Synthesis and unusual properties of the first 2,3,7,8,12,13,17,18-octabromo-5,10,15,20-tetraalkylporphyrin

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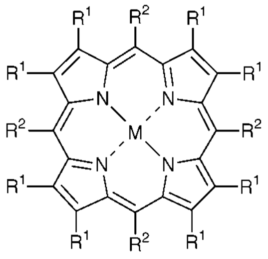
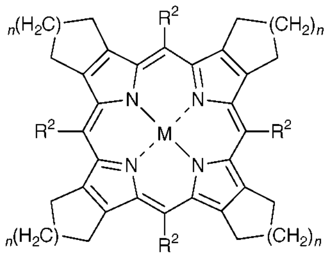
Received (in Corvallis, OR, USA) 3rd June 1999, Accepted 7th September 1999

The new perhalogenated porphyrin 2,3,7,8,12,13,17,18-octabromo-5,10,15,20-tetrakis(trifluoromethyl)porphinato-nickel(II) exhibits several striking features, including an extremely ruffled macrocycle with a very short Ni–N distance, an unusually red-shifted optical spectrum, and, surprisingly, hindered rotation of the *meso*-trifluoromethyl substituents ($\Delta G^{\ddagger}_{278}$ = 47 kJ mol^{-1}).

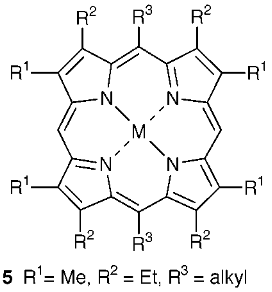
During the last decade a number of highly nonplanar dodecasubstituted porphyrins have been synthesized, including dodecaarylporphyrins (*e.g.* **1**), dodecaalkylporphyrins (*e.g.* **2**), octaalkyltetraphenylporphyrins (*e.g.* **3**), tetraaryloctahaloporphyrins (*e.g.* **4**), octaethyltetranitroporphyrin (**5**), and systems with substituents fused to the pyrrole rings (*e.g.* **6**).[1] Detailed studies of these compounds have provided a much greater understanding of the effects of nonplanar distortions on the properties of porphyrins, and have also led to speculation about possible functional roles for the nonplanar deformations seen for some tetrapyrroles in biological systems.[1] Two classes of dodecasubstituted porphyrin which have so far proved elusive are the tetraalkyloctahaloporphyrins (**7**) and octaalkyltetrahaloporphyrins (**8**); the non-availability of these compounds can be related to undesirable side-reactions (*e.g.* benzylic substitution and bromodealkyation) which occur during the bromination of tetraalkyl- and octaalkyl-porphyrins.[2] Here we report the first synthesis of a tetraalkyloctahaloporphyrin, **9** (M = Ni), and describe some of the unusual features of this compound.



1 $R^1 = R^2 = Ph$
3 $R^1 = Et, R^2 = Ph$
4 $R^1 = Br, R^2 = Ph$
5 $R^1 = Et, R^2 = NO_2$
7 R^1 = halogen, R^2 = alkyl
8 R^1 = alkyl, R^2 = halogen
9 $R^1 = Br, R^2 = CF_3$
10 $R^1 = H, R^2 = CF_3$
11 $R^1 = H, R^2 = Bu^t$
12 $R^1 = Br, R^2 = C_6F_5$
13 $R^1 = H, R^2 = Ph$
14 $R^1 = H, R^2 = C_6F_5$



2 $R^2 = (CH_2)_4CH_3, n = 1$
6 $R^2 = Ph, n = 2$ or 3



15 $R^1 = Me, R^2 = Et, R^3$ = alkyl

In an attempt to avoid the side-reactions seen during the bromination reactions of tetraalkyl- and octaalkyl-porphyrins, we investigated bromination of the tetra(perfluoroalkyl)porphyrin **10** (M = Ni). The precursor porphyrin **10** (M = 2H) was prepared using a literature procedure.[3] Refluxing **10** (M = 2H) with Ni(acac)$_2$ in toluene gave **10** (M = Ni) which was more suitable for use in the bromination reactions. Bromination of **10** (M = Ni) proved difficult but was eventually achieved by refluxing a solution of the porphyrin in CHCl$_3$ containing a large excess of Br$_2$ for 10 days under argon. The perhalogenated porphyrin **9** (M = Ni) was then isolated in 88% yield after column chromatography (silica gel/cyclohexane) and recrystallization (from CH$_2$Cl$_2$ with slow diffusion of MeOH). Porphyrin **9** (M = Ni) gave satisfactory mass spectral analysis (M$^+$ 1269.27; calc. for $C_{24}N_4Br_8F_{12}Ni$ 1269.27) and microanalysis (found C, 23.54; H, 0.00; N, 4.43; calc. C, 23.79; H, 0.00; N, 4.62%), and was further characterized by X-ray crystallography and visible and NMR spectroscopy as described below.

The crystal structure of **9** (M = Ni)† (Fig. 1) revealed a very ruffled macrocycle in which the *meso* positions were displaced alternately up or down by an average of 1.06 Å with respect to the least-squares plane of the porphyrin ring. The average out-of-plane displacement for all of the porphyrin atoms with respect to the least-squares plane of the porphyrin macrocycle was 0.50 Å. By these measures **9** (M = Ni) is the most ruffled porphyrin ever reported; the largest ruffling distortion previously observed was for **11** (M = Zn), where the corresponding displacements were only 0.90 and 0.44 Å.[4] The conformation seen for **9** (M = Ni) can be contrasted with the saddle conformation seen for the perhalogenated tetraarylporphyrin **12** (M = Ni),[5] where the *meso* carbons are in the least-squares plane of the porphyrin macrocycle and the pyrrole rings are tilted alternately up or down. The strongly ruffled structure of **9** (M = Ni) is accompanied by an extremely short Ni–N distance of only 1.88 Å. This can be compared to Ni–N distances of 1.90 Å in the very saddle-distorted porphyrin **12** (M = Ni)[5] and 1.96 Å in planar (triclinic A) NiOEP.[6] The significant shortening of the Ni–N distance seen for **9** (M = Ni) is consistent with the

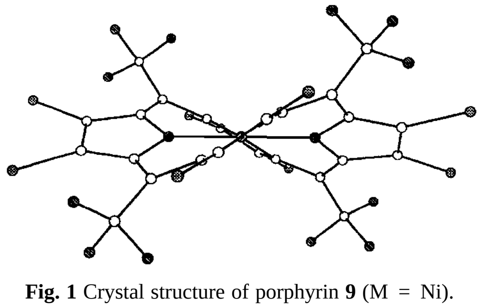


Fig. 1 Crystal structure of porphyrin **9** (M = Ni).

larger degree of core contraction expected for ruffling *versus* other types of nonplanar distortion.[7] Molecular modelling studies using a previously published force-field[7–9] demonstrated that the conformations seen in the crystal structures of **9** (M = Ni) and **12** (M = Ni) were the minimum energy structures for these porphyrins, and that the different Ni–N distances in the two compounds could be accurately reproduced.

Porphyrin **9** (M = Ni) possesses some unusual spectroscopic characteristics. Nonplanarity is known to cause a red-shift in the optical spectra of porphyrins due to a greater destabilization of the HOMO compared with the LUMO,[1] and the optical spectrum of **9** (M = Ni) [λ/nm (ε/dm^3 mol^{-1} cm^{-1}) 444 (77 000), 636 (8100) and 690 (24 000)] is indeed red-shifted compared to the spectrum of **10** (M = Ni) [408 (120 000), 550 (7700) and 590 (25 000)]. However, the red-shift of the $Q_{(0,0)}$ band upon addition of eight β bromo substituents to **10** (M = Ni) (2450 cm^{-1}) is substantially larger than that seen upon addition of eight β bromo substituents to **13** (M = Ni) (1050 cm^{-1}) or **14** (M = Ni) (1250 cm^{-1}) which yields saddle-distorted macrocycles. This suggests that the porphyrin π-system may be more sensitive to ruffle *versus* saddle distortions of the macrocycle. Additional support for this idea comes from the fact that other properties related to the porphyrin π-system (*e.g.* the frequencies of Raman marker lines[10] and the magnitude of the porphyrin ring current effect[11]) are also affected more by ruffle than by saddle distortions.

The 283 MHz ^{19}F NMR spectrum of **9** (M = Ni) in CD_2Cl_2 at ambient temperature displayed an unusually broad signal at δ −39 (referenced to internal CF_2Cl_2 at δ −8.0)[12] for the *meso* trifluoromethyl substituents. Heating the complex resulted in a sharp singlet at δ −39.0, whereas cooling produced two signals at δ −34.7 (d, 2F, $J_{\text{F-F}}$ = 114 Hz) and −47.8 (t, 1F, $J_{\text{F-F}}$ = 114 Hz). The activation energy ($\Delta G^{\ddagger}$) for the observed dynamic process was calculated to be 47 kJ mol^{-1} at the coalescence temperature of 278 K. In contrast, the unbrominated precursor **10** (M = Ni) gave a single sharp CF_3 signal at all of the temperatures studied. The non-equivalence of the trifluoromethyl fluorines in **9** (M = Ni) indicates that rotation of the CF_3 groups is slow on the NMR timescale at low temperatures. Hindered CF_3 rotation is a rare phenomenon but has been observed in some very sterically crowded compounds. For example, the activation energy for CF_3 rotation in CF_3CCl_2I is 36 kJ mol^{-1} at 201 K,[13] with the coupling constant between the fluorines being 101 Hz in the slow exchange spectrum. The unusually slow rotation of the CF_3 groups in **9** (M = Ni) provides evidence of a very high degree of steric crowding in this compound.

In earlier NMR studies of nonplanar porphyrins, dynamic processes in **1** (M = 4H),[14] **2** (M = Ni)[14] and **15** (M = 2H or Zn)[15] were initially attributed to macrocyclic inversion but subsequently reassigned as substituent rotation.[16–18] In an attempt to avoid any confusion about the nature of the dynamic process in **9** (M = Ni), we used molecular mechanics calculations[8,9] to estimate the energies of the two possible CF_3 rotation pathways (CF_3 rotation about a ruffled porphyrin core *versus* CF_3 rotation during inversion of the porphyrin macrocycle). The barrier for rotation of the CF_3 groups in the ruffled structure was calculated to be 34 kJ mol^{-1}. The lowest energy inversion–rotation barrier (103 kJ mol^{-1}) was found between the ruffled structure (designated αβαβ) and a structure which had three CF_3 groups on the same side of the porphyrin plane (designated αααβ). On the basis of these calculated energies it seems probable that the process being observed for **9** (M = Ni) is rotation of the CF_3 groups in the ruffled structure.

Porphyrin **9**, with a novel combination of a strongly ruffled macrocycle and very electron-withdrawing substituents, clearly has many unusual features even when compared with other very nonplanar dodecasubstituted porphyrins. It will be interesting to investigate this porphyrin further and perhaps to examine how **9** compares with tetraaryloctahaloporphyrins in terms of catalyzing the oxygenation reactions of unactivated alkanes.[19]

This work was supported by grants from the National Institutes of Health (HL 22252) and the National Science Foundation (CHE-96-23117). Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed-Martin company, for the United States Department of Energy under Contract DE-ACO4-94AL85000.

Notes and references

† Crystals were grown by the slow diffusion of cyclohexane into a CH_2Cl_2 solution of **9** (M = Ni) ($C_{24}N_4Br_8F_{12}Ni$). The selected crystal (0.06 × 0.06 × 0.04 mm) had an orthorhombic unit cell, space group *Pnma*, cell dimensions a = 8.1106(7), b = 23.587(2), c = 15.5831(14) Å, V = 2981.2(5) Å^3, Z = 4 (FW = 1270.27). Data were collected in ω scan mode to 2θmax = 63° (29685 total reflections measured) on a Bruker SMART 1000 diffractometer with graphite monochromated radiation from a ceramic sealed tube source [λ(Mo-Kα) = 0.71073 Å]. The crystal was cooled to 93(2) K during data collection with an anhydrous N_2 stream supplied from a CryoIndustries low temperature apparatus. The structure was solved by direct methods (SHELXS-97) and refined (based on F^2 using all data) by full matrix least-squares methods with 232 parameters (SHELXL-97). Of 3511 unique reflections used in the refinement ($2\theta_{\text{max}}$ = 55°), 1937 were observed [$I > 2\sigma(I)$]. An empirical absorption correction (SADABS) (ref. 20) was applied [T_{min} = 0.546, T_{max} = 0.657, ρ_{calc} = 2.83 g cm^{-3}, μ = 11.47 mm^{-1}]. Final R factors were $R1$ = 0.042 (observed data) and $wR2$ = 0.077 (all data). CCDC 182/1413.

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Communication 9/04532E