'-diethyloxatricarbocyanine iodide (DOTC), (Table I in ref 12) indicated that induced dimerization by CD was governed by steric factors. As an empirical rule, dimerization did not occur for dyes with (a) bulky end groups or bulky atoms on the linking chain and (b) short linking chains. In some cases a bulky end group that hindered induced dimerization of the dye with the short linking chain did not hinder dimerization of the dye with a longer linking chain (e.g. DOC and DODC with $\beta$-CD). These findings strongly suggested that the linking chains of a dye dimer were contained within the cavity of a CD and the end groups were located outside. The $D_2$-CD (2:1), not $D_2$-$(CD)_2$ (2:2), stoichiometry was found from the concentration dependence of absorbance at the wavelength of the dimer band.[12] (The structure suggested above also ruled out the $D_2$-$(CD)_2$ composition, since the linking chains of a dye dimer could not thread two CDs.) These experimental results are consistent with a structure of the inclusion compound in which a dye dimer is contained within the cavity of a CD.

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(1) Burkert, U.; Allinger, N. L. *Molecular Mechanics*; American Chemical Society: Washington, DC, 1982.
(2) Wipff, G.; Weiner, P.; Kollman, P. *J. Am. Chem. Soc.* **1982**, *104*, 3249.
(3) Weiner, P. K.; Kollman, P. A. *J. Comput. Chem.* **1981**, *2*, 287.
(4) Watson, W. H.; Jain, P. C. *J. Inclusion Phenom.* **1986**, *4*, 397.
(5) Geue, R.; Jacobson, S. H.; Pitzer, R. *J. Am. Chem. Soc.* **1986**, *108*, 1150.
(6) Dharanipragada, R.; Ferguson, S. B.; Diedrich, F. *J. Am. Chem. Soc.* **1988**, *110*, 1679.
(7) Imashiro, F.; Kuwahara, D.; Nakai, T.; Terao, T. *J. Chem. Phys.* **1989**, *90*, 3356.
(8) Bender, M. L.; Komiyama, M. *Cyclodextrin Chemistry*; Springer: New York, 1977.
(9) Saenger, W. *Angew. Chem., Intl. Ed. Engl.* **1980**, *19*, 344.
(10) Ramamurthy, V.; Eaton, D. F. *Acc. Chem. Res.* **1988**, *21*, 300.
(11) Kasatani, K.; Ohashi, M.; Kawasaki, M.; Sato, H. *Chem. Lett.* **1987**, 1633.
(12) Kasatani, K.; Ohashi, M.; Sato, H. *Carbohydr. Res.* **1989**, *192*, 197.

0002-7863/90/1512-5824$02.50/0 