Synthesis, structure, and reactivity of crystalline molecular complexes of the {[C₅H₃(SiMe₃)₂]₃Th}¹⁻ anion containing thorium in the formal +2 oxidation state†

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Reduction of the Th³⁺ complex Cp₃,Th, 1 [Cp" = C₅H₃(SiMe₃)₂], with potassium graphite in THF in the presence of 2.2.2-cryptand generates [K(2.2.2-cryptand)]Cp₃,Th, 2, a complex containing thorium in the formal +2 oxidation state. Reaction of 1 with KCl in the presence of 18-crown-6 generates the analogous Th²⁺ compound, [K(18-crown-6)]Cp₃,Th, 3. Complexes 2 and 3 form dark green solutions in THF with ε = 23 000 M⁻¹ cm⁻¹, but crystallize as dichroic dark blue/red crystals. X-ray crystallography revealed that the anions in 2 and 3 have trigonal planar coordination geometries, with 2.521 and 2.525 Å Th—(Cp" ring centroid) distances, respectively, equivalent to the 2.520 Å distance measured in 1. Density functional theory analysis of (Cp₃,Th)¹⁻ is consistent with a 6d² ground state, the first example of this transition metal electron configuration. Complex 3 reacts as a two-electron reductant with cyclooctatetraene to make Cp₂,Th(C₅H₄), 4, and [K(18-crown-6)]Cp".

One of the fundamental characteristics of any metal is the extent to which it loses electrons to form charged species in different formal oxidation states. This ionization can occur in the gas phase to form short-lived species in a wide range of oxidation states, but the number of oxidation states available in solution in molecular metal complexes for productive chemistry is smaller. Chemists have tested the limits of oxidation states of all the elements for over 100 years and the boundaries of oxidation states accessible in solution are well established.

Nevertheless, it was recently discovered that the +2 oxidation state is accessible in soluble molecular complexes for all the elements in the lanthanide series except promethium, eqn (1).†

Previously, it was thought that only the traditional six Ln²⁺ ions of Eu, Yb, Sm, Tm, Dy, and Nd were obtainable in solution on the basis of calculated reduction potentials and solid state chemistry. Extension of this reductive chemistry to uranium was not initially tried since it is well known that the redox chemistry of uranium, which includes multiple oxidation states, +3, +4, +5, and +6, is quite different from that of the rare earths. Although it was likely that uranium would be different, an analogous synthesis was eventually attempted and the first fully characterizable U²⁺ complex, [K(2.2.2-cryptand)][Cp₂,U] (Cp" = C₅H₃SiMe₃)₃, was isolated according to eqn (2).§

Synthesis of a Th²⁺ complex via eqn (1) or (2) seemed even more unlikely for several reasons. Complexes of Th³⁺ are already difficult to obtain. The Th⁴⁺/Th³⁺ redox potential is estimated to be −3.0 and −3.8 V vs. NHE and a Th⁵⁺/Th⁴⁺ redox potential of −4.9 V vs. NHE is in the literature. Reduction to metallic thorium would be predicted to be favored before formation of a Th²⁺ species. Many studies have been reported to find oxidation states lower than 4 for thorium, but only five Th³⁺ complexes have ever been structurally characterized. An
analogue of equation (2) was not possible since Cp₃Th has not yet been synthesized. Despite these issues, thorium reduction chemistry was examined using Cp₃Th [Cp" = C₅H₅(SiMe₃)₂-1,3],²⁷ prepared by Lappert et al. in 1986, and the results are described here.

Addition of potassium graphite to a dark blue solution of Cp₃Th, 1, and 2.2.2-cryptand in THF immediately forms a green solution from which dichroic dark blue/red crystals of [K[2.2.2-cryptand]][Cp₃Th], 2, can be isolated and crystallographically characterized, Fig. 1, eqn (3). The analogous reaction with 18-crown-6 instead of 2.2.2-cryptand as the potassium chelator provides [K(18-crown-6)(THF)]₂[Cp₃Th], 3, which was also crystallographically characterized [see (ESI†)], eqn (3). Elementary analysis was consistent with the structures determined crystallographically. The ¹H and ¹³C NMR spectra of 2 and 3 gave resonances in the diamagnetic region with a Me₃Si ³H NMR resonance shifted about 0.4 ppm from that of KCp". A resonance was observed in the ²⁹Si NMR spectrum of 3 at −6 ppm in the region close to the −8 and −15.5 ppm signals of diamagnetic Cp₃ThBr and KCp", respectively. Evans method measurements⁸ on both 2 and 3 and SQUID analysis⁸ at low temperature suggest the [Cp₃Th]^− anion is diamagnetic. No EPR spectra were observed for 2 and 3. Decomposed samples showed the EPR spectrum of Cp₃Th."
is interesting to note that the calculations for the Th$^{3+}$ complex show a slightly longer metal ligand distance than for the Th$^{5+}$ complex. The calculations indicate a spin-paired ground state of 6$d^2$ for (Cp$_3$Th)$^{1-}$ and a 6$d^1$ ground state for Cp$_3$Th; the latter is consistent with previous analyses of Cp$_3$Th,7m–(C$_5$Me$_5$)$_2$[PrNC(Me)NPr]Th$^{19}$ and [K(DME)$_2$][CaH$_4$(Si'BuMe$_2$)$_2$]Th.$^{27}$ Gas-phase studies of Th$^{2+}$ indicate a ground state of 5$f^6$6$d^1$, but the 6$d^2$ configuration is just 63 cm$^{-1}$ higher and the 5$f^7$7$s$ is 2527 cm$^{-1}$ higher than the ground state.$^{25}$ For (Cp$_3$Th)$^{1+}$ the triplet 5$f^6$6$d^1$ state is computed to be 9–14 kcal mol$^{-1}$ higher in energy than the singlet 6$d^2$ ground state.

The 6$d^2$ singlet ground state can arise in this case due to stabilization of a d$_{xy}$ orbital by the trigonal ligand environment as found in DFT calculations on (Cp$_3$Ln)$^{1-}$ and (Cp$_3$U)$^{1-}$ complexes$^{16a,4}$ and noted earlier in the literature for tris(cyclopentadienyl) metal complexes.7m–16a Indeed, both the lowest unoccupied molecular orbital (LUMO) of Cp$_3$Th and the highest occupied molecular orbital (HOMO) of (Cp$_3$Th)$^{1-}$ have d$_{xy}$ character, Fig. 3. Complexes 2 and 3 provide the first examples of the 6$d^2$ configuration since stable transition metal ions are only known with the 5$d^n$ configurations of the third row transition metals. The 6$d^2$ configuration is that predicted for ions like Re$^{2+}$ and Db$^{3+}$.$^{17}$

Time-dependent density functional theory was used to simulate the UV-Vis spectra for the (Cp$_3$Th)$^{1-}$ anion as shown in Fig. 2 (see ESI† for a description of the predicted excitations). The maxima in the calculated spectra are lower in energy than those observed experimentally, but this is often the case with such calculations.$^{18}$ Analysis of the calculated low energy peak shows that it arises from metal-to-metal transitions that have d $\rightarrow$ f and d $\rightarrow$ p character. The high energy peaks arise from metal-to-ligand charge transfer transitions similar to those found in the spectral analysis of (Cp$_3$Ln)$^{1-}$18a–20 and (Cp$_3$U)$^{1-}$4. However, the d $\rightarrow$ f transitions found for (Cp$_3$Th)$^{1-}$ were not apparent in the analysis of the spectra of (Cp$_3$Ln)$^{1-}$ and (Cp$_3$U)$^{1-}$.$^{4}$

The rate of decomposition of [K(18-crown-6)][THF]$_2$[Cp$_3$Th], 3, at room temperature was studied by $^1$H NMR spectroscopy since monitoring by UV-Vis spectroscopy is complicated by the formation of highly colored Cp$_3$Th, as identified by X-ray crystallography.$^{27}$ The rate of decomposition of 3 is much slower than that of the U$^{2+}$ complex, [K(2.2.2-cryptand)][Cp$_3$U], which has a half-life of 1.5 h in THF at room temperature.$^4$ Complex 3 decomposed only 8% after 8 days at 298 K and a sample kept in the dark showed even less decomposition. This suggests that the formally Th$^{2+}$ species are significantly more stable than the other newly discovered +2 ions.$^{14}$

Complexes 2 and 3 were treated with H$_2$ to determine if a Th$^{3+}$ hydride complex such as [K(2.2.2-cryptand)][Cp$_3$ThH]$^{1+}$ would form in analogy to the complex formed by reaction of (K$^{2+}$2.2.2-cryptand)[$Cp_3$U] with H$_2$.4 Analogous chemistry is not observed with either H$_2$ or KH. Complexes 2 and 3 react in solution within minutes with 1 atm of H$_2$ and also over several hours at 60 psi in the solid state to make EPR active new crystalline complexes that appear to be bimetallic, but suitable models for the crystallographic data on the products have not been obtainable. The reactivity of 2 and 3 with H$_2$ contrasts with that of the Th$^{3+}$ complex, Cp$_3$Th, which does not react under analogous conditions.

The (Cp$_3$Th)$^{1-}$ anion displays net two-electron reduction chemistry in its reaction with 1,3,5,7-cyclooctatetraene (C$_8$H$_8$). The Th$^{4+}$ complex Cp$_3$Th(C$_8$H$_8$), 4, is formed as shown in eqn (4) and was characterized by X-ray crystallography, Fig. 4. The (C$_8$H$_8$)$^{2-}$ ring in 4, like that of (C$_5$Me$_4$H)$_2$U(C$_8$H$_8$),20 displays considerable distortion from the normal planar geometry with several atoms 0.095 Å out of the best plane of the eight carbon atoms. This is reflected by a large range of Th–C(C$_8$H$_8$) distances: 2.736(4) to 2.841(4) Å. This 0.105 Å range is similar to the 0.123 Å range in (C$_5$Me$_4$H)$_2$U(C$_8$H$_8$).20

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\text{[Cp}_3\text{Th][K(18-crown-6)][THF]_2]}_3 \rightarrow \text{[K(18-crown-6)][Cp}_3\text{Th}]
\]

The isolation of the formally Th$^{2+}$ ion in (Cp$_3$Th)$^{1-}$ is likely aided by the stabilization of the potassium counter-cation by the 18-crown-6 and 2.2.2-cryptand ligands. This was also observed with U$^{2+}$ in the (Cp$_3$U)$^{1-}$ anion$^4$ and in the (Cp$_3$Ln)$^{1-}$ complexes of the new Ln$^{2+}$ ions.$^1$ In the absence of these

\[\text{[Cp}_3\text{Th][K(18-crown-6)][THF]_2]}_3 \rightarrow \text{[K(18-crown-6)][Cp}_3\text{Th}]
\]

Fig. 3 Contour plots of (a) the LUMO of Cp$_3$Th and (b) the HOMO of the (Cp$_3$Th)$^{1-}$ anion in 3. Contour value is 0.05.

Fig. 4 Molecular structure of Cp$_3$Th(C$_8$H$_8$), 4. Thermal ellipsoids are drawn at the 50% probability level and hydrogen atoms are omitted for clarity. Th–C(C$_8$H$_8$) distances (Å): Th–C12, 2.815(4); Th–C13, 2.841(4); Th–C14, 2.769(3); Th–C15, 2.736(4).
potassium-stabilizing chelates, isolation of $\text{Th}^{2+}$ appears to be more difficult as described in a 2001 paper by Lappert and co-workers on the formation of $\text{Cp}_2\text{Th}$ by Na–K reduction of $\text{Cp}_2\text{ThCl}$. In that paper, Lappert reports that treatment of $\text{Cp}_2\text{ThCl}$ with excess Na–K alloy caused the initially blue solution (presumably $\text{Cp}_2\text{Th}$) to change to dark green. They isolated a diamagnetic green compound they postulated to be $[\text{K(THF)}_3][\text{THCp}_2]$ and/or $\text{THCp}_2(\text{THF})_2^-$ but they could not characterize it or obtain reproducible analytical results. Hence, the ($\text{Cp}_2\text{Th}$)$^{1-}$ anion was probably generated over 10 years ago, but could not be isolated in pure form as a simple $[\text{K(THF)}_3]^-$ salt.

In summary, although it is difficult to obtain $\text{Th}^{1+}$ complexes, further reduction is still possible with thorium: the $+1$ oxidation state diversity for the f elements is further as attempts are made to synthesize soluble molecular complexes. The $\text{Th}^{2+}$ complexes provide the first examples of an isolable ion with a 6$d^2$ electron configuration, the configuration possible for fourth row transition metal congeners of $\text{Hf}^{2+}$ or $\text{Ta}^{3+}$. The synthesis of these complexes demonstrates the power of specific ligand fields to generate new ground states with actinides. The identification of $\text{Th}^{2+}$ is more evidence that the oxidation state diversity for the f elements is still increasing. Stabilization of higher-lying d orbitals by the ligand field appears to be a key factor in isolating these new ions and provides a new option in expanding the oxidation state chemistry of these elements. This approach should be pursued further as attempts are made to synthesize soluble molecular complexes of +1 ions of these metals.

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Notes and references

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