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3,2-HOPO Complexes of Near Infra-Red (NIR) Emitting Lanthanides: Sensitization of Ho^{III} and Pr^{III} in Aqueous Solution

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There is a growing interest in Near Infra-Red (NIR) emission originating from organic complexes of Ln^{III} cations.[1,2] As a major impetus, biological tissues are considerably more transparent at these low energy wavelengths when compared to visible radiation, which facilitates deeper penetration of incident and emitted light.[3] Furthermore, the long luminescence lifetimes of Ln^{III} complexes (eg. Yb^{III}, $\tau_{\text{rad}} \sim 1$ ms) when compared to typical organic molecules can be utilized to vastly improve signal to noise ratios by employing time-gating techniques. While the improved quantum yield of Yb^{III} complexes when compared to other NIR emitters favours their use for bioimaging applications, there has also been significant interest[4,5,6] in the sensitized emission from other 4f metals such as Ln = Nd, Ho, Pr and Er which have well recognised applications as solid state laser materials[7] (eg. Nd ~ 1.06 μm , Ho ~ 2.09 μm), and in telecommunications (eg. Er ~ 1.54 μm) where they can be used for amplification of optical signals.[8]

As a result of their weak (Laporte forbidden) *f-f* absorptions, the direct excitation of Ln^{III} cations is inefficient, and sensitization of the metal emission is more effectively achieved using the so-called antenna effect.[1] We have previously examined[9] the properties of several Eu^{III} complexes which feature 1-hydroxypyridin-2-one (Fig. 1) as the light harvesting chromophore. While the 1,2-HOPO isomer was found to strongly sensitize Eu^{III}, we noted the analogous Me-3,2-HOPO isomer does not, which prompted further investigation of the properties of this chromophore with other metals.

The synthesis of the 5LIO-Me-3,2-HOPO ligand has been previously reported.[10,11] Our initial *in situ* screening of this ligand with Pr^{III}, Ho^{III} and Er^{III} revealed sensitized emission in the NIR region only for the former two metal cations. As such, the corresponding Ln^{III} complexes (Ln = Ho, Pr) were then prepared using well established methodologies (see experimental) and the desired compounds were obtained in analytically pure form as the charge neutral ML₂H complexes. Single crystals[12] of Na[Ho(5LIO-Me-3,2-HOPO)₂] suitable for X-ray analysis were also grown from a 5 % aqueous 1:1 (v/v) DMF:MeOH solution diffused with diethyl ether, and the resulting X-ray structure, which was collected at the Advanced Light Source (ALS, Beamline 11.3.1) at Lawrence Berkeley National Laboratory (LBNL), is shown in Fig. 2.

This compound crystallizes in the triclinic space group, $P\bar{1}$, with a single independent complex molecule in the asymmetric unit, together with one molecule of co-crystallized solvent DMF. Notably, the crystal structure of Na[Ho(5LIO-Me-3,2-HOPO)₂] is very similar to that reported[11] for the analogous Ce^{IV} complex, and also the Ln^{III} complexes

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formed with the 5LIO-1,2-HOPO ligand.[9] As expected, the Ho^{III} atom is coordinated by eight oxygen atoms of the two 5LIO-Me-3,2-HOPO ligands in a sandwich-like structure (Fig. 2), and the average Ho-O bond lengths are 2.36 Å. The Ho-O (hydroxyl) bonds are significantly shorter than the corresponding Ho-O (keto), at *avg.* 2.30 versus *avg.* 2.41 Å respectively. Another structural parameter which can be obtained from the crystallographic data is the shape measure, *SM*, as detailed elsewhere,[13,14] which is a measure of agreement between the observed coordination polyhedron and the idealized cases. For a coordination number of eight, the three most common polyhedra are the bicapped trigonal prism (*C*_{2v}), square antiprism (*D*_{4d}) and trigonal dodecahedron (*D*_{2d}). Analysis of the Ho^{III} cation reveals the metal in this case is best described as having an Archimedean antiprismatic (*D*_{4d}) geometry (*SM*; *D*_{4d} = 4.49, *C*_{2v} = 11.16, *D*_{2d} = 12.75). The counter cation is Na⁺, which is *ca.* 3.58 Å distant from the Ho^{III}, with its own hexadentate coordination geometry formed by a bridging interaction with three of the four Me-3,2-HOPO chelates *via* the keto oxygen atoms and a single coordinated water molecule. The remaining two oxygen donors for the Na⁺ originate from adjacent ligand amide carbonyl oxygens, O11' and O12', which link two complexes together to form dimers. The Na⁺ counter cation has another interesting effect: each of the tetradentate ligand strands are in similar orientations with respect to each other unlike the structures in our previous reports[15] which used non-coordinating alkyl amine counter cations, wherein the least-square faces of the top and bottom ligands were offset by *ca.* 120°. Nonetheless, upon dissolution in aqueous solution, we anticipate the Na⁺ cation will dissociate to form the aqua cation, Na⁺_(aq), allowing each of the ligand strands to freely rotate.

The electronic absorption spectra of the Pr^{III} and Ho^{III} complexes are essentially identical, displaying a broad ligand centered absorption band (with poorly resolved vibrational structure) at 346 nm ($\epsilon_{\text{max}} \sim 31,250 \text{ M}^{-1} \text{ cm}^{-1}$) as shown in Fig. 3. for Pr^{III}. Also shown in Fig. 3 are the emission spectra in the visible region for the two [Ln(L)₂]⁻ complexes in 0.1 M TRIS buffered aqueous solution (pH *ca.* 7.4). These show the predominance of residual ligand emission common to both the complexes centered at *ca.* 412 nm for Ho^{III} and *ca.* 420 nm for Pr^{III}, indicating incomplete energy transfer to the metal ion. The emission spectra in the visible region are of particular interest since these two Ln^{III} cations are known[16] to sometimes display metal centred emission bands in the visible region (*vide infra*).

The corresponding spectra in the NIR region for both complexes are shown in Fig. 4. Both display emission peaks which, when combined with the results from the visible region, are distinctive. For example, on the basis of the observed visible emission bands, we can unequivocally assign the observed 980 nm peak in the NIR region for the Ho^{III} complex (and the weaker shoulder at 1018 nm) to the ⁵F₅ → ⁵I₇ transition, since the corresponding peak for the ⁵F₅ → ⁵I₈ transition is clearly evident at *ca.* 650 nm (Fig. 3). To the best of our knowledge, only two other examples of sensitised Ho^{III} emission in solution have been previously reported, the first in aqueous solution by Quici *et. al.*[17] in 2005, and then shortly thereafter in DMSO by Petoud *et. al.*[18] In both these cases, the authors did not report on the presence (or absence) of visible emission bands from the complexes. Of interest, the corresponding ⁵F₅ → ⁵I₆ transition which should be anticipated for Ho^{III} at *ca.* 1445 nm was not observed in the spectra of our complex. Previously, the intensity of this band is much weaker when compared with the ⁵F₅ → ⁵I₇ transition (*eg.* in DMSO),[18] and was notably absent in the aqueous emission spectra reported by Quici.[17] This suggests the absence of this band may be due to strong re-absorption of the weakly emitted NIR radiation by the solvent, which has a known[19] absorption co-efficient nearly two orders of magnitude higher at 1.5 μM vs 1 μM (*ca.* 21.6 cm⁻¹ vs 0.41 cm⁻¹).

The assignment of the emission observed from the Pr^{III} complex was less straight forward, since this metal can in principle emit from three excited states, namely the ³P₀, ¹D₂ or ¹G₄

levels. From a closer analysis of the visible emission, a weak faintly structured band at *ca.* 605 nm is apparent (see Inset, Fig. 3), which we can attribute to the $^1D_2 \rightarrow ^3H_4$ transition. Notably, other expected peaks originating from the 3P_0 excited level (*eg.* $^3P_0 \rightarrow ^3H_4 \sim 490$ nm, $^3P_0 \rightarrow ^3F_2 \sim 645$ nm) are absent, suggesting the sensitizing triplet level of the Me-3,2-HOPO ligand is too low to effectively populate this excited state. Assuming a common excited state origin, we can then assign the observed NIR emission from the Pr^{III} complex at 1030 nm to the $^1D_2 \rightarrow ^3F_4$ transition which agrees well with other reports.[16,20] By analogy to the case with Ho^{III} , the absence of the expected $^1D_2 \rightarrow ^1G_4$ transition for Pr^{III} in the NIR region at *ca.* 1440 nm is likely due to re-absorption by the aqueous solvent. As was the case with Ho^{III} , a survey of the literature reveals that sensitized emission from Pr^{III} complexes in the NIR is quite rare.

Lastly, in addition to the steady state emission, we also performed time resolved measurements in the visible and NIR regions using the TCSPC technique.[21] For the Ho^{III} complex, emission of the $^5F_5 \rightarrow ^5I_8$ band monitored at 650 nm gave a satisfactory fit to a monoexponential lifetime with $\tau_{obs} = 6.4 \pm 0.1$ ns. For the Pr^{III} $^1D_2 \rightarrow ^3H_4$ band, monitored at 605 nm, the corresponding lifetime decay data required fitting to a biexponential decay function, with $\tau_1 = 2.7 \pm 0.2$ ns (99 %) and $\tau_2 = 8.8 \pm 0.6$ ns (1 %). Given the very weak intensity of the Pr^{III} centred emission at *ca.* 605 nm compared to the residual ligand singlet emission, we assigned the longer lifetime component to the metal centre and the shorter lifetime component to the ligand. These assignments were then independently confirmed by lifetime measurements in the NIR region. Since the NIR emission band at 1010-1060 nm observed for the Pr^{III} complex originates from the same 1D_2 excited state, the lifetime should necessarily be the same as that observed in the visible region, and the resulting lifetime obtained was monoexponential (see Supp. Info) with a τ_{obs} of 8.0 ± 0.4 ns, which is identical within the experimental error. This value is in good general agreement with that previously reported[20] of $\tau_{obs} = 13$ ns for the 1D_2 excited state of a Pr^{III} complex determined in CH_3OH solution at 1030 nm. Similarly, for the $[Ho(5LIO-Me-3,2-HOPO)_2]^-$ complex, the luminescence lifetime obtained in the NIR region was again monoexponential with $\tau_{obs} = 6.5 \pm 0.3$ ns, consistent with our measurements performed in the visible region using the $^5F_5 \rightarrow ^5I_8$ band at 650 nm. To the best of our knowledge, this observation represents the first ever NIR lifetime determination in solution for a Ho^{III} complex, which are rarely emissive since their electronic structure facilitates highly competitive non-radiative deactivation.

Experimental Section

General

All chemicals and solvents were used as received unless otherwise noted. The Ln^{III} salts utilized were of the highest possible purity (> 99.99 %). The synthesis of 5LIO-Me-3,2-HOPO has been previously reported.[10,11] Elemental analyses were performed by the Microanalytical Laboratory at University of California, Berkeley, CA.

Preparation of $[Ln(5LIO-Me-3,2-HOPO)_2]$ Complexes

A solution of $LnX_3 \cdot 6H_2O$ (for $Ln = Ho$, $X = Cl$, for $Ln = Pr$, $X = Br$) (0.026 mmol) in methanol (1 mL) was added to a stirred solution of 5LIO-Me-3,2-HOPO (*ca.* 20 mg, 0.05 mmol) in methanol (5 mL). An excess of pyridine (20 μ L) was added and the suspension was heated to assist dissolution, then refluxed for *ca.* 4 hours. After cooling to room temperature, slow addition of diethyl ether induced precipitation of the $[Ln(L)_2]^-$ complexes in their protonated charge neutral form, which were collected by filtration and air dried yielding *ca.* 10-15 mg of the desired products (*ca.* 60-85%). Anal. Calc'd. (Found) for $H^+[Pr(C_{18}H_{20}N_4O_7)_2]^- \cdot 2H_2O$ (986.71 $g \cdot mol^{-1}$): C, 43.97 (43.66); H, 5.04 (4.92); N, 11.26

(11.11). Anal. Calc'd. (Found) for $\text{H}^+[\text{Ho}(\text{C}_{18}\text{H}_{20}\text{N}_4\text{O}_7)_2] \cdot 5\text{H}_2\text{O}$ ($1064.78 \text{ g}\cdot\text{mol}^{-1}$): C, 40.61 (40.14); H, 4.83 (4.65); N, 10.52 (10.25).

Crystallography—Crystals suitable for X-ray analysis were grown by vapor diffusion of diethyl ether into a 5 % aqueous DMF solution of the isolated complex and data collection was performed at the Advanced Light Source (ALS), Beamline 11.3.1, Lawrence Berkeley National Laboratory (LBNL), using well established protocols. Resulting drawings of molecules were produced with Ortep-3 for Windows.[22] Full crystallographic data in CIF format has been deposited at the Cambridge Crystallographic Data Centre (CCDC # 688308) and further details regarding data collection and refinement are also given in the supporting information.

Photophysical Measurements

UV-Visible spectra were recorded on a Varian Cary 300 double beam spectrometer using quartz cells of 1 cm path length. Emission spectra were measured using a HORIBA Jobin Yvon Fluorolog-3 spectro-fluorometer equipped with an IBH TBX-04-D detector for the visible domain and a Hamamatsu H9170-75 detector for the NIR domain. Spectra were reference corrected for both excitation light source variation (lamp and grating) and emission spectral response (detector and grating). Time-resolved measurements were performed by the TCSPC technique, and further details are given in the supporting information.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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- [12]. Crystal data: $C_{39}H_{49}N_9O_{16}YbNa$ ($M_r = 1087.79$ g/mol), Colourless plate, $0.05 \times 0.02 \times 0.01$ mm, Triclinic, Space group $P-1$ (No. 2), $a = 10.6416$ (6) Å, $b = 12.9722$ (7) Å, $c = 17.6879$ (10) Å, $\alpha = 74.467$ (1), $\beta = 80.512$ (1), $\gamma = 74.316$ (1), $V = 2253.7$ (2) Å³, $Z = 2$, $\rho_{\text{calcd}} = 1.603$ g/cm³, $\mu = 2.303$ mm⁻¹, synchrotron X-ray radiation source $\lambda = 0.77490$ Å, $T = 150$ (2) K, 28531 measured reflections, 11352 independent reflections ($8227 > 2\sigma(I)$), R_1 ($I > 2\sigma(I)$) = 0.0531, wR_2 (all data) = 0.1224, GOF = 0.969
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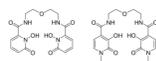


Figure 1.
Chemical structure of 5LIO-1,2-HOPO (left) and 5LIO-Me-3,2-HOPO (right) tetradentate ligands.

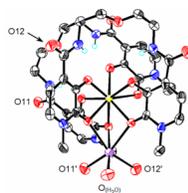


Figure 2.

A view of the X-ray crystal structure for Na[Ho(5LIO-3,2-HOPO)₂]. Thermal ellipsoids of non-H atoms are drawn at the 50 % probability level (C = black, O = red, N = blue, Ho = yellow, Na = purple). Co-crystallized DMF and selected H atoms have been omitted for clarity.

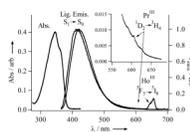


Figure 3.

The absorption spectrum (left axis) of $[\text{Pr}(\text{5LIO-Me-3,2-HOPO})_2]^-$ in 0.1 M TRIS buffered aqueous solution (pH 7.4). Emission spectra (right axis) of the $[\text{Ln}(\text{5LIO-Me-3,2-HOPO})_2]^-$ complexes ($\lambda_{\text{ex}} = 345 \text{ nm}$) with $\text{Ln} = \text{Pr}^{\text{III}}$ and Ho^{III} in 0.1 M TRIS buffered aqueous solution (pH 7.4) Inset: Expansion of the $\text{Pr}^{\text{III}} \text{ } ^1\text{D}_2 \rightarrow \text{ } ^3\text{H}_4$ transition at *ca.* 605 nm (see text).

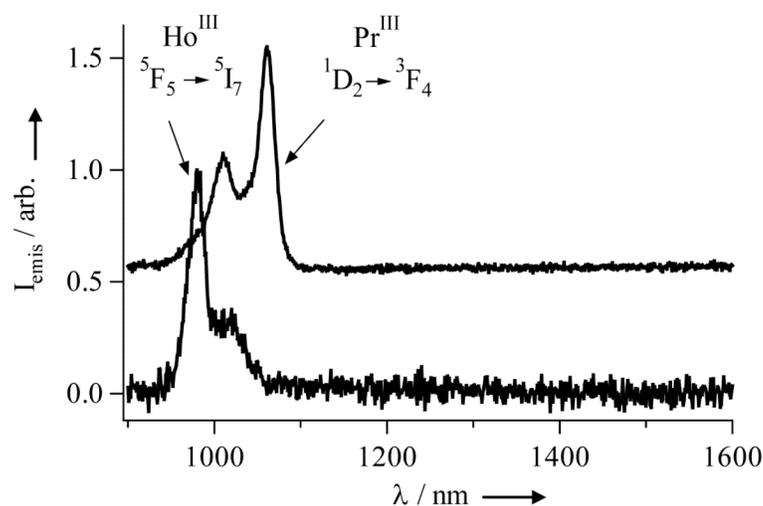


Figure 4.

The NIR emission spectra ($\lambda_{\text{ex}} = 345 \text{ nm}$) of the $[\text{Ln}(\text{5LIO-Me-3,2-HOPO})_2]^-$ complexes in 0.1 M TRIS buffered aqueous solution (pH 7.4) with $\text{Ln} = \text{Pr}^{\text{III}}$ and Ho^{III} . The emission spectra of the Pr^{III} complex is vertically offset for clarity.

The 1-Methyl-3-hydroxy-pyridin-2-one (Me-3,2-HOPO) chromophore has been investigated as a sensitizer for Pr^{III} and Ho^{III} , with a tetradentate ligand, and the complex with the latter was structurally characterized. Characteristic visible and Near-Infra-Red (NIR) emission bands were observed in aqueous solution, and the kinetics of this luminescence decay in the NIR for Ho^{III} have been determined in solution for the first time.##Aqueous NIR Emission from Ho^{III} and Pr^{III}

Coordination Complex

Holmium

Lanthanide

NIR Emission

Praeseodymium