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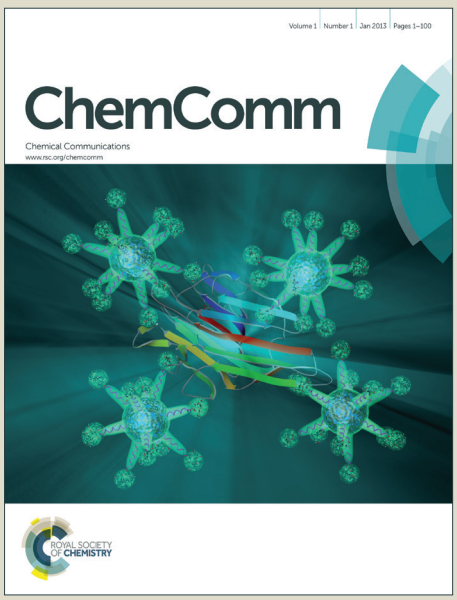

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adj-Dicarbachlorin, the first free base carbaporphyrinoid system with an internal methylene unit †

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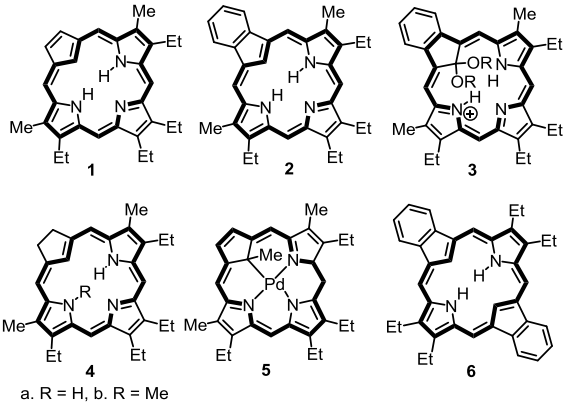
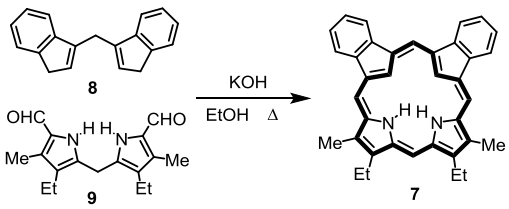
Base-catalyzed condensation of dicyclopentadienylmethane with a dipyrrylmethane dialdehyde gave a dicarbachlorin with an internal CH_2 group. This unusual porphyrinoid retained highly diatropic characteristics and exhibited a porphyrin-like UV-vis spectrum.

Carbaporphyrins are porphyrin analogues with a cyclopentadienyl unit in place of one of the usual pyrrole moieties and include structures such as **1** and **2**.[1-4] In fact, the majority of studies in this area have been conducted on benzo-fused versions like **2** because of the relative ease of synthesis and due to the robust nature of these structures.[3] Carbaporphyrins are fully aromatic porphyrinoids and the proton NMR spectra for these compounds typically show the external *meso*-protons downfield near +10 ppm, while the internal CH resonance is strongly shifted upfield to approximately -7 ppm.[3,4] These porphyrinoids form stable organometallic derivatives with Ag(III),[5] Au(III)[5b] and Pd(II),[6] and also exhibit unique reactivity undergoing unusual regioselective oxidation reactions.[7] Treatment of carbaporphyrins such as **2** with ferric chloride in alcohol solvents affords carbaporphyrin ketals **3** that have strong absorptions in the far red[7] and have been shown to be active agents in the treatment of leishmaniasis.[8] Carbachlorins have also been investigated, including **4a**, and these also exhibit highly diatropic characteristics.[4,9] Carbachlorin **4a** could be oxidized to carbaporphyrin **1** and was also alkylated with methyl iodide and potassium carbonate to give *N*-methyl derivative **4b**.[4] Treatment with palladium(II) acetate induced a cascade reaction involving metalation, oxidation and methyl group migration to afford the Pd(II) complex **5**.[4] Similar palladium complexes had previously been prepared from *N*-alkyl carbaporphyrins.[6,10] Given the interesting properties of carbaporphyrins,



porphyrin analogues with two carbocyclic subunits have also been investigated.[11-13] An aromatic *opp* dicarbaporphyrin **6** was obtained by reacting diformylindane with diethylpyrrole, but this system proved to be somewhat unstable.[11] Recently, the first example of a base catalyzed MacDonald reaction was used to prepare *adj*-dicarbaporphyrin **7** by reacting diindenylmethane **8** with dipyrrylmethane dialdehyde **9** in the presence of KOH in refluxing ethanol (Scheme 1).[12] This remarkable system retained porphyrin-like characteristics and the proton NMR spectrum showed the internal CH resonance at -6.24 ppm while the *meso*-protons appeared at downfield values between 8.9 and 9.5 ppm. Dicarbaporphyrin **7** reacted with palladium(II) acetate to give a unique tripalladium sandwich complex encapsulating a Pd(IV) ion.[12]



Scheme 1 Synthesis of an *adj*-dibenzodicarbaporphyrin

In order to gain a deeper perspective on carbaporphyrins, a DFT investigation was conducted and this

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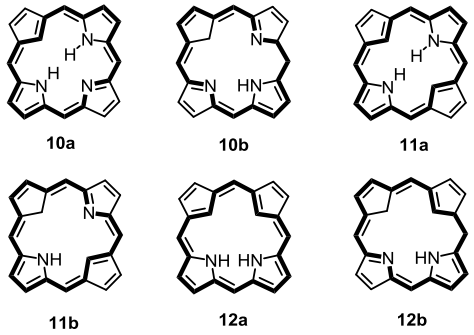
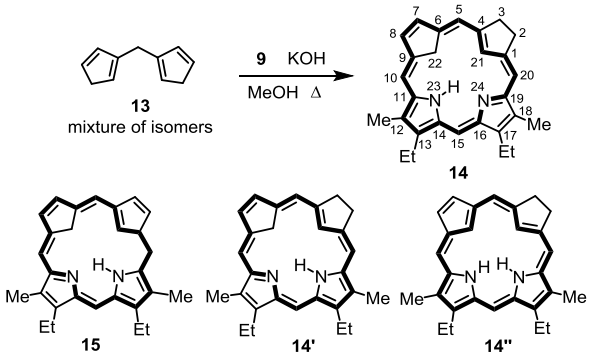
† Electronic Supplementary Information (ESI) available: Experimental details, UV-vis, proton and carbon-13 NMR spectra, AICD plots and Cartesian coordinates. For ESI and crystallographic data in CIF format, see DOI: 10.1039/x0xx00000x



showed that tautomer **10b** with an internal CH_2 unit was only 2.98 kcal/mol higher in energy than the conventional tautomer **10a**.[14] Metal complexes like **5** can be considered to be derivatives of tautomer **10b**,[4] as can carbaporphyrin ketals **3**,[7] but no examples of free base porphyrinoids with this structural arrangement are presently known. For *opp*-dicarbaporphyrins, DFT calculations show that tautomer **11a** is 2.47 kcal/mol more stable than **11b**, but in the case of *adj*-dicarbaporphyrins the DFT calculations predict that tautomer **12b** with an internal methylene unit is the more favored tautomer being 4.78 kcal/mol more stable than **12a**.[14] The related dibenzodicarbaporphyrin **7** does not favor this structural arrangement, and this was also confirmed by DFT calculations.[12] Therefore, it would be necessary to prepare dicarbaporphyrins without the presence of fused benzene rings in order to see whether porphyrin analogues with inner methylene groups are accessible.[15]



Scheme 2 Synthesis of a dicarbachlorin

With this goal in mind, dicyclopentadienylmethane **13** was reacted with **9** and KOH in refluxing methanol (Scheme 2). The best results were obtained when the reaction was carried out for 4 days using excess **13** and the product was purified on grade 2 alumina. A red colored fraction was collected and this gave a porphyrinoid product in 5-7% yield. The UV-vis spectrum for this product was very similar to porphyrins or carbaporphyrins such as **2**[1] in that it showed a strong Soret band at 398 nm (ε = 1.2 x 10^5 $M^{-1}cm^{-1}$) and a series of Q bands at 501, 533, 619 and 683 nm (Fig. 1). However, the proton NMR spectrum for the product immediately established that dicarbachlorin **14** had been isolated rather than the corresponding dicarbaporphyrin **15**. This result was not particularly surprising as no oxidant was used in the procedure. In addition, the moderate sized absorption at 683 nm is reminiscent of a chlorin-type product.[16]

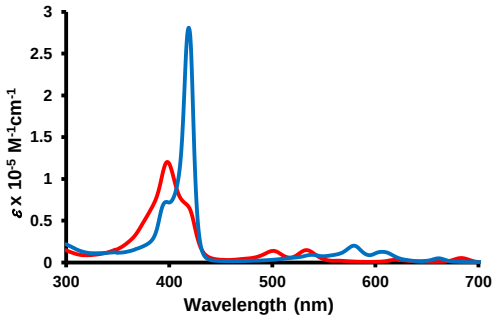


Fig. 1 UV-vis spectra of dicarbachlorin **14** in 1% Et_3N-$CHCl_3$ (free base, red line) and 0.05% TFA-$CHCl_3$ (**14**H^+, blue line).

The proton NMR spectrum of **14** in $CDCl_3$ indicated that an asymmetrical porphyrinoid product had been generated and showed upfield resonances at -6.68 (2H) and -4.03 ppm (1H) for the internal CH_2 and CH units, respectively (Fig. 2). These results clearly show that the compound corresponds to **14** and/or **14'** rather than tautomer **14''** with two internal NHs, although it is worth noting that the remaining NH resonance is too broad to resolve in this spectrum. It seems likely that **14** and **14'** undergo rapid interconversion at room temperature. The *meso*-protons gave rise to four singlets at 9.07, 9.51, 9.52 and 9.97 ppm, while the cyclopentadienyl unit afforded two doublets at 9.47 and 9.68 ppm, which further attest to the highly diatropic character of **14**. The CH_2CH_2 moiety associated with the reduced ring afforded two characteristics multiplets near 4.6 ppm, while the CH_2 units of the ethyl substituents produced two downfield quartets at 3.81 and 3.89 ppm due to their proximity to the macrocyclic ring current. The carbon-13 NMR spectrum showed the inner methylene group at 32.9 ppm and the internal methine unit at 132.2 ppm. As is the case for porphyrins, the *meso*-carbons give comparatively upfield resonances for sp^2 carbons showing up at 100.6, 105.7, 106.8 and 114.6 ppm. The identity of **14** was supported by high resolution mass spectrometry. Addition of TFA to solutions of **14** afforded the corresponding cation **14**H^+. The UV-vis spectrum for this species gave a greatly intensified Soret band at 419 nm (ε > 2.8 x 10^5 $M^{-1}cm^{-1}$), together with a series of minor absorptions between 500 and 680 nm (Fig. 1). The proton NMR spectrum of **14**H^+ in TFA-$CDCl_3$ indicated that this species had enhanced diatropicity and the internal protons were shifted significantly upfield to give resonances at -7.42 (22-CH_2), -5.53 (21-H), -4.19 (NH) and -4.04 ppm (NH). The external *meso*-protons were similarly shifted downfield to give four singlets at 9.52 (20-H), 10.06 (5-H), 10.15 (15-H) and 10.51 (10-H), while the cyclopentene protons (7,8-H) gave rise to two doublets at 10.02 and 10.24 ppm.

Crystals of **7** and **14** that were suitable for X-ray diffraction (XRD) analysis were obtained and these confirmed the identities of the dicarbaporphyrinoids. Dicarbaporphyrin **7** (Fig. 3) exhibits framework bond distances consistent with a delocalized π-bonding model with the π-systems for the indenyl benzo-units decoupled from the [18]annulene core, as evidenced by the more single-bond-like 1.47 ± 0.01 Å C1–C2, C3–C4, C6-C7 and C7-C8 bond distances. The dicarbaporphyrin adopts a more

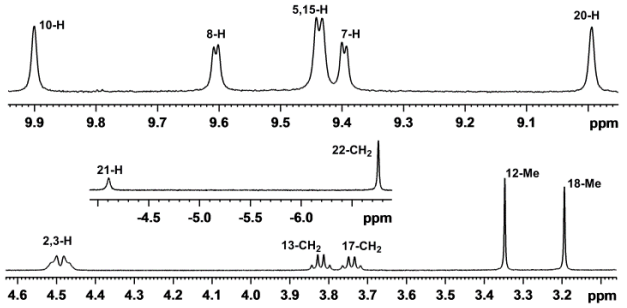


Fig. 2 Partial 500 MHz proton NMR spectrum of dicarbachlorin **14** in $CDCl_3$.

planar conformation than had been predicted by DFT calculations[12] with the internal N-H hydrogen atoms, which were freely refined, necessarily being distorted out of the crowded central cavity. The local minimum derived from the X-ray structure is 2.40-3.35 kcal/mol higher in energy than the conformational minimum (ESI, Table S5) and these results are attributed to conformational changes due to crystal packing forces. Dicarbachlorin **14** clearly shows the methylene units at C7, C8 and C21 of the macrocyclic framework (Fig. 3). The identification of the freely refined N24 hydrogen atom in the difference Fourier, and the absence of residual electron density near N23, confirms that tautomer **14** is present. In addition, the more single-bond-like C11–C12 (1.466(2) Å) and C13–C14 (1.496(2) Å) bond distances, and the shorter C16–C17 (1.427(2) Å) and C18–C19 (1.422(2) Å) bond distances, together with the remaining framework atom bond metrics, are consistent with a delocalized π-bonding model with an [18]annulene core including C22 and N23, but not C21 and N24.

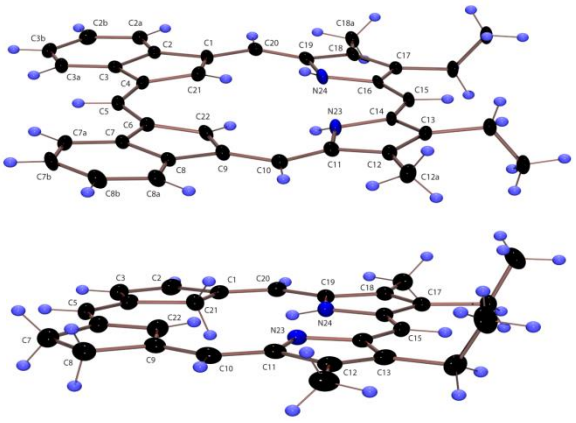
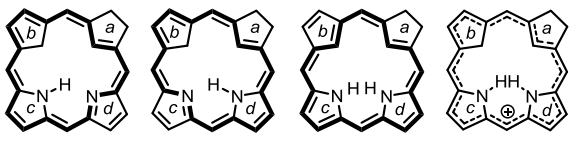


Fig. 3 ORTEP III drawings (50% probability level, hydrogen atoms rendered arbitrarily small for clarity) for dicarbaporphyrin **7** (above) and dicarbachlorin **14** (below). In each case only one of two crystallographically independent molecules are shown.

In order to obtain further insights into the dicarbachlorin system, density functional theory (DFT) calculations were performed on the unsubstituted structure **16** (Table 1). Tautomers **16**, **16'** and **16''** together with cation **16**H$^+$ were optimized using DFT-B3LYP/6-311++G(d,p). Unlike dicarbaporphyrin **15**, tautomer **16** was shown to be planar. Single point energy calculations were also performed on the minimized structures using Mu 2X/6-311++G(d,p) and B3LYP-D/6-311++G(d,p). As ha been noted for calculations on related structures,[12,] energies obtained from the M06-2X and B3LYP-D functionals were consistent with the results calculate using the B3LYP functional (Table 1). The relative ΔG values were also very similar, indicating that no significa t entropic factors are involved. Tautomer **16'** is only 0.25-0.57 kcal/mol higher in energy than **16**. However, both f these tautomers are approximately 7 kcal/mol more stable than structure **16''** with two pyrrolic NHs (Table 1). The aromatic character of these molecules was assessed using the GIAO method, which has commonly been used to prob porphyrinoid diatropic ring currents,[12,17] and nucleu independent chemical shifts (NICS) were used to assess th diatropic character of these species.[18] As standard NIC calculations include the effects of both σ and π-electr NICS$_{zz}$ calculations were also carried out 1 Å above the ring (NICS(1)$_{zz}$) as this has been shown to primarily meas contributions from the π-system and thereby gives a more reliable assessment of aromatic character.[19] B techniques gave similar trends and for convenience only th NICS values will be discussed in detail (it is worth noting that the numerical values obtained using NICS$_{zz}$ are muc larger than those calculated using NICS, but in both case strongly negative values are indicative of aromatic character). Tautomers **16**, **16'** and **16''** all gave NICS(0 values that are consistent with strongly aromatic species. For **16**, rings *b* and *c* gave large negative NICS values but th upfield shift for ring *d* was small and ring *a* gave a NICS value of +5.83 ppm. The latter result is to be expected a ring *a* lies outside of the macrocyclic conjugation pathways and ring *d* is also external to the expected 18π electro pathway depicted in bold. The AICD plot[20] for **16**, which provides a measure of relative current density, als indicates that this pathway is favoured (Fig. 4). Similar

Table 1 Relative energies and NICS values for dicarbachlorin tautomers and the related dication.



	16	**16'**	**16''**	**16**H$^+$
Molecule				
Rel. ΔG	0.00	0.36	7.12	****
B3LYP/ **M06-2X**/B3LYP-D	0.00	0.37/ **0.57**/0.25	7.27/ **6.88**/7.00	****
NICS(0)/ **NICS(1)$_{zz}$**	-12.60/ **-30.59**	-12.33/ **-31.01**	-13.21/ **-32.31**	-12.96/ **-32.07**
NICS(*a*)/ **NICS (1*a*)$_{zz}$**	+5.83/ **+12.92**	+5.40/ **+9.30**	+5.20/ **+8.45**	+5.92/ **+8.88**
NICS(*b*)/ **NICS(1*b*)$_{zz}$**	-17.99/ **-50.43**	-17.42/ **-51.57**	+3.99/ **+16.25**	-18.00/ **-52.97**
NICS(*c*)/ **NICS(1*c*)$_{zz}$**	-14.26/ **-35.35**	-3.90/ **-16.43**	-15.21/ **-41.72**	-15.02/ **-43.70**
NICS(*d*)/ **NICS(1*d*)$_{zz}$**	-3.85/ **-15.94**	-14.01/ **-34.21**	-15.37/ **-31.29**	-14.44/ **-29.58**

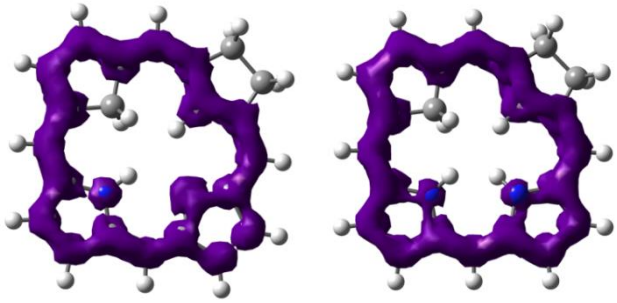


Fig. 4 AICD plots (isosurface values 0.07) for dicarbachlorin **16** and the related cation **16**H$^+$.

analyses can be made for **16'**, although in this case it is ring *c* that lies outside of the major delocalization pathway. Tautomer **16** gives positive NICS values for rings *a* and *b* because these lie outside of the [18]annulene pathway indicated for this structure. The calculated NICS(0) value for cation **16**H$^+$ was -12.96 ppm, which is slightly larger than the values for **16** and **16'** in accord with the proton NMR data. In this case, rings *b*, *c* and *d* all give strongly negative NICS values suggesting that the nineteen atom 18π electron delocalization pathway denoted by the dotted lines in this structure is favored and the AICD plot for **16**H$^+$ also indicates that this pathway is significant (Fig. 4).

Attempts to metalate dicarbachlorin **14** with palladium(II) acetate afforded insoluble materials that could not be characterized. In addition, attempts to dehydrogenate **14** to give the related dicarbaporphyrin **15** have been unsuccessful and in all cases resulted in decomposition. However, in one experiment when **9** and **13** were reacted together under the usual conditions (Scheme 2), the formation of a small amount of **15** was noted. Although the result was not reproducible, and the product could not be isolated in pure form, the proton NMR spectrum confirmed that this species also favors a tautomer with an inner methylene unit. The internal CH_2 and CH units gave upfield resonances at -6.36 and -4.62 ppm, respectively, while the *meso*-protons were observed as four 1H singlets at 9.58, 9.63, 9.86 and 9.96 ppm. The external cyclopentene protons gave doublets at 9.60 and 9.78 ppm, but the cyclopentadiene protons afforded doublets of doublets at 7.79 and 7.94 ppm. These results confirm that dicarbaporphyrin **15** is a highly diatropic compound, and as expected indicate that the external double bond on the cyclopentadiene ring lies outside the favored aromatic delocalization pathway.

In conclusion, the first example of a carbaporphyrinoid system with an internal methylene unit has been characterized. This dicarbachlorin exhibits a strongly porphyrin-like UV-vis spectrum, and proton NMR spectra, NICS calculations and AICD plots demonstrate that this porphyrinoid possesses strongly macrocyclic aromatic properties. This system represents a new, albeit long anticipated, structural variation for porphyrin analogues and opens up new possibilities for carbaporphyrin research.

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