Assembly of Nano-Scale Circular Supramolecular Arrays through $\pi-\pi$ Aggregation of Arc-Shaped Helicate Units**

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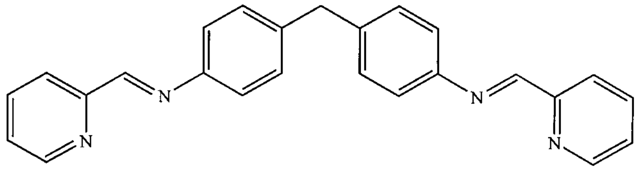
While not yet attaining the level of sophistication of biomolecular systems, the supramolecular synthetic approach is facilitating the construction of a wide-range of arrays of defined size and architecture whose scale is greater than that traditionally found in molecular chemistry.[1] In this context *metallo*-supramolecular chemistry has enjoyed considerable success and a variety of nano-scale arrays have been constructed.[2] The helical motif has provided an attractive forum for the development of design principles and discrete linear and circular helical systems have been designed.[3] Covalent construction of the ligands places a limit on the size of the arrays and pentanuclear linear helicates[4] (~2.5 nm length) and hexa- and octonuclear circular helicates[5] (2–3 nm diameter) represent the largest monodisperse helicate systems reported. Alternative synthetic approaches and construction principles are required to circumvent these covalent synthetic limitations. One possible approach to generate nano-scale structures is to develop routes to further aggregate small supramolecular units into larger arrays using a second supramolecular event.[6] To this end we have described the use of metal–ligand and $\pi-\pi$ interactions to achieve aggregation of metallo-supramolecular units into polymeric arrays.[6] Williams and co-workers[7] have also reported systems in which $\pi-\pi$ interactions link small helicate units into infinite linear chains in the solid state and Constable and co-workers[8] have reported $\pi-\pi$ helicate dimerization. However, exerting sufficient control over this aggregation to afford monodisperse aggregates rather than polymeric assemblies remains a challenge. We have recently developed imine-based ligand systems through which a variety of supramolecular architectures may be assembled.[9] The ease of synthesis of these ligand systems has allowed us to systematically probe the effects of modifications to the ligand backbone through which we are attempting to control the precise topography, or microarchitecture, of the arrays.[9b,c] While investigating this we have chanced upon a means by which helicate topography may be used to control the way that helicate units aggregate into larger discrete (rather than polymeric) arrays, and herein we describe this method.

We have shown that the reaction of ligand L with tetrahedral metal ions leads to a solution equilibrium of two dimeric isomers; a helicate (*rac* isomer) and a metallo-cyclophane (*meso* isomer).[9c] We reasoned that the inherent twisting in the ligand could be enhanced by switching from a 4,4′-diphenylmethane spacer to a 3,3′-diphenylmethane and that consequently this modification should favor the formation of the helical isomer.



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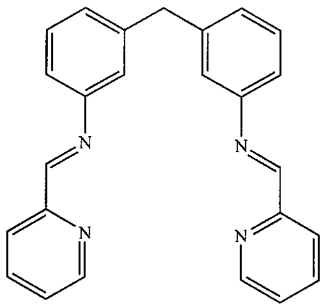

L_a

Ligand L_a was prepared in 89% yield by mixing two equivalents of 2-pyridinecarboxaldehyde and one equivalent of 3,3′-methylenedianiline in toluene with ground 3 Å molecular sieves. Ligand L_a can also be prepared by mixing ethanolic solutions of the two starting materials. Reaction of L_a with $[Cu(MeCN)_4]BF_4$ in methanol yielded a red solution from which a red solid precipitated on cooling. Mass spectrometry (FAB and ESI) is consistent with the formation of a dimeric species of formula $[Cu_2(L_a)_2](BF_4)_2$ which could correspond to either the *rac* or *meso* isomer. Partial microanalytical data is consistent with a formula $\{Cu(L_a)(BF_4)\}_n$ and the red color (arising from an metal to ligand charge transfer (MLCT) transition) is characteristic of copper(I) in a bispyridylimine environment ($\lambda = 507$ nm, $\varepsilon = 4000$ mol^{-1}dm^{3}cm^{-1}). The ^{1}H NMR spectra of the compound have been recorded in both CD_2Cl_2 and CD_3CN solution. In both these solvents, at room temperature, a single set of resonance signals is observed. In CD_2Cl_2 at low temperature (253 K), a second set of resonances is observed. The assignment of helix and cyclophane is readily made from the splitting pattern of the central methylene unit.[9c] The ratio of helix:cyclophane (*rac*:*meso*) is 9:1 indicating that the inherent ligand twisting has indeed favored the helical isomer. This ratio does not alter significantly when the temperature is lowered to 193 K.

Recrystallization of the compound from acetonitrile by diffusion of diethyl ether afforded crystals from which we confirmed the molecular structure by X-ray crystallography.[10] The structure reveals a $[Cu_2(L_a)_2]^{2+}$ helical cation (Figure 1).

Each copper(I) center occupies a four-coordinate pseudo-tetrahedral environment bound to two pyridylimine units, one

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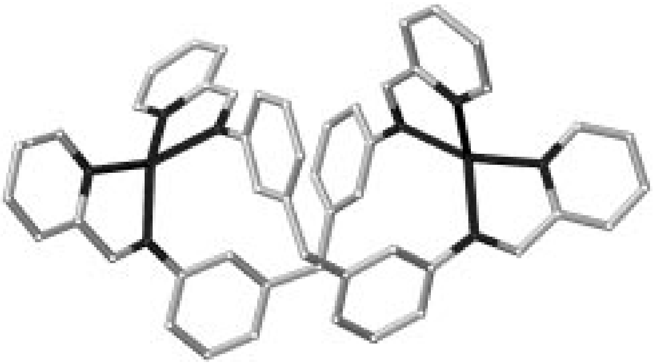

Figure 1. View of the cation $[Cu_2(\mathbf{L_a})_2]^{2+}$, the copper coordination sphere is shown in black.

from each ligand. However, the 1,3 link in the spacer means that the ligands are unable to wrap precisely about the M–M axis and consequently a "bowed" (arc-shaped) helical conformation is adopted. Arc-shaped covalently prepared building blocks containing two hydrogen-bonding units have been described by Lehn and co-workers[11a] and Whitesides et al.[11b] and aggregate into cyclic supramolecular arrays. The arc-shaped topography has similar consequences for the solid-state aggregation of our helicates: in contrast to conventional linear helicates the arc-shaped helicates aggregate to form a cyclic array of four metallo-supramolecular units held together by π–π interactions[12] (Figure 2). The diameter of the circular aggregate is ~2.5 nm (C–C; ~2.7 nm H–H) and four BF_4 counter anions are located in the internal cavity.[13] The chirality of each helicate alternates around the circle so that the overall structure is achiral. The nano-scale structure nevertheless bears a striking resemblance to the circular helical arrays recently reported,[5] but it is achieved without the need for extensive covalent ligand synthesis.

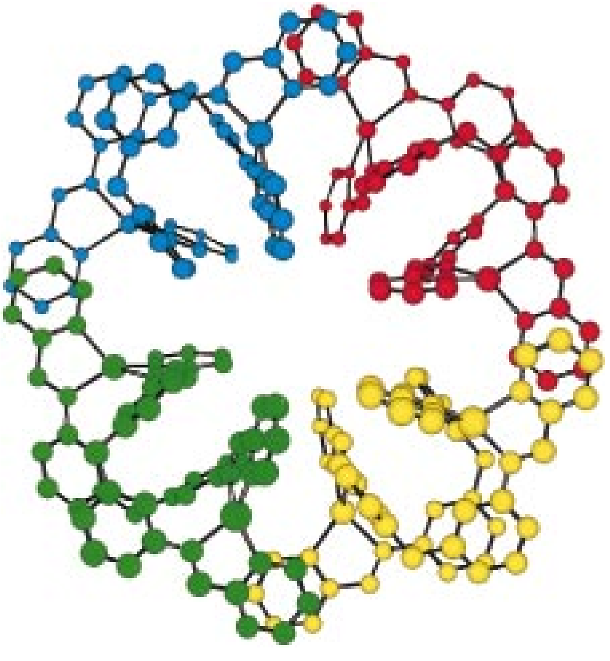

Figure 2. The cyclic array resulting from the aggregation of four $[Cu_2(L_a)_2]^{2+}$ helicates; each helicate is shown in a different color.

While these circular aggregates form in the solid state, the weak nature of the non-covalent π–π interactions means that they lack the solution robustness of the circular helicates. Nevertheless, since weak, non-covalent interactions are capable of achieving order at surfaces and interfaces this does not necessarily provide a barrier to application or manipulation of the nanostructures. Extension of this topographical encoding approach to solution will require use of stronger non-covalent interactions (e.g. π-electron rich and deficient systems or multiple hydrogen bonds).

We have shown that by introducing curvature into the topography of the basic supramolecular unit, the aggregation into a larger discrete (rather than polymeric) array may be achieved. This result coupled with the ease of synthesis of the pyridylimine systems means that with judicious design quite large metallo-supramolecular nanostructures may be prepared rapidly from commercial materials.

Experimental Section

L_a: Ground 3 Å dried molecular sieves (5 g) and 3,3′-methylenedianiline (0.193 g, 0.975 mmol) were added to toluene (30 cm³) and stirred under a nitrogen atmosphere. 2-pyridinecarboxaldehyde (0.186 cm³, 1.947 mmol) was added and the mixture stirred at room temperature for 24 hours. The molecular sieves were removed by filtration and the filtrate concentrated by rotary evaporation to produce a yellow oil (0.326 g, 89%). ^1H NMR ($CDCl_3$): $\delta = 8.69$ (d, $J = 5.0$ Hz, 1H; H_6), 8.57 (s, 1H; H_{imine}), 8.18 (d, $J = 7.9$ Hz, 1H; H_3), 7.80 (td, $J = 7.4$, 1.5 Hz, 1H; H_4), 7.35 (m, 2H; H_5, H_{Ph5}), 7.15 (m, 3H; H_{Ph2}, H_{Ph6}, H_{Ph4}), 3.97 (s, 1H; CH_2); MS (EI): m/z: 376 [M^+]; elemental analysis calcd. (%) for $C_{25}H_{20}N_4$: C 79.8, H 5.4, N 14.9; found: C 79.1, H 5.3, N 14.8.

$[Cu_2(L_a)_2](BF_4)_2$: Ligand L_a (0.107 g, 0.284 mmol) and $[Cu(MeCN)_4](BF_4)$ (0.089 g, 0.284 mmol) were heated under reflux in methanol overnight. The solution was cooled to room temperature and treated with methanolic NH_4BF_4 (excess). On standing, a dark red solid precipitated and was collected by filtration and dried with diethyl ether (0.248 g, 83%). ^1H NMR (CD_2Cl_2, 298 K): $\delta = 9.02$ (s, 1H; H_{imine}), 8.29 (d, $J = 4.3$ Hz, 1H; H_6), 8.14, (d, $J = 7.5$ Hz, 1H; H_3), 8.13 (d, $J = 7.7$, 1.5 Hz, 1H; H_4), 7.52 (m, 2H; H_5, $H_{Ph4/Ph6}$), 7.11 (t, $J = 7.6$ Hz, 1H; H_{Ph5}), 6.78 (d, $J = 7.6$ Hz, 1H; $H_{Ph4/Ph6}$), 6.47 (s, 1H; H_{Ph2}), 3.49 (s, 1H; CH_2); MS (ESI): m/z: 967 $\{Cu_2(L_a)_2(BF_4)\}^+$, 440 $\{Cu_2(L_a)_2\}^{2+}$; MS (FAB): m/z: 967 $\{Cu_2(L_a)_2(BF_4)\}^+$ and 880 $\{Cu_2(L_a)_2\}^+$; elemental analysis calcd (%) for $Cu_2C_{50}H_{40}N_8B_2F_8 \cdot 2.5\,H_2O$: C 54.7, H 4.1, N 10.2; found: C 54.7, H 3.7, N 10.0; UV/Vis: λ_{max} [nm] (ε/mol^{-1} dm^3 cm^{-1}) 507 (4000), 310 (31300), 240 (31000).

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[10] a) Crystal structure data for $C_{50}H_{40}N_8Cu_2B_2F_8 \cdot C_2H_3N$, $M_r = 1094.65$, red plates, dimensions = 0.6 × 0.4 × 0.3 mm, triclinic, space group $P\bar{1}$, $a = 16.826(3)$, $b = 17.931(2)$, $c = 18.402(3)$ Å, $\alpha = 106.351$, $\beta = 103.046(5)$, $\gamma = 102.983(5)^\circ$, $V = 4937.2(11)$ Å^3, $T = 180(2)$ K, $\lambda = 0.71073$, $Z = 4$, $\rho_{calcd} = 1.473$ Mg m^{-3}, $F(000) = 2232$, $\mu(Mo_{K\alpha}) = 0.939$ mm^{-1}. Data collected with a Siemens SMART three-circle system with CCD area detector. The crystal was held at 180(2) K with an Oxford Cryosystem Cryostream Cooler; $\theta_{max} = 29.16^\circ$. A total of 31991 reflections were measured, 22935 unique ($R_{int} = 0.0359$). Absorption correction by Psi-scan. Weighting Scheme $w = 1/(\sigma(F_0^2) + (0.0383P)^2)$, where $P = (F_0^2 + 2F_c^2)/3$. GoF on F^2 was 0.890, $R1$ (for 10956 reflections with $I > 2\sigma(I)) = 0.0537$, $wR2 = 0.1324$. Data/restraints/parameters 22935/0/1317. Largest difference Fourier peak and hole 0.907 and −0.842 e Å^{-3}. Refinement used SHELXL 97 (G. M. Sheldrick, **1997**). b) Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-146854. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB21EZ, UK (fax: (+44) 1223-336-033; e-mail: deposit@ccdc.cam.ac.uk).

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[12] Centroid–centroid distances of 3.84 and 4.18 Å. Shortest C–centroid distance = 3.88 Å. Shortest C–C distance = 3.53 Å.

[13] The aggregation of arc-shaped units could potentially lead to either a closed cyclic array or an infinite undulating tape structure (see ref. [11]). The ability of the cyclic array to encapsulate the anions may provide a driving force for its formation. Anion encapsulation in the formation of circular helicates is believed to be important (see ref. [5]).

A Dendritic Structure Containing a Designed Cleft which Controls Ligand Coordination Behavior in an Analogous Way to Proteins[**]

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Nature uses metal–ion coordination complexes to undertake many tasks. Frequently it imparts function by modifying the conventional behavior of a metal complex by incorporation within a protein superstructure.[1] For example, by isolating heme groups in the center of globular proteins oxidative dimerization is prevented and *reversible* oxygen binding is achieved. Steric isolation owes much to the dimensions of such globular proteins which are much larger than the small molecules prepared by synthetic chemists. Dendrimers represent a class of monodisperse synthetic macromolecules[2] which approach the dimensions of proteins and have been proposed as potential protein and enzyme mimics.[3] For example, porphyrins have been encapsulated at the center of spherical organic dendrimers to create compounds analogous to globular electron-transfer proteins[4] and then used as oxidation catalysts.[5]

However, in nature, coordination sites are often not completely encapsulated in the core of a protein. For example, in carbonic anhydrase (CA) the N_3 zinc(II)-coordination site is situated at the foot of a cleft accessible to the solvent. The essentially hydrophobic protein cleft plays an important role in the catalytic cycle, by binding the substrate, creating a hydrogen-bonded solvent network to facilitate proton transfer, and expelling the hydrophilic product.[6] Equally importantly this cleft modifies and controls the chemistry of the coordination site. Investigations of zinc(II) species with tripodal N_3 ligands (L) reveal a strong tendency to form $[ZnL_2]^{2+}$ complexes or hydroxy-bridged dimers.[7, 8] In the enzyme the protein cavity sterically prevents the formation of these species and discrete mononuclear 1:1 complexes $[ZnL(OH)]^+$ and $[ZnL(OH_2)]^{2+}$ result. We were interested to see if we could imitate this natural approach to modify and control the behavior of a transition metal complex. Rather than simply isolating a complex within a globular dendritic structure we have focused on the design of systems in which a dendritic unit could be used to generate a cavity around a metal complex.

We reasoned that blocking one direction of "growth" of a dendrimer would lead to a large cleft in the structure around the site of the "blockage". If the metal binding site forms the blocking group, or is attached to it, then at high generation

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