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Very Bright Europium Complexes that Stain Cellular Mitochondria

James W. Walton\textsuperscript{b}, Adrien Bourdolle\textsuperscript{a}, Stephen J. Butler\textsuperscript{b}, Marine Soulie\textsuperscript{c}, Martina Delbianco\textsuperscript{b}, Brian K. McMahon\textsuperscript{b}, Robert Pal\textsuperscript{a}, Horst Puschmann\textsuperscript{b}, Jurriaan M. Zwier\textsuperscript{c}, Laurent Lamarque\textsuperscript{c}, Olivier Maury*\textsuperscript{a}, Chantal Andraud\textsuperscript{a} and David Parker *\textsuperscript{b}

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The synthesis, structure and photophysical properties of a series of highly emissive europium complexes is reported. Certain complexes enter mammalian cells by macropinocytosis and stain the mitochondria selectively, allowing observation of the Eu emission \textit{in cellulo} by time-gated spectral imaging.

Emissive lanthanide complexes for use as tags in bioassays or as optical probes require both a high emission quantum yield and large molar absorptivity at an excitation wavelength in the range 337 to 405 nm to give high brightness, $B$, where $B = \epsilon \phi$.\textsuperscript{1} Using sensitised emission, the incorporation of multiple chromophores into a polydentate ligand has been studied, allowing efficient energy transfer to a bound Eu(III) ion that is efficiently shielded from vibrational deactivation by solvent.\textsuperscript{2} In aqueous media, no 1:1 [Eu.L] systems have been reported with a brightness ($\lambda_{\text{exc}} > 337$ nm) exceeding 3000 M\textsuperscript{-1}cm\textsuperscript{-1}.

Here, we report systems in which the brightness is an order of magnitude larger. Moreover, certain complexes are taken into mammalian cells, allowing their use in microscopic imaging. In designing these systems, we have combined the very effective shielding of the Eu(III) ion using nonadentate ligands based on triazacyclononane\textsuperscript{3,4} with strongly absorbing $p$-substituted aryl-alkynyl groups, [Eu.L\textsuperscript{1-4}].\textsuperscript{5} Both carboxylate and phosphinate substituted systems have been prepared\textsuperscript{6}, and the synthetic pathway allows the preparation of derivatives that can be conjugated to a vector. In the phosphinate systems,\textsuperscript{3} the phosphorus substituents adopt a common configuration in the complex, and more effectively shield the excited Ln ion from intermolecular quenching processes.

The ligands and their Eu complexes were prepared using established methods.\textsuperscript{6} In the case of [Eu.L\textsuperscript{2}]-, the third substituent, bearing a remote protected amine group, was introduced last, following stepwise alkylation and de-protection of mono-BOC-triazacyclononane.\textsuperscript{6} Crystals of [Eu.L\textsuperscript{2}]- grew from aqueous methanol and the structure of [Eu.L\textsuperscript{2}]- revealed that the Eu ion is encapsulated by the ligand in a tricapped trigonal prismatic array (Figure 1). The nearest waters are over 6Å from the metal ion, and the complex is slightly distorted from $C_3$-symmetry. This distortion may be related to the presence of several disordered solvent molecules in the lattice.

Figure 1 Molecular structure of the europium complex [Eu.L\textsuperscript{2}]- (120K) showing part of the hydration sphere; mean bond lengths (±0.02 Å) are: Eu-N(ring) 2.68 Å; Eu-N(py) 2.66 Å; Eu-O 2.32 Å. Nearest waters are H-bonded to each P=O, with an average O-O distance of 2.66 Å; CCDC 857545.
This complex, in common with the other triphosphinate systems, exists as a 50:50 mixture of \( \Lambda-(\text{SSS}) \) and \( \Lambda-(\text{RRR}) \) isomers. In solution, one \( ^{31} \text{P} \) NMR resonance is observed; the paramagnetically shifted \( ^{1} \text{H} \) NMR spectra of each Eu complex are consistent with average \( C_{3} \) symmetry.

**Table 1** Selected photophysical data\(^c\) for Eu(III) complexes (295K, MeOH, or as stated)

<table>
<thead>
<tr>
<th>Complex</th>
<th>( \lambda_{\text{max}}/) nm</th>
<th>( c/) mM(^{-1}) cm(^{-1} )</th>
<th>( \phi_{\text{em}}/) %</th>
<th>( \tau/) ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>([\text{Eu.L}^\text{1a}])</td>
<td>338</td>
<td>58.0</td>
<td>48</td>
<td>0.95</td>
</tr>
<tr>
<td>([\text{Eu.L}^\text{1b}])</td>
<td>338</td>
<td>55.0</td>
<td>25</td>
<td>1.06</td>
</tr>
<tr>
<td>([\text{Eu.L}^\text{2a}])</td>
<td>332</td>
<td>58.0</td>
<td>52</td>
<td>1.30</td>
</tr>
<tr>
<td>([\text{Eu.L}^\text{2b}])</td>
<td>331</td>
<td>58.1</td>
<td>39</td>
<td>1.03</td>
</tr>
<tr>
<td>([\text{Eu.L}^\text{3}])</td>
<td>322</td>
<td>59.2</td>
<td>37</td>
<td>1.24</td>
</tr>
<tr>
<td>([\text{Eu.L}^\text{4}])</td>
<td>307</td>
<td>63.5</td>
<td>15</td>
<td>1.35</td>
</tr>
</tbody>
</table>

\(^{a}\) in water; \( \text{MeOH} \) \( \phi_{\text{em}} = 43\% \) and \( \tau = 1.18 \) ms; \(^{b}\) in 3:1 \( \text{H}_{2}\text{O}/\)MeOH; \(^{c}\) errors on quantum yields and lifetimes are \( \pm 15\% \); at 77K, \( \phi_{\text{em}} \) and \( \tau \) were typically 0.2 to 0.3 ms longer, e.g. for \([\text{Eu.L}^\text{2c}]\), \( \tau(\text{D}_{2}\text{O}) \) was 1.28 ms, consistent with a metal solvation state, \( q = 0 \).

![Figure 2: Europium emission spectra of \([\text{Eu.L}^\text{1a}]\) (green) and \([\text{Eu.L}^\text{2b}]\) (295K, \text{H2O}, \( \lambda_{\text{exc}} 355\) nm), showing minor changes in spectral form in the hypersensitive \( \Delta f = 2 \) manifold around 615 nm, associated with variation of oxygen donor polarisability.](image)

Each chromophore absorbs around 310 to 340 nm, with an overall extinction coefficient of \( 55-60,000 \) M\(^{-1}\)cm\(^{-1} \) (Table). Emission spectra in aqueous or methanol solutions were very similar for each Eu complex (Figure 2). The Eu complexes of \([\text{L}^\text{1a}],\) \([\text{L}^\text{2a}],\) \([\text{L}^\text{3}]\) and \([\text{L}^\text{4}]\) dissolved readily in MeOH, but were not soluble in water. The water solubility was higher with the complexes \([\text{L}^\text{2b}],\) the limiting solubility was about 20 \( \mu \)M. A very intense set of \( \Delta f = 2 \) transitions was observed around 610-620 nm, and the spectral form was consistent with \( C_{3} \)-symmetry. Overall emission quantum yields ranged from 15-54\%, with the lower values for the \( p-\text{CF}_{3} \) substituted complex, \([\text{Eu.L}^\text{4}]\) presumably reflecting a less efficient intramolecular energy transfer step.

Following incubation of \([\text{Eu.L}^\text{2b}]\) (10mM, 30 min) in the growth medium of NIH-3T3 (mouse skin fibroblasts), CHO (Chinese hamster ovarian) or PC-3 (human prostate cancer) cells, staining of the cell could be observed by confocal fluorescence microscopy. The cell images (Figure 3) revealed selective staining of the mitochondria, confirmed by co-localisation experiments with Mitotracker Green\(^{26,27}\), (ESI). Spectral imaging of washed cells, using time-gated methods, showed the characteristic europium spectral signature, confirming internalization of the intact complex. The europium complexes bearing PEG groups, were not internalized by live mammalian cells.

![Figure 3: left: Bidirectional confocal microscopy images (Leica SP5 II) showing staining of cellular mitochondria in NIH 3T3 cells for \([\text{Eu.L}^\text{2b}]\) (10µM, 15 min loading time, \( \lambda_{\text{exc}} 355\)nm, 100 Hz scan, hybrid detector 600-720 nm, 0.77µm\(^3\) voxel size, 12mW laser power, 40k image acquisition time); right: time-gated spectral image of a cell (\( \lambda_{\text{exc}} 365 \) nm, \( \tau_{\text{em}} 2 \) ms, \( \Phi_{\text{em}} 10\mu\text{s} \)); 10,000 scans averaged duty cycle using a 2D CCD detector, 100x acquisition time). The upper image shows a dividing cell (bar = 20 \( \mu \)M).](image)
cell to be 0.65(±0.3) µM for a 10µM loading, under the stated conditions. 8

Furthermore, these Eu complexes can act as effective donors to near-IR acceptor dyes, such as the cyanine dye, I, allowing their use in time-resolved homogeneous FRET assays. 9 A short comparative analysis of the efficiency of energy transfer was undertaken, comparing the behaviour of [Eu.L1]2−, [Eu.L2]2− and [Eu.L3]2− in MeOH and 1:1 aqueous methanol. The quenching of the Eu emission was monitored as a function of added dye concentration over the range 0.3 to 5µM, using 5 µM solutions of the Eu complex. The second order rate constants characterizing intermolecular energy transfer were 1.45, 0.57 and 0.65 mM−1s−1 associated with Forster radii of 6.86, 6.95 and 6.76 nm respectively. 10 The lower efficiency of quenching with each phosphinate complex may reflect both the slightly larger spectral overlap integral in [Eu.L1]2− (Figure 3: AJ = 2 manifold is about 10% larger for [Eu.L1]2− vs [Eu.L2−/2]), as well as the different electric dipole transition moments in the complexes.

In conclusion, the europium complexes defined here possess a brightness that lies in the range 15,000 to 30,000 M−1 cm−1 at 337 nm, auguring well for a role as donors in FRET bio-assays and as near-IR acceptor dyes, such as the cyanine dye, allowing their use in bio-assays and as bioactive species. 11 Furthermore, these examples highlight the opportunities to develop emissive metal coordination complexes as more general stains and probes for the biociences. 12

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Notes and references


6. Details of complex synthesis and characterization are given in the supporting information.


9. In the rapid diffusion limit, energy transfer from a Eu donor to the dye acceptor (Q) obeys pseudo-first order kinetics, where 1/t = kobs = k−1 = k2/ko [Q] hence τ = k−1/k0 = k−1 [Q].

10. Hence the slope of the plot of 1/τ vs [Q] is k−1, allowing the second order rate constant for energy transfer, k−1, to be estimated; C. F. Meares, T. G. Wensel, Acc. Chem. Res. 1984, 17, 202.
