

Heteroannulenes

Induced Correspondence of a Local π -Aromatic Sextet in Heteroannulenes: Synthesis and Characterization

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Dedicated to Professor Tavarekere K Chandrashekar on the occasion of his 60th birthday

Abstract: Acid-catalyzed [3+3] condensation reactions of two hitherto unknown tripyrrane moieties with pentafluorobenzaldehyde has led to the formation of new generation heteroannulene (4.1.4.1) and mutant heteroannulene (1.1.1.1.1.1). Inclusion of local π -aromatic sextets, namely the *N*-methyl pyrrole rings through β , β -linkages and α , β -linkages, has led to the isolation of first ever heteroannulenes cross-conjugated at four points and two points respectively within the macrocycles.

 π -Conjugated macrocycles have attracted considerable attention owing to their unusual optical and magnetic properties based on their effective cyclic conjugation.^[1] Whereas through conjugated systems have been extensively explored, cross-conjugated compounds^[2] have received only relatively little attention owing to much less ability to promote electron delocalization along the conjugation path, thus offering much less opportunity to tune properties by means of functionalization. Recently, however, the synthesis of extended cross-conjugated systems has seen substantial progress, allowing the development of nanometer-size cross-conjugated entities.^[3] The peculiarity of cross-conjugation is the presence of competing conjugation paths that may be exploited for the design of functional materials, and thus materials based on these compounds are now being explored more rigorously as they may present new opportunities to nanomaterial science.^[4,5] Porphyrins and expanded porphyrins serve as benchmarks for extreme manifestation of aromaticity, antiaromaticity, pseudo aromaticity, and

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- Supporting information for this article can be found under http:// dx.doi.org/10.1002/chem.201600380.

Möbius aromaticity.^[6,7] However, there are only a handful of reports on cross-conjugated expanded porphyrins.^[8] Prompted by our recent findings^[9] where inclusion of β , β -linkages of *N*methyl pyrrole ring into the macrocyclic core led to the isolation of hitherto unknown smallest ever metal-free Möbius aromatic [20] heterocyclic macrocycles, we were curious in exploring more about the connection between structure and electron delocalization on the one hand and the ability of macrocyclic system to sustain an induced diamagnetic or paramagnetic ring current on the other. Thus, we report herein hitherto unknown heteroannulene (4.1.4.1) through the connectivity of β , β -carbons of *N*-methyl pyrrole into the core of macrocycles and mutant heteroannulene (1.1.1.1.1) through the connectivity of α,β -carbons of *N*-methyl pyrrole into the core of macrocycles. We have examined the consequences on aromaticity both in the free base and upon protonation, as it is a wellknown fact that electron delocalization is significantly enhanced in excited or charged states of cross-conjugated systems, which may disclose new applications for this neglected type of conjugation.

To grasp the target macrocycles, a synthetic design has been logically approached in arriving at the tripyrrane moieties **6** and **10** (Supporting Information, Scheme S1). Rational synthesis of the macrocycles **11** and **12** entails a [3+3] acid catalyzed condensation of N-confused *N*-methyl tripyrrane **6** and **10**, respectively, with pentafluorobenzaldehyde followed by oxidation with chloranil (Scheme 1).^[10] The best yield was obtained with 0.1 equiv of *p*-toluene sulfonic acid as catalyst. Column chromatographic separation over basic alumina followed by repeated silica gel (200—400 mesh) chromatographic separation yielded the respective macrocycle **11** in 10% yield and macrocycle **12** in 8% yield as green solids.

The structures of these new macrocycles have been established by a thorough characterization by spectroscopic and single-crystal X-ray diffraction analysis. Macrocycle **11** shows parent ion peak at 1130.436 and macrocycle **12** shows parent ion peak at 1130.279 under positive ionization conditions in MALDI-TOF mass spectrometry (Supporting Information, Figure S7, S8), thus confirming the composition. Substitution of *N*methyl pyrrole in the core of porphyrins alters the electronic structure of the ring and this is reflected in the altered spectroscopic and structural properties. The free base form of both the macrocycles exhibit ill-defined absorption spectra in the Soret band region without having any Q-like bands accounted for by nonaromatic nature of these macrocycles. Figure 1

Chem. Eur. J. 2016, 22, 5504 - 5508

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Scheme 1. Synthesis of macrocycles 11 and 12.



Figure 1. UV/Vis absorption spectra of 11 and 12.

shows the UV/Vis absorption spectra of free base and protonated forms of **11** and **12**. As can be seen, protonation of both the macrocycles lead to significant change in the absorption spectra; the generation of an intense band at 641 nm with illdefined band within 700–950 nm for **11** and a sharp band at 660 nm with broad and ill-defined band within 850–1200 nm for **12** typifying porphyrinic nature of these macrocycles with lack of aromaticity.^[11]

The twisted structure for the macrocycles in free base is preserved in solution, as determined by ¹H NMR (Figure 2). For macrocycle 11, well-resolved peaks were observed at ambient temperature in free base form itself, despite the unusual way of linking N-methyl pyrrole into the conjugation pathway. Based on the 2D COSY (Supporting Information, Figure S28) and ROESY (Figure S29) spectra, the peak at 3.37 ppm has been assigned to methyl peak of N-methyl pyrrole ring due to space correlation with signals at 6.32 ppm and 7.6 ppm (Figure S29), confirming the later signals as α -CHs of *N*-methyl pyrrole ring since both these signals exhibit correlation in 2D COSY spectra (Figure S28). The broad signal at 6.02 ppm exhibiting bond correlation with the doublet at 6.06 ppm (Figure S28) in 2D COSY spectra confirms that these signals are β -CHs of same pyrrole ring. The observation of correlation between doublet at 6.15 ppm with the doublet at 6.59 ppm in 2D COSY spectra indicates that these signals are β -CHs of an-



Figure 2. ¹H NMR spectra of free base (top) and protonated (bottom) **11** at 298 K (* indicates residual solvent peak or solvent impurity).

other pyrrole ring. The NH signal appeared as a broad signal at 13.62 ppm confirmed by D₂O exchange experiment (Figure S38). There are two magnetically distinct phenyl rings. Based on the scalar coupling between the peaks as well as the dipolar coupling with heterocyclic β -CHs, the peaks in the range 6.93-7.15 ppm correspond to one phenyl ring whereas the peaks in the range 7.29-7.45 ppm correspond to another phenyl CHs. The fact that all the β -CHs and α -CHs of heterocycles in the macrocycle resonate in the same region as that of an isolated pyrrole/heterocycle, the free base 11 can be gauged as nonaromatic. Upon lowering the temperature neither any marked difference in spectral pattern nor any conformational change was observed. Only rotation of one of the phenyl ring is locked, thereby the signals of phenyl CHs are separated without any shift (Figure S27). Next we attempted to find the impact of protonation on the conformational change of the macrocycle, however not much change in the spectral pattern was observed in the completely protonated state at 298 K. To differentiate the heterocyclic β -CHs from *meso*-aryl CHs, 2D ROESY (Figure S34) spectra were recorded in addition to 2D COSY (Figure S33) spectra at ambient temperature, as lowering the temperature led to merging of signals and no conclusive results were obtained (Figure S32). The ¹H NMR spectrum of protonated 11 at 298 K showed two distinctly different signals at 10.90 and at 12.00 ppm accounted for -NH groups of the pyrrolic and protonated pyrrolenic rings, as confirmed by a D₂O exchange experiment (Figure S39). Furthermore, both these NH signals exhibit exchange correlation in 2D EXSY spectra (Figure S34a). The β -CHs of both the pyrrolic pyrrole rings and protonated pyrrolenic rings exbihit a typical COSY pattern (Figure S33a) and they have one set of protons centered at 5.88, 6.29 ppm and another set of protons centered at 6.33 and 6.79 ppm and hence the observation of two sets of correlations in 2D COSY spectra (Figure S33a). These as-



signments were further confirmed by scalar coupling that each of the NH signals exhibits to these well-resolved doublets (Figure S33b). The spatial proximity between the signal at 3.73 ppm and the singlets at 6.67 ppm and 7.23 ppm enabled us to identify two sets of correlations in 2D ROESY spectra (Figure S34b) and thus these signals correspond to the α -CHs of N-methyl pyrrole rings. Here it is worth mentioning that there are two different magnetically distinct phenyl groups with the observation of multiplets in the range 7.13-7.19 ppm for one phenyl ring and a set of signals in the range 7.32-7.52 ppm for the other phenyl group, as observed in the free base form as well. The CH groups of meso-phenyl substituents have been assigned based on 2D COSY spectra (Figure S33c), ROESY spectra (Figure S34) and EXSY spectra (Figure S35). Further confirmation of the individual signals came from HSQC spectra (Figure S36). The observations of heterocyclic α -CHs and β -CHs resonating in the region as those of isolated pyrrole/heterocycle clearly indicate absence of any sizable macrocyclic ring current, and hence the protonated 11 can be gauged as nonaromatic.

In our next attempt, we tried to investigate the impact of α,β linkages of N-methyl pyrrole rings into the macrocyclic core upon the aromaticity in macrocycle 12. Even though macrocycle 12 exhibits well-resolved spectra at RT in free base form itself, but only upon lowering the temperature to 243 K (Supporting Information, Figure S41), the NH signal was generated along with β -CH of *N*-methyl pyrrole. The spectral observation (Figure S43) indicates absence of ring current and thus non-aromaticity in the free base form of the macrocycle. The diprotonated 12 however shows drastic change in NMR spectral pattern. The diprotonated 12 was obtained by adding 70 μL of 10% $CF_3COOH/CDCl_3$ owing to the fact that stepwise addition of 10% CF₃COOH/CDCl₃ led to precipitation and, hence an excess amount was added in one step to get a clear solution in the NMR tube. Upon lowering the temperature to 243 K, well-resolved spectra were obtained for 12.2H⁺ (Figure S44). The inner NH proton resonated as a singlet at 15.45 ppm, whereas the two doublets at 9.7 ppm and 10.7 ppm have been assigned to the inner β -CH protons of inverted pyrrole ring. Similarly the singlet at 10.3 ppm has been assigned to the inner β -CH protons of N-confused N-methyl pyrrole ring. The outer NH proton of inverted pyrrole ring resonated at 4.3 ppm, the outer $\alpha\text{-CH}$ proton of N-confused Nmethyl pyrrole ring resonated at 6.4 ppm and the outer β -CH protons of non-inverted pyrrole ring resonated at 5.9 ppm and 6.4 ppm (Figure S46). All of these assignments were confirmed by using a ¹H–¹H correlation spectroscopy (COSY) experiment (Figure S45). These observations clearly indicate the presence of moderate paratropic ring current and hence antiaromaticity in 12.2H⁺. The observed spectral patterns for free base and protonated forms of macrocycles 12 are well-supported by calculated NMR spectra (Figures S59, S60).

The solid-state X-ray crystallographic analysis and structure optimization calculation revealed the involved structural changes of macrocycles **11** and **12** by protonation. For macrocycle **11**, its crystal structure was strongly puckered (Figure 3 a). Here, the protruding *N*-methyl pyrrole rings preserve all fea-



Figure 3. X-ray crystal structure of free base 11 (a,b) and protonated 12 (a',b'). Top view (a,a') and side view (b,b'). $^{[15]}$

tures of isolated N-methyl pyrrole and bond lengths are practically unperturbed; that is, $C\beta - C\beta > C\alpha - C\beta$ (1.438 Å vs 1.369 Å) for 11. For macrocycle 12, failure to obtain a good single crystal suitable for X-ray diffraction in free base form forced us to resort to geometry optimization based on DFT calculations. With the B3LYP/6-31G* basis set,^[12] a minimum energy structure turned out to be a figure-eight structure (Supporting Information, Figure S51). On the other hand, single crystals suitable for X-ray diffraction were obtained by slow diffusion of cyclohexane into TFA/dichloromethane solution of 12. Macrocycle 12 upon protonation turned out to have a flat geometry (Figure 3a'). The interesting features were observed in $12 \cdot 2H^+$, where four TFA molecules were involved in the flat geometry of 12·2H⁺. Each half of the macrocycle contains one neutral pyrrole NH and one protonated pyrrole NH. The TFA molecule which is protonating the pyrrole, the carbonyl oxygen of this TFA is involved in strong H-bonding with carboxyl group of other TFA. The carbonyl oxygen of this second TFA molecule is in turn involved in H-bonding with the free pyrrole NH (Supporting Information, Figure S48). The short distance for O-O was estimated to be 2.47 Å. These features suggest that while the highly distorted structures of 11 and 12 lead to nonaromaticity, planar 12·2H⁺ induced by protonation allows its antiaromatic character.

In contrast to **12-2H**⁺, the energy-minimized structure for **11-2H**⁺ obtained was a substantially bent shape (Supporting Information, Figure S50). The β - β linkages of *N*-methyl pyrrole would provide the steric restriction on a planar structure, which results in the bent shape of **11-2H**⁺ and accounts for its nonaromaticity.

Such nonaromaticity and weak antiaromaticity of free-base and protonated **11** and **12** were well-described by nucleus-independent chemical shifts (NICS) and anisotropy of induced current density (AICD) calculations in their optimized structures.^[13] In both **11** and **12**, the NICS values at the center of the macrocycle were calculated to be $\delta = 0.46$ and -2.87 ppm, respectively (Supporting Information, Figure S53, S55), and the AICD plot (Figure S57a, S58a) showed the localized ring current



on the pyrrolic subunits, representing their nonaromatic characters. Compound **11·2H**⁺ having a substantially bent shape displayed similar results to **11** and **12**, where the NICS value at the center of the macrocycle was $\delta = -1.45$ ppm (Figure S54) and its ring current was not fully delocalized in the AICD plot (Figure S57b). In the case of **12·2H**⁺, the NICS values of $\delta =$ 3.15–4.51 ppm (Figure S56) were estimated inside the macrocycle, and the AICD plot (Figure S58b) showed the counterclockwise ring current over the whole macrocycle. These results are in accordance with the ¹H NMR result of **12·2H**⁺, indicating its weak antiaromatic character.

The excited state dynamics also reflect the nonaromatic and weak antiaromatic nature of free-base and protonated **11** and **12** (Figure 4; Supporting Information, Figure S62). The femto-



Figure 4. The femtosecond transient absorption (fs-TA) spectra and decay profiles of **11** and protonated **11**. The a) TA spectra and b) decay profile of **11** are recorded by photoexcitation and monitoring at 600 nm. The c) TA spectra and d) decay profile of protonated **11** are recorded by photoexcitation at 640 nm and monitoring at 650 nm.

second transient absorption (fs-TA) spectra of **11**, **11·2**H⁺, and **12** showed simple excited dynamics with a single decay component with time constants of 5–20 ps, indicating their nonaromatic characters. On the other hand, the TA spectra of weak antiaromatic **12.2**H⁺ was fitted with two decay components, 0.7 and 18 ps, indicating the existence of characteristic dark state of antiaromatic expanded porphyrinoids.^[14] Since the optically dark state works as a ladder in the excited state dynamics, **12·2**H⁺ showed the internal conversion process with the time component of 0.7 ps and the subsequent relaxation process with the time component of 18 ps.

In conclusion, two interesting variations in the hexapyrrolic macrocycle skeleton are reported for the first time via inclusion of two *N*-methyl pyrrole units into the macrocycle core with α,β or β,β connections. The unconventional linkage of the *N*-methyl pyrrole unit admirably serves as incentive to two different types of highly stable cross-conjugated hexapyrrolic macrocycles. It follows that appropriate combination of the structural constituents of the heteroannulenes triggers whether it will be possible to construct either highly aromatic^[9] or alterna-

tively rather nonaromatic macrocycles. Research into this promising field is currently under progress in the author's laboratory.

Acknowledgement

The work at IACS, Kolkata was supported by DST-SERB (SR/S1/ IC-37/2012), CSIR (02(0120)/13/EMR-II), New Delhi, India and DST-SERB Ramanujan Fellowship (SR/S2/RJN-93/2011), India. A.M. thanks CSIR for senior research fellowship. The work at Yonsei University was supported by the Global Research Laboratory Program (2013K1A1A2A02050183) funded by the Ministry of Science, ICT & Future, Korea. The quantum calculations were performed using the supercomputing resources of the Korea Institute of Science and Technology Information (KISTI). The work at Kyushu University, Japan was supported by JSPS Grant-in-Aid for Scientific Research (25248039, 26810024). The DBT-funded single-crystal X-ray diffraction facility in the Department of Organic Chemistry, IACS and the single-crystal Xray diffraction facility in IISER, Pune are acknowledged.

Keywords: aromaticity · cross-conjugation · heteroannulenes · unconventional pyrrole connectivity · unorthodox tripyrranes

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- [15] CCDC 1020263 (11) and 1020262 (12) contain the supplementary crystallographic data for this paper. These data are provided free of charge by The Cambridge Crystallographic Data Centre.

Received: January 27, 2016 Published online on March 8, 2016

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