Recent advances in the formation of luminescent lanthanide architectures and self-assemblies from structurally defined ligands†

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This article gives some highlights of the recent advances in the development of novel lanthanide based complexes, conjugates and self-assembly structures formed from the use of organic ligands and organo-metallic (transition metal) complexes, that are designed with the aim of capitalising on the high coordination requirement of the lanthanide ions. The examples shown, demonstrate the versatility of the lanthanide ions as luminescent probes and sensors that emit at long wavelength either in the visible or the near infrared (NIR) part of the electromagnetic spectrum.

Introduction

The lanthanides have both intriguing physical and chemical properties. They possess characteristic 4f open-shell configurations, where the most stable oxidation state is +3, and exhibit a close chemical resemblance across the periodic series due to the small and regular decrease in their ionic radii. The lanthanide ions have high charge density and high ionisation potentials, consequently these ions are hard Lewis acids, which can form strong coordinating bonds with a variety of ligands, and are mainly paramagnetic, with the exception of La(III) and Ce(III). The lanthanide ions usually possess coordination requirements as high as ten, though for Eu(III) and Tb(III) nine is very common. Although such high coordination is difficult to fulfill, using a single coordinating organic ligand, the use of functionalised macrocyclic ligands such as cyclen has come close to achieving such coordination.[1]

The lanthanides also present very special spectroscopic properties which originate from the shielding of the 4f orbitals and hence symmetry forbidden f–f electronic transitions.[1,2] Most of the lanthanide ions are luminescent, emitting with characteristic narrow-line-like emission bands, mostly in the visible and near infrared ranges. Their excited state emission depends on how efficiently their excited state(s) can be populated and their non-radiative deactivation paths minimised, which can be tuned by

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† Dedicated to Sigrúnu Gísladóttur on her 75th birthday.

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ligand design. Hence, ions such as Tb(III) and Eu(III) have become particularly attractive as biomolecular markers, as their emission occurs at long wavelength with long lived excited states. The hard Lewis acid nature makes these ions particularly attractive towards ligands possessing amides, carboxylates and nitrogen based heterocycles. Therefore the prospect of designing structurally discrete organic ligands with the aim of developing complex metallo supramolecular architectures is particularly attractive. However, in comparison to transition metal-based supramolecular structures, such lanthanide structures are rare.[1] Nevertheless, in the last few years some excellent examples of such structures have been published, often from the use of simple organic ligands. These are designed so as to satisfy the need for high coordination of the lanthanide ions, either in a single molecule, but more often through the self-assembly of more than one such organic ligand around the lanthanide ions, in some cases mediated by the presence of transition metal ions. As a result structurally complex architectures have been formed which have fascinating photophysical properties, many of which have recently been reviewed.[1,2] This article gives some selected examples of the design principles employed in the developments of such f, f–f and f–d architectures in recent times. It is not meant to be a comprehensive review of the field but rather to give some flavour of this fast growing area of research.

The use of organic ligands in the self-assemblies of f, f–f and f–d metal ion architectures

A series of oxyacetate-functionalised *m*-terphenyl-based ligands incorporating sulfonamido, **1**, and amide groups **2a** and **2b** have been reported and the structures of their corresponding neutral lanthanide complexes have been studied by ^{1}H-NMR and luminescence experiments.[3] Several lanthanide ion complexes were formed from these ligands. In **Eu**.**1**, **Eu**.**2a–b**, **Tb**.**1**, and **Tb**.**2a** (Fig. 1) the ligand occupies eight coordination sites of the metal ion by means of three chelating oxyacetate groups and two amide or sulfonamide oxygens. A solvent molecule completes the inner coordination sphere. The luminescence properties of the Eu(III), Tb(III), Dy(III), and Sm(III) complexes were investigated through excitation of the terphenyl moiety using methanol as a solvent for Eu(III) and Tb(III) and DMSO for the Dy(III) and Sm(III) complexes; the choice of the solvent was dictated by the higher sensitivity of the latter two ions to quenching by solvent hydroxyl groups compared to Eu(III) and Tb(III). Laser excitation at 350 nm of **Er**.**2a**, **Nd**.**2a**, and **Yb**.**2a** also resulted in metal-based luminescence demonstrating that Er^{III}, Nd(III) and Yb(III) can accept energy even from high lying ligand centred triplet states. Organic dyes with a lower energy excited triplet state (around 14 000–17 000 cm^{-1}) have been employed as *antennae* for the near-infrared luminescent Yb(III), Nd(III), and Er(III) complexes of **3** and **4**, (Fig. 2).[4] The 1 : 1 complexes can be efficiently excited with visible light, $\lambda_{exc} = 488$ nm for both fluorescein (in **3**) and eosin (in **4**) derivatives, displaying intense lanthanide luminescence at low concentration ($\approx 10^{-6}$ mol l^{-1}) in D_2O as a result of energy transfer from the chromophore. However, this process occurs rather slowly, as indicated by measurements on the effects of quenching by molecular oxygen.

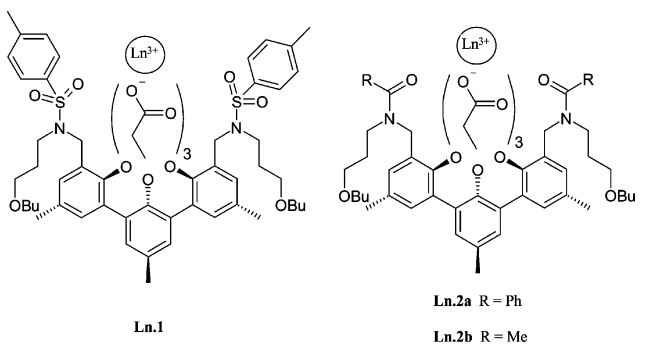

Fig. 1

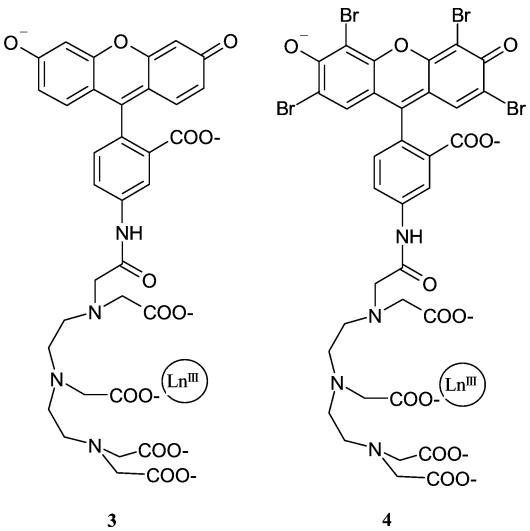

Fig. 2

A hairpin-shaped heterotrimetallic luminescent neodinium complex **5** (Fig. 3), has been designed for sensing biological substrates, such as DNA.[5] In this system, the ligand can wrap around the lanthanide ion through a hard binding core, *i.e.* the diethylenetriaminepentaacetic acid derivative moiety, as well as providing two soft thiol sites available for binding transition metal ions, such as Pt(II). The two planar Pt(II) complexes act as strong DNA intercalators and also as sensitisers for Nd(III) NIR

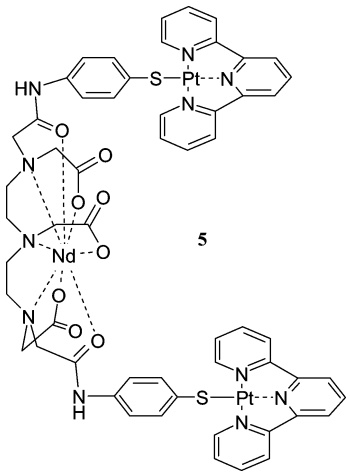

Fig. 3

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luminescence. The lanthanide unit does not interact with DNA, thus acting as a luminescent "reporter".

Tsukube and co-workers prepared the Eu(III) complex of tris(2-pyridylmethyl)amine **6**, as a luminescent sensor for nitrate, NO_3^-, while the corresponding Tb(III) complex displayed Cl^- selectivity, (Fig. 4).[6] The Eu(III) complexes of **6** and **7** possess 1 : 1 stoichiometry and are stable enough for use in solution. In this case, the pyridine units fulfill the role of the sensitising antenna, absorbing at 260 nm before transferring their excited state energy to the lanthanide ion. However, the complexes are coordinatively unsaturated and hence the metal bound solvent molecules effectively quench the luminescence. Nevertheless, upon addition of three equivalents of NO_3^- to **Eu**.**6**, or Cl^- in the case of **Tb**.**6**, in CH_3CN, the solvent molecules are displaced and the luminescence is increased by factors of 4.9 and 5.4, respectively. Conversely, anions such as I^-, Br^-, Fl^-, ClO_4^-, SCN^-, HSO_4^-, and $H_2PO_4^-$ do not show the same response. The achiral ligand **7** displayed similar anion selectivity in CH_3CN, although to a lesser extent than the chiral analogue.

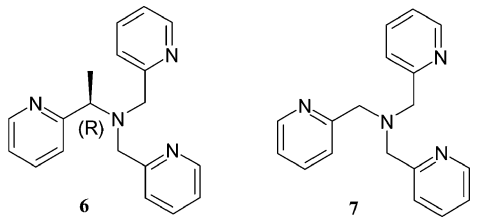

Fig. 4

Charbonnière *et al.* reported on the time-resolved luminescent properties of a nona-coordinated Eu(III) complex.[7] The ligand comprises a podand incorporating bipyridine arms, each of which bears a carboxylate unit, **8** (Fig. 5). In the resulting Eu(III) complex, the metal ion coordinates to six nitrogen atoms from the three bipy subunits together with three oxygen atoms of the carboxylate groups, providing an overall coordination number of 9. The ^{1}H-NMR spectrum of the Eu(III) complex in d_6-DMSO shows unambiguously a C_3 symmetry in solution. From the analysis of its photophysical properties in water at room temperature, the Eu(III) complex exhibited a long excited state lifetime ($\tau = 1.85$ ms) and a relatively high quantum yield ($\Phi = 0.12$). The stability constant of the complex was proven to be of the same order of magnitude as the corresponding EDTA complex, under the same conditions ($\log K = 14.3 \pm 0.8$). Bioaffinity assays based on time-resolved luminescence were carried out using the Eu(III) complex, suggesting that suitable [Eu(**8**-2H)]$^+$ derivatives could be used as luminescent labels in time-resolved luminescence microscopy.

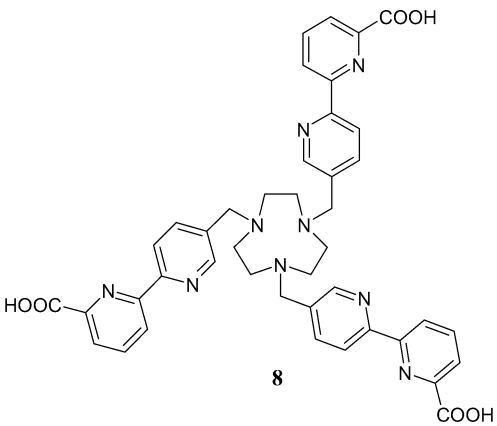

Fig. 5

Pikramenou and co-workers prepared the bis(β-diketone) ligands **9** and **10** (shown in their enolic forms, Fig. 6) which bind to Ln(III) or Yb(III) ions to form neutral homodimetallic triple-stranded complexes [M_2(**9**-2H)$_3$] where M = Eu, Nd, Sm, Yb, Gd and [M_2(**10**-2H)$_3$], where M = Eu, Nd or anionic quadruple-stranded dinuclear lanthanide units, [Eu_2(**9**-2H)$_4$]^2.[8] The complexes have been thoroughly investigated by NMR confirming the formation of a single complex species with high symmetry and chiral nature, as demonstrated by the splitting of the NMR signals upon addition of Pirkle's reagent. The absorption spectra of both **9** and **10** exhibit an intense band centred at 357 nm, attributed to the π–π* enol absorption. This is typical of the enol form of β-diketones. The complexes have high molar absorption coefficients (*ca.* 13×10^4 M^{-1} cm^{-1}) and display strong visible or NIR luminescence, depending on the chosen lanthanide, upon excitation of the ligand band at 350 nm. The bis-diketonate ligand proved to be an efficient sensitiser, particularly for Sm(III) and Nd(III). Compared with the triple stranded Eu(III) complex in the solid state, the quadruple-stranded complex displays a more intense luminescence with a distinct emission pattern indicating its higher symmetry.

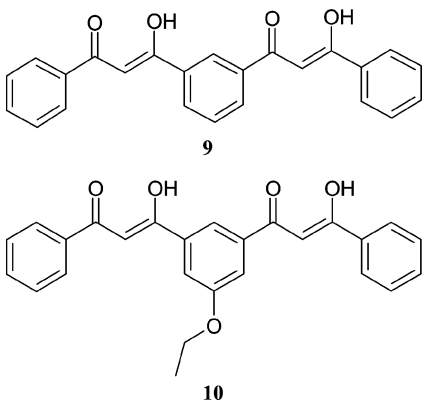

Fig. 6

Faulkner and Pope investigated the synthesis and luminescence properties of a hetero-trimetallic lanthanide complex containing two terbium ions and one ytterbium ion **11**, (Fig. 7).[9] In this elegant f–f–f system, the Yb(III) centred NIR emission at 980 nm is sensitised *via* energy transfer from the terbium centres when

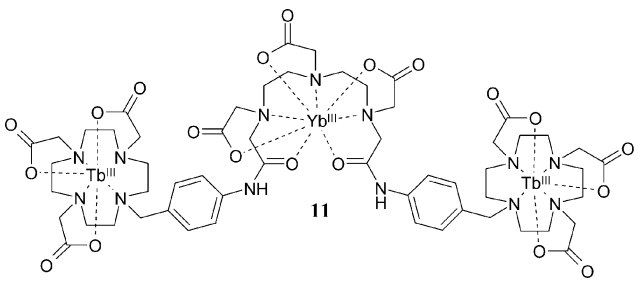

Fig. 7

excited at 488 nm. It is worth noting that neither ytterbium nor the aryl chromophore of the aminobenzyl group possess any absorption bands at 488 nm. Therefore, it was deduced that ytterbium sensitisation occurred by means of energy transfer from the terbium ions. This is one of the first examples of a lanthanide centred NIR emission sensitised by a lanthanide ion.

Bünzli and co-workers designed a new class of highly stable and luminescent dimetallic carboxylates which self-assemble in water forming lanthanide helicates.[10] Ligand **12** (Fig. 8) yields neutral triple-stranded dimetallic helicates with the entire series of lanthanide ions $[Ln_2(\mathbf{12}\text{-}2H)_3]$; such complexes are stable in water in the pH range 4–13, with stability comparable to that of DOTA-derived complexes (pLn ≈ 21–22; where $pLn = -\log[Ln(III)(aq)]^{3+}$ when $[Ln(III)]_t = 10^{-6}$ M and [DOTA] = 10^{-5} M, at pH = 7.4).[11] This indicates that the large hydration energy of the trivalent lanthanide ions is adequately compensated by the favourable thermodynamic contribution of the self-assembly process.

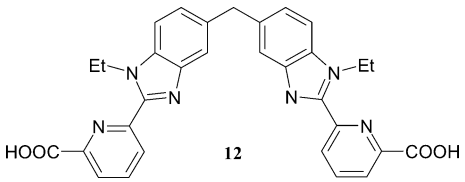

Fig. 8

In the case of the Ln(III) complexes of **12** (and related examples from these groups)[1,11] the three ligand strands are wrapped around the two nine-coordinate Ln^{III} ions in a helicate shaped structure with a pseudo-D_3 symmetry around the metal, as demonstrated by X-ray crystallography, which showed that the Tb(III) complex of **12** had the chemical formula: $[Tb_2(\mathbf{12}\text{-}2H)_3]\cdot 20.5H_2O$. These results were confirmed by ^{1}H-NMR studies in D_2O, as further evidence that the complexes adopt a helical structure in solution as well as in the solid state. Moreover, the q value of the Eu(III) complex was found to be zero, which proves that the Eu(III) ions are completely protected from direct water interaction, thus providing a good Eu(III)-containing luminescent probe. A thorough investigation of the metal-centred luminescence spectra of the Eu(III) and Tb(III) complexes, both in solution and in the solid state, were also in perfect agreement with the D_3 symmetry reflected in the NMR spectra.

Recently, the disassembly of bimetallic triple-stranded lanthanide helicates has been thoroughly investigated in the presence of an excess of metals, revealing the competitive formation of standard linear bimetallic complexes and circular trimetallic single-stranded helicates.[12] Except for ligand **15** (Fig. 9), which quantitatively forms the triple-stranded helicate $[Ln_2(\mathbf{15})_3]^{6+}$ for a 2 : 3 Ln : **15** ratio, all other ligands (**13**, **14**, **16**, Fig. 9) slowly interconvert into a mixture of complexes, as detected by ^{1}H NMR in $CH_3CN/CHCl_3$ (1 : 1) and ESI-MS titrations. For these complexes, the assembly of the bimetallic triple-stranded helicates (2 : 3, Ln : Ligand) competes with the formation of complexes with a 1 : 1 stoichiometry. The crystal structure of the Eu(III) assembly with ligand **17** with a 1 : 1 stoichiometry is shown in Fig. 10 and represents the first example of such a circular single-stranded lanthanide helicate.[13]

The challenging development of heteropolymetallic f–f′ complexes has been achieved by Piguet *et al.* by assembling the tris-

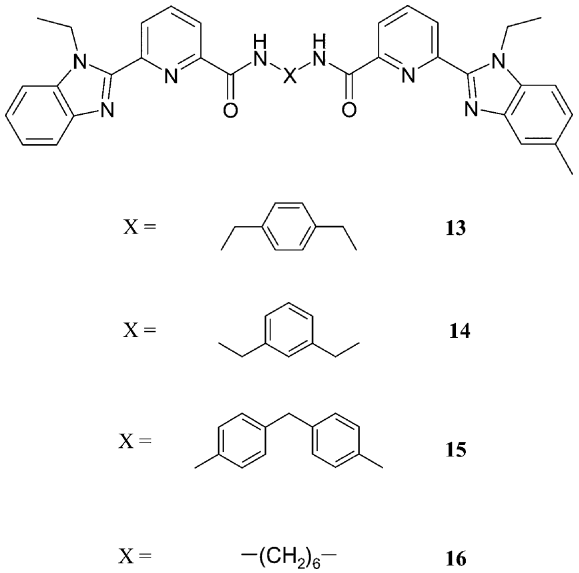

Fig. 9

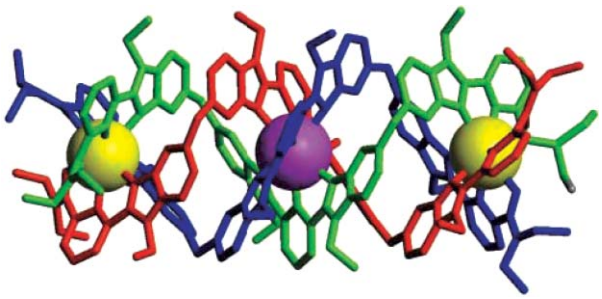

Fig. 10 The crystal structure of the Eu(III) triple-stranded helicate formed from ligand **17**. (Reproduced with permission from ref. 13. Copyright 2004 Wiley Interscience.)

tridentate ligand **17** (Fig. 11) and two different lanthanide metal ions (Ln^1 and Ln^2).[13] In acetonitrile, the self-assembly under stoichiometric conditions yields a mixture of heterotrimetallic triple stranded helicates $[(Ln^1)_x(Ln^2)_{3-x}(\mathbf{17})_3]^{9+}$ ($x = 0$–3) with Ln^1, Ln^2 = La(III), Nd(III), Sm(III), Eu(III), Yb(III), Lu(III), Yb(III). The statistical analysis of the thermodynamic data obtained through qualitative (ESI-MS) and quantitative (^{1}H-NMR) investigations highlighted the importance of the different affinities of each specific lanthanide for the terminal sites (N_6O_3) and the central one (N_9). These parameters depend on the ionic radius, thus providing size-discriminating effects which favour the formation of heterotrimetallic helicates with the central site occupied by the larger metal.

In 2000, Horrocks and Lessmann reported the second example of neutral helicates in aqueous solution.[14] The ligands used, **18** and **19** (Fig. 12) consist of two tridentate chelating units linked by an organic diamine (1,2-diaminocyclohexane in **18**, 4,4′-diaminodiphenylmethane in **19**, Fig. 12). Thus, each ligand coordinates to two different metal ions and the complexes formed are dinuclear with two 9-coordinate lanthanide ions and a stoichiometry of $[Ln_2L_3]$. The coordinating units chosen by Horrocks are based on the well-known **dpa** ligand (**dpa** = 2,6-pyridinedicarboxylic acid). This ligand forms the well-studied, propeller-shaped complex $[Ln(\mathbf{dpa})_3]^{3-}$,[15,16] which is 9-coordinate

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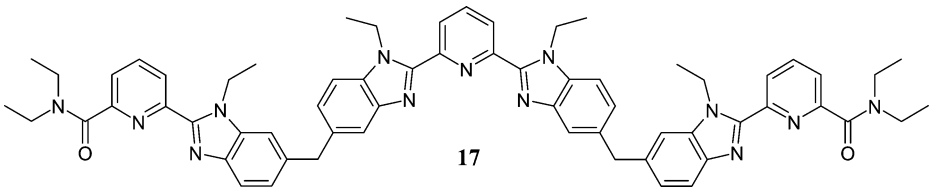

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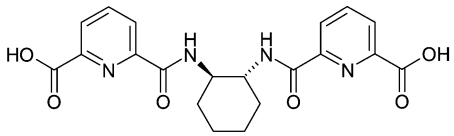
Fig. 11



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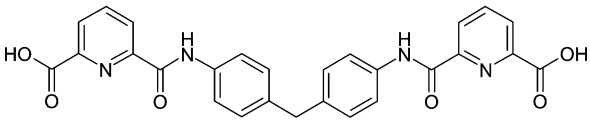

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Fig. 12

with trigonal prismatic, D_3 geometry and either Δ or Λ chirality at the metal centre. The diamines link the coordinating moieties *via* amide bonds. In **18**, both *R*,*R* and *S*,*S* enantiomers of the diamine linker have been used in order to impose a handedness to the helicate and to produce a complex which retains its metal-centred (ΔΔ or ΛΛ) optical activity in solution. $[Ln(\mathbf{dpa})_3]^{3-}$ and other chiral lanthanide complexes of this type all racemize rapidly in solution, resulting in racemic mixtures.[14]

The formation and speciation of the lanthanide complex assemblies derived from **18** and **19** have been further studied by laser-induced lanthanide luminescence spectroscopy in aqueous solution. However, X-ray crystal structure analysis of these complexes has not been reported to date. Nevertheless, molecular mechanic modelling calculations have been used to predict the likely structures of dinuclear helicates with a 3 : 2 ligand : metal (L : M) stoichiometry and D_3 symmetry. The results indicate the formation of the true helix form (ΔΔ or ΛΛ configuration at the metal ion centres) and also the side-by-side helicate (ΔΛ configuration). In the latter, the authors predicted that ligand **18** was able to form a bridged structure, where one ligand chelates one metal ion through both binding sites; two such coordinated metal ions are then bridged by a third ligand.

The diastereoselective self-assembly of a trinuclear Eu(III) array has been elegantly presented by Mamula *et al.* which exhibits a supramolecular helical chirality related to the arrangement of the ligands **20** (Fig. 13) around the metallic core.[17a] An elegant crystal structure of the trinuclear assembly was obtained and revealed that the ligands adopt a left-handed helical configuration, which was also proven by the circular dichroism (CD) spectrum of the complex. Preliminary investigations were conducted, which showed that the trinuclear assembly persists in the solution state. Upon UV irradiation, the Eu^{III} array displays bright red luminescence both in solution and the solid state. The properties of the assembly in the excited state were therefore investigated by circularly polarised luminescence (CPL) spectroscopy. The excitation of the organic chromophore at 315 nm in CH_3CN gave rise to polarised emission

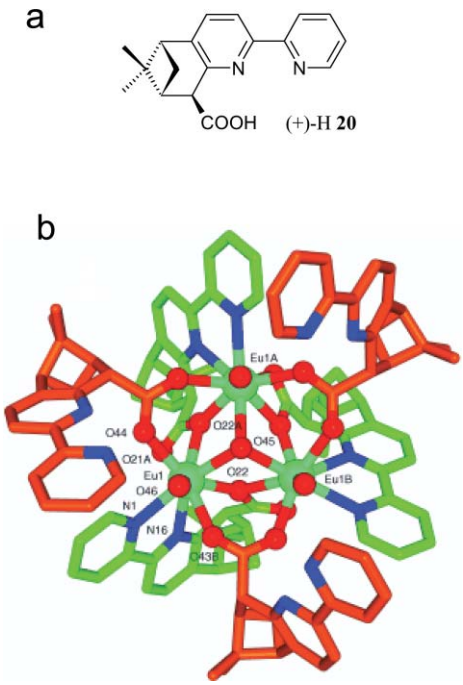
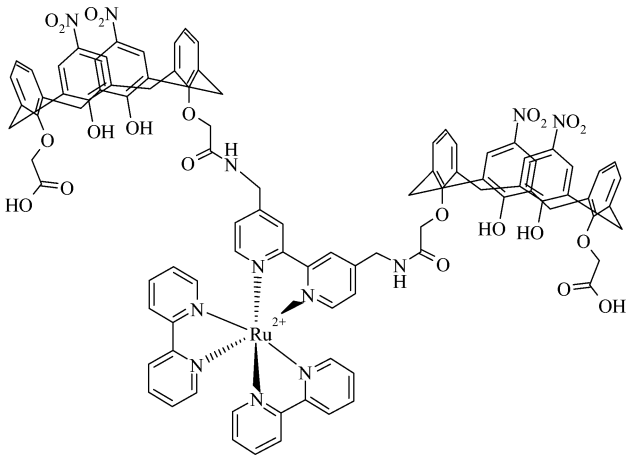


Fig. 13 a) Ligand **20**; b) The crystal structure of $[Eu_3\{(+)\text{-}\mathbf{20}\}_6(\mu_3\text{-}OH)(H_2O)_3](ClO_4)_2\cdot 3H_2O$ (O red, Eu turquoise, N dark blue; O-coordinated pinene-bipyridyl groups orange, N,O-coordinated pinene-bipyridyl groups green). View parallel to the crystallographic C_3 axis with a simplified labelling scheme. Hydrogen atoms, perchlorate counterions, and water molecules of crystallization have been omitted for clarity. (Reproduced with permission from ref. 17. Copyright 2006 Wiley Interscience.)

bands corresponding to the Eu(III)-centred $^5D_0 \rightarrow {}^7F_J$ transitions. Mamula *et al.*, have recently extended this self-assembly strategy by developing switchable chiral architectures, which are solvent dependent, containing Pr(III) ions.[17b]

Beer and co-workers synthesised and studied the photophysical properties of luminescent ruthenium(II) bipyridyl complexes containing one, two (**21**, Fig. 14) or six lower rim acid-amide modified calix[4]arene moieties, covalently linked to the bipyridine groups.[18] The Ru-calixarene complex **21** is able to coordinate Nd(III), Eu(III) and Tb(III) in a 2 : 1 Ln^{3+} : complex ratio. Addition of lanthanide ions (as nitrate salts) to acetonitrile solutions of the ruthenium complex **21** caused noticeable changes in the absorption and emission spectra allowing the evaluation of the association constants.

The luminescence studies upon excitation of the tris(bipyridine)–ruthenium(II) complex at 452 nm, show that the adduct formation affects the ruthenium luminescence, which is strongly quenched by Nd(III) and increased by Tb(III) and Eu(III). In the case of Nd(III), the excitation spectra show

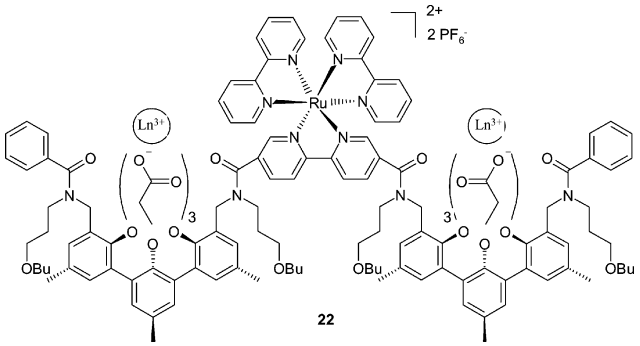


21 $2(PF_6^-)\cdot{}_2H_2O$

Fig. 14

that (*i*) the quenching of the ruthenium luminescence occurs *via* energy transfer to the Nd(III) centre and (*ii*) the electronic energy of the excited calixarene is not transferred to the $Ru(bpy)_3$ but again to Nd(III), due to its proximity to the calixarene moiety. As a consequence, the neodymium emission at 1064 nm is greatly enhanced. In the case of Tb(III), the emission intensity and the lifetime of the ruthenium bipyridine moiety both increase. This behaviour was ascribed to the electric field created by the lanthanide ion around the ruthenium–calixarene complex by comparison with the Gd(III) ion, which behaves identically and can affect ruthenium only through its charge. Another contribution may have come from the decrease of vibrational motions (therefore of non-radiative processes) upon complexation with Tb(III) due to the rigidification of the structure. Finally, in the case of Eu(III), it was found that the ruthenium bipyridine emission intensity and lifetime both increased if the lanthanide ion was added as a nitrate salt; whereas the addition of Eu(III) as a triflate salt did not affect the ruthenium luminescence. This led to the conclusion that the luminescence behaviour is strongly dependent on the lanthanide counterion. Moreover, the electron transfer (*Ru → Eu) quenching process, although thermodynamically allowed, does not occur due to kinetic reasons. Most probably the quenching process is rendered inefficient by the specific geometry/conformation of the [**21**·$2Eu^{3+}$] adduct, where the nitrate plays a very important role.

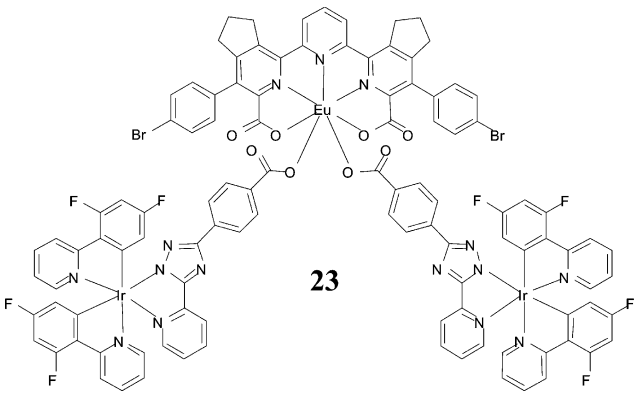
One of the first examples of the use of Ru(III) based moieties to achieve sensitised lanthanide emission *via* the excitation of the Ru(III) centre is **22** (Fig. 15).[19] Here the ligands for the complexations of the Ln-centres were similar to those seen in Fig. 1. However, in the case of **22**, two such ligands were employed giving rise to two Ln-binding sites. In this trimetallic $RuLn_2$ complex the near-infrared luminescence of neodinium and ytterbium was sensitised by energy transfer from the triplet excited state of the ruthenium–tris(bipyridine) complex.[19] The transition metal-based antenna absorbs in the visible part of the electromagnetic spectrum. The luminescent nature of the donating state (the ^{3}MLCT state) has allowed a detailed study of the energy transfer process to the lanthanide centres. The rate of the sensitisation process measured for both Nd(III) and Yb(III) complexes are 1.1×10^6 s^{-1} and $\leq 10^5$ s^{-1}, respectively.



22

Fig. 15

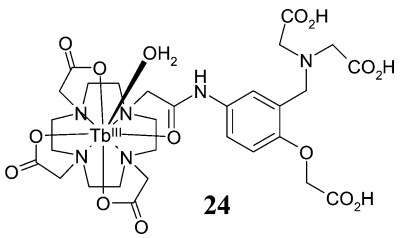
A remarkable example of self-assembly is represented schematically in Fig. 16, by DeCola *et al.*[20] The supramolecular system **23** consists of a heterotrimetallic complex, in which the photoexcitation of the Eu(III) occurs *via* energy transfer from a transition-metal-based antenna. In such a system, the Ir(III)-based moiety acts as a sensitiser for the Eu(III) red emission. Interestingly, the emission of almost-white light can be observed if there is only partial energy transfer from the excited Ir-based chromophore. If this occurs, the Eu(III) red emission combined with the residual blue emission from the iridium complex gives rise to a global white light emission.



23

Fig. 16

Incorporation of potential metal ion binding sites into the macrocyclic ligand can yield metal-specific luminescent probes. In the Tb(III) complex **24** (Fig. 17), for instance, the selective zinc ion binding at pH 7.4 in a competitive ionic background resulted in a luminescence enhancement of the terbium emission by 26%.[21a] Pope *et al.* have also recently elegantly demonstrated such Zn(II) sensing.[21b]



24

Fig. 17

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In a similar manner, we have investigated the effect on the ground, singlet excited states and the Tb(III) emission of **25** and **26** (Fig. 18) as a function of pH and concentration of alkali metal cations.[22] By analysing the photophysical properties of the complexes in water, upon excitation at 300 nm, it was established that both their ground and excited states were modulated by changes in pH and by the presence of ions such as Na^+ and K^+. Both **25** and **26** were found to be pH independent between pH 4 and 8, where their luminescence was "switched off". However, in buffered pH 7.4, the Tb(III) emission was highly modulated by either Na^+ and K^+, **26** showing higher sensitivity due to the more suitable size of the receptor. In all cases, the photophysical changes were attributed to the modulation of the antenna-receptor moiety and of the energy transfer process from the antenna to the lanthanide centre.

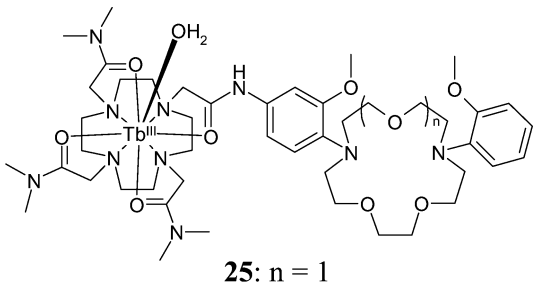


Fig. 18

The work of Parker *et al.* has featured many excellent examples of cyclen based lanthanide architectures. One example of these is **27**, in which a palladium porphyrin has been covalently linked to a chiral Yb(III) complex.[23] In this hetero-metallic system the quenching of the excited triplet state of the Pd(II) porphyrinate by molecular oxygen is suppressed upon DNA binding resulting in an enhancement of the NIR Yb(III) luminescence. This is one of the first examples of such self-assembly architectures. Parker *et al.* have elegantly developed other self-assembly systems between simple lanthanide complexes and anions such as carboxylates, phosphates and phosphorylated amino acids. These will be discussed later.

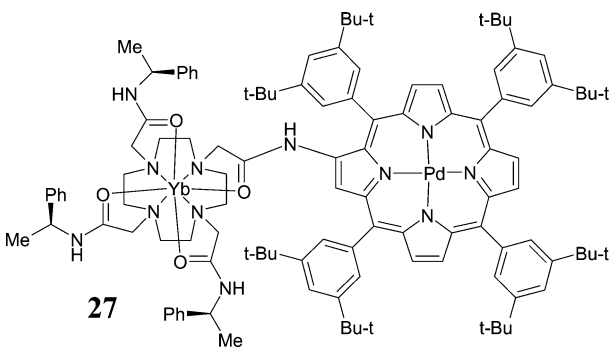


Fig. 19

Faulkner, has developed interesting f–d self-assemblies. Here we see the detection of carboxylates at the lanthanide metal centre, in the self-assembly system **28** (Fig. 20),[24] which was formed from the coordinating unsaturated lanthanide (Ln = Yb(III), Nd(III) or

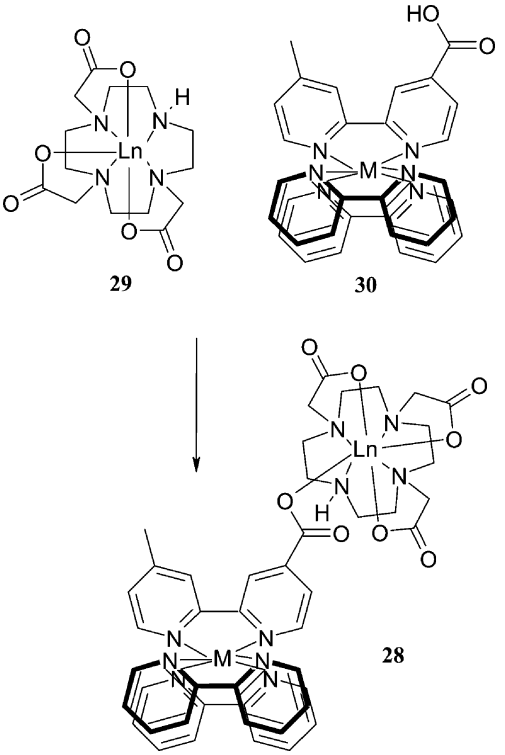


Fig. 20

Er(III)) complexes **29** and the M = Ru(II) or the Os(II) complexes **30**. This enabled the population of the lanthanide ion by the MLCT band of the transition metal ion similar to examples **21** and **23**, however, unlike these examples the MLCT moiety was directly coordinating to the lanthanide ion centres.

In 2004, we designed a cationic cyclen based Eu(III) complex as a luminescent copper sensor, **31** (Fig. 21).[25] In this system, a simple 1,10-phenanthroline group was conjugated to the cyclen macrocycle, where it serves as the antenna for the complex as well as being a potential coordination site for transition metal ions. It was hoped that this system could be used to form a mixture of f–d–f trimetallic self-assembly, which can be schematically described as **B** in Fig. 22, where the luminescence of the lanthanide centre would be modulated upon formation of the assembly. Indeed, **31** (shown as **A** in Fig. 22) did form self-assemblies as expected with various ions such as Co(II), Fe(II) and Cu(II). However, we did not form exclusively the desired f–d–f network **B**, but also the tetranuclear polymetallic supramolecular complex where Cu(II) was coordinated by three **31** complexes. Even though this was not desirable, nevertheless, the assembly was formed in aqueous

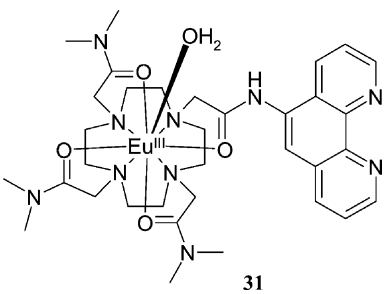


Fig. 21

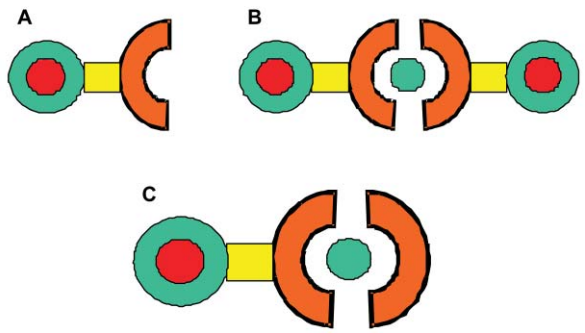
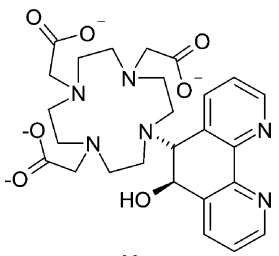


Fig. 22 Schematic representation of linear self-assembly **B**, made from the cyclen based conjugate **A** (red ball = Eu(III)) upon coordination to d-metal ions such as Fe(II) (green ball) and **C**; the formation of capped–self-assembly from **A** (red ball = Yb(III) and Nd(III)) and $[Ru(bipy)_2Cl_2]$ (Ru(II) = green ball).[29]

solution at pH 7.4 (but we had previously shown that the Eu(III) emission was highly pH sensitive, being switched on in neutral pH while being switched off in either acidic or alkaline media)[26] which was highly desirable. Hence, the above self-assembly between **31** and Cu(II) can be considered as one of the first examples of supramolecular self-assembly of mixed f–d metal ion conjugates. The recognition of Cu(II) in water at pH 7.4 gives rise to the quenching of the Eu(III) luminescence showing good selectivity over other ions such as Co(II), Fe(II), and Fe(III).

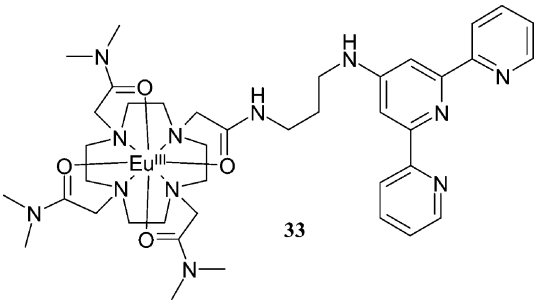
In a related work, Desreux *et al.* have also developed related self-assembly complexes using the 6-hydroxy-5,6-dihydro-1,10-phenantholine appended cyclen derivative **32** (Fig. 23).[27] They showed that the Gd(III) complex of **32**, and using either Fe(II) or Ni(II), gives rise to the formation of a mixed f and d metal ion self-assembly. This is very similar to that observed for **31** above. While this system was not studied for its luminescent properties, but rather as a potential contrast agent for MRI, the design strategy employed was the same as in **31**. Similarly, Livramento *et al.* have used an octa acidic acid derivative of a 2,2′-bipyridine moiety as an MRI contrast agent, which was formed by self-assembly around an Fe(II) ion, giving a 6 : 1 ratio between the f and the d metal ions in the self-assembly.[28]



32

Fig. 23

In order to fine-tune the self-assembly process set out in Fig. 22, **31** above, a different kind of mixed linear trimetallic f–d supramolecular self-assembly based on **28** was developed in our laboratory. Here, a Eu(III) cyclen derivative appended with a terpyridine, **32**, was developed (Fig. 24), in which the terpyridine moiety acts as a sensitizer for the lanthanide centre as well as a suitable ligand for transition metal ions, such as Fe(II) and

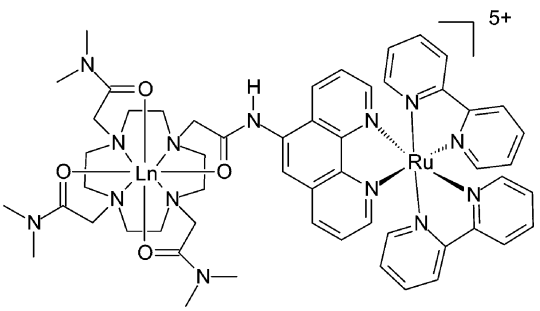


33

Fig. 24

Ni(II).[29] The hydration state of the complex (q) was found to be 1.2 indicating that complex **32** had one metal-bound water molecule, giving an overall nine-coordinate environment. The lanthanide luminescence of the Eu(III) complex was monitored as a function of pH resulting in the emission being switched on above pH 3 and switched off above pH 9. The UV-vis, fluorescence and europium luminescence spectra were then measured at neutral pH upon addition of a series of transition metal ions. The changes in the ground state of **32** showed the formation of a ternary complex with a new MLCT band appearing at *ca.* 570 nm upon coordination of Fe(II) and Ni(II) to the terpyridine moiety. As for the fluorescence, the emission band at 422 nm was quenched upon titration with both Fe(II) and Ni(II). The coordination of these metal ions to the antenna also caused the quenching of the delayed europium luminescence, probably due to back energy transfer from the lanthanide emissive state ($^5D_0$) to the excited triplet state of the antenna. The Eu(III) ion can therefore be used as an "impartial luminescent reporter" for the formation of the self-assembly complex, as it is not directly involved in the binding of the transition metal ions.

Having formed the desired structure **B**, we set out to form the f–d analogue depicted as **C** in Fig. 22. Here the underlying objective was, as in the examples **22** and **23**, to achieve IR emission from Nd(III), Yb(III) or Er(III) by using an antenna that would absorb in the visible region. To achieve this, we employed the Nd(III), Yb(III) or Er(III) complexes of the ligand shown for **31** and a capping ligand.[30] This gave the f–d conjugates **34** and **35** respectively (Fig. 25). This design places the two metal ion centres close to each other and enables fast and efficient population of the near IR emitting ions from the MLCT band (at *ca.* 450 nm) of the Ru-centre. Excitation of the 450 nm band gave emission centred at 610 nm assigned to the d-block emission. This gives



34 Ln = Yb(III)
35 Ln = Nd(III)

Fig. 25

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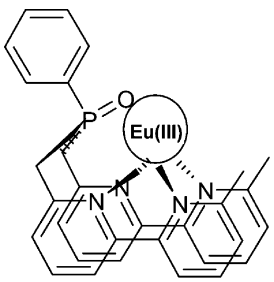
rise to the necessary overlap with the symmetry forbidden f–f absorption bands of Yb(III) and Nd(III) (which have low extinction coefficients), allowing for the necessary sensitization of **34** and **35**, respectively, in the visible region. These are the first examples of such f–d dyads, based on the design principle **C** in Fig. 22 using the cyclen based ligands.

The use of organic ligands in the formation of self-assemblies between f-ions and anions

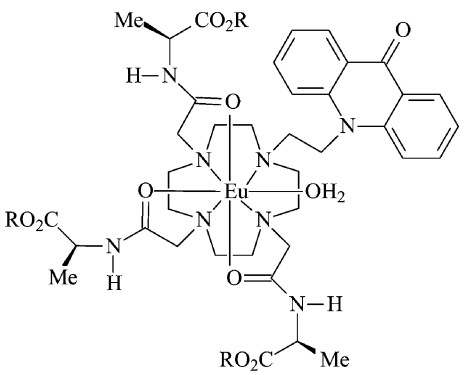
As discussed above both Parker *et al.* and Faulkner *et al.* have developed self-assembly systems by using coordinately unsaturated lanthanide complexes.[24,31] Such complexes have also been made in a similar manner by Ziessel *et al.* who have developed a sensor for anions using the coordinately unsaturated complex **36** (Fig. 26).[32] Here a bis-bpy-phenyl phosphine oxide ligand, was designed as an anion sensor when complexed with Eu(III). This pentadentate ligand is unable to fully complex the lanthanide thus leaving an open face that acts as the receptor site for anion coordination. Luminescence was produced by energy transfer from the bpy moiety. The complexes were made *in situ* in MeCN with either Eu(III) triflate or nitrate salts. In studies with a number of anions an 11-fold increase in emission intensity was seen on the addition of two equivalents of NO_3^-.



36

Fig. 26

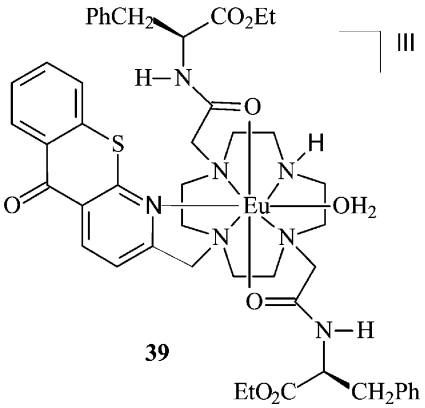
Two examples from Parker *et al.* of sensors for anions, where the lanthanide ion emission is modulated upon the formation of a self-assembly between a lanthanide complex and an anion are **37** and **38** (Fig. 27).[33] These were developed for the detection of bicarbonate in intra- or extra-cellular environments, and as such



37 R = Et
38 R = -

Fig. 27

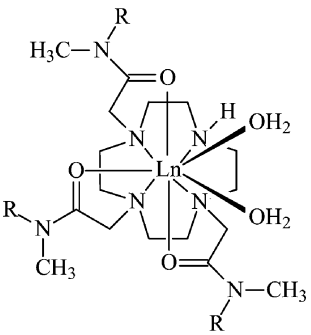
are potential probes for such anion sensing in cells. This idea has recently been elegantly developed further with the formation of selective nucleoli stains based on the Eu(III) complex **39**, (Fig. 28). This complex was used to stain nucleoli of NIH 3T3, HeLa and HDF cells, and the complex was shown to function as a probe in both live and fixed cell imaging.[34]



39

Fig. 28

We have recently demonstrated that similar coordinatively unsaturated complexes, *e.g.* **40** (Fig. 29) which lack the covalently attached antenna seen in the above complexes, can be used to detect anions that themselves are antennae, such as salicylic acid, in competitive media.[35] Here the prodrug aspirin was not detected and **40** can be used to selectively discriminate between the two antennae. Similar work has also been published by Wong *et al.*[36] Faulkner *et al.* have also developed similar systems using a Nd(III) analogue, to study the efficiency of the near-IR sensitisation process in ternary complexes, using various antennae including a pyrene carboxylate.[37]



40 Ln = Tb(III); R = CH_3

Fig. 29

Having established in our own laboratory that lanthanide complexes such as **40** (which we describe as being 'photophysically silent' as they lack the antenna that is necessary for the population of the lanthanide excited state) could be used as carboxylate sensors, we set out to develop analogues of this design by using two metal ion complexes, tethered together with a short aliphatic spacer or by using a xylene moiety.

An example of the latter design is the bis-lanthanide complex **41** (Fig. 30).[38] This complex was found to bind either to mono-anions such as salicylic acid or to bis-anions such as bis-carboxylates.

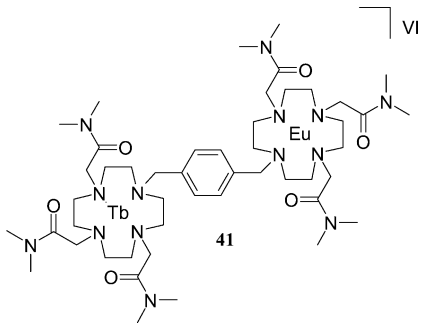


Fig. 30

For most of these anions the lanthanide emission was switched on upon anion recognition, in a similar manner to that observed for **40**. In the case of those anions lacking antenna, we used the xylene spacer as the antenna, by excitation at low wavelengths. While this is not ideal for the population of the Tb(III) excited sate, the emission was still modulated upon anion sensing, being enhanced, with the exception of tartaric acid where the emission was quenched upon sensing of the anion. The binding mode for this recognition was 1 : 2 (complex to ions) for those anions that only had a single binding site and 1 : 1 binding for the biscarboxylates. In all cases the emission enhancements were significantly larger for those anions having antennae. We are currently developing other analogues of this design to allow for the formation of larger self-assembly structures. Faulkner *et al.* have similarly developed such sensors that can be used for anions in the near-IR.[39] Similarly to **41**, the excitation of the bridging antenna gave, on all occasions, the characteristic metal luminescence from the lanthanide ions.

An alternative design strategy for the development of such self-assembly formation for sensing purposes has recently been developed in our group.[40] Here a self-assembly between a β-diketonate and the Eu(III) complex of **40** was formed in buffered pH 7.4 solution. This assembly (Fig. 31) was highly luminescent, and the Eu(III) emission was clearly visible to the naked eye under a UV-lamp (UV-excitation). The formation of the assembly was also found to be highly pH sensitive, where it was only formed within the physiological pH range. However, we discovered that this assembly could also be dissociated upon the addition of certain anions such as HCO_3, lactic acid and F^- at pH 7.4 in water. Hence, the assembly can be described as a lanthanide based 'displacement assay' for anions in aqueous solution.[41] We are currently developing this strategy further.

Conclusions

This article has dealt with some of the many examples of lanthanide based architectures that have been published in the last a few years. It is obvious from this account that the area of lanthanide mediated self-assembly formation and the use of lanthanide ions in sensing and luminescent biological imaging is a fast growing field and full of opportunities. Moreover, many of the lanthanide ions have relevance for the telecommunication industry, such as Er(III) and a large body of work has been published in the past where such complexes have been developed. It will thus be very interesting to follow this exciting development in the coming years.

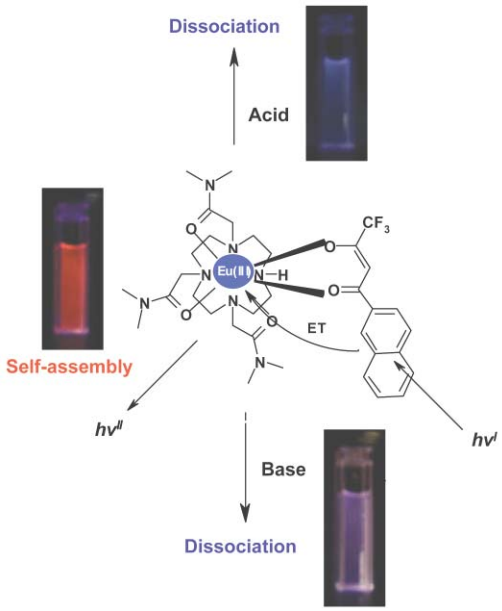


Fig. 31 The formation of the self-assembly between the Eu(III) complex of **40** and β-diketonate at pH 7.4 gives rise to red Eu(III) emission, while in acidic or alkaline media the self-assembly dissociates and the blue emission of the organic antenna is only observed.

Acknowledgements

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