Self-assembly formation of mechanically interlocked [2]- and [3]catenanes using lanthanide ion [Eu(III)] templation and ring closing metathesis reactions†

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The formation of interlocked lanthanide-based catenanes using Eu(III)-directed synthesis is described (catenation being achieved via a ring-closing metathesis reaction); the self-assembly formation of the supramolecular structures was analysed by HRMS, NMR and luminescent spectroscopies.

The development of mechanically interlocked molecules such as catenanes and rotaxanes using metal ion directed self-assembly templating is now a well-established synthetic strategy in supramolecular chemistry.^{1–3} While d-metal ions are commonly used in such synthesis, Beer *et al.* have recently also demonstrated the use of anions in such self-assembly.⁴ The templating ions can be employed as an integrated part of the resulting self-assembly structure or be removed after its formation by competitive extraction/displacement, changing their oxidation states, chemical reactions, *etc.*⁵ Many examples of such elegantly designed systems have been reported by leading scientists in this field, including those of Sauvage *et al.*,⁵ Stoddart *et al.*⁶ and Leigh *et al.*⁷ All have demonstrated the use of d-metal ion directed synthesis of interlocked molecules.^{8,9} In contrast, the use of lanthanide ions (f-metal ions) in the formation of such interlocked molecules has remained relatively unexplored to date. To the best of our knowledge, only a few examples of this kind exist, including those of Beer, Faulkner, and coworkers¹⁰ who used lanthanide ions for the formation of [2]rotaxanes and Loeb *et al.*,¹¹ who developed interlocked MOF structures. However, the formation of lanthanide template [n]catenanes has not yet been reported.

Over the last few years we have developed many examples of the use of lanthanide ions in directing the synthesis of supramolecular architectures.¹² These include the formation of self-assembled gels and Langmuir–Blodgett films,¹³ chiral luminescent bundles (termed the “Trinity Sliotar”)¹⁴ and triple-stranded dimetallic helicates.¹⁵ Of these, the *bundles* were formed by the self-assembly of three

Fig. 1 The synthetic strategy for the Ln-directed synthesis of [3]catenane, involving 1 : 3 (M : L) self-assembly formation between the **L1** (in different colours for clarity) and Ln(III), yielding **Ln·L1₃**, and catenation by ‘triple clipping’ to give **cat·Ln·L2₃**.

chiral pyridyl di-amide ligands (PDA) using ions such as Eu(III). We envisaged that such PDA ligands could also provide a structural platform for the development of [3]catenanes, where the three rings would be ‘all’ interlocked around a single metal ion, and not in a linear ‘chain’ fashion, as demonstrated by Sauvage *et al.*^{5c} and recently by Rowan *et al.*¹⁶ Our synthetic strategy is shown schematically in Fig. 1, where by using PDA ligands containing polyethoxy spacers and terminal alkene groups, the initial self-assembly with the lanthanide (1 : 3 **Ln : L**) would result in preorganization of the alkene groups in a manner that could facilitate their catenation or ‘closing’ by ‘triple clipping’ of adjacent alkenes using a ring-closing metathesis (RCM) reaction. Here we present, to the best of our knowledge, the first examples of Ln-based [2]- and [3]catenanes, the formation and structures of which were elucidated in solution using UV-vis, luminescence and NMR spectroscopy and HRMS.

The synthetic strategy chosen for this approach is shown schematically in Scheme 1. Having unsuccessfully explored a large number of ligand structures related to **L1** (Scheme 1) as candidates for the catenation process, results from MM2 force field calculations (see ESI†) indicated that the [3]catenane **cat·Ln·L2₃** could be formed upon a RCM reaction of **Ln·L1₃**, which was derived from the PDA ligand **L1**.† The synthesis of **L1** (see ESI†) was achieved by reacting 2,6-pyridinedicarboxylic acid chloride (**1**) with 3-(2-(2-(2-aminoethoxy)ethoxy)ethoxy)propen-1-ene (**2**)¹⁷ (see ESI†). **L1** was isolated in 48% yield as a yellow oil after a series of acid–base extractions and flash column chromatographic purification. The ¹H-NMR analysis (400 MHz, CDCl₃) of **L1** confirmed its successful

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Scheme 1 The synthesis of **L1**, **L2**, and **cat-Ln-L2₃**: (i) = TEA, CH₂Cl₂, 48 h; (ii) = 2nd generation Grubbs catalyst; CH₂Cl₂, 72 h.

Fig. 2 The ¹H NMR spectra of (a) **L1**, (b) **Eu-L1₃**, (c) **cat-Eu-L2₃**.

formation (Fig. 2a), where the allylic protons were observed as a multiplet at 5.89 ppm (for the CH), while the terminal protons of the allyl group appeared at 5.14 and 5.29 ppm. The successful formation of **L1** was further confirmed by ESI mass spectrometry ($m/z = 472.28$ [$M + Na^+$] see ESI†). The formation of **Ln-L1₃** (**Ln** = Eu) was achieved using Eu(III) as the templating ion, where **L1** was mixed with 0.33 equivalent of Eu(CF₃SO₃)₃ in anhydrous MeCN and refluxed for 24 h, after which **Ln-L1₃** was isolated in 32% yield as a yellow oil after precipitation and diethyl-ether diffusion into CH₃OH. The ¹H NMR spectrum of the Eu(III) complex **Ln-L1₃** is shown in Fig. 2b, which indicates the presence of a single species in solution with a C₃ symmetry. For PDA ligands of this nature, the ¹H NMR spectrum is normally not greatly shifted upon complexation with Eu(III),¹⁴ but does become broadened as shown in Fig. 2; the alkene proton signals can be distinguished at 5.3 and 5.9 ppm, respectively.

The photophysical properties of **L1** and **Ln-L1₃** were also investigated in CH₃CN, H₂O and D₂O solutions as part of this study. In the past, we have shown that the appearance of the lanthanide centered emission upon the formation of such self-assemblies, or changes in the ligand absorption or the emission properties, can be used to quantify both the stability and the stoichiometry

of the self-assembly formation effectively.^{13–15} The UV-vis absorption spectrum of **L1** (see ESI†) displayed two absorption bands centred at $\lambda = 227$ nm ($\epsilon = 9500$ M⁻¹ cm⁻¹) and $\lambda = 278$ nm ($\epsilon = 4010$ M⁻¹ cm⁻¹). The excitation of these transitions gave rise to only weak fluorescence emission (ESI†). The UV-vis absorption spectra of **Ln-L1₃** (see ESI†) demonstrate that the absorption band of **L1** experienced a large hyperchromic effect upon complexation with Eu(III), indicative of the successful formation of the desired 1 : 3 complex. This was further confirmed by excitation at 281 nm, which gave rise to metal centred Eu(III) emission at 592, 615, 646 and 693 nm for the deactivation of the Eu(III) ⁵D₀ excited-state to ⁷F_J ($J = 1, 2, 3$ and 4 , respectively), demonstrating the successful sensitisation of the Eu(III) excited state by the pyridyl antenna.¹⁷ Excited state lifetime measurements of **Ln-L1₃** also supported the formation of this species in solution with a hydration state of zero. However, in water the excited state lifetimes were best fitted to a bi-exponential decay, an indication of the formation of a second minor stoichiometric species in solution. Because of this, the formation of **Ln-L1₃** was also monitored *in situ* by carrying out spectroscopic titrations of **L1** [2×10^{-5} M] with Eu(III), as well as carrying out Job's plot analysis in CH₃CN. The resulting changes in the absorption spectra of **L1** (see ESI†) demonstrated a strong hyperchromic effect upon varying the molar fraction of Eu(III) from 0 → 0.33, confirming the predominant formation of the 1 : 3 stoichiometry in solution. This was, however, followed by a sharp decrease in the absorbance at higher molar fractions, which is indicative of the formation of species of different stoichiometries in solution. The evolution of the Eu(III)-centred luminescence was also monitored and is shown in Fig. 3. The excitation spectrum of **Ln-L1₃** was also found to be structurally similar to the absorption spectrum. The results clearly support the formation of the **Ln-L1₃** self-assembly in high yield, as is evident from the changes in the $\Delta J = 2$ transition shown as an inset in Fig. 3. This transition is sensitive to the changes in the local environment of the Eu(III) ion. The plot clearly shows that the main changes in the Eu-emission occur upon the addition of 0–0.33 equivalents of Eu(III), demonstrating the successful formation of **Ln-L1₃** in solution. Beyond 0.33 equivalents, however, the emission was quenched, confirming the displacement of the equilibrium towards the formation of other stoichiometries in solution. To quantify this further the

Fig. 3 The changes in the Eu(III) centred emission upon formation of **Eu-L1₃** from **L1** and Eu(SO₃CF₃)₃ in a CH₃CN solution. Inset: the plot of intensity vs. Eu(III) equivalents showing the formation of the 1 : 3 complex.

Fig. 4 The MALDI-TOF mass spectrum of **cat-Eu-L23** and **cat-Eu-L22** obtained after the metathesis of **Eu-L13**. Insets: calculated isotopic distribution patterns for some of the Eu(III) based [2] and [3]catenanes m/z .

changes in the absorption spectra were analysed using a non-linear regression analysis program SPECFIT[®]. The results (see ESI[†]) indeed showed the presence of two major species in solution, namely the desired **Ln-L13** complex, which was formed in 82% yield after the addition of 0.33 equivalents of Eu(III), with a stability constant $\log \beta_{1,3} = 18.7 \pm 0.8$, and the 2:1 stoichiometry product **Ln-L12**, which became the dominant species at higher Eu(III) concentrations with a $\log \beta_{1,2} = 12.6 \pm 0.6$. These spectral changes and stability constants are similar in magnitude to those measured for related systems.^{13–15,18}

Before catenation of **Ln-L13**, **L1** was subjected to a RCM reaction in the presence of a second-generation Grubbs catalyst. This gave a clean single product, which was identified by ¹H NMR (see ESI[†]) as **L2**, the closed macrocyclic product of **L1** (Scheme 1) ESMS gave a mass of 504.2316, assigned to **L2** + Na⁺. To maximise the yield of the triple clipping catenation of **Ln-L13**, the RCM reaction was carried out at a low concentration (10^{−4} M) in the presence of a second-generation Grubbs catalyst at room temperature for three days under an inert atmosphere (see ESI[†]). After the removal of the catalyst, any unreacted material and possible oligomers by multiple organic extractions, a crude yellow oil was isolated in 25% yield by evaporation of the aqueous layer. The trituration of this oil, using CH₂Cl₂, allowed for the isolation of two products. One of which was identified as an 'all organic' compound that was, by ¹H NMR analysis (see ESI[†]), shown to possess a high degree of symmetry, having a similar ¹H NMR to that seen for **L2**. Indeed, MALDI-TOF MS analysis confirmed this product as **L23** with masses of 1466.7150

(**L23** + Na⁺) and 1482.6854 (**L23** + K⁺) being observed. This confirmed the successful closing of the three ligands of **L1** in an interlocked manner.[§] The second product was isolated as a brown oil after initial isolation from the aqueous phase and further precipitation using a mixture of CH₂Cl₂ and diethylether. However, unlike that above, this compound gave rise to typical Eu-emission upon excitation of the pyridyl antennae, demonstrating the presence of Eu(III) within its structure (ESI[†]). The ¹H NMR spectrum of this product is shown in Fig. 2c. Despite being somewhat broader, it resembled the ¹H NMR spectrum observed for **L2** (ESI[†]), and confirmed the formation of a single predominant species with a high degree of symmetry. The ¹H-NMR spectrum clearly showed that the RCM was successful, as the resonances assigned to the terminal allylic moieties in **Ln-L13** had disappeared, being replaced with a single resonance at 5.88 ppm assigned to the newly formed alkene protons. Further investigation using MALDI-TOF MS showed the presence of two species in the MS, both possessing isotopic patterns assigned to Eu(III)-containing products, Fig. 4. The first of these were detected at m/z = 1280.42 and 1430.66, which would support the formation of the [2]catenane species **Ln-L12** (with one or two SO₃CF₃[−]). The second complex supported the presence of [3]catenane which was detected at m/z = 1761.70 and 1919.57, resulting from a triple RCM clipping of **Ln-L13** (with one or two SO₃CF₃[−]) (cf. Fig. 4), but the observed isotopic distribution pattern matched the calculated. Hence, these results clearly demonstrate the formation of both **cat-Ln-L22** and **cat-Ln-L23** in solution. Furthermore, MS-MS experiments were also performed on both

of these (see ESI†) where the results showed no collapsing of these Eu(III) self-assemblies, indicating that the compounds formed were stable to further fragmentation. The stability of these interlocked systems and that of **Ln-L1₃** was further studied by carrying out titrations using DTPA, a ligand with a high affinity for lanthanide ions. The changes in the UV-vis absorption and the Eu(III) luminescence spectrum (see ESI†) clearly demonstrated de-complexation for both species. However, this occurred at twice the concentration of **cat-Ln-L2₃** than needed for the extraction of Eu(III) from **Ln-L1₃** (see ESI†). This stability was further confirmed by MALDI-TOF analysis where the addition of one equivalent of DTPA resulted in major dissociation of **Ln-L1₃** (see ESI†) while only minor changes were seen in the MS of **cat-Ln-L2₃** (see ESI†). This indicated that the catenation process resulted in an increase in the Eu(III)-complex stability, suggesting an efficient wrapping of the Eu(III) ion within the [2]- and [3]catenanes. In summary we have developed, to the best of our knowledge, the first examples of lanthanide template [2]- and [3]catenanes. We are currently exploring other such interlocked Ln-supramolecular structures.

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Notes and references

- ‡ This simple design strategy could also, however, lead to the possible formation of mixture of other supramolecular species in solution (such as [2] and [3]pseudorotaxanes as well as macrocyclic structures) due to intramolecular olefin 'scrambling' in **Ln-L1₃** (ESI) in the RCM reaction. § This product could be due to the inter-ligand metathesis resulting in the formation of a possible molecular knot or interlocked [3]catenane.
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