

Anion control of ligand self-recognition in a triple helical array†

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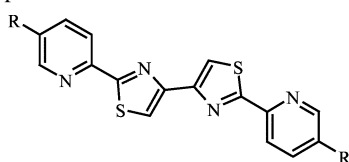
Received (in Cambridge, UK) 21st October 2003, Accepted 14th January 2004

First published as an Advance Article on the web 10th February 2004

Self-assembly of the ligand L¹ with Co²⁺ into a dinuclear triple helicate [Co₂(L¹)₃]⁴⁺ produces an anion binding pocket which encapsulates perchlorate anions. Furthermore we demonstrate how this ability to bind anions can control ligand self-recognition properties.

The self-assembly of structurally elaborate metallo-supramolecular complexes from relatively simple components (metal ions, ligands, counter-ions) is controlled by the geometric information which is inherent in these components.^{1–5} In some cases the geometric information is obvious. For example, the stereoelectronic preference of particular metal ions for specific coordination geometries or the ability of ligands to partition into different binding domains^{6,7} are all factors in controlling the assembly of species such as helicates, grids and cages. Other factors controlling the assembly process include templating by counter ions,^{8–10} differing spacers between the binding sites of the ligand¹¹ and chirality of the ligand.¹²

In this communication, we describe the self-assembly of the new ligand L¹ with Co²⁺ into a dinuclear triple helicate [Co₂(L¹)₃]⁴⁺ which contains an anion receptor cavity. Furthermore we demonstrate how the binding of NO₃[−] ions can control the ligand self-recognition properties.

L¹ R = (S)-CONHCH(CH(CH₃)₂)CO₂MeL² R = CONHCH(CH₃)₂ L³ R = H

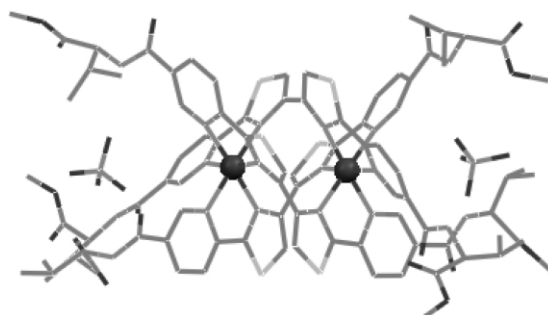
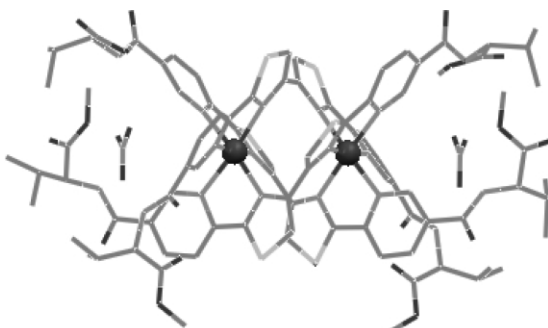
The novel potentially tetradentate N-donor ligand L¹ was synthesised from 6-cyanonicotinic acid in 4 steps in high yield (67% overall). Reaction of L¹ with [Co(ClO₄)₂]-6H₂O in acetonitrile in a 3:2 ratio afforded an orange solution, from which a good yield of orange crystalline product could be isolated by diffusion of MeCO₂Et. Electrospray mass spectrometry and elemental analysis indicated formation of a dinuclear triple helicate [Co₂(L¹)₃]⁴⁺. This formulation was confirmed by X-ray crystallography,[‡] which showed two Co²⁺ ions coordinated by three bridging ligands L¹ in a triple helicate arrangement, as would be expected from this type of potentially tetradentate pyridyl-thiazole ligand (Fig. 1).¹³ Each of the Co centres has a pseudo-octahedral coordination geometry formed by coordination of three thiazole-pyridyl bidentate N-donor units [2.093(5)–2.192(5) Å] with each ligand twisted about the bond between the two thiazole rings. The ¹H NMR spectrum of a solution of [Co₂(L¹)₃]⁴⁺ is as expected for a paramagnetic Co²⁺ complex of this type with signals observed between 0 and 90 ppm.^{†14–16} The most informative signals are at 85.16, 73.10, 70.78 and 12.26 ppm which are due to the three pyridyl and one thiazole proton environments. The aromatic signal at 12.26 ppm shows two

† Electronic supplementary information (ESI) available: synthesis and characterisation of ligands and complexes. All new compounds were characterised by CHN, ¹H NMR and ESI-MS. ¹H NMR of the mixing experiment. See <http://www.rsc.org/suppdata/cc/b3/b313218h/>

resonances due to the formation of a mixture of diastereoisomers between the helicate (Δ or Λ) and the resolved chiral (S) amide substituents, an effect which is not observed when ligands with achiral substituents are employed, such as [Co₂(L²)₃]⁴⁺. The formation of roughly equal numbers of diastereoisomers is a surprising, but not unprecedented, result.¹⁷

The most interesting feature of the structure is that upon self-assembly into a dinuclear triple helicate two cavities are formed, at either end of the helicate, that contain amide groups capable of hydrogen bonding to anions. Indeed the structure shows a perchlorate anion is encapsulated within each of these self-assembled cavities (Fig. 1). Both perchlorates hydrogen bond, *via* two of their oxygens, to two of the three –NH donors at distances between 2.14–2.34 Å. In both cases the third amide N–H group is directed away from the perchlorate anion, outwards from the cavity with one forming an intermolecular N–O hydrogen bond (2.98 Å). This type of behaviour is similar to that observed in both mononuclear tris(5,5'-diamide-2,2'-bipyridine) and tris(5-carboxyl-2,2'-bipyridine) complexes.¹⁸

We have recently obtained the X-ray structure of [Co₂(L¹)₃](ClO₄)₂(NO₃)₂, formed by reaction of [Co₂(L¹)₃](ClO₄)₄ with two equivalents of Bu₄NNO₃ (Fig. 2). In this structure, not only are most of the anion hydrogen bond lengths shorter (2.06–2.38 Å) but, unlike that of the perchlorate analogue, all three amides point towards the nitrate anions. Furthermore the nitrate is sited deeper within the receptor cleft (av. Co⋯NO₃ 4.42 Å Co⋯ClO₄ 5.00 Å), demonstrating that the binding of the nitrate anion is stronger than that of perchlorate.

Fig. 1 Crystal structure of the complex cation [Co₂(L¹)₃](ClO₄)₂²⁺.Fig. 2 Crystal structure of the complex cation [Co₂(L¹)₃](NO₃)₂²⁺.

Since both ligands L¹ and L³ contain the same basic ligand chain, but L¹ contains a receptor for anions whereas L³ does not, we investigated their ability to form triple stranded heteroleptic (mixed-ligand) complexes. Thus the reaction of a mixture of L¹ and L³ with [Co(ClO₄)₂]-6H₂O (1.5:1.5:2 molar ratio) in CD₃CN was monitored by ¹H NMR spectroscopy to determine the product distribution.† The spectrum showed that four helical species were observed [Co₂(L¹)₃]⁴⁺, [Co₂(L¹)₂(L³)]⁴⁺, [Co₂(L¹)(L³)₂]⁴⁺ and [Co₂(L³)₃]⁴⁺ in the statistical ratio of 1:3:3:1. In this mixed system L¹ and L³ each afford four sets of aromatic signals. In the case of L¹, two sets of aromatic resonances are observed for the homoleptic species ([Co₂(L¹)₃]⁴⁺) and the monostranded L¹ heteroleptic species ([Co₂(L¹)(L³)₂]⁴⁺). The remaining two sets of signals arise from the two L¹ strands in the heteroleptic species [Co₂(L¹)₂(L³)]⁴⁺ which, due to the low symmetry of the complex, are diastereotopic and chemically inequivalent. These four sets of aromatic resonances for L¹ are accompanied by four similar sets of aromatic signals for L³.

This is most clearly seen for the proton resonances which occur at ca. 12 ppm where a total of eight signals, with equal intensity, are observed. This corresponds to the eight ligand environments, with some of the signals doubled due to the presence of a mixture of (ΔS or ΛS) diastereoisomers.¹⁹ The structures are further confirmed by ESI mass spectrometry which showed doubly charged ions at 642 [Co₂(L³)₃]²⁺, 799 [Co₂(L¹)(L³)₂]²⁺, 956 [Co₂(L¹)₂(L³)]²⁺ and 1113 [Co₂(L¹)₃]²⁺. Clearly in this system little or no ligand–ligand self-recognition takes place which is not unexpected given that L¹ and L³ differ only by the presence or absence of sterically non-demanding terminal amide substituents.

Potassium nitrate was then added to the mixed ligand sample and, after sonicating, the ¹H NMR spectrum was re-recorded. This showed that the spectrum was greatly simplified and that the major signals corresponded to the homoleptic species ([Co₂(L¹)₃]⁴⁺ and [Co₂(L³)₃]⁴⁺), with a low-intensity set of signals corresponding to a small amount (ca. 5%) of the heteroleptic complexes.

In the case of addition of the ligands to Co²⁺ in the presence of perchlorate anions there is no significant difference between the ligands and a statistical mixture is formed. However, upon addition of the nitrate anion, ligand–ligand recognition occurs and only small amounts of the mixed ligand helicates are observed. This change in ligand self-recognition can be attributed to the presence of amide substituents present on L¹, which upon self-assembly to the dinuclear triple helicate [Co₂(L¹)₃]⁴⁺ form an anion receptor cavity. Thus in the presence of perchlorate (very strong acid pK_a ≈ –8, very weak base) the self-assembly of a receptor cavity is not significantly favoured and hence a mixture of species is formed. However, upon addition of the nitrate anion (strong acid pK_a ≈ –1.64, weak base), which binds the amide receptor cavity much more strongly than the perchlorate anion,§ the formation of an anion receptor complex is now thermodynamically favoured and thus the major species present are [Co₂(L¹)₃](ClO₄)₂(NO₃)₂ and the other corresponding homoleptic species [Co₂(L³)₃]⁴⁺. Again this is confirmed by ESI mass spectrometry as the heteroleptic helicates reduce in intensity in the presence of nitrate anion in a comparable way to that observed in the NMR.

In summary we have shown that the ligand–ligand self-recognition process within a helical array containing a labile transition metal ion can be controlled by addition of a suitable anion. This is a unique and unprecedented example of how, by the incorporation of different functionalities within the ligand chain, the self-assembly process and ligand self-recognition of transition metal helicates can be controlled.

Notes and references

† Crystal data for [Co₂(L¹)₃](ClO₄)₄·(CH₃CO₂CH₂CH₃)·(H₂O)₂: C₉₄H₁₀₈Cl₄O₃₈N₁₈S₆, M_r = 2550.00, monoclinic, space group = P2₁,

a = 21.411(4), *b* = 12.431(2), *c* = 21.874(4) Å, α = 90, β = 92.147(4), γ = 90°, *V* = 5817.8(18) Å³, *Z* = 2, ρ_{calc} = 1.456 Mg m^{–3}, F(000) = 2640. A total of 61797 reflections were measured in the range 1.31 ≤ θ ≤ 27.51° (hkl range indices: –27 ≤ *h* ≤ 27, –16 ≤ *k* ≤ 15, –28 ≤ *l* ≤ 28), 26081 unique reflections (R(int) = 0.0738). The structure was refined on F² to R_w = 0.1574, R = 0.0642 (15554 reflections with I > 2σ(I)) and GOF = 1.004 on F² for 1534 refined parameters. CCDC reference number 217881. Crystal data for [Co₂(L¹)₃](ClO₄)₂(NO₃)₂·(CH₃CO₂CH₂CH₃)·(H₂O)₂: C₉₄H₁₀₈Cl₂Co₂N₂₀O₃₆S₆, M_r = 2475.12, Triclinic, space group = P1, *a* = 12.368(5), *b* = 12.739(6), *c* = 19.836(8) Å, α = 92.953(14), β = 93.284(13), γ = 118.520(15)°, *V* = 2730(2) Å³, *Z* = 1, ρ_{calc} = 1.505 Mg m^{–3}, F(000) = 1284. A total of 17863 reflections were measured in the range 1.83 ≤ θ ≤ 27.50° (hkl range indices: –16 ≤ *h* ≤ 14, –16 ≤ *k* ≤ 13, –19 ≤ *l* ≤ 25), 14632 unique reflections (R(int) = 0.0620). The structure was refined on F² to R_w = 0.1017, R = 0.0569 (14632 reflections with I > 2σ(I)) and GOF = 0.846 on F² for 1499 refined parameters. CCDC reference number 225994. See <http://www.rsc.org/suppdata/cc/b3/b313218h/> for crystallographic data in .cif or other electronic format.

§ ¹H NMR titration of the analogous, structurally characterized, zinc complex ([Zn₂(L¹)₃](ClO₄)₄) with two equivalents of Bu₄NNO₃ showed a marked perturbation in the chemical shift of the amide proton (7.4–9.0 ppm, 10^{–3} M, CD₃CN). No further change in chemical shift was observed upon addition of >2 equivalents of NO₃[–].

- 1 J.-M. Lehn, *Supramolecular Chemistry*, VCH, Weinheim 1995.
- 2 M. Albrecht, *Chem. Soc. Rev.*, 2001, **101**, 3547.
- 3 M. Albrecht, *Chem. Soc. Rev.*, 1998, **27**, 281.
- 4 C. Piguat, G. Bernardinelli and G. Hopfgartner, *Chem. Rev.*, 1997, **97**, 2005.
- 5 E. C. Constable, in *Comprehensive Supramolecular Chemistry, Volume 9: Polynuclear Transition Metal Helicates*, ed. J.-P. Sauvage, Elsevier, Oxford, 1996, pp. 213.
- 6 R. Krämer, J.-M. Lehn and A. Marquis-Rigault, *Proc. Natl. Acad. Sci. USA*, 1993, **90**, 3114.
- 7 B. Hasenknopf, J.-M. Lehn, G. Baum and D. Fenske, *Proc. Natl. Acad. Sci. USA*, 1996, **93**, 1397.
- 8 M. Albrecht, M. Schneider and H. Röttele, *Angew. Chem.*, 1999, **111**, 512; M. Albrecht, M. Schneider and H. Röttele, *Angew. Chem. Int. Ed.*, 1999, **38**, 557.
- 9 B. Hasenknopf, J.-M. Lehn, B. O. Kneisel, G. Baum and D. Fenske, *Angew. Chem., Int. Ed. Engl.*, 1996, **35**, 1838.
- 10 (a) R. L. Paul, Z. R. Bell, J. C. Jeffery, J. A. McCleverty and M. D. Ward, *Proc. Natl. Acad. Sci. USA*, 2002, **99**, 4883; (b) R. Vilar, *Angew. Chem. Int. Ed.*, 2003, **42**, 1460; (c) K. Umemoto, K. Yamaguchi and M. Fujita, *J. Am. Chem. Soc.*, 2000, **122**, 7150; (d) M. Scherer, D. L. Caulder, D. W. Johnson and K. N. Raymond, *Angew. Chem. Int. Ed.*, 1999, **38**, 1588.
- 11 D. Caulder and K. N. Raymond, *Angew. Chem., Int. Ed. Engl.*, 1997, **36**, 1440.
- 12 (a) M. A. Masood, E. J. Enemark and T. D. P. Stack, *Angew. Chem. Int. Ed.*, 1998, **37**, 928; (b) G. Baum, E. C. Constable, D. Fenske, C. E. Housecroft and T. Kulke, *Chem. Eur. J.*, 1999, **5**, 1862.
- 13 (a) C. R. Rice, S. Wörl, J. C. Jeffery, R. L. Paul and M. D. Ward, *Chem. Commun.*, 2000, 1529; (b) C. R. Rice, S. Wörl, J. C. Jeffery, R. L. Paul and M. D. Ward, *J. Chem. Soc., Dalton Trans.*, 2001, 550.
- 14 E. C. Constable, T. Kulke, M. Neuburger and M. Zehnder, *New J. Chem.*, 1997, **21**, 1091.
- 15 E. C. Constable, M. A. M. Daniels, M. G. B. Drew, D. A. Tocher, J. V. Walker and P. D. Wood, *J. Chem. Soc., Dalton Trans.*, 1993, 1947.
- 16 C. R. Rice, C. J. Baylies, J. C. Jeffery, R. L. Paul and M. D. Ward, *Inorg. Chim. Acta*, 2001, **324**, 331.
- 17 D.-R. Ahn, T. W. Kim and J.-I. Hong, *J. Org. Chem.*, 2001, **66**, 5008.
- 18 L. H. Uppadine, M. G. B. Drew and P. D. Beer, *Chem. Commun.*, 2001, 291; P. D. Beer and E. J. Hayes, *Coord. Chem. Rev.*, 2003, **240**, 167; N. C. Fletcher, M. Nieuwenhuyzen, R. Prabarahan and A. Wilson, *Chem. Commun.*, 2002, 1188; B. Wu, X.-J. Yang, C. Janiak and P. G. Lassahn, *Chem. Commun.*, 2003, 902.
- 19 The integrated intensities for the L¹ and L³ ligands in the homoleptic complexes are enhanced because they each have three chemically equivalent ligands, this result is consistent with the production of a statistical mixture (1:3:3:1) of the four possible homoleptic and heteroleptic complexes.