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# **{Np<sub>38</sub>} clusters: the missing link in the largest poly-oxo cluster series of tetravalent actinides†**

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**Two poly-oxo cluster complexes of tetravalent neptunium (Np(IV)), Np<sub>38</sub>O<sub>56</sub>Cl<sub>18</sub>(bz)<sub>24</sub>(THF)<sub>8</sub>·*n*THF and Np<sub>38</sub>O<sub>56</sub>Cl<sub>42</sub>(ipa)<sub>20</sub>·*m*ipa (bz = benzoate, THF = tetrahydrofuran, and ipa = isopropanol), were obtained via solvothermal synthesis and structurally characterised by single-crystal X-ray diffraction. The {Np<sub>38</sub>} clusters are comparable to the analogous {U<sub>38</sub>} and {Pu<sub>38</sub>} motifs, filling the gap in this largest poly-oxo cluster series of tetravalent actinides.**

Owing to its diversity as well as its technological importance in the nuclear industry, the polymer and cluster chemistry of actinides (An) has been flourishing since the last decade.<sup>1–5</sup> In particular, the poly-oxo/hydroxo polymer and cluster complexes of tetravalent actinides (An(IV)) have received considerable attention,<sup>6–20</sup> as the formation of these complexes stems primarily from their hydrolysis<sup>21–24</sup> and, hence, it would have significant implications for the natural and engineered aqueous systems associated with the nuclear industry.<sup>25</sup> The largest poly-oxo An(IV) cluster reported thus far is the {An<sub>38</sub>} complex, consisting of 38 An(IV) centres bridged by 56 oxygens. This type of cluster complex has been synthesised and characterised for U(IV)<sup>9,26</sup> and Pu(IV),<sup>13,15</sup> and this cluster motif could be stable in solution in a colloidal form.<sup>13,15,27</sup> In the periodic table, neptunium (<sup>93</sup>Np) is present between <sup>92</sup>U and <sup>94</sup>Pu. Despite its importance in nuclear fuel reprocessing and radioactive waste management,<sup>25</sup> the research on Np always lags behind those on U and Pu,<sup>28</sup> which is also the case for the chemistry of poly-oxo/hydroxo polymers and clusters. In order to fill the gap between the {U<sub>38</sub>} and {Pu<sub>38</sub>} clusters and to complete a series of these largest poly-oxo An(IV)

cluster complexes, we report herein the synthesis and characterisation of the first {Np<sub>38</sub>} cluster complexes, which are also the largest single molecules of Np reported thus far.

The first {Np<sub>38</sub>} complex, Np<sub>38</sub>O<sub>56</sub>Cl<sub>18</sub>(bz)<sub>24</sub>(THF)<sub>8</sub>·*n*THF‡ (1, bz = benzoate, THF = tetrahydrofuran), was obtained via solvothermal synthesis with NpCl<sub>4</sub>, benzoic acid, THF and deionised water (Sections 1 and 2 in the ESI†), which is a slight modification of the synthesis of the {U<sub>38</sub>} complex.<sup>9</sup> After 1 day of heating at 400 K, purple/brown crystals with an octahedral shape were deposited (Fig. 1, left). Single-crystal X-ray diffraction (SC-XRD) measurements on the obtained crystals reveal the discrete {Np<sub>38</sub>} motif shown in Fig. 2a. The second {Np<sub>38</sub>} complex, Np<sub>38</sub>O<sub>56</sub>Cl<sub>42</sub>(ipa)<sub>20</sub>·*m*ipa‡ (2, ipa = isopropanol), was synthesised solvothermally from a mixture of NpCl<sub>4</sub> and benzoic acid in isopropanol (Sections 1–3 in the ESI†). Heating the sample mixture at 370 K for 3 days resulted in the formation of purple/brown crystals with an octahedral shape (Fig. 1, right). The complex structure determined by SC-XRD shows another {Np<sub>38</sub>} motif, as illustrated in Fig. 2b.

Both compounds 1 and 2 crystallise in the tetragonal space group *I4/m* (Table S1 in the ESI†), which is the same as that observed for the analogous {U<sub>38</sub>} clusters U<sub>38</sub>O<sub>56</sub>Cl<sub>18</sub>(bz)<sub>24</sub>(THF)<sub>8</sub>·8THF<sup>9</sup> and U<sub>38</sub>O<sub>56</sub>Cl<sub>42</sub>(H<sub>2</sub>O)<sub>2</sub>(ipa)<sub>20</sub>·*x*ipa.<sup>26</sup> Both the {Np<sub>38</sub>} clusters are composed of a {Np<sub>14</sub>} core (light green polyhedra in Fig. 2) surrounded by six tetranuclear {Np<sub>4</sub>} subunits (blue and dark

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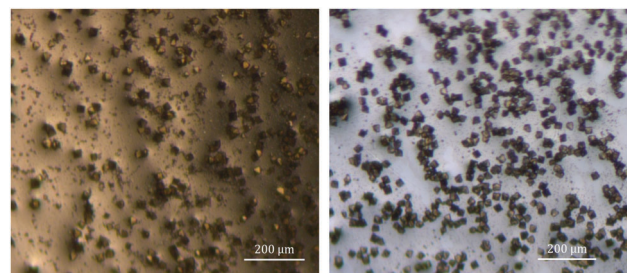


Fig. 1 Optical micrographs of single crystals of the {Np<sub>38</sub>} compounds synthesised from THF (1, left) and isopropanol (2, right).



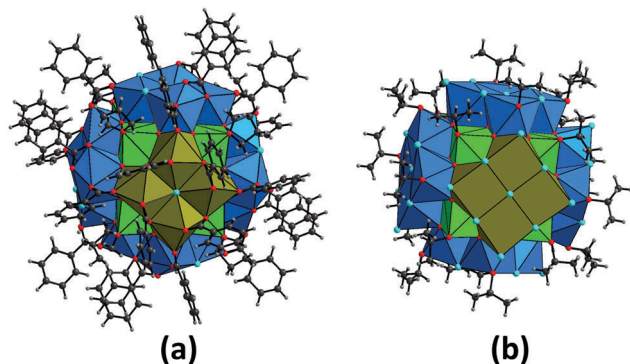


Fig. 2 Molecular structures of the two  $\{Np_{38}\}$  clusters  $Np_{38}O_{56}Cl_{18}(bz)_{24}(THF)_8$  (**1**, a) and  $Np_{38}O_{56}Cl_{42}(ipa)_{20}$  (**2**, b).§ The coordination geometry around neptunium atoms (as  $Np^{4+}$ ) is illustrated with coloured polyhedra, whilst carbon (black), chlorine (light blue), hydrogen (grey) and oxygen (red) atoms are shown as balls. The cubic  $\{Np_{14}\}$  cores are depicted with light green, whilst the exterior  $\{Np_4\}^{tetra}$  and  $\{Np_4\}^m$  subunits adhering to the  $\{Np_{14}\}$  core are illustrated with blue and dark brown, respectively.

brown polyhedra in Fig. 2). In the  $\{Np_{14}\}$  core, three crystallographically distinct Np atoms (Np1, Np2 and Np3) are packed in a dense manner, forming a primitive unit of the fluorite structure (Fig. S1 in the ESI†) which is the basis of bulk  $NpO_2$ .<sup>29,30</sup> The eight corners of the cubic  $\{Np_{14}\}$  core are all occupied by the oxygen atoms of THF- or isopropanol molecules for **1** and **2**, respectively (Fig. S1 in the ESI†). Each face of the cubic  $\{Np_{14}\}$  core is further decorated with the  $\{Np_4\}$  subunits, where there is a significant difference between **1** and **2**. In both the  $\{Np_{38}\}$  compounds, two types of  $\{Np_4\}$  subunits appear. The first type (referred to as “ $\{Np_4\}^{tetra}$ ” hereafter) appears four times by symmetry operation with respect to the tetragonal axis, whilst the second type (referred to as “ $\{Np_4\}^m$ ” hereafter) appears twice around the  $\{Np_{14}\}$  core as a result of the perpendicular mirror plane operation. The coordination polyhedra of the Np atoms in the inner  $\{Np_{14}\}$  core are cubic, whilst those in the exterior  $\{Np_4\}$  subunits are square antiprismatic polyhedra (Fig. 3). This results in two different types of oxo-bridging groups in the  $\{Np_{38}\}$  clusters;  $\mu_4$ -O with Np–O distances of 2.294(9)–2.408(9) and 2.28(4)–2.42(4) Å for **1** and **2**, respectively, and  $\mu_3$ -O with Np–O distances of 2.203(9)–2.335(10) and 2.15(4)–2.305(3) Å for **1** and **2**, respectively. These Np–O distances are comparable to those in the fluorite-based  $NpO_2$  structure (2.353–2.354 Å),<sup>29,30</sup> suggesting that the Np–O framework in the  $\{Np_{38}\}$  clusters could also be comparable to that in the bulk  $NpO_2$ .

In compound **1**, the  $\{Np_4\}^{tetra}$  subunit (blue polyhedra in Fig. 2a and 3a) is composed of three distinct Np centres (Np4, Np5 and Np6). The four Np atoms are linked *via* either  $\mu_2/\mu_4$ -Cl atoms or bidentately coordinating the carboxylate groups of bz, forming a ninefold coordination geometry with distorted trideca- and undecahedra around Np4 and Np5, respectively, and an eightfold geometry with a distorted nonahedron around Np6 (Fig. 3a). Each  $\{Np_4\}^{tetra}$  subunit adheres to one side of the cubic  $\{Np_{14}\}$  core *via* twelve O atoms facing the core, covering the four sides of the  $\{Np_{14}\}$  cube. On the other hand, the  $\{Np_4\}^m$  subunit (dark brown polyhedra in Fig. 2a and 3b) is composed of a single type of a distinct Np centre (Np7). The four Np atoms in the

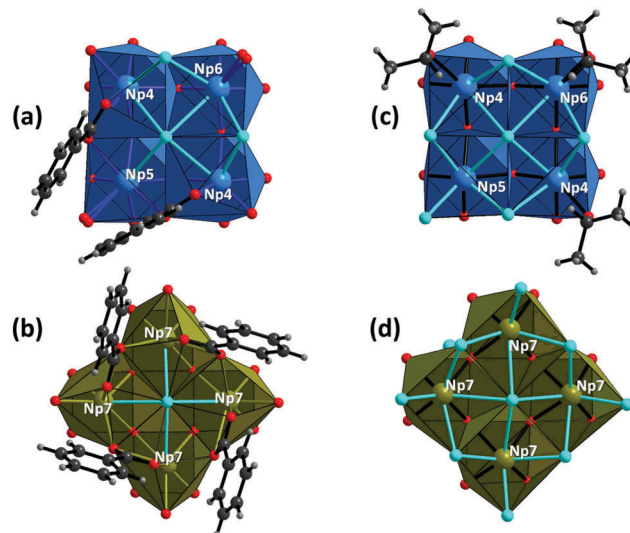
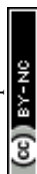


Fig. 3 Top-side views of the  $\{Np_4\}$  subunits in **1** and **2**; the  $\{Np_4\}^{tetra}$  and  $\{Np_4\}^m$  subunits in **1** (a and b, respectively) and those in **2** (c and d, respectively).§ All these subunits contain unique  $\mu_4$ -bridging Cl atoms. The coordination geometry around neptunium atoms (as  $Np^{4+}$ ) is illustrated with blue and dark brown polyhedra ( $\{Np_4\}^{tetra}$  and  $\{Np_4\}^m$ , respectively), whilst carbon (black), chlorine (light blue), hydrogen (grey) and oxygen (red) atoms are shown as balls.

$\{Np_4\}^m$  subunit are linked *via* one  $\mu_4$ -Cl atom and four carboxylate groups of bz, forming a ninefold coordination geometry with a dodecahedron around the Np7 atoms (Fig. 3b). This  $\{Np_4\}^m$  subunit covered the rest of the two sides of the  $\{Np_{14}\}$  cube, and is further connected with the  $\{Np_4\}^{tetra}$  subunit by the bidentate carboxylate groups of bz to overlay the  $\{Np_{14}\}$  core (Fig. 2a).

Despite the presence of benzoic acid in the initial sample solution, no benzoate groups are involved in the formation of the  $\{Np_{38}\}$  cluster in **2**, which is in contrast to **1**. The exterior  $\{Np_4\}$  subunits in **2** are composed of the O atoms of isopropanol molecules,  $Cl^-$  ions and the  $O_{oxo}$  groups shared with the  $\{Np_{14}\}$  core. The  $\{Np_4\}^{tetra}$  subunit in **2** is composed of three distinct Np centres (Np4, Np5 and Np6), all of which form an eightfold square antiprismatic geometry (Fig. 3c). In the  $\{Np_4\}^m$  subunit of **2**, there is only a single distinct Np centre (Np7) which is surrounded by four  $O_{oxo}$  groups shared with the  $\{Np_{14}\}$  core and four  $Cl^-$  ions, eventually forming an eightfold square antiprismatic geometry as well (Fig. 3d). In a similar manner to the arrangement in **1**, the six  $\{Np_4\}$  subunits decorate the exterior of the cubic  $\{Np_{14}\}$  core to form an  $\{Np_{38}\}$  cluster.

The chemical formulae of  $[Np_{38}O_{56}Cl_{18}(bz)_{24}(THF)_8]$  (**1**) and  $[Np_{38}O_{56}Cl_{42}(ipa)_{20}]$  (**2**) derived from SC-XRD both exhibit an excess negative charge of  $-2$ , assuming that the Np atoms in the clusters are all tetravalent (*i.e.*  $Np^{4+}$ ). No cationic species are identified in the crystal packing of **1** and **2** either, indicating that the  $\{Np_{38}\}$  cluster units should be neutral. This discrepancy can be, however, explained by the partial replacement of chloride anions ( $Cl^-$ ) with neutral water molecules ( $H_2O$ ) in the  $\{Np_4\}$  subunits and/or the replacement of the  $\mu_3$ -oxo groups with the hydroxo ones in the inner  $\{Np_{14}\}$  core. Further detailed discussions are provided in the ESI† (Section 3).



Albeit a series of  $\{\text{An}_{38}\}$  clusters (*i.e.*  $\{\text{U}_{38}\}$ ,<sup>9,26</sup>  $\{\text{Np}_{38}\}$  in this study, and  $\{\text{Pu}_{38}\}$ <sup>13,15</sup>) were successfully characterised, their formation mechanism has been unrevealed even to date. All the  $\{\text{An}_{38}\}$  clusters characterised thus far are composed of an inner  $\{\text{An}_{14}\}$  core decorated with six exterior  $\{\text{An}_4\}$  subunits. Given this construction manner, it is reasonable to infer that the formation of the primary  $\{\text{An}_{14}\}$  core is followed by the attachment of the  $\{\text{An}_4\}$  subunits to the surface of the cubic  $\{\text{An}_{14}\}$  core. Owing to their strong ololation/oxolation tendency,<sup>31</sup> An(IV) can form a variety of oligomer species<sup>2</sup> including soluble  $\mu_2$ -hydroxo-bridged dinuclear species,<sup>7,17,32</sup> which could further evolve into hexanuclear species *via* hydrolysis.<sup>6,10,11,14</sup> A similar evolution of such oligomer species was also observed for Ce(IV),<sup>33,34</sup> a chemical analogue of An(IV). The union of di- and hexanuclear species could also lead to the formation of  $\{\text{An}_{12}\}$  complexes.<sup>8</sup> However, to the best of our knowledge, no  $\{\text{An}_{14}\}$  complexes have been characterised for An(IV) thus far, indicating that the  $\{\text{An}_{14}\}$  motif is probably not stable at least as a discrete species. In contrast, several discrete  $\{\text{An}_4\}$  complexes have been characterised for Th(IV)<sup>35</sup> and U(IV),<sup>36–43</sup> seven of which exhibit a planar tetranuclear arrangement that is structurally comparable with the  $\{\text{An}_4\}$  subunits in the  $\{\text{An}_{38}\}$  clusters (Section 4 in the ESI†). A striking difference between the  $\{\text{An}_4\}$  subunits and the discrete tetranuclear An(IV) complexes is, however, the presence/absence of  $\mu_4$ -bridging groups. As illustrated in Fig. 3, there are unique  $\mu_4$ -bridging Cl atoms situated at the centre of the  $\{\text{Np}_4\}$  subunits, which are observed for the whole series of  $\{\text{An}_{38}\}$  clusters. On the other hand, none of the discrete tetranuclear An(IV) complexes contains  $\mu_4$ -bridging groups (Table S2 and Fig. S2 in the ESI†), except one Th(IV) complex<sup>35</sup> containing a  $\mu_4$ -bridging oxo group to form a unique non-planar boat conformation arrangement (Fig. S3 in the ESI†). Instead, these discrete tetranuclear complexes are composed of  $\mu_2$ - and  $\mu_3$ -bridging groups (Table S2 and Fig. S3 in the ESI†), suggesting that the planar  $\{\text{An}_4\}$  motif with a  $\mu_4$ -bridging group may also not be stable as a discrete species. Given all these facts, the formation process of the  $\{\text{An}_{38}\}$  clusters could be surmised as follows:

(1) the primitive but transient  $\{\text{An}_{14}\}$  core is formed *via* the ololation/oxolation of precursor species (*e.g.* dinuclear and/or hexanuclear species),

(2) owing to an extremely large negative charge of the primitive  $\{\text{An}_{14}\}$  core ( $-72$  based on the formula  $\text{An}_{14}\text{O}_{64}$  (Fig. S1 in the ESI†)), cationic species in the system (*i.e.*  $\text{An}^{4+}$ ) are further attracted to the surface of the  $\{\text{An}_{14}\}$  core immediately after the formation of the primitive core, forming dense  $\{\text{An}_4\}$  subunits containing  $\mu_4$ -bridging groups on the surface, and

(3) the attachment of six  $\{\text{An}_4\}$  subunits on each face of the cubic  $\{\text{An}_{14}\}$  core neutralises the negative charge of the  $\{\text{An}_{14}\}$  core, eventually stabilising the whole unit as  $\{\text{An}_{38}\}$ .

Based on this hypothetical formation process, it is obvious that the faces of the primitive  $\{\text{An}_{14}\}$  core provide a sort of “substrate” for the formation of unique planar  $\mu_4$ -bridged  $\{\text{An}_4\}$  subunits. In other words, such a planar  $\mu_4$ -bridged  $\{\text{An}_4\}$  motif could be formed and stabilised only when an appropriate substrate exists in the system.

As previously mentioned, the inner  $\{\text{An}_{14}\}$  core in the  $\{\text{An}_{38}\}$  cluster is a primitive unit of the fluorite-based  $\text{AnO}_2$  structure.

The  $\{\text{An}_4\}$  subunits in the cluster also show a closer structural conformity to the bulk  $\text{AnO}_2$  structure as compared with the discrete tetranuclear An(IV) complexes (Fig. S4 in Section 4, ESI†). All these facts indicate that the poly-oxo  $\{\text{An}_{38}\}$  clusters can be the origin of the formation of  $\text{AnO}_2$  in solution. As a matter of fact, the  $\{\text{An}_{38}\}$  clusters can easily evolve into bulk  $\text{AnO}_2$  by moderate hydrolysis.<sup>9,26</sup> Given the electroneutrality of the  $\{\text{An}_{38}\}$  clusters, the  $\{\text{An}_{38}\}$  motif will no longer attract additional metal cations (*i.e.*  $\text{An}^{4+}$ ) to form larger clusters. Hence, the  $\{\text{An}_{38}\}$  unit is probably the largest poly-oxo An(IV) cluster stabilised in solution, which is also the limiting point that defines the border between discrete poly-oxo oligomer/cluster complexes and insoluble bulk  $\text{AnO}_2$ , including colloidal species or aggregates.

In summary, this study succeeded in synthesising and structurally characterising the two poly-oxo Np(IV) cluster complexes **1** and **2** which are composed of 38 Np atoms. The characterised  $\{\text{Np}_{38}\}$  clusters are the largest discrete Np complexes reported thus far, filling the gap between the already reported  $\{\text{U}_{38}\}$  and  $\{\text{Pu}_{38}\}$  clusters to complete a series of  $\{\text{An}_{38}\}$  cluster complexes. Although hexavalent An cations (as actinyl(vi) cations:  $\text{AnO}_2^{2+}$ ) can form poly-oxo clusters larger than 100-mer based on the cage structure which is not directly comparable with open clusters,<sup>3</sup> the  $\{\text{An}_{38}\}$  motif is probably the largest open cluster unit for the poly-oxo An(IV) complexes that can be stabilised as a discrete species in solution. A series of poly-oxo  $\{\text{An}_{38}\}$  clusters (An = U, Np and Pu) exhibits a significant structural similarity, suggesting a similar ololation/oxolation (*i.e.* hydrolysis) behaviour amongst these lighter An(IV) series. A comparison of the series of  $\{\text{An}_{38}\}$  clusters with the large poly-oxo clusters of other metals (*e.g.*  $\text{Ti}^{44}$  or  $\text{Bi}^{45}$ ) will further highlight the peculiarity or generality of the chemistry of An(IV) on the periodic table, particularly in terms of hydrolysis and coordination chemistry.

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## Conflicts of interest

There are no conflicts to declare.

## Notes and references

‡ The Fourier maps of electronic density residues on the collected SC-XRD data show diffused peaks in the void between the  $\{\text{Np}_{38}\}$  units. These peaks probably correspond to neutral solvent molecules (*i.e.* THF in **1** and isopropanol in **2**) intercalated in the crystal structures, as observed in the analogous  $\{\text{U}_{38}\}$  compounds.<sup>9,26</sup> However, owing to the limited quality of the collected SC-XRD data, it is difficult to determine the positions of these intercalated solvent molecules. For this reason, the number of solvent molecules is not specified in the chemical formulae of **1** and **2**.

§ The carbon atoms of some benzoate (bz) molecules in **1** show disorder, statistically populating at two close sites with equivalent occupancy. This disorder is, however, not illustrated in Fig. 2a and 3a for clarity.

- 1 S. Hickam and P. C. Burns, in *Recent Development in Clusters of Rare Earths and Actinides: Chemistry and Materials*, ed. Z. Zheng, Springer-Verlag, Berlin, Heidelberg, 2017, vol. 173, pp. 121–153.
- 2 K. E. Knope and L. Soderholm, *Chem. Rev.*, 2013, **113**, 944–994.
- 3 J. Qiu and P. C. Burns, *Chem. Rev.*, 2013, **113**, 1097–1120.
- 4 T. Loiseau, I. Mihalcea, N. Henry and C. Volkringer, *Coord. Chem. Rev.*, 2014, **266–267**, 69–109.



- 5 W. Yang, T. G. Parker and Z.-M. Sun, *Coord. Chem. Rev.*, 2015, **303**, 86–109.
- 6 C. Tamain, T. Dumas, C. Hennig and P. Guilhaud, *Chem. – Eur. J.*, 2017, **23**, 6864–6875.
- 7 K. E. Knope, S. Skanthakumar and L. Soderholm, *Inorg. Chem.*, 2015, **54**, 10192–10196.
- 8 C. Falaise, C. Volkringer, C. Hennig and T. Loiseau, *Chem. – Eur. J.*, 2015, **21**, 16654–16664.
- 9 C. Falaise, C. Volkringer, J. F. Vigier, A. Beaurain, P. Roussel, P. Rabu and T. Loiseau, *J. Am. Chem. Soc.*, 2013, **135**, 15678–15681.
- 10 K. E. Knope and L. Soderholm, *Inorg. Chem.*, 2013, **52**, 6770–6772.
- 11 K. Takao, S. Takao, A. C. Scheinost, G. Bernhard and C. Hennig, *Inorg. Chem.*, 2012, **51**, 1336–1344.
- 12 B. Biswas, V. Mougél, J. Pecaut and M. Mazzanti, *Angew. Chem., Int. Ed.*, 2011, **50**, 5745–5748.
- 13 R. E. Wilson, S. Skanthakumar and L. Soderholm, *Angew. Chem., Int. Ed.*, 2011, **50**, 11234–11237.
- 14 S. Takao, K. Takao, W. Kraus, F. Emmerling, A. C. Scheinost, G. Bernhard and C. Hennig, *Eur. J. Inorg. Chem.*, 2009, 4771–4775.
- 15 L. Soderholm, P. M. Almond, S. Skanthakumar, R. E. Wilson and P. C. Burns, *Angew. Chem., Int. Ed.*, 2008, **47**, 298–302.
- 16 G. Nocton, F. Burdet, J. Pécaut and M. Mazzanti, *Angew. Chem., Int. Ed.*, 2007, **46**, 7574–7578.
- 17 R. E. Wilson, S. Skanthakumar, G. Sigmon, P. C. Burns and L. Soderholm, *Inorg. Chem.*, 2007, **46**, 2368–2372.
- 18 J. C. Berthet, P. Thuery and M. Ephritikhine, *Chem. Commun.*, 2005, 3415–3417.
- 19 L. M. Mokry, N. S. Dean and C. J. Carrano, *Angew. Chem., Int. Ed.*, 1996, **35**, 1497–1498.
- 20 D. W. Wester, *Inorg. Chem.*, 1982, **21**, 3382–3385.
- 21 *Chemical Thermodynamics of Thorium*, OECD Nuclear Energy Agency, Paris, France, 2007.
- 22 I. Grenthe, J. Fuger, R. J. M. Konings, R. J. Lemire, A. B. Muller, C. Nguyen-Trung Cregu and H. Wanner, *Chemical Thermodynamics of Uranium*, OECD-NEA, Paris, France, 2004.
- 23 R. Guillaumont, T. Fanghänel, J. Fuger, I. Grenthe, V. Neck, D. A. Palmer and M. H. Rand, *Update on the Chemical Thermodynamics of Uranium, Neptunium, Plutonium, Americium and Technetium*, Elsevier, Amsterdam, the Netherlands, 2003.
- 24 R. J. Lemire, J. Fuger, S. Spahiu, J. C. Sullivan, H. Nitsche, W. J. Ullman, P. Potter, P. Vitorge, M. H. Rand, H. Wanner and J. Rydberg, *Chemical Thermodynamics of Neptunium and Plutonium*, Elsevier, Amsterdam, the Netherlands, 2001.
- 25 *The Chemistry of the Actinide and Transactinide Elements*, 4th edn, Springer, The Netherlands, 2011.
- 26 N. P. Martin, C. Volkringer, N. Henry, X. Trivelli, G. Stoclet, A. Ikeda-Ohno and T. Loiseau, *Chem. Sci.*, 2018, **9**, 5021–5032.
- 27 C. Walther and M. A. Denecke, *Chem. Rev.*, 2013, **113**, 995–1015.
- 28 J. Ibers, *Nat. Chem.*, 2010, **2**, 996.
- 29 L. B. Asprey, F. H. Ellinger, S. Fried and W. H. Zacharlasen, *J. Am. Chem. Soc.*, 1955, **77**, 1707.
- 30 W. H. Zacharlasen, *Acta Crystallogr.*, 1949, **2**, 388–390.
- 31 M. Henry, J. P. Jolivet and J. Livage, *Struct. Bonding*, 1992, **77**, 153–206.
- 32 G. Johansson, *Acta Chem. Scand.*, 1968, **22**, 399–409.
- 33 C. Hennig, A. Ikeda-Ohno, W. Kraus, S. Weiss, P. Pattison, H. Emerich, P. M. Abdala and A. C. Scheinost, *Inorg. Chem.*, 2013, **52**, 11734–11743.
- 34 A. Ikeda-Ohno, S. Tsushima, C. Hennig, T. Yaita and G. Bernhard, *Dalton Trans.*, 2012, **41**, 7190–7192.
- 35 N. E. Travia, B. L. Scott and J. L. Kiplinger, *Chem. – Eur. J.*, 2014, **20**, 16846–16852.
- 36 C. Falaise, C. Volkringer and T. Loiseau, *Cryst. Growth Des.*, 2013, **13**, 3225–3231.
- 37 J. D. Rinehart, S. A. Kozimor and J. R. Long, *Angew. Chem., Int. Ed.*, 2010, **49**, 2560–2564.
- 38 L. Salmon, P. Thuéry and M. Ephritikhine, *Polyhedron*, 2006, **25**, 1537–1542.
- 39 J. Rebizant, M. R. Spirlet and C. Apostolidis, *Acta Crystallogr.*, 1992, **C48**, 452–454.
- 40 A. Domingos, N. Marques, A. Pires De Matos, I. Santos and M. Silva, *Polyhedron*, 1992, **11**, 2021–2025.
- 41 P. Charpin, G. Folcher, M. Nierlich, M. Lance, D. Vigner, A. Navaza and C. De Rango, *Acta Crystallogr.*, 1990, **C46**, 1778–1781.
- 42 N. Brianese, U. Casellato, F. Ossola, M. Porchia, G. Rossetto and P. Zanella, *J. Organomet. Chem.*, 1989, **365**, 223–232.
- 43 F. Calderazzo, G. Dell'Amico, M. Pasquali and G. Perego, *Inorg. Chem.*, 1978, **17**, 474–479.
- 44 M. Y. Gao, F. Wang, Z. G. Gu, D. X. Zhang, L. Zhang and J. Zhang, *J. Am. Chem. Soc.*, 2016, **138**, 2556–2559.
- 45 P. C. Andrews, G. B. Deacon, C. M. Forsyth, P. C. Junk, I. Kumar and M. Maguire, *Angew. Chem., Int. Ed.*, 2006, **45**, 5638–5642.

