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L-Cysteine as a Chiral Linker in Lanthanide–Cucurbit[6]uril One-Dimensional Assemblies

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Supporting Information

ABSTRACT: The reaction of neodymium, europium, or terbium nitrate with cucurbit[6]uril (CB6) in the presence of the α-amino acid L-cysteine (L-cys) gives the complexes $[\mathrm{Nd}(\text{L-cys})(\mathrm{CB6})(\mathrm{NO_3})(\mathrm{H_2O})_4]\cdot 2\mathrm{NO_3}\cdot 10\mathrm{H_2O}$ (**1**) and $\{[\mathrm{Ln}(\text{L-cys})(\mathrm{CB6})(\mathrm{H_2O})_5][\mathrm{Ln}(\text{L-cys})(\mathrm{CB6})(\mathrm{NO_3})(\mathrm{H_2O})_4]\}\cdot 5\mathrm{NO_3}\cdot 22\mathrm{H_2O}$ with Ln = Eu (**2**) or Tb (**3**). **2** and **3** only differ from **1** by the presence of two independent metal ions in slightly different environments. In all cases, each metal atom is bound to the bidentate CB6 and the monodentate L-cys molecules, with the latter being in its zwitterionic form. The ammonium group of L-cys is directed away from CB6 and is involved in ion–dipole and hydrogen bonding interactions with the uncomplexed portal of the neighboring molecule, which gives rise to the formation of chiral one-dimensional assemblies of columnar shape.

Among the supramolecular assemblies including cucurbit[6]uril (CB6)[1] as a rigid macrocyclic subunit, the metal-based polyrotaxanes and necklaces first synthesized by Kim et al. are most remarkable.[2] In particular, one-dimensional helical polyrotaxanes, isolated as racemic mixtures, have been obtained through the proper choice of the diaminoalkane used as a thread.[2c,g,h,j] However, pure enantiomeric forms, which would be of interest for heterogeneous asymmetric catalysis or enantioselective separations,[3] could not be isolated up to now by using this method in which chirality arises spontaneously from achiral ligands. A more straightforward approach to synthesizing pure enantiomers of CB6-based chiral complexes is to use pure enantiomeric forms of chiral ligands. Although they are unsuitable for the design of rotaxanes, α-amino acids appear to be particularly promising candidates because, in their zwitterionic form, they possess both a carboxylate group suitable for metal complexation and an ammonium group, which is likely to interact with CB6 through ion–dipole and hydrogen bonding interactions. The latter interactions have previously been used to build cucurbituril complexes of chiral ammonium guests,[4] leading in some cases to chiral recognition.[4a] The binding of common α-amino acids and of tripeptides by cucurbiturils was also investigated.[5]

In the course of the present work, several α-amino acids were investigated in association with CB6 and lanthanide ions, with the latter being chosen because they are readily complexed by both carboxylates and the carbonyl groups of CB6.[6] In the case of L-cysteine (denoted L-cys hereafter), it was possible to synthesize the three complexes $[\mathrm{Nd}(\text{L-cys})(\mathrm{CB6})(\mathrm{NO_3})(\mathrm{H_2O})_4]\cdot 2\mathrm{NO_3}\cdot 10\mathrm{H_2O}$ (**1**) and $\{[\mathrm{Ln}(\text{L-cys})(\mathrm{CB6})(\mathrm{H_2O})_5][\mathrm{Ln}(\text{L-cys})(\mathrm{CB6})(\mathrm{NO_3})(\mathrm{H_2O})_4]\}\cdot 5\mathrm{NO_3}\cdot 22\mathrm{H_2O}$ with Ln = Eu (**2**) or Tb (**3**),[7] which were crystallographically characterized.[8]

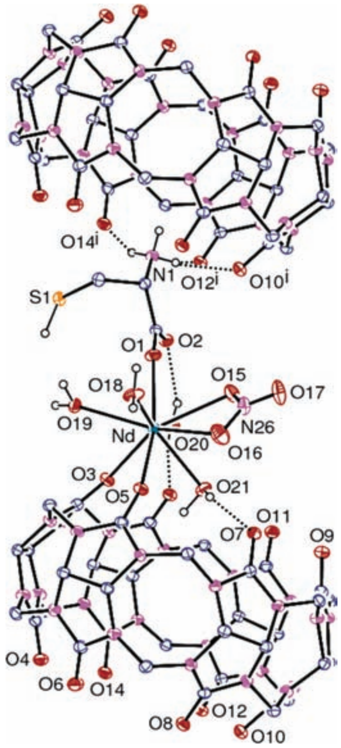

Figure 1. View of complex **1**. Counterions, solvent molecules, and carbon-bound H atoms are omitted. Hydrogen bonds are shown as dashed lines. Displacement ellipsoids are drawn at the 30% probability level. Selected bond lengths (Å): Nd–O1 2.3518(19), Nd–O3 2.4562(18), Nd–O5 2.4442(18), Nd–O15 2.619(2), Nd–O16 2.758(3), Nd–O18 2.445(2), Nd–O19 2.5293(19), Nd–O20 2.458(2), Nd–O21 2.4594(19).

All three complexes crystallize in the chiral space group $P2_1$. Complexes **2** and **3** are isomorphous, and they differ from **1** by the doubling of one unit cell parameter, which is due to the presence of two metal ions with slightly different environments in the asymmetric unit of the former compounds, while only one is present in **1**. The overall arrangement is similar in all cases, as shown in Figures 1 and 2. The metal cation is bound to two adjacent carbonyl groups of CB6, which is usual,[6] with average Ln–O bond lengths of 2.450(6), 2.41(4), and 2.38(4) Å for

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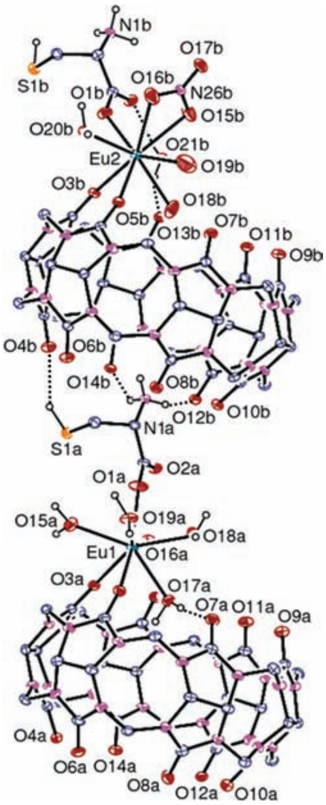

Figure 2. View of complex **2**. Counterions, solvent molecules, and carbon-bound H atoms are omitted. Hydrogen bonds are shown as dashed lines. Displacement ellipsoids are drawn at the 30% probability level. Selected bond lengths (Å) (values in the isomorphous terbium complex **3** are in brackets): Ln1−O1a 2.317(4) [2.307(3)], Ln1−O3a 2.384(4) [2.356(3)], Ln1−O5a 2.367(3) [2.332(3)], Ln1−O15a 2.427(4) [2.390(4)], Ln1−O16a 2.388(4) [2.353(3)], Ln1−O17a 2.485(4) [2.456(3)], Ln1−O18a 2.373(5) [2.352(5)], Ln1−O19a 2.397(4) [2.366(3)], Ln2−O1b 2.375(4) [2.354(4)], Ln2−O3b 2.478(3) [2.444(3)], Ln2−O5b 2.413(3) [2.395(3)], Ln2−O15b 2.517(4) [2.484(4)], Ln2−O16b 2.523(5) [2.497(5)], Ln2−O18b 2.418(5) [2.370(5)], Ln2−O19b 2.513(7) [2.472(7)], Ln2−O20b 2.454(4) [2.430(3)], Ln2−O21b 2.436(3) [2.406(3)].

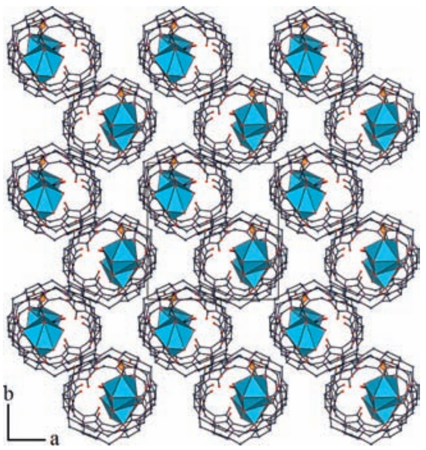

Figure 3. View of the packing in **2** down the column axis. Counterions, solvent molecules, and H atoms are omitted. The metal coordination polyhedra are shown in blue.

1−**3**, respectively, in agreement with the values in previous complexes. The L-cys ligand is in its zwitterionic, neutral form and is monodentate through one carboxylate O atom, with Ln−O bond lengths in the range of 2.31−2.38 Å (in **2** and **3**, the bond length for Ln2 is slightly larger than that for Ln1 because of the increase in the coordination number). It is notable that only one complex of a 4f ion (Tb) with DL-cysteine is reported in the Cambridge Structural Database (version 5.32)[9], but it was later reinterpreted as a disordered cystine complex [average Tb−O bond length of 2.38(2) Å].[10] As a general trend and in contrast to the present cases, lanthanide complexation by α-amino acids often gives polynuclear species.[11] The atoms Nd, Eu2, and Tb2 in **1**−**3** are further bound to a bidentate nitrate ion [average Ln−O bond lengths of 2.69(7), 2.520(3), and 2.491(6) Å, respectively] and four water molecules [average bond lengths of 2.47(3), 2.46(4), and 2.42(4) Å], while Eu1 and Tb1 are bound to five water molecules only [average bond lengths of 2.41(4) and 2.38(4) Å]. Eu1 and Tb1 are thus eight-coordinate and in a square-antiprismatic environment with the sets of atoms O1a, O3a, O15a, O16a and O5a, O17a, O18a, O19a defining the two faces (dihedral angle ca. 3°), while Nd, Eu2, and Tb2 are in nine-coordinate environments of capped square-antiprismatic geometry with either O3 in **1** or O21b in **2** and **3** in the capping position and dihedral angles between the two square faces of ca. 13 and 16°, respectively.

The L-cys ligand is directed away from the CB6 molecule and its ammonium group points toward the uncomplexed portal of the neighboring molecule along the *a* (**1**) or *c* (**2** and **3**) axis. The N atom is at 0.5−0.9 Å from the mean portal plane (on the exterior side), and two of its protons are involved in hydrogen bonds with carbonyl O atoms (N···O and H···O distances and N−H···O angles in the ranges 2.784(5)−3.100(6) Å, 1.95−2.37 Å, and 117−156°, respectively), while the third forms a bond with a solvent water molecule. In **1**, the SH group forms a hydrogen bond with a free nitrate ion, but in **2** and **3**, these groups add to the cohesion of the supramolecular assembly because they are bound to carbonyl groups from the neighboring molecules. Chiral columns of hydrogen-bonded complexes are thus formed, as is illustrated for **2** in Figure 3, which are shifted with respect to one another along the column axis so that the bumps of one match the hollows of its neighbors, a frequent situation with cucurbiturils. The intercolumnar spaces are occupied by the counterions and solvent molecules, and the packing index (estimated with *PLATON*[12]) of ca. 0.73 (ca. 0.64 with solvent excluded) indicates that no significant free space is present.

It is interesting to compare the present complexes with those formed by lanthanide ions with iminodiacetic acid in the presence of CB6.[6j] In the latter case, the metal ion is also bound to a monodentate carboxylate group, but not to CB6, and part of the ligand, including the uncoordinated carboxylic group, is further encapsulated in the macrocycle cavity, with ammonium−carbonyl hydrogen-bonding interactions being present. Inclusion of the ligand is also observed with 2-pyridylacetic acid, and CB6 is monodentate in this case.[6j] The formation of a supramolecular one-dimensional assembly in **1**−**3** is thus crucially dependent on the L-cys ligand not being hydrogen-bonded to the very macrocycle bound to the same metal ion as itself. It may well be that the thiol group plays an important role here, but further work with other α-amino acids will be necessary to clarify this point.

In summary, the present results show that it is possible to build chiral assemblies based on lanthanide ion complexes of CB6, with the pure enantiomeric form of the α-amino acid L-cys being used as an additional ligand. The latter is well suited both so as to introduce chirality and as a polyfunctional molecule able to act as an intermolecular linker through coordination bonds, and ion−dipole and hydrogen bonding interactions.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information. Tables of crystal data, atomic positions, and displacement parameters, anisotropic displacement parameters, and bond lengths and bond angles in CIF format. This material is available free of charge via the Internet at http://pubs.acs.org.

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(7) Synthesis of complexes **1**−**3**. CB6·5H_2O (11 mg, 0.01 mmol), Ln$(NO_3)_3\cdot xH_2O$ (Nd, x = 6, 44 mg, 0.10 mmol; Eu, x = 5, 43 mg, 0.10 mmol; Tb, x = 6, 45 mg, 0.10 mmol), and L-cys (24 mg, 0.20 mmol) were dissolved in demineralized water (1.5 mL) upon gentle heating. The solutions were then left to evaporate slowly, giving complexes **1**−**3** within 5 days. For **1**: 8 mg, 47% yield on the basis of CB6. Anal. Calcd for $C_{39}H_{71}N_{28}NdO_{37}S$: C, 27.55; H, 4.21; N, 23.06. Found: C, 27.70; H, 4.11; N, 23.01. For **2**: 8 mg, 46% yield. Anal. Calcd for $C_{78}H_{148}Eu_2N_{56}O_{77}S_2$: C, 26.99; H, 4.30; N, 22.60. Found: C, 27.69; H, 4.17; N, 23.16. For **3**: 10 mg, 57% yield. Anal. Calcd for $C_{78}H_{148}N_{56}O_{77}S_2Tb_2$: C, 26.89; H, 4.28; N, 22.51. Found: C, 27.64; H, 4.09; N, 22.77.

(8) Crystallographic data were collected at 150(2) K on a Nonius Kappa CCD area detector diffractometer[13] and processed with *HKL2000*.[14] Absorption effects were corrected with *SCALEPACK*.[14] The structures were solved by direct methods and were refined by full-matrix least squares on F^2 with *SHELXTL* (refinement software XH for **2** and **3**).[15] All non-H atoms were refined with anisotropic displacement parameters. The H atoms bound to S, O, and N atoms were found on Fourier difference maps, except for those of some water molecules, and the carbon-bound H atoms were introduced at calculated positions. All H atoms were treated as riding atoms with an isotropic displacement parameter equal to 1.2 times that of the parent atom. The known absolute configuration is in agreement with that determined from refinement of the Flack parameter.[16] The drawings were done with ORTEP-3[17] and VESTA.[18] Crystal data for **1**: $C_{39}H_{71}N_{28}NdO_{37}S$, M = 1700.54, monoclinic, space group $P2_1$, a = 14.3766(5) Å, b = 15.0916(3) Å, c = 14.9340(5) Å, β = 101.118(2)°, V = 3179.36(17) Å^3, Z = 2. Refinement of 966 parameters on 19 190 independent reflections out of 105 009 measured reflections (R_{int} = 0.033) led to R1 = 0.034, wR2 = 0.084, S = 1.039, $\Delta\rho_{min}$ = −0.82, $\Delta\rho_{max}$ = 1.13 e Å^{-3}, Flack parameter = −0.010(5). Crystal data for **2**: $C_{78}H_{148}Eu_2N_{56}O_{77}S_2$, M = 3470.56, monoclinic, space group $P2_1$, a = 14.9552(2) Å, b = 15.4216(2) Å, c = 28.7508(4) Å, β = 101.002(2)°, V = 6509.02(16) Å^3, Z = 2. Refinement of 1946 parameters on 39 548 independent reflections out of 187 594 measured reflections (R_{int} = 0.041) led to R1 = 0.054, wR2 = 0.160, S = 1.036, $\Delta\rho_{min}$ = −1.50, $\Delta\rho_{max}$ = 2.33 e Å^{-3}, Flack parameter = −0.006(5). Crystal data for **3**: $C_{78}H_{148}N_{56}O_{77}S_2Tb_2$, M = 3484.48, monoclinic, space group $P2_1$, a = 14.9551(4) Å, b = 15.3965(4) Å, c = 28.7244(5) Å, β = 101.091(2)°, V = 6490.4(3) Å^3, Z = 2. Refinement of 1946 parameters on 39 523 independent reflections out of 204 547 measured reflections (R_{int} = 0.023) led to R1 = 0.049, wR2 = 0.141, S = 1.030, $\Delta\rho_{min}$ = −1.22, $\Delta\rho_{max}$ = 2.53 e Å^{-3}, Flack parameter = 0.006(5).

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