Aromaticity

[32]π Fused Core-Modified Heptapyrin with Möbius Aromaticity


Abstract: A new fused core-modified 32π heptapyrin with Möbius aromatic character is reported. The 1H NMR data indicated a weak Möbius aromaticity at 298 K; however, at 213–183 K, the molecule predominates [4n]π Möbius conformation with strong diatropic ring current, which was further confirmed by X-ray analysis. The protonation experiment led to preservation of the Möbius aromaticity at 298 K. Nevertheless, the experimental results were further supported by theoretical studies. Overall, this study represents the first example of Möbius aromatic fused core-modified expanded porphyrin.

The concept of “Möbius aromaticity” in a closed-shell configuration with [4n]π-electron conjugation in molecular systems was proposed as early as 1964 by Heilbronner.[1] However, the first real example of a Möbius aromatic hydrocarbon was realized only in 2003 by Herges and co-workers.[2] Since then, several reports have appeared in literature on molecules, which exhibit [4n]π Möbius aromaticity especially in cyclic annulenes and its derivatives.[3] More recently, Mauksch and co-workers have demonstrated the presence of Möbius aromaticity in planar metallacycles.[4] The mechanisms involved in understanding of Möbius aromaticity in annulenes was reported by Karney and co-workers.[5]

The first example of expanded porphyrin analogue, which exhibit Möbius aromaticity, was reported in 2007.[6] Specifically, Latos-Grażyński and co-workers demonstrated in an elegant study that di-p-benzi-[28]hexaphyrin 1 shuttles between Hückel and Möbius topologies depending on temperature and the solvent polarity. Since then, several reports have demonstrated presence of Möbius aromaticity in various expanded porphyrins,[7] such as conformationally flexible 28π hexaphyrins,[8] 32π heptapyrins (2),[9] 36π octapyrins,[10] N-fused pentapyrins,[11] N-fused 28π hexaphyrins[12] under various conditions, such as protonation,[9,13] metal coordination,[14] fusion of the ring,[11,12,15] oxidation/reduction,[16] and variation in temperature[17] and solvents.[6,17b,18]

Heptapyrins are expanded porphyrins, in which seven heterocyclic units are linked through multiple meso-carbon bridges. A series of non-fused heptapyrins are reported by Sessler,[19] Osuka[20a–b] and Kim,[9,14a,20c] Mahon,[21] and our group.[22] We have demonstrated the synthesis of core-modified heptapyrins with four, five, and six (3) meso-carbon bridges.[22] All these macrocycles distinguish each other depending on: 1) the number of π-electrons; 2) the number of meso-links; 3) the conformational behavior; and 4) aromatic/antiaromatic/neutralaromatic character.[7,9–12] Introduction of fusion in the expanded porphyrin results in enhanced planarity of the framework leading to increased aromaticity. Earlier, we have described the synthesis of doubly fused rubyrin, which exhibit enhanced aromaticity relative to its non-fused congeners.[23] To date, there are only five reports on fused expanded porphyrins exhibiting Möbius topology, which are successfully demonstrated by Osuka and co-workers. This includes Rh- incorporated 24π N-fused pentapyrin,[11] Pd4-coordinated N-fused 28π hexaphyrin,[12] 28π hexaphyrin bearing thienyl-fused unit,[15a] benzopyrene-fused ring,[15b] and diethylamine unit.[15c] Recently, we have demonstrated the synthesis of monofused core-modified 32π-heptapyrins 4,[24] with six meso bridges, which maintains planarity both in freebase, as well as protonated state and follows [4n]π Hückel antiaromatic character; however, for the core-modified expanded porphyrins in general and fused heptapyrins in particular, the Möbius aromatic character is hitherto unknown in the literature. Herein, we report the synthesis of monofused core-modified 32π heptapyrins 5 and 6 with six meso-positions, which exhibits Möbius aromatic character in solution, as well as solid state, and retains the Möbius aromaticity in the protonated state.

The synthesis is outlined in Scheme 1. We have followed the acid-catalyzed condensation reaction of dithienothiophene (DTT) dipyrane 7, a rigid precursor with electron-rich center, and thio- or seleno-tripyrane (8 or 9), for the synthesis of fused heptapyrin 5 and 6. The rigid precursor was synthesized from the trifluoroacetic-acid-catalyzed condensation with excess pyrrole and gave 7 in 85% yield. The precursors 8 and 9 were synthesized from our earlier reported procedure.[22a] The final step involves the condensation of 1:1 equivalent of 7 and 8 or 9 with two equivalents of pentfluorobenzaldehyde in presence of 0.3 equivalent of p-toluenesulfonic acid (p-TSA) followed by oxidation with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ), which gave the crude product. Repeated purification by column chromatography over basic alumina fol-
ollowed by silica gel (100–200 mesh) column with CH$_2$Cl$_2$/hexane (35:65) gave a blue fraction, which was identified as 5 and 6. After evaporation of the solvent, further recrystallization from CH$_2$Cl$_2$/CH$_3$OH gave greenish blue solid in 8–10% yield. The composition of both macrocycles was confirmed by elemental analysis and ESI-MS data, in which compounds 5 and 6 show the molecular ion peaks at m/z 1417.3250 [M$^+$H$^+$] and 1464.2340 [M$^+$] (Figures S1 and S2 in the Supporting Information).

The solution state of 5 and 6 was analyzed by $^1$H NMR spectroscopy in CD$_2$Cl$_2$ (Figure 1). At 298 K, molecule exists in C$_2$ symmetry, in which the two DTT protons give a sharp singlet at $\delta = 8.41$ ppm. The four doublet signals at 7.22, 7.06, 6.76, and 6.73 ppm are assigned for pyrrolic $\beta$-CH protons (Figure 1A). These signals are confirmed by $^1$H–$^1$H correlation spectroscopy (COSY) experiment (Figure S3 in the Supporting Information). A sharp singlet at $\delta = 5.96$ ppm corresponds to two $\beta$-CH of thiophene ring, which are opposite to DTT moiety. The meso-mesityl-CH protons are observed as singlet between $\delta = 7.19$ and 6.15 ppm, whereas six sharp singlets corresponding to meso-mesityl methyl protons are in the upfield region between 2.49 and 0.17 ppm. A broad signal at 7.70 ppm is attributed to NH protons of pyrrolic unit, and this assignment was confirmed by D$_2$O exchange experiment. Overall, the appearance of thiophene $\beta$-CH and the meso-mesityl methyl signals in the upfield region reflects the weak M"obius aromatic character in 5 at 298 K. Similar pattern was observed in 6 at 298 K in CD$_2$Cl$_2$ (Figure S4 in the Supporting Information).

The variable-temperature $^1$H NMR spectra of 5 was recorded in CDCl$_3$, which revealed that NH proton gradually downfield shifted upon increasing the temperature from 298 to 323 K (Figure S9 in the Supporting Information). On the other hand, upon lowering the temperature from 298 to 223 K, the DTT protons are slightly downfield shifted and rest of the $\beta$-CH of pyrrolyl, thiophene, and meso-mesityl-CH protons are gradually

Scheme 1. Synthesis of fused core-modified heptaphyrins 5 and 6.
broadened; however, the meso-mesityl methyl protons are slightly upfield shifted.

The significant Möbius topology was observed upon lowering the temperature when the broad signals observed in CDCl$_3$ at 223 K are well resolved at 213–183 K in CD$_2$Cl$_2$. A set of sharp signals for DTT (8.73 and 8.64 ppm), β-CH thiophene (5.60 and 5.18 ppm), eight doublets for β-CH pyrrole between 7.49 and 6.04 ppm, six sharp signals for meso-mesityl-CH from 7.03 to 5.60 ppm, and twelve signals for meso-mesityl methyl protons between 2.71 and −0.32 ppm were observed, in addition, the pyrrolic NH signal became sharp and upfield shifted to 5.08 and 3.55 ppm (Figure 1B). The thiophene and pyrrolic β-CH signals are further confirmed by $^1$H–$^1$H COSY studies (Figures S5 and S6 in the Supporting Information), and the NH signals vanished during CD$_2$Cl$_2$/D$_2$O experiment. These observations suggest that there is an anomalous change in structure upon lowering the temperature. Overall, the $^1$H NMR spectrum at 213–183 K proves that molecule lost C$_2$ symmetry orientation and thus adopted Möbius conformation with stronger diatropic ring current. Similar trend was observed for 6 at 213–183 K in CD$_2$Cl$_2$ (Figures S7 and S8 in the Supporting Information). The results were further compared with 1, 2 and 4: 1) the NH and one of meso-mesityl methyl protons are upfield shifted in 1,[30] however, the methyl protons were not observed in the negative region, as it was observed in 5; 2) the figure-eight conformation in 2a,[31] adopts nonaromatic character; 3) the non-symmetrical pattern was observed in 2b at 183 K,[14d] and 4) the DTT and pyrrole units in 4 are inverted and experiencing the paratropic ring current.[22e] Overall, these results obtained for 5 are comparable with 1 and 2b, further confirm the Möbius aromatic character.

Upon protonation of 5 with TFA in CD$_2$Cl$_2$ at 298 K, following happens: 1) DTT proton, pyrrole-β-CH, and meso-mesityl-CH protons are slightly downfield shifted; 2) the NH proton is shifted upfield at 5.57 ppm upon increasing the concentration of TFA (Figure S12 in the Supporting Information); 3) the β-CH proton of thiophene is slightly shielded by 0.23 ppm and resonated at 5.73 ppm; and 4) similarly, the meso-mesityl methyl protons, which are in the aromatic ring current in the freebase form, are further upfield shifted and observed at $\delta = -1.16$ ppm. It can be concluded that the Möbius aromaticity with effective π-electron delocalization, even after protonation, is retained. A comparison of these results with protonated derivatives of 2 and 4 revealed that 2 adopts figure-eight conformation with Möbius aromatic character,[6,14a] while 4 maintains the Hückel antiaromatic character as such in solution.[22a]

The structure of 5 and 6 was unambiguously confirmed by single-crystal X-ray diffraction analysis (Figure 2, Table S5 in the Supporting Information). Both the compounds were crystalized in a triclinic crystal system with the P1 space group. The crystal structure of 5 is shown in Figure 2a. From the spectral analysis, the DTT-dipyrrin moiety and thia-tripyrrin units are connected by pentafluorophenyl groups and adopts a nonplanar structure with 32π-electron circuit, in addition, one of the meso-mesityl methyl protons are in the macrocyclic aromatic ring current (Figure 2a). The observed torsion angles of 32.13° (C5-C6-C7-S1) and 30.27° (S3-C14-C15-C16) in 5 and respective values in 6 are 30.44 and 29.54 (Figure S19, Table S1 in the Supporting Information) favor the overall π-electron conjugation and facilitating the aromatic Möbius stabilization in the

![Figure 1. $^1$H NMR spectrum of 5 at 298 K (A) and 213 K (B) in CD$_2$Cl$_2$.](image1)

![Figure 2. Single-crystal X-ray structure of 5. a) Top view and b) side view. The meso-aryl groups are omitted for clarity in the side view.](image2)
free-base form. Thus, the large strain associated with the figure-eight conformation is nicely distributed across the macrocycle, which leads to effective \( \pi \)-electron delocalization in the framework. The amino and imino nitrogen atoms present in dipyrrin moiety in 5 are in strong intramolecular hydrogen-bonding interactions (N2–H2–N1 and N4–H4–N3) with distances of 2.23 and 2.16 Å and angles of 119° and 122°, respectively. The DTT moiety in 5 is almost perpendicular to the thiophene unit with an angle of 84.6° (Figure 2b) and are apper- ealed over the other with the nonbonding distance between the \( \pi \) -electron cloud of thiophene ring, and S1 and S3 of DTT ring is 3.93 and 3.83 Å, respectively. In the case of 6, the respective angle is 83.3°, and the nonbonding distances are 3.90 and 3.88 Å (Figure S18 in the Supporting Information). On the other hand, the crystal analysis of 1 and 2a in protonated form and free base 2b adopt Möbius conformation,[6,9,14] while 4 retains the Hückel antiaromatic character in the solid state.[22a] An intriguing fact also noticed from crystal structure of 5 is that the molecule exists self-assembled dimer, one- and two-dimensional arrays through intermolecular hydrogen-bonding interactions in the solid state (Figures S15–S17 in the Supporting Information).

The electronic absorption spectrum of 5 in free base, as well as protonated form, is shown in Figure 3. The compound 5 in its free-base form illustrates well-defined peaks, with intense Soret-like band at \( \lambda = 604 \) nm and a distinct Q-band at 868 nm with molar absorption coefficient (\( \varepsilon \)) of 105, which suggests the aromatic character. The spectral pattern is similar to other Möbius aromatic expanded porphyrins. The results are further compared with 3 and 4: 1) the redshift of both the Soret and Q-bands in 5, compared to 3,[22b] reflects the extension in the \( \pi \)-electron conjugation; and 2) one fold higher in the molar absorption coefficient of intense band in 5, compared to 4,[22c] indicates the aromatic character. The absorption spectra of 5 remain unaltered upon changing the polarity of the solvent (Figure S21 in the Supporting Information), as observed in 2b.[14b] proves that the conformation remain intact; however, 1 and 2a in polar solvent adopt Möbius aromaticity.[5,9] Upon protonation by using a diluted solution of TFA, the intense band in 5 is redshifted to 651 nm with a shift value of 48 nm and a weak Q-band in the near IR region at 1026 nm.

![Figure 3](image-url)

Figure 3. Electronic absorption spectrum of 5 and 5.2H+ in CH2Cl2.

trend was observed for 6 (Figure S20 in the Supporting Information). Overall, the extension in the \( \pi \)-electron conjugation, as well as reduction in the number of heteroatom, reflects the Möbius aromaticity in 5 and 6 both in free base, as well as in protonated state.

The computational studies of 5, 6, and their protonated derivatives were performed with Gaussian 09,[24] at the M06L/6-31G** level[25] to visualize the geometry and electronic structure (Figure S22 and Table S3 in the Supporting Information). The nucleus-independent chemical shift (NICS)[26a] and aniso- tropy-induced current density (AICD)[26b] are considered as best index to evaluate the aromaticity of macrocycle. The NICS(0) values calculated at various geometrical positions within 5 in- dicate that center position of pyrrolic rings containing amino nitrogen have large negative values (−7.2 to −8.4 ppm) compared to imino nitrogen (−1.5 to −2.7 ppm). The higher negative values are observed for terminal thiophene rings of DTT (−16.3 to −18.3 ppm) and the core thiophene unit (−13.8 ppm). The NICS(0) value calculated at the center of the macrocycle was found to be −8.1 ppm, which clearly reflects the Möbius aromaticity. Moreover, protonation intensifies the centroid NICS(0) value to −9.9 ppm and also amplify the mag- nitude of negative values for all pyrrolic units in 5 (Figure S23 and Table S4 in the Supporting Information). The theoretical results are consistent with 6 and its protonated derivative, in which the NICS(0) values are −7.2 and −10.9 ppm, respectively. Overall, as was observed from the spectral and structural analy- sis, the Möbius character is reflected in the neutral state, and the extent of aromaticity is enhanced upon protonation. The Möbius aromatic character is further supported by AICD plots, which showed fairly clockwise current density vector at the iso- surface values of 0.025 for both 5 and 6 in the neutral and diprotonated state (Figure S24 in the Supporting Information), which proves that the diatropic ring current was induced by an external magnetic field and aromaticity.

In summary, we have successfully synthesized the [32]\( \pi \) fused core-modified heptaphyrin and demonstrated its Möbius aromatic character without any external stimuli. It is known from the literature that the right combination of certain degree of planarity, as well as distortion in the molecular framework, is important to achieve the Möbius topology. It can be defined as follows: 1) the introduction of rigid and planar DTT core and the core-modified and flexible tripyrrane unit in the macrocyclic framework; 2) reduction of number of heteroa- toms in the framework; 3) the number and right mixing of meso-aryl units; and 4) protonation, which keeps control over the geometry and modulate the system from [4n]\( \pi \) Hückel non-/antiaromatic topology towards [4n]\( \pi \) Möbius aromaticity with nonplanar conformation. In addition to the spectral and structural analysis, the Möbius aromaticity was unambiguously confirmed by theoretical calculations. The excited-state dyn- amics of these fused core-modified derivatives are currently underway in our research group.
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