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**Porphyrinoids**

# A Stable Radical Species from Facile Oxygenation of meso-Free 5,10,20,25-Tetrakis(pentafluorophenyl)-Substituted [26]Hexaphyrin(1.1.1.1.1.1)**

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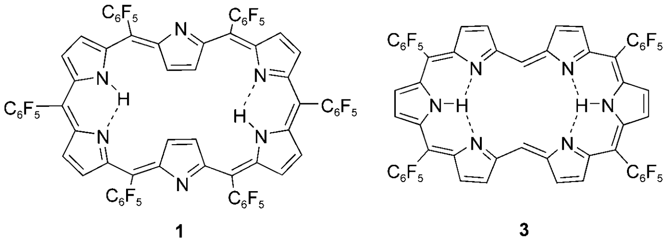
In recent years, the potential of expanded porphyrins (conjugated pyrrolic macrocycles larger than porphyrins) has been increasingly recognized owing to their unique chemical, optical, and electrochemical properties as well as rich coordination chemistry.[1] Besides their earlier uses as scaffolds for anion binding[2] and their unique metal–metal interactions,[3] recent interesting findings have been reported, including 1) a smooth metathesis-type splitting reaction of the bis($Cu^{II}$) complex of [36]octaphyrin(1.1.1.1.1.1.1.1) into two molecules of $Cu^{II}$ porphyrin,[4] 2) transannular annulation reactions between two ethynyl groups or between ethynyl and phenyl groups of meso-substituted hexaphyrins to provide unique rearranged products,[5] and 3) the facile formation of stable antiaromatic or twisted Möbius aromatic systems.[6] These results indicate that expanded porphyrins can fulfill roles that are not only difficult for porphyrins but are novel and important in their own right. Herein, we report another unexpected function of expanded porphyrins, namely of [26]hexaphyrin, to stabilize a radical species to the extent that it can be manipulated as a normal closed-shell organic molecule in the presence of air and moisture. To the best of our knowledge, this finding is without precedent in the chemistry of porphyrins.

In the area of expanded porphyrins, meso-aryl-substituted [26]hexaphyrins(1.1.1.1.1.1) have served as benchmark molecules in view of their flat molecular shapes and distinct aromaticity, as well as being more or less analogous to porphyrins. The chemical stability of these hexaphyrins is crucially dependant on the meso-aryl substituents. Namely, hexakis(pentafluorophenyl)-substituted hexaphyrin **1** is a stable aromatic molecule with type II conformation (flat rectangular shape; Scheme 1),[7,8] whereas the incorporation of phenyl or 2-tolyl substituents at the meso position causes a significant drop in the chemical stability of hexaphyrin.[9,10] According to DFT calculation (B3LYP/6-31G*) for the unsubstituted hexaphyrin, the type I conformation (flat spectacles-like shape; Scheme 1) is more stable than the type II conformation by 9.9 kcal$mol^{-1}$; this stability is due to more effective intramolecular hydrogen-bonding interactions in the former. Hence, the predominant type II conformation observed for **1** can be attributed to the severe steric repulsion between two inward-pointing meso-pentafluorophenyl substituents in its putative type I conformation. With this in mind, we embarked on the synthesis of 5,10,20,25-tetrakis(pentafluorophenyl)-substituted hexaphyrin **3** as the first example of a meso-free variant, with an expectation that **3** should take predominantly the type I conformation. The synthesis of **3** was also motivated by its structural resemblance to meso-free porphyrins, which have intriguing meso–meso coupling reactivity upon oxidation.[11]



**1** type II

**3** type I

***Scheme 1.*** Structures of [26]hexaphyrins(1.1.1.1.1.1) **1** and **3** that correspond to type II and type I conformations, respectively.

Hexaphyrin **3** was prepared by the condensation of 5,10-bis(pentafluorophenyl)tripyrrane (**2**)[12] with an excess amount of trimethyl orthoformate (22 equiv) in $CH_2Cl_2$ in the presence of methanesulfonic acid under argon, and the reaction was carried out in the dark at 0°C for 7 h (Scheme 2).[13] The resulting solution was oxidized using 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) for 1 h at room temperature. The usual workup was followed by quick separation by standard column chromatography on silica gel

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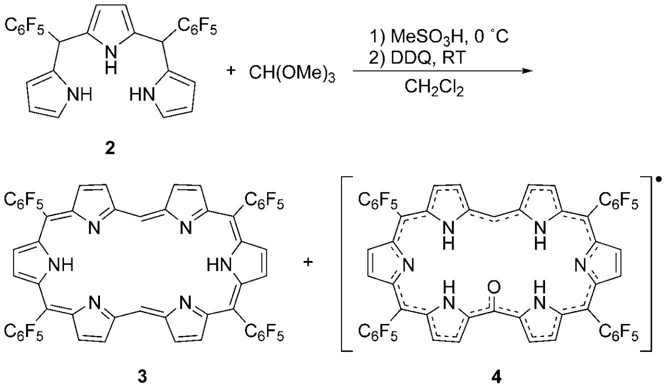


*Scheme 2.* Synthesis of **3** and **4**.

and gave hexaphyrin **3** (17%) and meso-oxygenated hexaphyrin **4** (15%). The yields of isolated **3** and **4** varied depending upon how quickly the workup and separation were carried out; this is because **3** gradually converted into **4** by oxygenation in aerated solution.

High-resolution electrospray ionization time-of-flight (HR ESI-TOF) mass spectrometry revealed the parent ion peak of **3** at *m*/*z* 1129.1178 (calcd for $C_{54}H_{17}F_{20}N_6$ ($[M+H]^+$): 1129.1190). The $^1$H NMR spectrum of **3** was quite simple, featuring a singlet ascribed to the inner meso protons at $\delta = -4.97$ ppm, a singlet corresponding to the inner NH protons at $\delta = -0.37$ ppm, a pair of doublets from the outer β protons at $\delta = 9.03$ and 10.49 ppm, and a singlet resulting from the outer β protons at $\delta = 9.08$ ppm.[15] These signals clearly indicate a type I conformation and a strong diatropic ring current arising from its 26π-electronic conjugation circuit. The structure of **3** was confirmed by X-ray crystallographic analysis (Figure 1a).[14] All the pyrrole rings are pointing inward, among which the two pyrrole rings at the short side were assigned as being of the amino type and the remaining four pyrrole rings as being of the imino type, based on the $C_\alpha$-N-$C_\alpha$ angles of the pyrrole ring.[15] As expected, the two inward-pointing meso hydrogen atoms do not cause severe steric repulsion, so that **3** takes on a flat shape as characterized by a small mean plane deviation (0.109 Å), which is much smaller than that of **1** (0.536 Å).[7] The harmonic oscillator model of aromaticity (HOMA) value, a measure of bond-length alternation and therefore of aromaticity,[16] has been calculated to be 0.783 Å for **3**, thus indicating it possesses a well delocalized macrocycle. The nucleus-independent chemical shift (NICS) value[17] at the center of the molecule has been calculated to be $\delta = -15.3$ ppm and is in line with its strong aromaticity. The strong aromaticity of **3** is also clearly indicated by its UV/Vis absorption spectrum. The Soret-like transition is observed at 549 nm ($\varepsilon = 380\,000\,\text{M}^{-1}\,\text{cm}^{-1}$) as a distinctly sharper band than that of **1**, and Q-like bands are observed in the low-energy region with a clear vibronic structure as a signature for the aromatic expanded porphyrins (Figure 2). The fluorescence peak of **3** is observed at 1089 nm with a very small Stokes shift (76 $\text{cm}^{-1}$), thus suggesting similar geometries between the $S_1$ and $S_0$ states.[15] Although oxygenation at the free meso positions proceeds gradually in solution, **3** can be stored as a solid under inert conditions for at least several months without any deterioration, hence constituting the first stable meso-free hexaphyrin.

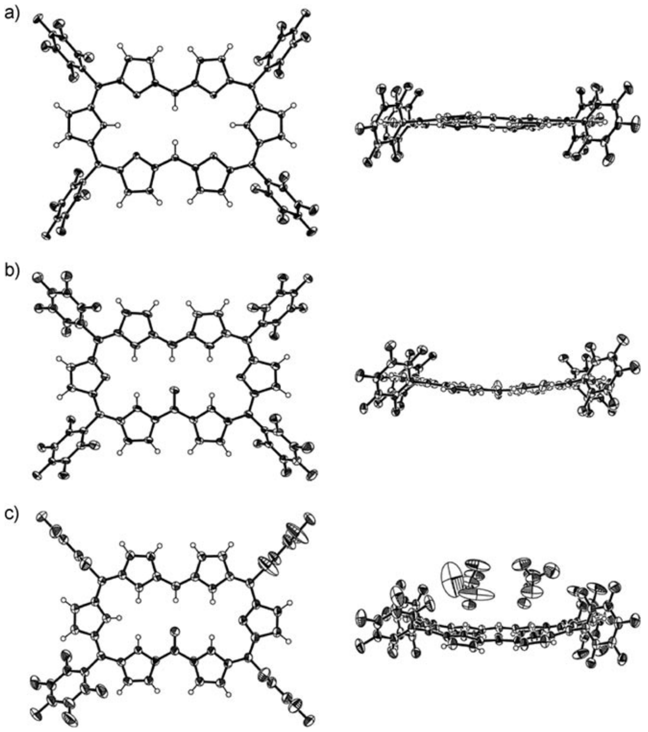


*Figure 1.* X-ray crystal structures of a) **3**, b) **4**, and c) **5**; top views (left) and side views (right). Solvent molecules and TFA counter anions in top view of **5** were omitted for clarity. The thermal ellipsoids are drawn at the 50% probability level.

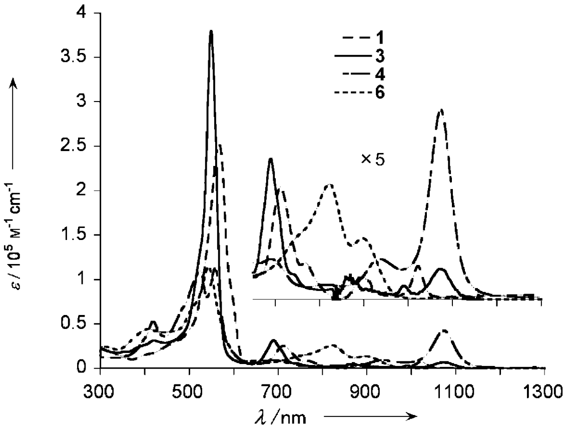


*Figure 2.* UV/Vis absorption spectra of **1**, **3**, **4**, and **6** in $CH_2Cl_2$.

To our surprise, meso-oxygenated hexaphyrin **4**, which was formed as a secondary side product of **3**, was identified as an extremely stable radical species. Also, **4** was quite unreactive to air and water at ambient temperature and thus could be manipulated like usual stable organic compounds. The HR MALDI-TOF mass spectrum of **4** exhibits the parent ion peak at *m*/*z* 1145.1252 and 1145.1266 under positive and negative ionization conditions, respectively. The elemental analysis shows its composition to be C 56.52%, H

1.42 %, and N 7.30 % in agreement with the molecular formula of $C_{54}H_{17}F_{20}N_6O$ (calcd: C 56.61 %, H 1.50 %, N 7.34 %), thus indicating no counterion or solvent molecule to be present in the solid form of **4**. Importantly, its $^1$H NMR spectrum exhibits no signal. The radical character of **4** was confirmed by ESR and magnetic susceptibility measurements. The mean $g$ value was determined to be 2.0089 by ESR spectroscopy in the solid state at room temperature. The temperature-dependent magnetic susceptibility $\chi$ value was measured over the range 2–300 K. In agreement with its monoradical character, **4** exhibits $\chi T = 0.364$ emu K mol$^{-1}$ at 300 K, which is slightly smaller than the expected value of 0.375 emu K mol$^{-1}$.[15] The observed temperature dependence of the $\chi$ value was reproduced by the Curie–Weiss model with the Weiss temperature $\theta = -8.0$ K. A negative $\theta$ value indicates an intermolecular antiferromagnetic interaction.[15] The structure of **4** was determined by X-ray crystallographic analysis (Figure 1 b).[14] While the type I conformation of the macrocycle is preserved, one of the meso positions is actually oxygenated to form an inward-oriented C–O bond with a bond length of 1.281 Å. This bond length is between those of C–O single bonds and C–O double bonds.[18] The mean plane deviation is somewhat large (0.211 Å), although the HOMA value is considerably large (0.744), thus emphasizing the well delocalized nature of π electrons on the macrocycle, and which may be responsible for the unique stable radical character of **4**. There are diverse stable organic radicals reported in the literature,[19] but **4** provides a rare example where the delocalization of the radical over a pyrrolic macrocycle leads to a special stabilization.

Radical **4** was considerably stable under ambient conditions but changed to a diamagnetic species upon dissolution in deuterated trifluoroacetic acid ([D]TFA), as indicated by its sharp $^1$H NMR spectrum. The spectrum displays twelve different signals in the range $\delta = 7.69$–$6.57$ ppm ascribed to the pyrrolic β protons and a singlet at $\delta = 7.99$ ppm corresponding to the inner meso proton, thus indicating a nonsymmetric and nonaromatic structure. Based on these data, the diamagnetic species was assigned to be keto-hexaphyrin dication **5**, whose structure was confirmed by the X-ray analysis of crystals grown from a [D]TFA solution (Figure 1 c and Scheme 3).[14] The C–O bond length is 1.242 Å, which is slightly shorter than that of **4**. The C–C bonds adjacent to the C–O bond are 1.456 and 1.455 Å, respectively, and are longer than those of **4** by about 0.04 Å. Two trifluoroacetate ions are included in the crystal structure and are required for charge balance. The nonsymmetric protonation of **5** is consistent with its $^1$H NMR spectrum. After neutralization of this solution with aqueous $Na_2CO_3$, meso-hydroxy hexaphyrin **6** was obtained, which shows the parent ion peak at $m/z$ 1145.1135 (calcd for $C_{54}H_{17}F_{20}N_6O$ ($[M+H]^+$): 1145.1139). Its $^1$H NMR spectrum in $CD_2Cl_2$ exhibits twelve signals in the range $\delta = 8.95$–$7.30$ ppm ascribed to the β protons, three broad signals of N–H and O–H protons around $\delta = 7.6$, 6.05, and 4.86 ppm, and a singlet corresponding to a meso proton at $\delta = 1.69$ ppm.[14] These data indicate a diatropic ring current for **6**. Alternatively, **6** can be quantitatively prepared by the oxidation of **4** with $MnO_2$.

The electrochemical characteristics of **3** and **4** were studied by cyclic voltammetry (Figure 3). As the oxidation processes were complicated, here we will only focus on the reduction steps. Hexaphyrin **1** undergoes reversible one-electron reduction at −0.52 and −0.85 V versus the ferrocene/ferrocenium ion (Fc/Fc$^+$) couple,[6c] whereas **3** and **4** show three reversible reduction potentials at −0.63, −0.93, −1.65 V, and at −0.62, −1.28, −1.78 V, respectively. Only the radical **4** displays a reversible wave at −0.14 V, which was assigned as the first oxidation step because the absorption spectrum of state (b) is identical with that of **4.** Meanwhile, the absorption spectrum of state (a) exhibits a new feature that includes a Soret-like band at 538 nm and a broad band around 800–900 nm,[15] which has been assigned to a one-electron oxidized species of **4**. In a separate experiment, titration of **6** against TFA was observed to proceed in a stepwise manner to provide monoprotonated and diprotonated species. Comparison of the absorption spectra indicates that the one-electron-oxidized species of **4** corresponds to the monoprotonated **6** and the keto-dication **5** corresponds to the diprotonated **6**. Accordingly, an electrochemical gap between the first oxidation and reduction potential of **4** is only 0.48 eV, in line with the nonbonding character of the frontier orbital.

The singlet excited-state lifetimes of **3** and **4** in toluene were determined by femtosecond transient absorption spectroscopy, and they show a dramatic change in decay times (Figure 4). The

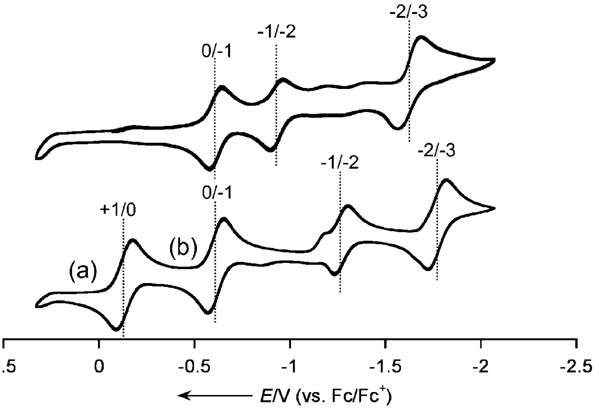
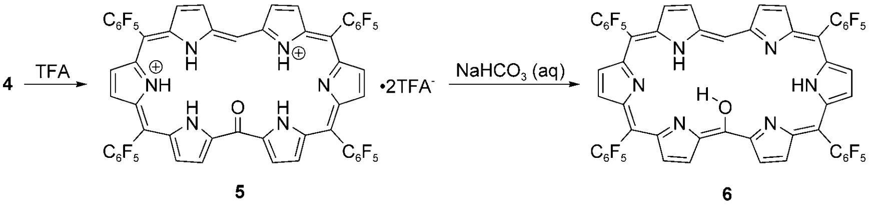


**Figure 3.** Cyclic voltammograms of **3** (top) and **4** (bottom) in $CH_3CN$ containing 0.1 M of $TBAPF_6$. Scan rate 0.1 V s$^{-1}$. TBA = tetra-*n*-butylammonium.



**Scheme 3.** Transformation of **4** into **5** and then **6**.

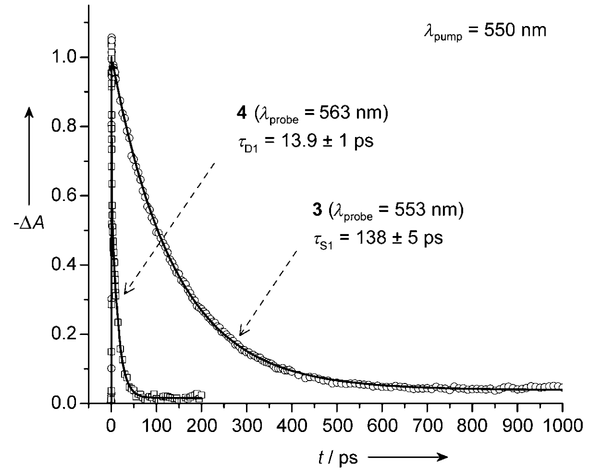


***Figure 4.*** The time profiles showing depopulation of the lowest excited state of **3** and **4** as measured by transient absorption spectroscopy.

observed $S_1$-state lifetime of **3** was found to be 138 ± 5 ps, which is slightly longer than that of **1** (98 ps),[20] this is due to the more planar and rigid geometry of **3** as revealed by the X-ray structure (Figure 1 a). Interestingly, the population of the lowest excited $D_1$ state of **4** decays rapidly with a time constant of 13.9 ± 1 ps, which is about ten times faster than that of **3**. The stable radical character of **4** probably reflects the greater density of states resulting from the presence of unoccupied orbitals—a feature that distinguishes this species from **3**. Thus, the overall excited-state dynamics of **4** is governed by the ultrafast internal conversion processes, which may be accelerated by its radical character. The particularly short excited-state lifetime of **4** is in good agreement with its lack of near-infrared fluorescence.[15] Here, it should be noted that the photophysical properties of the radical species have only been investigated in a limited manner because of their intrinsic instability. All the same, this is the first report on such species of expanded porphyrins.[21]

In summary, we have synthesized **3** as the first example of meso-unsubstituted [26]hexaphyrin(1.1.1.1.1.1) and confirmed its type I spectacles-like conformation with strong aromaticity. In aerated solution, **3** was oxygenated to **4**, which has been identified as an exceptionally stable radical species. These results demonstrate that large structural and electronic changes in [26]hexaphyrin can be caused by the simple removal of two meso-aryl substituents. Also, [26]hexaphyrins offer a nice platform to confer a particular stability to a monoradical probably owing to its delocalized electronic nature. Exploration of expanded porphyrins bearing free meso positions is actively in progress.

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**Keywords:** aromaticity · hexaphyrins · porphyrinoids · radicals

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[14] Crystal data for **3**: $C_{54}H_{16}F_{20}N_6$ ($M_r = 1129$), monoclinic, space group $P2_1/c$ (No. 14), $a = 13.653(5)$, $b = 10.545(3)$, $c = 18.317(7)$ Å, $\beta = 106.974(15)°$, $V = 2522.3(14)$ Å$^3$, $Z = 2$, $\rho_{calcd} = 1.486\ g\,cm^{-3}$, $T = 123(2)$ K, $R_1 = 0.0459$ ($I > 2\sigma(I)$), $R_W = 0.1534$ (all data), GOF = 1.119. In this crystal structure there are disordered solvent molecules, and their contribution to the scattering values have been removed by using the PLATON SQUEEZE program.[22] Crystal data for **4**: $C_{54}H_{17}F_{20}N_6O$-$(C_7H_{16})(C_6H_5CH_3)$ ($M_r = 1374$), orthorhombic, space group $Pbcn$ (No. 60), $a = 10.8232(10)$, $b = 35.604(3)$, $c = 31.278(3)$ Å, $V = 12\,053.0(19)$ Å$^3$, $Z = 8$, $\rho_{calcd} = 1.513\ g\,cm^{-3}$, $T = 90(2)$ K, $R_1 = 0.0783$ ($I > 2\sigma(I)$), $R_W = 0.2492$ (all data), GOF = 1.027. Crystal data for **5**: $C_{63.87}H_{18}F_{34.80}N_6O_{11.16}$ ($M_r = 1709$), triclinic, space group $P\bar{1}$ (No. 2), $a = 12.647(5)$, $b = 14.656(7)$, $c = 19.176(7)$ Å, $\alpha = 69.389(14)$, $\beta = 76.860(15)$, $\gamma = 77.937(17)°$, $V = 3207(2)$ Å$^3$, $Z = 2$, $\rho_{calcd.} = 1.770\ g\,cm^{-3}$, $T = 123(2)$ K, $R_1 = 0.0995$ ($I > 2\sigma(I)$), $R_W = 0.3290$ (all data), GOF = 1.218. Since the crystals of **5** were grown from [D]TFA, N−H protons in the crystal structure were replaced by deuterium atoms. CCDC 693211 (**3**), 693212 (**4**), and 693213 (**5**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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