Neptunyl(VI) centred visible LMCT emission directly observable in the presence of uranyl(VI)†

Sean D. Woodall,a Adam N. Swinburne,ab Nidhu Lal Banik,c Andrew Kerridge,‡e Poppy Di Pietro,e Christian Adam,cd Peter Kadenc and Louise S. Natrajan*ab

Room temperature detection of neptunyl(VI) LMCT emission in a coordination compound and in the presence of uranyl(VI) is reported for the first time. Differences in the excitation profiles of the complexes enable spectral editing so either exclusively neptunyl(VI) or uranyl(VI) emission is observed or a sum of the two.

There is an urgent need to address the many environmental problems the nuclear age has brought about; in particular, the identification of (trace) radiotopic actinide ions, their oxidation state and chemical form.1 In this regard, time resolved emission spectroscopy is becoming an invaluable tool with which to probe the electronic structure (oxidation state and coordination environment) of a given actinide ion in low concentrations that may represent those encountered in environmental and reprocessing conditions.2

The seminal work of Denning,3 amongst others, utilised the emissive properties of the uranyl(VI) ion to help construct the molecular orbital bonding diagram widely used today. However, corresponding studies on its periodic neighbour neptunyl(VI) are very limited.4 Currently, time-resolved spectroscopic studies of the uranyl(VI) ion are often used to provide valuable insight into the speciation of uranium species on minerals and sediments,5 particularly those present in geological disposal conditions, and to provide insight into the mechanisms behind promising bioremediation techniques for the immobilisation of aquatically mobile uranyl(VI) species.2 6 Laser induced emission spectroscopy of uranyl(VI) is also being used for its identification in aqueous wastes, in future sustainable partitioning and transmutation closed fuel cycles and in situations where the concentration and volume of the sample is too small (and the activity too high to consider concentration) for other analytical techniques to be of use.

The lack of analogous reports involving neptunyl (and plutonyl) ions is due in part to the relative redox instability of these ions in aqueous solutions (cf. uranyl(VI)).7 There are very few neptunyl(VI) compounds that are redox stable in solution since neptunyl(VI) is the most stable oxidation state, especially in aqueous (and therefore in most environmental and reprocessing) conditions. The relative proportion of each oxidation state (IV, V and VI) is heavily dependent on sample pH. In non-aqueous conditions, the + V oxidation state predominates; the neptunyl(V) chloride salt [NpO2Cl2(thf)] undergoes partial reduction in thf solution over several days producing an isolable mixed oxidation state neptunyl(V)–(VI) salt,8 whereas in MeOH, rapid reduction to neptunyl(VI) is observed. Clark reported that the addition of 18-crown-6 to perchloric or triflic acid solutions of NpO2(VI) ions resulted in the isolation of a NpO2(V) crown ether complex.9 Despite this, several pure oxidation state NpO2(V) complexes have been isolated.10 11

Here, we report on a redox stable neptunyl(VI) coordination compound that is prepared from both neptunyl(VI) and neptunyl(V) precursors with the ligand TPIP (tetraphenylimidodiphosphinate),12 that may well serve to model solvated forms of neptunyl(VI), in that no redox active ligands are present (eqn (1)). Previously, we reported that TPIP reacts with uranyl(VI) salts to yield discrete monometallic, bimetallic and trimetallic complexes [UO2(TPIP)(thf)], [UO2(TPIP)-(Cy3PO)], [UO2(TPIP)2]13 and [UO2(TPIP)3]13. Each uranyl(VI) ion possesses a unique luminescent fingerprint of emission maxima, spectral shape and radiative lifetimes to characterise the nuclearity and type of each complex. Limiting the absorption envelope of the chromophoric groups in the TPIP ligand to the UV (phenyl groups and relatively localized [N=–P–O] double bonds) gives rise to strongly emissive compounds in fluid solution at room temperature by...
inhibiting competitive back energy transfer processes from the emissive uranyl(VI) LMCT state. We reasoned that the same principles should apply for neptunyl(VI).

Treatment of neptunyl(V) chloride with two equivalents of NaTPIP and one of Ph₃PO in mixtures of chloroform and methanol (10–50% methanol) resulted in quantitative conversion to the neptunyl(V) complex [NpO₂²⁺(TPIP)₂(Ph₃PO)] (1). The same complex can also be prepared from [NpO₂⁺(ClO₄)₂] in chloroform. The complete oxidation of [NpO₂Cl₂] in the presence of TPIP and Ph₃PO in organic solvents upon crystallisation is surprising and even in 50% methanol:chloroform solutions, 1 can be prepared and isolated. Moreover, 1 is stable with respect to reduction in 100% halogenated solvents for an indefinite time period (monitored for 9 months) as confirmed by UV-vis-nIR absorption spectroscopy. A principal f-centred absorption at 1232 nm characteristic of NpO₂(VI) is observed and no significant absorptions at 980 nm that are typical for NpO₂(V) are present.⁸⁻¹⁰,¹⁴

The ³¹P solution NMR spectrum of 1 in CDCl₃ shows a sharp resonance at 29 ppm and two broader resonances at 21 and 29 ppm (assigned as unbound Ph₃PO, 29 ppm, and complexed Ph₃PO and TPPI) indicating slow exchange of monodentate Ph₃PO on the experimental timescale.† This chemical exchange was also corroborated by 2D ¹H diffusion ordered spectroscopic (DOSY) measurements, where in 1, two species with diffusion coefficients of 6.7(2) × 10⁻¹⁰ m² s⁻¹ and ca. 14 × 10⁻¹⁰ m² s⁻¹ are discernible at 295 K.† The most broadened and downfield shifted proton resonances belong to a faster diffusing species (here, Ph₃PO). The TPPI protons do not experience a large induced paramagnetic shift being more than three bonds away from the metal centre,¹² but the longitudinal proton relaxation times (T₁) are suggestive of a neptunyl 5f⁶ electronic configuration and range from 0.94 to 2.54 s at 300 K, providing further evidence of the assignment of the + VI oxidation state in 1.¹⁵ For comparison, resonances in uncomplexed Ph₃PO (at 300 K) have relaxation times of 3.70–4.40 s.

Yellow single crystals of 1 for X-ray diffraction analysis were grown from slow evaporation of an NMR tube reaction of [NpO₂Cl₂] plus two equivalents of TPIP and one of Ph₃PO in an 8:1 v/v CDCl₃:MeOD-d₄ solution (Fig. 1). For comparative purposes, the uranyl(VI) analogue [UO₂²⁺(TPIP)₂(Ph₃PO)]·CH₂Cl₂ (2) was prepared analogously.†

In the solid state, both complexes 1 and 2 are isostructural and the coordination geometries around the actinide cations are approximately pentagonal bipyramidal. Charge balancing together with optical and NMR data require a +VI oxidation state within the neptunium cation in 1. The neptunyl(VI) bond lengths of 1.7501(17) and 1.7470(17) Å (bond angle 179.21(8)°) are in the range for previously seen neptunyl(VI) complexes,⁹,¹⁶ directly comparable to those in 2 at 1.767(3) and 1.764(3) Å, with the decrease in bond length of between 0.015 and 0.020 Å attributable to the actinide contraction. The Np–O₅TPIP bonds are between 2.3558(16) and 2.3584(17), shorter than the Np–O₅Ph₃PO bond length of 2.4099(16) Å. Whilst this indicates a stronger bond to the TPIP ligands, this is in contrast to 2 where all the equatorial bond lengths range 2.375(3) to 2.429(3) Å (O—U—O bond angle 179.10(15)°).

Previous studies of the photophysical properties of the neptunyl(VI) ion have shown that emission from several excited states in the near infrared region between 1452 and 1580 nm can be achieved in two ways: (i) by LMCT sensitization in room temperature aqueous solution in a polyoxometalate complex (via the O → W LMCT transitions);¹⁷ (ii) by direct excitation into neptunyl(VI) f-centred absorption bands in a frozen glass or the solid state in Cs₂[NpO₂Cl₄]⁸ In both cases, the emission was assigned to interconfigurational transitions originating from excited states within the 5f⁶ manifold and no visible charge transfer emissions were reported.

In 1, excitation at these wavelengths (300–700 nm) in CH₂Cl₂ solution did not reveal any emission maxima in the near infrared region of the electromagnetic spectrum (using current instrumental set ups). However, excitation between 280 and 420 nm gave a vibrationally resolved emission band centred at 438 nm. The spectral shape of this emission band is independent of excitation wavelength suggesting that the emission originates from a common excited state. The fact that the excitation and emission profiles are broad indicates that the emission feature possesses considerable charge transfer character, which is confirmed by theoretical calculations (vide infra). The reconvoluted radiative lifetime of the emission, following 375 or 405 nm excitation is biexponential at 1.3 (95%) and 5.0 (5%) ns with the short lifetime difficult to measure accurately against a scatterer and the kinetic profile is monoexponential following tail fitting: τ = 1.5 ns. The lifetime is significantly shorter than its uranyl(VI) counterparts in fluid solution (1.66 μs in 2) and also than that reported from the 5f⁴ uranyl(VI) ion in the literature.¹⁹ All previous reports of emission from NpO₂⁺⁵¹⁸ and NpO₂(VI) species are short-lived (<62 ns in solution),§ and emission from 1 is also expected to be short due to efficient nonradiative relaxation pathways through the 5f⁶ manifold. The energy spacings between the three maxima (Fig. 2) are 1349 and 1489 cm⁻¹, are considerably higher than typical Np—O₅ Raman active symmetric stretch values (ca. 800 cm⁻¹) (ref. 7, 9 and 21) and more likely to correspond to a P—N stretch from the TPIP ligand as measured experimentally in the UO₂(VI) derivative 2 (range, 1163–1211 cm⁻¹). This suggests that the emissive excited state possesses significant TPIP ligand character (vide infra). Interestingly, the excitation spectra...
show absorptions that correspond to previously reported UV neptunyl(vi) absorptions; these largely remain unassigned in the literature, but we presume these to be Nd=O yl' and ligand–Nd (equatorial LMCT) transitions at ca. 340 nm and 380 nm in 1 respectively by analogy with uranyl(vi) TPIP complexes. Moreover, the excitation spectra show no transitions that correspond to TPIP π–π* absorptions, indicating that the emissive excited state is localised on the neptunyl unit itself. The possibility of the emission being phosphorescence from TPIP was also examined by recording the emission spectrum of the lanthanide analogue [Gd(TPIP)] at 77 K, which showed similar features but did not correspond exactly to the emission profile seen in 1 and additionally was very weak. The similarity of these spectra do however lend further weight to the TD-DFT calculations of the excited states of 1 have different excitation and emission profiles as well as radiative lifetime so we reasoned that it should be possible to discriminate between the two in solution. Indeed, addition of an equimolar dichloromethane solution of 2 to a dichloromethane solution of 1 (0.87 mM) resulted in an emission spectrum that is a sum of the individual components (following excitation at 320 and 420 nm). Interestingly, even in the presence of an excess of 2 (1.47 mM), both components are easily identifiable. Further, by changing the excitation wavelength, spectral editing can be achieved such as the response of purely NpO2(vi), (290 nm excitation), UO2(vi) (380 nm excitation) or a mixture of the two can be obtained (320 nm and 420 nm excitation, Fig. 3). In all spectra, the vibrational progression of each individual actinyl(vi) cation is evident suggesting no loss in structural integrity in 1 and 2.

Vibrational frequency analysis revealed the Np–OyL stretch frequencies to occur at 913 cm⁻¹ (symmetric) and 976 cm⁻¹ (asymmetric), significantly lower than the spacings between maxima observed in the emission spectra, however two N–P stretching modes were calculated at 1281 cm⁻¹ and 1282 cm⁻¹. The absence of any other modes in the region of these vibrations led us to the possibility that these N–P modes are responsible for the observed vibrational fine structure. To test this hypothesis further, time-dependent (TD-) DFT simulations of the excited states of 1 were performed. These calculations revealed several excitations in the 344–397 nm region with similar oscillator strengths of the order 10⁻⁴. Of these, three excitations, at 363, 390, and 397 nm, had well-defined neptunyl LMCT character as well as substantial NTPIP(2p) contributions of 55%, 22% and 20%, respectively. This finding lends strong support to our assertion that the origin of the observed fine structure is due to the TPIP N–P vibrational modes and that the emission is a combination of TPIP → Np and OyL → Np charge transfer.

Compounds 1 and 2 have different excitation and emission profiles as well as radiative lifetime so we reasoned that it should be possible to discriminate between the two in solution. Indeed, addition of an equimolar dichloromethane solution of 2 to a dichloromethane solution of 1 (0.87 mM) resulted in an emission spectrum that is a sum of the individual components (following excitation at 320 and 420 nm). Interestingly, even in the presence of an excess of 2 (1.47 mM), both components are easily identifiable. Further, by changing the excitation wavelength, spectral editing can be achieved such as the response of purely NpO2(vi), (290 nm excitation), UO2(vi) (380 nm excitation) or a mixture of the two can be obtained (320 nm and 420 nm excitation, Fig. 3). In all spectra, the vibrational progression of each individual actinyl(vi) cation is evident suggesting no loss in structural integrity in 1 and 2.

The kinetic profile of both components in fluid solution at room temperature, following 420 nm excitation, is multieponential and the major component (50%) possesses a radiative lifetime of 5 ns. The lifetimes of the minor components are 1 ns (23%) and 18 ns (24%). Moreover, the time resolved emission spectra show the dominance of NpO2(vi) emission at short delay times (0 to 25 ns) and only UO2(vi) emission at longer delay times (30 to 100 ns), meaning that the longer lived component can be assigned to UO2(vi) emission. The short lifetimes for the mixed solution of 1 and 2
suggests an efficient competitive pathway for emission quenching and the two complexes may be interacting with one another in solution. Overlap of the higher energy NpO$_2$(vi) charge transfer bands with TPIP absorption in the UV-vis spectrum means that the absorption maxima corresponding to the emission are obscured. This precludes the determination of a quantum yield and experimentally, the exact origin of the emission. The $^{31}$P, $^1$H NMR and $^2$H DOSY-NMR spectra also strongly suggest the two complexes may be aggregated in solution via loss of the Ph$_3$PO ligands; the 1D spectra are broadened at 295 K when compared to the individual complexes with many overlapping resonances and several species are suggested by the $^2$H DOSY spectrum. However, all attempts to isolate any intermediate (possible mixed metal) species were unsuccessful, producing in all cases single crystals of the most thermodynamically stable compounds 1 and 2 (and a solitary crystal of Ph$_3$PO). This indicates that any aggregated species is only a transient in solution. It is interesting to note that even in the presence of uranyl(vi), no redox reactions of 1 in CH$_3$Cl$_2$ solution are observed; the possibility of forming intermetallic actinyl-oxo-actinide interactions between NpO$_2$(v) and UO$_2$(vi) may be expected to be favourable, especially given that TPIP can promote such interactions with uranyl(vi). In conclusion, the neptunyl(vi) complex [NpO$_2$(TPIP)$_2$(Ph$_3$PO)], (1, where TPIP = tetraphenylidomethylphosphinate) has been prepared from both NpO$_2$(v) and NpO$_2$(vi) precursors and has been found to be indefinitely redox stable in chlorinated solvent solutions. The ligand TPIP is not redox-active, lacks peripheral chromophores in the visible region, and therefore enables us to detect the vibrationally resolved visible emission of the NpO$_2$(v) cation in 1 for the first time. A combination of experimental evidence and DFT calculations has enabled the assignment of the emission to be a combination of O$_3$ → Np LMCT and TPIP → NpO$_2$ LMCT emission (20 to 55%). Moreover, in an equimolar solution of 1 and its uranyl(vi) counterpart, 2, time resolved studies suggest that the two complexes may be aggregated in fluid solution and there is a cooperative pathway for emission quenching. Both broadband and selective excitation and time gating leads to spectral editing and this study illustrates that selective detection and discrimination of individual actinide cations is possible using time resolved emission techniques. We are currently investigating the effects of electron withdrawing and donating substituents in TPIP analogues to assess the relative contributions of the TPIP and Np=O LMCT on the emission of NpO$_2$(v) compounds. The authors gratefully acknowledge Simon Randall for help with the crystallographic data and Professor David Collison for helpful discussions. We thank the EPSRC for funding a Career Acceleration Fellowship (LSN and AK), postdoctoral funding (ANS), and studentships (SDW and PDP), The Royal Society for an equipment grant and The University of Manchester for support. The authors thank the European Commission Euratom FP7 funded project (no. 269923) EURACT-NMR for support.

Notes and references

§ It is worth noting here that the nIR emission of the NpO$_2$(vi) aqua ion has not been detected directly but the radiative lifetime has been estimated to be 7.6 ns (ref. 17).

1 For recent reviews, see: M. Altmayer, X. Gaona and T. Fanghanel, Chem. Rev., 2013, 113, 901; K. M. T. R. Bergar and J. E. Brown Jr., Inorg. Chem., 2013, 52, 510; L. S. Natrajan, A. N. Swinburne, M. B. Andrews, S. Randall and S. L. Heath, Coord. Chem. Rev., 2014, 266-267, 171.

2 L. S. Natrajan, Coord. Chem. Rev., 2012, 256, 1583.

3 R. G. Denning, Struct. Bonding, 1992, 79, 213; R. G. Denning, J. Phys. Chem. A, 2007, 111, 4125.

4 Su, W. H. E. Schwarz and J. Li, Inorg. Chem., 2012, 51, 3231. See for example: T. Arnold, S. Utsunomiya, G. Geipel, R. C. Ewing, N. Baumann and V. Brendler, Environ. Sci. Technol., 2006, 40, 4646; E. J. Elzinga, C. D. Tait, R. J. Reeder, K. D. Rector, R. J. Donohoe and D. E. Morris, Geochim. Cosmochim. Acta, 2004, 68, 2437; K. F. Smith, N. D. Bryan, A. N. Swinburne, P. Bots, S. Shaw, L. S. Natrajan, J. F. W. Mosselmans, F. R. Livens and K. Morris, Geochim. Cosmochim. Acta, 2015, 148, 143.

5 K. H. Williams, J. R. Bargar, J. R. Lloyd and D. R. Lovley, Curr. Opin. Biotechnol., 2013, 24, 489; K. Grossman, T. Arnold, E. Krawczyk-Barsch, S. Diessner, A. Wobers, G. Benhard and R. Krawitz, Environ. Sci. Technol., 2007, 41, 6498.

6 J. C. Hindman, L. B. Magnusson and T. J. LaChappelle, J. Am. Chem. Soc., 1949, 71, 867; R. Sjoblom and J. C. Hindman, J. Am. Chem. Soc., 1951, 73, 1714; H. A. Friedman and L. M. Toth, J. Inorg. Nucl. Chem., 1965, 27, 1347; T. W. Newton, D. E. Hobart and P. D. Palmer, Preparation and Stability of Pure Oxidation States of Neptunium, Plutonium, and Americium, Los Alamos National Laboratory, 1986, LA-UR-86-967.

7 S. M. Cornet, L. J. L. Häller, M. J. Sarsfield, D. Collison, M. Helliewell, I. May and N. Kaltsoyannis, Chem. Commun., 2009, 917.

8 D. L. Clark, D. W. Keogh, P. D. Palmer, B. L. Scott and C. D. Tait, Angew. Chem., Int. Ed., 1998, 37, 64.

9 [NpO$_2$(DPMMO)$_2$Cl]$_2$[NpO$_2$Cl$_4$] (DPMMO = bis(diphenyl-phosphino)methanedioxide) S. M. Cornet, M. P. Redmond, D. Collison, C. A. Sharrad, M. Helliewell and J. Warren, C. R. Chim., 2010, 13, 832.

10 Neptunyl(vi) bis(salicylidene)ethylenediamine (salen) is prepared from neptunyl(vi) in methanol. D. G. Chuguryan, V. I. Dzyubenko, M. S. Grigoriev, A. I. Yanovski and Y. T. Struchkov, Radiohimiya, 1988, 30, 41.

11 S. W. Magennis, S. Parsons and Z. Pikramenou, Chem. – Eur. J., 2002, 8, 5761.

12 M. P. Redmond, S. M. Cornet, S. D. Woodall, D. Whittaker, D. Collison, M. Helliewell and L. S. Natrajan, Dalton Trans., 2011, 40, 3914.

13 F. G. Hagan and J. M. Cleveland, J. Inorg. Nucl. Chem., 1966, 28, 2905.

14 In related neptunyl(vi) TPIP solutions, the $\Delta$, values of the proton resonances are of millisecond order (10–110 ms). S. D. Woodall, PhD thesis, The University of Manchester, 2014.

15 M. P. Willkerson, H. J. Dewey, P. L. Gordon and B. L. Scott, J. Chem. Crystallogr., 2004, 34, 807; N. W. Alcock, M. M. Roberts and D. Brown, J. Chem. Soc., Dalton Trans., 1982, 25.

16 C. Talbot-Eeckelaers, S. J. A. Pope, A. J. Hynes, R. Copping, C. J. Jones, R. J. Taylor, S. Faulkner, D. Sykes, F. R. Livens and I. May, J. Chem. Soc., 2007, 129, 2442.

17 M. P. Willkerson and J. M. Berg, J. Phys. Chem. A, 2008, 112, 2515; M. P. Willkerson and J. M. Berg, Radiochim. Acta, 2009, 97, 223.

18 R. Steudtner, T. Arnold, K. Grossman, G. Geipel and V. Brendler, Inorg. Chem., 2006, 9, 939.

19 R. Bradshaw, D. Sykes, L. S. Natrajan, R. J. Taylor, F. R. Livens and S. Faulkner, JOP Conf. Ser.: Mater. Sci. Eng., 2010, 9, 012047.

20 C. Madic, G. M. Begun, D. E. Hobart and R. L. Hahn, Inorg. Chem., 1984, 23, 1914.

21 B. Drobot, R. Steudtner, J. Raff, G. Geipel, V. Brendler and S. Tsushima, Chem. Sci., DOI: 10.1039/C4SC02022G.

22 R. Ahrlıchs, M. Bär, M. Häser, H. Horn and C. Kömler, Chem. Phys. Lett., 1989, 162, 165.

23 J. Perdew, K. Burke and M. Ernzerhof, Phys. Rev. Lett., 1996, 77, 3865; C. Adamo and V. Barone, J. Chem. Phys., 1999, 110, 6158.

24 F. Weigend and R. Ahrlıchs, Phys. Chem. Chem. Phys., 2005, 7, 3297.

25 S. Wang, J. Diwu, E. V. Alekseev, L. J. Jouffret, W. Depmeier and T. E. Albrecht-Schmitt, Inorg. Chem., 2012, 51, 7016; S. Skanthakumar, M. R. Antonio and L. Soderholm, Inorg. Chem., 2008, 47, 4591.