

Rational Design of a Ternary Supramolecular System: Self-Assembly of Pentanuclear Lanthanide Helicates

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 Supporting Information

ABSTRACT: The self-assembly of the first pentanuclear helicate was predicted on the structural basis obtained for linear and tetranuclear parent supramolecular compounds. Accordingly, the designed ternary supramolecular system requires appropriate polytopic organic receptors, which were successfully synthesized. Indeed, the formation of pentanuclear complexes was experimentally evidenced with NMR and ESMS spectra that perfectly reflect the expected pattern. The structural features in the europium pentanuclear complex are highlighted with semiempirical molecular modeling. The present work validates the combinatorial approach leading to the thermodynamically driven formation of tower-like pentanuclear edifices.

The self-assembly of polynuclear compounds with a discrete and synthetically controlled structure has been the subject of many studies. While this challenging task is quite successfully accomplished with transition metals, the polynuclear complexes with lanthanides were not developed to such an extent. The interest in lanthanide-containing compounds comes from a number of potential applications, such as lighting and light-converting devices,¹ contrast agents for MRI,² responsive probes,³ or nanomaterials.⁴ Different polynuclear edifices with Ln(III) have been extensively reviewed by Bünzli and Piguet in 2002.⁵ Since that time, new examples of interesting polynuclear lanthanide-based assemblies have been reported and include triangular complexes,⁶ circular helicates,⁷ linear tri- and tetranuclear helicates,⁸ coordination oligomers,⁹ and inorganic clusters.¹⁰ However, except linear helicates, these high-nuclearity complexes have been rarely obtained as the results of rational programming.

We have previously reported on a tripodal ligand **L1**, where three binding strands are anchored on a short spacer.¹¹ **L1** adopts a trefoil shape conformation favoring the coordination of one metal per each strand. This predisposition results in three-dimensional complexes with a tetrahedral arrangement of metal ions. Moreover, the ligand strands are wrapped about metal ions in the direction of four C_3 axes, which are defined by the metal ion and the tetrahedron center. Interestingly, this 3D organization offers the exciting possibility to extend the tetrahedral assembly by accommodating an additional metal ion along one C_3 axis. This operation will provide a pentanuclear complex composed of the tetrahedral and the linear parts. The resulting

unusual assembly thus combines different helical motifs, and that gives a new dimension to the chemistry of helicates.

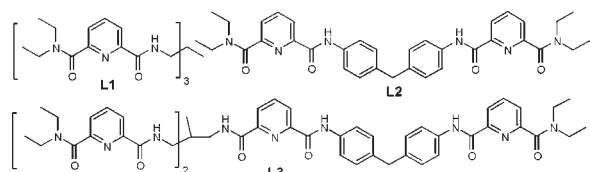
In order to realize such assemblies, one must prepare a polytopic ligand combining delicately the structural motifs responsible for the formation of both, tetrahedral complexes and linear dinuclear helicates. While the choice of **L1** is obvious, we must find a suitable bridge for connecting the coordination site of the linear part. The inspiration for this extension may be found in previously synthesized dinuclear triple-stranded helicates. Although a literature search offers few possible systems, we have chosen to employ a diaminodiphenyl moiety, which has been successfully used by Lessmann and Horrocks.¹² In this context, an analogous ditopic ligand **L2** bearing terminal carboxamide groups can be considered as a structural model for the linear part. Consequently, the structure of the desired multitopic ligand **L3** is obtained by merging the tripodal ligand **L1** and the linear ditopic strand **L2** (Scheme 1). **L3** may be thus described as a tripodal unsymmetrical ligand with two monotopic and one ditopic strands. The retrosynthetic analysis of the desired complex reveals that the targeted pentanuclear self-assembly can only be designed as a ternary system of Ln(III) cations and two different ligands in the ratio $[Ln]/[L1]/[L3] = 5:1:3$. One ligand **L1** will form the base of the tetrahedron, while three **L3** will form the side faces and the linear part of the edifice.

The chosen synthetic strategy of **L3** consists of coupling a ditopic precursor **4b** and an unsymmetrical precursor **5**¹³ (Scheme 2). Indeed, this reaction was achieved in a relatively good yield and **L3** was characterized with NMR (Figure S1) and ESMS. The reaction of 4,4'-diamino-diphenylmethane with **1**¹⁴ (see Supporting Information) provides not only the desired precursor **3** but also the disubstituted ligand **L2**, which was isolated as a secondary product. The NMR spectrum of **L2** (Figure S2) gives ten signals compatible with a C_{2v} -symmetrical conformation in acetonitrile. X-ray crystallography shows that **L2** crystallizes as a prolate-type molecule with a classical *trans-trans* conformation of potentially coordinating dicarbonyl moieties (Figure 1, Table S1). Since the lanthanide complexes with **L2** are not reported in literature and no crystal structure was determined by Lessmann et al.,¹² Ln(III) complexes with **L2** have been investigated to ascertain the formation of the expected triple-stranded helicates $[Ln_2L_2_3]^{6+}$. Therefore, the complexes with different Ln(III) were prepared by mixing **L2** with corresponding perchlorate salts in the $[Ln]_{tot}/[L2]_{tot}$ ratio equal to 0.67.

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Scheme 1. Chemical Structure of Ligands



Scheme 2. Synthetic Routine for L3

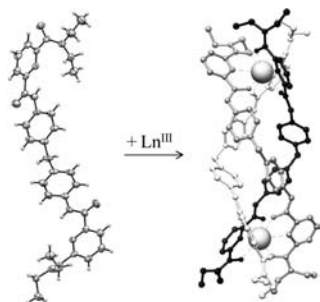
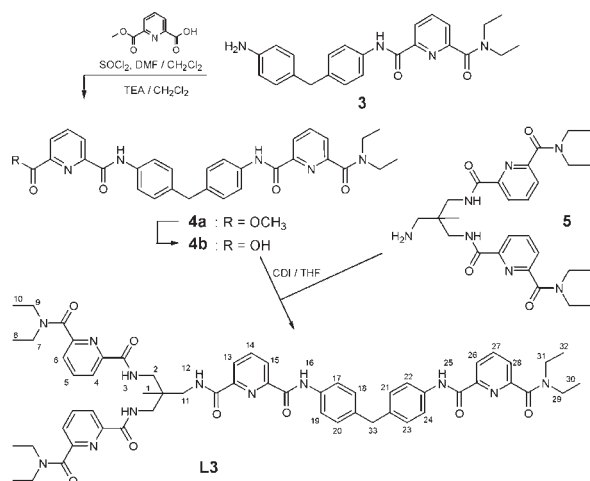


Figure 1. ORTEP view (50% probability level) of the crystal structure of L2 (left) and the crystal structure of $[\text{Nd}_2\text{L}_2\text{L}_3]^{6+}$ (right). Hydrogen atoms, perchlorate anions, and solvent molecules are omitted for clarity.

Crystals suitable for X-ray diffraction studies were obtained for $\text{Ln} = \text{Nd}, \text{Eu}, \text{Er}$, Eu by diffusion of *tert*-butylmethylether into the concentrated acetonitrile solution of $[\text{Ln}_2\text{L}_2\text{L}_3](\text{ClO}_4)_6$. Crystallographic data are summarized in Table S1. In all compounds, the complex adopts the same geometry of a triple-stranded dinuclear helicite. Moreover, the Nd(III) and Eu(III) complexes are isostructural and crystallize in the triclinic system, while the Er(III) and Lu(III) complexes crystallize in the orthorhombic system. Finally, the structures of acceptable quality for publishing are obtained for $[\text{Nd}_2\text{L}_2\text{L}_3]^{6+}$ and $[\text{Lu}_2\text{L}_2\text{L}_3]^{6+}$. As a representative example, we only describe in detail the crystal structure of the Nd(III) complex. The overall structure is reminiscent of the previously characterized dinuclear triple-stranded helicites and, more particularly, of the calculated structure of the analogous complex bearing terminal carboxylate groups.¹² Three binding

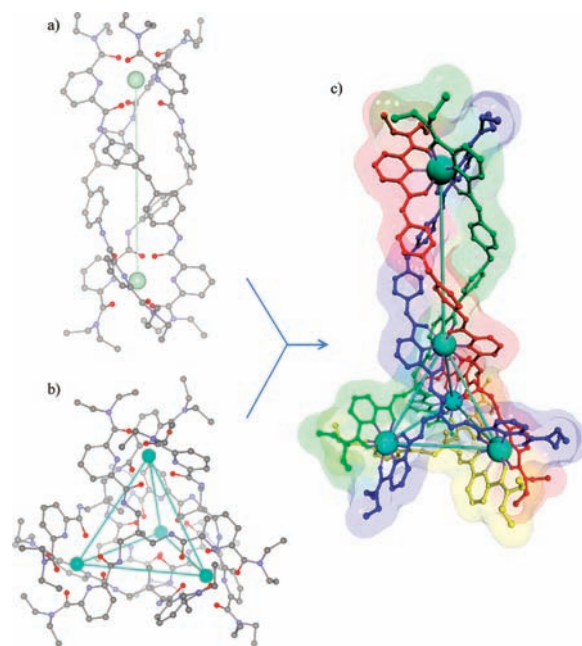


Figure 2. Design and the molecular modeling of a pentanuclear complex. (a) Crystal structure of $[\text{Nd}_2\text{L}_2\text{L}_3]^{6+}$. (b) Crystal structure of $[\text{Tb}_4\text{L}_1\text{L}_4]^{12+}$. (c) View of the calculated structure of $[\text{Eu}_5(\text{L}_1)(\text{L}_3)_3]^{15+}$ (SPARKLE/AM1 model). Hydrogen atoms are omitted for clarity. Ligands in the pentanuclear complex are represented in different colors.

strands are wrapped about two Nd(III), and each cation is coordinated by three different ligands. The helicite possesses a pseudo- D_3 axis passing through metallic cations. The intermetallic distance is equal to 14.03 Å, which is close to the calculated distance in the analogous Horrocks's helicite¹² (13.9 Å) and about 5 Å longer than in Piguet's helicites (≈ 9 Å).⁸ In acetonitrile, the ¹H NMR spectra are compatible with D_3 -symmetrical complexes with significant chemical shift changes compared to the uncomplexed L2, as shown in Figure S3 for $[\text{Eu}_2\text{L}_2\text{L}_3]^{6+}$ and $[\text{Lu}_2\text{L}_2\text{L}_3]^{6+}$. The ES-MS spectra unambiguously show the signals belonging to different perchlorate adducts with dinuclear helicites (Figure S4).

Prior to synthesis, the predicted pentanuclear assembly had been modeled using the crystal structures of the above-described $[\text{Nd}_2\text{L}_2\text{L}_3]^{6+}$ and $[\text{Tb}_4\text{L}_1\text{L}_4]^{12+11}$ by their superposition in one metallic cation and merging (Figure 3). This choice is justified by the absence of crystallographic data for a common Ln(III). However, as shown with NMR, the isostructurality of Ln(III) complexes with L1 and L2 is maintained along the series, and the structural parameters can be safely used as an initial set for calculating. The above operations were performed with the DS ViewerPro software followed by a semiempirical geometry optimization using the Sparkle program.¹⁵ The final structure given in Figure 2 shows the pentanuclear complex with Eu(III) and reflects the same features as in parent complexes. We do not expect significant structural deviations for the complexes that will be eventually prepared with other Ln(III). The ligand strands forming the tetrahedral part have the same helicity, which propagates into the linear part. We distinguish a pseudo-3-fold axis passing through two metallic cations of the linear part and the center of the tetrahedron. The Ln–Ln distances within the tetrahedron base are 10.8 Å, while slightly elongated distances are measured toward the fourth vertex (11.1 Å). On average, the distance is more than 1 Å longer in comparison with $[\text{Tb}_4\text{L}_1\text{L}_4]^{12+}$

(9.83 Å). Similarly, the intermetallic distance in the linear part is 15.4 Å compared with 14.3 Å in $[\text{Eu}_2\text{L}_2\text{L}_3]^{6+}$. The intermetallic distances in the calculated structure are thus more relaxed than in the crystal structures of parent complexes, which may be the consequence of the crystal packing and the neglected influence of counterions. In spite of this, the superposition of the model and the crystal structures is in satisfactory agreement (Figure S6).

For experimental evidence of pentanuclear assemblies, we have embarked on the preparation of ternary complexes with Eu(III) and Lu(III) as representative metal ions from the middle and end of the series. First, ligand **L3** is mixed with lanthanide perchlorates in the metal:ligand ratio 1.67 and we expect the formation of different isomers $[\text{Ln}_5\text{L}_3\text{L}_3]^{15+}$ (see the NMR spectrum in Figure S7a). The addition of 1 equiv of **L1** in the next step completes the assembly. Alternatively, both ligands **L1** and **L3** are mixed in the appropriate ratio, and metal ions are added in the second step. However, the composition of the reaction mixture at equilibrium is independent of the mixing order. Although the reactions of Ln(III) are kinetically rapid, a number of self-repairing steps in these complicated self-assemblies significantly extend the overall reaction time necessary to achieve thermodynamic equilibration. Upon diffusion of *tert*-butylmethylether into the acetonitrile solution, the pentanuclear complex precipitates as a white powder, whose elementary analysis corresponds to the stoichiometric ratio of components. Despite many trials, no suitable crystals for X-ray crystallography were obtained. However, the ^1H NMR spectra of the isolated complexes, and those recorded for the reaction mixtures *in situ*, are essentially the same (Figure S7b).

^1H and COSY NMR spectra of reaction mixtures in deuterated acetonitrile ($[\text{L}_3] = 1.6 \times 10^{-2}$ M; $[\text{Ln}]/[\text{L}_1]/[\text{L}_3] = 5:1:3$; Ln = Eu, Lu) were recorded after 6 days of equilibration. We can clearly distinguish a new series of proton signals in the spectrum of the Eu(III) complex despite a somewhat noisy baseline. Although the peaks belonging to methylene protons are mostly overlapped, we can unambiguously identify characteristic signals due to a paramagnetic shift induced by Eu(III) (Figure 3). First, we notice the presence of two peaks shifted to ~ 12.5 ppm. This large shift is typical for methyl protons of the anchor in **L1** and **L3** pointing to the tetrahedron center (*endo*- CH_3 : H^a , H^1), as reported previously for $[\text{Eu}_4\text{L}_1\text{L}_4]^{12+}$.¹¹ The integrated area of these peaks is close to the ratio 1:3, which corresponds to the expected ratio of ligands **L1**:**L3** in the pentanuclear complex. Second, five sets of triplet signals with equal intensities were identified and assigned to pyridine protons. That observation is attributed to the expected C_3 symmetrical complex $[\text{Eu}_5(\text{L}_1)(\text{L}_3)_3]^{15+}$, where the coordinated shorter strands of each ligand **L3** appear chemically nonequivalent. The inspection of other proton signals also agrees with the pattern expected for the pentanuclear complex. In addition, the COSY spectrum confirms the presence of diastereotopically split methylene protons, which results from a helical twist of binding strands about metallic cations. To further approve the pentanuclear assembly, we have compared the measured spectrum with the spectra of the parent Eu complexes with **L1** and **L2** (Figure 4). Indeed, we can easily identify the corresponding signals in the assemblies by considering the same structural motifs in the ligands. Small differences in chemical shifts are attributed to an altered paramagnetic environment in the pentanuclear complex. In conclusion, the ^1H signals obtained for the ternary complex correspond well to the expected pattern and confirm that the pentanuclear assembly is a major species in solution. Nevertheless, a small signal at

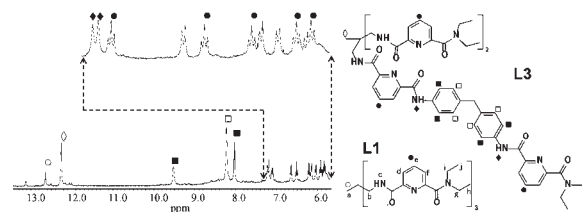


Figure 3. Part of the NMR spectrum of $[\text{Eu}_5(\text{L}_1)(\text{L}_3)_3]^{15+}$. The attribution is only given for selected peaks for the sake of clarity.

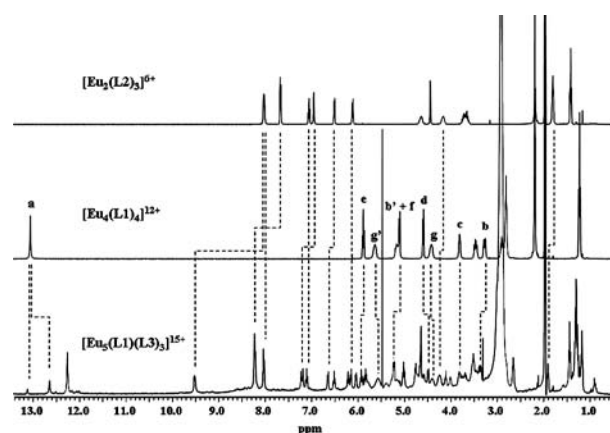


Figure 4. ^1H NMR spectra of $[\text{Eu}_2\text{L}_2\text{L}_3]^{6+}$, $[\text{Eu}_4\text{L}_1\text{L}_4]^{12+}$, and $[\text{Eu}_5(\text{L}_1)(\text{L}_3)_3]^{15+}$. The dashed lines indicate the transposition of ^1H signals from the parent europium compounds into the pentanuclear ternary complex. The proton numbering of **L1** refers to Figure 3.

~ 13.1 ppm (Figure 3) indicates the presence of $[\text{Eu}_4\text{L}_1\text{L}_4]^{12+}$. This observation, in addition to the unresolved baseline, suggests that the pentanuclear complex is under thermodynamic equilibria with other complexes of different stoichiometries.

The NMR spectrum of the pentanuclear complex with Lu(III) seems to be more difficult to interpret due to a number of signals overlapping in the same region as a consequence of relatively small chemical shifts in diamagnetic complexes. Nevertheless, we can clearly attribute several characteristic peaks (see Figure S8), especially two singlets at 10.05 and 10.23 ppm corresponding to the amide groups H^{25} and H^{16} , and methylene protons H^a and H^1 , whose peak area is in the expected ratio 1:3. In addition, the methyl protons H^{10} , H^{30} , H^1 give the expected peak area. We safely deduce that the formed Lu(III) assembly is compatible with the expected C_3 -symmetrical pentanuclear complex. Similarly to the Eu(III) complex, the incompletely resolved baseline suggests the presence of small quantities of other complexes in equilibrium. A direct comparison of the ^1H NMR spectrum of $[\text{Lu}_5(\text{L}_1)(\text{L}_3)_3]^{15+}$ with the parent complexes $[\text{Lu}_2\text{L}_2\text{L}_3]^{6+}$ and $[\text{Lu}_4\text{L}_1\text{L}_4]^{12+}$ is given in Figure S8 and evidences a good correspondence of related peaks in these compounds.

The prepared ternary complexes with Eu(III) and Lu(III) were analyzed with electrospray mass spectrometry under soft ionization conditions that were optimized for analyzing these highly charged systems. The ESMS spectrum measured with an API III instrument shows exclusively the signals of the pentanuclear complex $[\text{Eu}_5(\text{L}_1)(\text{L}_3)_3]^{15+}$ as a series of perchlorate adducts (Figure 5). Together with the expected isotopic profiles of peaks, the observed spectra clearly demonstrate that the pentanuclear complex species are present in solution in majority,

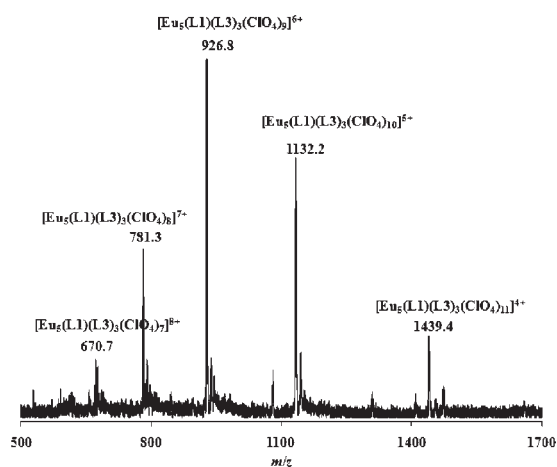


Figure 5. ESMS spectrum of $[\text{Eu}_5(\text{L1})(\text{L3})_3]^{15+}$ (API III, acetonitrile).

in agreement with NMR data. When the same samples are measured with a Finnigan instrument, the ESMS spectra also reveal the signals of other species (Figure S10). In addition to predominant perchlorate adducts with $[\text{Ln}_5(\text{L1})(\text{L3})_3]^{15+}$, the minor peaks belonging to $[\text{Ln}_3\text{L3}_3]^{9+}$, $[\text{Ln}_3(\text{L1})(\text{L3})_2]^{9+}$, and $[\text{Ln}_4\text{L1}_4]^{12+}$ have been identified (Table S2). However, this behavior is probably the consequence of different ionization conditions that not only may better reflect thermodynamic equilibria but also contribute to a partial dissociation of pentanuclear species.

The present work demonstrates the successful application of a rational combinatorial design for predicting intricate polynuclear functional assemblies with a controlled output, more specifically 3D helicates. We take advantage of structural elements responsible for the formation of relatively simple dinuclear and tetranuclear helicates and design an unsymmetrical multitopic ligand L3. The ternary self-assembly of the ligands L1 and L3 with lanthanide cations in stoichiometric quantities is thermodynamically driven to the formation of the first pentanuclear 3D helicate, in agreement with structural predictions and the principle of maximum occupancy. Obviously, it is difficult to obtain the crystal structure of this considerable complex. However, NMR and ESMS analyses clearly demonstrate the formation of the pentanuclear edifice as a major species. We can reasonably predict that the same complexes will be formed with other Ln(III), at least for those between Eu(III) and Lu(III). The semiempirical molecular modeling allows us to visualize the assembly that unambiguously reflects the experimental data. The particular structure of pentanuclear assemblies is of potential interest for preparing heteronuclear compounds in the near future.

■ ASSOCIATED CONTENT

Supporting Information. Full synthetic procedures for L2 and L3, dinuclear helicates $[\text{Ln}_2\text{L2}_3]^{6+}$, and pentanuclear helicates $[\text{Ln}_5(\text{L1})(\text{L3})_3]^{15+}$; ^1H NMR spectroscopic data; ESMS spectra; crystallographic data. Crystallographic CIF files for the new structures. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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