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Uranyl ion coordination with rigid aromatic carboxylates and structural characterization of their complexes[†]

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Uranyl complexes of rigid aromatic carboxylates were synthesized and their solid-state structures characterized by X-ray crystallography. The new ligands create cavities lined with endohedral functions to encapsulate the uranyl ion.

The principal form of uranium on Earth is the uranyl dication (UO_2^{2+}) . Recovery of this ion is a longstanding goal for the purposes of environmental remediation, nuclear waste processing, and harvesting for energy production.¹ The distinctive shape of the uranyl ion not only provides a basis for ligand design,² but its unique coordination environment has also given rise to the controlled selfassembly of uranyl polyhedra,3 and remarkable reactivity at the otherwise inert uranyl oxygen atoms.⁴ The linear UO_2^{2+} prefers to interact with hard oxygen donors and its characteristically short uranium-oxygen bonds limit coordination to five or six donor atoms about its equator. This is evidenced by the predicted form of uranium in sea water, uranyl tricarbonate $UO_2(CO_3)_3^{4-5}$ Due to the small bite angle of the planar carbonate ligand, three fit around the metal center with optimal placement of the oxygen atoms. Chelation of this type has been effectively extended to synthetic ligands using carboxylates as the coordinating unit.^{2,6} Specifically, three 2,6-terphenyl carboxylic acid ligands have been shown to assemble around the uranyl ion, encapsulating it within the cavity created by the flanking aromatic panels of the ligand.⁷ The new apolar environment surrounding the metal excludes polar solvent molecules, enhancing the attraction between the carboxylates and the uranyl ion-akin to effects observed within enzyme interiors.8 We report here the synthesis of two new ligand systems that expand this notion and incorporate aromatic



Scheme 1 Synthesis of 3,5-diphenyl-1*H*-pyrazole-4-carboxylic acid **4** and original 2,6-terphenyl carboxylic acid ligand **5**. DCM = dichloromethane; TFA = trifluoroacetic acid.

panels to surround the uranyl ion, and we provide solid-state structures of their respective complexes. Notably, the crystal structures of $UO_2(9)$ and $UO_2(10)$ (Fig. 3) are only the second and third examples of coordination between a tripodal carboxylate ligand and the uranyl ion.⁹

Our first ligand preserves the aromatic panels of the 2,6-terphenyl system but replaces the central ring with a 1*H*-pyrazole (Scheme 1). The 3,5-diphenyl-1*H*-pyrazole-4-carboxylic acid 4 was obtained in three steps from β -keto ester 1.¹⁰ Acylation of 1 with benzoyl chloride at room temperature with *N*,*N*-dimethylaniline as the solvent yields the substituted 1,3-diketone 2. Subsequent condensation with hydrazine and acetic acid afforded pyrazole 3 in excellent yield. Finally, removal of the *tert*-butyl ester with trifluoroacetic acid (TFA) in dichloromethane gave pyrazole ligand 4 as the TFA salt. The biphenyl pyrazole ligand class was initially chosen as an alternative to 5 because it maintains the flanking phenyl groups while allowing a rapid, modular synthesis: desymmetrizing the backbone can be achieved by altering the acid chloride component in the first step and further modifications can be made through the use of substituted hydrazine derivatives in the condensation step.

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Fig. 1 X-ray crystal structure of $UO_2(4)_2(pyr)_2$ highlighting the incorporation of pyridine ligands and the π - π stacking interactions.

Uranyl complexes with the new pyrazole-based ligand were prepared by combining methanolic solutions of uranyl nitrate hexahydrate and **4** in the presence of excess triethylamine (TEA). The resulting bright yellow solution was evaporated and crystallized by diffusing pentane onto pyridine solutions of the complex yielding pale yellow prisms suitable for X-ray diffraction‡ (Fig. 1). In contrast to our expectations, only two 3,5-diphenyl pyrazole ligands coordinate the uranyl ion in a *trans* orientation. In addition, two pyridine molecules serve as ancillary ligands, and are sandwiched between the phenyl rings of **4** at π - π stacking distances.¹¹ The closest contact of the inclined aromatics has a C···C distance of 3.80 Å and the stacking is easily seen in the space filling view of the structure (Fig. 1). An additional molecule of pyridine also forms a hydrogen bond with the N-H of the pyrazole ring at a N···N distance of 2.82 Å (see ESI[†]).

As pyridine clearly influences the coordination behavior of 4 with the uranyl ion, it was omitted from further crystallization attempts. By diffusing diethyl ether onto a methanolic solution of 4, TEA, and uranyl nitrate, single crystals of a new complex were obtained¹² (Fig. 2) (see ESI⁺). As was observed previously with the terphenyl carboxylate ligand 5,⁷ three pyrazole ligands surround the uranyl ion in the new complex. However, the structures of the two systems differ by the inclusion of solvent molecules. The splayed geometry of the flanking phenyl rings of 4 (($\sim 153^{\circ}$) compared to 5 ($\sim 123^{\circ}$), Scheme 1) creates an aperture that allows access of solvent molecules to the interior of the complex. In stark contrast with the original system based on 5, the solution behavior of both $UO_2(4)_2(pyr)_2$ and $UO_2(4)_3$ is dynamic and the signals in the ¹H NMR spectra from 4 are broad and unresolved (see ESI⁺). As highlighted in Fig. 2, the uranyl complex co-crystallized with a molecule of diethyl ether, which fills the open space directly above a uranyl oxygen atom. Additionally, the counter (triethylammonium) cation for the negatively charged complex is positioned between two of the



Fig. 2 X-ray crystal structure of the $UO_2(4)_3$ complex highlighting the open spaces for the accessibility of solvent to the uranyl ion.

pyrazole ligands, and forms bifurcated hydrogen bonds with the carboxyl groups of the adjacent ligands.

In both uranyl complexes with **4**, it is clear that the open geometry characteristic of the pyrazole ring impacts the coordination behavior when compared with **5**. The wider angle between the phenyl rings precludes effective encapsulation of the targeted ion and solvent molecules are free to interact with the complex. Perhaps tethering three molecules of **4** to a single scaffold or careful modification of the flanking phenyl rings by the addition of appropriate bulk could provide the desired encapsulation behavior, but we have yet to observe this with pyrazole ligand class **4**.

The original terphenyl motif **5** was revisited to improve encapsulation of the uranyl ion by fusing the three aromatic ligands onto a single core. We chose 1,3,5-triethylbenzene as the appropriate scaffold,¹³ as its alternating geometry preorganizes and directs ligands on the 2, 4 and 6 positions. Lithium–halogen exchange of 6^{14} with *n*BuLi at -78 °C followed by addition of trialdehyde 7^{15} and warming to room temperature gave benzylic alcohols **8** as a mixture of diastereomers. The phenyl groups flanking the methyl ester of **6** behave as protecting groups, shielding the ester from the lithium species formed under the reaction conditions. Triols **8** were converted into two ligands: oxidation with pyridinium chlorochromate (PCC) followed by acidic hydrolysis of the esters gave triketone ligand **9**; reduction with triethylsilane and borontrifluoride diethyl etherate then ester hydrolysis yielded **10**.

The solution behavior of rigid tripodal ligands **9** and **10** with the uranyl ion were examined by ¹H NMR. The respective complexes were prepared as described above by treating dilute methanolic solutions of either ligand with TEA followed by addition of uranyl nitrate. While the free methylene ligand **10** showed the expected, time-averaged C_{3v} symmetry in solution (provided by the steric gearing of the 1,3,5-triethylbenzene core), ligand **9** showed multiple resonances for the ethyl feet, suggesting a less symmetric geometry (C_s) in solution—with two terphenyl arms of **9** on one side of the benzene core and the third arm on the other (see ESI[†]). Despite the solution behavior of **9** and **10**, **1**:1 complexes with UO₂ were formed with each ligand. ¹H NMR spectra show the UO₂ complex with the comparatively more rigid **9** has some broad resonances, while the spectrum of the complex with **10** is sharp and well resolved (see ESI[†]).

Yellow, single crystals of $UO_2(9)$ suitable for X-ray diffraction were obtained by layering cyclopentane on dilute dichloromethane solutions of the complex[‡] (Fig. 3, left). All three carboxylates of 9 are directed inward, surrounding the uranyl ion. The upper phenyl rings of the ligand close around the top of the uranyl ion and shield it from solvent molecules. The negatively charged complex is accompanied by a triethylammonium counter cation that is sandwiched between the phenyl groups of adjacent complexes. Single crystals of UO2(10) were isolated by diffusing methanol into DMF solutions of the complex and its solid state structure closely resembles that of UO2(9) (Fig. 3, right). While these crystal structures reveal promising ligand leads, the inherent solubilities of 9 and 10 and the solution behavior of 9 are current limitations. Optimization of the linker may restore the desired time-averaged C_{3v} symmetry of 9 and the addition of solubilizing groups at the periphery of the ligands could increase their potential for use as effective extractants for the uranyl ion.¹⁶ Additionally, crystal structures $UO_2(9)$ and $UO_2(10)$ show that incorporation of a hydroxyl group on carbons 1 or 2 (Scheme 2), would position a hydrogen bond



Fig. 3 X-ray crystal structures of the $UO_2(9)$ and $UO_2(10)$ complexes. The triethylammonium counter cations are omitted for clarity.



 $\label{eq:scheme 2} \begin{array}{l} \mbox{(a) PCC, DCM, 2 h, r.t.; (b) CHCl_3, Et_3SiH, BF_3\cdot Et_2O, 0 \ ^{\circ}C, 45 \ min; (c) \\ \mbox{AcOH, 48\% HBr in } H_2O, 130 \ ^{\circ}C. \end{array}$

donor in close proximity to the uranyl oxygen atom, which could improve affinity.

In summary, we have synthesized and structurally characterized the uranyl complexes of rigid aromatic carboxylate ligands **4**, **9**, and **10**. With the pyrazole core, the adjacent phenyl groups are open wide, allowing solvent molecules to interact freely with the interior of the complex. The terphenyl-based ligands **9** and **10** more-or-less encapsulate the uranyl ion with aromatic panels. Their poor solubility and the unfavourable solution geometry of **9** will be addressed in our future pursuit of the encapsulation of the uranyl ion.

Notes and references

‡ Crystal data: (pyr)₂4₂UO₂: C₄₂H₃₂N₆O₆U, 2(C₅H₅N), M = 1112.96, Monoclinic, $P2_1/c$, a = 16.8356(11) Å, b = 9.0754(6) Å, c = 14.9921(10) Å, $\alpha = 90.00^{\circ}$, $\beta = 93.824(2)^{\circ}$, $\gamma = 90.00^{\circ}$, V = 2285.5(3) Å³, Z = 2, $\begin{array}{l} \rho_{\rm calcd} = 1.617 \ {\rm g} \ {\rm mL}^{-1}, \ \mu({\rm Cu-K}\alpha) = 10.49 \ {\rm mm}^{-1}, \ \theta_{\rm max} = 57.7^\circ, \ T = 100(2) \ {\rm K}, \ 17762 \ {\rm reflections} \ {\rm collected}, \ R_1 = 0.0218 \ {\rm for} \ 2709 \ {\rm reflections}, \ R_{\rm int} = 0.039, \ (304 \ {\rm parameters}) \ {\rm with} \ I > 2\sigma(I), \ {\rm and} \ R_1 = 0.0242, \ wR_2 = 0.0648, \ {\rm GooF} = 1.09 \ {\rm for} \ {\rm all} \ 3067 \ {\rm data}, \ {\rm CCDC} \ \# 30587. \ {\rm Et_3NH}^+.9{\rm UO_2}^-: \ {\rm C_{72}H_{51}O_{11}U}, \ 1.5({\rm C_5H_{10}}), \ 2.5({\rm CH_2Cl_2}), \ {\rm C_6H_{16}N}, \ M = 1749.86, \ {\rm Monoclinic}, \ P2_1/n, \ a = 19.6677(9) \ {\rm \AA}, \ b = 18.8428(9) \ {\rm \AA}, \ c = 22.6324(10) \ {\rm \AA}, \ \alpha = 90.00^\circ, \ \beta = 109.593(2)^\circ, \ \gamma = 90.00^\circ, \ V = 7901.8(6) \ {\rm \AA}^3, \ Z = 4, \ \rho_{\rm calcd} = 1.471 \ {\rm g} \ {\rm mL}^{-1}, \ \mu({\rm Mo-K}\alpha) = 2.286 \ {\rm mm}^{-1}, \ \theta_{\rm max} = 25.242^\circ, \ T = 100(2) \ {\rm K}, \ 64.835 \ {\rm reflections} \ {\rm collected}, \ R_1 = 0.0472 \ {\rm for} \ 10.896 \ {\rm reflections}, \ R_{\rm int} = 0.0846, \ (949 \ {\rm parameters}) \ {\rm with} \ I > 2\sigma(I), \ {\rm and} \ R_1 = 0.0915, \ {\rm wR_2} = 0.1028, \ {\rm GooF} = 1.010 \ {\rm for} \ {\rm all} \ 16.177 \ {\rm data}, \ {\rm CCDC} \ \# 930588. \ {\rm Et_3NH}^+.10UO_2^-: \ {\rm C}_{72}{\rm H}_{57}O_8U, \ {\rm C}_6{\rm H}_{16}{\rm N}, \ 4({\rm CH_4}O), \ M = 1518.57, \ {\rm Monoclinic}, \ P2_1/n, \ a = 14.2622(12) \ {\rm \AA}, \ b = 18.6958(15) \ {\rm \AA}, \ c = 26.384(2) \ {\rm \AA}, \ \alpha = 90.00^\circ, \ \beta = 93.484(3)^\circ, \ \gamma = 90.00^\circ, \ V = 7022.2(10) \ {\rm \AA}^3, \ Z = 4, \ \rho_{\rm calcd} = 1.436 \ {\rm gm} {\rm L}^{-1}, \ \mu({\rm Cu-K}\alpha) = 7.02 \ {\rm mm}^{-1}, \ \theta_{\rm max} = 68.00^\circ, \ T = 100(2) \ {\rm K}, \ 56.112 \ {\rm reflections} \ {\rm collected}, \ R_1 = 0.0228 \ {\rm for} \ 11.600 \ {\rm reflections}, \ R_{\rm int} = 0.030 \ (900 \ {\rm parameters}) \ {\rm with} \ I > 2\sigma(I), \ {\rm and} \ R_1 = 0.02246, \ {\rm wR_2} = 0.0568, \ {\rm GooF} = 1.062 \ {\rm for} \ 11.2372 \ {\rm data}, \ {\rm CCDC} \ \# 940964. \ \end{array}$

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