Synthesis and Switching the Aromatic Character of Oxatriphyrins(2.1.1)**

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Abstract: Triangularly shaped, contracted porphyrinoids belong to a group of molecules where the geometry significantly modifies the observed electronic properties. The need for a controllable, effective, and widely applicable approach to triphyrins drives extensive research towards macrocyclic materials that act as potential controlling motifs by switching their aromaticity. Two isomeric thiophene-fused triphyrins-(2.1.1) were synthesized by applying an innovative approach. Spectroscopic techniques (NMR, UV/Vis) show that both macrocycles are aromatic and quantitatively convert into anti-aromatic structures after reduction with a zinc amalgam. The reduced forms were stabilized through boron(III) coordination, thereby allowing the observation of anti-aromatic 16π delocalization within a contracted porphyrin.

Porphyrrins, or more broadly porphyrinoids, are regarded as an elementary motif for fundamental studies in several scientific fields,[1] including for medicinal applications[2] and an elementary motif for fundamental studies in several scientific fields.[1] Nevertheless, they reveal subgroup is rather small and there are only a few examples of organic alternatives of currently, widely explored inorganic molecular devices.

Triphyrins(n.1.1) (Scheme 1) are a new class of porphyrinic macrocycles with a reduced number of donors compared to porphyrins and are created by the removal of at least one pyrrole subunit. The rational approach for the synthesis of boron(III) triphyrin(1.1.1) 1-B,[3] boron(III) subporphyrinazines,[5] and boron(III) subphthalocyanines,[6] involves a templating effect. The formation of free-base subpyriporphyrin[7] and several triphyrins(n.1.1) (Scheme 1), where n varies from 2 to 6,[8] required a stepwise strategy. The triphyrin(n.1.1) subgroup is rather small and there are only a few examples of such macrocycles (Scheme 1). Nevertheless, they reveal intriguing properties, including the topology-dependent aromaticity switching of triphyrin(6.1.1) 3 on coordination.[9] The boron(III) triphyrin(1.1.1) complexes 1-B have demonstrated a variety of optoelectronic properties, such as nonlinear optical absorption and high emission quantum yields, that are directly related to the 14π aromatic delocalization path.[10] An alternative route to tune the properties of triphyrins is a modification of their coordination unit by replacing nitrogen atom(s) with other heteroatoms to yield aromatic thiatriphyrin(2.1.1) 4,[11] oxatriphyrin(4.1.1) 5,[12] and thiatriphyrins(4.1.1) 6,[13] as well as non-aromatic oxatriphyrin(3.1.1) 5.[14] On the other hand, the aromatic character of triphyrins(n.1.1) has not been explored to date, and research concentrates on an unmodified 14π electron circuit. All the above-mentioned aspects of triphyrin chemistry stimulate the intensive search for nontrivial synthetic routes that lead to controllable triphyrin scaffolds with appropriately defined functionality.

Here we report on the synthesis of two isomeric thiophene-fused oxatriphyrins(2.1.1) by a coherent method involving the use of precisely crafted synthons. Both macrocycles are aromatic with alternative delocalization and undergo reduction to afford anti-aromatic structures that can be stabilized as boron(III) complexes.

The reported rational approach to form meso-substituted triphyrins(2.1.1) 11 and 13 requires an effective synthesis of the synthons 8 and 10. Suzuki–Miyaura coupling was applied to achieve this demanding task (Scheme 2) under conditions adapted from those previously reported for heterocycles.[15] The formation of 7 and 9 has been accomplished in yields of 80 and 85%, respectively, starting from commercially available substrates. Both substituted thiophenes 7 and 9 are stable and can be stored without any degradation for several weeks. The deprotection step required the thermal removal of the

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The tert-butylxocarbonyl (Boc) group in refluxing ethylene glycol and led to the quantitative formation of 8 and 10. Formation of the desired products was confirmed by spectroscopic analysis (see the Supporting Information) as well as X-ray analysis (Figure 1). The substitution affects the C–S bond lengths in 8 and 10. The unsymmetrical substitution of thiophene in 8 causes a difference within the C–S bonds (1.704(3) Å and 1.678(1) Å), while the lengths of the C–S bonds in the fully symmetric 10 are equal (1.705(2) Å and 1.701(2) Å). The deprotected reagents are less stable and need to be condensed without any extended storage. 

The formation of target oxatriphyrin(2.1.1) 11 was achieved by condensation of 8 and 2,5-bis(p-tolylhydroxymethyl)furan in an equimolar ratio under standard Lindsey conditions (Scheme 3). The macrocycle was isolated solely as the monoprotonated form 11-H. An unidentified counterion obtained during condensation was subsequently replaced by a chloride ion (see the Supporting Information). The anion exchange process involves a quantitative conversion of the isolated macrocycle into a phlorin-like skeleton followed by acidification with HCl (Scheme 3, paths c and d), thereby resulting in the final formation of 11-HCl in 20% overall yield. 11-HCl has aromatic character, as proven by the features in the 1H NMR spectrum. The rather large and planar part of the final macrocycle—a thiophene and two pyrrole moieties—results in the high degree of aggregation observed in the NMR spectra. A nicely resolved spectrum was obtained after the addition of 1% TFA (Figure 2A), which increases the solubility and prevents aggregation (see the Supporting Information).

The lack of symmetry in 11-HCl is reflected by the presence of eight β-H heterocyclic signals in the aromatic region (δ = 9.2–8.3 ppm). The full assignment given in Figure 2A was made on the basis of 2D experiments (NOESY, COSY), taking an NOE contact between H(2 1) and H(4) as the starting point. In contrast to other aromatic porphyrinoids, the resonance of the inner hydrogen atom in 11-HCl is strongly downfield shifted (δ = 11.5 ppm). This peculiar shift reflects a deshielding contribution from a strong intramolecular N···HN hydrogen bond acting within the cavity, which dominates the typical shielding influence of a diatropic ring current. The effect resembles one reported previously for an N-fused porphyrin [13] and other triphyrins(n.1.1).[7, 8f,g] The aromaticity of 11-HCl can be accounted for by the 14π path of 11', which is typical for triphyrins(2.1.1). This interplays, however, with the alternative 18π delocalization route of 11'3, which is imposed by 2,3-thiophene fusion (Figure 3). To shed additional light on the control of the electronic structure, a thiophene ring was fused to the oxatriphyrin(2.1.1) backbone at its β positions, with the aim of limiting the 14π electron route in favor of the “extended” 18π electron one, albeit with involvement of the sulfur atom on the perimeter. 

By following the synthetic approach applied for 11 (Scheme 3), synthon 10 was condensed with 2,5-bis(p-tolylhydroxymethyl)furan to eventually form monoprotonated oxatriphyrin(2.1.1) 13-HCl in 15% yield. An unidentified counterion obtained during condensation was replaced with
a chloride by using the same procedure as reported for 11-HCl (see the Supporting Information). 13-HCl behaves similarly to 11-HCl and requires the use of trifluoroacetic acid to minimize the aggregation. The $^1$H NMR spectrum (Figure 2B) reveals the diminished macrocyclic aromaticity compared to 11-HCl. The $\alpha$-H thiopeptide resonance is observed at $\delta = 9.32$ ppm, whereas the pyrrole and furan resonances are located at $\delta = 8.0$–7.8 ppm. The resonance contributors for 11-H and 13-H are presented in Figure 3. 11$^3$ and 13$^3$ include the sulfur atom in the aromatic conjugation.

The difference in the aromatic character between 11-H and 13-H is related to the relative participation of the principal aromatic contributors, which implies 14$\pi$ (11$^3$) and 18$\pi$ (11$^3$, 13$^3$) delocalization pathways. The 6$\pi$ involvement (11$^3$ and 13$^3$) in both compounds is insignificant (Figure 3). Thus, the 14$\pi$ electron path is essential in 11-H, but negligible in 13-H. The 18$\pi$ route (13$^3$) is solely responsible for the aromatic character of 13-H.

DFT optimization of oxatriphyrin(2.1.1) monocations showed a planar structure stabilized by an N···HN hydrogen bond within the internal cavity (Figure 4). The N-N distances (2.57 Å for 11-H and 2.61 Å for 13-H) significantly increased in the neutral forms (2.70 Å for 11 and 2.75 Å for 13; see Figure S26 in the Supporting Information). The bond lengths within the frameworks of 11-H and 13-H are consistent with those expected for aromatic macrocycles. In particular, the aromaticity of 11-H and 13-H is clearly demonstrated by the equalization of the C$_s$–C$_{mex}$ distances (11-H: C(6)-C(7) 1.406 Å, C(7)-C(8) 1.431 Å; 13-H: C(6)-C(7) 1.404 Å, C(7)-C(8) 1.432 Å). The macrocyclic aromaticity has a relatively small effect on the thiopeptide moieties. The C$_s$–C$_p$ bonds are characteristically longer than the C$_{mex}$–C$_p$ bonds, closely resembling the pattern found in thiophene or tetrathiaporphyrinogen. The reverse is true for thiaporphyrinoids,[16] where the thiopeptide is built into the macrocyclic ring at two C$_s$ positions. An elongation of the C(1)–C(2) bond of 11-H is evident. The observed aromaticity is consistent with NICS values calculated for the cation 11-H ($\delta = -11.4$ ppm) and the neutral form 11 ($\delta = -9.4$ ppm), and are similar to that of simple oxathiaporphyrin(2.1.1) ($\delta = -13.8$ ppm). The lower aromatic character of 13-H was also confirmed by NICS ($\delta = -3.7$ ppm).

The presence of “porphyrinol” patterns in the UV/Vis electronic spectra of 11-H and 13-H confirm the aromaticity.
thenes resembling weakly anti-aromatic 22-oxybenziporphyrins, those of the 5.1 ppm range (Figure 2C), noticeably upfield compared to the dipole distribution. On the other hand the observed effect is a complement to the well-established upfield shift recorded for substituents located above (below) the plane of an aromatic compound (a strong shielding effect). The UV/Vis spectrum of 17 confirms its anti-aromaticity (Figure 5A). In addition, 17 remain absolutely silent in fluorescence experiments.

In contrast to 17, the paratropicity of 18 (NICS = +1.4 ppm) is less noticeable (Figure 2D), which indicates that the 20π contributor involving the external sulfur atom is less essential. Nevertheless, the ortho protons of the axial phenyl group resonate at δ = 8.11 ppm, which is slightly downfield shifted. 18 does not show any fluorescence over the whole tested region.

In conclusion, an efficient synthetic approach leading to thiophene-fused oxatriphyrins(2.1.1) has been developed. The generality of the method has been proven by the formation of two feasible isomers. Both macrocycles are aromatic and extend the aromatic delocalization over the external sulfur atom of the rigid C2 bridge derived from the specifically linked-in thiophene ring. Both fused macrocycles can be reduced, and the reduced forms were entrapped as stable boron(III) complexes, thus making them easier to manipulate. A paratropic current (16π) was observed for the very first time in a triphyrin skeleton.

The thiophene-fused oxatriphyrins(2.1.1) represent unique and stable heterotriphyrins and are part of the group of triphyrins(2.1.1)—a promising material for effective absorbers and emitters through modification of the electronic structure by the triangular geometry significantly changing the dipole distribution. On the other hand the observed ability to switch between aromatic/non-aromatic/anti-aromatic structures opens another aspect of exploration for compounds capable of acting as controlling motifs.

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