Synthesis, characterisation and application of lanthanide cyclen complexes in organic synthesis

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Hexadentate cyclen complexes of Sm(III), Eu(III) and Yb(III) have been prepared from 1,4-bis[(*R*)-α-methylbenzylaminocarbonylmethyl]-1,4,7,10-tetraazacycldodecane and characterised. The crystal structures of the isomorphous complexes of Eu(III) and Sm (III) have been determined. These may be electrochemically reduced to the +II oxidation state and employed in organic synthesis. However, no asymmetric induction was observed and this can be attributed to the fluxional nature of these complexes in solution and the limited asymmetric influence imparted by the *N*-(α-methylbenzyl)acetamide chiral auxiliary.

Introduction

The utility of low valent lanthanide compounds, notably SmI_2, to promote a diverse array of transformations has resulted in these reagents finding wide spread application.[1] Whilst these processes can exhibit very high levels of chemoselectivity and diastereoselectivity, absolute stereocontrol is a much less common observation. Many SmI_2 mediated cyclisations proceed with high diastereoselectivity that can be rationalised on the basis of substrate chelation to the highly co-ordinating samarium cation.[2] Similarly, good levels of asymmetric induction can be observed with some intermolecular reactions particularly when chelation is possible.[3] However efficient asymmetric induction in a Sm(II) promoted C–C bond forming process using an external source of chirality is limited to a single report by Mikami and Yamaoka.[4] In this, the addition of a samarium ketyl radical to acrylates in the presence of two equivalents of 2,2'-bis(diphenylphosphinyl)-1,1′-binaphthyl (BINAPO) (per Sm) produced the corresponding butyrolactones in reasonable enantiomeric excess (67%).[5] At a similar time to this report, we had started a study with similar objectives, probing for enantioselective variants of the samarium Barbier and pinacol reactions. Based on the well known ability of HMPA and related electron donating ligands to enhance the rate of SmI_2 reactions,[6] we considered the options for ligand accelerated catalysis. Following this concept, and the fact that lanthanide ions form complexes with high co-ordination numbers, we prepared and screened a large number of enantiomerically pure, multidentate electron donating ligands in the hope of observing asymmetric induction in either of these processes. Although in a few cases accelerated reaction rates could be observed, in no case could significant asymmetric induction be observed. Similar observations have been reported by other groups.[7] In many of the examples that we studied a very rapid decomposition of the SmI_2 appeared to occur on addition of the chiral 'ligand' and in general all these experiments are complicated by the extreme air sensitivity of samarium(II) species. Consequently, we were never very confident that complexation of samarium had occurred and felt that one way to explore this process would be to prepare stable, characterisable Sm(III) complexes and generate the reactive Sm(II) species *in situ* either through the use of a chemical co-reductant, photolysis or electrolysis.[8–12] Given that chemical recycling of the catalyst is frequently complicated by competing non-catalysed transformations mediated by the co-reductant, and that photolytic recycling has yet to be demonstrated to be synthetically viable, we opted to explore electrochemical generation of the active Sm(II) complex. Application of such a strategy using transition metal complex catalysts is well established,[13] whilst work by Dunach and co-workers has shown that sub-stoichiometric quantities of Sm(III) salts can be used to promote electrochemical mediated Barbier, pinacol and ketyl radical alkene additions.[14–20] On the basis of these precedents, the use of electrochemical reduction of well-defined stable lanthanide (III) complexes appeared to be a novel and viable approach to the challenge of asymmetric lanthanide (II) mediated organic synthesis. In this paper we describe our first efforts in this area.

Results and discussion

Ligand synthesis

With the hypothesis that we needed to prepare stable catalyst complexes that combine available binding sites for substrates together with a suitable steric environment for efficient asymmetric induction we considered the use of lanthanide cyclen‡ complexes. These complexes are known to exhibit high stability with respect to dissociation and consequently have found widespread application as MRI contrast agents.[21] Importantly, there is considerable precedent for chiral pendant binding groups on the cyclen ring to enforce a well defined stereochemical environment around the lanthanide core.[22] We therefore opted to prepare ligands comprising a cyclen base and two chiral pendant arms producing a total of six points of co-ordination to the lanthanide ion. The two pendant ligands can be situated either *cis* (N1, N4) or *trans* (N1, N7) to each other. Believing that the close proximity of the chiral groups to each other in the former would provide the greatest degree of stereochemical influence, the selective synthesis of this ligand system became the primary goal of the project. Selective protection of adjacent nitrogens of the cyclen ring was achieved following the precedent

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‡ The IUPAC name for cyclen is 1,4,7,10-tetraazacyclododecane.

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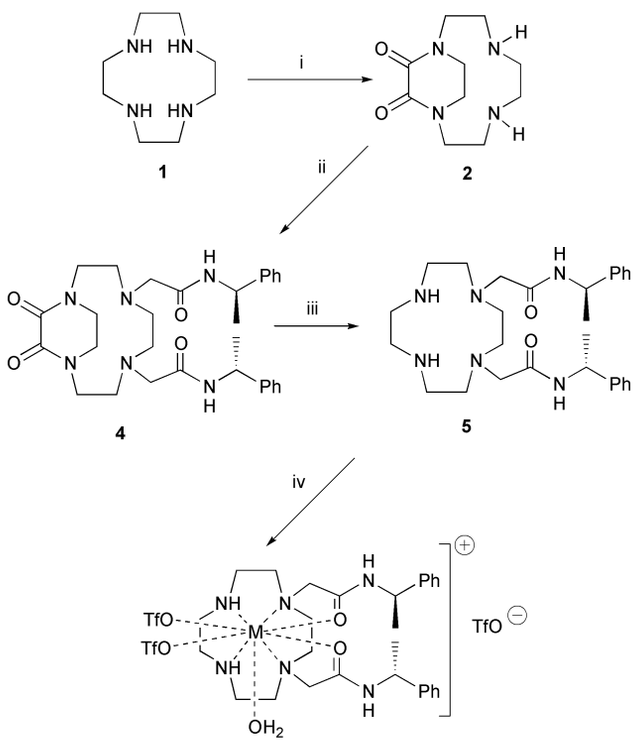
reported by Handel and co-workers through formation of the oxamide by condensation with diethyl oxalate.[23] With a view towards exploiting the known propensity of P=O donor ligands to enhance the activity of SmI_2 we initially attempted to prepare the aminomethylphosphonamide and phosphonate **9** and **10**.[24]

However, whilst the phosphonate could be generated we were able neither to achieve efficient conversion to the disubstituted derivative **10** nor to generate the desired amide. Consequently, we subsequently attempted the synthesis of the equivalent amides using the strategy described by Parker and co-workers.[25] Treatment of the diamide (**2**) with K_2CO_3, KI and (*R*)-*N*-(α-methylbenzyl)chloroacetamide **3**[26] in DMF at 100 °C for 86 h afforded after chromatography the desired C_2 symmetrical dialkylated cyclen **4**, Scheme 1. Reflecting the rigid nature of the



Scheme 1 *Reagents and conditions*: i. $(EtOCO)_2$, EtOH, rt, 3 d (93%); ii. (*R*)-$PhCH(CH_3)NHCOCH_2Cl$, K_2CO_3, KI, DMF, 100 °C, 86 h (75%); iii. 10 M NaOH (aq), (11%); iv. $M(OTf)_3$, MeCN.

bicyclic system the pendant side arms adopt well defined orientations that are slow to interconvert on the NMR timescale and two diasteromeric conformations are detected in the NMR spectra. Purification of this compound proved to be difficult and was not fully optimised with material of ≥95% purity being taken forward. Final deprotection involved selective hydrolysis of the bicyclic diamide in the presence of the newly generated side chains.[23] Although the hydrolysis appeared to proceed efficiently, final purification of the product again proved difficult. Despite considerable experimentation we have not been able to develop an efficient procedure for this transformation ultimately settling for a modest 11% yield of the desired N1, N4 functionalised cyclen **5** after column chromatography on alumina.

Table 1 Bond distances (Å) in **6** and **7**

	6	**7**
M–N(1)	2.707(3)	2.717(4)
M–N(4)	2.634(3)	2.633(4)
M–N(7)	2.580(3)	2.584(4)
M–N(10)	2.655(3)	2.658(3)
M–O(1)	2.377(2)	2.371(3)
M–O(2)	2.381(3)	2.384(3)
M–O(3)	2.460(3)	2.456(3)
M–O(4)	2.459(3)	2.473(3)
M–O(5)	2.437(3)	2.436(3)

Complex formation and characterisation

With the desired ligand in hand we sought to prepare complexes of the lanthanide metals known to have a readily accessible +II oxidation state (Sm, Yb, Eu). In each case the complexes were generated by reaction between the ligand and a solution of the metal triflate in acetonitrile. In each case microanalysis revealed that the complexes had three triflates associated with each metal ion. Single-crystal X-ray diffraction studies of the europium (**6**) and samarium (**7**) complexes showed them to be isostructural (Fig. 1, Table 1). The coordination polyhedra of the lanthanide

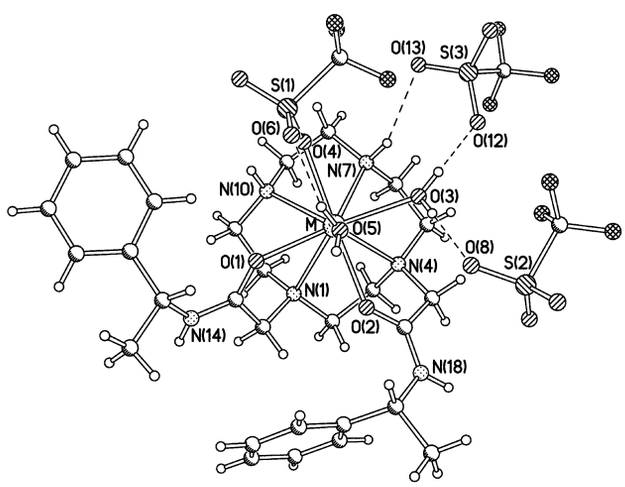


Fig. 1 X-Ray structure of isomorphous complexes $[M(\mathbf{5})(OH_2)_2(O_3SCF_3)](O_3SCF_3)_2$, where M = Eu (**6**) or Sm (**7**).

atom is a monocapped tetragonal antiprism, as in a number of previously studied lanthanide complexes with tetrapendant ligands.[25,27] Four N atoms of the macrocycle comprise one base of the antiprism; two pendant O atoms, an aqua-ligand and a monodentate triflate ligand comprise another base, over which the second aqua-ligand is situated. Two other triflate anions are linked to the cation only by hydrogen bonds; the structures contain no uncoordinated water molecules.

Whilst the solid state structures indicated that two pendant arms did provide an element of asymmetry we were concerned that in solution there may be considerable fluxionality present which would negate the effects of the chiral amides. ^1H NMR spectra in CD_3OD (400 MHz) recorded between 230 and 310 K showed a broadening of the axial and equatorial resonances which was reduced as the temperature was lowered. From this, and in comparison with the tri- (**11**) and tetramide (**12**) complexes, we believe that the complexes undergo exchange processes involving the interconversion of stereoisomers which are fast on the NMR timescale.

This was borne out by the circularly polarised luminesence (CPL) spectrum of the europium(III) complex. Observed emission dissymmetry values for the polarised emission from the diamide ($g^{\lambda}_{em\ (594\ nm)} = -0.013$) are lower than the corresponding tri- and tetramide complexes. ($g^{\lambda}_{em\ (594\ nm)} = -0.05$ and $g^{\lambda}_{em\ (594\ nm)} = -0.09$ respectively).[25,28] The increase in absolute

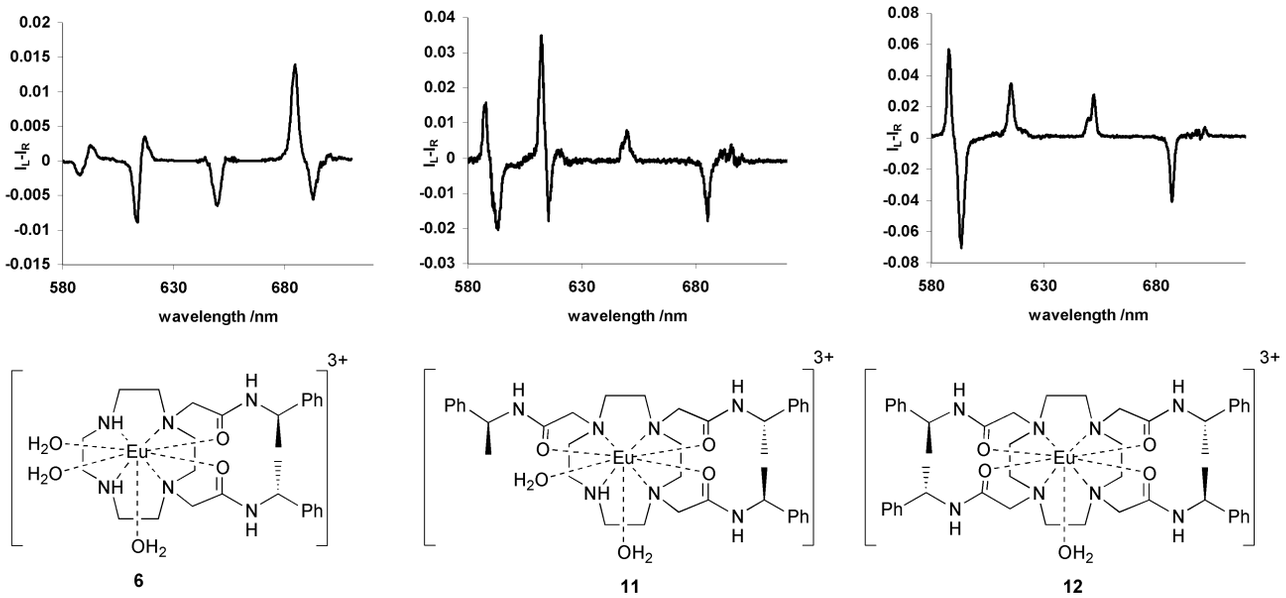


Fig. 2 CPL spectra for di-, tri- and tetramide complexes in aq. MeCN at 295 K (1 mM complex, λ_{exc} 255 nm).

value of the g_{em} in changing from the diamide, to the related tri- (**11**), and tetramide (**12**) complexes reflects the increasing comformational rigidity of the complexes upon increasing degree of substitution on the macrocyclic ring (Fig. 2).

The similarity of the form of the europium emission spectrum of the diamide complex in water and acetonitrile suggests that the remaining coordination sites are occupied by water molecules in solution.

While the exact processes (*e.g.* arm rotation, exchange of coordinated water) by which interconversion between the isomers occurs have not been studied in detail at present, it is evident that the hexadentate diamide complexes are fluxional in solution.

Application in synthesis—electrochemical analysis

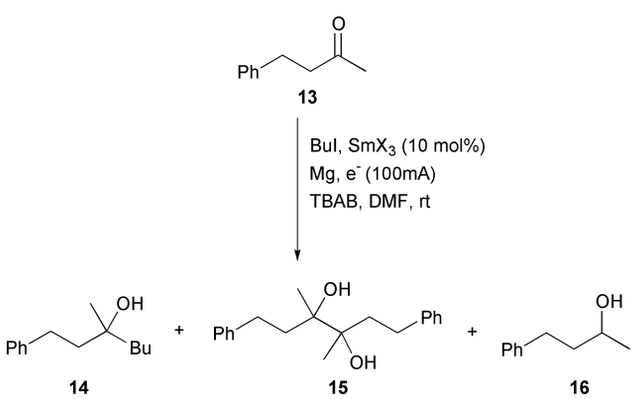
Before exploring the synthetic potential of the three complexes we undertook an electrochemical study to determine the effect of complexation on both the redox potential and the nature of the redox behaviour. Flowers and co-workers have studied the effect of additives on solutions of SmI_2 in THF and shown that changes in the reduction potential of lanthanide ions are sensitive to the co-ordination environment and this can be monitored electrochemically.[29–31]

The Sm and Yb complexes **7** and **8** gave very similar CV traces, with irreversible reduction waves observed at −0.74 and −0.97 V (*vs.* ferrocene) respectively. There was little improvement in the chemical reversibility of the waves at higher scan rates. Differential pulse voltammetry corroborated the CV results, and for the Sm complex two irreversible peaks were observed at approximately −0.78 and −1.060 V at a glassy carbon electrode (*vs.* Ag/AgCl). The Eu compound **6** displayed two reduction events (−0.45 and −0.83 V) which were only partially chemically reversible. The order of these reduction potentials is not that which is normally observed for these lanthanides (Eu < Yb < Sm for Ln^{3+}/Ln^{2+} in aqueous media) and suggests that the ligand is preferentially stabilising the Sm(II) complex relative to the Yb(II) complex.[32]

Although the complexes could be reduced to the +II state, this reduction was only partially chemically reversible. This may be due to ligand exchange (triflate for halide),[33] or simply slow back electron transfer, possibly a consequence of conformational change within the complex. With the hope that this would not affect the synthetic potential of the complexes we attempted the various electrochemical synthetic transformations following the procedures outlined by Dunach, Scheme 2, Table 2. Blank experiments, in which no lanthanide was present, gave no products confirming Dunach's earlier observations that the presence of the lanthanide ion is essential. Initial experiments indicated that whilst both $SmCl_3$ and $Sm(OTf)_3$ were effective, the former was marginally more efficient. In both cases pinacol coupling was the predminant outcome, producing known diol **15** in moderate yields. Whilst similar levels of conversion were realised using complex **7** no enhancement to the diastereoselectivity of the diol was observed. Attempts to enhance this latter transformation through the addition of TMSCl, to trap the pinacolate, resulted in exclusive reduction of the ketone, albeit in low yield with no observable enantioselectivity.

Table 2 Results of electrosynthesis experiments

Catalyst	Time/h	Yield **14** : **15** : **16**	Dr(**13**)
$SmCl_3$	6	2 : 48 : 0	1 : 1.4
$Sm(OTf)_3$	6	3 : 30 : 0	1 : 1.4
$Sm^*(OTf)_3$ **7**	6	3 : 25 : 0	1 : 1.4
$Sm^*(OTf)_3$ **7**–TMSCl	6	0 : 0 : 20	—



Scheme 2

Conclusions

In conclusion the selective synthesis of cyclen lanthanide complexes with two adjacent chelating arms has been achieved.

Whilst in the solid state there is evidence for the imposition of helicity at the metal centre the barrier for interconversion of the diastereomeric forms is low. Solution state NMR and CPL studies indicate that at room temperature these hexadentate lanthanide complexes are fluxional. Electrochemical studies of these complexes demonstrated that reduction to the Sm(II) state is feasible although this process is only partially chemically reversible. Although the samarium complex **7** can be used in electrosynthesis there is no evidence for any asymmetric induction. Whilst this can be attributed to the factors described above other possibilities exist, including decomplexation of samarium following reduction, which would account for the close similarity in the results obtained with $Sm(OTf)_3$, or the possibility for these processes to occur by an outersphere electron transfer process which may negate the effect of a chiral metal centre.[34]

These questions can be adressed by application of more stable, stereochemically defined complexes containing seven or eight binding ligands. Moreover, Dickins *et al.* have recently published results which indicate that the phenyl derived amide ligands, as used in this study, do not provide an efficient asymmetric environment at the metal centre to permit differential binding of lactate enantiomers.[35] Consequently, more discriminating chiral auxiliaries are required. These factors are under consideration and will be reported in due course.

Experimental

All air and/or moisture sensitive reactions were carried out under an argon atmosphere. Solvents were purified following established protocols. Ether refers to diethyl ether. Commercially available reagents were used as received unless otherwise stated. Flash column chromatography was performed according to the method of Still *et al.*[36] using 200–400 mesh silica gel. Yields refer to isolated yields of products of greater than 95% purity as determined by ^1H + ^{13}C NMR spectroscopy or elemental analysis (Durham University Microanalytical Laboratory).

Nuclear magnetic resonance (NMR) spectra were obtained on a Varian VXR-400 (^1H at 399.968 MHz, ^{13}C at 100.572 MHz), Varian Oxford Unity 300 (^1H at 299.908 MHz, ^{13}C at 75.412 MHz) and Varian Oxford Mercury 200 (^1H at 199.975 MHz, ^{13}C at 50.289 MHz) spectrometers. Chemical shifts (δ) are recorded in ppm relative to residual protonated solvent. Splitting patterns are described as singlet (s), doublet (d), triplet (t), quartet (q), or multiplet (m). Coupling constants were recorded in Hz. All ^{13}C spectra were proton decoupled. ES Mass spectra were recorded on a Micromass LCT TOF mass spectrometer. Optical rotations were measured on an Optical Activity LTD AA-10 Automatic Polarimeter and the values are given in units of 10^{-1} deg cm^2 g^{-1}. Melting points were determined using Gallenkamp melting point apparatus and are uncorrected.

(*R*)-*N*-(α-Methylbenzyl)chloroacetamide 3[26]

A solution of chloroacetyl chloride (7.25 ml, 113 mmol) in acetone (25 ml) was added to a solution of (*R*)-(+)-α-methylbenzylamine (10.8 g, 90 mmol) and Na_2CO_3 (13.5 g, 127 mmol) in acetone : water (1 : 1) (100 ml) at 0 °C. The resultant mixture was then stirred at this temperature for 1.5 h and then concentrated *in vacuo*. The residue was then acidified with 6 M HCl and extracted with ethyl acetate. The combined organic extracts were washed with brine, dried ($MgSO_4$) and concentrated. Recrystallisation (ethyl acetate : ether) afforded the title amide **3** as white needles (13 g, 74% yield). Mp: 94–95 °C (lit.[26] 94–95 °C). δ_H (300 MHz) 1.52 (3H, d, J = 8 Hz), 4.05 (2H, d, J = 3 Hz), 5.14 (1H, m), 6.85 (1H, br s), 7.30 (5H, m). δ_C (50 MHz) 165.1, 142.1, 128.7, 127.6, 126.0, 49.2, 42.5, 21.5.

11,12-Dioxo-1,4,7,10-tetraazabicyclo[8.2.2]tetradecane 2[23]

Diethyl oxalate (840 mg, 5.8 mmol) was added to a solution of cyclen **1** (1 g, 5.8 mmol) in ethanol (25 ml) and the resultant solution stirred at room temperature for 3 days. The reaction mixture was then concentrated and the crude product purified by chromatography eluting with chloroform and isopropyl amine (5 : 1) to afford the title diamide as a white solid (1.23 g, 93% yield). Mp. 96–98 °C (lit.[23] 96–98 °C). δ_H (300 MHz) 2.55–2.64 (4H, m), 2.80–3.0 (4H, m), 3.50 (4H, m), 4.39 (2H, m), 7.30 (4H, m). δ_C (50 MHz) 161.1, 49.1 (2C), 46.1, 44.2. *m*/*z* ES$^+$ 249 (M$^+$ + Na), 475 (M_2Na^+), 701 (M_3Na^+).

4,7-Bis[(*R*)-α-methylbenzylaminocarbonylmethyl]-11,12-dioxo-1,4,7,10-tetraazabicyclo[8.2.2]tetradecane 4

To a solution of oxalamide **2** (1.52 g, 6.73 mmol), K_2CO_3 (2.3 g, 16 mmol) in DMF (20 ml) was added chloroacetamide **3** (2.91 g, 14.8 mmol) followed by potassium iodide (1.9 g, 15 mmol). After stirring at 100 °C for 86 h, the reaction mixture was concentrated under reduced pressure and the residue suspended in dichloromethane (50 ml). The K_2CO_3 was then removed by filtration and the filtrate concentrated and purified by chromatography eluting with chloroform and methanol (95 : 5) to give the title tetramide **4** as a pale yellow semi-solid (2.7 g, 75% yield, 95% pure). δ_H (200 MHz) 1.35 (3H, d, J = 8 Hz), 1.55 (3H, d, J = 8 Hz), 2.1–2.7 (10H, m), 2.8–3.0 (2H, m), 3.2–3.6 (6H, m), 4.2–4.5 (2H, m), 4.85 (1H, quintet, J = 8 Hz), 5.1 (1H, quintet, J = 8 Hz), 7.10 (10H, m), 7.50 (2H, br d, J = 8 Hz). δ_C (50 MHz) 170.2, 170.0, 161.2, 161.0, 144.2, 143.7, 128.9, 128.7, 128.6, 127.9, 127.5, 126.6, 59.0, 54.2, 53.6, 52.1, 49.0, 47.6, 47.4, 45.0, 44.1, 22.0, 21.3. *m*/*z* (ES$^+$) 571 (M$^+$ + Na), 1119 (M_2Na^+).

4,7-Bis(diethoxyphosphorylmethyl)-11,12-dioxo-1,4,7,10-tetraazabicyclo[8.2.2]tetradecane 10

A solution of **2** (225 mg, 1 mmol) and paraformaldehyde (120 mg, 4 mmol) in tetrahydrofuran (20 ml) was brought to 65 °C, and stirred for 12 h. Triethyl phosphate (415 mg, 2.5 mmol) and 4 Å molecular sieves were then added the reaction mixture heated under reflux for 4 days. The reaction mixture was then concentrated and the crude product purified by chromatography on a silica gel column eluting chloroform and methanol (16 : 1). This gave **10** as a colourless semi-solid (180 mg, 30% yield). δ_H (200 MHz) 1.27 (12H, t), 2.55–2.9 (10H, m), 3.0–3.3 (4H, m), 3.45 (2H, m), 3.70 (2H, m), 4.05 (8H, q) 4.30 (2H, m). δ_C (50 MHz, $CDCl_3$) 159.8, 61.4, 61.2, 55.9, 51.9, 47.4, 45.7, 45.3, 16.4, 16.3. δ_P (81 MHz, $CDCl_3$) 27.6. *m*/*z* (ES$^+$) 549 (M$^+$ + 23) together with monophosphonate *4-(diethoxyphosphorylmethyl)-11,12-dioxo-1,4,7,10-tetraazabicyclo[8.2.2]tetradecane* (150 mg, 40% yield). δ_H (200 MHz) 1.22 (6H, t, J = 6 Hz), 2.55–3.2 (12H, m), 3.35 (1H, m), 3.5–3.7 (2H, m), 3.8–4.1 (2H, m), 4.01 (2H, q, J = 6 Hz), 4.04 (2H, q, J = 6 Hz), 4.30 (2H, m). δ_C (50 MHz) 161.3, 159.8, 61.6, 61.4, 57.8, 52.3, 50.0, 49.0, 47.2, 47.0, 45.1, 44.9, 27.6, 16.5 and 16.4. *m*/*z* (ES$^+$) 399 (M$^+$ + 23), 775(M_2Na^+).

1,4-Bis[(*R*)-α-methylbenzylaminocarbonylmethyl]-1,4,7,10-tetraazacycldodecane 5

Aqueous NaOH (12 ml of a 10 M solution) was added to a solution of **4** (2.7g, 5 mmol) in water (15 ml) and reaction mixture stirred at room temperature for 16 h. Following extraction with chloroform, the combined organic extracts were washed with brine, dried over $MgSO_4$ and concentrated. Chromatography on alumina eluting with chloroform and isopropyl amine (97 : 30) yielded the title cyclen derivative **5** as a fluffy yellow solid (270 mg, 11.3% yield). $[\alpha]_D^{20}$ = +66.26 (c = 3, CH_2Cl_2). δ_H (300 MHz) 1.44 (6H, d, J = 8 Hz), 2.48–2.63 (16H, m), 3.03 (4H, m), 5.00 (2H, m), 7.16 (10H, m), 8.03 (2H, br d, J = 8 Hz). δ_C (50 MHz) 170.1, 143.4, 128.5, 127.3, 126.6, 57.5, 53.9, 52.9, 48.7, 46.2, 46.1, 21.5. *m*/*z* (ES$^+$) 495 (M$^+$ + 1).

Found: C 68.00, H 8.00, N 17.00. $C_{28}H_{42}N_6O_2$ requires C 68.02, H 8.50, N 17.00%.

Synthesis of lanthanide (III) complexes[25]

Synthesis of Eu^{III} complex 6. To a solution of **5** (91 mg, 0.184 mmol) in acetonitrile (3 ml) was added europium(III) trifluoromethanesulfonate [$Eu^{III}(OTf)_3$] (110 mg, 0.184 mmol) in acetonitrile (3 ml) at 40 °C. The reaction mixture was brought to 60 °C and stirred for 18 h. The reaction mixture was concentrated under vacuum, redissolved in the minimum amount of acetonitrile and precipitated with ether (80 ml). The solid was filtered and recrystallised from acetonitrile and dichloromethane to give the title complex as yellow crystals **6** (160 mg, 80% yield). Mp 175–176 °C. Found: C 31.72, H 4.08, N 7.42. $C_{31}H_{42}F_9N_6O_{11}S_3Eu{\cdot}4H_2O$ requires C 31.93, H 4.32, N 7.21%. $[\alpha]_D^{20}$ = +94 (*c* = 1.0, MeOH). δ_H (400 MHz, d_4-MeOH) −23.5 (br s), −21.2 (br s), −19.8 (br s), 18.5 (br s), −10.2 (br s), −8.0 (br s), −4.5 (br s), −1.8 (s), −1.5 (s), −0.5 (m), 1.8 (s), 3.2 (s), 5.1 (m), 7.9 (br s), 13.5 (br s), 16.5 (br s). *m*/*z* (ES^+) 944 (M^{3+} + $(OTf)_2$).

Synthesis of Sm^{III} complex 7. In an identical fashion to that described above the samarium complex **7** was isolated as white crystals following recrystallisation from acetonitrile and dichloromethane (80% yield). Mp 212–214 °C. Found: C 33.00, H 4.06, N 7.41. $C_{31}H_{42}F_9N_6O_{11}S_3Sm{\cdot}2H_2O$ requires C 32.98, H 4.08, N 7.45%. $[\alpha]_D^{20}$ = +72 (*c* = 0.5, MeOH). δ_H (400 MHz, d_4-MeOH) 0.79 (br s), 1.15 (t), 1.8 (d, *J* = 8 Hz), 1.9 (br s), 2.80 (br s), 3.10 (br s), 3.30 (m), 3.5 (q), 4.92 (s), 5.5 (br s), 5.9 (br s), 7.35–7.60 (m), 7.80 (br s). *m*/*z* (ES^+) 942 (M^{3+} + $(OTf)_2$).

Synthesis of Yb^{III} complex 8. In an identical fashion to that described above the ytterbium complex **8** was isolated as a light yellow glassy solid (75% yield). Found: C 30.62, H 3.94, N 6.77. $C_{31}H_{42}F_9N_6O_{11}S_3Yb{\cdot}5H_2O$ requires C 30.90, H 4.34, N 6.97%. δ_H (400 MHz, d_4-MeOH) 1.10 (t), 1.41 (d, *J* = 8 Hz), 3.10 (br s), 3.30 (s), 3.5 (q), 4.95 (s), 7.30 (m). MS: (ES) *m*/*z* 966 (M^{3+} + $(OTf)_2$).

Electrochemical measurements

Cyclic voltammetry was performed using an EG&G Versastat II potentiostat operating under the PARC M270 software package. Data were collected at a Pt working electrode from room temperature solutions in NCMe containing 0.1 M $[NBu_4]BF_4$ as supporting electrolyte at 100 mV s^{-1} scan rates. Pt wire counter and pseudo reference electrodes were employed. All data reported has been referenced against an internal ferrocene/ferrocinium reference couple ($E_{½}$ = 0.40 V). Differential pulse voltammetry was carried out using MeCN solutions *ca.* 1 mM in analyte containing 0.01 M $[NBu_4]ClO_4$ supporting electrolyte on an EG&G PARC 273 Potentiostat/Galvanostat with Model 270/250 software. A glassy carbon working electrode, an Ag/AgCl reference electrode and a Pt counter electrode were employed. All experiments were performed under argon.

Bulk electrolysis was carried out using a Keithley 224 programmable current source with a 100 mA constant current background for 7 hours using a sacrificial Mg anode and a Pt mesh cathode.

Typical experimental procedure for electrochemical synthesis. In a single compartment cell (50 ml) fitted with Mg anode (diameter, 0.8 cm) and a platinum mesh cathode (apparent surface 20 cm^2) were introduced freshly distilled DMF (30 ml), n-Bu_4NBr (0.25 mmol), anhydrous catalyst (0.5 mmol), benzylacetone (5 mmol) and *n*-butyl iodide (5 mmol). Current was then passed at 20 °C at constant intensity of 100 mA (apparent current density 0.5 A dm^{-2}) under an argon atmosphere. After 6 h the reaction mixture was hydrolysed with 1 M HCl and extracted with ether. The organic layers were dried over $MgSO_4$ and concentrated. Chromatography over silica gel eluting with *n*-hexane : ethyl acetate (8 : 2) gave a mixture of Barbier adduct **14**, diol **15** and alcohol **16** as indicated in Table 2.

15: (Two diastereomers ~ 1 : 1) δ_H (200 MHz) 1.2 (3H, s, CH_3 diast. A), 1.25 (3H, d, *J* = 6 Hz, CH_3 diast. B), 1.78–2.61 (8H, m), 3.85 (2H, m), 7.20 (10H, m).

Table 3 Crystal data and experimental details

Compound	**6** (M = Eu)	**7** (M = Sm)
Formula	$[C_{28}H_{46}MN_6O_4]^{3+}(CF_3SO_3^-)_3$	
Formula weight	1129.88	1128.27
T/K	103	100
Symmetry	Orthorhombic	
Space group	$P2_12_12_1$ (No. 19), Z = 4	
a/Å	10.156(2)	10.143(1)
b/Å	13.194(2)	13.171(2)
c/Å	33.401(7)	33.280(4)
V/$Å^3$	4475.5(15)	4446.1(14)
μ/mm^{-1}	1.64	1.56
Reflections collected	37277	45120
Independent reflections	9301 (5309)[a]	10197 (5684)[a]
R_{int}	0.039	0.063
Reflections with $F^2 > 2\sigma(F^2)$	8997 (5144)[a]	9551 (5412)[a]
$R[F^2 > 2\sigma(F^2)]$	0.029	0.037
$wR(F^2)$, all data	0.063	0.068
Flack parameter	−0.005(7)	−0.004(8)

[a] Friedel equivalents merged.

X-Ray crystallography

Single-crystal diffraction experiments for **6** and **7** (Table 3) were carried out on a SMART 3-circle diffractometer with a 1K CCD area detector, using graphite monochromated Mo-Kα radiation (λ = 0.71073 Å) and covering nearly the full sphere of the reciprocal space by 4 runs of ω scans. The crystals were cooled using a Cryostream (Oxford Cryosystems) open-flow N_2 gas cryostat. Reflection intensities were corrected for absorption by the semi-empirical method based on comparison of Laue equivalents.[37] The structures were solved by direct methods and refined by full-matrix least squares against F^2 of all data, using SHELXTL software.[38] Non-H atoms were refined with anisotropic displacement parameters; all H atoms (found in difference Fourier syntheses) were treated as 'riding'. The absolute configuration was determined from anomalous X-ray scattering,[39] and was consistent with the *R*,*R*-configuration of the starting material. CCDC reference numbers 176831 and 176832. See http://www.rsc.org/suppdata/p1/b1/b111628b/ for crystallographic files in .cif or other electronic format.

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