

2 (curve C) $D = 4 \times 10^{-10}$ cm²/s. This corresponds, according to the Dahms–Ruff equation,^{9,10} to the rate constant of the electron exchange of ca. 2×10^4 M⁻¹ s⁻¹. The latter is two orders of magnitude smaller than a value obtained for a homogeneous solution.¹¹

$$D = \frac{\pi}{4} k_{ex} \delta^2 C \quad (1)$$

The results presented here are the first measurements of the lateral electron transport directly at the water/air interface under controlled surface pressure. It is easy to envision the relevance of these two-dimensional electrochemical experiments to the studies of the dynamics of lateral transport in organized monolayers and, in general, to the investigations of transport processes in biological membrane systems. Perhaps more importantly, the technique described here opens a possibility to investigate electron-transfer kinetics in well organized monolayer assemblies where the transfer of an electron involves molecules at known distances and in well defined and controllable orientations.

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Actinide Bis(porphyrinate) π -Radical Cations and Dications, Including the X-ray Crystal Structure of [(TPP)₂Th][SbCl₆]

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The chemistry of actinide porphyrin complexes remains in large part undeveloped.^{1–3} We report here the first synthesis, isolation, and detailed characterization of several actinide bis-porphyrin sandwich complexes, including the neutral, π -radical monocation, and π -radical dication complexes,⁴ [(TPP)₂M]ⁿ⁺, where M = Th(IV) or U(IV) and $n = 0, 1, \text{ or } 2$. In addition, the X-ray crystal structures of both the neutral Th complex and its oxidized π -radical cation, [(TPP)₂Th][SbCl₆], have been solved. These complexes are among the very first π -radical cations where close interaction between two porphyrins occurs. Moreover, these complexes belong to an unusual class of actinide complexes where redox processes can occur in near proximity to the f-element. In addition, the involvement of porphyrin π -radical cations is well established in a variety of biological processes, including the storage of oxidizing equivalents in the hydroperoxidases,⁵ the oxidation of hydrocarbons by cytochrome P450,⁶ and the generation of chemical potential in the photosynthetic reaction center.^{7,8}

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(4) Abbreviations used: TPP = 5,10,15,20-tetraphenylporphyrinate, OEP = octaethylporphyrinate, thf = tetrahydrofuran, acac = 2,4-pentanedionate.

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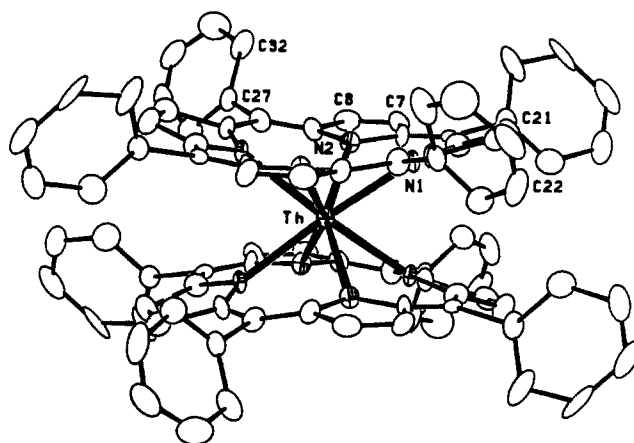


Figure 1. Molecular structure of the [(TPP)₂Th]⁺ cation. The Th–N average bond distance is 2.52 (2) Å; the distance between mean porphyrin planes is 2.89 Å with a twist angle of 31°.

We have recently described the preparation of the “sandwich” compound (TPP)₂U from U(NEt₂)₄ and H₂TPP in toluene¹ and find that the thorium analogue,⁹ (TPP)₂Th, may be obtained in a similar manner from Th(NEt₂)₄.¹⁰ Cyclic voltammetry experiments in CHCl₃ reveal that both (TPP)₂M compounds undergo two chemically reversible oxidation processes near 580 and 990 mV versus SCE. The similarities of the cyclic voltammograms for the thorium and uranium complexes strongly suggest that both oxidations are porphyrin based.¹¹

The oxidized [(TPP)₂M]⁺ species may be prepared and isolated by treatment of (TPP)₂M with phenoxathiinium hexachloroantimonate,¹² (C₁₂H₈SO)SbCl₆, in CH₂Cl₂. Crystallization from CH₂Cl₂/toluene or CH₂Cl₂/pentane yields [(TPP)₂Th][SbCl₆]¹³ and [(TPP)₂U][SbCl₆]¹⁴ as blue-violet crystalline solids. The Soret bands of these compounds appear at 396 and 392 nm, respectively, and are shifted to higher energy with respect to the neutral precursors (402 and 404 nm). The π -radical cation nature of [(TPP)₂M][SbCl₆] is supported by the presence of new bands in the IR spectra¹⁵ of the oxidized species at 1297 and 1264 cm⁻¹ for M = Th and at 1305, 1274, and 1266 cm⁻¹ for M = U. The [(TPP)₂M][SbCl₆] complexes are EPR active in frozen CH₂Cl₂ glasses at 77 K and exhibit signals at $g = 1.9985$ (line width 4.7 G) and $g = 1.9975$ (line width 5.9 G) for M = Th and U, respectively. In each case there is no observed anisotropy in the g -tensor under these experimental conditions.

[(TPP)₂Th][SbCl₆] is NMR silent in CH₂Cl₂, but [(TPP)₂U][SbCl₆] is not (although the lines are broadened), which

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(14) Anal. Calcd for [(TPP)₂U][SbCl₆]^{1/4}·2C₇H₈·2CH₂Cl₂: C, 58.0; H, 3.7; N, 5.2; U, 11.1; Sb, 5.7; Cl, 16.5. Found: C, 58.7; H, 3.6; N, 4.9; U, 10.9; Sb, 5.7; Cl, 17.1. ¹H NMR (CD₂Cl₂, –60 °C) δ 9.00 (d, $J_{HH} = 6.2$ Hz, o-H), 8.85 (s, fwhm = 18 Hz, m-H), 5.80 (t, $J_{HH} = 7.0$ Hz, p-H), 3.82 (s, fwhm = 27 Hz, m-H), 0.47 (s, fwhm = 30 Hz, o-H), –3.48 (s, fwhm = 29 Hz, pyrrole-H).

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suggests that there is some interaction between the unpaired electrons of the f^2 U(IV) center and the single unpaired electron of the porphyrin radical. [(TPP)₂U][SbCl₆] in CH₂Cl₂ at -60 °C exhibits six broadened ¹H NMR signals;¹⁴ the pattern is similar to that of the unoxidized starting precursor¹ (TPP)₂U except that the pyrrole signal is shifted significantly upfield. In the diamagnetic limit (infinite temperature), the five phenyl proton signals of [(TPP)₂U][SbCl₆] collapse to the normal δ 6 to 9 ppm region while the pyrrole signal extrapolates instead to δ -14 ppm. This behavior indicates that the porphyrin π-radical cation possesses high unpaired spin density near the pyrrole protons.

The [(TPP)₂M][SbCl₆] complexes in CH₂Cl₂ exhibit very broad, intense ($\epsilon \sim 10^3$ cm⁻¹ M⁻¹), featureless absorptions in the near-IR region at 1480 nm (fwhm 300 nm) and 1270 nm (fwhm 140 nm) for M = Th and U, respectively. These bands were first assigned in the analogous Ce(IV) complex to interporphyrin charge-transfer transitions;¹¹ recent resonance Raman data,¹⁶ however, show that the electron hole is delocalized over both porphyrins, which implies that this interporphyrin transition involves little charge transfer. Of interest in this context is the near-infrared transition observed in the special pair of bacteriochlorophyll-b found in the bacterial reaction center protein of *Rhodospseudomonas viridis*.^{7,8} The special pair radical cation dimer, (BChl)₂⁺, has an interplanar spacing of ≈ 3 Å and a characteristic intramolecular transition at 1300 nm.⁸ For comparison, [(TPP)₂Th][SbCl₆] has an interplanar spacing of 2.89 Å (see below) and an absorption at 1480 nm. Similar comparisons have previously been made for the lanthanide bis(porphyrinate) cations.^{11a,b}

(TPP)₂Th and [(TPP)₂Th][SbCl₆] have been structurally characterized by X-ray crystallography (Figure 1).¹⁷ While the (TPP)₂Th units in both the neutral species and the cation are generally similar, the Th–N bond distances, 2.55 (1) versus 2.52 (2) Å, and the displacement of the thorium atom from the mean N₄ plane of the porphyrinate core, 1.47 versus 1.45 Å, are slightly smaller in the cation. The structural parameters are similar to those of the half-sandwich complexes^{1,2} (TPP)UCl₂(thf) and (OEP)Th(acac)₂: the Th–N bond distances of the latter average 2.50 Å and the Th out-of-plane distance, Th–N₄, is 1.43 Å. The porphyrinate N₄ planes of [(TPP)₂Th][SbCl₆] are 2.89 Å apart with a twist angle of $\sim 30^\circ$, resulting in a distorted square antiprismatic geometry about thorium; this may be compared to the 2.75 Å interplanar spacing and a twist angle of 42° between the porphyrinate rings in the neutral species (OEP)₂Ce.^{11,18} The difference in interplanar spacing between the Th and Ce complexes reflects the smaller ionic radius¹⁹ of Ce^{IV} versus Th^{IV} and possibly the reduced steric demand of OEP versus TPP. Due to the high point symmetry of the crystallographic site (222), the two porphyrinate rings in [(TPP)₂Th][SbCl₆] are crystallographically identical, and no variations of the C–C or C–N bond lengths are apparent. We note that the porphyrinate rings in [(TPP)₂Th][SbCl₆] are close enough together to allow significant direct overlap of the two π-systems. Consistent with this, the NMR spectra suggest complete delocalization of the unpaired electron over both porphyrinate rings.

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(17) Crystal data for (TPP)₂Th·C₇H₈ ($T = 25$ °C): space group $I2/a$, $a = 15.377$ (4) Å, $b = 31.119$ (6) Å, $c = 15.378$ (3) Å, $\beta = 90.59$ (2)°, $V = 7358$ (5) Å³, $Z = 4$, $R_F = 5.4\%$, $R_{wF} = 6.9\%$ on 333 variables and 3646 unique data with $I > 2.58\sigma(I)$. Crystal data for [(TPP)₂Th][SbCl₆]·2C₇H₈·CH₂Cl₂ ($T = 25$ °C): space group $P4/nnc$, with $a = 19.104$ (3) Å, $c = 26.335$ (3) Å, $V = 9612$ (4) Å³, $Z = 4$, $R_F = 6.5\%$, $R_{wF} = 10.6\%$ on 248 variables and 1894 unique data with $I > 2.58\sigma(I)$. All non-hydrogen atoms except those of the solvate molecules were refined with independent anisotropic thermal parameters. The refinement of [(TPP)₂Th][SbCl₆] was complicated by the presence of disordered solvate molecules; however, the structural parameters of the [(TPP)₂Th] cation are well defined.

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Preliminary spectroscopic characterization of the bis(porphyrin) dications [(TPP)₂M][SbCl₆]₂ (M = Th, U) has also been completed.²⁰ These compounds are prepared in the same fashion as the monocations but with the use of 2 equiv of (C₁₂H₈SO)SbCl₆. The complexes possess intense near-infrared bands at 1080 nm (M = Th) and 990 nm (M = U), and spectroscopic data are consistent with a bis[porphyrin π-radical cation] formulation. Further characterization of the magnetic coupling present in these bis(porphyrinato)metal systems is underway.

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Supplementary Material Available: Tables of atomic coordinates, thermal parameters, and complete bond distances and angles for (TPP)₂Th and [(TPP)₂Th][SbCl₆] (8 pages); tables of observed and calculated structure factors (23 pages). Ordering information is given on any current masthead page.

(20) Anal. Calcd for [(TPP)₂Th][SbCl₆]₂·2CH₂Cl₂: C, 47.1; H, 2.6; N, 4.9; Th, 10.1; Sb, 10.6; Cl, 24.7. Found: C, 47.1; H, 2.7; N, 4.8; Th, 9.6; Sb, 10.1; Cl, 25.0. UV-vis near infrared (CH₃CN, 25 °C) 399 (Soret), 480, 549, 608, 1080 nm; ¹H NMR (CD₃CN, 18 °C) δ 7.55, 7.47, 7.37 (m, $I_{rel} = 3$), 6.98 (s, fwhm = 30 Hz, $I_{rel} = 1$), 6.30 (s, fwhm = 28 Hz, $I_{rel} = 1$); IR (Nujol) 1285, 1267 cm⁻¹. Anal. Calcd for [(TPP)₂U][SbCl₆]₂·2CH₂Cl₂: C, 47.0; H, 2.6; N, 4.9; U, 10.3; Sb, 10.6; Cl, 24.6. Found: C, 46.5; H, 2.5; N, 4.7; U, 10.2; Sb, 10.9; Cl, 24.0. UV-vis near infrared (CH₃CN, 25 °C) 396 (Soret), 990 nm; ¹H NMR (CD₃CN, 20 °C) δ 8.40 (s, fwhm = 19 Hz, o-H), 7.56 (s, fwhm = 18 Hz, m-H), 5.95 (s, fwhm = 14 Hz, p-H), 4.88 (s, fwhm = 32 Hz, m-H), 4.15 (s, fwhm = 93 Hz, pyrrole-H), -1.73 (s, fwhm = 23 Hz, o-H); IR (Nujol) 1295, 1287, 1269 cm⁻¹.

Theory of Vibrational Circular Dichroism: *trans*-2,3-Dideuteriooxirane

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We have recently developed^{1–3} and implemented^{3–10} an a priori theory of vibrational rotational strengths and vibrational circular dichroism (VCD) spectra. To date, comparisons of this theory with experimental VCD spectra have been limited by the paucity

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