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Unusual Coordination Behaviour of a Phosphonate- and Pyridine-Containing Ligand in a Stable Lanthanide Complex

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An experimental study of the coordination of lanthanide ions with {ethane-1,2-diylbis[imino(pyridin-2-ylmethanediyl)]}bis(phosphonic acid), a ligand containing phosphonate and pyridine arms attached to the well-known ethylenediamine scaffold, is reported. The X-ray crystal structure of an anionic, octacoordinate Eu^{III} complex of the formula $[C(NH_2)]_6[Eu_2(L)_2(CO_3)_2]\cdot 8H_2O$ has been obtained and found to contain cyclic dimeric complex anions in which the coordination environment of each Eu^{III} ion is composed of three oxygen atoms from phosphonate groups, two nitrogen atoms from imino groups and one nitrogen atom from a pyridine group, a combination that has seldom been observed for Ln^{III} complexes. In order to check the coordination behaviour of the ligand, an investigation of the complexes in solution has been performed, which revealed a different coordination mode. The protonation constants of the free ligand and the stability constants of their complexes with selected lanthanide ions (La^{III}, Sm^{III}, Eu^{III}, Gd^{III}, Tb^{III}, Ho^{III} and Lu^{III}) have been determined potentiometricaly at 25 °C and an ionic strength of 0.1 M (KCl). The results obtained show the formation of monomeric, protonated ($[LnH_2L]$, $[LnHL]$) and nonprotonated ($[LnL]$) species in the pH range studied (2–11). The determined stability constants ($\log\beta_{LnL}$) are relatively high, varying between 14.96 and 16.42. The Eu^{III}**L** system was also fully characterized by means of UV/Vis spectroscopy, which indicated that the coordination process starts above pH 3 and remains constant in the range pH 4–10. In contrast to the crystal structure, solution NMR and luminescence studies suggested that the pyridine moieties are not present in the Ln^{III} coordination sphere. These results suggest that this ligand–unsaturated metal ion coordination sphere may provide a potential binding site for other target molecules.

Introduction

The aqueous coordination chemistry of lanthanide complexes with polyaminophosphonate ligands has been a subject of intense interest over the last few years,[1] mainly due to lanthanides' ability to form thermodynamically very stable complexes with these ligands and therefore the strong possibility of medical applications for such complexes.[2] The Sm^{153}-EDTMP complex Quadramet®, for example, was approved by the US FDA in 1997 for use in clinical practice and soon became the most efficient drug for the treatment of painful skeletal metastases.[3] Since a number of linear polyaminocarboxylate ligands are of considerable interest due to their medical diagnostic applications,[4] the properties of polyaminophosphonates complexed with Gd^{III} have also been intensively studied as possible MRI contrast agents.[5,6] Although the solution coordination chemistry of both these types of ligands (with carboxylic and phosphonate functions) has been studied in the past,[5–9] their possible structures in solution and in the solid state, thermodynamic stability and spectroscopic properties are not yet well established. Even the large amount of literature data for the most extensively studied polyaminophosphonate ligand EDTMP show major differences in the values of the thermodynamic stability constants ($\log\beta_{SmL}$ = 12.02, pSm^{III} = 4.60;[10] $\log\beta_{SmL}$ = 14.44, pSm^{III} = 3.79;[11] $\log\beta_{SmL}$ = 20.71, pSm^{III} = 9.29[12]). These differences are considered to be a result of the different experimental conditions employed, especially the influence of different cations in the electrolyte.[10] Despite this, EDTMP is known to be a powerful ligand for stable lanthanide complexation which uses both imino groups and oxygen atoms from phosphonate groups to coordinate to the lanthanide ion.[13,14]

One of our main research interests is focused on the influence of the binding of nitrogen atoms on the thermodynamic stability of a complex, especially when such a coordination mode is available but not necessarily preferable. Herein we describe coordination studies with {ethane-1,2-diylbis[imino(pyridin-2-ylmethanediyl)]}bis(phosphonic acid) (**L**), which possesses three potential metal ion binding

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sites centered on phosphonate groups and two types of nitrogen donors (imino and pyridine group). Potentiometric and spectroscopic studies (UV/Vis, absorption, luminescence) have been used to describe the thermodynamic stability of the complexes formed, their stoichiometry and the possible structures of these species in aqueous solution. It should be noted that, despite the quality of the Eu^{III}**L** crystals obtained being rather low, which meant that we were unable to retrieve all crystallographic data, we were nevertheless able to propose a preliminary model for the crystal structure of this complex due to the fact that the present coordination pattern is very rare for Ln^{III} ions.

Results and Discussion

The Model of the Crystal Structure

$[C(NH_2)]_6[Eu_2(\mathbf{L})_2(CO_3)_2]\cdot 8H_2O$ crystallizes in the triclinic space group $P\bar{1}$. The crystal consists of dimeric $[Eu_2(\mathbf{L})_2(CO_3)_2]^{6-}$ complex anions, guanidinium cations and water molecules. The structure of the complex $[Eu_2(\mathbf{L})_2(CO_3)_2]^{6-}$ anions is shown in Figure 1.

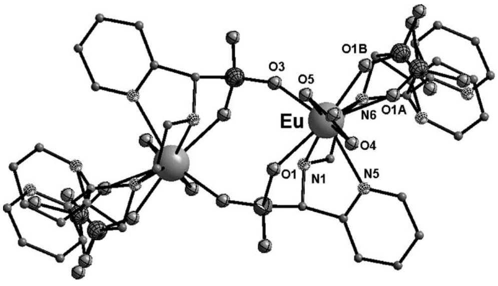


Figure 1. A view of the dimeric $[Eu_2\mathbf{L}_2(CO_3)_2]^{6-}$ complex.

The ligand coordinates to the metal ion through three oxygen atoms from the phosphonate groups, two nitrogen atoms from the imino groups and one nitrogen atom from a pyridine group. The remaining two coordination sites in the inner sphere of the Eu^{III} ion are occupied by the bidentate carbonate anion. One of the phosphonate groups is bidentate, with one oxygen atom coordinating to the Eu^{III} ion and the other oxygen atom to the europium cation generated by an inversion centre. This means that two Eu**L** entities are bonded together to create a dimeric complex containing an eight-coordinate Eu^{III} ion.

It should be noted that one of the ligand branches is disordered as the chiral carbon atom C10 is present in two configurations (*R* and *S*). The ligand used for the crystal synthesis was a mixture of all four possible enantiomers (*RR*, *SS*, *RS* and *SR*), and the structural data for the complex indicate that they are all present. For this reason only selected Eu–donor distances are presented in Table 1.

Table 1. Selected bond lengths [Å] in $[C(NH_2)_3]_6[Eu_2L_2(CO_3)_2]\cdot 8H_2O$.

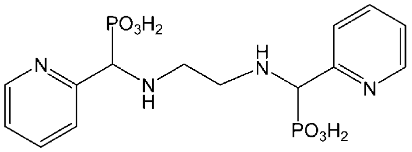
Eu–O3	2.289(4)
Eu–O1A	2.369(15)
Eu–O1	2.421(4)
Eu–O5	2.428(5)
Eu–O4	2.436(4)
Eu–N1	2.651(7)
Eu–N5	2.586(5)
Eu–N6	2.631(5)

It should also be noted that the coordination mode found in the $[Eu_2(\mathbf{L})_2(CO_3)_2]^{6-}$ complex anion is relatively rarely observed and, to the best of the authors' knowledge, this is the first example of such a structure for lanthanide complexes of linear polyaminophosphonic acids.

Potentiometry and NMR Studies

Protonation Constants

The protonation constants for ligand **L** (Scheme 1), as determined previously at slightly different ionic strengths,[15] are listed in Table 2. Protonation can theoretically take place at eight atoms, although under the experimental conditions used here **L** behaves as an H_5L acid. The two highest pK values (9.87 and 7.49) can be attributed to imino nitrogens and are similar to those reported for ethylenediaminediphosphonic acid (EDDP; pK_1 = 10.29 and pK_2 = 7.85[16]). The remaining three protonation constants belong to phosphonate functions and pyridine nitrogen atoms. A comparison between **L**, an analogous compound lacking a pyridine function (pK_3 = 5.77, pK_4 = 4.31)[15,17] and EDDP (pK_3 = 5.40 and pK_4 = 4.35)[16] suggests that the pK values of **L** at 5.47 and 4.46 probably result from partial deprotonation of the phosphonic acid groups. It was not possible to correctly and unequivocally assign the lowest pK value of 1.87.



{ethane-1,2-diylbis[imino(pyridin-2-ylmethanediyl)]}bis(phosphonic acid)

Scheme 1. Chemical structure and systematic name of the studied ligand.

Ln^{III}L Complexes

The stability constants and stoichiometry of the complexes obtained upon potentiometric titration of La^{III}, Sm^{III}, Eu^{III}, Gd^{III}, Tb^{III}, Ho^{III} and Lu^{III} with **L** are listed in Table 2. Analysis of the distribution curves plotted as a function of pH in Figure 2 shows that the coordination process starts with formation of the protonated species $[LnH_2\mathbf{L}]$ at around pH 2.5 for La^{III} and pH 2 for heavier Ln^{III} ions. An increase in pH leads to stepwise deprotonation of the species and formation of a final $[Ln\mathbf{L}]$ complex

Table 2. The protonation and complex formation constants and pLn^{III} values for the complexes of **L** with La^{III}, Sm^{III}, Eu^{III}, Gd^{III}, Tb^{III}, Ho^{III} and Lu^{III} at 25 °C and I = 0.1 M (KCl).[a]

Protonated complexes			Metal complexes						
			La^{III}	Sm^{III}	Eu^{III}	Gd^{III}	Tb^{III}	Ho^{III}	Lu^{III}
$\log\beta(H\mathbf{L})$	9.91(1)	$\log\beta(MH_2\mathbf{L})$	23.69(7)	24.51(4)	24.45(2)	24.91(3)	24.68(1)	24.78(2)	25.01(2)
$\log\beta(H_2\mathbf{L})$	17.46(1)	$\log\beta(MH\mathbf{L})$	19.80(6)	20.74(4)	20.65(3)	21.13(4)	21.17(1)	21.45(1)	21.82(2)
$\log\beta(H_3\mathbf{L})$	23.02(1)	$\log\beta(M\mathbf{L})$	14.96(9)	15.61(7)	15.63(4)	15.68(2)	15.72(1)	16.18(2)	16.42(7)
$\log\beta(H_4\mathbf{L})$	27.59(1)								
$\log\beta(H_5\mathbf{L})$	29.48(2)								
$\log K_1(H\mathbf{L})$	9.91	$pK(MH_2\mathbf{L})$	3.89	3.77	3.80	3.78	3.51	3.33	3.19
$\log K_2(H_2\mathbf{L})$	7.55	$pK(MH\mathbf{L})$	4.84	5.13	5.02	5.50	5.45	5.27	5.40
$\log K_3(H_3\mathbf{L})$	5.56								
$\log K_4(H_4\mathbf{L})$	4.57								
$\log K_5(H_5\mathbf{L})$	1.87								
pLn^{III}			7.02	7.67	7.69	7.74	7.78	8.24	8.48

[a] Standard deviations of calculated values are given in parentheses. $pLn^{III} = -\log[Ln^{III}]_{free}$ calculated for $[\mathbf{L}]_{tot} = 10^{-5}$ M, $[Ln^{III}]_{tot} = 10^{-6}$ M at pH 7.4.

for all Ln^{III} ions studied below pH 4. The $\log K$ values for the first deprotonation reaction of $LnH_2\mathbf{L}$ species range between 3.19–3.89; those for $LnH\mathbf{L}$ species fall in the range 4.84–5.50. Both these ranges are distinctly lower than the $\log K$ values for deprotonation of the phosphonate groups in the metal-free ligand, thereby indicating that both phosphonates are involved in coordination to Ln^{III}. The concentration of $LnH\mathbf{L}$ species varies from around 55% for La^{III} to around 85% for Lu^{III} in the series of lanthanides studied. A comparison of the stability constants of [Ln**L**] species shows that the complexes formed are stable in aqueous solution and that the values increase from 14.96 to 16.42 with atomic number. High stability constants may suggest that the imino nitrogens in MH_2L complexes are already coordinated and that the stepwise deprotonation detected by potentiometry results from coordination of the phosphonate groups. A comparison of these data with those of EDTA ($\log\beta_{GdL}$ = 17.32, pGd = 9.48)[18] and CDTP ($\log\beta_{GdL}$ = 15.27, pGd^{III} = 4.61),[19] in which imino nitrogens, phosphonates and carboxylates are involved in coordination, shows that the ligand studied here is slightly less stable. However, we were unable to determine potentiometrically whether the pyridine nitrogens are involved in metal ion coordination. The pK values of the pyridine nitrogens in such ligands are acidic[15] and most probably overlap with the lower pK values of the phosphonate functions.

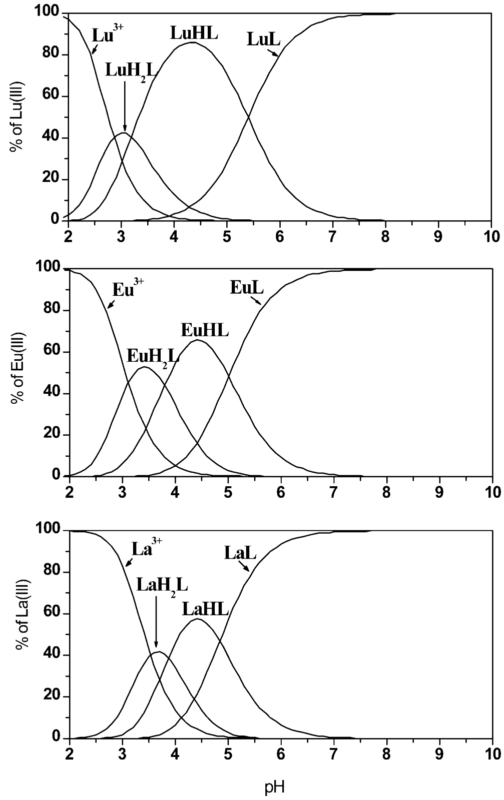


Figure 2. Species distribution of the Ln**L** systems (Ln/**L**: 1:1.1; I = 0.1 M KCl; T = 25 °C).

^1H and ^{31}P NMR spectra were recorded for these diamagnetic $La^{III}\mathbf{L}$ complexes in order to detect coordination of the pyridine group to the Ln^{III} ions. The spectra of solutions containing free or complexed ligand recorded at pH 2, 7 and 12 are presented in Figures 3 and 4, respectively. The distinct sets of signals in the range δ = 7–9 ppm were attributed to the aromatic pyridine group. Inspection of these ^1H and ^{31}PNMR spectra confirmed the involvement of phosphonate in the coordination of **L** to La^{III} ion and excluded the involvement of pyridine moieties.

UV/Vis Spectroscopy

Absorption Spectra

The UV absorption spectra of **L** and its Eu^{III} complex (Eu/**L** = 1:1) recorded in aqueous solution over the whole pH range studied are presented in Figure 5. This spectral region is dominated by an intense band located between 235 and 290 nm, which is attributed to the $^1\pi\rightarrow\pi^*$ transition in the pyridine rings. The maximum of the band splits into two not well separated peaks for the ligand solutions in the pH range 2.1–7.2. The intensity of the higher-energy peak increases with increasing ligand deprotonation. The

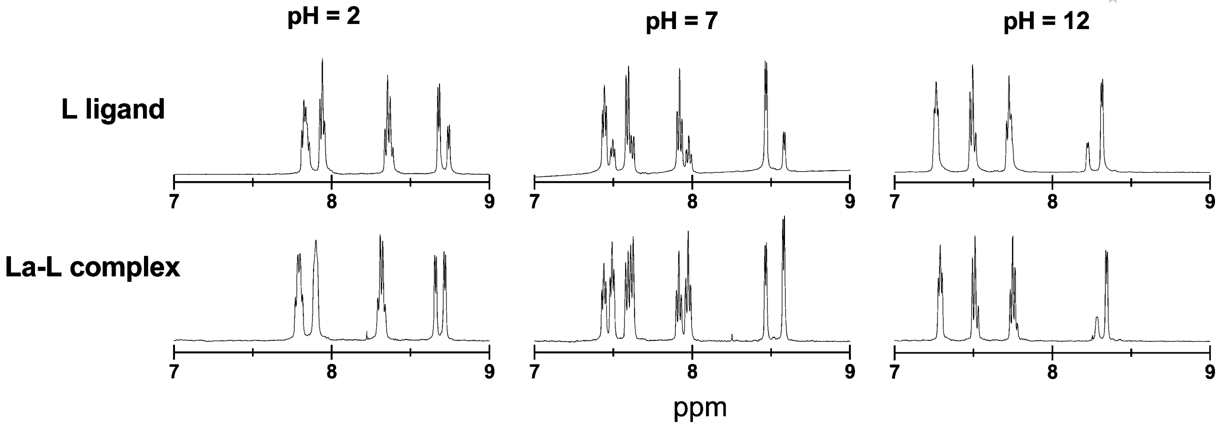


Figure 3. ^{1}H NMR spectra of the La^{III}**L** complexes (bottom) and **L** (top) at different pH values.

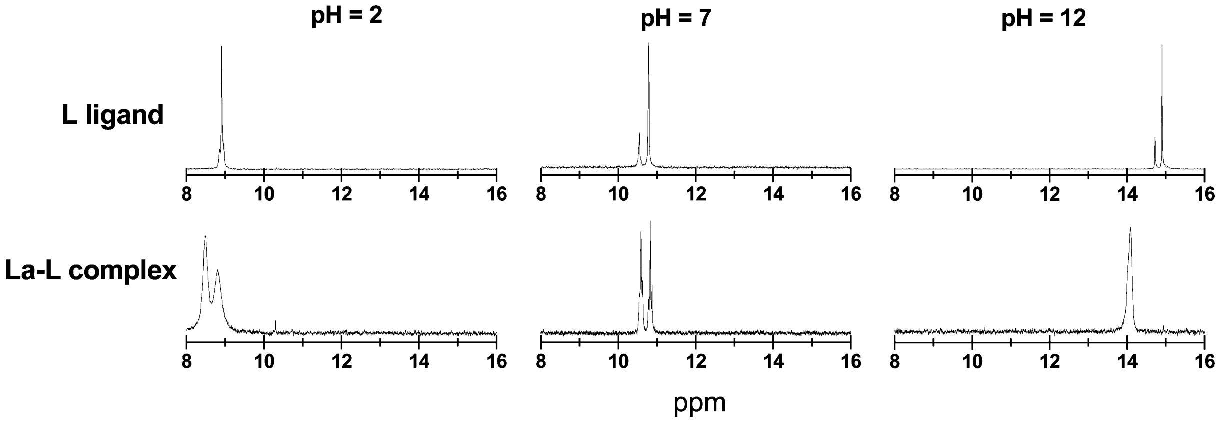


Figure 4. ^{31}P NMR spectra of the La^{III}**L** complexes (bottom) and **L** (top) at different pH values.

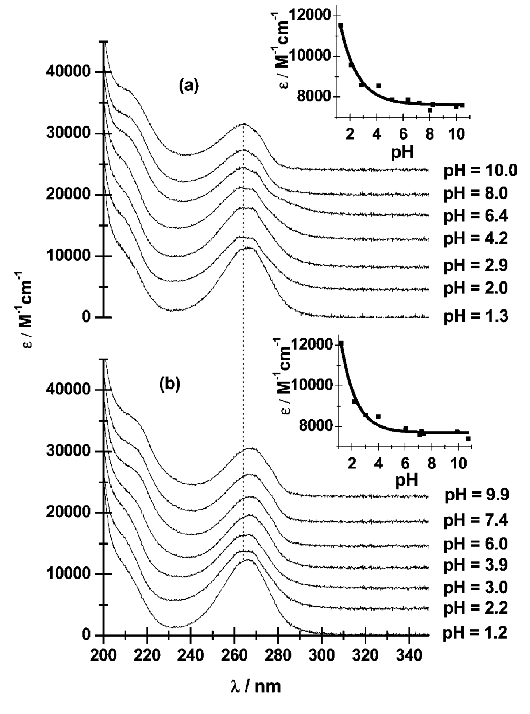


Figure 5. Absorption spectra of **L** (c_L = 0.54 mM; **a**) and Eu**L** (c_{Eu} = 0.54 mM; **b**) at different pH.

changes observed in the band maximum (Figure 2) reflect equilibria between different protonated species. Formation of the Eu**L** complex has a very slight influence on the position of the $^1\pi \rightarrow \pi^*$ peaks for solutions with a pH of up to 3. Above this pH, the band maximum of the Eu**L** complex is red-shifted by 480 cm^{-1} with respect to that of the free ligand at a pH above 8. As can be seen from the insets in Figure 5, almost identical changes in molar absorption coefficient (ε) with solution pH are observed in the spectra of **L** and Eu**L**. Thus, ε decrease up to pH ≈ 5 and then remains constant above this pH.

Emission Spectra

As **L** has three possible binding sites (oxygen atoms from phosphonate groups and nitrogen atoms from pyridine and imino groups), the influence of these donor atoms on the inner sphere of the Eu^{III} ion, and the influence of ligand deprotonation on formation of the Eu**L** complex, were monitored by emission spectroscopy. Typical visible emission bands for the Eu^{III}**L** complex corresponding to the $^5D_0 \rightarrow {}^7F_J$ transitions (J = 0, 1, 2, 3 and 4) were recorded upon excitation of the metal ion to the $^5L_6$ level (λ_{exc} = 394 nm) in both the solid state and in solution (see Figure 6).

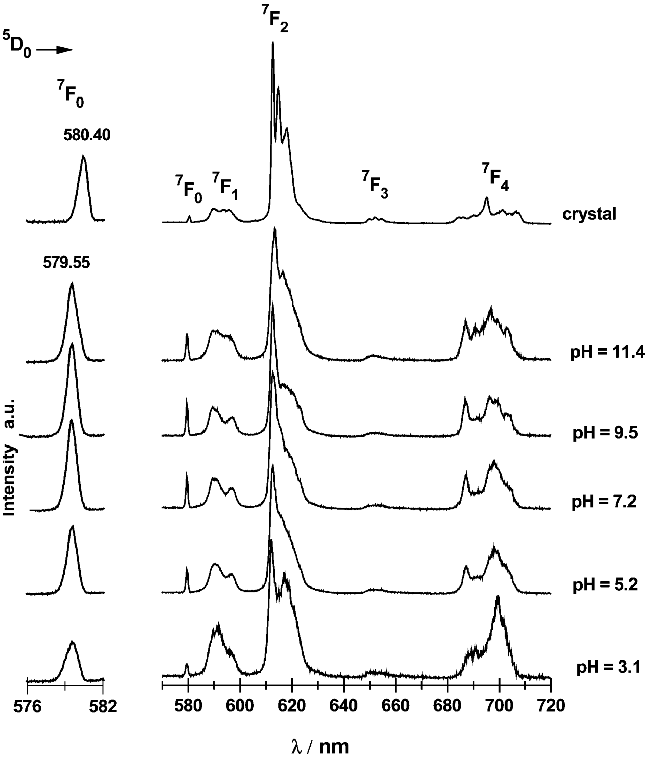


Figure 6. Emission spectra of Eu**L** solutions at different pH (c_{Eu} = 20 mM, λ_{exc} = 394 nm).

Since the ground $^7F_0$ and emitting $^5D_0$ states are nondegenerate, the number of components observed in the $^7F_0 \leftrightarrow {}^5D_0$ spectra may render the number of different chemical environments of the Eu^{III} ion.

It should be pointed out that the energy of the $^5D_0 \leftrightarrow {}^7F_0$ peak is red-shifted in the spectrum of the crystal with respect to that in solution, which may indicate a different coordination environment of the Eu^{III} ion in both phases. One peak in the $^5D_0 \rightarrow {}^7F_0$ spectra of solutions at different pH, with a half-width of around 30 cm^{-1} and constant wavenumber for its maximum, may imply an equilibrium between several species in which the same donor atoms are coordinated to the Eu^{III} ion.

As a change of intensity of the hypersensitive transition would also provide information regarding changes in the coordination sphere of the Ln^{III} ion, the relative intensity ratios of the $^5D_0 \rightarrow {}^7F_2$ transition vs. magnetic dipole $^5D_0 \rightarrow {}^7F_1$ transition were determined. A significant increase of the $^5D_0 \rightarrow {}^7F_2$ hypersensitive transition intensity in the solid-state spectrum with respect to that measured in solution was observed. The high polarisability of pyridine nitrogen atoms means that their binding with Eu^{3+} ion, which occurs in the crystal, results in an increase of the $^5D_0 \rightarrow {}^7F_2$ transition intensity, as reported previously for a similar europium complex with ligands containing a pyridine group.[20] This may suggest that coordination of the pyridine nitrogen atoms to Eu^{III} ion does not take place in solution.

Measurements of emission intensity as a function of pH were performed for emission spectra recorded at excitation wavelengths of 394 (Figure 7, a) and 284 nm (Figure 7, b).

The influence of ligand deprotonation on Eu**L** complex formation can also be seen in the excitation spectra recorded with an emission wavelength of 617 nm. The differences in intensity observed in both curves in the pH range 4–7 are consistent with the results obtained from the excitation spectra (Figure 8), thereby indicating that some ligand energy is transferred to the 4f^6 excited states. Moreover, the emission spectra reveal that this transfer is stronger for protonated Eu**L** species.

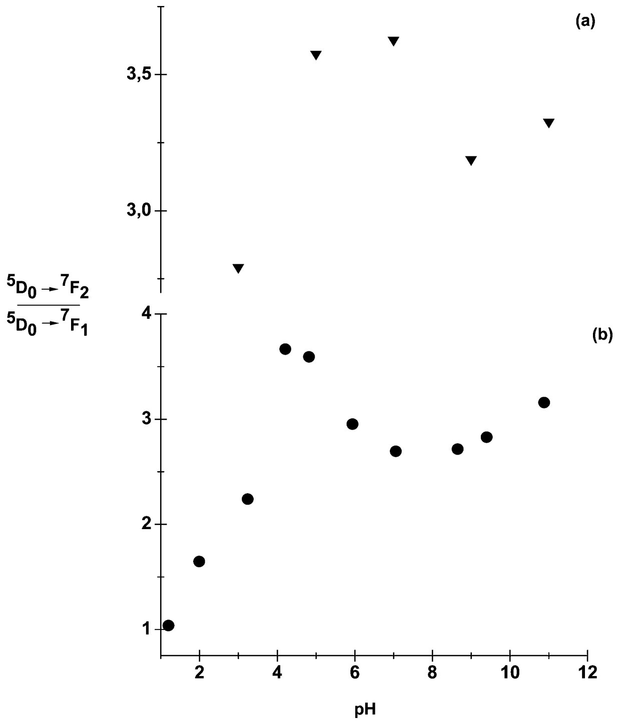


Figure 7. Relative ratios of $^5D_0 \rightarrow {}^7F_2/{}^5D_0 \rightarrow {}^7F_1$ intensity as a function of pH for Eu**L**: (**a**) c_{Eu} = 20 mM, λ_{exc} = 394 nm; (**b**) c_{Eu} = 0.54 mM, λ_{exc} = 284 nm.

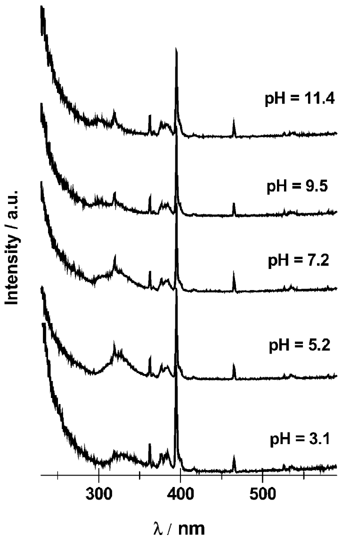


Figure 8. Excitation spectra of Eu**L** solutions at different pH (c_{Eu} = 20 mM, λ_{em} = 615 nm).

As can be seen from Figure 8, deprotonation of the LnH_nL complex is associated with a ligand-to-metal charge-transfer transition. As the concentration of protonated LnH_nL species decreases, the CT absorption band shifts to lower wavelength and the band becomes narrower. The acceptance of UV energy into the CT excited state of the Eu^{III} ion probably explains why energy transfer does not lead to significant, sensitized emission in this system.[21]

Luminescence Lifetime Measurements

Luminescence lifetime measurements of Eu**L** complexes in H_2O and D_2O solution were performed to determine the hydration number (q_{H_2O}) in the studied system using Equation (1).[22]

$$q_{H_2O} = 1.11 \cdot (1/\tau_{H_2O} - 1/\tau_{D_2O} - 0.31) \qquad (1)$$

where $\tau_{H_2O}^{-1}$ and $\tau_{D_2O}^{-1}$ are the luminescence decay rates measured in H_2O and D_2O solution, respectively.

This relation, which also takes into account the deactivation of the emitting state by water molecules of the second coordination sphere (0.31 ms^{-1}), gave the most reliable q_{H_2O} values for phosphonate complexes, previously studied by us, in solution and in the form of monocrystals.[13,19] The average luminescence lifetime of aqueous solutions of Eu**L** at a pH above 4 was equal to 270 µs, shorter than that for the complexes studied previously (approx. 520 µs).[21,22] As can be seen from Figure 9, the ligand is not bound to the Eu^{III} ion at a pH of about 2 as the number of coordinated water molecules is nine. Coordination of **L** to the Eu^{III} ion begins at around pH 3, since q_{H_2O} drops to about six. The hydration number is approximately constant and equal to four for solutions with a pH of between 4 and 11.

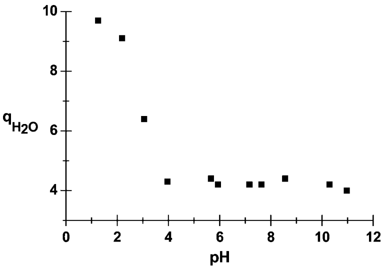


Figure 9. Dependence of coordinated water molecules (q_{H_2O}) on pH of Eu**L** solutions (c_{Eu} = 0.54 mM).

Conclusions

The exchange of carboxylic functions for phosphonates in linear ligands based on the well-known ethylenediamine scaffold leads, in most cases, to more stable complex formation with lanthanide ions, with the metal coordinated to the imino nitrogen atoms and O atoms of the phosphonate arms. The {ethane-1,2-diylbis[imino(pyridin-2-ylmethanediyl)]}bis(phosphonic acid) ligand studied herein contains both phosphonate groups and a pyridine moiety to create a third potential binding site. The crystal structure of the Eu^{III} complex shows that all three donor types are employed in binding to the metal ion. Thus, **L** is coordinated to Eu^{III} via three oxygen atoms from the phosphonic groups, two nitrogen atoms from the imino groups and one nitrogen atom from a pyridine group. Both phosphonate groups in the ligand molecule are bidentate, thus giving rise to a dimer. The stability constants for the series of Ln^{III} ions have allowed to determine that **L** is a powerful ligand for lanthanide ions, with $\log\beta$ values varying between 14.96 and 16.42 and increasing gradually with decreasing ionic size of lanthanide ion. The hydration numbers obtained indicate that the coordination process starts above pH 3 and stays constant from pH 4 up to 10, which is in a good agreement with potentiometric studies. The pyridine moieties are coordinated to the Ln^{III} centre in the crystal but are not coordinated in solution.

Experimental Section

Reagents: All chemicals used were of analytical grade. The stock solutions of anhydrous Ln^{III} chlorides (Aldrich) were standardised against EDTA using xylenol orange as indicator. {Ethane-1,2-diylbis[imino(pyridin-2-ylmethanediyl)]}bis(phosphonic acid) was synthesised as described previously.[15]

Crystal Preparation: Crystals of $[Eu_2(\mathbf{L})_2(CO_3)_2]^{6-}$ were prepared by the method described by Ruloff et al.[23] The molar ratio of Eu_2O_3 and H_4L was 1:1.1. After dissolution of the substrates, the solution was basified with $[C(NH_2)_3]_2CO_3$ to a final pH of around 10 and left to crystallize. Small, colourless and low-quality crystals were formed during very slow solvent evaporation after around one year.

X-ray Crystal Analysis: Crystals were cut from larger ones, mounted on a Kuma KM4 diffractometer equipped with a CCD counter and data recorded at 100 K. These data were corrected for polarization, Lorentz and absorption factors. The structures were solved using Patterson and subsequent difference Fourier maps. The data were obtained from small, low-quality crystals suffering from partial decomposition. The pyridine group, which is not bound to the Eu^{III} ion, a guanidinium cation, a phosphonate group and water molecules were found ot be disordered due to the racemic nature of the ligand. The C atoms from the pyridine group were therefore placed in positions calculated from the geometry. The final refinements were anisotropic for all ordered non-H atoms, whereas the disordered C, N and P atoms were treated isotropically. All computations were performed using SHELXS-97 and SHELXL-97.[24] The molecular graphics were prepared with DIAMOND.[25]

Crystal and Structural-Refinement Data: $C_{36}H_{84}Eu_2N_{26}O_{26}P_4$, M = 1725.09, triclinic, $P\bar{1}$, a = 10.816(4), b = 11.764(4), c = 15.152(5) Å, α = 68.91(3)°, β = 80.02(3)°, γ = 81.02(3)°, T = 100(2) K, Z = 2, V = 1765.8(1) $Å^3$, μ = 1.93 mm^{-1}, $D_{calcd.}$ = 1.622 $g\,cm^{-3}$, $F(000)$ = 876, crystal size 0.10 × 0.12 × 0.11 mm^3, θ = 3–37°, index range: $-16 \le h \le 18$, $-16 \le k \le 19$, $-24 \le l \le 25$, reflections collected/unique = 15124/9353 (R_{int} = 0.0368). Final R indices for $I > 2\sigma(I)$: $R(F)$ = 0.0889, $R_w(F2)$ = 0.2490 and for all data $R(F)$ = 0.1311, $R_w(F2)$ = 0.2752, data completeness to 2θ = 36.9° 84.3 %. Largest diff. peak 5.043 and hole –1.575 $e\,Å^{-3}$.

CCDC-761356 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Potentiometry: The formation constants for proton and Ln^{III} complexes were calculated from pH-metric titration curves carried out at 25 °C. Samples with a total volume of 1.6–1.8 mL were stirred and kept under Ar flow. Titrations were performed over the pH range 2–11 in 0.1 M KCl using a MOLSPIN automatic titration system with Russell CMAW711 semi-combined electrode. A standard solution of CO_2-free NaOH (0.1 M) under argon was added from a 0.250-mL syringe, which was calibrated by both weight titration and titration of standard materials. The electrode was calibrated daily for hydrogen ion concentration by titrating HNO_3 with NaOH. The results were processed using the Gran method.[26] The HYPERQUAD2006 computer program was used to calculate the stability constants.[27] The results were obtained in the form of concentration overall stability constants $\beta_{pgr} = [M_pH_qL_r]/[M]^p[H]^q[L]^r$ where M stands for metal, H is proton and L the deprotonated form of the ligand. The standard deviations quoted were computed by HYPERQUAD2006 and refer to random errors only. They are, however, a good indication of the importance of a particular species in the equilibrium. In all cases at least three titrations were carried out at metal to ligand ratios of between 0:1 and 1:1.2. The **L** concentration was 1×10^{-3} M in all titrations.

pM values for literature examples of complexes were calculated based on p*K* and log*β* values estimated by authors under experimental conditions described in cited papers.

NMR Spectroscopy: The ^1H and ^{31}P NMR spectra were recorded at 25 °C on a Bruker AMX 500 spectrometer at 298 K. The ligand concentration used in the NMR measurements was 1.1×10^{-3} M and the La^{III} concentration 1×10^{-3} M. Chemical shifts were referenced to the signal of a 5% solution of orthophosphoric acid used as external standard. All NMR measurements were performed in D_2O at adjusted pH* (pH not corrected for the isotope effect) values after pH equilibrium had been reached.

UV/Vis Spectroscopy: Stock solutions of europium chloride were prepared by dissolving Eu_2O_3 (99.99%, Standford Materials) in 2 M hydrochloric acid. The metal concentration was determined complexometrically with xylenol orange as indicator. The solutions of Eu^{III}**L** used for spectroscopic measurements were prepared for a 1:1.1 (Eu/**L**) ratio at Eu^{III} concentrations of 20 and 0.54 mM and with $I = 0.1$ M KCl. The pH of solutions was adjusted by addition of HCl or KOH. Absorption and emission spectra of **L** and Eu^{III}**L** solutions were recorded with a Cary 500 UV/Vis/NIR spectrophotometer and a SLM Aminco 500 spectrofluorometer, respectively. The luminescence decay curves for Eu**L** in H_2O and D_2O solutions were recorded with an FLS920 Edinburgh Instruments Ltd. with the emission monitored at 617 nm.

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