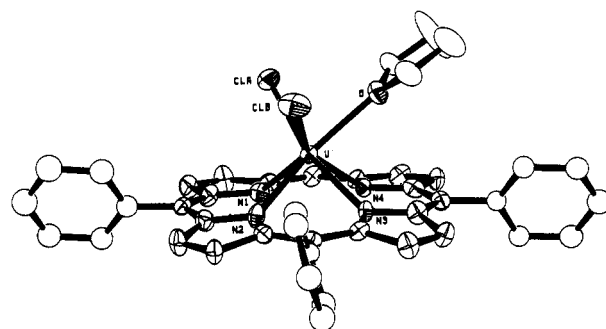


## Communications

## Synthesis and Characterization of Actinide Mono- and Bis(porphyrin) Complexes

Sir:

There has been increasing interest in lanthanide porphyrin and phthalocyanine complexes<sup>1</sup> as paramagnetic NMR shift reagents,<sup>2</sup> electrochromic flat-panel displays,<sup>3</sup> and potential luminescent probes of heme proteins.<sup>4</sup> In contrast, the only actinide porphyrin<sup>5</sup> complexes that have been described are Th(TPP)(acac)<sub>2</sub>,<sup>6</sup> Th(OEP)Cl<sub>2</sub>L<sub>2</sub>,<sup>7</sup> and U(OEP)Cl<sub>2</sub>L<sub>2</sub>,<sup>7</sup> while the only reported phthalocyanine<sup>5</sup> complexes are Th(pc)<sub>2</sub>,<sup>8</sup> U(pc)<sub>2</sub>,<sup>9</sup> and the "superphthalocyanine" UO<sub>2</sub>(N<sub>2</sub>C<sub>3</sub>H<sub>4</sub>)<sub>5</sub>.<sup>10</sup> No structural data on actinide porphyrin complexes are available, and only the two uranium phthalocyanine derivatives have been crystallographically



**Figure 1.** Molecular structure of U(TPP)Cl<sub>2</sub>(thf) (rear phenyl ring omitted for clarity). Selected distances (Å) and angles (deg): U-N1 = 2.40 (1), U-N2 = 2.40 (1), U-N3 = 2.43 (1), U-N4 = 2.41 (1), U-C1A = 2.624 (4), U-C1B = 2.642 (4), U-O = 2.496 (9); N1-U-N2 = 73.1 (3), N2-U-N3 = 74.0 (3), N3-U-N4 = 72.7 (3), N4-U-N1 = 73.6 (3), N1-U-N3 = 115.2 (3), N2-U-N4 = 115.2 (3), C1A-U-C1B = 89.1 (1), C1A-U-O = 77.7 (2), C1B-U-O = 79.7 (2).

characterized. We now report the synthesis, characterization, and first X-ray crystal structure of an actinide porphyrin complex, U(TPP)Cl<sub>2</sub>(thf). In addition, we report the synthesis and full spectroscopic characterization of the "sandwich" compound U(TPP)<sub>2</sub>.

5,10,15,20-Tetraphenylporphyrin, H<sub>2</sub>TPP, was treated with 5 equiv of anhydrous UCl<sub>4</sub> and excess 2,6-lutidine in benzonitrile at 150 °C, while argon was slowly passed over the solution to remove HCl. Heating was continued for 4 h until the Soret band of H<sub>2</sub>TPP near 418 nm had disappeared. Removal of the solvent under vacuum and extraction of the residue with a 1:1 mixture of CH<sub>2</sub>Cl<sub>2</sub>/CH<sub>3</sub>CN followed by concentration and cooling to -30 °C gave large red crystals of a nonstoichiometric acetonitrile solvate, U(TPP)Cl<sub>2</sub>·xCH<sub>3</sub>CN. Solvate-free U(TPP)Cl<sub>2</sub> is readily obtained by washing with pentane followed by exposure to vacuum.

U(TPP)Cl<sub>2</sub> is only sparingly soluble in neat CH<sub>2</sub>Cl<sub>2</sub> or neat CH<sub>3</sub>CN but readily dissolves in a 1:1 mixture of these two solvents; this behavior is probably due to the formation of an acetonitrile adduct that is insoluble in that medium but soluble in dichloromethane. The electronic spectrum of U(TPP)Cl<sub>2</sub> in CH<sub>2</sub>Cl<sub>2</sub> shows a Soret band at 427 nm and two less intense Q bands at 553 and 590 nm (supplementary material). The field-desorption mass spectrum shows a strong parent envelope at *m/z* = 920 for U(TPP)Cl<sub>2</sub>. A 300-MHz <sup>1</sup>H NMR spectrum at 25 °C in CD<sub>2</sub>Cl<sub>2</sub>/CD<sub>3</sub>CN shows that rotation of the phenyl groups is slow on this time scale, since five different proton environments are observed.<sup>11</sup> One of the ortho protons is shifted significantly upfield

- (1) (a) Kasuga, K.; Tsutsui, M. *Coord. Chem. Rev.* **1980**, *32*, 67. (b) Buchler, J. W.; Kapellmann, H.-G.; Knoff, M.; Lay, K.-L.; Pfeifer, S. *Z. Naturforsch. B. Anorg. Chem., Org. Chem.* **1983**, *38B*, 1339. (c) Buchler, J. W.; Knoff, M. *Optical Properties and Structure of Tetrapyrroles*; Blauer, G., Sund, H., Eds.; de Gruyter: West Berlin, 1985; p 91. (d) Buchler, J. W.; Elsässer, K.; Kihn-Botulinski, M.; Scharbert, B. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 286. (e) Srivastava, T. S. *Bioinorg. Chem.* **1978**, *8*, 61. (f) Kirin, I. S.; Moskalev, P. N.; Makashev, Y. A. *Russ. J. Inorg. Chem. (Engl. Transl.)* **1965**, *10*, 1065. (g) Kirin, I. S.; Moskalev, P. N.; Makashev, Y. A. *Russ. J. Inorg. Chem. (Engl. Transl.)* **1967**, *12*, 369. (h) Kirin, I. S.; Moskalev, P. N.; Ivannikova, N. V. *Russ. J. Inorg. Chem. (Engl. Transl.)* **1967**, *12*, 497. (i) Mackay, A. G.; Boas, J. F.; Troup, G. J. *Aust. J. Chem.* **1974**, *27*, 955.
- (2) (a) Wong, C.-P.; Venteicher, R. F.; Horrocks, W. D. *J. Am. Chem. Soc.* **1974**, *96*, 7149. (b) Horrocks, W. D.; Wong, C.-P. *J. Am. Chem. Soc.* **1976**, *98*, 7157. (c) Horrocks, W. D.; Hove, E. G. *J. Am. Chem. Soc.* **1978**, *100*, 4386.
- (3) (a) Moskalev, P. N.; Kirin, I. S. *Russ. J. Phys. Chem. (Engl. Transl.)* **1972**, *46*, 1019. (b) Moskalev, P. N.; Shapkin, G. N.; Darovskikh, A. N. *Russ. J. Phys. Chem. (Engl. Transl.)* **1979**, *24*, 188. (c) Corker, G. A.; Grant, B.; Clecak, N. J. *J. Electrochem. Soc.* **1979**, *126*, 1339. (d) Walton, D.; Ely, B.; Elliott, G. *J. Electrochem. Soc.* **1981**, *128*, 2479. (e) Chang, A. T.; Marchon, J. C. *Inorg. Chim. Acta* **1981**, *53*, L241.
- (4) (a) Martarano, L. A.; Wong, C.-P.; Horrocks, W. D.; Goncalves, A. M. P. *J. Chem. Phys.* **1976**, *80*, 2389. (b) Gouterman, M.; Schumaker, C. D.; Srivastava, T. S.; Yonetani, T. *Chem. Phys. Lett.* **1976**, *40*, 456. (c) Tsvirko, M. P.; Stehlmakh, G. F.; Pyatosin, V. E.; Solovyov, K. N.; Kachura, T. F. *Chem. Phys. Lett.* **1980**, *73*, 80. (d) Horrocks, W. D.; Venteicher, R. F.; Spilburg, C. A.; Vallee, B. L. *Biochem. Biophys. Res. Commun.* **1975**, *64*, 317.
- (5) Abbreviations used: TPP = 5,10,15,20-tetraphenylporphyrinato, OEP = octaethylporphyrinato, pc = phthalocyaninato, acac = 2,4-pentanedionato, thf = tetrahydrofuran.
- (6) Wong, C.-P.; Horrocks, W. D. *Tetrahedron Lett.* **1975**, *31*, 2637.
- (7) Dormond, A.; Belkalem, B.; Guillard, R. *Polyhedron* **1984**, *1*, 107.
- (8) Lux, F.; Dempf, D.; Graw, D. *Angew. Chem., Int. Ed. Engl.* **1968**, *7*, 819.
- (9) (a) Gieren, A.; Hoppe, W. *J. Chem. Soc., Chem. Commun.* **1971**, 413. (b) Kirin, I. S.; Kolyadin, A. B.; Lychev, A. A. *J. Struct. Chem. (Engl. Transl.)* **1974**, *15*, 415.
- (10) (a) Bloor, J. E.; Schlabit, J.; Walden, C. C.; Demerdache, A. *Can. J. Chem.* **1964**, *42*, 2201. (b) Day, V. W.; Marks, T. J.; Wachter, W. A. *J. Am. Chem. Soc.* **1975**, *97*, 4519.

- (11) Anal. Calcd for U(TPP)Cl<sub>2</sub>: C, 57.3; H, 3.06; N, 6.08; Cl, 7.69; U, 25.8. Found: C, 57.3; H, 3.21; N, 5.88; Cl, 7.74; U, 26.0. Mp: >250 °C. <sup>1</sup>H NMR (CD<sub>3</sub>CN/CD<sub>2</sub>Cl<sub>2</sub>, 25 °C): δ 8.29 (s, fwhm = 21 Hz, *o*-H), 7.67 (s, fwhm = 16 Hz, pyrrole H), 7.16 (s, fwhm = 21 Hz, *m*-H), 6.41 (t, *J*<sub>HH</sub> = 7.2 Hz, *p*-H), 5.51 (s, fwhm = 23 Hz, *m*-H), 0.52 (s, fwhm = 27 Hz, *o*-H).

to  $\delta$  0.52, evidently due to its proximity to the paramagnetic ( $f^2$ ) uranium(IV) center.

Recrystallization of  $U(TPP)Cl_2$  from tetrahydrofuran/1,2-dichloroethane/heptane gives X-ray-diffraction-quality crystals of the tetrahydrofuran adduct  $U(TPP)Cl_2(thf)$ .<sup>12</sup> A drawing of the molecular structure<sup>13</sup> along with selected bond distances and angles is given in Figure 1. The coordination geometry about the uranium center is best described as a 4:3 piano stool with the porphyrin occupying the square base. The U–N distance of 2.41 (1) Å is comparable to the U–N(sp<sup>2</sup>) contacts of 2.43 Å in  $U(pc)_2$ <sup>9</sup> and 2.48 Å in  $U(bpy)_4$ <sup>14</sup> but is significantly longer than typical U–N distances of 2.20–2.25 Å in uranium amido (NR<sub>2</sub>) complexes.<sup>15</sup> The U–Cl and U–O contacts of 2.63 (1) and 2.50 (1) Å are similar to distances observed in other uranium(IV) complexes.<sup>16</sup> The most interesting features of the structure are that the uranium atom is 1.29 Å out of the porphyrin N<sub>4</sub> plane and the porphyrin ring itself is slightly "saucer-shaped", which may improve bonding between the nitrogen atoms and the uranium center. Such large displacements of the metal atom out of the ring plane and similar saucer- or domelike conformations of the macrocycle have been noted in the structure of  $U(pc)_2$ <sup>9</sup> and several lanthanide phthalocyanine<sup>17</sup> and porphyrin<sup>18</sup> complexes.

- (12) Anal. Calcd for  $U(TPP)Cl_2(thf) \cdot \frac{1}{2}C_2H_4Cl_2$ : C, 56.4; H, 3.67; N, 5.37; Cl, 10.2; U, 22.8. Found: C, 56.7; H, 3.69; N, 5.30; Cl, 10.2; U, 23.1. Mp: >250 °C. <sup>1</sup>H NMR (C<sub>2</sub>D<sub>6</sub>O, 25 °C):  $\delta$  8.55 (s, fwhm = 45 Hz, o-H), 7.31 (s, fwhm = 5 Hz, pyrrole H), 7.23 (s, fwhm = 45 Hz, m-H), 6.34 (t,  $J_{HH} = 7.2$  Hz, p-H), 5.42 (s, fwhm = 48 Hz, m-H), 3.80 (s, C<sub>2</sub>H<sub>4</sub>Cl<sub>2</sub>), 0.28 (s, fwhm = 48 Hz, o-H). The amount of 1,2-dichloroethane by integration was  $\frac{1}{2}$  equiv/equiv of  $U(TPP)Cl_2(thf)$ .
- (13) Red crystals of  $U(TPP)Cl_2(thf)$  are triclinic, space group  $P\bar{1}$ , with  $a = 12.785$  (4) Å,  $b = 14.211$  (5) Å,  $c = 12.422$  (4) Å,  $\alpha = 93.85$  (3)°,  $\beta = 115.69$  (2)°,  $\gamma = 88.06$  (3)°,  $V = 2029$  (1) Å<sup>3</sup>,  $Z = 2$ ,  $d_{\text{calcd}} = 1.627$  g/cm<sup>3</sup>, and  $\mu_{\text{calcd}} = 39.64$  cm<sup>-1</sup>. X-ray diffraction data were collected at 25 °C on a 0.1 × 0.1 × 0.3 mm crystal for 5683 independent reflections having  $2\theta < 46^\circ$  and for  $\pm h, \pm k, \pm l$ , on a Syntex P2<sub>1</sub> automated four-circle diffractometer using graphite-crystal-monochromated Mo K $\alpha$  radiation,  $\lambda = 0.71069$  Å, and  $\omega/2\theta$  scans. The centric space group was confirmed by successful refinement of the proposed model. The nonunique data were averaged, and the data were corrected for Lorentz, polarization, anomalous dispersion, crystal decay (<4%), and absorption effects; for the last, the maximum and minimum transmission factors were 0.817 and 0.680. The structure was solved by Patterson methods followed by difference Fourier syntheses. All heavy atoms were independently refined with anisotropic thermal parameters except the carbon atoms of the phenyl substituents, which were independently refined isotropically. The final residuals for 386 variables refined against the 3874 data for which  $I > 2.58\sigma(I)$  were  $R_F = 5.5\%$  and  $R_w = 5.5\%$ . In the final cycle, hydrogen atoms were placed in calculated positions and included in the structure factor calculations and a common isotropic thermal parameter was refined for the group. The four largest peaks in the final difference map had electron densities of 1.1–2.2 e/Å<sup>3</sup> and were symmetrically disposed in pairs around the uranium center at chemically unreasonable sites, suggesting that these peaks result from inaccuracies in the scattering factors for uranium. There was no evidence in the final electron density difference map of a 1,2-dichloroethane molecule of solvation that was clearly present in the bulk sample as shown by microanalytical and <sup>1</sup>H NMR data. Therefore, the crystal from which data were collected differed from the bulk sample in that no solvate molecules were included in the crystal lattice.
- (14) Del Piero, G.; Perego, G.; Zazzetta, A.; Brandi, G. *Cryst. Struct. Commun.* **1975**, *4*, 521.
- (15) (a) Andersen, R. A.; Zalkin, A.; Templeton, D. H. *Inorg. Chem.* **1981**, *20*, 622. (b) Reynolds, J. G.; Zalkin, A.; Templeton, D. H.; Edelstein, N. M. *Inorg. Chem.* **1977**, *16*, 1090.
- (16) (a) McCullough, L. G.; Turner, H. W.; Andersen, R. A.; Zalkin, A.; Templeton, D. H. *Inorg. Chem.* **1981**, *20*, 2869. (b) Ernst, R. D.; Kennelly, W. J.; Day, C. S.; Day, V. W.; Marks, T. J. *J. Am. Chem. Soc.* **1979**, *101*, 2656.

We have synthesized other actinide porphyrin complexes as well. The "sandwich" complex bis(5,10,15,20-tetraphenylporphyrinato)uranium(IV) may be prepared under nonacidic conditions by refluxing a solution of tetrakis(diethylamido)uranium(IV),  $U(NEt_2)_4$ ,<sup>19</sup> and 2 equiv of H<sub>2</sub>TPP in toluene. After 12 h, the solution was evaporated to dryness and the residue chromatographed on basic alumina with CH<sub>2</sub>Cl<sub>2</sub> as eluent. A purple band of H<sub>2</sub>TPP was eluted first and discarded, and a brown second band was retained. This fraction was filtered and evaporated to dryness, and the residue was treated with chloroform/pentane to give dark purple microcrystals of  $U(TPP)_2$ .<sup>20</sup> Its electronic spectrum in CH<sub>2</sub>Cl<sub>2</sub> shows a Soret band at 404 nm and less intense Q bands at 485, 550, and 620 nm (supplementary material). The fast atom bombardment mass spectrum shows a parent envelope at  $m/z = 1465$ , and the <sup>1</sup>H NMR data are fully consistent with a square-antiprismatic geometry similar to that of  $U(pc)_2$ .<sup>9</sup>

The uranium complexes reported here include the first structurally characterized actinide porphyrin. We are continuing to explore the reaction chemistry of these complexes and the synthesis of related actinide porphyrins such as the thorium analogues Th(TPP)Cl<sub>2</sub> and Th(TPP)<sub>2</sub>.<sup>21</sup>

**Acknowledgment.** We thank the Research Corp., the University of Illinois Research Board, the donors of the Petroleum Research Fund, administered by the American Chemical Society, and the National Institutes of Health (Grant No. HL 25934) for their support. K.S.S. gratefully acknowledges an NIH Research Career Development Award and a Sloan Foundation Research Fellowship. Structural work by Dr. Scott R. Wilson is greatly appreciated.

**Supplementary Material Available:** Electronic spectra of  $U(TPP)Cl_2(thf)$  and  $U(TPP)_2$ , ORTEP view of  $U(TPP)Cl_2(thf)$  perpendicular to the porphyrin plane with full numbering scheme, and tables of atomic coordinates and thermal parameters for the crystal structure of  $U(TPP)Cl_2(thf)$  (5 pages). Ordering information is given on any current masthead page.

- (17) (a) Kasuga, K.; Tsutsui, M.; Petterson, R. C.; Tatsumi, K.; Van Opendenbosch, N.; Pepe, G.; Meyer, E. F. *J. Am. Chem. Soc.* **1980**, *102*, 4835. (b) Darovskikh, A. N.; Tsytsenko, A. K.; Franck-Kamenetskaya, O. V.; Fundamenskii, V. S.; Moskalev, P. N. *Sov. Phys.—Crystallogr. (Engl. Transl.)* **1984**, *29*, 273. (c) De Cian, A.; Moussavi, M.; Fischer, J.; Weiss, R. *Inorg. Chem.* **1985**, *24*, 3162.
- (18) (a) Buchler, J. W.; De Cian, A.; Fischer, J.; Kihn-Botulinski, M.; Paulus, H.; Weiss, R. *J. Am. Chem. Soc.* **1986**, *108*, 3652. (b) Moussavi, M.; De Cian, A.; Fischer, J.; Weiss, R. *Inorg. Chem.* **1986**, *25*, 2107.
- (19) (a) Jones, R. G.; Karmas, G.; Martin, G. A.; Gilman, H. *J. Am. Chem. Soc.* **1956**, *78*, 4285. (b) Reynolds, J. G.; Zalkin, A.; Templeton, D. H.; Edelstein, N. M.; Templeton, L. K. *Inorg. Chem.* **1976**, *15*, 2498.
- (20) Anal. Calcd for  $U(TPP)_2$ : C, 72.2; H, 3.86; U, 16.3. Found: C, 72.1; H, 4.37; U, 16.2. Mp: >250 °C. <sup>1</sup>H NMR (CDCl<sub>3</sub>, 25 °C):  $\delta$  9.77 (s, fwhm = 22 Hz, o-H), 7.12 (s, fwhm = 24 Hz, m-H), 5.67 (t,  $J_{HH} = 7.0$  Hz, p-H), 4.58 (s, fwhm = 8 Hz, pyrrole H), 3.82 (s, fwhm = 24 Hz, m-H), -3.83 (s, fwhm = 22 Hz, o-H).
- (21) The synthesis and crystal structure of Th(OEP)(acac)<sub>2</sub> have recently been described: Dormond, A.; Belkalem, B.; Charpin, P.; Lance, M.; Vigner, D.; Folcher, G.; Guillard, R. *Inorg. Chem.* **1986**, *25*, 4785.

School of Chemical Sciences  
University of Illinois at  
Urbana-Champaign  
Urbana, Illinois 61801

Gregory S. Girolami\*  
Stanley N. Milam  
Kenneth S. Suslick\*

Received October 16, 1986