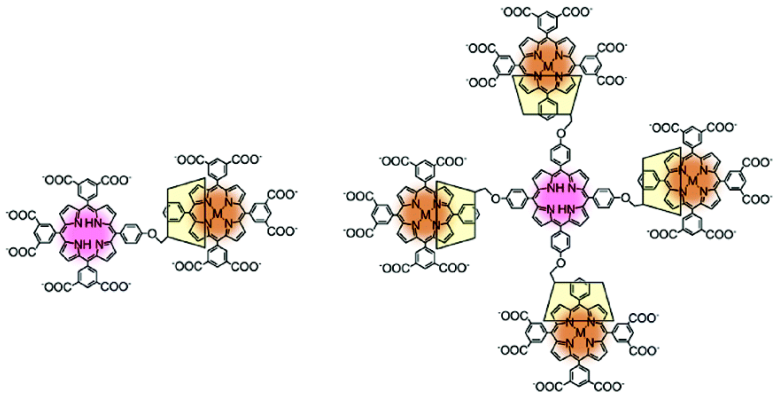
Article

Convenient Scaffold for Forming Heteroporphyrin Arrays in Aqueous Media

Koji Kano, Ryuhei Nishiyabu, Tomoko Yamazaki, and Iwao Yamazaki

J. Am. Chem. Soc., **2003**, 125 (35), 10625-10634• DOI: 10.1021/ja035055q • Publication Date (Web): 08 August 2003



J|A|C|S
ARTICLES
Published on Web 08/08/2003

Convenient Scaffold for Forming Heteroporphyrin Arrays in Aqueous Media

Koji Kano,*,† Ryuhei Nishiyabu,† Tomoko Yamazaki,‡ and Iwao Yamazaki‡

Contribution from the Department of Molecular Science and Technology, Faculty of Engineering, Doshisha University, Kyotanabe, Kyoto 610-0321, Japan, and Department of Chemical Process Engineering, Graduate School of Engineering, Hokkaido University, Kita-13-Nishi-8, Kita-ku, Sapporo 060-8628, Japan

Received March 7, 2003; E-mail: kkano@mail.doshisha.ac.jp.

Abstract: A new methodology for preparing heteroporphyrin arrays in aqueous solution has been presented. The present method is based on the extremely strong ability of heptakis(2,3,6-tri-*O*-methyl)-β-cyclodextrin (TMe-β-CD) to include 5,10,15,20-tetrakis(*p*-substituted-phenyl)porphyrins (Por) affording trans-type 1:2 complexes of the porphyrins and TMe-β-CD. Two different Por-per-*O*-methylated β-CD (per-Me-β-CD) conjugates were synthesized. Conjugate **2** was prepared by an S_N2 reaction of 5,10,15,20-tetrakis(*p*-hydroxyphenyl)porphyrin and per-*O*-methylated β-cyclodextrin having one primary OTs group. Four per-Me-β-CD moieties are attached to the meso positions of **2**. Conjugate **3**, synthesized from 5-(*p*-hydroxyphenyl)-10,15,20-tris(3,5-dicarboxyphenyl)porphyrin and monotosylated per-*O*-methylated β-cyclodextrin, has one per-Me-β-CD moiety at the periphery of the porphyrin. Conjugate **2** yields a stable 1:4 complex with the zinc complex of 5-phenyl-10,15,20-tris(3,5-dicarboxyphenyl)porphyrin (**8**) in the dissociated form. In this system, the energy transfer from photoexcited Zn-**8** to free base **2** occurs with 85% efficiency. Conjugate **3** forms a very stable 1:1 complex with Zn-**8** ($K = (7.0 \pm 0.3) \times 10^5$ dm^3 mol^{-1}) with an energy transfer efficiency (93%) larger than that obtained in the case of **2**. The structure of the **3**−Zn-**8** complex, which can account for the efficient energy transfer, was deduced from ^{1}H NMR spectroscopy. Intramolecular fluorescence quenching of **2** and **3** by Fe(III)-**8** also occurred through an electron-transfer process as the main quenching mechanism. The present method is a very simple and convenient means to construct various heteroporphyrin arrays in aqueous solution.

Introduction

A porphyrin (Por)-β-cyclodextrin (β-CD) conjugate, where the cyclodextrin (CD) moiety is attached to the para position of the peripheral phenyl group of a tetraarylporphyrin, was synthesized for the first time by Gonzalez et al.[1] The Por-CD conjugate is a very attractive supramolecular system, since it possesses simple functions closely mimicking those of biological materials. In particular, the Por and CD parts of a conjugate are regarded as representing artificial coenzyme or active sites and apoenzyme or binding sites, respectively. From this viewpoint, several Por-β-CD conjugate systems were prepared to mimic the process of photosynthesis.[2−5] A cyclodextrin-sandwiched porphyrin and its ferric complex were also synthesized in an effort to reproduce the function of oxygenases.[6] A tetraphenylporphyrin having a di-*O*-methylated CD moiety at an ortho position of a phenyl group catalyzed the enantioselective photooxidation of α-pinene in organic media.[7] Breslow et al. modeled cytochrome P-450 in the Por-β-CD conjugate **1** having four β-CD moieties at the meso positions of the tetraarylporphyrin (Figure 1).[8] The metal complexes of **1** can bind stilbene derivatives with hydrophobic substituents at the 4,4′-positions of the substrates by incorporating the hydrophobic tails into the β-CD cavities at the 5- and 15-positions of porphyrin **1**. Substrate-selective oxidation of stilbenes by iodosyl benzene has been achieved using **1** as an artificial enzyme.[8a] A carotene dioxygenase model composed of a metalloporphyrin and two β-CD moieties was also prepared.[9] Most of these Por-CD conjugates carry an unmodified β-CD moiety or moieties.

† Doshisha University.
‡ Hokkaido University.

(1) Gonzalez, M. C.; McIntosh, A. R.; Bolton, J. R.; Weedon, A. C. *J. Chem. Soc., Chem. Commun*. **1984**, 1138−1140.
(2) Nango, M.; Higuchi, M.; Gondo, H.; Hara, M. *J. Chem. Soc., Chem. Commun*. **1989**, 1550−1553.
(3) Carofiglio, T.; Fornasier, V.; Gennari, G.; Lucchini, V.; Simonato, L.; Tonellato, U. *Tetrahedron Lett*. **1997**, *38*, 7919−7922.
(4) Carofiglio, T.; Fornasier, R.; Lucchini, V.; Simonato, L.; Tonellato, U. *J. Org. Chem*. **2000**, *65*, 9013−9021.
(5) Lang, K.; Král, V.; Kapusta, P.; Kubát, P.; Vasek, P. *Tetrahedron Lett*. **2002**, *43*, 4919−4922.
(6) (a) Kuroda, Y.; Hiroshige, T.; Sera, T.; Shiroiwa, Y.; Tanaka, H.; Ogoshi, H. *J. Am. Chem. Soc*. **1989**, *111*, 347−350. (b) Kuroda, Y.; Ito, M.; Sera, T.; Ogoshi, H. *J. Am. Chem. Soc*. **1993**, *115*, 7003−7004.
(7) Weber, L.; Imiolczyk, I.; Haufer, G.; Rehorek, D.; Henning, H. *J. Chem. Soc., Chem. Commun*. **1992**, 301−303.
(8) (a) Breslow, R.; Zhang, X.; Xu, R.; Maletic, M.; Merger, R. *J. Am. Chem. Soc*. **1996**, *118*, 11678−11679. (b) Breslow, R.; Huang, Y.; Zhang, X.; Yang, *J. Proc. Natl. Acad. Sci. U. S. A*. **1977**, *94*, 11 156−11 158. (c) Breslow, R.; Zhang, X.; Huang, Y. *J. Am. Chem. Soc*. **1997**, *119*, 4535−4536. (d) Breslow, D.; Gabriele, B.; Yang, J. *Tetrahedron Lett*. **1998**, *39*, 2887−2890. (e) Yang, J.; Breslow, R. *Angew. Chem., Int. Ed*. **2000**, *39*, 2692−2694. (f) Yang, J.; Gabriele, B.; Belvedere, S.; Huang, Y.; Breslow, R. *J. Org. Chem*. **2002**, *67*, 5057−5067.
(9) (a) French, R. R.; Wirz, J.; Woggon, W.-D. *Helv. Chim. Acta* **1998**, *81*, 1521−1527. (b) French, R. R.; Holzer, P.; Leuenberger, M. G.; Woggon, W.-D. *Angew. Chem., Int. Ed*. **2000**, *39*, 1267−1269.

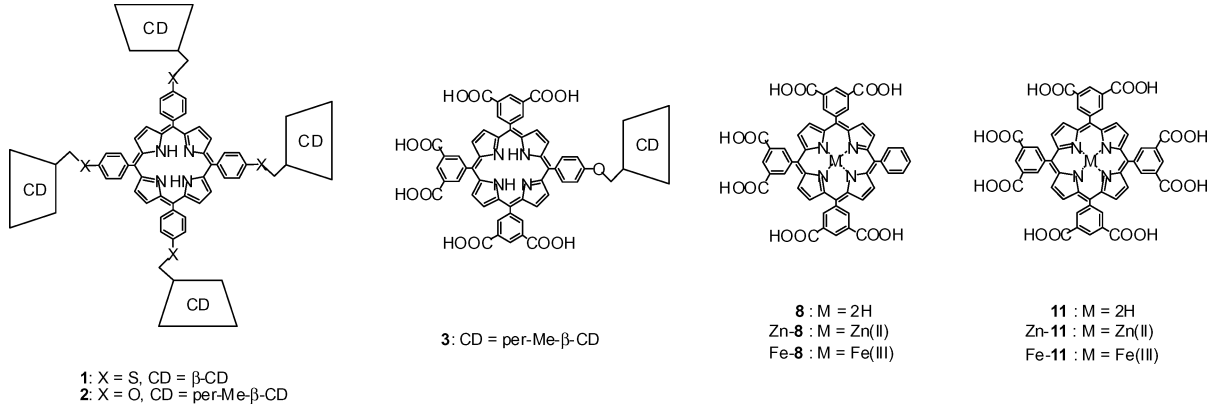


Figure 1. Structures of Por-CD conjugates and guest porphyrins.

Recent studies revealed that heptakis(2,3,6-tri-*O*-methyl)-β-cyclodextrin (TMe-β-CD) forms extraordinarily stable 1:2 complexes with water-soluble porphyrins (Por: TMe-β-CD = 1:2), while the complexes with native β-CD are very unstable.[10,11] These findings led us to design the Por-CD conjugate **2** (Figure 1), which is a tetraphenylporphyrin derivative where the para-positions of the phenyl groups are substituted by per-*O*-methylated β-CD (per-Me-β-CD) moieties. Conjugate **2** was expected to easily form various heteroporphyrin arrays through noncovalent bonding simply by mixing **2** with another water-soluble porphyrin in aqueous solution.

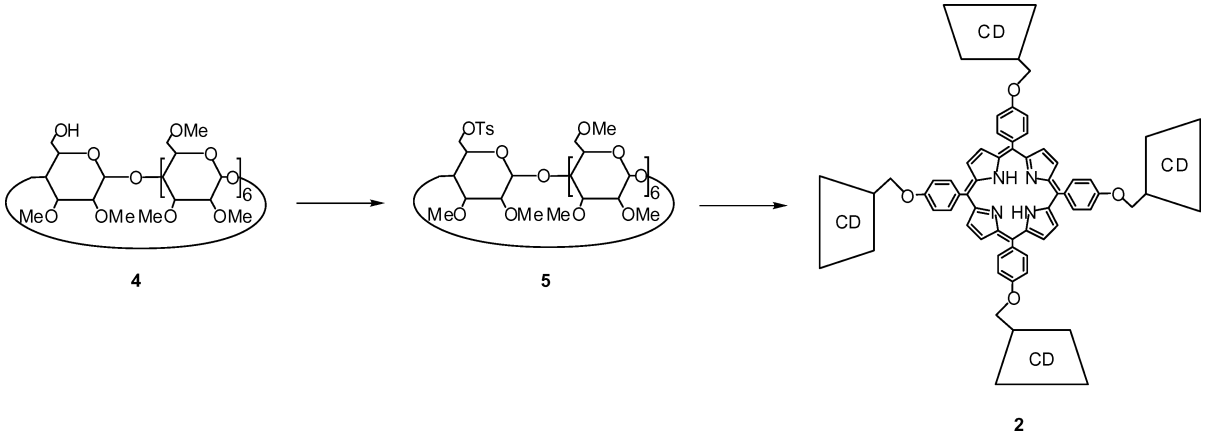
Developing and refining methods for the preparation of heteroporphyrin arrays are very important in areas relating to the study of energy transfer and/or electron transfer in artificial photosynthetic systems. To date, the organization of heteroporphyrin molecules has been achieved by using covalent bonds,[12,13] coordination bonds to metal ions,[14−27] complementary hydrogen bonds between nucleo bases,[28] and Coulomb interactions.[29,30] Porphyrin arrays constructed by covalent bonds between the porphyrin moieties require great effort to synthesize each array. Although the use of coordination bonds is rather sophisticated, the systems employed require, in some cases, the inclusion of additional heavy atom(s), which quenches the fluorescence of the porphyrin. To the best of our knowledge, there is no example of porphyrin architecture that has been prepared through the use of coordination bonds in aqueous solution. The employment of complementary hydrogen bonding is a clever approach used in the preparation of heteroporphyrin arrays. However, this approach can only be used in organic solvents. Although Coulomb interactions between oppositely charged porphyrins are very convenient for forming heteroporphyrin aggregates in aqueous solution,[29] this concept is hardly applied for a general method to prepare the porphyrin arrays having well-defined stoichiometry. An interesting method for forming cationic heteroporphyrin pile blocks has been developed by using a polyanionic calix[4]arene as a connector of the cationic porphyrin molecules.[30] We prepared a new strategy for the construction of heteroporphyrin arrays just by mixing two types of porphyrins in aqueous solution. We took advantage of the extraordinarily strong ability of TMe-β-CD to include aryl moieties at the meso positions of the porphyrins.[10,11] For example, TMe-β-CD quantitatively yields a 1:2 complex of tetrakis(*p*-sulfonatophenyl)porphyrin ($TPPS_4$) in aqueous solution even when the concentration of $TPPS_4$ is below 10^{-6} mol dm^{-3}, although the ability of β-CD to complex with $TPPS_4$ is much weaker.[11] Conjugates **2** and **3** (Figure 1) were designed as the building blocks of heteroporphyrin arrays that are soluble in aqueous solution.

Results

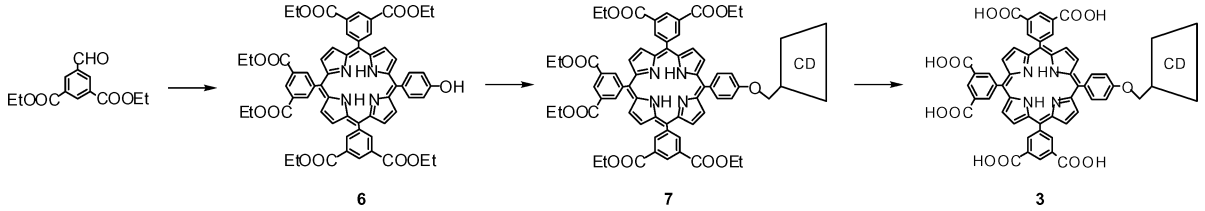
Synthesis of Porphyrins. Por-CD conjugate **2** was synthesized via a route shown in Scheme 1. Monohydroxy per-*O*-

(10) Carofiglio, T.; Fornasier, R.; Lucchini, Y.; Rosso, C.; Tonellato, U. *Tetrahedron Lett*. **1996**, *37*, 8019−8022.
(11) (a) Kano, K.; Tanaka, N.; Minamizono, H.; Kawakita, Y. *Chem. Lett*. **1996**, 925−926. (b) Kano, K.; Nishiyabu, R.; Asada, T.; Kuroda, Y. *J. Am. Chem. Soc*., **2002**, *124*, 9937−9944.
(12) (a) Prathapan, S.; Johnson, T. E.; Lindsey, J. S. *J. Am. Chem. Soc*. **1993**, *115*, 7519−7520. (b) Hsiao, J.-S.; Krueger, B. P.; Wagner, R. W.; Johnson, J. E.; Delaney, J. K.; Mauzerall, D. C.; Fleming, G. R.; Lindsey, J. S.; Bocian, D. F.; Donohoe, R. J. *J. Am. Chem. Soc*. **1996**, *118*, 11 181−11 193. (c) Li, J.; Diers, J. R.; Seth, J.; Yang, S. I.; Bocian, D. F.; Holten, D.; Lindsey, J. S. *J. Org. Chem*. **1999**, *64*, 9090−9100. (d) Kuciauskas, D.; Liddell, P. A.; Lin, S.; Jphnson, T. E.; Weghorn, S. J.; Lindsey, J. S.; Moore, A. L. Moore, T. A.; Gust, D. *J. Am. Chem. Soc*. **1999**, *121*, 8604−8614.
(13) (a) Choi, M.-S.; Aida, T.; Yamazaki, T.; Yamazaki, I. *Angew. Chem., Int. Ed*. **2001**, *40*, 3194−3198. (b) Choi, M.-S.; Aida, T.; Yamazaki, T.; Yamazaki, I. *Chem.—Eur. J*. **2002**, *8*, 2668−2678.
(14) (a) Brum, A. M.; Atherton, S. J.; Harriman, A.; Heitz, V.; Sauvage, J.-P. *J. Am. Chem. Soc*. **1992**, *114*, 4632−4639. (b) Chambron, J.-C.; Harriman, A.; Heitz, V.; Sauvage, J.-P. *J. Am. Chem. Soc*. **1993**, *115*, 6109−6114. (c) Andersson, M.; Linke, M.; Chambron, J.-C.; Davidsson, J.; Heitz, V.; Sauvage, J.-P.; Hammarström, L. *J. Am. Chem. Soc*. **2000**, *122*, 3526−3527.
(15) (a) Chi, X.; Guerin, A. J.; Haycock, R. A.; Hunter, C. A.; Sarson, L. *J. Chem. Soc., Chem. Commun*. **1995**, 2567−2569. (b) Hunter, C. A.; Hyde, R. K. *Angew. Chem. Int. Ed. Engl*. **1996**, *35*, 1936−1939. (c) Haycock, R. A.; Yartsev, A.; Michelsen, U.; Sundström, V.; Hunter, C. A. *Angew. Chem., Int. Ed*. **2000**, *39*, 3616−3619.
(16) Yuan, H.; Thomas, L.; Woo, L. K. *Inorg. Chem*. **1996**, *35*, 2808−2817.
(17) Slone, R. V.; Hupp, J. T. *Inorg. Chem*. **1997**, *36*, 5422−5423.
(18) Burrell, A. K.; Officer, D. L.; Reid, D. C. W.; Wild, K. Y.*Angew. Chem., Int. Ed*. **1998**, *37*, 114−116.
(19) Fan, J.; Whiteford, J. A.; Olenyuk, B.; Levin, M. D.; Stang, P. J.; Fleischer, E. B. *J. Am. Chem. Soc*. **1999**, *121*, 2741−2752.
(20) Kim, H.-J.; Bampos, N.; Sanders, J. K. M. *J. Am. Chem. Soc*. **1999**, *121*, 8120−8121.
(21) Prodi, A.; Indelli, M. T.; Kleverlaan, C. J.; Scandola, F.; Alessio, E.; Gianferrara, T.; Marzilli, L. G. *Chem.—Eur. J*. **1999**, *5*, 2668−2679.
(22) (a) Kuroda, Y.; Sugou, K.; Sasaki, K. *J. Am. Chem. Soc*. **2000**, *122*, 7833−7834. (b) Sugou, K.; Sasaki, K.; Kitajima, K.; Iwaki, T.; Kuroda, Y. *J. Am. Chem. Soc*. **2002**, *124*, 1182−1183.
(23) Lo Schiavo, S.; Pocsfalvi, G.; Serroni, S.; Cardiano, P.; Piraino, P. *Eur. J. Inorg. Chem*. **2000**, 1371−1375.
(24) (a) Iengo, E.; Milani, B.; Zangrando, E.; Geremia, S.; Alessio, E. *Angew. Chem., Int. Ed*. **2000**, *39*, 1096−1099. (b) Prodi, A.; Kleverlaan, C. J.; Indelli, M. T.; Scandola, F.; Alessio, E.; Iengo, E. *Inorg. Chem*. **2001**, *40*, 3498−3504.
(25) Ogawa, K.; Kobuke, T. *Angew. Chem., Int. Ed*. **2000**, *39*, 4070−4073.
(26) Rucareanu, S.; Mongin, O.; Schuwey, A.; Hpyler, N.; Gossauer, A.; Amrein, W.; Hediger, H.-U. *J. Org. Chem*. **2001**, *66*, 4973−4988.
(27) Splan, K. E.; Keefer, M. H.; Massari, A. M.; Walters, K. A.; Hupp, J. T. *Inorg. Chem*. **2002**, *41*, 619−621.
(28) Sessler, J. L.; Wang, B.; Harriman, A. *J. Am. Chem. Soc*. **1995**, *117*, 704−714.
(29) Endisch, C.; Fuhrhop, J.-H.; Buschmann, J.; Luger, P.; Siggel, U. *J. Am. Chem. Soc*. **1996**, *118*, 6671−6680.
(30) Moschetto, G.; Lauceri, R.; Gulino, F. G.; Sciotto, D.; Purrello, R. *J. Am. Chem. Soc*. **2002**, *124*, 14536−14537.

Scheme 1



Scheme 2



methylated β-CD (**4**) was obtained according to the procedures previously described.[31] Compound **4** was tosylated affording **5,** which yielded **2** (36%) upon reaction with 5,10,15,20-tetrakis-(4-hydroxyphenyl)porphyrin in dry DMF containing K_2CO_3. Spectroscopic data indicated that **2** in aqueous media aggregates spontaneously at higher concentrations ($\sim 5 \times 10^{-4}$ mol dm^{-3} for ^{1}H NMR measurements) but exists as the monomer at lower concentrations ($\sim 1 \times 10^{-6}$ mol dm^{-3} for fluorescence measurements).

The porphyrin having one per-Me-β-CD moiety (**3**) was prepared via the route outlined in Scheme 2. The six carboxy groups of **3** are necessary in an effort to prevent self-inclusion and to solvate the Por-CD conjugate in water. Additionally, the carboxylate groups are expected to check self-aggregation of the porphyrin in aqueous solution. Six singlet signals due to the primary OCH_3 groups were observed with **3** at 0.99−2.90 ppm (vide infra). The signals of the secondary OCH_3 groups were observed at 3.3−3.7 ppm. The primary OCH_3 group signals of **3** shifted to higher magnetic fields due to ring current effects of the porphyrin ring. It is quite reasonable to assume that the per-Me-β-CD moiety of **3** sits on the porphyrin ring, where the primary OCH_3 groups face the porphyrin ring.

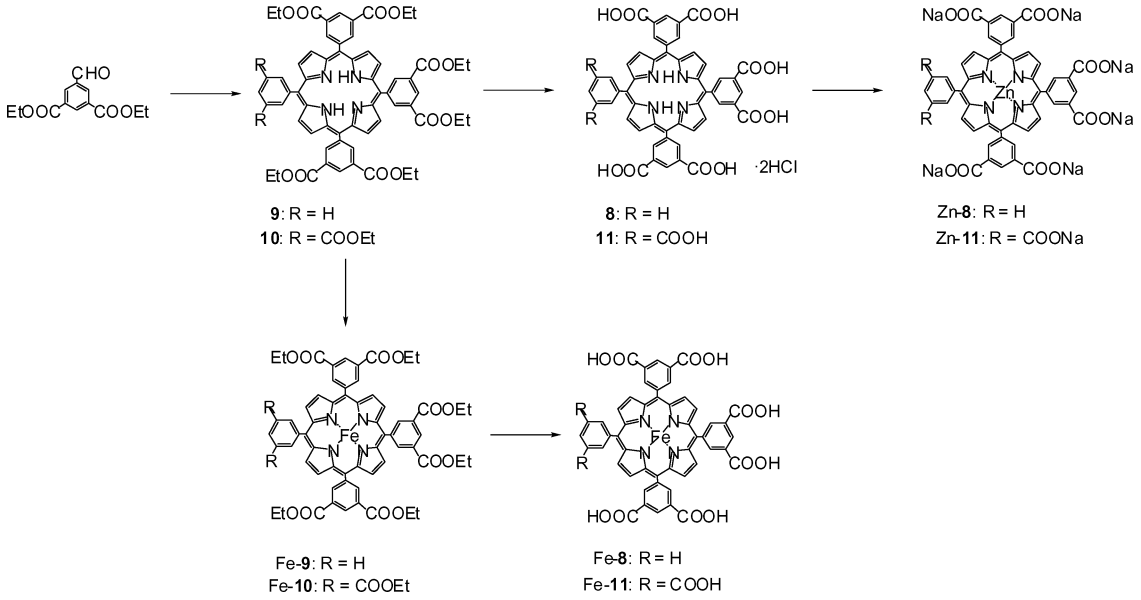
In an effort to prepare heteroporphyrin arrays, the Zn(II) and Fe(III) complexes of tetraphenylporphyrinhexacarboxylic acid (**8**) were synthesized (Scheme 3). The Lindsey's method[32] afforded both **9** and **10**. Porphyrins **9** (12% yield) and **10** (10%), separated by silica gel column chromatography, were hydrolyzed to afford **8** and **11**, respectively. The Zn(II) complex of **8** (Zn-**8**) was prepared by reacting **8** with zinc oxide in water and purified by means of gel filtration and ion-exchange column chromatography (75%). The Fe(III) complex of **8** (Fe-**8**) was prepared by reaction of the ester **10** with $FeCl_2$ in DMF−dichloromethane yielding Fe-**10** (81%), which was hydrolyzed in aqueous methanol containing KOH.

Complexation of Zn-8 and Fe-8 with TMe-β-CD. The interactions of Zn-**8** and Fe-**8** with TMe-β-CD in aqueous solution were initially investigated in an effort to foresee the structure and stability of the porphyrin arrays. The absorption spectrum of Zn-**8** changed continuously upon addition of TMe-β-CD (supporting information). In particular, addition of TMe-β-CD caused a decrease in the optical densities (OD) at 422 nm and a simultaneous increase in the ODs at 424 nm. A Job's plot corroborated the formation of a 1:1 complex. The UV−vis titration curves fitted well with the formation of a 1:1 complex and yielded a binding constant (K) of $(1.5 \pm 0.1) \times 10^7$ dm^3 mol^{-1} in 0.1 mol dm^{-3} phosphate buffer at pH 7.0 and 25 °C. ^{1}H NMR data including ROESY clearly revealed the presence of the phenyl moiety and the absence of any carboxylate groups of Zn-**8** being incorporated into the TMe-β-CD cavity from the secondary OCH_3 group side (supporting information). The two CO_2^- groups of each dicarboxyphenyl group of Zn-**8** prevent the incorporation of this substituent into the TMe-β-CD cavity. We reported that the anionic porphyrin, $TPPS_4$, formed an extraordinarily stable 1:2 complex with TMe-β-CD ($TPPS_4$: TMe-β-CD = 1:2) in aqueous solution and that the K value (K_1K_2) was too large to be determined.[11] Although the complex of Zn-**8** and TMe-β-CD is rather less stable than that of $TPPS_4$, the K value for the Zn-**8**−TMe-β-CD complex is still large. A K value of $(1.8 \pm 0.3) \times 10^6$ dm^3 mol^{-1} was also determined from the UV−vis absorption spectroscopic titration for the 1:1 complex of Fe-**8** and TMe-β-CD in 0.01 mol dm^{-3} succinic acid buffer at pH 5.5 and 25 °C. These data suggest that the Por-CD conjugates **2** and **3** produced stable heteroporphyrin arrays by incorporating Zn-**8** and Fe-**8.**

Complexation of 2 and 3 with Zn-8 and Fe-8. The employment of UV−vis absorption spectroscopy in the inves-

(31) Chen, Z.; Bradshaw, J. S.; Lee, M. L. *Tetrahedron Lett.* **1996**, *37* (*38*), 6831−6834.
(32) (a) Lindsey, J. S. In *The Porphyrin Handbook*; Kadish, K. M.; Smith, K. M.; Guilard, R., Eds.; Academic Press: San Diego, 2000; Vol. I, pp 45−118. (b) Fudickar, W.; Zimmerman, J.; Ruhlmann, L.; Scheider, J.; Röder, B.; Siggel, U.; Fuhrhop, J.-H. *J. Am. Chem. Soc.* **1999**, *121*, 9539−9545.

Scheme 3



tigation of complexation of **2** and **3** with Zn-**8** and Fe-**8** is very difficult due to the overlap of the absorption bands. A microcalorimetric method was applied to determine the stability of the heteroporphyrin arrays. The sigmoidal calorimetric titration curve obtained for the **3**−Zn-**8** system fitted well with the theoretical curve for 1:1 complexation (supporting information). The *K* value and the enthalpy (ΔH) and entropy changes (ΔS) for complexation of **3** with Zn-**8** in 0.1 mol dm^{-3} phosphate buffer at pH 7.0 and 25 °C were determined to be $(7.02 \pm 0.33) \times 10^5$ dm^3 mol^{-1}, -47.1 ± 0.4 kJ mol^{-1}, and -46.1 ± 2.1 J mol^{-1} K^{-1}, respectively. The *K* value for the **3**−Zn-**8** system was considerably smaller than that for the TMe-β-CD−Zn-**8** system. This could be ascribed to electrostatic repulsion between the CO_2^- groups of **3** and Zn-**8**. The result of the calorimetric titration for the **2**−Zn-**8** system is shown in Figure 2. As with the case of the **3**−Zn-**8** system, a sigmoidal titration curve was obtained. The midpoint of the titration curve corresponds to a molar ratio of ca. 3.3, suggesting the formation of 1:3 and/or 1:4 complexes of **2** and Zn-**8**. Since there are no CO_2^- groups in **2**, Zn-**8** should be more strongly bound to **2** than in the case of **3**. The formation of a 1:4 complex of **2** and Zn-**8** was supported by UV−vis absorption spectroscopy. Figure 3 shows the differential absorption spectral changes of Zn-**8** upon addition of **2**. Since the absorption bands of **2** and Zn-**8** overlap, analysis of the data is considerably difficult; however, the change in the absorbance at 604 nm is characteristic. As shown in Figure 3, the difference in the absorbances (ΔA) at 604 nm decreased as the molar ratio of **2**:Zn-**8** approached 1:4 and then increased above this molar ratio. This result confirms the formation of a stable 1:4 complex of **2** and Zn-**8**.

The interactions of **2** and **3** with Fe-**8** were also investigated by means of microcalorimetry. The data for the **3**−Fe-**8** system indicated the formation of a 1:1 complex, with *K*, ΔH, and ΔS being $(2.56 \pm 0.17) \times 10^5$ dm^3 mol^{-1}, -60.4 ± 0.8 kJ mol^{-1}, and -99.0 ± 3.2 J mol^{-1} K^{-1}, respectively. In comparison to the data for the **3**−Zn-**8** system, the complexation is enthalpically more favorable and entropically less favorable. Although the calorimetric titration curve for the **2**−Fe-**8** system suggested

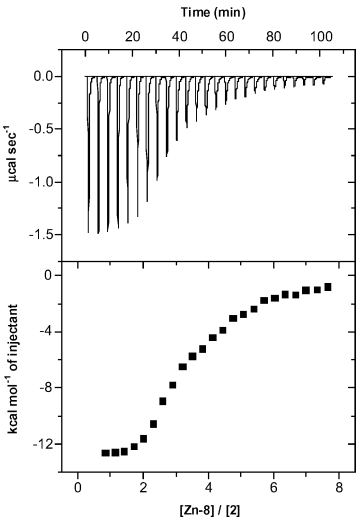


Figure 2. Titration of 1.0×10^{-5} mol dm^{-3} of **2** with 25 aliquots (10 mL each) of Zn-**8** (4.0×10^{-4} mol dm^{-3}) in 0.1 mol dm^{-3} phosphate buffer solution at pH 7.0 and 25 °C. The top panel shows the raw data, denoting the amount of generated heat after each injection of Zn-**8**. The bottom panel shows the plot of amount of heat generated per injection as a function of the molar ratio of Zn-**8** to **2**.

the formation of a multi-porphyrin array, further detailed analysis could not be done.

Energy Transfer from Photoexcited Zn-8 to 2 and 3. Figure 4 shows the fluorescence spectra of **2**, Zn-**8**, and an equimolar mixture of **2** and Zn-**8** in 0.1 mol dm^{-3} phosphate buffer at pH 7.0. Each sample was excited at 556 nm, at which point the extinction coefficients of **2** and Zn-**8** are 7715 and 18 860 dm^3 mol^{-1} cm^{-1}, respectively. Therefore Zn-**8** is preferentially excited at 556 nm. The fluorescence intensity of **2** in the presence of equimolar amounts of Zn-**8** is ca. 3 times larger than that in the absence of Zn-**8**, indicating that energy transfer from photoexcited Zn-**8** (donor) to **2** (acceptor) had occurred. It is well-known that the singlet energies of photoexcited Zn(II) complexes of porphyrins are transferred to the porphyrin-free bases through the Förster's mechanism.[12,13,15c,22,27,28] Figure 5 shows the decrease in fluorescence intensity of Zn-**8** at 605 nm and the increase in fluorescence intensity of **2** at

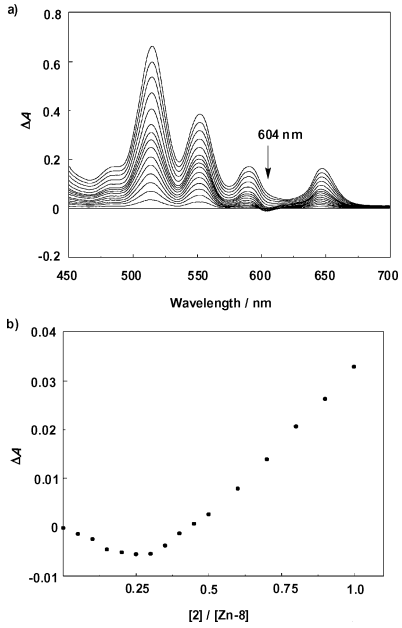


Figure 3. (a) Differential absorption spectral changes of Zn-**8** (2.0×10^{-5} mol dm^{-3}) upon addition of **2** in 0.1 mol dm^{-3} phosphate buffer at pH 7.0 and 25 °C and (b) changes in absorbances (ΔA) at 604 nm.

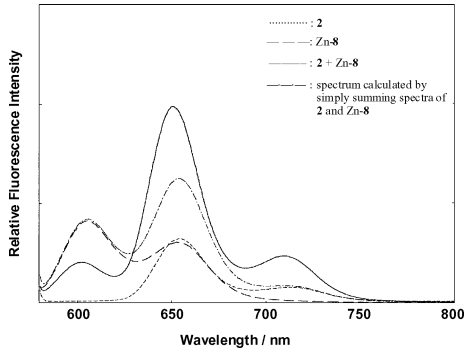


Figure 4. Fluorescence spectra of **2**, Zn-**8**, and equimolar mixture of Zn-**8** and **2** in 0.1 mol dm^{-3} phosphate buffer at pH 7.0 and 25 °C. The concentration of each porphyrin was 1×10^{-6} mol dm^{-3} and each sample was excited at 556 nm.

712 nm upon addition of **2** into the 1×10^{-5} mol dm^{-3} Zn-**8** solution. Up to [**2**]/[Zn-**8**] = 0.25, both Zn-**8** and **2** fluorescence intensities changed abruptly. At [**2**]/[Zn-**8**] > 0.25, the changes in fluorescence intensities were less abrupt. Since the fluorescence lifetime of Zn-**8** is 1750 ps in the absence of acceptor (vide infra), intermolecular energy transfer via a dynamic process would be negligible under the present conditions. It can be concluded, therefore, that the very efficient energy transfer from Zn-**8** to **2** proceeds intramolecularly through the formation of the **2**−Zn-**8** inclusion complex(es). No energy transfer occurred when the Zn complex (Zn-**11**) of **11**, which does not interact with **2** at all, was used in place of Zn-**8**.

As in the case of **2**, the energy transfer occurred from photoexcited Zn-**8** to **3** possessing one per Me-β-CD moiety. The results are shown in Figure 5. Both the decrease in fluorescence intensity of the donor (Zn-**8**) and the increase in fluorescence intensity of the acceptor (**3**) are less abrupt than in the case of **2**. The photoenergy is gathered more efficiently by **2** than by **3**. At [acceptor]/[donor] < 1, donor molecules are captured by **2** more effectively than by **3** due to the greater number of donor binding sites present in **2**. The largest

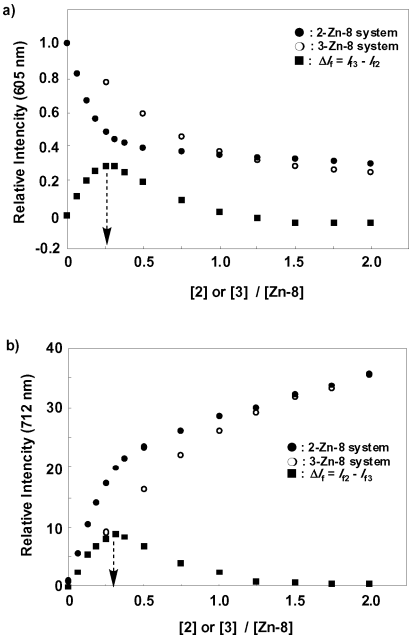


Figure 5. Changes in fluorescence intensities at (a) 605 nm and (b) 712 nm upon addition of **2** (l) and **3** (m) to the solution of Zn-**8** (1.0×10^{-5} mol dm^{-3}) in 0.1 mol dm^{-3} phosphate buffer at pH 7.0 and 25 °C and differences in the fluorescence intensities (ΔI_f) between the systems of **2** and **3** (n).

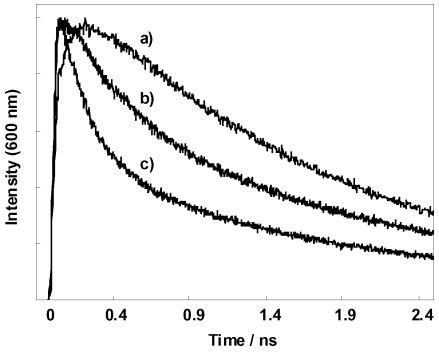


Figure 6. Fluorescence decay profiles of (a) Zn-**8** (1×10^{-5} mol dm^{-3}), (b) Zn-**8** in the presence of equimolar amounts of **2** (1×10^{-5} mol dm^{-3}), and (c) Zn-**8** in the presence of equimolar amounts of **3** (1×10^{-5} mol dm^{-3}). The decays were monitored at 600 nm in 0.1 mol dm^{-3} phosphate buffer at pH 7.0 upon exciting Zn-**8** at 415 nm.

difference in photon-gathering efficiency between **2** and **3** ($\Delta I_f = |I_{f2} - I_{f3}|$) should be observed at [acceptor]/[donor] = 0.25 if the binding constants for complexation of **2** and **3** with Zn-**8** are satisfactorily large. Indeed, the maximum ΔI_f was found at [acceptor]/ [donor] = 0.25 (Figure 5). In other words, the acceptor molecule **2** gathers four Zn-**8** molecules even at low Zn-**8** concentrations.

The fluorescence decay curves of Zn-**8** (1×10^{-5} mol dm^{-3}) in 0.1 mol dm^{-3} phosphate buffer at pH 7.0 in the absence and presence of equimolar amounts of **2** and **3** are shown in Figure 6. Zn-**8** was excited at 415 nm and the time course of the fluorescence of Zn-**8** was monitored at 600 nm. The fluorescence lifetime of Zn-**8** in the absence of an energy acceptor is 1750 ps, while the decay in the presence of **2** was apparently composed of three components: 128 ps (34%), 494 ps (22%), and 2237 ps (44%). The longest component is due to the Zn-**8** molecule, which does not participate in energy transfer. The two shorter components can be ascribed to the excited Zn-**8** molecules whose energies were transferred to **2**. The geometry

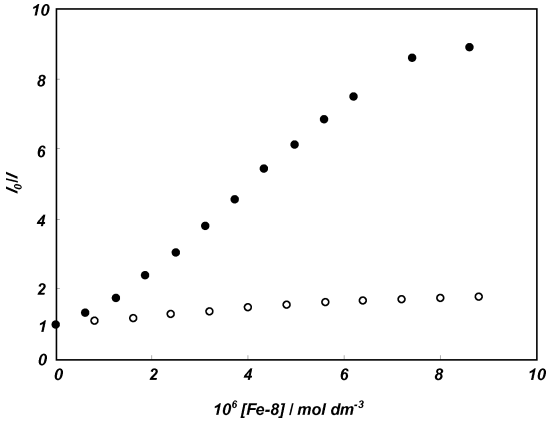


Figure 7. Stern-Volmer plots for fluorescence quenching of **2** (1.0×10^{-5} mol dm^{-3}, l) and **3** (1.0×10^{-5} mol dm^{-3}, m) by Fe-8 in 0.01 mol dm^{-3} succinic buffer solutions (pH 5.5) containing 0.1 mol dm^{-3} $NaClO_4$. The porphyrin free bases were excited at 590 nm and the fluorescence intensities were monitored at 700 nm.

between the donor and acceptor parts of the **2**−Zn-**8** complex is anticipated to be rather complicated since the acceptor **2** has four binding sites. Four shorter components might exist in the fluorescence decay of Zn-**8**. Presumably, two components were apparently observed. The mean rate constant (k_{EnT}) and the efficiency of the energy transfer ($\Phi = k_{EnT}\tau_{DA} = 1 - \tau_{DA}/\tau_D$, where τ_D and τ_{DA} represent the fluorescence lifetimes of donor in the absence and presence of acceptor) in the **2**−Zn-**8** system was calculated to be 3.1×10^9 s^{-1} and 85%, respectively.

The fluorescence decay of Zn-**8** in the presence of equimolar amounts of **3** was composed of 122 ps (73%) and 1800 ps (27%). In this case only one binding site exists in **3**, and so, the fluorescence decay was relatively simple. The rate constant and the energy transfer efficiency were 7.6×10^9 s^{-1} and 93%, respectively. Very efficient energy transfer took place in the **3**−Zn-**8** system.

Fluorescence Quenching of 2 and 3 by Fe-8. The interactions of **2** and **3** with Fe-**8** were also studied. The fluorescence spectral changes of **2** and **3** were monitored in 0.01 mol dm^{-3} succinic acid buffer at pH 5.5 as a function of [Fe-**8**]. Measurements were carried out at pH 5.5 to completely eliminate the contribution of the μ-oxo dimers. UV−vis spectroscopy indicated that Fe-**11** did not form the μ-oxo dimer even in alkaline solution. The K_a value for the equilibrium between the diaqua and monohydroxo-monoaqua forms of Fe-**11** was determined to be 8.0. Meanwhile, formation of the μ-oxo dimer was detected with Fe-**8** in aqueous alkaline solution when [Fe-**8**] > 1×10^{-5} mol dm^{-3}. At lower concentrations of Fe-**8**, the pK_a value for the equilibrium between the diaqua and monohydroxo-monoaqua forms of Fe-**8** was determined to be 7.7. Therefore no μ-oxo-dimer of Fe-**8** was formed at pH 5.5 at any concentrations of Fe-**8**. These results (Stern−Volmer plots) are shown in Figure 7. Very efficient fluorescence quenching occurred with **2**. The Stern−Volmer plot for **2** shows a sigmoidal shape. The Stern−Volmer plot should be linear if only static quenching through formation of a 1:1 nonfluorescent complex proceeds.[33] The sigmoidal Stern−Volmer plot for **2** can be interpreted in terms of the formation of a complex(es) having stoichiometry other than 1:1, where the quenching efficiency of the complex carrying more than one Fe-**8** molecule is higher than that of the 1:1 complex.[34] We failed to determine the stoichiometry of the **2**−Fe-**8** complex by means of absorption spectroscopy. However, it is reasonable to assume that the 1:4 complex is predominant at higher Fe-**8** concentrations as in the case of the **2**−Zn-**8** system. Meanwhile, the fluorescence quenching of **3** by Fe-**8** hardly occurred and was saturated at much lower I_0/I (Figure 7).

Discussion

Water-soluble porphyrins tend to form self-aggregates in aqueous solutions.[35] Well-ordered porphyrin aggregates are *J*-aggregates which consist of edge-to-edge aggregates having large association numbers.[36] However, it is difficult to control the molecular architecture of the self-aggregates at will. To arrange the porphyrin moieties intentionally, the linking of moieties through covalent bonds and/or noncovalent bonds such as coordination and hydrogen bonds is required. van der Waals interactions have been recognized to be inadequate for this purpose. As mentioned above, porphyrin arrays can be prepared by connecting more than one porphyrin through covalent bonds.[12,13,37] With this methodology, however, each porphyrin array has to be synthesized by individual processes. The preparation of many porphyrin arrays might be troublesome. Coordination bonds are useful and convenient in the construction of both homo- and heteroporphyrin arrays in organic solvents.[14−27] To the best of our knowledge, however, no successful examples of porphyrin architectures prepared by coordination bonds or covalent bonds in aqueous solution have been reported. The use of hydrogen bonding is also an unfavorable approach in the formation of porphyrin arrays in aqueous media.[28] There are very few examples of porphyrin arrays known to have been

(33) Nemzek, T.; Ware, W. R. *J. Chem. Phys.* **1975**, *62*, 477−489.

(34) David, E.; Born, R.; Kaganer, E.; Joselevich, E.; Dürr, H.; Willner, I. *J. Am. Chem. Soc.* **1997**, *119*, 7778−7790.

(35) (a) Pasternack, R. F.; Huber, P. R.; Boyd, P.; Engasser, G.; Francesconi, L.; Gibbs, E.; Fasella, P.; Venturo, G. C.; Hinds, L. deC. *J. Am. Chem. Soc.* **1972**, *94*, 4511−4517. (b) Krishnamurthy, M.; Sutter, J. R.; Hambright, P. *J. Chem. Soc., Chem. Commun.* **1975**, 13−14. (c) Chandrashekar, T. K.; Van Willigen, H.; Ebersole, M. H. *J. Phys. Chem.* **1984**, *88*, 4326−4332. (d) Kano, K.; Minamizono, H.; Kitae, T.; Negi, S. *J. Phys. Chem. A* **1997**, *101*, 6118−6124. (e) Kano, K.; Fukuda, K.; Wakami, H.; Nishiyabu, R.; Pasternack, R. F. *J. Am. Chem. Soc.* **2000**, *122*, 7494−7502.

(36) (a) Stone, A.; Fleischer, E. B. *J. Am. Chem. Soc.* **1968**, *90*, 2735−2748. (b) Chandrashekar, T. K.; van Willigen H. *J. Am. Chem. Soc.* **1983**, *105*, 6323−6324. (c) Ohno, O.; Kaizu, Y.; Kobayashi, H. *J. Chem. Phys.* **1993**, *99*, 4128−4139. (d) Ribo, J. M.; Crusats, J.; Farrera, J.-A.; Valero, M. L. *J. Chem. Soc., Chem. Commun.* **1994**, 681−682. (e) Pasternack, R. F.; (f) Maiti, N. C.; Ravikanth, M.; Mazumdar, S.; Periasamy, N. *J. Phys. Chem.* **1995**, *99*, 17192−17197. (g) Akins, D. L.; Zhu, H.-R.; Guo, C. *J. Phys. Chem.* **1996**, *100*, 5420−5425. (h) Jin, R.-H.; Aoki, S.; Shima, K. *J. Chem. Soc., Faraday Trans.* **1997**, *93*, 3945−3953. (i) Huang, C. Z.; Li, Y. F.; Li, N.; Li, K. A.; Tong, S. Y. *Bull. Chem. Soc. Jpn.* **1998**, *71*, 1791−1797. (j) Parkash, J.; Robblee, J. H.; Agnew, J.; Gibbs, E.; Collings, P.; Pasternack, R. F.; de Paula, J. C. *Biophys. J.* **1998**, *74*, 2089−2099. (k) Purrello, R.; Monsu Scolaro, L.; Bellacchio, E.; Gurrieri, S.; Romeo, A. *Inorg. Chem.* **1998**, *37*, 3647−3648. (l) Micali, N.; Mallamace, F.; Romeo, A.; Purrello, R.; Monsu Scolaro, L. *J. Phys. Chem. B* **2000**, *104*, 5897−5904. (m) Micali, N.; Romeo, A.; Lauceri, R.; Purrello, R.; Mallamace, F.; Monsu Scolaro, L. *J. Phys. Chem. B* **2000**, *104*, 9416−9420. (n) Ribo, J. M.; Crusats, J.; Sagues, F.; Claret, J.; Rubires, R. *Science* **2001**, *292*, 2063−2066. (o) Ribo, J. M.; Bofill, J. M.; Crusats, J.; Rubires, R. *Chem.—Eur. J.* **2001**, *7*, 2733−2737. (p) Castriciano, M. A.; Romeo, A.; Monsu Scolaro, L. *J. Porphyrins Phthalocyanines* **2002**, *6*, 431−438.

(37) (a) Sessler, J. L.; Capuran, V. L.; Harriman, A. *J. Am. Chem. Soc.* **1993**, *115*, 4816−4628, (b) Biemans, H. A. M.; Rowan, A. E.; Verhoeven, A.; Vanoppen, P.; Latterini, L.; Foekema, J.; Schenning, R. J. M.; Meijer, E. W.; de Schryver, F. C.; Nolte, R. J. M. *J. Am. Chem. Soc.* **1998**, *120*, 11 054−11 060. (c) Aratani, N.; Osuka, A.; Kim, Y. H.; Jeong, D. H.; Kim, D. *Angew. Chem., Int. Ed. Engl* **2000**, *39*, 1458−1462. (d) Tsuda, A.; Osuka, A. *J. Inclusion Phenom. Macrocyclic Chem.* **2001**, *41*, 77−81. (e) Nakano, A.; Osuka, A.; Yamazaki, T.; Nishimura, Y.; Akimoto, S.; Yamazaki, I.; Itaya, A.; Murakami, M.; Miyasaka, H. *Chem. —Eur. J.* **2001**, *7*, 3134−3151. (f) Aratani, N.; Osuka, A. *Org. Lett.* **2001**, *3*, 4213−4216. (g) Aratani, N.; Osuka, A. *Bull. Chem. Soc. Jpn.* **2001**, *74*, 1361−1379. (h) Aratani, N.; Tsuda, A.; Osuka, A. *Synlett* **2001**, 1663−1674.

prepared in aqueous solution.[29,30] For the first case, we succeeded in making water-soluble heteroporphyrin arrays utilizing the inclusion capacity of per-Me-β-CD, which can function as an intramolecular energy and electron-transfer system. The present methodology is based on the extraordinarily strong ability of TMe-β-CD to incorporate aryl substituents at the meso positions of water-soluble porphyrins.[10,11] We designed the Por-per-Me-β-CD conjugates **2** and **3**. Breslow et al. synthesized the porphyrin-β-CD conjugate **1,** whose structure is similar to **2**.[8a] However, conjugate **1** has four native β-CD moieties whose ability to include tetraarylporphyrins is much weaker than the per-Me-β-CD moiety.[11] In contrast, conjugate **2** was expected to strongly bind with other types of tetraarylporphyrins through van der Waals interactions. Conjugate **3** was designed to form a porphyrin dyad. A characteristic feature of conjugate **3** is ascribed to the three dicarboxyphenyl groups at the meso positions of **3**. The dissociated dicarboxyphenyl groups prevented self-inclusion of conjugate **3**. Therefore **3** can exclusively incorporate another porphyrin component to form the heteroporphyrin dimer.

In the present study, the design of the guest porphyrin was also very important. We used porphyrin **8** and its Zn(II) and Fe(III) complexes as the guests. The guest porphyrin **8** has only one site for binding, which facilitates the formation of porphyrin arrays having maximum stoichiometries of 1:4 for **2** and 1:1 for **3**.

Microcalorimetric measurements confirmed the formation of the very stable 1:1 complexes of **3** and Zn-**8** ($K = (7.02 \pm 0.33) \times 10^5$ dm^3 mol^{-1}, $\Delta H = -47.1 \pm 0.4$ kJ mol^{-1}, $\Delta S = -46.1 \pm 2.1$ J mol^{-1} K^{-1}) and **3** and Fe-**8** ($K = (2.56 \pm 0.17) \times 10^5$ dm^3 mol^{-1}, $\Delta H = -60.4 \pm 0.8$ kJ mol^{-1}, $\Delta S = -99.0 \pm 3.2$ J mol^{-1} K^{-1}). The K values for the complexes of **3** are significantly smaller than those for the complexation of TMe-β-CD with Zn-**8** ($K = (1.5 \pm 0.1) \times 10^7$ dm^3 mol^{-1}) and Fe-**8** ($K = (1.8 \pm 0.3) \times 10^6$ dm^3 mol^{-1}). The smaller K values for the host **3** can be accounted for in terms of the electrostatic repulsion between the carboxylate anion groups of the host **3** and of the guest Zn-**8** or Fe-**8**. As indicated by the thermodynamic parameters, the complexation of **3** with Zn-**8** and Fe-**8** represents an enthalpically favorable and entropically unfavorable process. The main binding force seems to be van der Waals interactions. Absorption spectroscopy suggested the formation of a 1:4 complex of **2** and Zn-**8** (Figure 3). Calorimetric titration also supported the formation of the 1:4 complex.

Efficient Förster-type energy transfer occurred in the heteroporphyrin dimer system composed of **3** and Zn-**8**. The energy transfer efficiency obtained from the fluorescence decay was 93%. Sessler et al. reported an energy transfer efficiency of 57% for the heteroporphyrin dimer prepared by complementary hydrogen bonding between a guanosine-bearing Zn-porphyrin and a cytidine-bearing porphyrin free base in dichloromethane.[28] They calculated a critical distance (R_c) for the Förster-type energy transfer from the photoexcited Zn-porphyrin to the porphyrin free base of ca. 2.4 nm. An energy transfer efficiency of 57% suggests that the mean distance between the energy donor and the acceptor of the nucleo base pair is close to R_c. Indeed the estimated distance was ca. 2.25 nm.[28] It might be assumed, therefore, that the mean distance of the **3**−Zn-**8** system is much shorter than that of the nucleo base pair. Lindsey and co-workers prepared a heteroporphyrin dimer using C−C triple bonds for linking a Zn-porphyrin moiety with a tetraphenylporphyrin free base.[12b] This porphyrin conjugate is similar to the **3**−Zn-**8** conjugate. The energy transfer efficiency of their covalently linked heteroporphyrin dimer was estimated to be 98% in toluene, which is comparable to that obtained for the **3**−Zn-**8** system (93%). Aida et al. also reported the energy transfer from Zn-porphyrin to free-base porphyrin in the heteroporphyrin dimer where the two porphyrin components are connected by a $-C_6H_4-OCH_2-C_6H_4-$ linkage.[13] The energy transfer efficiency of their system is 86% in THF.[13b] On the basis of these findings, it can be concluded that the **3**−Zn-**8** heteroporphyrin dimer prepared through a noncovalent bond in aqueous solution displays characteristics similar to or better than those of the covalently linked heteroporphyrin dimers in organic solvents.

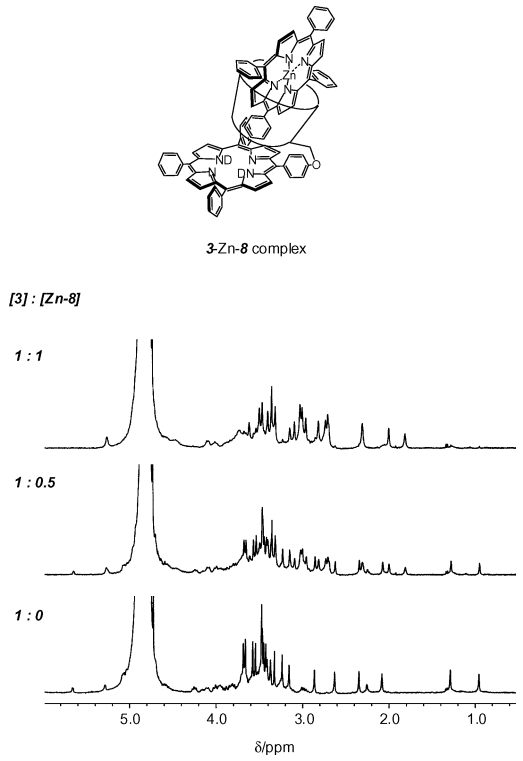


Figure 8. ^{1}H NMR spectra of **3** (1.0×10^{-3} mol dm^{-3}) in the presence of various amounts of Zn-**8** ([Zn-**8**] = 0, 0.5, and 1.0×10^{-3} mol dm^{-3}) at 25 °C in 0.1 mol dm^{-3} phosphate buffer (D_2O, pD = 7.0) and plausible structure of **3**−Zn-**8** complex in D_2O (the corboxylato groups of **3** and Zn-**8** are omitted for clarity).

Figure 8 shows the ^{1}H NMR spectra of **3** in the absence and presence of Zn-**8**. In the absence of Zn-**8**, six singlet signals due to the CH_3 groups at the primary OCH_3 side of per-Me-β-CD were clearly observed at ca. 1−3 ppm. The signals of the OCH_3 groups at the 2-, 3-, and 6-positions of TMe-β-CD appeared at 3.568, 3.659, and 3.435 ppm in D_2O,[38] and shifted to 2.967, 2.475, and 3.489 ppm, respectively, upon addition of equimolar amounts of Zn-**8**. It is noteworthy that the signal due to the OCH_3 groups at the 6-positions shifted to lower magnetic field resulting from a deshielding effect due to the ring current of the porphyrin ring. Large upfield shifts of the CH_3 protons at the 6-positions of **3** in the absence of Zn-**8** indicate that the per-Me-β-CD moiety of **3** is placed on the porphyrin ring, which

(38) Botsi, A.; Yannakopoulou, K.; Hadjoudis, E. *Magn. Reson. Chem.* **1996**, *34*, 419−423.

hangs over the primary OCH_3 group side of the CD cavity. In the presence of half-equivalent amounts of Zn-**8**, the signal intensities of the primary OCH_3 groups were diminished without any shifts. New singlet signals appeared at ca. 1.8−3.0 ppm upon addition of Zn-**8**. Since the signals of the secondary OCH_3 groups of the per-Me-β-CD moiety are expected to shift to ca. 2.5−3 ppm upon inclusion of Zn-**8** (vide supra), the singlet signals that appeared at least in the 1.8−2.5 ppm range should be assigned to the primary OCH_3 groups. In other words, the folding structure of **3** is maintained even after incorporating Zn-**8** (Figure 8).

As shown in Figure 5, the energy transfer from photoexcited Zn-**8** to **2** apparently occurred more efficiently than that from Zn-**8** to **3**. However, the energy transfer efficiency of the **2**−Zn-**8** system (85%) was considerably lower than that of the **3**−Zn-**8** system (93%). Assuming the formation of a 1:4 complex of **2** and Zn-**8**, four types of geometrical orientations should be assumed for the four donor−acceptor pairs in the **2**−Zn-**8** system. Each pair has independent energy transfer efficiency. The probability of photon absorption of **2** is 4 times higher than that of **3**. Since the energy transfer efficiency evaluated from fluorescence decay represents the mean, it should be lower than that of the **3**−Zn-**8** system where the orientation between the donor and the acceptor is opportune for energy transfer due to its holding conformation. This situation is the same as that observed for the energy transfer in dendritic multiporphyrin arrays.[13] The efficiency of the energy transfer from the surrounding Zn(II) porphyrin moiety to a central free-base porphyrin decreases as the generation of dendrimer increases.[13] The heteroporphyrin array composed of a tetraarylporphyrin free base and four zinc tetraarylporphyrins was synthesized by linking each zinc porphyrin with the free-base porphyrin by a C−C triple bond.[12a] This heteroporphyrin array is similar to the **2**−Zn-**8** array. In this covalently linked heteroporphyrin array, the orientations of the four donor−acceptor pairs are almost the same since each donor is bound to the acceptor by a C−C triple bond. The energy transfer efficiency of the covalently linked pentad in dichloromethane was reported to be ca. 90%, which is slightly higher than that of the **2**−Zn-**8** system. A detailed ^{1}H NMR study could not be carried out due to self-aggregation of **2** (5×10^{-4} mol dm^{-3}) in D_2O, which resulted in the broadening of all NMR signals. However, it was confirmed that no ^{1}H NMR signals due to a folded conformation appeared at 1.5−2.5 ppm with **2** in the absence or presence of **8** (supporting information).

Efficient fluorescence quenching of **2** by Fe-**8** took place, while that of **3** by Fe-**8** was leveled off at lower I_0/I (Figure 7). Two mechanisms can be considered to account for the fluorescence quenching: electron transfer for a short donor−acceptor distance and energy transfer for a long distance.[39] A linear relationship was observed between I/I_0 (not I_0/I) and the percentage of **3**−Fe-**8** complex formed under certain conditions for the **3**−Fe-**8** system. From this relationship, the I/I_0 value for the conditions where 100% of **3** forms the complex can be evaluated to be 0.34. The rate constant for quenching of the photoexcited singlet state of donor (k_{ET}) can be estimated from

$$k_{ET} = [(I_0/I)_{sat} - 1]/\tau_0$$

where τ_0 is the fluorescence lifetime of the donor. The τ_0 values were determined to be 10.0 and 7.4 ns for **2** and **3**, respectively. The k_{ET} value for the **3**−Fe-**8** system was determined to be 2.6×10^8 s^{-1}. In the case of the **2**−Fe-**8** system, the experimentally determined value of $(I/I_0)_{sat}$ was 0.11, which leads to a k_{ET} value of 7.9×10^8 s^{-1} ($\tau_0 = 10.0$ ns for **2**). Heiler et al. prepared a heteroporphyrin dimer composed of free-base porphyrin and Fe(III) porphyrin that are linked to each other by a phenyl group.[40] The fluorescence quenching rate of this dyad was reported to be 2×10^{11} s^{-1}. The k_{ET} values in the present systems are much smaller than that in the covalently bonded heteroporphyrin dimer. This could be ascribed to a barrier effect of the cyclodextrin cavity impeding electron transfer. We found that the very stable 1:2 complex of $TPPS_4$ and TMe-β-CD was completely inactive toward fluorescence quenching by 9,10-anthraquinone-2-sulfonate (AQS) via electron transfer, though AQS quenched the fluorescence of $TPPS_4$ in the absence of TMe-β-CD. The per-Me-β-CD cavity in **2** or **3** seems to act as a barrier toward electron transfer from **2** or **3** to Fe-**8** incorporated in the per-Me-β-CD cavities or cavity of **2** or **3**. The difference in efficiency of the fluorescence quenching by Fe-**8** between **2** and **3** can be accounted for in terms of the diversity in spatial relationship between the donor and the acceptor in the **2**−Fe-**8** system.

We would like to emphasize that the present systems provide a very convenient means to prepare heteroporphyrin arrays in aqueous solution. Simply mixing **2** or **3** with other water-soluble porphyrins can yield a variety of heteroporphyrin arrays whose character is almost the same as covalently linked heteroporphyrin arrays.

Experimental Section

Syntheses of Porphyrin-Cyclodextrin Conjugates. Conjugates **2** and **3** were synthesized via routes shown in Schemes 1 and 2, respectively.

Mono-6-*O*-*tosyl* Permethylated β-Cyclodextrin (5). *p*-Toluenesulfonyl chloride (0.36 g, 1.91 mmol) was added to a solution of **4**[31] (1.8 g, 1.27 mmol) in 50 mL of dry pyridine at 0 °C under N_2. The mixture was warmed to 50 °C and stirred for 12 h. The solvent was removed and the residue was dissolved in $CHCl_3$ (50 mL). The chloroform solution was washed with water (50 mL) and saturated aqueous NaCl (2 × 50 mL) and dried over Na_2SO_4. The solvent was evaporated and the solid residue was purified by silica gel column chromatography with $CHCl_3/CH_3OH$ (1/50). Yield 90%. ^{1}H NMR (δ/ppm, $CDCl_3$, 400 MHz, 25 °C): 2.47 (s, 3 H, tosyl-CH_3), 3.05−4.52 (m, 102 H), 5.01−5.20 (m, 7 H), 7.38 (d, 2 H, phenyl), 7.78 (d, 2 H, phenyl). MS (FAB, *m*-NBA) *m*/*z* 1592 $(M + Na)^+$.

Conjugate 2. A mixture of **5** (600 mg, 3.8×10^{-4} mol), 5,10,15,-20-tetrakis(4-hydroxyphenyl)porphyrin (45 mg, 6.6×10^{-5} mol), and K_2CO_3 (100 mg) in dry DMF (10 mL) was stirred at 80 °C for 60 h under N_2. The solvent was removed and the residue was dissolved in $CHCl_3$ (50 mL). The chloroform solution was washed with water (50 mL) and saturated aqueous NaCl (2 × 50 mL) and then dried over Na_2SO_4. The purple solid obtained by evaporating the solvent was purified by silica gel column chromatography with $CHCl_3$ and $CHCl_3/CH_3OH$ (50/1). Yield 36%. ^{1}H NMR (δ/ppm, $CDCl_3$, 400 MHz, 25 °C): −2.79 (s, 2 H, NH), 3.11−4.76 (m, 408 H), 5.02−5.35 (m, 7 H), 7.34 (d, 8 H, phenyl), 8.09 (d, 8 H, phenyl), 8.84 (s, 8 H, β-pyrrole). MS (MALDI-TOF, dithranol): *m*/*z* 6264.9 (calcd for M^+: 6268.9). UV− vis (CH_2Cl_2, 25 °C): 422 (ϵ 493 400 dm^3 mol^{-1} cm^{-1}), 518 (17 600), 555 (12 650), 594 (5800), 649 nm (6300). Anal. Calcd for

(39) Kilsa, K.; Kajanus, J.; Larsson, S.; Macpherson, A. N.; Mårtensson, J.; Albinsson, B. *Chem.—Eur. J.* **2001**, *7*, 2122−2133.
(40) Heiler, D.; McLendon, G. L.; Rogalsky, P. *J. Am. Chem. Soc.* **1987**, *109*, 604−606.

$C_{292}H_{462}N_4O_{140}$: C, 55.95; H, 7.43; N, 0.89; O, 35.75. Found: C, 55.26; H, 7.35; N, 0.70; O, 36.02.

Porphyrin 6. 5-Formyldiethylisophthalate (1.56 g, 6.19 mmol), *p*-hydroxybenzaldehyde (0.46 g, 3.77 mmol), and pyrrole (0.69 mL, 10 mmol) were dissolved in 1 L of CH_2Cl_2 under N_2 atmosphere and then BF_3 etherate (190 μL) was added into this solution. After the solution was stirred at room temperature for 1 h, 2,3-dichloro-5,6-dicyanobenzoquinone (2.5 g) was added into the reaction mixture and the resulting solution was refluxed for 1 h. The solvent was evaporated and the residue was purified twice by silica gel column chromatography with CH_2Cl_2/CH_3OH (20/1) and CH_2Cl_2/ethyl acetate (100/1). Yield 5%. ^{1}H NMR (δ/ppm, $CDCl_3$, 400 MHz, 25 °C): −2.78 (s, 2 H, NH), 1.42 (t, 18 H, $CO_2CH_2CH_3$), 4.49 (q, 12 H, $CO_2CH_2CH_3$), 5.25 (s, 1 H, OH), 7.24 (d, 2 H, phenyl), 8.09 (d, 2 H, phenyl), 8.73 (m, 6 H, β-pyrrole), 8.93 (d, 2 H, β-pyrrole), 9.06 (s, 6 H, diethoxycarbonylphenyl), 9.14 (s, 3 H, diethoxycarbonylphenyl). MS (FAB, *m*-NBA): *m*/*z* 1063 (M^+), 1064 $(M + H)^+$. UV−vis (CH_2Cl_2): 422 (ϵ 462 650 dm^3 mol^{-1} cm^{-1}), 517 (21 200), 552 (8450), 591 (6400), 646 nm (4050).

Conjugate 7. A mixture of **5** (92 mg, 5.8×10^{-5} mol), **6** (50 mg, 4.7×10^{-5} mol), and K_2CO_3 (100 mg) in dry DMF (10 mL) was stirred at 60 °C for 48 h under N_2 atmosphere. After the solvent was removed, the residue was dissolved in $CHCl_3$ (50 mL). The chloroform solution was washed with water (50 mL) and saturated aqueous NaCl (2 × 50 mL) and then dried over Na_2SO_4. The purple solid obtained by evaporating $CHCl_3$ was purified by silica gel column chromatography with $CHCl_3$ to $CHCl_3$/ethyl acetate/CH_3OH (100/0.75/0.25). Yield 83%. ^{1}H NMR (δ/ppm, $CDCl_3$, 400 MHz, 25 °C): −2.80 (s, 2 H, NH), 1.40 (t, 18 H, $CO_2CH_2CH_3$), 3.16−4.68 (m, 102 H), 4.47 (q, 12 H, $CO_2CH_2CH_3$), 5.09−5.29 (m, 7 H), 7.33 (d, 2 H, phenyl), 8.11 (d, 2 H, phenyl), 8.70 (d, 2 H, β-pyrrole), 8.73 (s, 4 H, β-pyrrole), 8.90 (d, 2 H, β-pyrrole), 9.02 (s, 6 H, diethoxycarbonylphenyl), 9.12 (s, 3 H, diethoxycarbonylphenyl). MS (MALDI-TOF, dithranol): *m*/*z* 2459.0 (calcd for M^+: 2460.7). UV−vis (CH_2Cl_2): 422 (ϵ 442 500 dm^3 mol^{-1} cm^{-1}), 517 (19 850), 552 (7900), 593 (5800), 646 nm (3350).

Conjugate 3. A solution of **7** (50 mg) and KOH (0.4 g) in a mixed solvent of water (10 mL), methanol (30 mL), and dioxane (10 mL) was refluxed for 12 h. The organic solvents were evaporated and the aqueous residue was acidified to pH 1 with hydrochloric acid. The green precipitate was extracted using $CHCl_3$ (100 mL) and the organic layer was washed with water (3 × 100 mL) and dried over Na_2SO_4. Evaporation of $CHCl_3$ afforded **3** as a purple solid. Yield: 87%. ^{1}H NMR (δ/ppm, 0.1 mol dm^{-3} phosphate buffer (D_2O), pD = 7.0, 400 MHz, 25 °C): 0.96−5.56 (m, 109 H), 7.45 (d, 2 H, phenyl), 8.40 (d, 2 H, phenyl), 8.70−8.84 (m, 9 H, dicarboxylatophenyl), 8.90−9.10 (br, β-pyrrole). MS (MALDI-TOF, dithranol): *m*/*z* 2313.4 (calcd for $(M + Na)^+$: 2315.3). UV−vis (0.1 mol dm^{-3} phosphate buffer, pH = 7.0): 417 (ϵ 370 950 $dm^3mol^{-1}cm^{-1}$), 516 (14 250), 551 (5600), 584 (5450), 636 nm (3100).

Esters 9 and 10. BF_3 etherate (190 μL) was added to a mixture of 5-formyldiethylisophthalate (1.8 g, 7.1 mmol), benzaldehyde (0.32 g, 3.0 mmol), and pyrrole (0.69 mL, 10 mmol) in 1 L of CH_2Cl_2 under the N_2 atmosphere. After stirring the solution at room temperature for 1 h, 2,3-dichloro-5,6-dicyanobenzoquinone (2.5 g) was added and the reaction mixture was refluxed for 1 h. TLC (SiO_2; CH_2Cl_2/ethyl acetate: 20/1 (v/v)) suggested two major products with R_f values of 0.59 (**9**) and 0.38 (**10**). The solvent was evaporated and the residue was purified by silica gel column chromatography with CH_2Cl_2/ethyl acetate (50/1). Yield: **9**, 12%; **10**, 10%. **9.** ^{1}H NMR (δ/ppm, $CDCl_3$, 400 MHz, 25 °C): −2.78 (s, 2 H, NH), 1.42 (t, 18 H, $CO_2CH_2CH_3$), 4.50 (q, 12 H, $CO_2CH_2CH_3$), 7.79 (m, 3 H, phenyl), 8.22 (d, 2 H, phenyl), 8.74−8.76 (m, 6 H, β-pyrrole), 8.90 (d, 2 H, β-pyrrole), 9.05 (m, 6 H, diethoxycarbonylphenyl), 9.15 (m, 3 H, diethoxycarbonylphenyl). MS (FAB, *m*-NBA): *m*/*z* 1046 (M^+), 1047 $(M + H)^+$. UV−vis (CH_2Cl_2): 420 (ϵ 569 000 dm^3 mol^{-1} cm^{-1}), 514 (23 300), 549 (7870), 589 (6935), 645 nm (3455). Anal. Calcd for $C_{62}H_{54}N_4O_{12}$: C, 71.12; H, 5.20; N, 5.35; O, 18.33. Found: C, 71.12; H, 5.50; N, 5.11; O, 18.05. **10**. ^{1}H NMR (δ/ppm, $CDCl_3$, 400 MHz, 25 °C): −2.78 (s, 2 H, NH), 1.43 (t, 24 H, $CO_2CH_2CH_3$), 4.50 (q, 16 H, $CO_2CH_2CH_3$), 8.78 (d, 8 H, β-pyrrole), 9.06 (s, 8 H, diethoxycarbonylphenyl), 9.15 (s, 4 H, diethoxycarbonylphenyl). MS (FAB, *m*-NBA): *m*/*z* 1190 (M^+), 1191$(M + H)^+$. UV−vis (CH_2Cl_2): 420 (ϵ 580 500 dm^3 mol^{-1} cm^{-1}), 514 (24 200), 549 (7600), 589 (7220), 644 nm (3150). Anal. Calcd for $C_{68}H_{62}N_4O_{16}$: C, 68.56; H, 5.25; N, 4.70; O, 21.49. Found: C, 68.57; H, 5.17; N, 4.60; O, 21.49.

Carboxylic Acids 8 and 11. An aqueous methanol solution (H_2O/MeOH = 10 mL/60 mL) of a mixture of **9** (200 mg) and KOH (1.6 g) was refluxed for 12 h. After the reaction, methanol was evaporated. The aqueous residue was acidified to pH 1 with aqueous HCl and cooled by ice. The precipitate of **8** was collected by filtration. Compound **11**[32b] was prepared by the same procedure. Yield: **8**, 84%; **11**, 94%. **8.** ^{1}H NMR (δ/ppm, 0.1 mol dm^{-3} phosphate buffer (D_2O), pD = 7, 400 MHz, 25 °C): 7.79 (t, 2 H, phenyl), 7.85 (d, 1 H, phenyl), 8.16 (d, 2 H, phenyl), 8.78 (m, 3 H, diethoxycarbonylpheny), 8.83 (m, 6 H, diethoxycarbonylphenyl), 9.10 (br, 8 H, β-pyrrole). MS (FAB, glycerol): *m*/*z* 878 $(M - H)^-$, 879 (M^-). UV−vis (0.1 mol dm^{-3} phosphate buffer, pH = 7.0): 414 (ϵ 526 900 dm^3 mol^{-1} cm^{-1}), 514 (17 125), 549 (7045), 589 (6535), 645 nm (3845).

Zn-8. An aqueous solution (30 mL) of the free-base porphyrin **8** (50 mg) and zinc oxide (50 mg) was refluxed for 2 days in the dark. After the reaction, excess zinc oxide was removed by filtration. The reaction mixture was concentrated and passed through DOWEX HCR-W2 (Na form) ion-exchange resin and Sephadex G-25 columns. The purple solid was obtained by evaporating the solvent. Yield: 75%. ^{1}H NMR (δ/ppm, D_2O, 400 MHz, 25 °C): 7.87 (m, 3 H, phenyl), 8.32 (d, 2 H, phenyl), 8.74 (s, 3 H, dicarboxylatophenyl), 8.81 (s, 6 H, dicarboxylatophenyl), 8.99−9.07 (m, 8 H, β-pyrrole). MS (MULDI-TOF, 1,5-naphthalenediamine): *m*/*z* 941.0 $(M - 6Na + 5H)^-$. UV−vis (0.1 mol dm^{-3} phosphate buffer, pH = 7.0): 422 (ϵ 601 400 dm^3 mol^{-1} cm^{-1}), 556 (18 860), 595 nm (8405).

Zn-11. The procedure used was the same as that for Zn-**8**. Yield 76%. ^{1}H NMR (δ/ppm, D_2O, 400 MHz, 25 °C): 8.76 (s, 4 H, dicarboxylatophenyl), 8.83 (s, 8 H, dicarboxylatophenyl), 9.03 (br s, 8 H, β-pyrrole). MS (MULDI-TOF, 1,5-naphthalenediamine): *m*/*z* 1028.7 $(M - 8Na + 7H)^-$. UV−vis (0.1 mol dm^{-3} phosphate buffer, pH = 7.0): 422 (ϵ 597 000 dm^3 mol^{-1} cm^{-1}), 557 (18 350), 596 nm (7475).

Fe-9. A solution of free-base porphyrin **9** (100 mg) in $FeCl_2 \cdot nH_2O$-saturated DMF (10 mL) was added to CH_2Cl_2 (60 mL) and stirred for 12 h at 50 °C in the dark under N_2 atmosphere. The progress of the reaction was monitored by fluorescence spectroscopy and TLC (SiO_2; CH_2Cl_2/ethyl acetate (20/1); R_f value, 0.59 (**9**) and 0.24 (Fe-**9**)). The solvent was removed under reduced pressure and the residue was dissolved in $CHCl_3$ (100 mL). The chloroform solution was washed with water (200 mL) and saturated aqueous NaCl (2 × 200 mL) and then dried over Na_2SO_4. A dark purple solid was obtained after evaporating the solvent. Yield: 81%. MS (FAB, *m*-NBA): *m*/*z* 1101 (M^+).

Fe-10. The procedure used was the same as that for Fe-9. Yield: 86%. MS (FAB, *m*-NBA): *m*/*z* 1245 (M^+).

Fe-8. An aqueous methanol solution (H_2O/MeOH = 10 mL/60 mL) of a mixture of Fe-**9** (85 mg) and KOH (1.5 g) was refluxed for 12 h. Methanol was evaporated and the aqueous residue was acidified to pH 1 with aqueous HCl. The resulting solution was cooled by ice and the Fe-**8** precipitate was collected by filtration. Yield: 84%. MS (MULDI-TOF, 1,5-naphthalenediamine): *m*/*z* 931.6 $(M - H)^-$. UV−vis (aqueous NaOH solution containing 0.1 mol dm^{-3} $NaClO_4$ at pH = 9.9) 333 (ϵ 41 650 $dm^3mol^{-1}cm^{-1}$), 416 nm (148 225). UV−vis (0.01 mol dm^{-3} succinic acid buffer containing 0.1 mol dm^{-3} $NaClO_4$ at pH = 5.5): 395 (ϵ 153 200 dm^3 mol^{-1} cm^{-1}), 529 nm (14 875).

Fe-11. Similar treatment afforded Fe-**11**. Yield 94%. UV−vis (aqueous NaOH solution containing 0.1 mol dm^{-3} $NaClO_4$ at pH = 9.5): 333 (ϵ 37 175 dm^3 mol^{-1} cm^{-1}), 415 nm (141 375). MS (MULDI-TOF, 1,5-naphthalenediamine): *m*/*z* 1020.2 $(M - H)^-$. UV−vis (0.01

mol dm^{-3} succinic acid buffer containing 0.1 mol dm^{-3} $NaClO_4$ at pH = 5.5): 395 (ϵ 144 275 dm^3 mol^{-1} cm^{-1}), 529 nm (13 825).

Other Materials. TMe-β-CD (Nacalai) was purchased and used without further purification. β-CD (Nacalai) was washed with THF using a Soxhlet extractor and dried. D_2O (CEA, 99.8%) and $CDCl_3$ (CEA, 99.8%) were used as received.

Measurements. Absorption and fluorescence spectra were recorded on a Shimadzu UV-2100 spectrometer and a Shimadzu RF-5300PC spectrofluorometer, respectively. ^{1}H NMR spectra were taken using a JEOL JNM-A400 spectrometer (400 MHz). TMS (Nacalai) and sodium 3-trimethylsilyl[2,2,3,3-$^2H_4$]propionate (TSP, Aldrich) were used as internal (for organic solvents) and external (for D_2O) standards, respectively. FAB MS and MALDI-TOF MS spectra were recorded on a JEOL JMS-700 spectrometer and a Shimadzu/Kratos KOMPACT MALDI IV spectrometer, respectively. Microcalorimetric measurements were carried out with an Isothermal Titration Calorimeter VP-ITC and the titration data were analyzed with the ORIGIN software program. Fluorescence decay curves were recorded by exciting the samples at 415 nm using a picosecond pulse laser (a Coherent model Mira 900 mode-locked Ti-sapphire laser pumped by Coherent model Innova 300 Ar-ion laser combined with a Coherent model 9200 pulse picker) and counting the photons with a single photon timing apparatus. The photons emitted were collected by a Hamamatsu model R2809U-01 microchannel-plate photomultiplier. The fluorescence decay curves were analyzed by using the IGOR software program. Energy transfer efficiencies were calculated from fluorescence lifetimes of the donor in the absence or presence of the acceptor by an ordinary method.[13a]

The determination of K values from UV−vis spectroscopic titrations were carried out by the method previously described.[11]

The reproducibility of all data shown herein was confirmed by repeated experiments.

Acknowledgment. This work was supported by a Grant-in-Aid for Scientific Research B (KAKENHI 14340224) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

Supporting Information Available: Absorption and ^{1}H NMR spectra of Zn-**8** in the absence or presence of TMe-β-CD, calorimetric titration data for the **3**−Zn-**8** system, and ^{1}H NMR spectra of **2** in the absence or presence of **8** and **11**. This material is available free of charge via the Internet at http://pubs.acs.org.

JA035055Q