Photoreduction of *N,N'*-Bridged Porphyrins to 20π Antiaromatic Isophlorins

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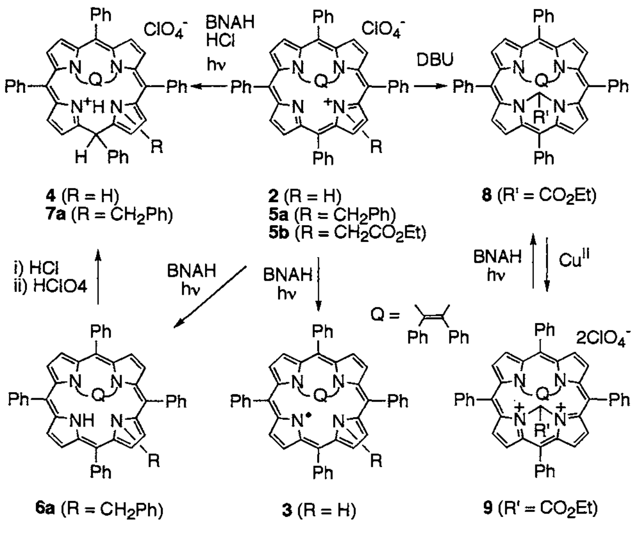
20π Antiaromatic isophlorins of N^{21},N^{22}-bridged N^{23}-alkylporphyrins were prepared through photoreduction with N-benzyl-1,4-dihydronicotinamide or intramolecular nucleophilic alkylation at the N(24)-position. The ring structure of these N^{21},N^{22}-bridged isophlorins is not highly deviated from planarity and their antiaromaticity was indicated by the great paramagnetic ring current effect.

Isophlorin in which hydrogen atoms are added to two nitrogens of porphyrin is regarded as a 20π-annulene.[1] Thus, isophlorin is not so common as its isomers, namely, chlorin, phlorin, and porphodimethenes in which hydrogenation occurs at the porphyrin periphery.[2] $N^{21},N^{22},N^{23},N^{24}$-tetramethyl-2,3,7,8,12,13,17,18-octaethylisophlorin (**1**), the only one example of isophlorin so far known, is highly saddle-shaped and does not show paramagnetic ring current.[3] The relationship between the geometrical feature and the electronic structure has been the focus of studies in the chemistry of 4nπ and (4n+2)π annulenes.[4] The isophlorin - porphyrin redox chemistry is of importance in exploring new redox catalysis of porphyrins and it should be governed by stereochemistry. Thus, more planar isophlorins having effective π-conjugation are of interest. In this paper is described that photoreduction of N^{21},N^{22}-bridged N^{23}-alkylporphyrins with N-benzyl-1,4-dihydronicotinamide (BNAH) led to isophlorins which show great paratropicity.

We have shown earlier that the electron transfer reduction of N^{21},N^{22}-(1,2-diphenyletheno)-bridged tetraphenylporphyrin hydroperchlorate, N^{21},N^{22}-(PhC=CPh)(TPP)HClO$_4$ (**2**), with BNAH or Na$_2$S$_2$O$_4$ under acidic conditions gives a monoprotonated 15*H*-phlorin **4** exclusively.[5] This reaction is induced by visible light irradiation and a porphyrin radical **3** is formed in the absence of acid through the photo-induced single electron transfer process (Scheme 1).[6] The X-ray crystallographic structure of **2** indicates that the N^{21},N^{22}-bridge forces the pyrrole rings to tilt from the 4N mean plane by 22.9°, 20.6°, -10.6°, and -19.9°.[7] This non-planar porphyrin structure should be responsible for the unusual reduction behavior of **2**. Introduction of the third N-alkyl group would lead to further deformation of the π-conjugated porphyrin core and influence on the reactivity. When a THF solution of N^{21},N^{22}-(1,2-diphenyletheno)-N^{23}-(benzyl)tetraphenylporphyrin perchlorates (**5a**) and BNAH (3 equiv) was irradiated with a 300-W xenon lamp at 0 °C under argon, the color of the solution changed from green to orange in 1 min. Since the product is soluble and fairly stable in non-polar hydrocarbon solvents, a hexane extract from the reaction mixture gave a practically pure isophlorin **6a**[8] in a 83% yield. A signal due to the pyrrole NH proton at 23.62 ppm disappeared by adding D$_2$O in the ^{1}H NMR spectrum of **6a**. The inner-ring N-methylene protons and the outer-ring ß-pyrrole protons of **6a** show much greater paramagnetic ring current effects than in the case of **1**, whereas the corresponding porphyrins, **5a** and dicationic $N^{21},N^{22},N^{23},N^{24}$-tetramethyl-2,3,7,8,12,13,17,18-octaethylporphyrin[9] (**1'**), show similar diamagnetic ring current effects as summarized in Table 1.



Scheme 1.

Table 1. The ^{1}H NMR chemical shifts (δ) of isophlorins (**1**, **6a**, **8**) and the corresponding porphyrins (**1'**, **5a**, **9**).

	inner-ring protons			outer-ring protons	
	N-CH$_3$	N-CH$_2$-^{a}	N-CH-N	*meso*-H	ß-pyrrole-H^a
1^b	3.91			5.05	
6a		13.92			3.81
8			23.34		3.26
1'^{c}	-4.59			9.94	
5a		-4.39			8.65
9			-5.79		9.16

^{a} An averaged shift. ^{b}Taken from reference 3. ^{c} Taken from reference 9.

The photo-induced single electron transfer from BNAH to **5a** would generate a porphyrin π-radical similar to **3**. The AM1-UHF semi-empirical MO calculations[10] of model π-radicals **3'** (R = H) and **3"** (R = Me) of N^{21},N^{22}-(MeC=CMe)-N^{23}-R-(porphyrin) showed that the frontier electron density based on the HOMO (α-spin) and LUMO (ß-spin) is the greatest at C(19) and N(24) for **3'** and at N(24) and C(16) for **3"** (see Figure 1).[11] Since reactions at the quaternary carbons, C(19) and C(16), should not be favored due to the steric factor, a hydrogen atom would be transferred from BNAH to the N(24) position of N^{21},N^{22}-bridged porphyrin π-radicals. The isophlorin **6a** was converted into a monoprotonated N^{21},N^{22}-bridged N^{23}-benzyl-15*H*-phlorin **7a** in a 88% yield by adding HCl. **7a** was directly obtained in a 66% yield by the photoreduction of **5a** with BNAH in the presence of HCl. Thus, the photoreduction of **2** and **5a** to **4** and **7a**, respectively, under acidic conditions would occur via intermediacy of isophlorins.

Since the porphyrin plane is almost planar in the optimized structure of **3'** as shown in Figure 1, a radical center is effectively delocalized. This would not be the case with **3"** due to the cant of the N(23)-substituted pyrrole ring. In contrast, the model isophlorins **6'** and **6"** show apparently the same degree of deviation from planarity. Thus, the N(23)-substituent makes the isophlorin **6"** much more stable than the porphyrin π-radical **3"** ($\Delta\Delta H$ = 14.5 Kcal/mol) and the phlorin **7"** ($\Delta\Delta H$ = 8.4 Kcal/mol), whereas the relative stabilities of **6'** to **3'** and **7'** are 6.6 Kcal/mol and 4.5 Kcal/mol, respectively. This calculation is qualitatively consistent with the fact that the N(23)-unsubstituted porphyrin **2** is readily reduced to the stable porphyrin π-radical **3** while the N(23)-alkylated porphyrin **5a** is further reduced to isophlorin **6a**.

When N^{21},N^{22}-(PhC=CPh)-N^{23}-(CH_2CO_2Et)(TPP)ClO_4 (**5b**) was treated with 1,8-diazabicyclo-[5,4,0]-7-undecene (DBU) in THF, the isophlorin **8**[8] was obtained in a 93% yield. The C_s-symmetric molecular structure of **8** proved by the ^1H NMR spectrum is consistent with the formation of a N^{23},N^{24}-(methano)-bridge through the intramolecular N(24)-attack of the enolate anion formed by the deprotonation from the N-methylene position of **5b**. The chemical shifts of the methine proton at the N^{23},N^{24}-(methano)-bridge (δ 23.34) and the pyrrole ß-protons (δ 3.54 - 2.63) clearly indicate the antiaromatic character of **8**. These chemical shifts are in contrast to those observed for the dicationic porphyrin **9** which was prepared in a 93% yield by oxidation of **8** with $Cu(ClO_4)_2$ (See Table 1). The cyclic voltammograms of **8** and **9** are identical and show two reversible redox couples at $E_{1/2}$ = +0.12 and -0.17 V vs. Ag/AgCl in MeCN containing Bu_4NClO_4 (0.1 mol dm^{-3}).

We had already reported that nucleophilic attack of hydride and carbanions on **2** occurs exclusively at the 5-*meso* position to give 5*H*-phlorins.[12] In contrast, isophlorins have now been found to occur via single electron transfer mechanism or by the intramolecular nucleophilic reaction which is forced to attack on the N(24)-position. Since the N^{21},N^{22}-bridge fixes the macroring structure, **6a** and **8** seem to retain higher order of planarity of the π-conjugated system than **1**.[3] This accounts for the great difference in the ^1H NMR paramagnetic ring currents between **6a** (or **8**) and **1**.

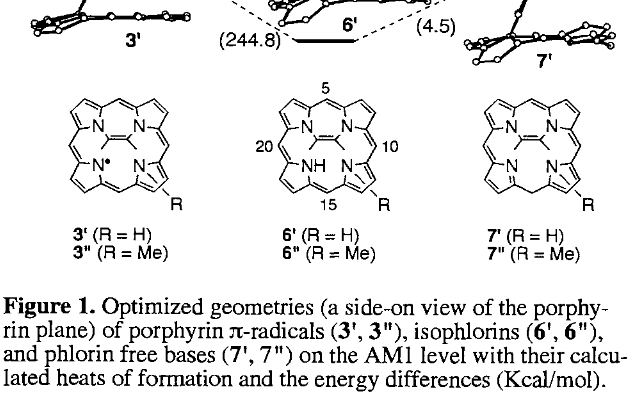


Figure 1. Optimized geometries (a side-on view of the porphyrin plane) of porphyrin π-radicals (**3'**, **3"**), isophlorins (**6'**, **6"**), and phlorin free bases (**7'**, **7"**) on the AM1 level with their calculated heats of formation and the energy differences (Kcal/mol).

References and Notes

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8 **6a**: ^1H NMR (400 MHz, $CDCl_3$, 20 °C, TMS): δ 23.62 (s, 1H, NH), 14.24, 13.60 (d x 2, 1H x 2, J = 14.8 Hz, N-CH_2), 12.19, 10.83 (br x 2, 2H x 2, bridge-phenyl-*o*-H), 8.18, 8.09 (br x 2, 2H x 2, bridge-phenyl-*m*-H), 7.93, 7.69 (t x 2, 1H x 2, bridge-phenyl-*p*-H), 9.42 (d, 2H, N-benzyl-*o*-H), 7.85 (t, 2H, N-benzyl-*m*-H), 7.73 (t, 1H, N-benzyl-*p*-H), 7.04, 6.87, 6.86, 6.66 (t x 4, 1H x 4, *meso*-phenyl-*p*-H), 7.11, 6.85, 6.83, 6.50 (t x 4, 2H x 4, *meso*-phenyl-*m*-H), 6.78, 6.61, 5.95, 5.40 (d x 4, 2H x 4, *meso*-phenyl-*o*-H), 4.32, 4.28, 3.93. 3.92, 3.77, 3.19 (d x 6, 1H x 6, pyrrole-ß-H), 3.81, 3.28 (dd x 2, 1H x 2, J = 4.4, 2.0 Hz, pyrrole-ß-H); UV/Vis (CH_2Cl_2): λ_{max}(log ε) 364 (4.63), 414 (4.77), 468 (sh, 4.13), 521 (sh, 3.80) nm; TOFMS (dithranol): m/z 882.49 (theory for the average mass: 883.12); Anal. Found: C, 79.87; H, 5.54; N, 5.36 %. Calcd for $C_{65}H_{46}N_4\cdot(5.5)H_2O$: C, 79.48; H, 5.85; N, 5.71%. **8**: ^1H NMR (C_6D_6): δ 23.34 (s, 1H, N^{23},N^{24}-CHCO), 12.05 (d, 4H, bridge-phenyl-*o*-H), 8.29 (t, 4H, bridge-phenyl-*m*-H), 7.81 (t, 2H, bridge-phenyl-*p*-H), 6.7-6.4 (m, 20H, *meso*-phenyl-H), 6.23 (q, 2H, OCH_2), 2.36 (t, 3H, $OCCH_3$), 3.54, 2.63 (d x 2, 2H x 2, pyrrole-ß-H), 3.44 (s, 4H, pyrrole-ß-H); UV/Vis (C_6H_6): λ_{max}(log ε) 363 (4.71), 408 (4.80), 452 (sh, 4.08), 481 (sh, 4.04), 519 (sh, 3.90) nm; TOFMS (dithranol): m/z 877.58 (theory for the average mass of **8**: 877.07), 792.59 (**8** - $CHCO_2Et$), 804.23 (**8** - CO_2Et), 894.76 (**8** + O), 964.75 (**8** + $CHCO_2Et$), 980.81(**8** + $CHCO_2Et$ + O), 1050.98 (**8** + $2CHCO_2Et$), 1066.73 (**8** + $2CHCO_2Et$ + O); Anal. Found: C, 78.61; H, 5.63; N, 6.10%. Calcd for $C_{62}H_{44}N_4O_2\cdot4H_2O$: C, 78.46; H, 5.52; N, 5.90%.
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11 Atoms with frontier electron density greater than 0.1; **3'**: C(19) 0.255, N(24) 0.244, C(15) 0.168, C(1) 0.147, C(17) 0.138, C(20) 0.134, C(11) 0.113, C(5) 0.106; **3"**: N(24) 0.252, C(16) 0.248, C(15) 0.202, C(14) 0.195, C(20) 0.140, C(18) 0.126, C(10) 0.125.
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