Electronic Supplementary Information

Trimeric uranyl(VI)–citrate forms Na⁺, Ca²⁺, and La³⁺ sandwich complexes in aqueous solution

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EXPERIMENTAL DETAILS

Sample preparation

All preparation steps were performed with safety precautions according to both radio- and chemotoxicity of natural uranium (U-nat). All chemicals were used without further purification. Samples were protected from light by covering the sample tubes with aluminum foil.

Stock solutions, respectively 0.5 M (M denoting moles per liter), were prepared by weighing and dissolving appropriate amounts of either citric acid (VWR Chemicals, > 99.8%) or trisodium citrate (Roth, *p.a.*), UO₂(NO₃)₂·6H₂O (A = 25.3 kBq g⁻¹ U-nat), Ca(NO₃)₂·4H₂O (Alfa Aesar, 97%), KNO₃ (Merck, *p.a.*), RbNO₃ (Aldrich, 99.99%), and La(NO₃)₃·6H₂O (Merck, *p.a.*). Exact concentrations were determined by ICP-MS (Elan 6000, Perkin Elmer).

For dissolution and dilution, deuterated water, D₂O (Deutero, 99.98% D), was used. pD was carefully adjusted to avoid addition of another sort of anions, by means of D₂O solutions of NaOD (Deutero, 40% in D₂O with 99% D) in the case of the Na-containing samples, and freshly prepared D₂O solutions of D₂O-washed LiOH·H₂O pellets (Merck, *p.a.*) in case of the other metal ions (Li, K, Rb, Ca, La). In order to prevent precipitation, and particularly since La³⁺ is susceptible to hydrolysis for the given concentrations, samples were prepared at pD values of 5.4 and 4.8 for Ca²⁺ and La³⁺, respectively; pD adjustment was according to pD = pH + 0.4, *i.e.*, addition of 0.4 units to the pH meter reading.¹

The Ca²⁺ and La³⁺ containing samples were prepared as follows. First, to ensure formation of uranyl citrate complexes, a mixture prepared from aliquots of uranyl nitrate and citric acid stock solutions was adjusted to a pD of about 4.5 with LiOD. The solution then was split into two samples, with aliquots of D₂O solutions of the nitrates of calcium and lanthanum being added prior to adjusting pD to the respective final values. Finally, the solutions' composition was [U(VI)] = [Cit] = 125 mM, [M] = 100 mM (M = Ca²⁺ or La³⁺).

The dilution series for determining the critical concentration of the U(VI)–Cit 6:6 Na⁺ complex comprised the following sample concentrations: 125, 25, 12.5, 6.2, 3.1, and 2.5 mM. Therefore, based on a [U(VI)] = [Cit] = 125 mM pD 7.0 sample solution successive dilutions were obtained from appropriate aliquots thereof, and pD re-adjusted with NaOD to values of 6.9 ± 0.1.

Sample series for studying whether sandwich complexes of other alkali metal ions are formed were prepared as follows, carefully avoiding to introduce Na⁺. Initially, a D₂O solution finally being 125 mM each in uranyl nitrate and citric acid was prepared. Freshly prepared LiOD (see above) was used for adjusting pD to 6.9. After ascertaining that with Li⁺ no uranyl–citrate sandwich complex forms, the aforementioned LiOD containing U(VI)–Cit solution was used as the basis for alkali metal ion titration series investigating (stepwise) sandwich complex formation upon introducing Na⁺, K⁺, or Rb⁺, respectively. For either series, in consecutive steps aliquots of 20, 50, and 200 µl of 2 M NaNO₃, KNO₃, or RbNO₃ pD 7 D₂O solution were added to 600 µl of the pD 6.9 LiOD containing 125 mM uranyl citrate solution directly inside an NMR tube. The resulting Na⁺, K⁺, and Rb⁺ concentrations thus corresponded to 65, 210, and 620 mM, respectively.

Nuclear magnetic resonance spectroscopy (NMR)

NMR spectra were obtained at 298 K on a 14.1 T Agilent DD2-600 NMR system; corresponding resonance frequencies (in MHz) are: 599.8 (¹H), 150.8 (¹³C), 233.2 (⁷Li), 158.7 (²³Na), 84.7 (¹³⁹La), and 81.4 (¹⁷O). A 10 mm low-gamma broadband direct detection probe was utilized for ¹³⁹La and natural abundance ¹⁷O measurements, while a 5 mm oneNMRTM probe was used for the other experiments. ¹H NMR spectra were in part acquired with suppression of the residual HDO signal upon application of

a 2 s pre-saturation pulse with offset on the water resonance prior to detection. Quartz NMR tubes were used to avoid the Na background from regular borosilicate glass NMR tubes. ¹H and ¹³C were referenced relative to the trimethylsilyl signal of 4,4-dimethyl-4-silapentane-1-sulfonic acid sodium salt (DSS; Sigma-Aldrich, 98%) with $\delta_{\rm H} = 0.00$ ppm and $\delta_{\rm C} = 0.15$ ppm. ¹⁷O NMR chemical shifts are reported relative to internal bulk ¹⁷OHD, $\delta_{\rm O} = 0$ ppm. In case of metal ion NMR, ²³Na, ⁷Li, and ¹³⁹La NMR spectra are externally referenced to the signal obtained from the respective 1 M metal chloride D₂O solutions, according to $\delta = 0$ ppm.

H,C-HSQC and H,C-HMBC spectra were recorded by means of their gradient-selected versions, respectively using $1k \times 512$ complex points in F_2 and F_1 , 20 transitions per F_1 increment, and a relaxation delay of 1.5 s. For polarization transfer in HSQC ¹J was opted as 120 Hz, in HMBC ⁿJ was opted as 8 Hz, with one-bond suppression between 135 and 105 Hz.

Owing to the large molecular mass of the U(VI)–Cit 6:6 Na⁺ and La⁺ sandwich complexes (2803.7 and 2919.7 u, according to $C_{36}H_{24}NaO_{56}U_6$ and $C_{36}H_{24}LaO_{56}U_6$, respectively) ROESY instead of NOESY was chosen, applying $1k \times 1k$ (Na⁺) and $2k \times 256$ (La³⁺) complex points in F_2 and F_1 , with 16 (Na⁺) and 48 (La³⁺) transitions per F_1 increment. For both Na⁺ and La³⁺ a relaxation delay of 1 s, a spin-lock mixing time of 300 ms, and 1 s pre-saturation for HDO signal suppression were used.

The DOSY spectrum was acquired as a series of ¹H spectra (no HDO signal suppression), applying 2 ms diffusion gradient length and a diffusion delay of 200 ms, for 16 incremented gradient strengths.

The following parameters, in parentheses listed as *acquisition time*; *relaxation delay*; *number of transitions* were chosen for acquisition of spectra for the quadrupolar nuclei: ⁷Li (5 s; 15 s; 32), ²³Na (0.1 s; 0.5 s; 1k through 8k, depending on dilution), ¹³⁹La (0.05 s; 0.1 s; 412k), and ¹⁷O (0.1 s; 0.2 s; 256k, 326k, and 257k for Na⁺, Ca²⁺, and La³⁺ containing samples, respectively).

Raman spectroscopy

Raman spectra at 25 °C were obtained from the Na⁺ or La³⁺ containing 125 mM uranyl(VI)–citrate NMR sample solutions (in D₂O) in 50 μ l quartz cuvettes, by means of a Malvern Panalytical Zetasizer Nano at an excitation wavelength of 785 nm and accumulation of six spectra after 10 s exposure time and one replicate per step, using a cosmic ray filter and dark subtraction.

COMPUTATIONAL DETAILS

Quantum chemical calculations were performed using the Gaussian 16 program (Gaussian Inc.) rev.B01² employing density functional theory (DFT) by using a conductor-like polarizable continuum model.³ Structure optimizations were performed at the B3LYP level^{4, 5} followed by NMR chemical shift analysis at the same level through Gauge-Independent Atomic Orbital (GIAO) method.⁶ The energy consistent small-core effective core potential (ECP) and the corresponding basis set suggested by Küchle *et al.* were used for U,⁷ whereas large-core ECP was used on C,O and Na.⁸ The most diffuse basis functions on uranium with the exponents 0.005 (all s, p, d, and f type functions) were omitted. These basis functions had a very small effect on the reaction energies (less than 1 kJ mol⁻¹). For H, the valence triple- ζ plus polarization basis was used. The spin–orbit effects and basis set superposition error corrections were neglected. All the calculations were performed on a TSUBAME 3.0 supercomputing system at the Tokyo Institute of Technology.

The high negative charge of the complexes requires compensating counter-cations, whose number and positions influence the results. By taking a single sandwich unit from the crystal structure⁹ of the Na⁺ sandwich complex without including any counter-cation, the ¹⁷O NMR chemical shift of the inner "yl"-oxygens and the outer "yl"-oxygens (relative to water) was calculated to be in the 972 – 98 ppm and the 1271 – 1288 ppm ranges, respectively. Taking again the crystal structure and including 6 Na⁺ and 8 [piperazinium]²⁺ cations, the calculated values approach the measured values much better. Hence, the signals of the inner "yl"-oxygens and the outer "yl"-oxygens shifted to 1099 – 1212 ppm and 1037 – 1207 ppm, respectively.

Aqueous solution molecular model



Fig. S1. Spectroscopically derived model of the U(VI)–Cit 6:6 Na⁺ sandwich complex aqueous solution structure, highlighting the different types of Na⁺: sandwiched, dark violet; peripheral, pale green; and aquo ion, white; as well as U (blue); C (black); O (red); H (grey).

NMR spectra

U(VI)–Cit 6:6 Na⁺ sandwich complex





Fig. S2. H,C-HSQC spectrum of the U(VI)–Cit 6:6 Na⁺ sandwich complex in pD = 7.0 D₂O solution. ${}^{1}J_{H,C}$ opted as 120 Hz according to 4.17 ms for single-bond polarization transfer.



Fig. S3. H,C-HMBC spectrum of the U(VI)–Cit 6:6 Na⁺ sandwich complex in pD = 7.0 D₂O solution. ${}^{n}J_{H,C}$ opted as 8 Hz according to 62.5 ms for multiple-bond polarization transfer.

By means of H,C correlation spectra the correct C–H connectivity is revealed. That is, the hydrogen associated with the remarkably shifted signal (F1) belongs to the unbound $-CH_2COO^-$ moieties as the corresponding carbons F and C are more shielded than carbons E and B, indicating that the latter belong to the U(VI)-bound moieties.

This principal assignment holds true for all U(VI)–Cit 6:6 M (M = Na⁺, Ca²⁺, La³⁺) sandwich complexes. Note that ${}^{3}J_{C,H}$ are in principle larger than either ${}^{2}J_{C,H}$ or ${}^{4}J_{C,H}$, and that, according to the Karplus relationship, ${}^{3}J_{H,C}$ couplings of *transoid* arrangement are preferentially detected over those of *cisoid* arrangement for the opted (rather large) coupling constant of 8 Hz – see, for instance, the ${}^{3}J$ coupling between carbon A and hydrogen F1.



Fig. S4. ROESY spectrum (mixing time 300 ms) of the uranyl(VI)–citrate 6:6 Na⁺ sandwich (pD = 7.0).



Fig. S5. Diffusion-ordered ¹H NMR spectrum (DOSY) of the U(VI)–Cit 6:6 Na⁺ sandwich pD = 7.0 solution.

U(VI)–Cit 6:6 *Ca*²⁺ sandwich complex



Fig. S7. H,C-HMBC spectrum of the U(VI)–Cit 6:6 Ca²⁺ sandwich complex in pD = 5.4 D₂O solution. ${}^{n}J_{H,C}$ opted as 8 Hz according to 62.5 ms for multiple-bond polarization transfer.

U(VI)–Cit 6:6 La³⁺ sandwich complex





Fig. S8. ROESY spectrum (mixing time 300 ms) of the uranyl(VI)–citrate 6:6 La³⁺ sandwich complex (pD = 4.8). The above shown structure represents the La³⁺ sandwich complex.



Fig. S10. H,C-HMBC spectrum of the U(VI)–Cit 6:6 La³⁺ sandwich complex in pD = 4.8 D₂O solution. ${}^{n}J_{H,C}$ opted as 8 Hz according to 62.5 ms for multiple-bond polarization transfer.

| | $M^{n+} = Na^+ (pD = 7.0)$ | | $\mathbf{M}^{n+} = \mathbf{C}\mathbf{a}^{2+} (p\mathbf{D} = 5.4)$ | | $M^{n+} = La^{3+} (pD = 4.8)$ | |
|----------------------------------|---|----------------------|---|----------------------|---|----------------------|
| ${}^{1}\mathrm{H}$ | δ / ppm, ² J / Hz | $\Delta\delta$ / ppm | δ / ppm, 2J / Hz | $\Delta\delta$ / ppm | δ / ppm, 2J / Hz | $\Delta\delta$ / ppm |
| F1 F2 | 4.39, 16.8 3.82, 16.8 | 0.57 | 4.34, 16.5 3.96, 16.5 | 0.37 | 4.33, 16.1 3.98, 16.1 | 0.35 |
| E1 E2 | 3.69, 15.9 3.60, 15.9 | 0.09 | 3.84, 16.0 3.70, 16.0 | 0.15 | 3.82, 16.2 3.64, 16.2 | 0.31 |
| ¹³ C | δ / ppm | $\Delta\delta$ / ppm | δ / ppm | $\Delta\delta$ / ppm | δ / ppm | $\Delta\delta$ / ppm |
| A B C D E F | 194.5 185.0 180.5 89.0 51.1 47.9 | 4.5 3.2 | 196.2 186.8 183.4 92.1 53.3 50.1 | 3.4 3.1 | 196.8 186.2 183.9 92.2 52.5 49.9 | 2.3 2.6 |
| ¹⁷ O * | δ / ppm | $\Delta\delta$ / ppm | δ / ppm | $\Delta\delta$ / ppm | δ / ppm | $\Delta\delta$ / ppm |
| O _o O _i | 1105 1117 | 12 | 1092 1161 | 69 | 1086 1179 | 93 |

 $[M{\eta^{3}-((UO_{2})_{3}(\mu_{3}-O)(Cit)_{3})}_{2}]^{n-16}$

* Consider the uranyl(VI) units as O₀=U=O_i, where the 'outer' oxygen atoms are denoted O₀, and the 'inner', i.e. metal ion coordinating, oxygen atoms are denoted O_i.

The ¹H NMR spectra imply some small but significant conformational changes for increasing Lewis acidity (Na⁺ < Ca²⁺ < La³⁺) of the sandwiched metal ion (Table S1). Along this series, $\Delta \delta_{\rm H}$ of the protons F1/F2 successively decrease while $\Delta \delta_{\rm H}$ of E1/E2 successively increase. That is, the diastereotopicity of the F1/F2 hydrogens decreases, while that of the E1/E2 hydrogens increases. The respective geminal coupling constants (²*J*_{H,H}) show an analogous trend. We attribute these findings to an increased convexity of the η^3 -triuranyl-tricitrato residues, which may also contribute to the drastic increase in $\Delta \delta_{\rm O}$ of the O₀=U=O₁ units.

¹³C NMR chemical shift differences, $\Delta\delta_{\rm C}$, between free and U(VI)-bound -CH₂COO moieties for both the carboxyl (B and C) and methylene carbons (E and F) decrease. This effect cannot be due to protonation of the respective free -CH₂COO moiety since this process would increase $\Delta\delta_{\rm C}$ as protonation results in upfield shifts (cf. Fig. S11). Instead it is likely that the cations (partly) coordinate to the six unbound carboxylates according to the strong association of peripheral Na⁺ / La³⁺ as observed in the ²³Na (-9 ppm) and ¹³⁹La NMR (-45 ppm) spectra. Thus the "free" -CH₂COO moieties (carbons C and F) become partly bound to Mⁿ⁺ and increasingly sense electron withdrawal and hence $\Delta\delta_{\rm C}$ decreases for -CH₂COOU vs. -CH₂COONa > -CH₂COOCa > -CH₂COOLa, especially for the carboxyl carbon as binding site.



Fig. S11. ¹³C NMR spectra of 300 mM citric acid D₂O solutions for the pD values indicated.

Raman spectra



Fig. S12. Raman spectra of uranyl(VI)–citrate 6:6 complexes sandwiching Na⁺ (green) and La³⁺ (magenta), obtained from D₂O solutions 125 mM each in uranyl(VI) nitrate and Cit. The 100 mM La³⁺ containing sample was prepared using citric acid and pD adjusted to 4.8 with LiOD, while for the Na⁺ containing sample, adjusted to pD = 7.0, trisodium citrate and NaOD were used.

Dilution series (U(VI)–Cit 6:6 Na⁺ sandwich complex)



Fig. S13. ¹H NMR dilution series showing the dissolution of the uranyl(VI)–citrate 6:6 Na⁺ sandwich complex below a critical concentration of about 3 mM in uranyl citrate at $pD = 6.9 \pm 0.1$. The respective concentrations decrease from top to bottom and amount to 125 mM, 25 mM, 12.5 mM, 6.2 mM, 3.1 mM, and 2.5 mM, respectively. Note the magnified spectral region of the signals associated with free citrate ligand (right), evidencing that the U(VI)–Cit complexes are of a 1:1 stoichiometry, since no ligand is liberated.

Alkali metal ion variation: uranyl(VI) citrate in presence of $Li^+ / K^+ / Rb^+$



Fig. S14. ¹H (A) and ⁷Li (B) NMR spectra of a pD = $6.9 \text{ D}_2\text{O}$ solution, prepared 125 mM each in uranyl(VI) nitrate and citric acid, with pD adjusted by LiOD. An asterisk indicates residual free citrate (4% as determined from signal area integration). The insets show the same ⁷Li spectra for different line broadening factors (FID multiplied by exponential function prior to Fourier transform) to better observe any broad signals from possibly sandwiched Li⁺.



Fig. S15. ¹H NMR spectra of a D₂O solution 125 mM each in uranyl(VI) nitrate and citric acid, pD adjusted to 6.9 with LiOD (bottom spectra). Stepwise addition of D₂O pD = 7.0 solutions of KNO₃ (A) or RbNO₃ (B) respectively corresponding to $[K^+]$ and $[Rb^+]$ of 0, 65, 210, and 620 mM (from bottom to top). The asterisk indicates residual free citrate.

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