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Metal-Directed Synthesis of Enantiomerially Pure Dimetallic Lanthanide Luminescent Triple-Stranded Helicates

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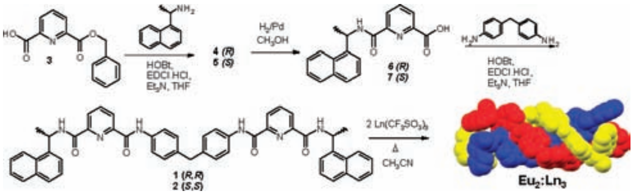
The synthesis of novel architectures through the use of metal-directed synthesis and structurally defined ligands is of great current interest in supramolecular chemistry.[1] To date, the use of transition-metal ions to achieve such structures is well-documented.[2] In contrast, while the use of lanthanides for sensing and imaging purposes is well-established,[3] their use in metal-directed synthesis of supramolecular systems has been much less explored.[4] However, some very elegant examples have recently been developed by Bünzli,[5] Piquet,[6] and several others.[7] We have focused our research on the formation of such f-based supramolecular structures and recently demonstrated the formation of mixed f−d metal ion self-assemblies,[8] luminescent ternary complexes between sensitizing antennae and f-metal ions on gold nanoparticles,[9] and the formation of highly ordered and chiral 1:3 metal/ligand self-assembled bundles using f-metal ions.[10] Herein we describe the use of the chiral ligands **1** (*R*,*R*) and **2** (*S*,*S*) (shown in Scheme 1) to form the novel, enantiomerically pure, dinuclear triple-stranded helicates **Eu$_2$:1$_3$** and **Eu$_2$:2$_3$** via Eu(III)-directed synthesis. These structures are, to the best of our knowledge, among the first examples of such highly stable, chiral dimetallic f-helicates[11] that give rise to Eu(III)-centered circularly polarized luminescence (CPL) upon excitation of the naphthalene antennae.

Scheme 1. Synthesis of **1** (*R*,*R*), **2** (*S*,*S*), and the Corresponding Dinuclear Triple-Stranded Helicates **Eu$_2$:1$_3$** and **Eu$_2$:2$_3$**



Ligands **1** and **2** were designed to enable coordination to lanthanides via each of the two pyridyl nitrogens and the 2,6-dicarboxylic amides. Their synthesis was achieved in a few steps and in high yield from commercially available starting materials (Scheme 1). The monoprotected 2,6-pyridinedicarboxylic acid **3**[12] were reacted with the *R* and *S* isomers of 1-(1-naphthyl)ethylamine using standard peptide-coupling methodology to give the intermediates **4** and **5** in ~80% yield, after which deprotection of the benzyl ester using 10% Pd/C catalyst under 3 atm H_2 yielded **6** and **7** in quantitative yields. Both were reacted with 4,4′-diaminodiphenylmethane via a peptide-coupling reaction using EDCI·HCl, and **1** and **2** were isolated after aqueous workup in ~80% yield. The ^{1}H NMR spectrum (400 MHz, CD_3CN) of **1** (Figure 1a and Figure S1 in the Supporting Information) demonstrated the presence of C_2 symmetry, while circular dichroism (CD) spectroscopy confirmed the enantiomeric relationship of **1** and **2**; the CD spectrum of **1** gave rise to two negative bands centered at 230 and 298 nm (Figure S2). Both **1** and **2** were complexed with Eu(III) triflate in a ligand/metal ratio of 3:2 by refluxing in MeOH or $CH_3CN/CHCl_3$ followed by precipitation upon addition to diethyl ether, giving the **Eu$_2$:1$_3$** and **Eu$_2$:2$_3$** complexes as off-white-colored powders in ~50% yield; elemental analysis confirmed the formation of the desired products. The ^{1}H NMR spectrum (400 MHz, CD_3CN) of **Eu$_2$:1$_3$** (Figure 1b) confirmed the formation of a single product with a high degree of symmetry. Moreover, **Eu$_2$:1$_3$** and **Eu$_2$:2$_3$** gave rise to identical ^{1}H NMR spectra, demonstrating that the two were formed as a pair of enantiomers.[13] This was further confirmed by CD spectroscopy (Figure S4). **Eu$_2$:1$_3$** was characterized using ^{1}H−^{13}C and ^{1}H−^{15}N heteronuclear single-quantum correlation (HSQC) NMR spectroscopy (600 MHz, CD_3CN) (Figures S5 and S6), which showed that the methylene protons of the spacer were equivalent, appearing as a singlet at 4.37 ppm; this indicates that **Eu$_2$:1$_3$** was formed as a single, helical (*rac*) isomer.[14] The formation of **Eu$_2$:1$_3$** was further analyzed by ^{1}H NMR titration (400 MHz) of **1** with Eu(III)$(SO_3CF_3)_3$ in 1:1 (v/v) $CD_3CN/CDCl_3$. The results demonstrate chemical shift changes and gradual broadening of several resonances in the ^{1}H NMR spectrum of **1** upon addition of 0 to 0.6 equiv of Eu(III), after which no significant changes occurred (Figure S7). This confirmed the formation of a solution species with 2:3 stoichiometry (Figure S8), in which three ligands wrap around two Eu(III) ions in an helical fashion, resulting in the formation of a nine-coordinate environment for each ion, as depicted in Scheme 1. Furthermore, we were able to determine the hydration states (q) of both **Eu$_2$:1$_3$** and **Eu$_2$:2$_3$** by measuring their Eu(III) excited-state decays in H_2O and D_2O, which indicated that $q \approx 0$ (Tables S1 and S2 in the Supporting Information) for both complexes, suggesting that each Eu(III) ion is nine-coordinated within these dimetallic helicates.

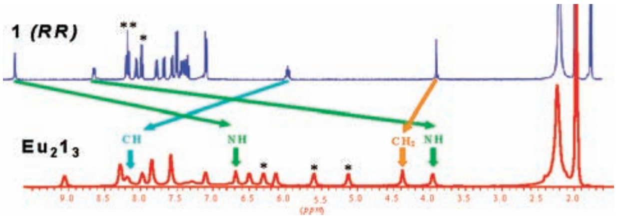


Figure 1. ^{1}H NMR spectra (400 MHz, CD_3CN) of (top) **1** (*R*,*R*) and (bottom) **Eu$_2$:1$_3$**. Pyridyl proton peaks are labeled with *.

The spectroscopic properties of **Eu$_2$:1$_3$** and **Eu$_2$:2$_3$** were further investigated in H_2O, MeOH, CH_3CN, and 1:1 (v/v) $CH_3CN/CHCl_3$. The absorption spectra of **Eu$_2$:1$_3$** and **Eu$_2$:2$_3$** in MeOH showed the presence of a broad band for the naphthalene moieties (Figures S9

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and S10). Excitation of this band gave rise to naphthalene-centered emission with $\lambda_{max} = 340$ nm (Figure S14). Eu(III) emission was also clearly evident upon excitation of the naphthalene antennae or the pyridyl moieties (Figures S13 and S14). The total luminescence spectrum for **Eu$_2$:2$_3$** (Figure 2) demonstrates the sensitization of the $^5D_0$ excited state by the six antennae and the deactivation to the ^7F_J ($J = 0-4$) states, with narrow emission bands occurring at 590, 593, 613, 647, and 693 nm respectively. The fluorescence excitation spectra of the antennae in MeOH and 1:1 (v/v) $CH_3CN/CHCl_3$ also clearly demonstrated that both complexes successfully sensitized the $^5D_0$ excited state (Figures S15−S18). The presence of the $^5D_0 \rightarrow {}^7F_0$ band (Figure 2) in the emission spectrum suggests that the local symmetry at the Eu(III) centers is C_3 rather than D_3, which is the symmetry of the dimetallic helixes as a whole. However, the ^{1}H NMR spectra also suggest that D_3 symmetry is favored on the NMR time scale. Figure 2 also shows the CPL spectra of **Eu$_2$:1$_3$** and **Eu$_2$:2$_3$**, which have opposite signs and equal magnitudes, confirming the enantiomeric nature of **Eu$_2$:1$_3$** and **Eu$_2$:2$_3$**, which is driven by asymmetric induction from **1** and **2**. The large values of the dissymmetry factor $2\Delta I/I$ (e.g., -0.23 for the higher-energy component of the 593 nm transition of **Eu$_2$:1$_3$**) have the same sign and almost identical magnitude as those for the corresponding monomeric complexes previously developed by us.[10] This implies not only that the absolute configurations of **Eu$_2$:1$_3$** and **Eu$_2$:2$_3$** are the same as those of the corresponding monomers (i.e., **Eu$_2$:1$_3$** has the Λ,Λ and **Eu$_2$:2$_3$** the Δ,Δ absolute configuration) but also that the degrees of twist of the ligators away from octahedral geometry must be very similar (within about ±2°) for the dimetallic and monomeric Eu(III) complexes. Thus, the CPL spectra show that dimetallic Eu(III) triple-stranded homochiral helicates are formed in solution for **Eu$_2$:1$_3$** and **Eu$_2$:2$_3$**.[11]

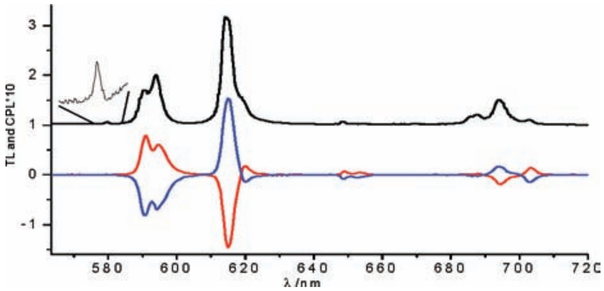

Figure 2. Luminescence spectrum of **Eu$_2$:2$_3$** (black) and CPL spectra (×10) of **Eu$_2$:1$_3$** (blue) and **Eu$_2$:2$_3$** (red) in MeOH. The $\Delta J = 0$ band is expanded.

The formation of **Eu$_2$:1$_3$** and **Eu$_2$:2$_3$** was also investigated in 1:1 (v/v) $CH_3CN/CHCl_3$ by observing the changes in their absorption and Eu(III) emission spectra upon variation of the amount of $Eu(III)(SO_3CF_3)_3$ at fixed concentrations of **1** and **2** (10 μM) after 24 h of equilibration. Significant changes were observed in the absorption spectra, which were red-shifted to 320 nm (Figures S19 and S20), and in the Eu(III)-centered emission (Figures S21 and S22), which was "switched on" for both systems within the addition of ~0.7 equiv of Eu(III) upon formation of both **Eu$_2$:1$_3$** and **Eu$_2$:2$_3$**. The 3:2 stoichiometry of these helicates was further confirmed using Job's method of continuous variations, where $\chi_{max} = 0.6$ was determined from both the absorption (Figures S23 and S24) and the Eu(III) emission (Figure 3).

In summary, we have developed novel, enantiomerially pure dimetallic lanthanide luminescent triple-stranded helicates using Eu(III)-directed synthesis. We are in the process of evaluating their properties and developing related f-based helical structures.

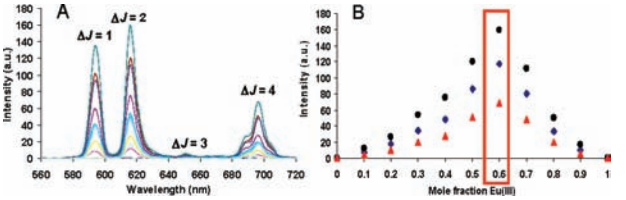

Figure 3. (A) Overall changes in the Eu(III) emission of **2** in 1:1 (v/v) $CH_3CN/CHCl_3$ using Job's method of continuous variations. (B) Job's plot analyses for $\Delta J = 1$, 2, and 4, showing the formation of **Eu$_2$:2$_3$**.

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Supporting Information Available: Synthesis and characterization of all novel compounds, Figures S1−S24, and Tables S1 and S2. This material is available free of charge via the Internet at http://pubs.acs.org.

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(13) The Tb(III) complex of **1** was also formed. The ^{1}H NMR spectrum (Figure S3) showed the formation of a single species.

(14) **Eu$_2$L$_3$** can be formed either as rac isomers ($\Lambda\Lambda$ and $\Delta\Delta$) or as a meso isomer ($\Lambda\Delta$). In the meso form, the methylene protons would be diastereotopic and give rise to two doublets in the ^{1}H NMR spectrum. See: Goetz, S.; Kruger, P. E. *Dalton Trans.* **2006**, 1277.

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