Porphyrinoids

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Formation and Isolation of a Four-Electron-Reduced Porphyrin Derivative by Reduction of a Stable 20π Isophlorin

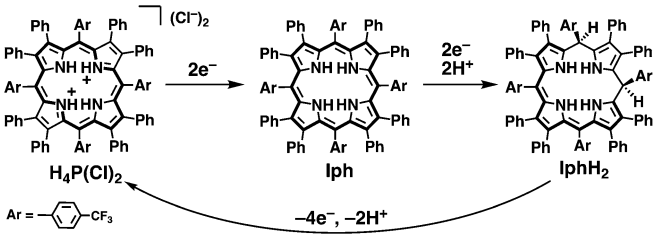
*Wataru Suzuki, Hiroaki Kotani, Tomoya Ishizuka, Yoshihito Shiota, Kazunari Yoshizawa, and Takahiko Kojima**

Abstract: *The two-electron reduction of a diprotonated dodecaphenylporphyrin derivative by $Na_2S_2O_4$ gave a corresponding isophlorin (**Iph**) selectively. Formation of **Iph** was confirmed by spectroscopic measurements and the isolation of tetramethylated **Iph**. Further reduction of **Iph** proceeded to form an unprecedented four-electron-reduced porphyrin (**$IphH_2$**), which was fully characterized by spectroscopic and X-ray crystallographic analysis. **$IphH_2$**, with a unique conformation, could be oxidized to reproduce the starting porphyrin, resulting in a proton-coupled four-electron reversible redox system.*

Porphyrins are widely known to be 18π-conjugated aromatic macrocycles and redox-active molecules that demonstrate reversible multi-redox processes. For several decades, the interesting redox properties of porphyrins have been investigated mainly through electrochemical measurements.[1] In addition, porphyrins with a phenolic moiety as a redox-active site at the periphery have been reported to show reversible multi-electron redox behavior by external stimuli.[2] As an alternative candidate for a porphyrinoid showing multi-electron redox behavior without redox-active moieties at the periphery, a multi-electron reduced porphyrin, such as porphyrinogen and isophlorin, which have been proposed as intermediates in the synthetic pathway of porphyrins, have been considered.[3] However, there is no report of a reversible redox system comprised of a multi-electron pool based on a porphyrin framework without redox-active sites because of the instability of multi-electron reduced porphyrinoids.

Among various species of reduced porphyrinoids, isophlorin, which is a two-electron reduced form of a porphyrin in a 20π-conjugated system, has attracted much attention owing to the fact that it undergoes two-electron oxidation to afford a porphyrin.[3–7] Some isophlorin derivatives have been isolated through the reduction of the corresponding porphyrins with highly positive central ions (Si^{IV}, Ge^{IV})[4] or core-modified porphyrins,[5] such as tetraoxaporphyrin, with 20π anti-aromatic character. However, no investigation on further reduction of isophlorin has been reported, in spite of the fact that a porphyrin-based redox system is expected to act as a reversible multi-electron redox system.

We have focused on a diprotonated saddle-distorted dodecaphenylporphyrin ($\mathbf{H_4DPP^{2+}}$)[8] as an appropriate precursor for the formation of a corresponding isophlorin derivative because $\mathbf{H_4DPP^{2+}}$ shows a high reduction potential to induce disproportionation of one-electron reduced species of $\mathbf{H_4DPP^{2+}}$ ($H_4DPP^{\bullet+}$), affording two-electron reduced species.[8b] Herein, we report the selective formation of an isophlorin derivative (**Iph**) from $\mathbf{H_4DPP^{2+}}$ that has electron-withdrawing trifluoromethyl (CF_3) groups at the *para*-position of the *meso*-phenyl groups ($\mathbf{H_4P(Cl)_2}$). Interestingly, it was found that **Iph** could be further reduced to form a unique four-electron-reduced porphyrin ($\mathbf{IphH_2}$), which was fully characterized for the first time. In addition, $\mathbf{IphH_2}$ undergoes four-electron oxidation to afford the starting porphyrin, and therefore acts as a reversible multi-redox system (Scheme 1).



Scheme 1. The multi-electron redox cycle composed of a four-electron-reduced porphyrin ($\mathbf{IphH_2}$) via the selective formation of **Iph** from $\mathbf{H_4P(Cl)_2}$.

A diprotonated dodecaphenylporphyrin derivative with four CF_3 groups, $\mathbf{H_4P(Cl)_2}$, was synthesized based on a literature method.[9] Characterization of $\mathbf{H_4P(Cl)_2}$ was conducted by spectroscopic measurements, elemental analysis, and X-ray crystallography. In the molecular structure of $\mathbf{H_4P(Cl)_2}$ (see Figure S1 in the Supporting Information), $\mathbf{H_4P(Cl)_2}$ shows a large saddle distortion ($\Delta rms = 0.81$ Å),[10] which is similar to that of $\mathbf{H_4DPP^{2+}}$ ($\Delta rms = 0.87$ Å).[8a] Cyclic voltammetry (CV) and differential pulse voltammetry (DPV) of $\mathbf{H_4P(Cl)_2}$ showed reversible two-electron-reduction waves of $\mathbf{H_4P(Cl)_2}$ at −0.67 V vs. Fc/Fc^+ in DMSO at 298 K containing 0.1 M $[N(n\text{-butyl})_4]PF_6$ ($TBAPF_6$) as an electrolyte (Figure S2a). The reduction potential of $\mathbf{H_4P(Cl)_2}$ (−0.67 V) is slightly more positive than that of $\mathbf{H_4DPP^{2+}}$ (−0.73 V) because of the electron-withdrawing CF_3 groups (Figure S2b).

[*] W. Suzuki, Dr. H. Kotani, Dr. T. Ishizuka, Prof. Dr. T. Kojima
Department of Chemistry
Graduate School of Pure and Applied Sciences
University of Tsukuba
1-1-1 Tennoudai Tsukuba, Ibaraki 305-8571 (Japan)
E-mail: kojima@chem.tsukuba.ac.jp
Prof. Dr. Y. Shiota, Prof. Dr. K. Yoshizawa
Institute for Materials Chemistry and Engineering
Kyushu University
Motooka, Nishi-Ku, Fukuoka 819-0395 (Japan)
Supporting information and the ORCID identification number(s) for the author(s) of this article can be found under: https://doi.org/10.1002/anie.201711058.

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Upon addition of four equivalents of $Na_2S_2O_4$ in H_2O to a DMSO solution containing $\mathbf{H_4P(Cl)_2}$ under Ar, UV/Vis spectral changes were observed as shown in Figure S3. The Soret band at 494 nm and the Q band at 688 and 729 nm resulting from $\mathbf{H_4P(Cl)_2}$ disappeared completely with a concomitant appearance of new bands at 474 and 568 nm (Figure S3). When the reduction reaction of $\mathbf{H_4P(Cl)_2}$ by $Na_2S_2O_4$ in [D_6]DMSO was monitored by ^{1}H NMR spectroscopy, ^{1}H NMR signals from $\mathbf{H_4P(Cl)_2}$ disappeared together with an appearance of new signals at 13.99 and 7.1–6.5 ppm (Figure 1). The ^{1}H NMR signal at 13.99 ppm was assigned to

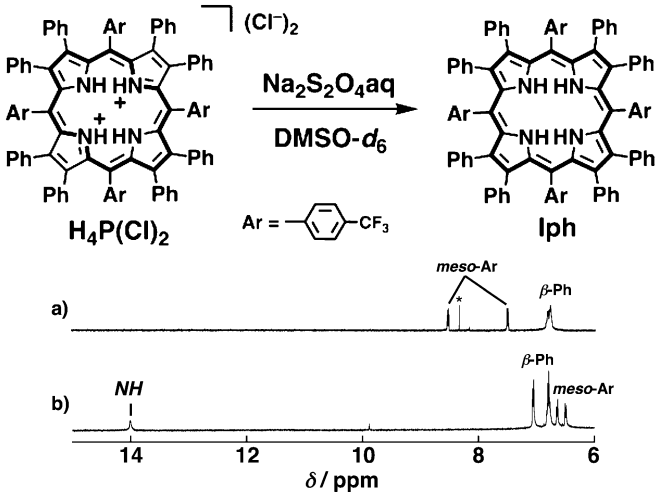


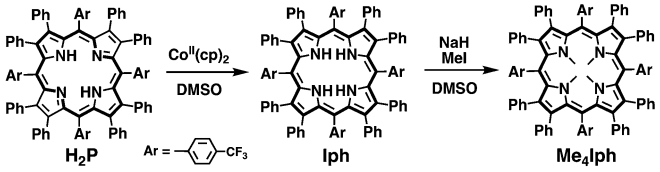
Figure 1. ^{1}H NMR spectra of a) $\mathbf{H_4P(Cl)_2}$, and b) $\mathbf{H_4P(Cl)_2}$ in the presence of four equivalents of $Na_2S_2O_4$(aq) in [D_6]DMSO at 298 K. *:$CHCl_3$ in crystals of $\mathbf{H_4P(Cl)_2}$.

the NH protons of pyrrole rings, and was confirmed by the disappearance of the signal after H/D exchange in the presence of D_2O (Figure S4). The NH proton signal of the pyrrole rings at a low magnetic field indicates the loss of aromaticity in $\mathbf{H_4P(Cl)_2}$ by the chemical reduction. In addition, the ^{1}H NMR signals from the β-Ph and *meso*-Ph groups and one singlet signal in the ^{19}F NMR spectrum were indicative of the symmetrical structure of the reduced derivative of $\mathbf{H_4P(Cl)_2}$. Therefore, these spectroscopic data suggested the selective formation of **Iph** as the two-electron-reduced product of $\mathbf{H_4P(Cl)_2}$ as seen in the previous report for the formation of an isophlorin derivative.[6] It should be noted that no formation of **Iph** isomers, such as a phlorin derivative (**Phl**) and a 5,15-porphodimethene derivative (**Pdm**), was observed because there were no singlet signals from their methine protons around 6 ppm.[11]

To evaluate the aromaticity of **Iph**, the nucleus-independent chemical shift (NICS(0))[12] was calculated at the B3LYP/6-31G** level of theory (Figure S5). The estimated NICS(0) value (+2.97 ppm) at the ring center of **Iph** was comparable with that of the previously reported non-aromatic isophlorin (+2.25 ppm).[6] In the case of planar anti-aromatic isophlorins, the estimated NICS(0) values were estimated to be above +20 ppm owing to the paratropic-ring-current effect of a 4nπ macrocycle.[4,5] Thus, **Iph** is interpreted as having a non-aromatic character.

The requirements for the reaction conditions to form **Iph** were investigated by varying the reductants and solvents (Table S1). Formation of **Iph** was also confirmed by using cobaltocene ($Co^{II}(cp)_2$) or zinc powder (Zn) as an electron donor instead of $Na_2S_2O_4$, whereas the reduction of $\mathbf{H_4P(Cl)_2}$ by $NaBH_4$ afforded unidentified species. In addition, the formation of **Iph** was confirmed in polar aprotic solvents, such as DMSO and DMF (Figure S6): **Iph** is stable in these solvents for several days under deaerated conditions at room temperature. In contrast, mixtures of reduced products were produced in other solvents, such as methanol, acetone, and acetonitrile, although the formation of **Iph** was detected at the beginning of the reaction by ^{1}H NMR measurements in each solvent. In the case of methanol, formation of **Pdm** as one of the reduced products was confirmed by X-ray crystallography (Figure S7). To compare the thermodynamic stability of **Iph**, **Phl**, and **Pdm**, DFT calculations were conducted. As a result, **Iph** was thermodynamically disfavored compared with **Phl** (−6.3 kcal mol^{-1} relative to **Iph**) and **Pdm** (−15.3 kcal mol^{-1} relative to **Iph**) (Figure S8). However, the similarity of saddle-distorted structures between $\mathbf{H_4P(Cl)_2}$ and **Iph** is assumed to induce kinetically favorable formation of **Iph** as described above. In the case of DMSO, **Iph** was stabilized by hydrogen bonding with DMSO molecules and **Phl** and **Pdm** were not.[13,14] Therefore, the electron-transfer reduction of $\mathbf{H_4P(Cl)_2}$ in polar aprotic solvents is essential for the selective formation of **Iph**.

Unfortunately, crystallization of **Iph** was not achieved owing to limitations of the reaction conditions described above. As an alternative method for the characterization of **Iph**, methylation of the inner-pyrrole nitrogen atoms was employed to characterize **Iph** derivatives by X-ray crystallography. As shown in Scheme 2, tetramethylation of **Iph** was



Scheme 2. Synthesis of $\mathbf{Me_4Iph}$ via formation of **Iph**.

accomplished sequentially in a one-pot reaction in DMSO by two-electron reduction of $\mathbf{H_2P}$ with $Co^{II}(cp)_2$ and methylation by iodomethane (MeI) in the presence of sodium hydride (NaH) as a base. The tetramethylated **Iph** derivative ($\mathbf{Me_4Iph}$) was characterized by MALDI-TOF-MS and ^{1}H NMR analysis (Figure S10). The observed ^{1}H NMR signal, under air, at 5.24 ppm from an inner-methyl group suggested the formation of non-aromatic air-stable $\mathbf{Me_4Iph}$ (Figure S10b). The UV/Vis spectrum of $\mathbf{Me_4Iph}$ in acetone shows a characteristic absorption band at 475 nm owing to $\mathbf{Me_4Iph}$, which is similar to that of non-aromatic **Iph** (Figure S11).[6,7a] The molecular structure of $\mathbf{Me_4Iph}$ was then found by X-ray crystallography and is shown in Figure 2. Single crystals of $\mathbf{Me_4Iph}$ were obtained by vapor diffusion of

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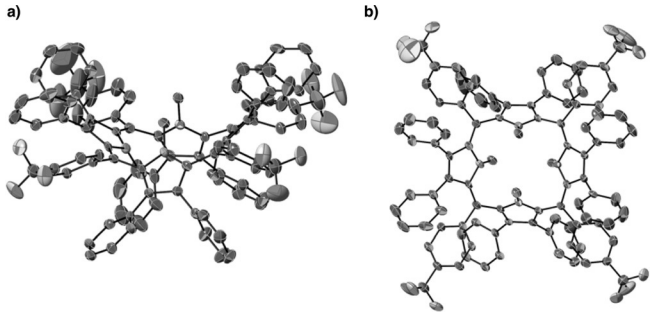


Figure 2. ORTEP drawings of **Me_4Iph** a) side view, and b) top view. Hydrogen atoms were omitted for clarity.

2-propanol to a CH_2Cl_2 solution containing **Me_4Iph**. As shown in Figure 2, **Me_4Iph** shows a large saddle distortion (Δrms = 0.83 Å), which is comparable to that of **Iph** (Δrms = 0.96 Å) estimated by DFT calculations. No inclusion of counter anions in the structure indicates that the macrocycle should be without charge and maintains the two-electron-reduced form after methylation of **Iph**, in contrast to the case of **H_4P(Cl)$_2$** that includes two chloride ions as the counter anions (Figure S1).[15]

Next, we investigated the reductive transformation of **Iph** in the presence of excess $Na_2S_2O_4$ in DMSO. It was revealed that **Iph** was further reduced to form a four-electron-reduced porphyrin (**$IphH_2$**) as seen in Figure 3. The ^{1}H NMR signals of **Iph** were completely converted to those resulting from **$IphH_2$** with lower symmetry as can be seen in three kinds of NH protons around 10 ppm. A characteristic singlet signal was also observed at 5.99 ppm owing to the two protons attached to the *meso*-carbon atoms in the reduced porphyrin ring. MALDI-TOF-MS analysis showed a peak cluster at m/z = 1499.67, which was assigned to $[\mathbf{IphH_2}+H]^+$ as a four-electron-reduced **H_4P(Cl)$_2$** (Figure S13). UV/Vis spectral changes from **Iph** to **$IphH_2$** were observed with isosbestic points (519 and 580 nm) as shown in Figure S3b. The single

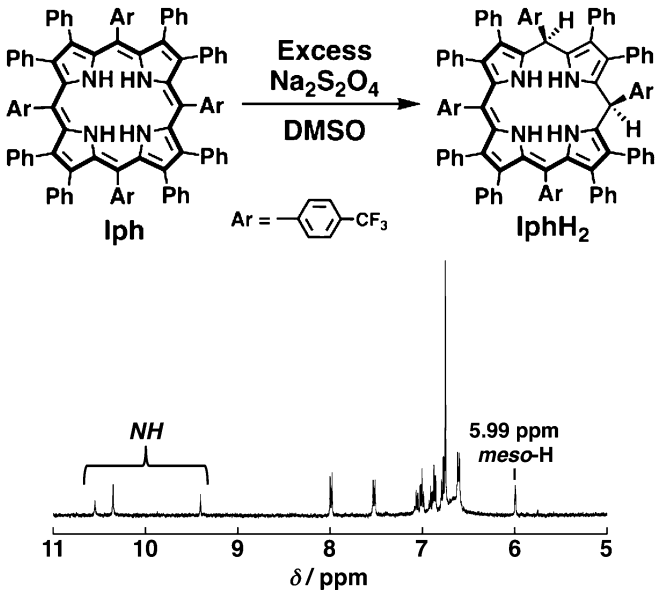


Figure 3. ^{1}H NMR spectrum of **$IphH_2$** in [D_6]DMSO at 298 K.

crystals of **$IphH_2$** were successfully obtained by vapor diffusion of EtOH to a DMF solution containing **$IphH_2$**. The molecular structure of **$IphH_2$** was unambiguously revealed by X-ray crystallography and is shown in Figure 4.

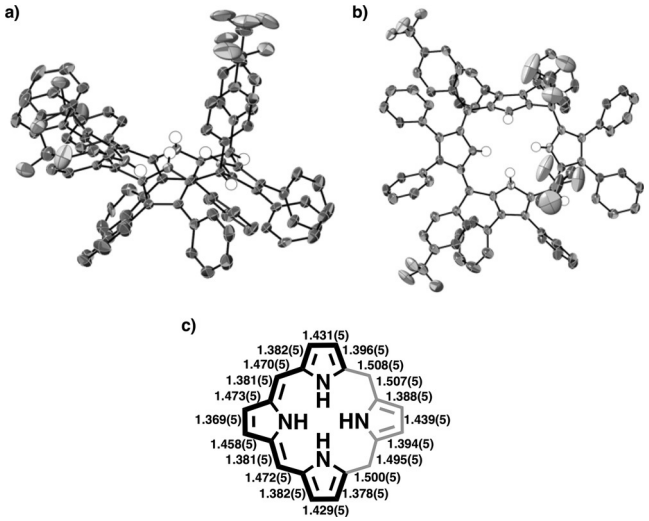


Figure 4. ORTEP drawings of **$IphH_2$** a) side view, and b) top view. Hydrogen atoms were omitted for clarity except for protons of nitrogen atoms and protons attached to the *meso*-carbon atoms. c) The C–C bond lengths [Å] of the macrocycle in **$IphH_2$**.

In the structure, the 5,10-*meso* carbon atoms were reduced to sp^3 configurations in a "*syn*" geometry for the two adjacent 4-CF_3-phenyl groups attached to the carbon atoms, forming a unique conformation of the porphyrinoid core. The left part shows an isophlorin-like conformation and the right part shows a porphodimethene-like conformation. As shown in Figure 4c, a C–C bond-length alternation was observed in the left part (black) of **$IphH_2$**, as seen in the case of **Me_4Iph**;[15] in the right part (grey), the C–C bond lengths around the *meso*-carbon atoms were determined to be 1.508(5), 1.507(5), 1.495(5), and 1.500(5) Å. This C–C bond elongation and the detection of methine protons in ^{1}H NMR measurements clearly indicate that the further reduction and protonation occur at the *meso*-carbon atoms.

To compare the thermodynamic stability of **$IphH_2$** with other structural isomers, DFT-optimized structures of three possible isomers of four-electron-reduced porphyrins were calculated at the (U)B3LYP/6–31G** level of theory. We considered **5,10-*Anti*** and **5,15-*Syn*** of a triplet biradical form as structural isomers of **$IphH_2$** (**5,10-*Syn***, Figures 5, S14). The stability of **5,15-*Syn*** is thermodynamically disfavored compared with that of **5,10-*Syn*** (+ 20.7 kcal mol^{-1} relative to **5,10-*Syn***) owing to the unstable open-shell structure. **5,10-*Anti*** was destabilized by 7.2 kcal mol^{-1} in comparison to **5,10-*Syn*** because of steric repulsion between a *meso*-aryl group and a β-phenyl group. Therefore, it was clarified that ***5*,10-*Syn*** should be the most stable isomer of the four-electron-reduced species.

Finally, the thermodynamic stability and redox behavior of **$IphH_2$** were investigated to ascertain that **$IphH_2$** could act as a reversible multi-redox system. No ^{1}H NMR spectral

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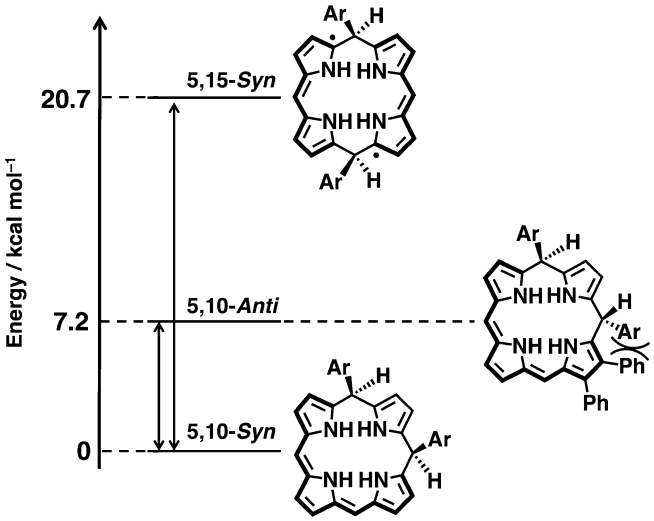


Figure 5. Comparison of the thermodynamic stability of **5,10-*Syn*** (**$IphH_2$**) with structural isomers (**5,10-*Anti*** and **5,15-*Syn***) based on DFT calculations.

change was observed for **$IphH_2$** in [D_6]DMSO under deaerated conditions at 353 K for two days (Figure S15), therefore, the compound should be thermodynamically stable. In contrast, **$IphH_2$** was smoothly oxidized by an excess amount of 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) to produce **$H_4P(Cl)_2$** (Figure S16), which is derived from protonation of **H_2P** formed as the oxidized product. The yield of **$H_4P(Cl)_2$** was determined to be 96% by ^{1}H NMR measurements. This result clearly indicates that a reversible four-electron redox cycle between **$H_4P(Cl)_2$** and **$IphH_2$** was established (Scheme 1).

In summary, we have established a methodology for the selective formation of an isophlorin derivative (**Iph**), by using a saddle-distorted diprotonated dodecaphenylporphyrin derivative, through reduction with electron donors in polar aprotic solvents (DMSO or DMF). Surprisingly, further two-electron reduction of **Iph** by $Na_2S_2O_4$ afforded a novel four-electron-reduced porphyrinoid (**$IphH_2$**), which has a unique conformation. Finally, we have demonstrated a four-electron reversible redox system by re-oxidation of **$IphH_2$** to reproduce the starting diprotonated dodecaphenylporphyrin, **$H_4P(Cl)_2$**.

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Conflict of interest

The authors declare no conflict of interest.

Keywords: electrochemistry · electron transfer · isophlorins · porphyrins · redox chemistry

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[1] a) K. M. Kadish, M. M. Morrison, *J. Am. Chem. Soc.* **1976**, *98*, 3326–3328; b) Y. Fang, P. Bhyrappa, Z. Ou, K. M. Kadish, *Chem. Eur. J.* **2014**, *20*, 524–532; c) Y. Fang, Y. G. Gorbunova, P. Chen, X. Jiang, M. Manowong, A. A. Sinelshchikova, Y. Y. Enakieva, A. G. Martynov, A. Y. Tsivadze, A. Bessmertnykh-Lemeune, C. Stern, R. Guilard, K. M. Kadish, *Inorg. Chem.* **2015**, *54*, 3501–3512; d) X. Ke, P. Yadav, L. Cong, R. Kumar, M. Sankar, K. M. Kadish, *Inorg. Chem.* **2017**, *56*, 8527–8537; e) K. Rybicka-Jasińska, W. Shan, K. Zawada, K. M. Kadish, D. Gryko, *J. Am. Chem. Soc.* **2016**, *138*, 15451–15458.

[2] a) K. M. Kadish, E. Wenbo, R. Zhan, T. Khoury, L. J. Govenlock, J. K. Prashar, P. J. Sintic, K. Ohkubo, S. Fukuzumi, M. J. Crossley, *J. Am. Chem. Soc.* **2007**, *129*, 6576–6588; b) S. Hayashi, J. Sung, Y. M. Sung, Y. Inokuma, D. Kim, A. Osuka, *Angew. Chem. Int. Ed.* **2011**, *50*, 3253–3256; *Angew. Chem.* **2011**, *123*, 3311–3314; c) S. Ishihara, J. P. Hill, A. Shundo, G. J. Richards, J. Labuta, K. Ohkubo, S. Fukuzumi, A. Sato, M. R. J. Elsegood, S. J. Teat, K. Ariga, *J. Am. Chem. Soc.* **2011**, *133*, 16119–16126.

[3] B. K. Reddy, A. Basavarajappa, M. D. Ambhore, V. G. Anand, *Chem. Rev.* **2017**, *117*, 3420–3443.

[4] a) J. A. Cissell, T. P. Vaid, A. L. Rheingold, *J. Am. Chem. Soc.* **2005**, *127*, 12212–12213; b) J. A. Cissell, T. P. Vaid, G. P. A. Yap, *J. Am. Chem. Soc.* **2007**, *129*, 7841–7847; c) H. Song, J. A. Cissell, T. P. Vaid, D. Holten, *J. Phys. Chem. B* **2007**, *111*, 2138–2142.

[5] a) R. Bachmann, F. Gerson, G. Gescheidt, E. Vogel, *J. Am. Chem. Soc.* **1992**, *114*, 10855–10860; b) E. Vogel, M. Pohl, A. Herrmann, T. Wiss, C. König, J. Lex, M. Gross, J. P. Gisselbrecht, *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 1520–1524; *Angew. Chem.* **1996**, *108*, 1677–1682; c) A. Weiss, M. C. Hodgson, P. D. W. Boyd, W. Siebert, P. J. Brothers, *Chem. Eur. J.* **2007**, *13*, 5982–5993; d) J. S. Reddy, V. G. Anand, *J. Am. Chem. Soc.* **2008**, *130*, 3718–3719; e) Y. Matano, T. Nakabuchi, S. Fujishige, H. Nakano, H. Imahori, *J. Am. Chem. Soc.* **2008**, *130*, 16446–16447; f) P. J. Brothers, *Chem. Commun.* **2008**, 2090–2102; g) J. Yan, M. Takakusaki, Y. Yang, S. Mori, B. Zhang, Y. Feng, M. Ishida, H. Furuta, *Chem. Commun.* **2014**, *50*, 14593–14596; h) B. K. Reddy, S. C. Gadekar, V. G. Anand, *Chem. Commun.* **2015**, *51*, 8276–8279; i) S. P. Panchal, S. C. Gadekar, V. G. Anand, *Angew. Chem. Int. Ed.* **2016**, *55*, 7797–7800; *Angew. Chem.* **2016**, *128*, 7928–7931; j) A. Yamaji, H. Tsurugi, Y. Miyake, K. Mashima, H. Shinokubo, *Chem. Eur. J.* **2016**, *22*, 3956–3961.

[6] C. Liu, D.-M. Shen, Q.-Y. Chen, *J. Am. Chem. Soc.* **2007**, *129*, 5814–5815.

[7] a) M. Pohl, H. Schmickler, J. Lex, E. Vogel, *Angew. Chem. Int. Ed. Engl.* **1991**, *30*, 1693–1697; *Angew. Chem.* **1991**, *103*, 1737–1741; b) J. Setsune, K. Kashihara, K. Wada, H. Shinozaki, *Chem. Lett.* **1999**, *28*, 847–848; c) J. Setsune, K. Kashihara, K. Wada, *Chem. Lett.* **2001**, *30*, 72–73; d) T. P. Vaid, *J. Am. Chem. Soc.* **2011**, *133*, 15838–15841; e) M. Umetani, T. Tanaka, T. Kim, D. Kim, A. Osuka, *Angew. Chem. Int. Ed.* **2016**, *55*, 8095–8099; *Angew. Chem.* **2016**, *128*, 8227–8231.

[8] a) R. Harada, T. Kojima, *Chem. Commun.* **2005**, 716–718; b) T. Kojima, T. Nakanishi, R. Harada, K. Ohkubo, S. Yamauchi, S. Fukuzumi, *Chem. Eur. J.* **2007**, *13*, 8714–8725.

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[9] C.-J. Liu, W.-Y. Yu, S.-M. Peng, T. C. W. Mak, C.-M. Che, *J. Chem. Soc. Dalton Trans.* **1998**, 1805 – 1812.
[10] W. Jentzen, I. Turowska-Tyrk, W. R. Scheidt, J. A. Shelnutt, *Inorg. Chem.* **1996**, *35*, 3559 – 3567.
[11] a) T. Kojima, K. Hanabusa, K. Ohkubo, M. Shiro, S. Fukuzumi, *Chem. Commun.* **2008**, 6513 – 6515; b) B. Liu, X. Li, X. Xu, M. Stępień, P. Chmielewski, *J. Org. Chem.* **2013**, *78*, 1354 – 1364.
[12] a) Z. Chen, C. S. Wannere, C. Corminboeuf, R. Puchta, P. v. R. Schleyer, *Chem. Rev.* **2005**, *105*, 3842 – 3888; b) P. v. R. Schleyer, C. Maerker, A. Dransfeld, H. Jiao, N. J. R. v. E. Hommes, *J. Am. Chem. Soc.* **1996**, *118*, 6317 – 6318.
[13] a) P. Bhyrappa, P. Bhavana, *Chem. Phys. Lett.* **2001**, *342*, 39 – 44; b) J. Tanaka, M. Sato, *Chem. Lett.* **1995**, 971 – 972.
[14] We conducted DFT calculations on **Iph** and other isomers in the presence of two DMSO molecules. As a result, the difference of energy between **Iph** and **Phl** or **Pdm** decreased to 1.2 and 1.7 kcal mol^{-1}, respectively, as shown in Figure S9. This result suggested the stabilization of **Iph** through hydrogen bonds with a polar solvent such as DMSO.
[15] The core structure of **Me$_4$Iph** (Figure S12) also suggests the preservation of a 20π-conjugated isophlorin skeleton (see ref. [6]).

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