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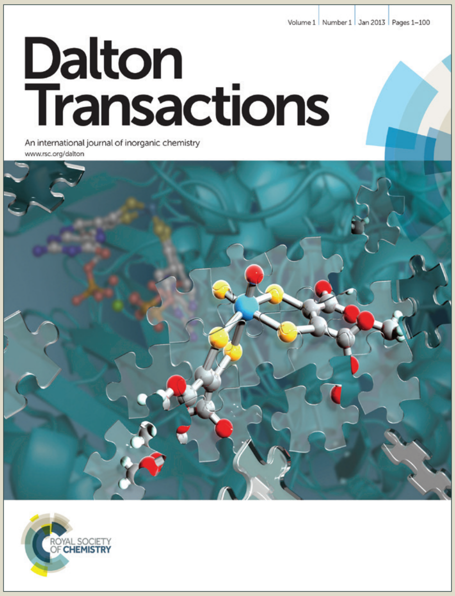

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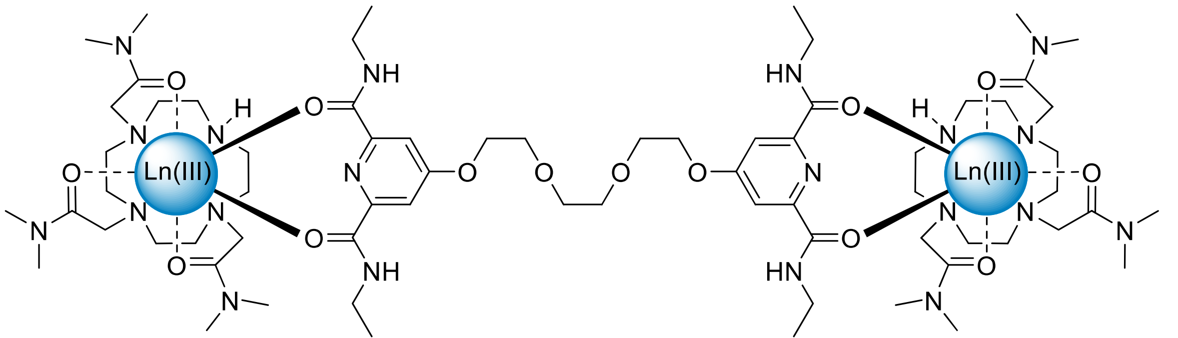

Ln = Eu or Tb

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# Displacement assay detection by a dimeric lanthanide luminescent ternary Tb(III)-cyclen complex: High selectivity for of phosphate and nitrate anions

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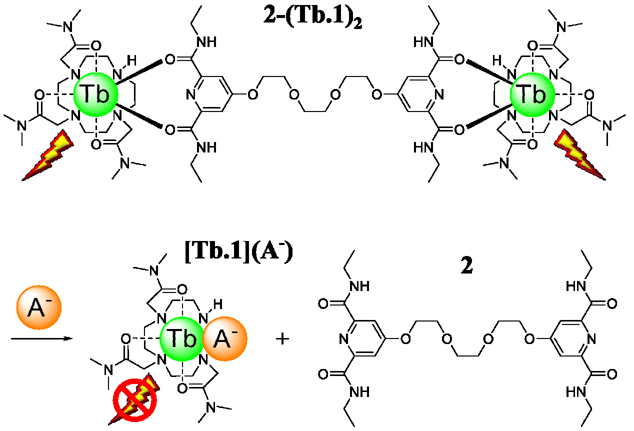
The luminescent dimeric ternary lanthanide-cyclen complexes (2-(**Ln.1**)$_2$; Ln = Tb/Eu) were designed and both their self-assembly formation and their ability to detect anions *via* a displacement assays were investigated using spectrophotometric titrations in MeOH solution. The formation of **2**-(**Tb.1**)$_2$ and **2**-(**Eu.1**)$_2$ was investigated in solution, and determination of the binding constants and stoichiometry showed that the former was formed almost exclusively over the 1:1 complex **2**-(**Tb.1**) after the addition of two equivalents of **2**; while for **2**-(**Eu.1**)$_2$ a mixture of both stoichiometries existed even after the addition of four equivalents of **2**. Of these two systems, **2**-(**Tb.1**)$_2$ was studied in detail as probes for anions, where significant changes where observed in the photophyscal properties of the complex; the characteristic Tb(III)-centred emission being fully *switched off* upon sensing of phosphates and nitrate, giving rise to the formation of a $H_2PO_4^-$:**Tb.1** complex in 1:2 stoichiometry upon sensing of $H_2PO_4^-$ by 2-(**Tb.1**)$_2$, while $NO_3^-$ gave 1:1 complex formation and two equivalents of $NO_3^-$ ·**Tb.1**.

## Introduction

Phosphates and nitrate are essential anions in biology and industry. Consequently, the design of luminescent and colorimetric sensors for the detection of such anions (*e.g.* phosphate, pyrophosphate, AMP, ADP and ATP) and polyanions (*e.g.* DNA, RNA, *etc.*) has become an increasingly topical area of research within supramolecular chemistry.[1-3] The use of visible-emitting Ln(III)-based systems in the design of targeting luminescent sensors is particularly attractive, as we[4] and others[5] have demonstrated in the past. This stems from the distinct long wavelength emissions and long excited state lifetimes inherent to these metal ions, which allow for time-resolved detection in biological media, overcoming background scattering and auto-fluorescence.[6] As part of this programme, we have developed several examples of Ln(III)-cyclen complexes for such sensing,[4,7] as well as self-assembly lanthanide complexes based on dipicolinic acid (**dpa**) derivatives[8]. Similarly, Parker *et al.*, Faulkner *et al.* and others have developed responsive systems for anions based on Ln(III)-cyclen complexes.[9-11]

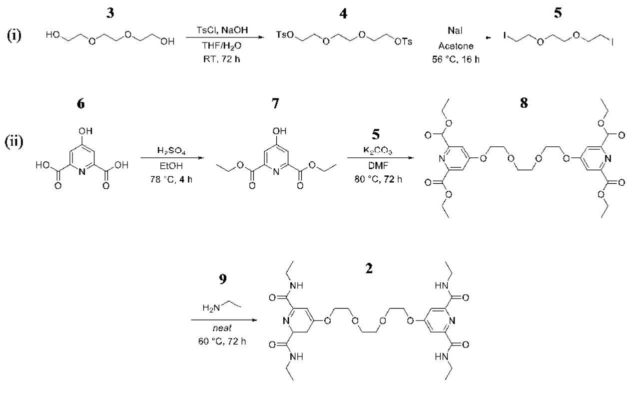
The use of luminescent ternary Ln(III)-cyclen complexes for application in luminescent displacement assays[12] for ion sensing is particularly attractive[13] as these can be formed in solution through the use of Ln(III)-directed self-assembly synthesis[14,15]. The target ion then displaces one, or more, labile ligands from the ternary lanthanide ion complex, giving rise to concomitant changes in the photophysical properties of the self-assembly. Herein, we describe an example of a displacement assay for anions based on a cylen–**dpa** based ternary self-assembly structure. The sensor, **2-(Ln.1)$_2$** is a bis-ternary Ln(III)-cyclen complex formed by reacting the **dpa** derivative **2** with two equivalents of **Ln.1** (Ln = Eu or Tb) *in situ*, Scheme 1.



**Scheme 1:** Schematic illustration of **2-(Tb.1)$_2$** (emission *switched on*) and the displacement assay upon addition of anion (emission *switched off*).

We demonstrate that **2-(Tb.1)$_2$**, is a particularly effective displacement sensor, which is selective for phosphate and nitrate. To the best of our knowledge this is the first example of this kind of luminescent bis-ternary cyclen lanthanide complexes to be developed as displacement assays for anions. Moreover, this is also the first time that such cyclen based lanthanide displacement assays for the sensing of nitrate has been demonstrated, but this anion is a common environmental pollutant due to its use in fertilisers.

## Results and discussion



**Scheme 2** Synthesis of (i) the spacer **5** and (ii) the ligand **2**.

The synthesis and characterisation of **1** and its Ln(III) complexes, **Ln.1** (where Ln = Eu or Tb), have been previously reported by us.[16] The synthesis of the ditopic ligand **2** was achieved in a few steps as shown in Scheme 2, starting from the commercially available chelidamic acid **6**. Esterification of **6** was achieved in refluxing ethanol with catalytic amount of sulphuric acid for 4 hours, giving **7** in 70% yield, as oil that later solidified upon drying under vacuum. Compound **7** was then reacted with the linker **5** in anhydrous DMF in the presences of $K_2CO_3$, under elevated temperature (See Experimental) followed by aqueous acidic workup, giving **8** as a white solid in 44% yield. The linker **5** (Scheme 2) was synthesized in two steps from **3** using classical Finkelstein reaction (of the di-tosylated derivative **4**) in moderate yield. The conversion of **8** into **2** was simply achieved by treating **8** with need ethylamine (40% w/v in toluene) at 60 °C for 72 hours. This was followed by precipitation upon addition of the reaction mixture to ice, followed by filtration and further purification of the desired product by flash silica column chromatography (gradient elution 100:0→95:5 $CH_2Cl_2$/MeOH) yielding **2** as a white solid in 32% yield. The $^1$H NMR of **2** is shown in Figure 1, clearly show the C2 symmetry of the ligand, but using HSQC experiments (See ESI) allowed for full assignment of the structure. Moreover, HRMS (ES+) showed the appearance of m/z at 611.2805, attributed to the $[\mathbf{2} + Na]^+$ species. Both the synthesis and characterisation of the cyclen ligand **1** and the corresponding Ln(III) complexes, **Ln.1**, (where Ln = Eu or Tb) have been reported by us previously.[15b,16]

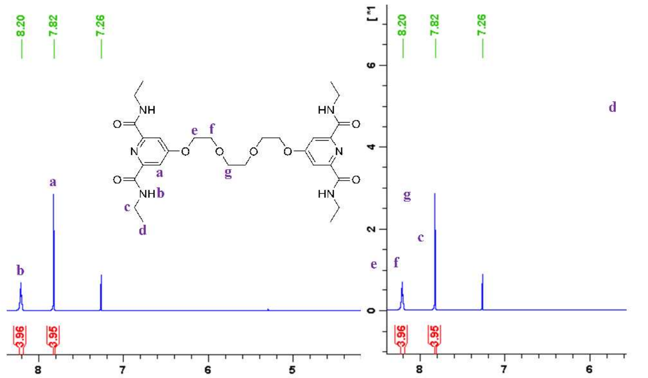


**Figure 1.** The 1H NMr (400 MHz) of compound **2**.

The self-assembly formation of **2** [$1\times10^{-5}$ M] and **Ln.1** to give **2-(Ln.1)$_2$** was monitored in MeOH solution by a series of photophysical titrations at room temperature (See ESI Scheme S1). Here, the changes in the UV-Vis absorption, fluorescence emission and the lanthanide-centred emission were all monitored to probe this self-assembly process upon titration with Eu(III) and Tb(III) complexes of **1**. For both systems, the changes in the lanthanide-centred emission were the most notable. The changes in the UV-Vis absorption spectra of **2** upon binding to **Tb.1** are shown in Figure 2, with the changes seen at 250 nm shown as inset. The 2:1 stoichiometry was clearly evident from the absorption titration. Identical changes were seen for **Eu.1** and **Tb.1** (See ESI); with the absorption of **2** being blue shifted and slightly enhanced upon addition of **Ln.1**. However, and as discussed below the saturation point, and hence, the formation of the 2:1 complex was not as clear fro Eu(III) (See ESI) an indication of lesser affinity of **Eu.1** for **2**. For both titrations, the changes in the fluorescence emission of **2** were quenched upon addition of **Ln.1**.

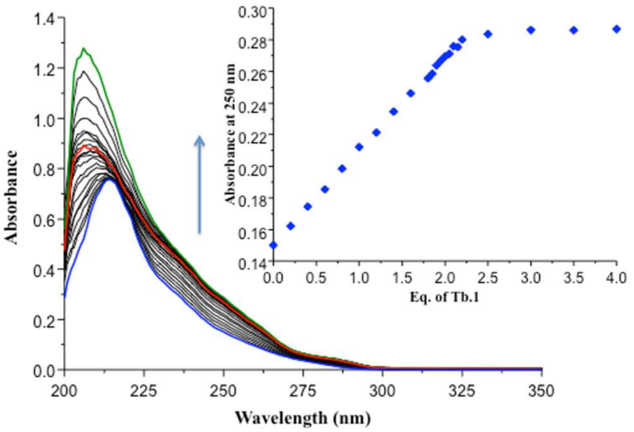


**Figure 2.** Changes in the absorption spectra of **2** ($1 \times 10^{-5}$ M) upon titration of **Tb.1** (0 → 4 eq.) in MeOH ($\lambda_{exc}$ = 279 nm). *Inset:* Binding isotherms at 250 nm demonstrating the formation of the 1:2 complex.

Upon excitation of various wavelengths in the absorption spectra above for **2** (such as at 220 and 240 nm) and monitoring the Ln(III) centred emission, it was apparent that the liganand was able to successfully populate the excited states of both Eu(III) and Tb(III). This was further confirmed by analysis of the excitation spectra, which was structurally similar to that seen in the absorption spectra (See ESI). We choose to use excitation at 279 nm, which is assigned to the n→π* of the **dpa** antenna **2**, in our measurements, but this also provided successful sensitisation of the lanthanide excited states

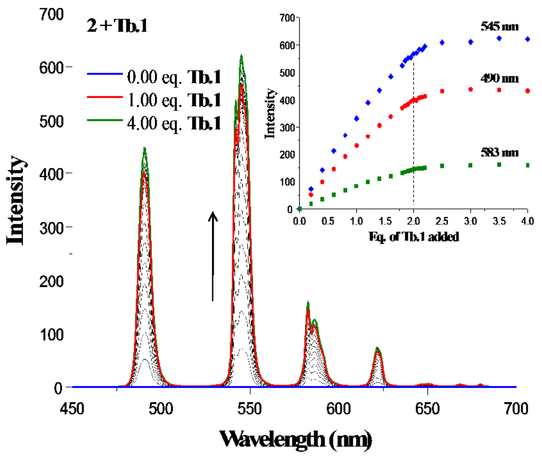


**Figure 3.** Evolution of the Tb(III)-centred emission for the titration of **2** ($1 \times 10^{-5}$ M) with **Tb.1** (0 → 4 eq.) in MeOH ($\lambda_{exc}$ = 279 nm), showing the *switching on* of emission. *Inset:* Binding isotherms at 490 nm, 545nm, and 583 nm.

occurred as is evident from Figure 2 for Tb(III). Here, upon addition of **Ln.1** and excitation of **2** at 279 nm, both self-assembly systems gave rise to line-like emission spectra corresponding to the Eu(III) $^5D_0 \rightarrow {}^7F_J$ ($J$ = 0 – 4) and Tb(III) $^5D_4 \rightarrow {}^7F_J$ ($J$ = 6 – 0) transition, respectively, as seen in Figure 3 for Tb(III), thus demonstrating the successful sensitisation of the Ln(III) excited states of both complexes by **2**. In both instances, enhancements were seen in the lanthanide emission up to the addition of 2 equivalents of **Ln.1**, after which the emission became saturated (*c.f.* inset Figure 3). This 2:1 stoichiometry signifies the formation of the desired **2-(Ln.1)₂**, ternary species in solution.

The self-assembly formation between **2** and **2-Ln.1** was further analysed by fitting the changes in the spectroscopic data using non-linear regression analysis program SPECFIT®. In agreement with the evolving factor analysis, the fits generated for both cyclen complexes accounted for he stepwise formation of two luminescent ternary complex formations, namely **2-Ln.1** and **2-(Ln.1)₂**, in solution. The binding constants for these two processes were determined as log $\beta_{1:1}$ = 5.2 ± 0.2, and log $\beta_{2:1}$ = 11.0 ± 0.1 for **Tb.1** (see ESI for fits), while for **Eu.1** log $\beta_{1:1}$ = 4.9 ± 0.2, and log $\beta_{2:1}$ = 11.9 ± 0.1 were determined for the 1:1 and the 2:1 (**Ln.1:2**) stoichiometries, respectively. From these titrations, the percentage formation of **2-(Tb.1)₂** was evaluated as being *ca*. 82% and 98% at 2 and 4 equivalents of **Tb.1**, respectively. Moreover, the large difference in the binding affinity of the 2:1 complex over that of the 1:1 system, is interesting, as it seem to indicate the possibility that its formation could be an example of positive cooperative binding whereby the binding of the first **Tb.1** complex to **2**, to give **2-Tb.1**, promotes increased affinity for the second binding event and hence drives the formation of **2-(Ln.1)₂**. It is also worth highlighting that, in the case of **Tb.1,** the overall stability of **2-(Tb.1)₂** was somewhat larger than that observed in the titration of **2** with **Eu.1,** and that the percentage formation of **2-(Eu.1)₂** was significantly lower at 2 equivalents of **Eu.1**, being only 42%, *vs.* that seen for **Tb.1**. This we also saw by observing the changes in the absorption spectra above. We have seen in the past that such Tb(III)-cyclen complexes often have higher affinity for anions (such as salicylic acid) over that seen for structurally identical Eu(III) complexes[17] and it is possible that such preference is also seen here in the ternary complex formation between **2** and **Tb.1** compared to that of **Eu.1**.

The formation of **2-(Ln.1)₂** was also evaluated by probing the hydration state (the *q*-value) of **2-(Ln.1)₂** *vs.* that of **Ln.1**; the latter we previously shown to give $q$ = 2 (*i.e.* two metal bound water molecules).[17] The luminescent lifetime measurements for Eu(III), showed that in the presence of ligand **2** (upon excitation at 279 nm) excited state lifetimes of $\tau$ = 0.48 ± 0.01 ms and $\tau$ = 0.56 ± 0.03 ms were measured in MeOH and MeOD, respectively. This gave $q \approx 0$ (*i.e.* no metal bound water molecules), further supporting the successful self-assembly formation of **2-(Ln.1)₂** in solution. Having successfully formed **2-(Ln.1)₂** we next evaluated the ability of these supramolecular ternary structures to detect anions through luminescent displacement assays. While these were formed for both systems, due to its higher stability constant the focus of this communication will be on the Tb(III) system. The ability of **2-(Tb.1)₂** to participate in anion displacement assays was investigated using tetrabuytlammonium (TBA) salts of acetate, chloride, nitrate, phosphate and pyrophosphate.

The changes seen in the Tb(III)-centred emission of **2-(Tb.1)₂** upon titration with $H_2PO_4^-$ let to quenching in the **2-(Tb.1)₂** emission due to the displacing of the two equivalents of **Tb.1** from the **2-(Tb.1)₂** self-assembly, as shown graphically in Scheme 1. The overall changes observed in the Tb(III) emission are shown in Figure 4 as a function of $H_2PO_4^-$ equivalents, with the changes in the 545 nm transition being shown as an inset. Analysis of these changes showed that the emission was *ca.* 90% quenched upon the addition of 1 equivalent of $H_2PO_4^-$; being fully quenched after the addition of a second equivalent. These changes were further analysed by using non-linear regression analysis, which gave excellent fits; showing two stepwise equilibrium processes for the displacement of **Tb.1** by $H_2PO_4^-$ with an initial binding constant of log $\beta_{1:1}$ = 6.6 ± 0.1, followed by the second displacement process with a log $\beta_{1:2}$ of 13.8 ± 0.1. These results demonstrated that the displacement of the two equivalents of **Tb.1** from **2-(Tb.1)₂** resulted in the formation of a new Tb(III) self-assembly in solution, consisting of the binding of two equivalents of **Tb.1** to a single anion. This is evident from the speciation distribution diagram in Figure 5. This was quite an unexpected result, as it was anticipated that the 1:1 complex formation would be more favourable. In fact, the 1:2 stoichiometric species was found to be favoured, reaching 80% formation after the addition of 1 equivalent of $H_2PO_4^-$. Moreover, comparison of these displacement assay results with that of the formation of **2-(Tb.1)₂**, indicated that the ternary complex formation between **Tb.1** and $H_2PO_4^-$ was significantly more favoured; being *ca.* 1.4 orders of magnitude greater than that seen for the association constant between **2** and **Tb.1** (to yield **2-(Tb.1)₂**). The changes in the UV-Vis absorption spectra were also monitored during these titrations, and

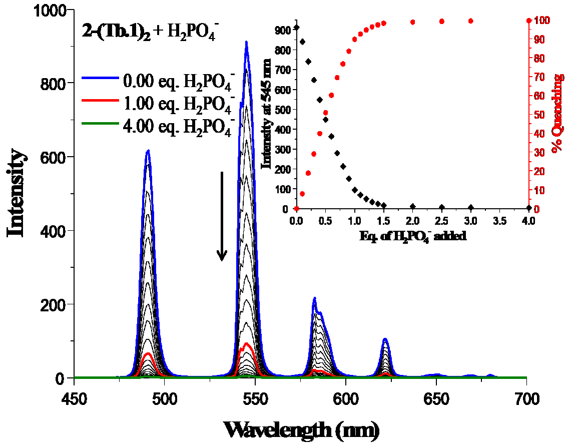


**Figure 4.** Changes in the phosphorescence spectra of **2-(Tb.1)₂** ([**2**] = 1 × $10^{-5}$ M) upon titrating with $H_2PO_4^-$ (0 → 4 eq.) in MeOH ($\lambda_{exc}$ = 279 nm). *Inset:* Changes in emission intensity (black) and percentage quenching (red) at 545 nm.

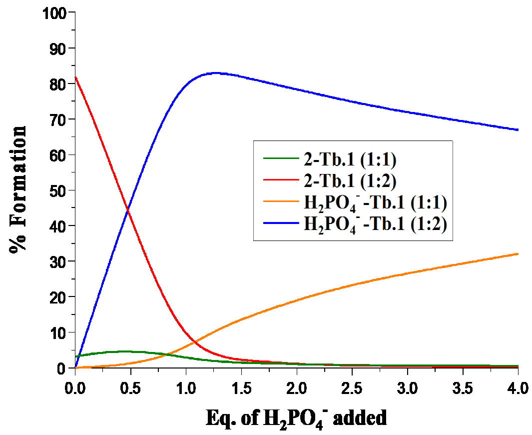


**Figure 5:** Speciation-distribution diagram obtained from the fit of the phosphorescence titration of **2-(Tb.1)₂** ([**2**] = 1 × $10^{-5}$ M) with $H_2PO_4^-$ (0 → 4 eq.) in MeOH ($\lambda_{exc.}$ = 279 nm).

were seen to be reversed compared to those seen above for the formation of **2-(Tb.1)$_2$**, indicating the full dissociation of **2-(Ln.1)$_2$** to give **2**, and $H_2PO_4^-$ ·**(Tb.1)$_2$**, respectively.

Having shown that $H_2PO_4^-$ could be recognised by the above displacement assay, we carried out similar titrations with other anions. Here, both $CH_3CO_2^-$ and $Cl^-$ only gave rise to minor quenching in lanthanide-centred emission (*ca.* 8% and 4% at 4 eq. of anions, respectively; see ESI). In contrast, pyrophosphate ($H_2P_2O_7^{2-}$) gave rise to complete quenching in the Tb(III) luminescence (See ESI). The changes observed as a function of equivalents of $H_2P_2O_7^{2-}$ at 546 nm demonstrated that the Tb(III) emission was quenched by *ca.* 83% after the addition of 0.5 equivalents of $H_2P_2O_7^{2-}$ and that the emission was fully quenched after only 0.8 equivalents of the anion (See ESI). Unfortunately, fitting these changes using both linear and non-linear regression analysis gave unreliable binding constants due to a multiple binding equilibrium, but we have previously seen such complex binding for $H_2P_2O_7^{2-}$ using cyclen urea based Tb(III) sensors.[4a]

Nitrate is another important biological anion that is also commonly found in fertilisers. As such it is also a well-known environmental pollutant for which the detection on farmlands, in lakes and rivers is an essential requirement. Being intrigued by the formation of the 1:2 stoichiometry for the displacement of **Tb.1** from **2-(Tb.1)$_2$** by $H_2PO_4^-$, we wondered if nitrate could be detected in a similar manner; but we expected that here the 1:1 would be the only possible stoichiometry. Indeed, $NO_3^-$ gave rise to quenching in the Tb(III) emission. However, unlike that seen for both and $H_2PO_4^-$ and $H_2P_2O_7^{2-}$ this quenching was only 60% after the addition of three equivalents of the $NO_3^-$, Figure 4a, and even upon saturation in the emission changes at the addition of 25 equivalents, the Tb(III) emission was only 89% quenched. Nevertheless, these results clearly demonstrate that **2-(Tb.1)$_2$** can be employed for the sensing of nitrated in competitive media. Treatment of the spectroscopic data gave a binding constant similar to that seen for $H_2PO_4^-$, but by treating the quenching data using Stern-Volmer fitting, Figure 4b, dynamic quenching was demonstrated. This yielded a log $\beta_{1:1}$ value of 4.70 ± 0.01; a slightly higher binding constant than that seen for the formation of **2-(Tb.1)$_2$**. To the best of our knowledge this is the first time that that $NO_3^-$ has been sensed by a cyclen based lanthanide complex by a displacement assay mechanism. These results demonstrate the flexibility of this ternary displacement assay for probing anions of both physiological and industrial relevance using systems based on **2-(Tb.1)$_2$**, where the selectivity can be summarised as $H_2P_2O_7^{2-} > H_2PO_4^- > NO_3^- >>> Cl^-$ and $CH_3CO_2^-$.

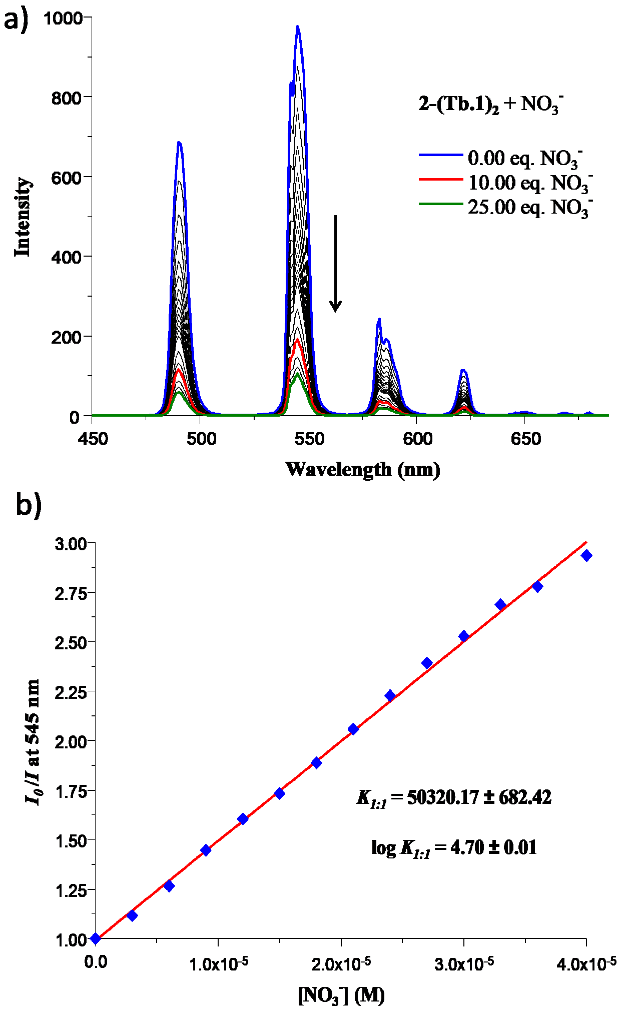


**Figure 6:** a) Changes in the Tb(III) emission of **2-(Tb.1)$_2$** ([2] = 1 × $10^{-5}$ M) upon addition of $NO_3^-$ (0 → 25 eq.) in MeOH. b) The Stern-Volmer fitting of the Tb(III) emission data at 545 nm.

## Conclusions

In summary, we have shown that dimeric ternary Ln(III)-cyclen complexes can be formed in solution based on the general self-assembly structure **2-(Ln.1)$_2$**, and that these self-assemblies can function as anion displacement probes, with **2-(Tb.1)$_2$** acting as a sensor or probe for the detection of $H_2P_2O_7^{2-}$, $H_2PO_4^-$ and $NO_3^-$. In comparison the displacement of **2** from **2-(Eu.1)$_2$** upon addition of these anions was only minor. We are currently exploring the use of lanthanide based displacement assays for sensing of ions and molecules in greater details, and the application of structures such as 2 in the formation of higher order self assemblies by coordination to dimetallic lanthanide complexes.

## Experimental

**Materials and methods:** All chemicals were purchased from Sigma-Aldrich Ireland Ltd., Acros Organics, and TCI Ltd., and were used without further purification, unless otherwise stated. Deuterated solvents for NMR analysis were all obtained from Apollo Scientific. Dry solvents were prepared in accordance with standard procedures described by Vogel, with distillation prior to each use.[1] Chromatographic columns were performed manually using either silica gel 60 (230-240 mesh ASTM) or aluminium oxide (activated, neutral, Brockman I STD grade, 150 mesh). Chromatographic columns were also run on a Teldyne Isco Combiflash Companion automatic machine using pre-packed silica or alumina columns. Thin-layer chromatography (TLC) was conducted using both Merck Kiesegel 60 $F_{254}$ silica plates and Polygram Alox N/UV$_{254}$ aluminium oxide plates, and observed by UV light or developed in an iodine chamber. Melting Points were determined using an Electrothermal IA900 digital melting point apparatus. NMR spectra were recorded using either a Bruker Spectrospin DPX-400 instrument, operating at 400.13 MHz for $^1$H NMR and 100.6 MHz for $^{13}$C NMR, or a Bruker AV-600 instrument, operating at 600.1 MHz for $^1$H NMR and 150.2 MHz for $^{13}$C NMR. All NMR spectra were measured at 293 K. Chemical shifts are expressed in parts per million (ppm or δ) relative to the non-deuterated solvent peak and, for $^1$H NMR spectra, are reported alongside the number of protons, splitting pattern, coupling constant where applicable, and proton assignment (in that order). Multiplicities are abbreviated as follows; singlet (s), doublet (d), triplet (t), quartet (q), multiplet (m), and broad (br). Electro mass spectra were recorded using a Mass Lynx NT V 3.4 on a Waters 600 controller connected to a 996 photodiode array detector, with HPLC grade carried solvents. Accurate molecular weights were determined by a peak-matching method, using leucine enkephaline (H-Tyr-Gly-Gly-Phe-Leu-OH) as the standard reference (*m/z* = 556.2771); all accurate mass were reported within ± 5 ppm of the expected mass. Infrared spectra were recorded on a Perkin Elmer Spectrum One FT-IR spectrometer fitted with a universal ATR sampling accessory

**4,4'-((Ethoxy)-ethoxy)ethyl)-bis(diethylester-2,6-pyridine) (8)**
Compound **7** (0.85 g, 3.55 mmol, 2.20 eq.) and anhydrous $K_2CO_3$ (0.67 g, 4.85 mmol, 3.00 eq.) were stirred in anhydrous DMF (30 mL) at 25 °C for 30 min. Compound **4** (0.60 g, 1.62 mmol, 1.00 eq.) was added and the solution was heated at 80 °C for 72 h. The solvent was then removed under reduced pressure and $CH_2Cl_2$ was added to the residue. The organic layer was washed twice with 1% aqueous acetic acid and $H_2O$ before drying over $MgSO_4$. Solvent evaporation under reduced pressure afforded a crude yellow oil, which was subsequently recrystallised from EtOH to give **8** as a white solid (0.42 g, 0.71 mmol, 44% yield); m.p. 77 – 79 °C; HRMS (*m/z*) ($ES^+$) Calculated for $C_{28}H_{36}N_2O_{12}Na$ *m/z* = 615.2166 $[M + Na]^+$. Found *m/z* = 615.2156; $^1H$ NMR (400 MHz, $CDCl_3$) $\delta_H$: 7.80 (4H, s, py-$\underline{H}$), 4.45 (8H, q, *J* = 7.2 Hz, $C\underline{H_2}CH_3$), 4.30 (4H, t, *J* = 4.5 Hz, $C\underline{H_2}$), 3.90 (4H, t, *J* = 4.5 Hz, $C\underline{H_2}$), 3.74 (4H, s, $C\underline{H_2}$), 1.43 (12H, t, *J* = 7.2 Hz, $CH_2C\underline{H_3}$); $^{13}C$ NMR (100 MHz, $CDCl_3$) $\delta_C$: 166.77, 164.69, 150.17, 114.44, 71.00, 69.26, 68.26, 62.45, 14.20; IR $\upsilon_{max}$ ($cm^{-1}$): 3076, 2983, 2933, 2905, 1742, 1706, 1594, 1567, 1478, 1435, 1371, 1369, 1342, 1328, 1244, 1230, 1158, 1134, 1102, 1067, 1023, 994, 938, 887, 866, 817, 786, 732, 701.

**4,4'-((Ethoxy)-ethoxy)ethyl)-bis(diethylamide-2,6-pyridine) (2)**
Compound **8** (0.15 g, 0.25 mmol, 1.00 eq.) and ethylamine (40 wt. % in toluene) (50 mL) were heated together at 60 °C for 72 h. The reaction mixture was then poured onto ice, resulting in the precipitation of a brown solid. Upon melting of the ice, the solid was isolated by filtration and dissolved in $CH_2Cl_2$. The organic phase was washed twice with $H_2O$ before drying over $MgSO_4$. The solvent was then removed under reduced pressure to give a crude brown solid. Purification by flash silica column chromatography (gradient elution 100:0 → 95:5; $CH_2Cl_2$/MeOH) yielded **2** as a white solid (0.05g, 0.08 mmol, 32% yield). m.p. 222 – 224 °C; HRMS (*m/z*) ($ES^+$) Calculated for $C_{28}H_{40}N_6O_8Na$ *m/z* = 611.2805 $[M + Na]^+$. Found *m/z* = 611.2808; $^1H$ NMR (600 MHz, $CDCl_3$) $\delta_H$: 8.20 (4H, t, *J* = 5.9 Hz, $N\underline{H}$), 7.82 (4H, s, py-$\underline{H}$), 4.04 (4H, t, *J* = 4.5 Hz, $C\underline{H_2}$), 3.77 (4H, t, *J* = 4.5 Hz, $C\underline{H_2}$), 3.65 (4H, s, $C\underline{H_2}$), 3.48 (8H, m, $C\underline{H_2}CH_3$), 1.22 (12H, t, *J* = 7.3 Hz, $CH_2C\underline{H_3}$); $^{13}C$ NMR (150 MHz, $CDCl_3$) $\delta_C$: 167.87, 163.64, 151.07, 111.46, 71.08, 69.31, 67.95, 34.63, 15.01; IR $\upsilon_{max}$ ($cm^{-1}$): 3310, 3080, 2972, 2934, 2876, 1737, 1647, 1601, 1523, 1445, 1366, 1281, 1241, 1144, 1129, 1056, 1044, 997, 885, 875, 817, 752, 695

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## Notes and references

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