The Helicates: Structural Principles and Supramolecular Properties

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Abstract: The structural principles involved in the construction of polynuclear helical complexes are reviewed. Some properties of the helicates show significant differences from related mononuclear complexes as a result of the mechanical coupling between metal centres.

Keywords: Coordination compounds · Helical compounds · Supramolecular chemistry

The polynuclear complexes known as helicates [1][2] occupy a privileged position in supramolecular chemistry: they were among the earliest systems in which the potential of metal-ligand coordination was used to assemble large molecular structures. In this brief review based on work carried out in Geneva, I would like firstly to illustrate the structural principles which have been identified, and which may be applied to any other metal-assembled system, and secondly to examine briefly some of the properties of the resulting complexes to draw attention to the fact that the polynuclear complexes show significant differences from their related mononuclear siblings: the helicates are more than simple pretty structures.

The essentials of helicate architecture are summarised in Fig. 1. A ligand carrying more than one binding site is wrapped around an axis along which are disposed

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metal ions which hold the ligand in place. The helical axis may be linear, or in the circular helicates, a circle along which the metal ions are disposed regularly, forming a polygon. The ligands form the strands of the helix and systems are known with one to four strands. It is the free energy of complexation of the metal ions which drives the formation of the helicate. It was recognised quite quickly that the interplay of the nature of the ligand binding sites and the metal coordination preference could determine the number of strands of the resulting helicate. Thus the first helicates synthesised by Lehn and co-workers [3] used bidentate binding sites on the ligands which were assembled into double-stranded helicates around tetrahedral metal ions such as copper(I), with each strand supplying one bidentate unit. It seemed to us that such a ligand might give a triple-stranded helix if coordinated around an octahedral metal ion, and, indeed, reaction of ligand 1 with cobalt(II) gave the triple helical complex $[Co_2(1)_3]^{4+}$ (Fig. 2) [4]: the three strands supply the six atoms required for the octahedral complexation of the metal. This idea could readily (within the constraints of ligand synthesis) be extended to other metal coordination spheres: the lanthanide ions, which show higher coordination numbers, form triple helices with three strands carrying tridentate sites $[Ln_2(4)_3]^{6+}$ [5]. It is

also possible to generate heteronuclear species such as $[FeAg(5)_2]^{3+}$ in which the ligand supplies a bidentate site to one metal and a tridentate site to a second, different ion [6].

If helicate synthesis requires matching of metal coordination preference with denticity of the ligand, the other elements of the ligand sketched in Fig. 1 are also important. Thus the bridge should be sufficiently flexible or structured to allow the ligand to wrap around the helical axis, but not so flexible as to allow the different binding sites to complex the same metal: a ligand such as triethylenetetramine will favour a mononuclear complex over a dinuclear helicate. The ligands 6 and 7 differ only in the structure of the bridge: 6 is sufficiently curved to be able to twist around the helical axis to give triple-helical $[Fe_2(6)_3]^{4+}$ whereas in 7 the bidentate groups cannot wrap around a helix and a tetranuclear adamantane structure $[Fe_4(7)_6]^{8+}$ is formed instead [7]. Raymond has prepared a series of dicatecholate ligands with a variety of bridging groups in which the choice between cage and helicate may be rationalised in geometrical terms [8][9].

The ancillary group may also influence the formation of the helicate if the wrapping of the ligand around the axis produces interactions between groups. This can be used to tune the properties of the resulting complex: in the triple heli-

cate $[Co_2(1)_3]^{4+}$ the interactions between the methyl groups α to the pyridine units prevents close approach of the pyridines to the metal ion. As a consequence the cobalt(II) complex cannot be oxidised to the cobalt(III) complex in which the Co-N bond lengths are shorter [10], and the equivalent iron(II) complex is high spin [11]. If the methyl group is shifted from the α position as in ligand 2 the interligand repulsion is reduced and $[Co_2(2)_3]^{4+}$ is readily oxidised, while the iron(II) complex is low spin (at room temperature, *vide infra*). Repulsions involving

the ancillary groups offer a simple method to effect the stereoselective synthesis of helicates, as shown by the related family of ligands 8–11.

Ligand 8 is apparently a simple terdentate ligand, but with metals such as Cu^I and Ag^I, a double-helical complex $[M_2(8)_2]^{2+}$ is formed in which the metal is coordinated linearly by two benzimidazole groups from different ligands, the pyridyl moiety acting essentially as a non-coordinating bridge [12]. If the achiral benzimidazole group is replaced by a chiral oxazoline as in 9, stereospecific
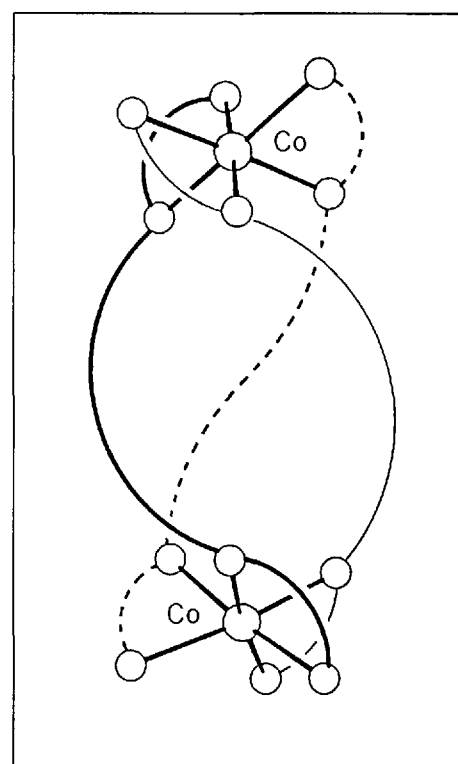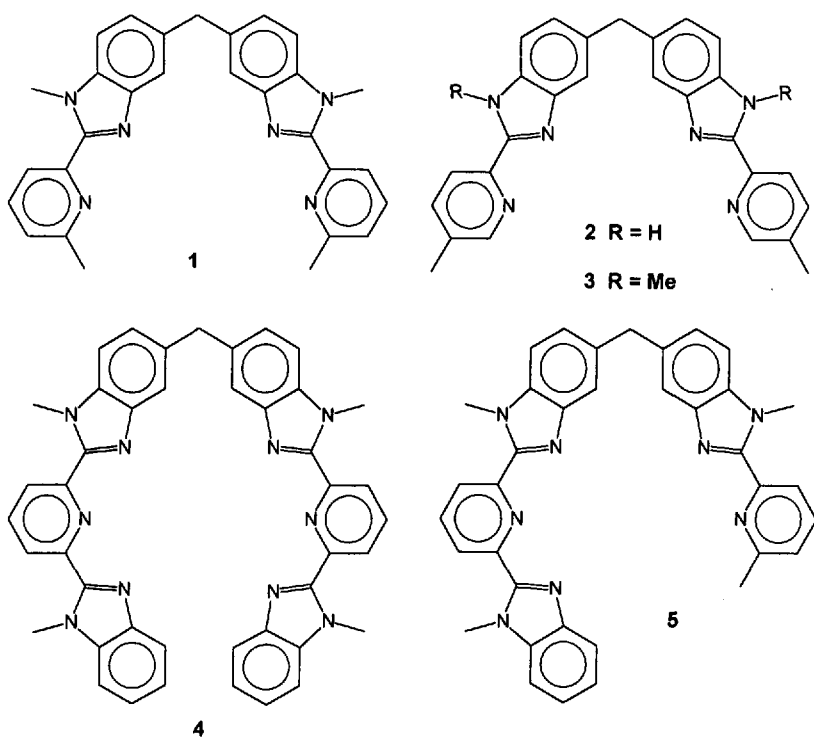

Fig. 2. Schematic drawing of the triple helicate $[Co_2(1)_3]^{4+}$.

1

2 R = H

3 R = Me

4

5

axis

metal ion → ← binding site

← bridge

← ancillary group

Fig.1. Structural elements of a helicate.

formation of the *P* helix (Fig. 3) is observed.[13] When we tested a ligand with the opposite chirality, 10, rather surprisingly the structure of the crystalline product showed it to be a circular helicate $[Ag_3(10)_3]^{3+}$ (Fig. 4). Careful NMR studies showed that a mixture of $[Ag_3(10)_3]^{3+}$ and $[Ag_2(10)_2]^{2+}$ was present in solution, and examination of the crystal structure suggested that $[Ag_3(10)_3]^{3+}$ might be stabilised by the stacking interaction between phenyl groups of two ligands with a pyridine of the third [14]. This hypothesis was tested with ligand 11 where the alkoxo substituent increases the electron density on the phenyl group. The trinuclear species was now formed virtually quantitatively even at low concentration, showing a rare example of attractive interligand interactions.

Let us now consider the properties of these polynuclear complexes. Since the formation of the helicates is driven by the free energy of coordination of the metal cation, the coordination sphere of the metal cannot be too greatly distorted from that found in related mononuclear complexes. The properties specific to the metal centre itself would not therefore be anticipated to be very different from mononuclear analogues, and this is generally the case. Such differences as arise will come from the polynuclear character of the helicates, and thus from the inter-
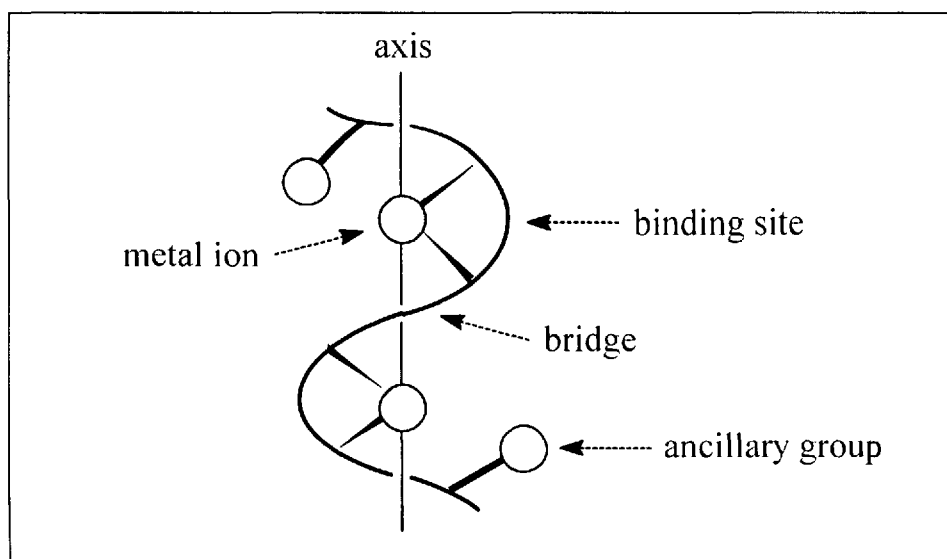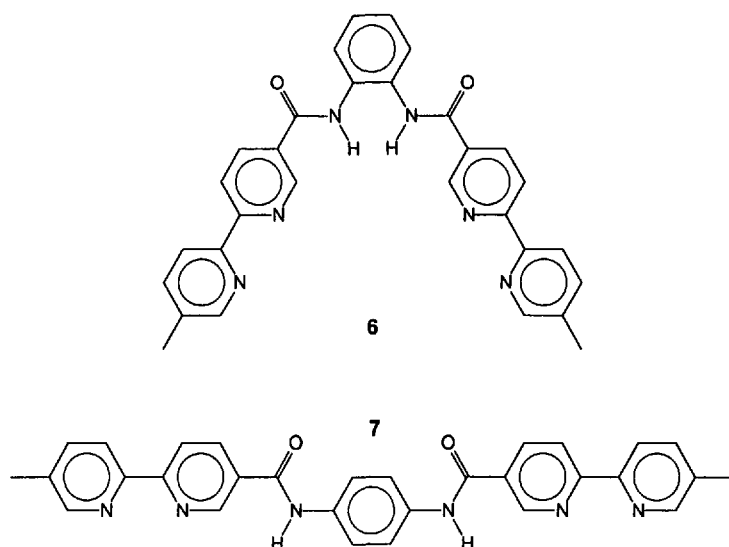
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Fig. 3. Molecular structure of P-[Ag₃(9)₂]²⁺. The two ligand strands are distinguished by filled and empty bonds.

actions between the different metal centres. Our work has concentrated on the triple helicates based on ligands such as 1–3. In these complexes the metals are separated by 8–9 Å and direct electronic interaction appears to be negligible, as shown for example by the strong localisation of the valence states in the mixed valence helicate $[Co_2(2)_3]^{5+}$ [11]. Energy transfer between lanthanide ions in mixed metal complexes such as $[EuTb(4)_3]^{6+}$ has however been observed [15]. If the electronic coupling is weak, the mechanical coupling through the relatively rigid bonds bridging the metal centres is strong, and this can produce significant differences in properties between helicates and related mononuclear systems.

The first difference we observed was in the stabilities of complexes such as $[Co_2(2)_3]^{4+}$; titration of the free ligand with cobalt ion showed complete and exclusive formation of the triple helicate, even at concentrations of the order of 10^{-5} M. Indeed the stabilities of the helicates are such that nature uses triple helical complexes such as rhodorotulic acid complexes for iron transport in certain

yeasts, and Raymond and co-workers studying iron transport published a triple helical structure some years before us – and before the term helicate had been coined [16][17].

The origin of this stability was something of a mystery until we investigated the kinetics of these systems. The enantiomers of kinetically inert $[Co_2(2)_3]^{6+}$ were resolved and showed chiroptical properties for the metal centres which were what one might expect for two non-interacting cobalt(III) centres [18]. Reduction of $(+)-[Co_2(2)_3]^{6+}$ to the cobalt(II) helicate was expected to give a labile species, but to our surprise, the half-life of racemization of the cobalt(II) helicate was about 13 hours at room temperature – about a million times slower than isomerization at an equivalent mononuclear cobalt(II) centre [19]. The explanation of this difference was established by electrospray mass spectrometry (ESMS): these triple helicates, by virtue of their stability, give very clean ESMS spectra, showing essentially only the molecular ion [20]. It is thus possible to distinguish the two complexes $[Co_2(2)_3]^{4+}$ and $[Co_2(3)_3]^{4+}$ which differ only by their mo-
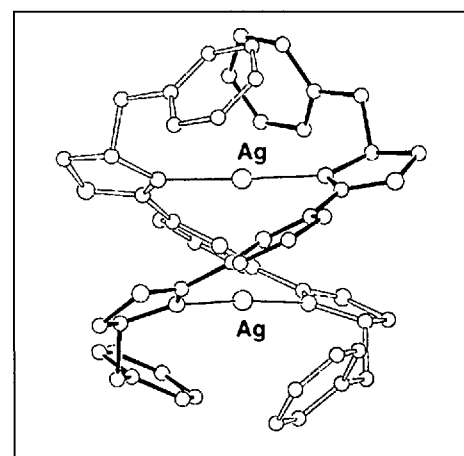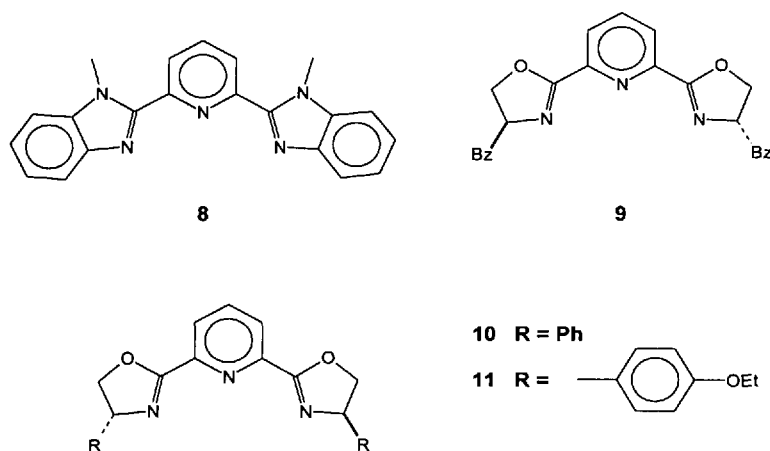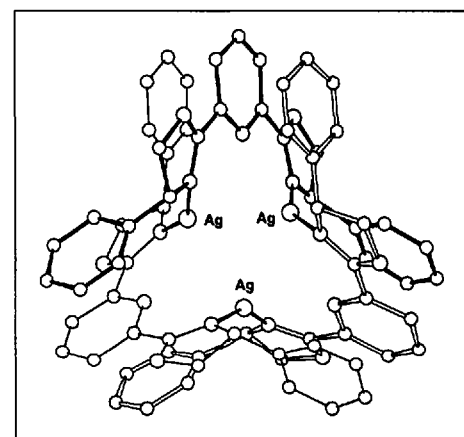

Fig. 4. Molecular structure of P-[Ag₃(10)₃]³⁺. The three ligand strands are distinguished by filled, empty and line bonds. The parallel stacking of the pyridine moiety with the phenyls of other ligands is clearly seen.
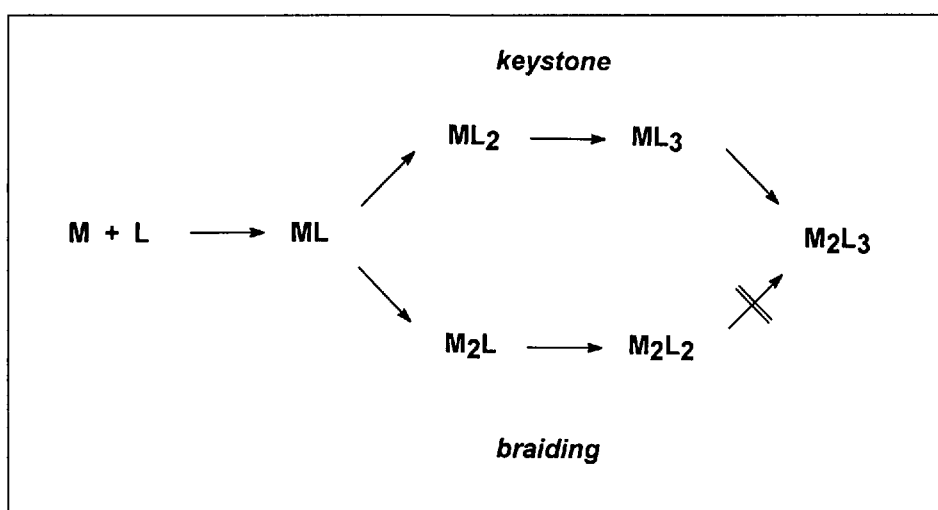
lecular weight (illustrating C.K. Jørgensen's maxim that the methyl group is the fourth isotope of hydrogen). A mixture of solutions of $[Co_2(2)_3]^{4+}$ and $[Co_2(3)_3]^{4+}$ followed by ESMS showed the gradual formation of $[Co_2(2)_x(3)_{3-x}]^{4+}$ species over a period of hours, confirming that ESMS may be used to follow the reaction. The crucial experiment was the reaction of $[Co_2(3)_3]^{4+}$ with an excess of free ligand 2. ESMS showed the rapid disappearance of $[Co_2(3)_3]^{4+}$ but the species which grew in fastest was $[Co_2(2)_3]^{4+}$, the mixed ligand complexes appearing only after some time. If we refer to the Scheme, the possible routes for complex formation are (1) the braiding mechanism, in which two metals bind initially to one ligand, followed by twisting a second and then a third ligand around the axis, and (2) the keystone mechanism in which three ligands are assembled around one metal, which is then capped by a second metal to form the final complex.

8

9

10 R = Ph

11 R = OEt

If we assume microscopic reversibility, then the ESMS results allow us to eliminate the braiding mechanism which would predict the successive replacement of strands, and consequently the early formation of mixed ligand species. The keystone mechanism is however in agreement with the results, since it predicts the initial liberation of Co from $[Co_2(3)_3]^{4+}$; the free Co is then trapped by free **2** as $[Co(2)_3]^{2+}$ which is converted in a second step to $[Co_2(2)_3]^{4+}$, as observed. The keystone mechanism explains the kinetic inertness of these complexes, since it is necessary to break all six bonds to one cobalt ion before it can dissociate, and the ligand strands are all held close to the metal by virtue of their complexation to the second metal. In a similar way to macrocycles, the helicates owe their stability to their slow dissociation kinetics.

The effects of the mechanical coupling of metal centres may also be seen in $[Fe_2(2)_3]^{4+}$ which shows spin crossover behaviour in solution. The related mononuclear complex $[Fe(12)_3]^{2+}$ shows a clean one step crossover from low spin to high spin with a transition temperature of 320 K.
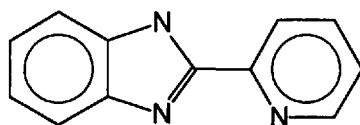
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The dinuclear complex $[Fe_2(2)_3]^{4+}$ also shows spin crossover in solution, but it is spread over a much greater temperature range [21]. It is not possible to fit the data with a one step model, but a two step model, supposing a mixed spin state, does fit the data satisfactorily, with two transition temperatures of 329 and 392 K. This implies a negatively cooperative interaction between the two metal centres, the switch to high spin at one centre stabilising the low spin form at the other. Contrary to solid state systems, the cooperativity here must arise from intramolecular rather than intermolecular forces, in a similar way to the transmission of allosteric effects in biological macromolecules. The helicates offer the chemist an interesting field to study mechanical effects at a molecular level. The investigation of the properties of these attractive and novel complexes is only just beginning.

Scheme. Mechanisms for formation and dissociation of triple helicates.

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