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TiCl₃ forms colorless crystals of octaammine titanium(III) chloride ammonia (1/6), [Ti(NH₃)₈]Cl₃ · 6 NH₃, which presents the first example of a homolectic, square-antiprismic coordination sphere for monodentate ligands around a Ti(III)-cation and the first structurally characterized octaammine complex of a transition metal. Chemical evidence shows that the absorption in the [Ti(NH₃)₈]Cl₃-molecule is clearly red-shifted in comparison to the absorption of the well-known [Ti(H₂O)₆]Cl₃-cation. An excess of TiCl₃ reacts with UF₄ in anhydrous liquid ammonia under abstraction of three fluoride ions and the compound octaammine fluorido uranium(IV) chloride ammonia (1/3.5), [UF(NH₃)₈]Cl₃ · 3.5 NH₃, is formed which shows a distorted threefold-capped trigonal-prismatic coordination sphere around U(IV). The compound presents a rare example of coordination number nine in mononuclear U(IV)-complexes, and is the first where the ligands are simple inorganic species. Due to the similarity of NH₃ and H₂O as solvents, the finding presents an important aid for the speciation of actinoids in aqueous solutions as well.

In the recent decades uranium chemistry experienced a renaissance, as more “non-nuclear” uses of uranium compounds, for example, in small molecule activation, or catalysis were investigated. Also, the workup of radioactive wastes and actinoid containing nuclear fuels, the selective extraction of actinoids, as well as the understanding of their geological fate in the environment after an accident, requires a profound knowledge of actinoid species in solution. Single crystal X-ray structures would be of aid for the assessment of potential structural motifs in the solution chemistry of the actinoids. However, structural information from single crystal X-ray diffraction was often not available asolation and oxolation reactions occur with actinoids in aqueous solutions. These were believed to lead to “ill-defined structures and chemistry” and thus it remained crystallographically unexplored. The structural chemistry of actinoid complexes obtained from aqueous solutions is therefore rather poorly understood. Liquid ammonia is a solvent system similar to water, and it may serve as a model system to obtain crystalline actinoid species which are otherwise difficult or impossible to isolate from aqueous media. Liquid ammonia shows a much lower autoprotolysis and has a broader pH range which may allow easier access to products coming from protonation and deprotonation reactions. The literature on the coordination chemistry of uranium with only simple, inorganic, monodentate ligands, with exception of the aqua ligand, is very scarce compared to the magnitude of literature of multidentate-binding organic ligands. Uranium compounds may feature various coordination numbers, often from six to eight, but also higher in the case of multidentate ligands, and even coordination numbers of twelve or more, for example in the borohydrides, are known. A coordination number of nine for monodentate ligands is however rare and has, to the best of our knowledge, been reported only for the threefold capped trigonal prismatic cations of Ba³⁺,[13] La³⁺,[14] Sm³⁺,[15] and for uranium compounds with DMSO, DMF, or acetonitrile as a ligand.[16–19] Our compound seems to be a rare example of such a threefold-capped trigonal-prismatic coordination sphere where only simple inorganic ligands are present on the uranium atom. We have previously investigated the reactions of UF₄ and UF₆ with anhydrous ammonia,[20] in our attempts to identify usable fluoride ion acceptors for the liquid ammonia system, and in order to expand the chemistry of UF₄, we report here the usage of titanium(III) chloride as a fluoride ion acceptor in anhydrous ammonia besides the unusual coordination spheres of U(IV) and Ti(III) in the resulting compounds.

The coordination chemistry of titanium has been extensively reviewed.[21–24] Titanium(III)-complexes of the formula types TiL₆³⁺, TiL₆L₅⁻ or TiL₅L₄⁻ show an octahedron-like coordination. In aqueous solution the hexaqua-cation [Ti(H₂O)₆]³⁺ is known.[25] In a reaction of TiI₃ in liquid ammonia at room temperature, only a byproduct with the composition [(NH₃)₃Ti−O−Ti(NH₃)₃]I₃−NH₃ (octahedral coordination) was observed.[26] A square-antiprismic coordination sphere for titanium has been reported for multidentate ligands, such as bidentate binding oxalate, and tridentate binding C₆H₅N₃O₃.[27] and in the compounds TiBr₆,[28] and TiMn₆P₁₂ (Ti(IV)).[29] For monodentate ligands, a Ti atom was observed in a meta-organic-framework compound which was coordinated by seven H₂O ligands and one hydroxide anion in a distorted square-antiprismic manner.[30] Octammine complexes of other metal cations are also quite rare, and structural proof is only available in case of the two-fold capped trigonal prismatic cations [M(NH₃)₈]³⁺ (M = Ca, Sr, Ba),[31–34] and the square-antiprismic cation [Yb(NH₃)₈]³⁺.[14,35] During the synthesis of TiX₃ · 6 NH₃ (X = Cl, Br) colorless-greyish compounds with the composition of TiBr₃ · 8 NH₃ and TiCl₃ · 7 NH₃ have been observed without the possibility of further characterization.[32] Other investigations in the system TiCl₃/NH₃ showed that also...
colorless-greyish TiCl$_3$·6 NH$_3$ was always obtained as the only product.\cite{37,38} In all these cases, the colorless appearing solids were allowed to warm to room temperature after removal of the excess liquid NH$_3$ and the compositions were then determined by elemental analyzes.

Pure TiCl$_3$ reacts with anhydrous liquid ammonia at ~40 °C under formation of colorless crystals of octaamine titanium(III) chloride ammonia(1/6), [Ti(NH$_3$)$_3$]Cl$_3$·6 NH$_3$ of which the composition was elucidated using single-crystal X-ray analysis at low temperature (details available in Table S1). The observed color is in agreement with reports on other Ti(III)-ammine complexes (see above) and pale blue colors may be easily overlooked as the moisture and temperature sensitive crystals had to be manipulated in dry, cold perfluoro-ether oil. The compound crystallizes in the monoclinic space group $P2_1/c$. The asymmetric unit contains a Ti(1) atom on the 2e position which is coordinated by eight ammine ligands (Ni1 to N(4) and symmetry equivalents) in the shape of a square antiprism (Fig. 1). Due to symmetry, the centers of both squares are 1.2619(7) Å away from the titanium atom and are tilted only by 1° towards each other. Hoffmann and coworkers analyzed the deviation from $S_4$-symmetry by measuring the angle between the metal-ligand bond and the $S_4$-axis.\cite{39} In an ideal system this angle should be 59.22°. Keper however showed that the ideal $S_4$-symmetry is slightly less stable compared to a marginally distorted arrangement of the ligands where the respective angle is 57.1°.\cite{40} In the titanium compound the angles are observed with 57.1° (Ti(1)−N(1)−S$_4$-axis) and 56.2° (Ti(1)−N(2)−S$_4$-axis) and thus the coordination polyhedron is best described as distorted square-antiprismatic. The Ti−N-distances are observed in the coordination polyhedron is best described as distorted square-antiprism (Fig. 1). The unit cell of the compound [Ti(NH$_3$)$_3$]Cl$_3$·6 NH$_3$ can be converted to yield the respective compound. The decomposition of TiCl$_3$·6 NH$_3$ has been studied in the temperature range from ~40 to +450 °C.\cite{43} At room temperature TiCl$_3$·6 NH$_3$, as well as a compound with the composition TiCl$_3$·5 NH$_3$, were both reported to be stable.\cite{43} TiCl$_3$·6 NH$_3$ decomposes to TiCl$_3$·5 NH$_3$ at +7 °C.\cite{43} The crystals of [Ti(NH$_3$)$_3$]Cl$_3$·6 NH$_3$ burst upon warming to temperatures higher than approximately ~40 °C without autogeneous pressure present. At room temperature TiCl$_3$·5 NH$_3$ was obtained as evidenced by elemental analysis (calc.: N:29.26%; H:6.32%, det.:29.83%, 6.231%).

Aqueous solutions of Ti(III) are known to be violet/blue. Typically they show small extinction coefficients as the electronic $d$-$d$ transition is forbidden. [Ti(NH$_3$)$_3$]$^{3+}$ crystallizes in colorless crystals of [Ti(NH$_3$)$_3$]Cl$_3$·6 NH$_3$, suggesting that it might show interesting electronic differences in comparison to the known Ti(III) compounds. Because the compound is not stable above ca. ~40 °C, we could not obtain a UV/VIS spectrum. Instead, we investigated the spectroscopic properties of [Ti(NH$_3$)$_3$]$^{3+}$ using $ab$ initio quantum chemical methods (high level coupled cluster calculations at the CC2/def2-TZVPP level of theory, for further computational details see Experimental. We first investigated the well-known
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N(4), N(5), N(7), respectively, are not parallel to each other which are formally formed by the atoms N(1), N(2), F(1) and distorted, trifold-capped trigonal prism. The trigonal faces, which are capped by the ammine ligands N(6), N(8), and N(3) with distances of 1.755(2), 1.734(2), and 1.671(2) Å, to these planes, respectively. The nitrogen atoms of the tetragonal face deviate only by ± 0.049(1) Å from the respective least-squares-planes.

The uranium atom is coordinated by one fluorine atom and eight ammine ligands (N(1-8)) forming the octaammine fluorido uranium(IV) cation \([\text{UF}(\text{NH}_3)_8]^{3+}\). The imaginary edges of the trigonal prism are shown dashed. Displacement ellipsoids are shown at the 70% probability level at 123 K, H-atoms isotropic with arbitrary radii. Selected atomic distances [Å]: U(1)—F(1) 2.1174(11), U(1)—N(1) 2.5599(17), U(1)—N(2) 2.5670(17), U(1)—N(3) 2.6302(16), U(1)—N(4) 2.6106(16), U(1)—N(5) 2.6094(17), U(1)—N(6) 2.5966(19), U(1)—N(7) 2.5590(16), U(1)—N(8) 2.5875(17).

The identity of the resulting titanium(III) compound could not be established besides numerous attempts and is therefore referred to as “\(\text{TiF}_3\)”. It is obtained in the form of a greyish precipitate of variable N, H, and F content, and is X-ray amorphous. Its IR spectrum shows that besides bound NH₃ molecules also NH₃⁻ and eventually NH₂⁻ anions may be present. The compound \([\text{UF}(\text{NH}_3)_8]\text{Cl}_3 \cdot 3.5 \text{NH}_3\) is obtained in the form of green crystals. The composition has been determined using single-crystal X-ray analysis (details in Table S1). The atoms of the asymmetric unit of \([\text{UF}(\text{NH}_3)_8]\text{Cl}_3 \cdot 3.5 \text{NH}_3\) occupy only two crystallographic sites: The atoms U(1), F(1), N(1) to N(10), N(12), and Cl(1) to Cl(3) reside on the 8f position and the nitrogen atom N(11) occupies the 4e position. The uranium atom is coordinated by one fluorine atom and eight ammine ligands (N(1-8)) forming the octaammine fluorido uranium(IV) cation \([\text{UF}(\text{NH}_3)_8]^{3+}\), shown in Fig. 3. The coordination polyhedron may be best described as a distorted, trifold-capped trigonal prism. The trigonal faces, which are formally formed by the atoms N(1), N(2), F(1) and N(4), N(5), N(7), respectively, are not parallel to each other but deviate by 5.24(8)°. The centers of these faces are 1.872(1) and 1.648(1) Å away from the U atom, respectively. The tetragonal planes show angles of 63.27(3), 58.37(4) and 58.38(4)° towards each other. They are capped by the ammine ligands N(6), N(8), and N(3) with distances of 1.755(2), 1.734(2), and 1.671(2) Å, to these planes, respectively. The nitrogen atoms of the tetragonal face deviate only by ± 0.049(1) Å from the respective least-squares-planes.
see the Supporting Information. Fig. 4 shows the unit cell of the compound. Upon warming to room temperature an X-ray amorphous powder is obtained of which the IR spectrum shows the presence of ammine ligands. As the compound cannot be separated from the titanium compounds, elemental analysis was not undertaken. Our compound seems to be a rare example of a mononuclear uranium complex with monodentate ligands showing coordination number nine, and only a few other examples have been characterized, however with organic ligands such as dimethylformamide, acetonitrile, and dimethylsulfoxide. As we could characterize such a species in liquid ammonia is an important addition and seems to present the first example of a mononuclear uranium complex with monodentate ligands. Due to the similarity of the aqueous and ammonia solutions as well.

The compound [Ti(NH$_3$)$_3$]Cl$_3$ · 6 NH$_3$ presents so far the compound with the highest observed ammonia content in the system TiX$_3$ / NH$_3$ (X = Cl, Br). It contains a square-antiprismatic octaamine titanium(III) cation, which, to the best of our knowledge, represents the first example of this coordination number with monodentate homoleptic ligands on Ti. Also, the compound seems to be the first example of an octaammine complex of a transition metal. Interestingly, the titanium(III)-compound appears colorless to the eye. As it is unstable towards the loss of ammonia above ~40 °C, further analytic methods were hampered. Quantum chemical calculations show that the absorption in [Ti(NH$_3$)$_3$]$_{11}^+$ is clearly red-shifted in comparison to the absorption of the well-known [Ti(H$_2$O)$_6$]$_{11}^+$, resulting in a pale blue complementary color that might be difficult to observe with the naked eye.

Titanium(III)-chloride seems to be a fluoride ion acceptor usable for the liquid ammonia system. It is able to subtract three fluoride ions from UF$_5$ and green crystals of [UF(NH$_3$)$_3$]Cl$_3$ · 3.5 NH$_3$ are formed as a product. The [UF(NH$_3$)$_3$]$_{11}^+$ cation is best described as a distorted, trifold-capped trigonal prism. Despite the coordination number of nine, the U–F-distance is quite short with 2.117(1) Å, thus showing the high Lewis-acidity of U(IV). The compound seems to present the first example of a mononuclear uranium complex of coordination number nine with inorganic monodentate ligands. Due to the similarity of the aqueous and the ammonia solvent systems, we believe that the existence of such a species in liquid ammonia is an important addition and aid for the knowledge and detection of actinoids in aqueous solutions. Eventually, the respective aquo complex [UF(H$_2$O)$_3$]$_{11}^+$ can also be detected in dilute aqueous solutions from which UF$_5$ or its hydrates do not yet precipitate.

Notes and references

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