Synthesis and properties of trifluoroethoxy-coated binuclear phthalocyanine†

Hideyuki Yoshiyama, Norio Shibata,* Takefumi Sato, Shuichi Nakamura and Takeshi Toru

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A genuine example of non-aggregated highly fluorescent binuclear phthalocyanines is reported; spectroscopic studies and computations revealed that the two halves of trifluoroethoxy-coated binuclear phthalocyanine are rotated in the same directions so as to contact each other as much as possible.

The suppression and control of aggregation properties of phthalocyanines (Pcs) both in solvents and in solid films only by their inherent specificity without any external source is a challenge in materials science, especially for solar cells, sensors and photodynamic therapy.[1] The outstanding optical and photosensitizing properties of Pcs with both a wide absorbing range of the spectrum and high luminescence quantum yields are often perturbed in a randomly aggregated state. Pcs free from molecular aggregation are particularly desirable for solar cells and photodynamic therapy because self-association quenches fluorescence and interferes with the formation of singlet oxygen. In addition, controlling the aggregation of phthalocyanine (Pc) macrocycles should be an indispensable factor for nonlinear optical applications.[1] Even though aggregation can be reduced by the introduction of bulky substituents into peripheral positions of Pc cores,[1,2] only a few examples of covalently linked binuclear Pcs free from aggregation are known. Covalently linked binuclear Pcs have gained attention within the last decade because of interesting effects arising from the further extension of the 18 π-conjugation.[3] The coupling between electronic states of the two tethered Pc nuclei leads to important changes in the absorption spectra of the molecules, which renders binuclear Pcs as appealing building blocks with excellent fluorescence properties for the construction of multicomponent photoinduced electron-transfer supramolecular systems, such as artificial porphyrin dimers mimicking the special pair of a photosynthetic reaction.[4] Several relevant examples of dimeric Pc systems have been reported and their propensity to form aggregates has become very apparent. We recently synthesized trifluoroethoxy-substituted zinc Pcs conjugated with deoxyribonucleosides and noted their prominent avoidance of aggregation, with appropriate properties as photodynamic therapy agents.[5a] As an extension of our work on fluorine chemistry,[5] we disclose here the synthesis of a previously unknown trifluoroethoxy-coated (TFEO-coated) binuclear Pc ($CF_3Pc{\equiv}{\equiv}PcCF_3$, **1**) which is the first genuine example of a fluorescent covalently linked binuclear Pc free from aggregation and showing properties independent of solvent and concentration (Fig. 1). Spectroscopic investigations and computations revealed that the two halves of **1** are rotated in the same direction so as to contact each other as much as possible. The results demonstrate that the power of "fluorophilic attraction" is unexpectedly stronger than that of steric repulsion in this covalently linked system, while the powerful intermolecular "fluorophobic repulsion" is clearly responsible for the non-aggregation property of **1** (Fig. 2).

The TFEO-coated binuclear Pc **1** was successfully synthesized by palladium-catalyzed Sonogashira cross-coupling of iodide **2** with an alkyne followed by Glaser coupling as key reactions (Scheme 1). Zinc 23-iodododecakis(2,2,2-trifluoroethoxy)phthalocyaninate **2**[2i] was first coupled with trimethylsilylacetylene under Sonogashira cross-coupling conditions to furnish trimethylsilylated ethynylphthalocyanine **3** in 97% yield. The trimethylsilyl group on **3** was removed to give the terminal acetylene **4**, $CF_3Pc{\equiv}H$, in 99% yield. Target homodimer **1** linked by the butadiynediyl group was synthesized under Glaser coupling conditions *via* dimerization of **4** in high yield. The *tert*-butylated homodimer **5**, *t*BuPc–≡–≡–Pc*t*Bu, was prepared from *t*BuPc–≡–H **6**, according to a previously reported method[3h] for the purpose of comparison. The identity and purity of **1** were confirmed by ^1H, ^{19}F NMR and analytical HPLC. MALDI-TOF MS spectra of **1** showed the isotopic distributions caused by Zn(II), providing proof for its characterization (see ESI†).

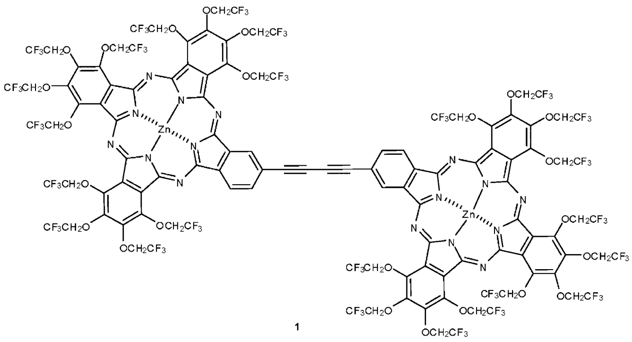

Fig. 1 Structure of trifluoroethoxy-coated homobinuclear Pc **1**.

Department of Applied Chemistry, Graduate School of Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya, 466-8555, Japan. E-mail: nozshiba@nitech.ac.jp; Fax: +81-52-735-5442; Tel: +81-52-735-7543

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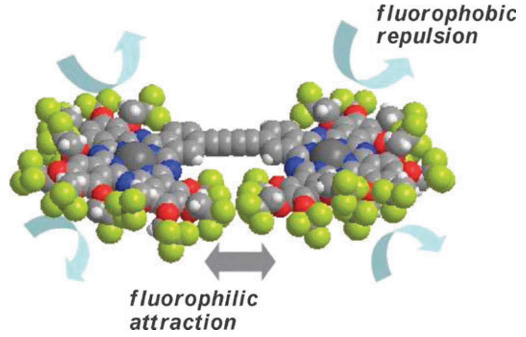


Fig. 2 Fluorophobic repulsion and fluorophilic attraction exist together in the molecule **1**.

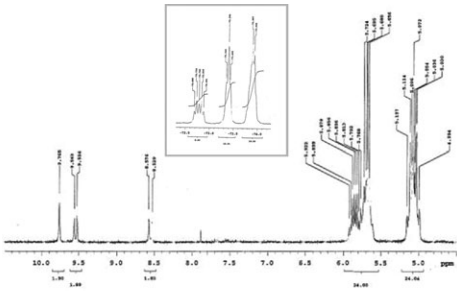
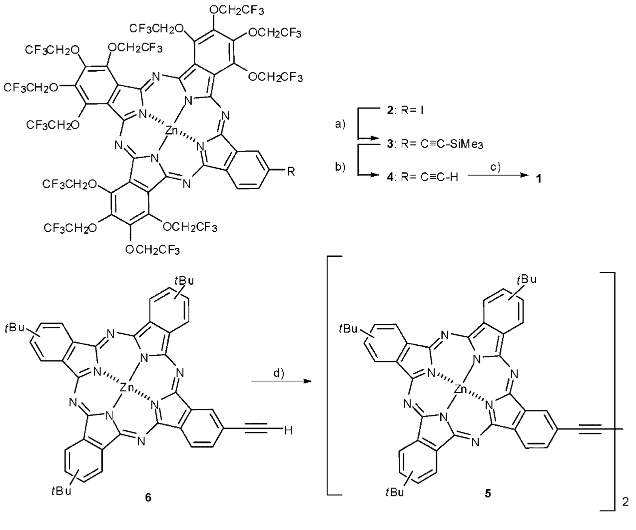


Fig. 3 ^{1}H NMR spectrum of **1** (inset: ^{19}F NMR spectrum).

With the target molecules in hand, their aggregation properties were scrutinized using NMR and UV-Vis spectra. The solution state of binuclear Pcs has been extensively studied and they have a remarkably high tendency toward aggregation, and that the monomeric state only occurs under very specific conditions of solvent and high dilution.[2,3] However, it is interesting to note that the ^{1}H and ^{19}F NMR spectra of **1** showed surprisingly resolved, easily assignable signals in accordance with the proposed structure (*ca.* 1×10^{-3} M, THF-d_8) (Fig. 3, also see Fig. S1 and S2 in ESI†). The high resolution in these spectra is indicative of a very low degree of aggregation in solution. On the other hand, the *tert*-butyl homodimer **5** gave broad ^{1}H NMR signals corresponding to the aliphatic and aromatic protons in the same concentration indicating that **5** forms aggregate structures (Fig. S3 in ESI†).

The optical behavior of **1** and **5** was then investigated using UV-Vis spectra in a variety of solvents in the concentration range 1×10^{-4} to 5×10^{-7} M (dioxane, $CHCl_3$ and benzotrifluoride). Selected examples of absorption spectra of **1** and **5** in $CHCl_3$ are shown in Fig. 4 and 5. The TFEO-coated **1** possesses a distinct feature: a strong absorption Q band appears at longer wavelengths and is that of a monomer irrespective of the solvent and concentration, as characterized by sharp absorption bands in the B- and Q-band regions (λ_{max} ($CHCl_3$)/nm = 363 and 707, respectively). Similar behavior was found in a variety of solvents at different concentrations, even in non-polar benzotrifluoride (Fig. S4 and S5 in ESI†). This kind of behavior is surprising. Furthermore, the spectrum of **1** remained essentially unchanged after the addition of a drop of pyridine (approximately 100-fold excess relative to **1**, Fig. 4). These results clearly prove that the TFEO-coated **1** exists as a monomer totally free from aggregation. In contrast, *t*BuPc–≡–≡–Pc*t*Bu **5** mainly exists as aggregates according to its broad spectra, and its monomer state was only partially observed under dilute conditions[1b] or in coordinating solvents (Fig. 5, also see Fig. S6 in ESI†).



Scheme 1 Preparation of phthalocyanines. *Reagents and conditions*: (a) trimethylsilylacetylene, $Pd(PPh_3)_2Cl_2$, CuI, Et_3N, THF, 40 °C, 24 h, 97%; (b) K_2CO_3, MeOH, RT, 4 h, 99%; (c) CuCl, pyridine, RT, 3 days, 74%; (d) CuCl, pyridine, RT, 3 days, 85%.

It is obvious that the strong encapsulation and lipophobicity effects intrinsic to TFEO-coating effectively remove the possibility for self-aggregation. The strong electron withdrawing effect of the fluorine atoms might also act to reduce aggregation by lowering the energies of the HOMOs of the Pc rings.[6] To our knowledge, this is the first genuine example of a covalently linked binuclear Pc absolutely free from aggregation regardless of solvent and concentration. Further, despite the unsymmetrical structural nature of **1**, the Q-band at 707 nm does not split, a quite rare phenomonen. Splitting of the Q-bands is common for unsymmetrical binuclear Pcs, presumably as a consequence of splitting of the energetic levels due to electronic coupling between two neighboring Pc moieties[1,3,7] (see the spectra of **5** in Fig. 5, also see, Fig. S6 and S7 in ESI†). No splitting observed for **1** would indicate that either no electronic communication exists between the two independent TFEO-coated phthalocyanine moieties or that the geometry of **1** in solution is symmetrical. Absorption spectra of the mononuclear Pcs, CF_3Pc–≡–H **4**, and *t*BuPc–≡–H **6** were also superimposed in the corresponding figures for

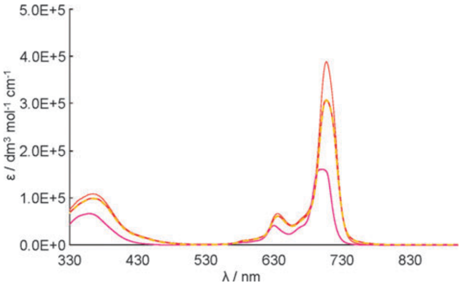


Fig. 4 UV-Vis spectra of CF_3Pc–≡–≡–$PcCF_3$ **1** (red: 1.0×10^{-5} and 10^{-6} M; broken orange: 1.0×10^{-5} M with a drop of pyridine), CF_3Pc–≡–H **4** (pink: 2.0×10^{-5} M) in $CHCl_3$.

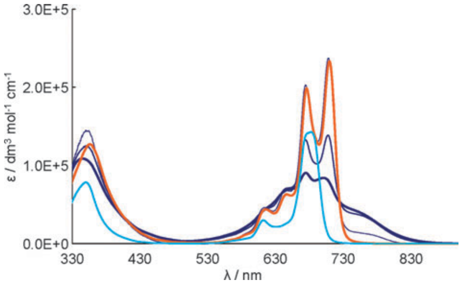


Fig. 5 UV-Vis spectra of *t*BuPc–≡–≡–Pc*t*Bu **5** (blue: 1.0 × 10^{-4}–10^{-6} M, orange: 1.0 × 10^{-4} M with a drop of pyridine), *t*Bu-Pc–≡–H **6** (pink: 2.0 × 10^{-5} M) in $CHCl_3$.

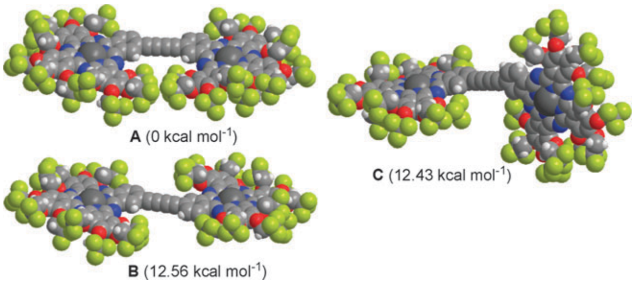


Fig. 6 PM3 geometry optimization of **1**: (A) symmetric form; (B) opposite form; (C) cross form.

comparison (Fig. 4 and 5). While there is a significant difference in the UV-Vis spectra of binuclear **5** and mononuclear **6**, little difference was observed between **1** and **4**. The spectroscopic properties of TFEO-coated Pc **1** are clearly unique and interesting.

PM3 semiempirical computations using Spartan 06 find a symmetric form **A** is the lowest energy conformation (by >12 kcal mol^{-1}) (Fig. 6). The two halves of binuclear Pc are favorably rotated in the same directions to produce a symmetrical conformation **A** , albeit with greater steric interactions in this orientation, and the unfavored orientations have the Pc groups positioned away each other (opposite form **B** and cross-form **C**). It is quite surprising that the CF_3 groups at *peri* positions in Pcs prefer to form $CF_3\cdots CF_3$ contacts rather than avoid them owing to steric repulsive forces. Why should **1** exhibit such a geometry? The behavior of the CF_3 substituent in Pc is clearly very different from the heavier bulky alkyl substituents, despite its size being between those of *i*Pr and *t*Bu groups.[8] The results demonstrate that the power of "fluorophilic attraction"[9] is unexpectedly stronger than that of steric repulsion in this covalently linked system.

In conclusion, TFEO-coated **1** is the first genuine example of a non-aggregated highly fluorescent binuclear Pc[11] due to strong "intermolecular fluorophobic repulsion". On the other hand, the preferred symmetrical conformation of **1** demonstrates that the power of "fluorophilic attraction" is unexpectedly stronger than that of steric repulsion in a covalently linked system. The two halves of binuclear Pc **1** sit close together as to minimize the fluorous surface, which is an additional explanation for the observed very weak intermolecular fluorous interaction and non-aggregation. Although the net effects of TFEO in these Pcs are difficult to explain and our present explanation would be a matter of debate, this result corresponds to one more possible application of fluorine's unique powers in organic chemistry.[9,10]

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11 Fluorescence: ($CHCl_3$): λ_{em} = 721 nm, Φ_f = 0.23; (dioxane): λ_{em} = 724 nm, Φ_f = 0.28.