## Chirality-Memory Molecule: A *D2*-Symmetric Fully Substituted Porphyrin as a Conceptually New Chirality Sensor

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Molecules recognize one another when they are interacting, but on dissociation, they generally lose any trace of the interaction.[1] Herein we report a conceptually new chirality-sensing molecule (**1**),[2] which reads out the chirality of asymmetric molecules through self-assembly and *memorizes* the acquired information within its skeleton even after the assembly is broken. Furthermore, the *chirality memory*, thus imprinted, can be erased by the action of external stimuli, but it is automatically retrieved when the stimuli are switched off. We designed this unique molecule on the basis of a saddle-shaped, fully substituted porphyrin.
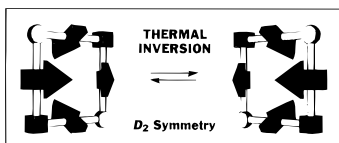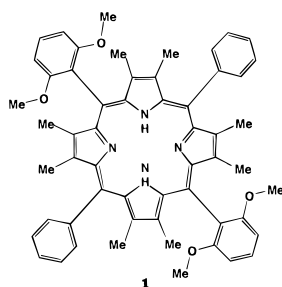
Unlike ordinary porphyrins, fully substituted porphyrins are very unique in that they adopt highly nonplanar conformations due to the steric repulsion among the neighboring substituents.[3] In particular, octaalkyltetraarylporphyrins show a strong preference for a "saddle" conformation with the pyrrole units pointing up and down alternately.[4,5] Therefore, saddle-shaped **1** having two different aryl groups at the opposite meso-positions should be chiral with a symmetry group *D2*. Smith *et al.* have reported a rapid saddle-to-saddle macrocyclic inversion for octaalkyl-tetraarylporphyrins at room temperature,[4] which, for chiral **1**,

Scheme 1. Schematic Representation of the Principle of Chirality Sensing by **1**

corresponds to racemization. In fact, there was no sign of optical resolution of **1** in chiral HPLC.[6]

Fully substituted porphyrins are highly basic due to their nonplanarity and bind two molecules of carboxylic acids via the formation of four hydrogen bonds (Scheme 1).[4,7] When a hot AcOEt solution of a mixture of **1** and 2 equiv of *(S)*-mandelic acid was allowed to cool to room temperature, fine green needles formed. ^{1}H NMR spectroscopy (23 °C) of the product in CDCl3 showed that **1** actually binds two molecules of mandelic acid to form a diastereoisomeric complex (**2**): The signals due to the mandelate moieties in **2** shifted upfield from those of mandelic acid,[8] due to the strong magnetic shielding by the porphyrin ring current. In dichloroethane (DCE), **2** exhibited distinct circular dichroism (CD) bands with a split Cotton effect around its Soret band (Figure 1). The CD patterns of the *(R)*- and *(S)*-mandelate complexes (**2**) were perfect mirror images of each other, thus reflecting the absolute configuration of mandelic acid.

The mandelate complex (**2**), when dissolved in AcOH, was completely transformed into an enantiomeric diacetate complex (**3**)[9] with a release of two molecules of free mandelic acid.[10] Although **3** no longer has any chiral elements at the carboxylate moieties, we still observed clear and further enhanced CD bands

(1) The concept of "molecular hysteresis" has been reported: (a) Sano, M.; Taube, H. *J. Am. Chem. Soc.* **1991**, *113*, 2327. (b) Sano, M.; Taube, H. *Inorg. Chem.* **1994**, *33*, 705.
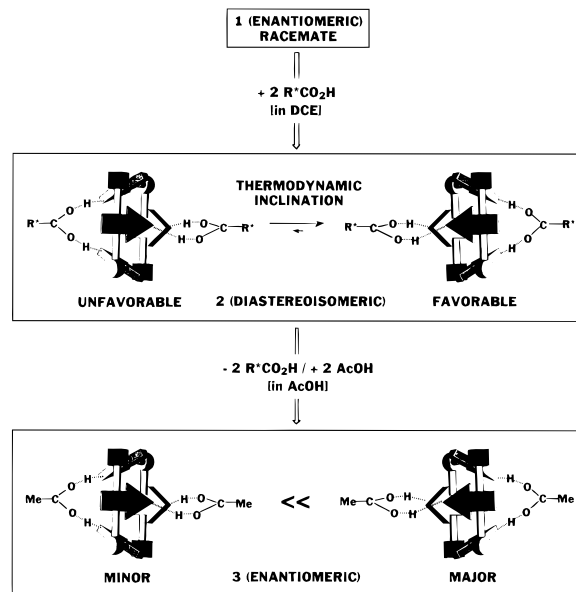
(2) ^{1}H NMR (270 MHz, CDCl3, 23 °C): δ 8.14−8.21 (4H, m, *o*-H in C6H5), 7.65−7.70 (6H, m, *m*- + *p*-H in C6H5), 7.64 (2H, t, *J* = 8.4 Hz, *p*-H in C6H3(OMe)2), 6.93 (4H, d, *J* = 8.4 Hz, *m*-H in C6H3(OMe)2), 3.69 (12H, s, OCH3), 2.05 (12H, s, β-CH3 closed to C6H3(OMe)2), 1.84 (12H, s, β-CH3 closed to C6H5), −1.9 (2H, s, NH). UV−vis (CHCl3/0.1% Et3N): λ_{max} (ε) in nm = 447 (170 000), 545 (20 000), 686 (9700). HRMS: calcd. for C56H55N4O4 (M + H) 847.4223, found 847.4279.

(3) Nurco, D. J.; Medforth, C. J.; Forsyth, T. P.; Olmstead, M. M.; Smith, K. M. *J. Am. Chem. Soc.* **1996**, *118*, 10918.

(4) Barkigia, K. M.; Berber, M. D.; Fajer, J.; Medforth, C. J.; Renner, M. W.; Smith, K. M. *J. Am. Chem. Soc.* **1990**, *112*, 8851.

(5) Medforth, C. J.; Hobbs, J. D.; Rodriguez, M. R.; Abraham, R. J.; Smith, K. M.; Shelnutt, J. A. *Inorg. Chem.* **1995**, *34*, 1333.

(6) For our previous reports on optical resolution of chiral porphyrins, see: (a) Konishi, K.; Sugino, T.; Aida, T.; Inoue, S. *J. Am. Chem. Soc.* **1991**, *113*, 6487. (b) Konishi, K.; Oda, K.; Nishida, K.; Aida, T.; Inoue, S. *J. Am. Chem. Soc.* **1992**, *114*, 1313. (c) Konishi, K.; Takahata, Y.; Aida, T.; Inoue, S.; Kuroda, R. *J. Am. Chem. Soc.* **1993**, *115*, 1169. (d) Konishi, K.; Mori, Y.; Aida, T.; Inoue, S. *Inorg. Chem.* **1995**, *34*, 1292.

(7) Barkigia, K. M.; Faler, J.; Berber, M. D.; Smith, K. M. *Acta Crystallogr. Sect. C* **1995**, *C51*, 511.

(8) For **2** ((*S*)-mandelate): ^{1}H NMR (270 MHz, CDCl3, 23 °C) δ 8.42 (4H, dd, *o*-H in C6H5), 7.77−7.93 (6H, m, *m*− + *p*-H in C6H5), 7.72 (2H, t, *J* = 8.34 Hz, *p*-H in C6H3(OMe)2), 6.96 (4H, d, *J* = 8.34 Hz, *m*-H in C6H3(OMe)2), 6.50−6.62 (6H, m, *m*- + *p*-H in mandelate Ph), 5.39 (4H, d, *J* = 6.84 Hz, *o*-H in mandelate Ph), 3.75 (12H, s, OCH3), 2.03 (12H, s, β-CH3 closed to C6H3(OMe)2), 1.70 (12H, s, β-CH3 closed to C6H5); UV−vis (DCE) λ_{max} (ε) in nm = 471 (230 000), 681 (17 000). For (*S*)-mandelic acid: ^{1}H NMR (270 MHz, CDCl3, 23 °C) δ 7.50−7.36 (5H, m, C6H5), 5.27 (1H, s, CH).

(9) ^{1}H NMR (270 MHz, CD3CO2D, 23 °C): δ 8.45−8.49 (4H, m, *o*-H in C6H5), 7.98−8.06 (6H, m, *m*- + *p*-H in C6H5), 7.94 (2H, t, *J* = 8.35 Hz, *p*-H in C6H3(OMe)2), 7.24 (4H, d, *J* = 8.35 Hz, *m*-H in C6H3(OMe)2), 4.02 (12H, s, OCH3), 2.18 (12H, s, β-CH3 closed to C6H3(OMe)2), 1.94 (12H, s, β-CH3 closed to C6H5). UV−vis (AcOH): λ_{max} (ε) in nm = 467 (220 000), 619 (8300), 680 (21 000).

(10) ^{1}H NMR (270 MHz, CD3CO2D, 23 °C): δ 7.54−7.58 (2H, m, *o*-H in Ph), 7.37−7.48 (3H, m, *m*- + *p*-H in Ph), 5.39 (1H, s, CH).
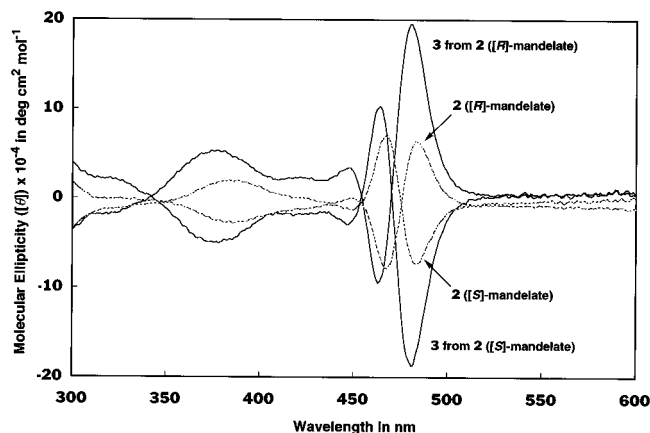
Figure 1. Circular dichroism (CD) spectra at 23 °C of the diastereo-isomeric mandelate complexes (**2**) in DCE and enantiomeric diacetate complexes (**3**, derived from **2**) in AcOH.

Figure 2. Photoresponsive change in optical purity of the *(S)*-mandelate complex (**2**) in DCE/AcOEt (9:1) at 23 °C upon irradiation at its Soret band ($\lambda_{ext} = 470 \pm 5$ nm). The optical purity was evaluated from the intensity of the circular dichroism (CD) band (450−500 nm) after conversion into the diacetate complex (**3**) in AcOH (see ref 12).

(Figure 1). This observation indicates that the diacetate complex (**3**), thus formed, is rich in either of the two possible enantiomers, as a consequence of the strong inclination of **2** toward a thermodynamically favorable diastereoisomer (Scheme 1), and therefore exhibits optical activity. The optical purity of **2** was >98% (diastereoisomeric excess), as estimated from the NMR profile at −50 °C.[11] Therefore, the porphyrin **1** can read out the chirality of mandelic acid through hydrogen-bonding interaction and records the acquired information within its D_2-symmetric saddle-shaped skeleton.
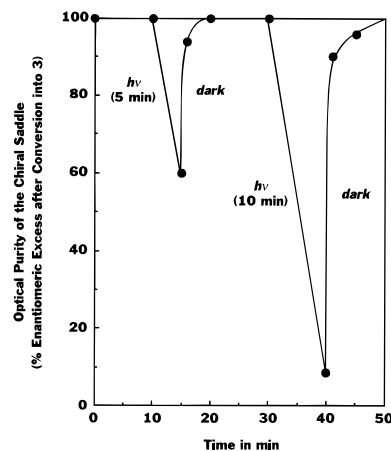
As expected, the optical activity of **2** was instantly erased upon addition of a base such as Et$_3$N, as a result of neutralization of **2** into easily invertible **1**.[4] On the contrary, in AcOH, the optical activity lasted for a long period of time, where the half-life at 23 °C was as long as 200 h. As the temperature was higher, the lifetime of the optical activity of **3** became shorter (half-lives of 38, 21, and 5 min at 60, 70, and 84 °C, respectively), and the activation free energy ($\Delta G^{\ddagger}_{298}$) for the macrocyclic inversion in AcOH was evaluated to be 26.1 kcal mol^{-1} ($\Delta H^{\ddagger} = 29.1$ kcal mol^{-1}, $\Delta S^{\ddagger} = 10.6$ cal K^{-1} mol^{-1}).

Quite interestingly, **3** also lost its optical activity upon excitation by visible light. One of the interesting demonstrations of this phenomenon is the photoswitching of the optical activity of the mandelate complex (**2**) (Figure 2): When the *(S)*-mandelate complex (**2**) in DCE/AcOEt (9:1) was irradiated for 5 min at its Soret band (xenon arc light, $\lambda_{ext} = 470 \pm 10$ nm),[12] the optical purity of the chiral saddle was decreased to 60% (quantum yield = 4.7%). However, when the light was switched off, the optical purity automatically reverted to the initial value within 5 min. Such a photoerasure/self-retrieval cycle could be repeated many times, where the depth of erasing was controlled by the irradiation time. The self-retrieval (self-repairing) of the optical activity of **2** is obviously a result of the reassembly of the racemized porphyrin with *(S)*-mandelic acid.

Porphyrin derivatives have attracted considerable attention as chirality sensors,[13] since they provide highly enhanced exciton-coupled circular dichroism (CD) bands[14] at visible regions without interfering absorptions of usual organic molecules (<300 nm). From this point of view, we investigated the assembly of **1** with several other chiral carboxylic acids including amino acid derivatives, such as 2-methylbutanoic acid, 2-hydroxypropanoic acid, 2-methylphenylacetic acid, 2-methoxyphenylacetic acid, camphanic acid, *N*-(benzyloxycarbonyl)-alanine, and *N*-(benzyloxycarbonyl)phenylalanine, and observed a certain correlation between the sign of the CD bands of **2** (**3**) and the absolute configurations of the acids.[15] In addition to carboxylic acids, enantiomers of a phosphoric acid such as 1,1′-binaphthyl-2,2′-diyl hydrogen phosphate were also distinguishable.

In conclusion, we have exploited the conceptually new chirality-sensing molecule (**1**), which diagnoses and *memorizes* the absolute configurations of chiral acids through hydrogen-bonding interaction, and can then release and retrieve the *chirality memory* in response to the switching of external stimuli such as heat and light. Determination of the absolute configurations of **2** and **3** and their correlation with the circular dichroism profiles are the subjects worthy of further investigation.

(11) In the ^{1}H NMR spectrum in CDCl$_3$ at −50 °C, negligibly small signals assignable to a thermodynamically unfavorable diastereoisomer were detected at δ 8.27 (*o*-H in C$_6$H$_5$) and 3.84 (OCH$_3$). For evaluation of the diastereoisomeric excess, see Supporting Information.

(12) A quartz cell, containing a DCE/AcOEt (9:1) solution of **2**, was irradiated at 23 °C by a 300 W xenon arc lamp through a band-path filter (470 ± 10 nm) and a thermal-cut filter, and an aliquot of the solution was periodically taken out by a glass pipet under irradiation and immediately poured into a large volume of AcOH in a bottle wrapped in aluminum foil, in order to suppress further conformational change of the porphyrin ring. The AcOH solution of **3**, thus obtained, was then subjected to CD spectroscopy for evaluation of the optical purity.

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(15) Similar to that for the mandelate complex (**2**), **3** derived from *(R)*- and *(S)*-dicarboxylate complexes in AcOH showed positive and negative CD bands at 480 nm, respectively.