Aromaticity

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Protonation-Triggered Conformational Changes to Möbius Aromatic [32]Heptaphyrins(1.1.1.1.1.1.1)**

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In recent years, the chemistry of expanded porphyrins[1] has attracted considerable interest because of their unique properties such as extensive and flexible π conjugation,[2] multimetal coordination,[3] versatile oxidation states,[4] anion binding,[5] and large two-photon absorption cross section.[6] A recent topic of interest is the ability of expanded porphyrins to form Möbius aromatic molecules.[7]

The concept of Möbius aromaticity, which was first proposed by Heilbronner in 1964, predicts an electronically delocalized aromatic circuit for a [4*n*]annulene when lying on a single-sided, nonorientable Möbius strip.[8] This concept has been extensively challenged from both the theoretical and experimental viewpoints, as it is simple and aesthetically pleasing.[9] The first synthesis of a stable, neutral Möbius aromatic molecule was reported by Herges and co-workers in 2003,[10] in which the smart combination of a normal conjugated system and a belt-shaped conjugated system were employed to implement a molecular twist, however, the reported [16]annulene of Möbius topology exhibited relatively weak aromaticity with respect to its ring current and nuclear-independent chemical shift (NICS) value.[11] Quite recently, Latos-Grażyński and co-workers reported the temperature-dependent topology change between Hückel and Möbius conformations for di-*p*-benzi[28]hexaphyrin(1.1.1.1.1.1).[7a] Soon after, our research group demonstrated that facile metalations of a series of meso-aryl-substituted expanded porphyrins led to conformationally rigid, twisted structures with distinct Möbius aromaticity.[7b,d] We also found that there is a fast equilibrium among Möbius conformers of free-base [28]hexaphyrins(1.1.1.1.1.1), which is frozen on the NMR time scale at 173 K.[7e] Despite these findings, Möbius aromatic compounds are still rare and it is highly desirable to develop a more general route towards these molecules. Herein, we report that conformations of meso-aryl-substituted [32]heptaphyrins(1.1.1.1.1.1.1) are dependent upon meso-aryl substituents, solvents, temperature, and protonation, among which the protonation process provides a general and reversible means to realize a twisted Möbius structure with distinct aromaticity.

meso-Pentafluorophenyl-substituted [32]heptaphyrin **1** takes a figure-eight conformation in nonpolar solvents such as hexane, toluene, and CH_2Cl_2 as confirmed by ^{1}H NMR and UV/Vis spectroscopic, and X-ray diffraction analysis.[12] Crystals were grown from a pentane solution and the X-ray structure is shown in Figure 1 a. The macrocyclic conjugation

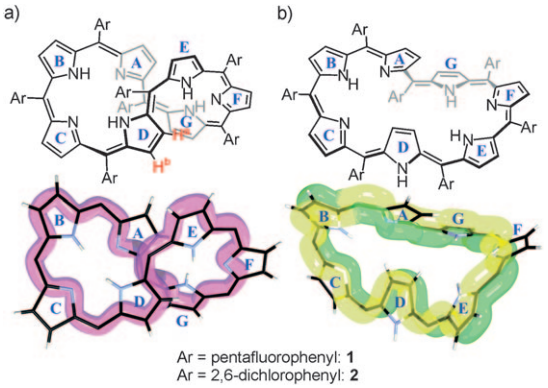

Figure 1. a) Hückel conformation of [32]heptaphyrin(1.1.1.1.1.1.1) based on the crystal structure of **1** (crystals were grown from a solution of pentane),[12] and b) Möbius conformation of [32]heptaphyrin(1.1.1.1.1.1.1) based on the crystal structure of **2** (crystals were grown from a solution of hexane).[7b]

is nicely preserved with the dihedral angles between the pyrrole and meso carbon units being smaller than 26°. This structure is consistent with a 32π-electron circuit within what can be considered a twisted double-sided (orientable) Hückel topology with C_2 symmetry. In fact, the ^{1}H NMR spectrum of **1** in [D_8]toluene exhibits a moderate paratropic ring current by recording signals for H^a and H^b located inside the macrocyclic conjugation at $\delta = 11.27$ and 8.50 ppm, respectively (Figure 2 a. Meanwhile, the rest of the pyrrolic β-protons are in a shielded region of $\delta = 5.11$–6.42 ppm). The absorption spectra of **1** in nonpolar solvents exhibit rather broad bands and without bands in a low-energy region, which is a feature consistent with antiaromatic character (Figure 3 a).[6,13] Accordingly, a NICS value at the center of the

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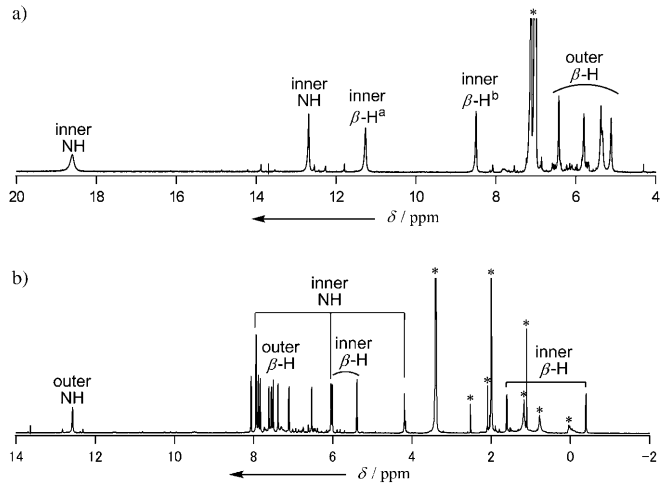

Figure 2. ^{1}H NMR spectra of **1** a) in [D_8]toluene at room temperature (Hückel conformation) and b) in [D_6]acetone at 213 K (Möbius conformation). Solvents and impurities are indicated by ⋆.

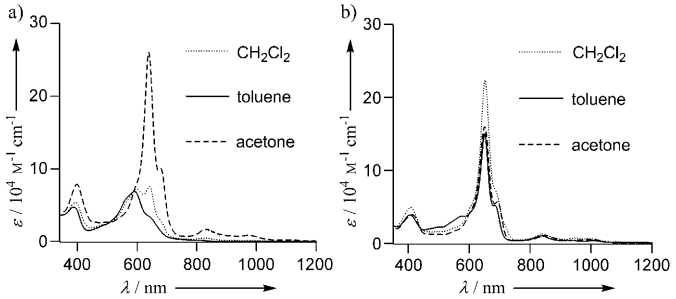

Figure 3. UV/Vis absorption spectra of a) **1** and b) **2** in CH_2Cl_2, toluene, and acetone.

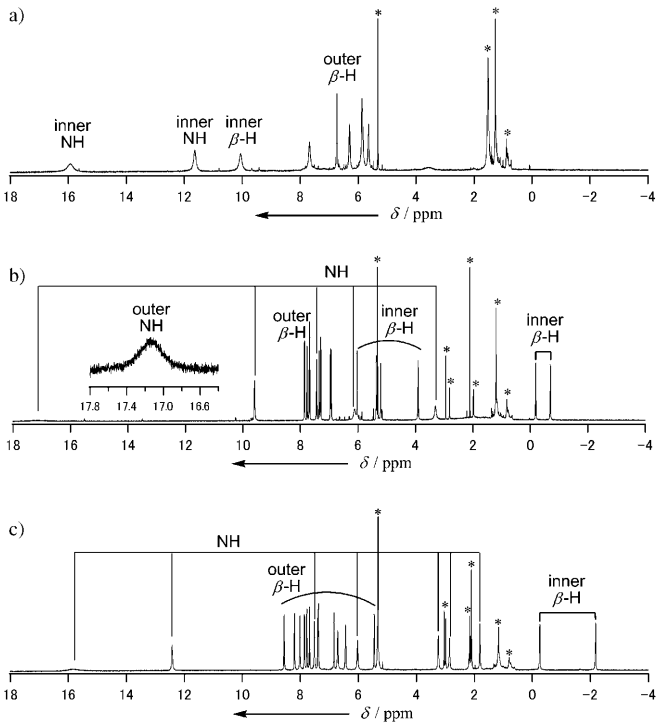

Figure 4. ^{1}H NMR spectra for the TFA titration experiments of **1** in CD_2Cl_2; a) without TFA at room temperature, b) with one equivalent of TFA at 223 K, and c) with four equivalents of TFA at 203 K. Solvents and impurities are indicated by ⋆.

macrocycle of **1** has been calculated to be $\delta = +10.1$ ppm. Interestingly, the conformation of **1** is dependent on the polarity of the solvent. Typically, the absorption spectrum of **1** in acetone is entirely different from those in nonpolar solvents, as it has a sharp and intense Soret-like band with a small shoulder as well as Q-like bands (Figure 3a). These bands are characteristic of Möbius aromatic expanded porphyrin.[7b,d] The ^{1}H NMR spectrum of **1** in [D_6]acetone recorded at 213 K exhibits a characteristic nonsymmetric feature consisting of doublet signals at $\delta = -0.39$ and 1.61 ppm that are considerably shielded by the inner β protons of the inverted pyrrole subunit **D**, moderately shielded doublet signals at $\delta = 5.39$ and 6.01 ppm ascribed to the inner β protons of the tilted pyrrole subunit **A**. Furthermore, broad singlet signals at $\delta = 4.19$, 6.04, and 7.94 ppm corresponding to the inner NH protons, and a broad singlet signal at $\delta = 12.58$ ppm from the outer NH proton of the pyrrole subunit **D** were observed (Figures 1b and 2b).

More importantly, we found that protonation-induced conformational changes of **1** gives twisted Möbius topology with distinct aromatic character. Titrations were performed with trifluoroacetic acid (TFA) to protonate the macrocycle. One equivalent of TFA was added to a solution of **1** in CD_2Cl_2 (Figure 4a; where a twisted Hückel conformation with antiaromatic character was predominant), and caused a drastic change to the ^{1}H NMR spectrum to give very broad signals at room temperature, but which became sharpened when recorded at 223 K (Figure 4b). This sharp spectrum displays five NH signals, hence indicating the formation of monoprotonated heptaphyrin **1-TFA$_1$**. In addition, the spectrum reveals a diatropic ring current as indicated by the inner pyrrolic β protons at −0.69 and −0.18 ppm, those of the tilted pyrrolic part at 3.91, 5.21, 5.36, and 6.03 ppm, and the rest in the range of $\delta = 6.93$–7.86 ppm. By considering 32π electrons in the circuit, this ^{1}H NMR spectrum suggests a twisted Möbius structure for **1-TFA$_1$**. Careful addition of four equivalents of TFA caused the formation of another protonated species. Once again, lowering the temperature to 203 K was needed to observe a sharp ^{1}H NMR spectrum (Figure 4c), which displays seven NH signals, hence indicating the formation of a triprotonated species (**1-TFA$_3$**), and a stronger diatropic ring current as compared with **1-TFA$_1$**. The maximum chemical shift difference (Δδ) between the inner and outer β protons is $\delta = 10.75$ ppm for **1-TFA$_3$**, which is larger than that of **1-TFA$_1$** ($\delta = 8.55$ ppm). We also found that the addition of eight equivalents of TFA led to a sharper ^{1}H NMR spectrum of **1-TFA$_3$**, even at room temperature. Notably, this is the first example of the formation of Möbius aromatic expanded porphyrins at room temperature without metal coordination.

The TFA titration experiments of **1**, which were analyzed by UV/Vis absorption spectroscopy, were consistent with the ^{1}H NMR measurements. As the concentration of TFA increased, the Soret-like absorption band at 653 nm as well

as a shoulder at 707 nm increased steadily with isosbestic points at 381, 437 and 622 nm (Figure 5a). In the near-IR region, Q-like bands at 884, 953 and 1090 nm increased at the cost of the absorption at 834 nm. Successive addition of TFA caused further spectral changes, also with clear isosbestic

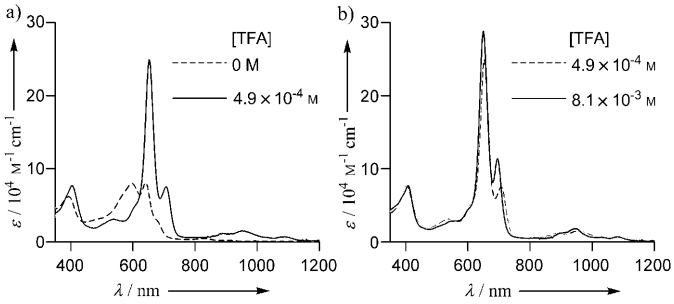

Figure 5. UV/Vis absorption spectra for the TFA titration experiments of **1** in CH_2Cl_2. a) First and b) second protonation steps.

points; the intense Soret-like band at 653 nm was further enhanced and a shoulder was slightly blue-shifted to 695 nm (Figure 5b). The final absorption coefficient at the Soret-like band reached a value of $2.9\times10^5\,M^{-1}\,cm^{-1}$. The titration data were analyzed by Hill plots to reveal that the first step up to $[TFA]=4.9\times10^{-4}\,M$ is a monoprotonation process and the second step up to $[TFA]=8.1\times10^{-3}\,M$ is a diprotonation process (see the Supporting Information).

The twisted Möbius structure of **1-TFA$_1$** has been unambiguously confirmed by single-crystal X-ray crystallography (Figure 6).[14] The twisted structure contains a fully

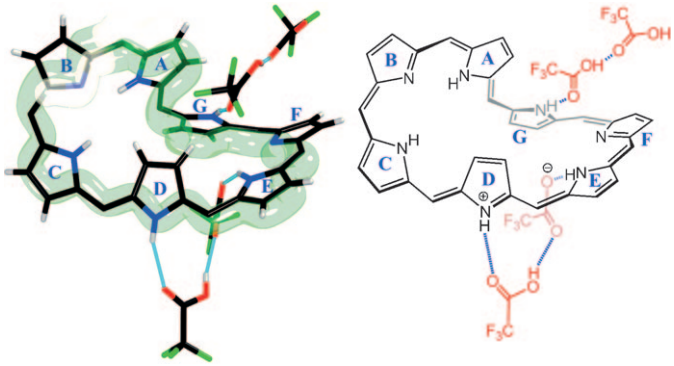

Figure 6. X-ray crystal structure of monoprotonated heptaphyrin **1-TFA$_1$**. The meso-aryl groups are omitted for clarity.

inverted pyrrole ring (**D**) and a half tilted pyrrole ring (**G**) in addition to the inward-pointing five pyrrole groups, hence constituting a smoothly linked π-conjugated network within a dihedral twist angle of less than 29°. Interestingly, effective hydrogen-bonding networks are found for pyrrole ring **D**···TFA···TFA···pyrrole ring **E**, and pyrrole ring **G**···TFA···TFA, which help maintain the twisted conformation by forcing the constitutional pyrrole subunits to be tilted or fully inverted. This structural feature contrasts with that of neutral **1** in toluene, in which all the pyrrole groups are pointing inward. This type of hydrogen-bonding interaction may explain the observed Möbius structures for **1** in polar solvents, particularly in hydrogen-bond-accepting solvents. The NICS value has been calculated to be $\delta=-9.5$ ppm at the center of the macrocycle, this value is in line with the delineation of **1** as a Möbius aromatic molecule. Notably, the protonation also led to complete suppression of the irreversible N-fusion reaction of **1**, which gradually proceeds in a neutral solution at room temperature.[12]

meso-(2,6-Dichlorophenyl)-substituted [32]heptaphyrin **2** intrinsically takes the twisted Möbius conformation both in nonpolar and polar solvents (Figure 3b). In fact the X-ray structure of **2**, with crystals grown from a hexane solution, showed it to have a twisted Möbius structure with smoothly linked 32π-electron conjugation within a dihedral twist angle of 27° (Figure 1b).[7b] The ^{1}H NMR spectrum of **2** in CD_2Cl_2 has very broad signals at room temperature, but became sharp enough to allow the assignment of its Möbius conformations at 183 K. The UV/Vis absorption spectrum of **2** at low temperature was also consistent with the Möbius aromaticity, as it features a sharp and intense Soret-like band at 652 nm as well as Q-like bands at 842, 946 and 980 nm. Importantly, the protonation of **2** with TFA triggered the formation of slightly different Möbius aromatic structure even at room temperature, as revealed by ^{1}H NMR and UV/Vis absorption measurements. This assumption was strongly supported by the unexpected isolation of a monoprotonated complex of **2** with a hydrolyzed product of DDQ as a counter anion (see the Supporting Information). The X-ray crystal structure of the complex revealed a twisted but smoothly linked structure for the [32]heptaphyrin moiety. Both the ^{1}H NMR and UV/Vis spectra were essentially the same as those of **2-TFA$_1$**. The heptaphyrin **2** undergoes the similar stepwise protonation to form monoprotonated and triprotonated species upon increasing the amount of TFA. These results indicate an effectiveness of the protonation for the formation of Möbius aromatic structure for [32]heptaphyrins(1.1.1.1.1.1.1) regardless of the meso-aryl substituent, solvent polarity, and temperature. In addition, these protonated [32]heptaphyrins were easily turned back to their neutral form upon treatment with aqueous $NaHCO_3$, thus demonstrating the achievement of switching between Hückel antiaromaticity and Möbius aromaticity.

In our previous works, we suggested that the two-photon absorption (TPA) cross-section value ($\sigma^{(2)}$) can be used to measure the degree of aromaticity of expanded porphyrins.[7b,d,13] In line with our suggestions, the relationship between TPA cross-section values and aromaticity is also preserved in the case of [32]heptaphyrins, as measured by the open-aperture Z-scan method (Table 1). When [32]heptaphyrin **1** takes the Hückel conformation in CH_2Cl_2 or toluene, the TPA cross-section values were found to be the lowest (1800 and 2000 GM). Once [32]heptaphyrin takes the Möbius conformation, however, $\sigma^{(2)}$ values become larger for both **1** and **2** (2300–2800 GM). Interestingly, the addition of TFA induces a dramatic change in the TPA cross-section values. The smallest value of **1** in CH_2Cl_2 (1800 GM) was gradually changed to 5100 GM by the first protonation and to 6600 GM

Table 1: Two-photon absorption cross-section values and excitation wavelength.

Compound	Solvent	Topology	$\sigma^{(2)}$ [GM] (λ_{ex} [nm])[a]
1	CH_2Cl_2	Hückel	1800 (1220)
	toluene	Hückel	2000 (1300)
	acetone	Möbius	2800 (1220)
1-TFA$_1$	CH_2Cl_2	Möbius	5100 (1240)
1-TFA$_3$	CH_2Cl_2	Möbius	6600 (1220)
2	CH_2Cl_2	Möbius	2600 (1240)[7b]
	toluene	Möbius	2300 (1240)
	acetone	Möbius	2500 (1240)
2-TFA$_1$	CH_2Cl_2	Möbius	3200 (1220)
2-TFA$_3$	CH_2Cl_2	Möbius	4800 (1200)

[a] TPA cross-section value and wavelength were determined by the open-aperture Z-scan method.

by the second protonation. The $\sigma^{(2)}$ value of **2** was also increased by protonation from 2600 to 3200 and 4800 GM.

In summary, the conformations of meso-aryl-substituted [32]heptaphyrins(1.1.1.1.1.1.1) have been demonstrated to be dependent upon the meso-aryl substituents, solvents, and temperature. Importantly, protonation of the [32]heptaphyrins triggers a drastic conformational change to form a Möbius aromatic conformation. This is the first example to realize Möbius aromatic expanded porphyrins in a reversible manner, even at room temperature without coordination to a metal.

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[14] a) Crystallographic data for **1-TFA$_1$**: $C_{87}H_{22}F_{50}N_7O_{10}$, $M_w = 2275.12$, triclinic, space group $P\bar{1}$ (No. 2), $a = 14.531(5)$, $b = 18.338(5)$, $c = 21.833(6)$ Å, $\alpha = 101.389(10)$, $\beta = 107.408(11)$, $\gamma = 106.575(10)°$, $V = 5060(3)$ Å^3, $\rho_{calcd} = 1.493$ g cm^{-3}, $Z = 2$, $R_1 = 0.1213$ [$I > 2.0\sigma(I)$], $R_w = 0.3807$ (all data), GOF = 0.930 [$I > 2.0\sigma(I)$]. These values have been obtained by removal of the solvent molecules by using the PLATON SQUEEZE program. CCDC 701508 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

