

# Supramolecular Chirogenesis in Weakly Interacting Hosts: Role of the Temperature, Structural, and Electronic Factors in Enhancement of Chiroptical Sensitivity

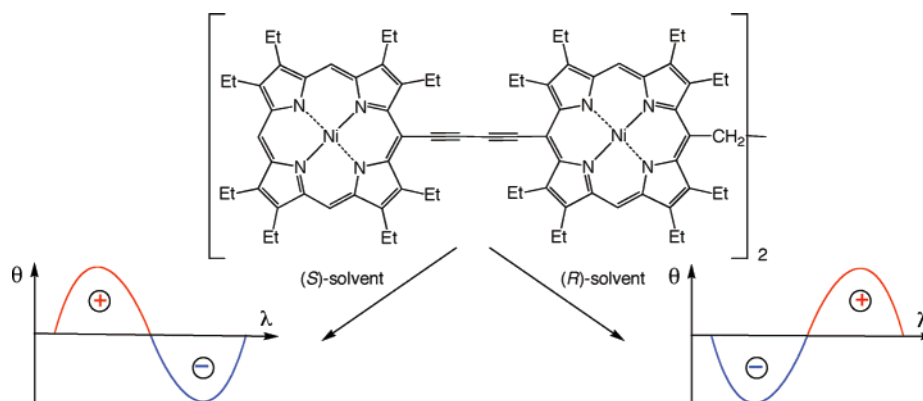
Victor Borovkov,<sup>\*,†</sup> Takuro Yamamoto,<sup>‡</sup> Hiroyuki Higuchi,<sup>\*,‡</sup> and Yoshihisa Inoue<sup>\*,†</sup>

Japan Science and Technology Agency (JST) and Department of Applied Chemistry, Osaka University, 2-1 Yamada-oka, Suita 565-0871, Japan, and Department of Chemistry, Faculty of Science, University of Toyama, 3190 Gofuku, Toyama 930-8555, Japan

victrb@chem.eng.osaka-u.ac.jp; higuchi@sci.u-toyama.ac.jp; inoue@chem.eng.osaka-u.ac.jp

Received January 25, 2008

## ABSTRACT



A new supramolecular chirogenic system on the basis of tetrakis(nickel porphyrin) and various enantiopure solvents, which was specifically designed for investigation of the chirogenic phenomenon upon extremely weak interaction modes and marginal chiroptical responses, is reported. The temperature was found to be a key factor controlling the chirality transfer process in these assemblies.

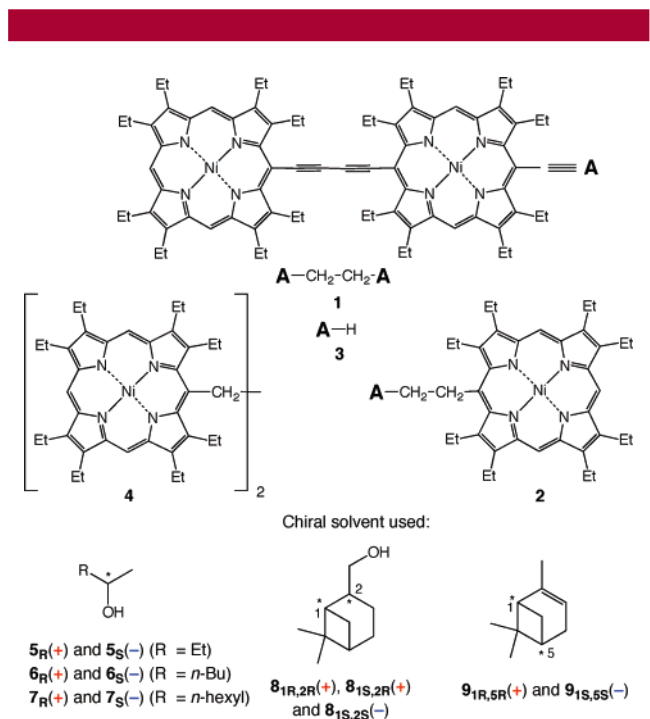
Supramolecular chirogenesis is a new and fast-growing branch of modern interdisciplinary science dealing with various aspects of chirality in supramolecular chemistry, materials science, molecular devices, sensors, and natural systems.<sup>1</sup> Since the major driving forces of these phenomena are inherently noncovalent in nature, there are many external and internal factors influencing the chiroptical properties of these systems, which have been investigated extensively by

us and other research groups particularly on relatively strong, specific interactions, such as coordination, hydrogen bonding, electrostatic interactions, etc.<sup>1a,2</sup> The controlling stimuli are of particular significance especially in the case of extremely weak interaction modes and marginal chirogenic responses, which are often observed in a variety of artificial and natural supramolecular systems and play an important role in effective functioning of the whole assembly. However, the lack of appropriate model systems makes it difficult to study this important subject comprehensively. In order to fill this

<sup>†</sup> JST, Osaka University.

<sup>‡</sup> University of Toyama.

gap, we designed a special achiral porphyrin host (**1**)<sup>3</sup> on the basis of the corresponding tetranickel complex (Figure 1), which satisfies the following requirements for this



**Figure 1.** Structures of weakly interacting hosts (**1**–**4**) and chiral solvents (**5**–**9**) used. The subscripts (R and S) indicate the absolute configuration of the asymmetric carbon, which is marked by asterisk, while the induced chirality sign (+ or –) in **1** is shown in parentheses.

purpose: (1) total inertness toward most of the conventional host–guest binding modes as was well-documented for

(1) (a) Hembury, G. A.; Borovkov, V. V.; Inoue, Y. *Chem. Rev.* **2008**, *108*, 1. (b) Borovkov, V. V.; Inoue, Y. *Top. Curr. Chem.* **2006**, *265*, 89. (c) Lintuluoto, J. M.; Nakayama, K.; Setsune, J.-i. *Chem. Commun.* **2006**, 3492. (d) Balaban, T. S. *Acc. Chem. Res.* **2005**, *38*, 612. (e) Marchon, J.-C.; Ramasseul, R. In *The Porphyrin Handbook*; Kadish, K. M., Smith, K. M., Guillard R., Eds.; Academic Press: San Diego, 2003; Vol. 11, pp 75. (f) Tsukube, H.; Shinoda, S. *Chem. Rev.* **2002**, *102*, 2389. (g) Onouchi, H.; Miyagawa, T.; Morino, K.; Yashima, E. *Angew. Chem., Int. Ed.* **2006**, *45*, 2381. (h) Lauceri, R.; Purrello, R. *Supramol. Chem.* **2005**, *17*, 61. (i) Li, W.-S.; Jiang, D.-L.; Suna, Y.; Aida, T. *J. Am. Chem. Soc.* **2005**, *127*, 7700. (j) Muranaka, A.; Okuda, M.; Kobayashi, N.; Somers, K.; Ceulemans, A. *J. Am. Chem. Soc.* **2004**, *126*, 4596. (k) Ribó, J. M.; Crusats, J.; Sagués, F.; Claret, J.; Rubires, R. *Science* **2001**, *292*, 2063. (l) Kubo, Y.; Ohno, T.; Yamanaka, J.-i.; Tokita, S.; Iida, T.; Ishimaru, Y. *J. Am. Chem. Soc.* **2001**, *123*, 12700. (m) Kurtan, T.; Nesnas, N.; Li, Y.-Q.; Huang, X.; Nakanishi, K.; Berova, N. *J. Am. Chem. Soc.* **2001**, *123*, 5962. (n) Crossley, M. J.; Mackay, L. G.; Try, A. C. *J. Chem. Soc., Chem. Commun.* **1995**, 1925.

(2) (a) Bhyrappa, P.; Borovkov, V. V.; Inoue, Y. *Org. Lett.* **2007**, *9*, 433. (b) Ishii, Y.; Soeda, Y.; Kubo, Y. *Chem. Commun.* **2007**, 2953. (c) Stepanek, P.; Dukh, M.; Saman, D.; Moravcova, J.; Kniez, L.; Monti, D.; Venanzi, M.; Mancini, G.; Drasar, P. *Org. Biomol. Chem.* **2007**, *5*, 960. (d) Kajitani, T.; Okoshi, K.; Sakurai, S.-i.; Kumaki, J.; Yashima, E. *J. Am. Chem. Soc.* **2006**, *128*, 708. (e) Kim, O.-K.; Je, J.; Jernigan, G.; Buckley, L.; Whitten, D. *J. Am. Chem. Soc.* **2006**, *128*, 510. (f) Borovkov, V. V.; Inoue, Y. *Org. Lett.* **2006**, *8*, 2337. (g) Percec, V.; Dulcey, A. E.; Peterca, M.; Iliés, M.; Sienkowska, M.; Heiney, P. A. *J. Am. Chem. Soc.* **2005**, *127*, 17902. (h) Borovkov, V. V.; Hembury, G. A.; Inoue, Y. *Acc. Chem. Res.* **2004**, *37*, 449 and references therein. (i) Borovkov, V. V.; Fujii, I.; Muranaka, A.; Hembury, G. A.; Tanaka, T.; Ceulemans, A.; Kobayashi, N.; Inoue, Y. *Angew. Chem., Int. Ed.* **2004**, *43*, 5481. (j) Borovkov, V. V.; Lintuluoto, J. M.; Inoue, Y. *J. Am. Chem. Soc.* **2001**, *123*, 2979.

nickel porphyrins,<sup>4</sup> (2) possession of an open cavity between the two bis-porphyrin subunits owing to the syn-orientation in **1**,<sup>3</sup> which allows chiral guest molecules to be incorporated into it and thus to interact with the host in a stereospecific manner, and (3) the presence of spectrally separated electronic transitions ( $B_x$ ) aligned along the diacetylene bridges and located at the low energy region of the porphyrin B band due to the enhanced interporphyrin interactions through the unsaturated linkage, which are typical for the butadiyne-linked bis- and multiporphyrins.<sup>5</sup> This particular property (energetic isolation and clear spectral definition) of the porphyrin  $B_x$  transitions provides an effective and convenient tool for the chirality sensing ability. Hence, even a small deviation from the coplanar arrangement or a minute shift from the racemic mixture of right- and left-handed *syn*-**1** should immediately produce the corresponding chiroptical response, which can be detected by conventional CD spectroscopy. Also, as reference compounds a series of achiral nickel complexes (**2**–**4**)<sup>6</sup> containing the main fragments of the structure of **1** have been synthesized and consequently used in evaluation of the chiroptical efficiency of the chosen tetrameric system in this particular study. The chirogenic abilities of achiral **1** along with **2**–**4** have been evaluated in a series of chiral solvents (**5**–**9**),<sup>7</sup> which as mentioned above do not form any stable complexes with the corresponding nickel porphyrins.

The chirogenic processes and structural modulations in achiral hosts **1**–**4** upon interaction with chiral solvents **5**–**9** were monitored by conventional and variable-temperature (VT) UV–vis, CD, and <sup>1</sup>H NMR spectroscopy. Typical spectral responses of **1** in **5<sub>R</sub>** and **5<sub>S</sub>** are shown in Figure 2 as an example of the corresponding antipodal pair. The UV–vis spectra of **1** as expected are the same in both enantiomeric solvents and similar to that reported previously (Figure 2b).<sup>3</sup> Upon lowering the temperature, the spectral profile remains essentially unchanged down to 223 K, which was however followed by noticeable enhancement of the  $B_x$  transition apparently due to the possible increase in solute–solvent interactions (with the final spectrum at 163 K becoming closely resemble to that in a good solvent, such as  $\text{CHCl}_3$ )<sup>3</sup> rather than intermolecular association. Although the aggrega-

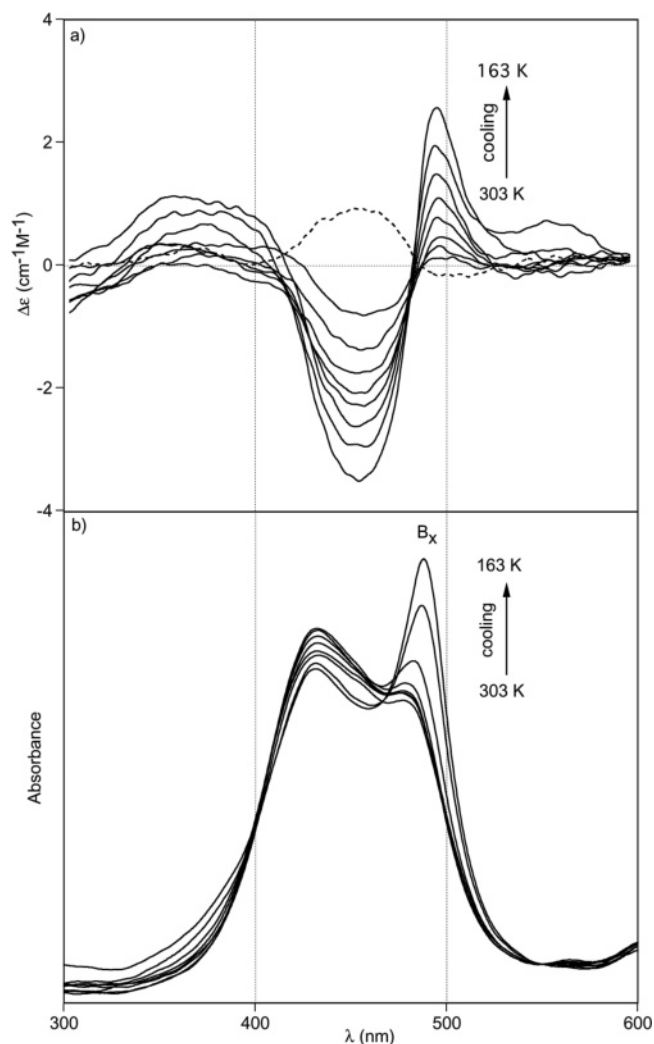
(3) Tetrameric **1** was synthesized according to Higuchi et al. (Hayashi, N.; Naoe, A.; Miyabayashi, K.; Yamada, M.; Miyake, M.; Higuchi, H. *Tetrahedron Lett.* **2004**, *45*, 8215), and its purity was documented by various spectroscopic data and elemental analysis (see the Supporting Information).

(4) Sanders, J. K. M.; Bampos, N.; Clyde-Watson, Z.; Darling, S. L.; Hawley, J. C.; Kim, H.-J.; Mak, C. C.; Webb, S. J. In *The Porphyrin Handbook*; Kadish, K. M., Smith, K. M., Guillard R., Eds.; Academic Press: San Diego, 2000; Vol. 3, p 1.

(5) (a) Susumu, K.; Dunkan, T. V.; Therien, M. J. *J. Am. Chem. Soc.* **2005**, *127*, 5186. (b) Anderson, H. L. *Chem. Commun.* **1999**, 2323. (c) Beljonne, D.; O’Keefe, G. E.; Hamer, P. J.; Friend, R. H.; Anderson, H. L.; Bredas, J. L. *J. Chem. Phys.* **1997**, *106*, 9439. (d) Anderson, H. L. *Inorg. Chem.* **1994**, *33*, 972.

(6) Trimeric **2** was synthesized via heterocoupling of the corresponding monomeric and dimeric fragments, and its purity was documented by various spectroscopic data and elemental analysis (see the Supporting Information). Dimeric **3** and **4** were synthesized according to the standard procedures (see Arnold, D. P.; Johnson, A. W.; Mahendran, M. *J. Chem. Soc., Perkin Trans. 1* **1978**, 366 and Arnold, D. P.; Johnson, A. W.; Winter, M. *J. Chem. Soc., Perkin Trans. 1* **1977**, 1643, respectively) and their purity was documented by their <sup>1</sup>H NMR spectra (see the Supporting Information).

(7) Chiral solvents **5**–**9** were purchased from Aldrich Chemical Co. and Fluka Chemica AG and used as received.



**Figure 2.** VT (a) CD and (b) UV-vis spectra of **1** in **5<sub>R</sub>** upon cooling from 303 to 163 K (solid lines) and in **5<sub>S</sub>** at 303 K (dashed line in the CD spectra) ( $C_1 = 3.3 \times 10^{-5}$  M).

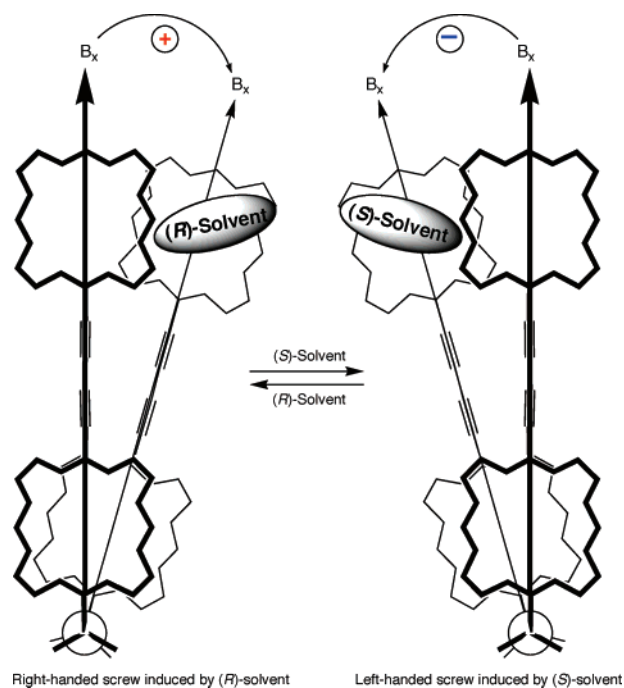
tion of the diacetylene fragments is well documented<sup>8</sup> and may also take place in the present case, **1** appears to be well protected from the intermolecular interaction/aggregation due to the reasonably strong intramolecular diacetylene–diacetylene interactions leading to the syn conformation. This was further supported by the relatively invariant VT <sup>1</sup>H NMR spectra of **1** (see the Supporting Information).

The CD spectra of **1** in **5<sub>R</sub>** and **5<sub>S</sub>** exhibit the mirror-imaged profiles, as one can expect for a pair of enantiomeric forms induced by the antipodal chiral influences, and consist of the two bisignate Cotton effects of small-to-moderate intensities in the region of the porphyrin  $B_x$  transition (Figure 2a). In particular, (*R*)-solvent yields positive first and negative second Cotton effects, while the (*S*)-enantiomer gives the opposite signs. Upon lowering the temperature, while the corresponding CD maxima and minima are kept constant

(8) Shetty, A. S.; Zhang, J.; Moore, J. S. *J. Am. Chem. Soc.* **1996**, *118*, 1019.

(also indicating the absence of the aggregation), the CD amplitude is increased stepwise as a consequence of the enhanced solvent–solute interactions.

A schematic drawing of the chirogenesis mechanism in **1** upon interaction with chiral solvents is depicted in Figure 3. As mentioned above, **1** exists in the syn conformation,



**Figure 3.** Schematic representation of supramolecular chirogenesis in **1** upon interaction with chiral solvents.

which is apparently stabilized by the intramolecular diacetylene–diacetylene (along with porphyrin–porphyrin) interactions, resulting in formation of a small-sized cavity between two terminal porphyrin moieties. The solvent molecules are able to penetrate inside this space to enhance the solvent–solute interactions and thus transfer the chiral information to the achiral host inducing a unidirectional screw in **1**. Although the precise mechanism of host–guest binding is yet to be studied in detail, it is most likely to be based on van der Waals forces rather than the solvent coordination as evidenced by the well-known property of nickel porphyrins to be inert toward the alcohol ligation<sup>4</sup> and the observed chirality induction in **1** in the case of hydroxyl-free solvent (**9**). As can be seen in Figure 2, the direction of screw is governed by the guest’s absolute configuration. In order to confirm this assumption, several chiral solvents (**5–9**) were tested, and in all cases studied, (*R*)-solvents induced a positive CD couplet in the region of the  $B_x$  transition, while (*S*)-solvents yielded a negative couplet that corresponded to the right- and left-handed screws, respectively, according to the exciton chirality method<sup>9</sup> (see Figures 1–3 and the Supporting Information). This regularity allows **1** to be used as a chirality sensor for a wide variety of chiral solvents

with the chiroptical sensitivity that can be sufficiently enhanced by lowering the temperature.

In contrast to the tetrameric **1**, other nickel-containing porphyrin hosts (**2–4**) did not produce any appreciable CD couplet that could be used as an appropriate indicator for the chirality sensing purposes (see the Supporting Information). In particular, trimeric **2** exhibits a CD signal reproducing the absorption profile, which considerably decreases and eventually quenches upon lowering the temperature, apparently as a result of intermolecular aggregation and/or intramolecular conformational modulations owing to the presence of the single diacetylene moiety in the molecule. This was also supported by the considerable changes observed in the corresponding VT  $^1\text{H}$  NMR spectra upon lowering the temperature (see the Supporting Information). Dimeric **3** is essentially CD silent at any temperature used,

---

(9) (a) Harada, N.; Nakanishi, K. *Circular Dichroic Spectroscopy. Exciton Coupling in Organic Stereochemistry*; University Science Books: Mill Valley, CA, 1983. (b) Berova, N.; Nakanishi, K. In *Circular Dichroism: Principles and Applications*; Berova, N., Nakanishi, K., Woody, R. W., Eds.; Wiley-VCH: New York, 2000; pp 337–382.

while **4** gives a small monosignate Cotton effect in the region of the B band transition, which is also almost thermally independent. These results clearly show importance of the rational structural design of host for the effective chirality detection under particular conditions of the weak host–guest interactions, which was achieved in the case of tetrameric **1**.

In summary, we demonstrated that even in the case of extremely weak nonspecific host–guest interactions the chirality can be successfully detected upon proper consideration of all structural, electronic, and environmental factors of the supramolecular assembly. Further studies to expand the applicability and enhance the sensitivity of this type of achiral hosts to various chiral compounds are currently in progress and will be reported in due course.

**Supporting Information Available:** Various synthetic and spectroscopic data. This material is available free of charge via the Internet at <http://pubs.acs.org>.

OL800179C