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<td><strong>Complete List of Authors:</strong></td>
<td>Hardie, M; University of Leeds, School of Chemistry</td>
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<td>Henkelis, James; University of Leeds, School of Chemistry</td>
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Tuning the coordination chemistry of cyclotraveratrylene ligand pairs through alkyl chain aggregation†

James J. Henkelis and Michaele J. Hardie*

Propylated cyclotraveratrylene (CTV) ligands display different coordination chemistry over their methylated congeners as a result of increased solubility, an affinity for alkyl chain aggregation and steric factors. The propylated ligand tris(isonicotinoyl)-tris(propoxy)cyclotravechylene (L1p) forms a 1D coordination polymer within complex [{Ag(L1p)[Co(C2B9H11)2][DMF]}∞ (complex 1p), and a 2D sheet of 4·8 topology in [{Cd(L1p)(ONO2)2(H2O)·(DMF)·0.5(Et2O)}∞ (complex 2p), neither of which are formed with the analogous methylated ligand tris(isonicotinoyl)-cyclotriguaiacylene (L1m). Both complexes 1p and 2p display multiple sites of aggregation of hydrophobic groups. The new propylated ligand tris(2-quinolylmethyl)-tris(propoxy)cyclotravechylene (L2p) forms a 1D coordination polymer with Ag(I) in complex [{Ag4(L2p)2}[Co(C2B9H11)2]·1.5(MeNO2)}∞ (complex 3p) and a novel, compressed octahedral structure with palladium(II) cations, [Pd6(L2p)3(CF3CO2)12] (complex 4p). Neither complex was accessible with the methylated congener tris(2-quinolylmethyl)-cyclotriguaiacylene (L2m).

1. Introduction

The ability of suitably pre-functionalised building blocks to recognise each other in solution and spontaneously self-assemble to form a complex is well understood.1,2 Discrete coordination cages and infinite coordination networks of increasing complexity have been prepared utilising the self-assembly of multifunctional ligands and metal cations,3-5 and their applications range from catalysis6-10 to sophisticated guest incarceration.11-13

The study of sterically and interactionally similar ligand sets has garnered much interest due to their ability to selectively form homo- and heteroleptic complexes, allowing the formation of structures ordinarily inaccessible with a single ligand system.14-16 This phenomenon relies on a sliding scale of kinetic stability, whereby the dynamic nature of the coordination bond can be either exploited to lend aigual exchange, or relied upon for kinetic stability.17 The tailoring of organic ligands and assembly conditions allows the chemist to exercise a degree of control over their self-assembly.18-19 Fujita and co-workers, for example, have demonstrated an intricate system where small alterations to bridging ligand bite angle are enough to effect a large structural change between M12L24 and M24L18 polyhedra.20 Likewise, the groups of Stang and Yamaguchi have shown how multi-ligand systems can undergo reversible exchange at room temperature to afford a variety of products.21-23

Alternatively, Ward and co-workers have shown how a sterically and interactionally similar ligand pair of multidentate pyridine-pyrazole ligands can each self-assemble into a tetrahedral complex when a templating tetrahedral anion is used;24 yet heteroleptic complexes are formed when largely different ligand systems are employed in direct competition. London dispersion forces represent the weakest van der Waals interactions between molecules25,26 and, whilst they are ubiquitous in nature, they are generally overlooked with respect to metallo-supramolecular chemistry due to the higher comparative strength of ion-ion and ion-dipole interactions.27,29 Such dispersive interactions are usually exhibited as part of the hydrophobic effect,30-32 which helps describe how and why proteins fold, alongside the mechanics of membranes.32,33 Their contribution to self-assembly can be significant, however, and Cockroft and co-workers have presented experimental measurements describing how cohesive solvent interactions, otherwise known as solvophobic effects, play a strong and dominant role in driving the reorganisation and aggregation of apolar surfaces in solution.34

Our research concerns derivatives of the relatively rigid and macrocyclic cavatind, cyclotraveratrylene (CTV). Its open upper rim allows for facile functionalisation, whereby donor moieties may be appended to afford ligands. Tripodal derivatives such as those shown in Scheme 1 are chiral.
The self-assembly of derivatised CTVs with metal cations is well established, and coordination polymers,\textsuperscript{34-36} discrete metallo-cages,\textsuperscript{37-42} and mechanically interlocked architectures\textsuperscript{43-45} are known. However, the chemistry of mixed ligand systems is generally limited to the solution-phase, and we have recently demonstrated how the formation and manipulation of homo- and heteroleptic [Pd4L4]\textsuperscript{2+} octahedral cages can be controlled with high fidelity.\textsuperscript{46} These represent examples in which both ligands are suitably pre-designed to undergo metal-mediated self-assembly to afford structurally analogous complexes.

Herein we report a study of two interactionally and sterically similar ligand pairs which do not self-assemble to form identical complexes, and instead show dissimilar coordination chemistry which is driven, in part, by aggregation effects.

2 Results and discussion

Ligands (±)-tris(isonicotinoyl)-cyclotriguaiacylene (L1m), (±)-tris(isonicotinoyl)-tris(propoxy)-cyclotricatechylene (L1p) and (±)-tris(2-quinolymethyl)-cyclotriguaiacylene (L2m) were prepared according to literature procedures.\textsuperscript{47-50} The previously unreported ligand (±)-tris(2-quinolymethyl)-tris(propoxy)-cyclotricatechylene (L2p) was prepared through reaction of propylated-cyclotriguaiacylene (p-CTG)\textsuperscript{46} with 2-chloromethylquinoline in basic acetonitrile (MeCN), using an adapted version of a previously reported procedure, and isolated as a racemic mixture in high yields.\textsuperscript{47} Ligands L1m, L1p, L2m and L2p were employed as racemic mixtures for all coordination studies and their molecular structures can be seen in Scheme 1. Whilst individual ligand pairs are essentially isosstructural and differ only by the length of ortho-alkoxy substituents, we postulate that their dissimilar coordination chemistry may be attributable, in part, to aggregation effects present in the complexes of the longer-chained ligands.

2.1 Aggregation as a directing interaction

In our hands ligands crystalline complexes of L1m or L1p and silver(I) cations were only isolated with the bulky cobalt(III) bis(dicarbollide) counter-anion, [Co(C2B9H11)2]. This bulky and weakly coordinating anion may have a structure-directing effect on coordination polymer formation,\textsuperscript{51,52} and we have previously reported that methylated ligand L1m forms an intertwined 1D polymeric structure when crystallized with Ag[Co(C2B9H11)2] from an acetonitrile (MeCN) solution, {[Ag(L1m)]2[Co(C2B9H11)2]·6(MeCN)}\textsubscript{∞}, complex 1m, Figure 1b.\textsuperscript{48} Propylated ligand L1p, under similar conditions, affords a different 1D polymer whose formation may be facilitated by aggregation of propyl moieties. Such aggregation was also evident in the previously reported crystal structure of ligand L1p, whereby six individual ligands were observed to pack to create a highly hydrophobic pocket that is filled with six, inwardly-orientated propyl chains, Figure 1a.\textsuperscript{46}

The stoichiometric reaction of propylated ligand L1p and Ag[Co(C2B9H11)2] in N,N'-dimethylformamide (DMF) afforded complex {[Ag(L1p)[Co(C2B9H11)2]]·2.5(DMF)·(H2O)}\textsubscript{∞}, 1p, which features a 1-D coordination polymer. Single crystals were grown by diffusing diethyl-ether vapours into the DMF solution and the structure was elucidated using synchrotron radiation. The structure was solved in the triclinic space group P-1 to display the asymmetric unit contents as a molecule of both ligand L1p and [Co(C2B9H11)2], each coordinated to a silver(I) centre, alongside solvent molecules. Host-guest interactions are present between a DMF molecule and ligand L1p, where the solvent molecule is non-covalently bound by the hydrophobic cavity of the host ligand. Analogous host-guest behaviour was reported for complex 1m with acetonitrile solvent.\textsuperscript{48}

In complex 1p, individual L1p ligands coordinate to three symmetry-equivalent silver(I) centres, all of which are of distorted tetrahedral geometry, and the [Co(C2B9H11)2] anion coordinates to the metal centre through a hydridic interaction. Pyridyl N-ag and (B)H-Ag bond lengths were measured at 2.264(4), 2.280(4) and 2.176 Å, respectively, alongside N-Ag-N bond angles of 127.48(14), 101.76(14) and 97.97(13) °. This is contrasting behaviour to that observed for complex 1m, where silver(I) centres were coordinated by four pyridyl donors and the [Co(C2B9H11)2] anion remained uncoordinated, Figure 1b.\textsuperscript{48} Symmetry expansion of complex 1p gives rise to a 1-D ladder-type motif, whereby L1p ligands are all inwardly orientated to afford a quasi-cylindrical arrangement of head-to-head ligands. Individual ligands are of the same enantiomer, rendering each 1D polymer homochiral. The inwardly orientated ligand arrangement gives rise to small pockets of space which are filled with solvent of crystallization. In comparison to individual coordination polymers of complex 1m, individual L1m ligands are only 2-coordinate and the third ligand arm acts to interdigitate neighbouring 1D chains to afford the extended, intertwined structure, Figure 1b.\textsuperscript{48}

The individual 1D ‘cylinders’ of complex 1p again exhibit aggregation of propyl chains, where the inwardly orientated propyl moieties aggregate across the polymer akin to the rungs of a ladder. Such interactions act to sculpt the shape of individual 1D polymers and, alongside the coordinating [Co(C2B9H11)2] anion, drive the expansion of the 1D polymer from 2-connected, as seen for complex 1m, to 3-connected, Figure 1c.\textsuperscript{48} There is no evidence for further
intermolecular interactions between individual 1D polymers. In a similar manner to complex 1m, the extended structure of complex 1p features back-to-back π-stacking of 1Lp ligands, of a neighbouring 1D chains, and displays aromatic centroid separations of 3.856 Å. The result is a densely packed extended lattice with solvent DMF in the interstitial sites. The composition of complex 1p was confirmed with IR spectroscopy and combustion analysis.

The stoichiometric reaction of 1Lp and Cd(NO₃)₂ in DMF, and subsequent diffusion of diethyl-ether vapours into the reaction mixture, resulted in the formation of complex [Cd(L1p)(ONO₂₂H₂O)](DMF)·0.5(Et₂O). Complex 2p features a 2D network, and aggregation of the hydrophobic groups is again apparent in the structure. The crystal structure was solved in the monoclinic space group C2/c, and the asymmetric unit was a molecule of 1Lp, coordinating a cadmium(II) centre with two chelating nitrates and one molecule of coordinated water, alongside a molecule of solvent DMF and half a molecule of diethyl-ether. The structure showed considerable disorder which is described in Supplementary Information, and only one of the disordered positions is depicted in Figure 2 for the sake of clarity. Each 1Lp ligand coordinates the Cd(II) centre with N₂Cd bond lengths between 2.335(8) and 2.456(12) Å. The Cd(II) centre has octahedral geometry and is facially coordinated by 1Lp ligands, with nitrate anions coordinating in a monodentate manner at O-Cd bond lengths of 2.315(7) and 2.343(9) Å. In addition, and similarly to complexes 1m and 1p, above, host-guest interactions are present between the electron rich CTV core and a DMF molecule, whereby the non-polar N-methyl moiety is directed towards the centre of the cavity host.

Akin to complex 1p, the complex also features aggregation of hydrophobic 1Lp propyl chains. The cis-coordinated 1Lp ligands are orientated in a head-to-head manner, affording an off-set, cylindrical arrangement, where opposing ligands are opposite enantiomers and thus the network is a racemate. Any resultant free space is filled with diethyl-ether and DMF solvent. This cylindrical motif gives rise to 4-gons within the resultant 2D net, which are extended 2-dimensionally through coordination of the third independent 1Lp ligand about the fac-Cd(II) centre. Thus, the network comprises a series of linked 4- and 8-gons to afford a 4-8² topology, where both ligand and metal centres represent 3-connected
nodes. The formation of these 2D sheets is facilitated through intermolecular interactions, whereby the methylene protons of the cyclononatriene core hydrogen bond to the electron rich upper rim of the CTG core, displaying C-H···O separations of 3.105 and 3.185 Å. In addition, the core aromatics of the [a,d,g]cyclononatriene scaffold highlight π-π interactions with neighbouring pyridyl functions and display off-set centroid separations of 3.741 Å. Individual 2D sheets close-pack, in the absence of intermolecular interactions, to construct the extended network. The proposed network composition was fully concordant with elemental analysis and IR spectroscopy.

![Image](313x310 to 563x440)

**Fig. 2** From the crystal structure of complex 2p. (a) As viewed down the crystallographic b axis, depicting the inwardly orientated head-to-head orientation of individual L1p ligands giving rise to aggregation of the hydrophobic propyl chains across each 2D sheet. Propyl chains displayed in green and all solvent molecules are omitted for clarity; (b) the simplified connectivity diagram, where the blue and pink spheres are metal and ligand, respectively. The resultant 4- and 8-gons giving rise to the overall 4 Pt network topology. Only one ligand disorder position is shown for clarity.

An analogous complex to 2p but with ligand L1m in place of L1p was not formed. In fact, we did not isolate any cadmium(II) complexes of L2m. This may be solubility driven, whereby the added solubility of L1p ligands facilitate the self-assembly in solution and prevents random oligomerisation of the starting components. A further factor may be the large van der Waals interactive surface that is present between individual L1p ligands. Such interactions, observed for both complex 1p and 2p, are in keeping with the results of Cockroft and co-workers, confirming the driving force for alkyl-alkyl interactions based on the solvophobic effect.  

### 2.2 The role of solubility and steric

We have previously reported that tris-(2-quinolylmethyl)cyclotriguaiacylene L2m forms an unusual twisted tetrahedral structure with silver(I) cations, [Ag₂(L2m)]₄·4(BF₄), complex 3m, Figure 3. Complex 3m is close-packed and displays a hydrophobic core with four inwardly pointing methyl moieties in close proximity to one another. Despite our best efforts, metallo-supramolecular constructs were not identified to form from L2m with other transition metals. Whilst methylated ligand L2m forms a discrete, tetrameric cube with Ag(I) cations, reactions of the propylated congener L2p under the same conditions did not. This is as expected, however, due to the larger propyl groups not being able to be accommodated within the close-packed core of the Ag₄L₄ tetrahedron. A complex was formed from the propylated ligand and Ag(I), however, with the stoichiometric reaction of L2p and Ag[Co(C₂B₅H₁₁)₂] resulting in the formation of a 1D coordination polymer, [Ag Ag(L2p)Co(C₂B₅H₁₁)₂·1.5(MeNO₂)]ₐ, complex 3p. Crystals were obtained from a nitromethane (MeNO₂) solution and were small, twinned and weakly diffracting; nevertheless, a data collection was made using synchrotron radiation and the structure solved in the monoclinic space group P2₁/c.

![Image](563x661)

**Fig. 3** Crystal structure of the previously reported complex [Ag₂(L2m)]₄·3m. (a) Highlighting the twisted tetrahedral core, and (b) space-filling diagram displaying the resultant cube-like appearance.  

The asymmetric unit contains two molecules of ligand L2p, two Ag(I) cations, and two [Co(C₂B₅H₁₁)₂]⁻ counter anions, alongside nitromethane solvent. The 1D coordination polymer formed is a racemate and features the inclusion of both enantiomers of L2p ligands per 1D chain, Figure 4. Ligands have approximate C₃-symmetry and coordinate two Ag(I) cations, with one ligand arm remaining uncoordinated, akin to complex 3m. Each Ag(I) cation is approximately linear and is coordinated by two independent L2p ligands, with N-Ag bond lengths and N-Ag-N angles of 2.189(7)-2.197(7) Å and 174.3(3) and 176.2(3) °, respectively. There is some bonding contribution from a proximal etheral oxygen, with O···Ag separation of 2.513(7) Å. In a similar manner to complex 3m, this system also displays host-guest interactions between quinolyl arm and the shallow hydrophobic cavity of the ligand core; however, in this instance the interaction is not reciprocal.
and instead is unidirectional along the length of each 1D chain, Figure 4b.

![Figure 4](image)

**Figure 4** From the crystal structure of complex 3p. (a) Displaying an individual ([Ag(L1p)])∞ 1D polymer unit; (b) Intra-polymer Quinolyl-CTG aromatic interactions that are present along the length of individual 1D chains. Independent ligands are colour-coded for clarity; (c) Interstrand aggregation of propyl chains across neighbouring 1D polymers. Individual 1D chains are colour coded, propyl moieties are shown in green and anions and solvent are omitted for clarity.

This interaction is further stabilised by π···π interactions between the quinolyl moiety and [a,d,g]cyclononatriene core, with centroid separation of 3.809 Å, Figure 4. Neighbouring 1D chains aggregate through π···π interactions, with aromatic centroid separations of 3.687 Å, and aggregation of propyl moieties which affords small pockets that are filled with disordered solvent and [Co(CF3C6H4)Cl]2 anions, Figure 4c. Whilst there are similarities to be noted, such as host-guest interactions and complex stoichiometry, it is ultimately the presence of sterically demanding propyl chains that renders the formation of the M3L4 tetramer seen with ligand L2m improbable.

Comparatively, methylated ligand L2m was not seen to form coordination complexes with palladium(II) salts, whereas its more soluble propylated congener resulted in the formation of an unusual, compressed [Pd4(L2p)6(CF3CO2)12] cyclic assembly with dimensions that are similar to the 2D clathrates of CTV. The reaction of two equivalents of propylated L2p with three equivalents of Pd(CF3CO2)2 in an acetonitrile, nitromethane and water solvent mixture gave a discrete, hexanuclear complex [Pd4(L2p)6(CF3CO2)12] (Et2O) 4p on diffusion of diethyl-ether anti-solvent. Once formed, the complex was highly insoluble in most common solvents and was isolated as an inhomogeneous, amorphous/crystalline yellow solid. Suitable single crystals were isolated from the bulk product and were small and weakly diffracting; nevertheless, a solution was obtained in the monoclinic space group C2/c. The asymmetric unit comprises half the overall complex and features two crystallographically distinct L2p ligands, three inequivalent palladium(II) centres and six coordinating trifluoroacetate anions, alongside half a molecule of diethyl-ether. The two ligands in the asymmetric unit are of the opposite enantiomer to each other which results in a meso-complex, akin to complex 3m.

Pd(II) centres are square planar and are exclusively trans coordinated by the quinolyl donors and display Pd-N bond lengths in the range 2.051(6)-2.070(7) Å and N-Pd-N angles of 176.3(3), 177.2(3) and 177.5(4)°. Two trifluoroacetate anions coordinate each palladium(II) centre to render the overall complex charge-neutral and display Pd-O bond lengths ranging 1.971(7)-2.060(9) Å, and O-Pd-O angles of 172.5(3), 175.0(3) and 176.5(3)°, Figure 5. Interestingly, the use of trifluoroacetate anion was integral to complex formation and the complex did not form with other coordinating anions, such as nitrate or acetate.

Complex 4p is centrosymmetric and displays both host-guest and π-π interactions, but has no internal space, Figure 5. Two sets of off-set, clathrate-type, bowl-in-bowl L2p stacking pairs are observed within the complex, where the methylene protons of the [a,d,g]cyclononatriene core are directed towards the hydrophobic bowl of the underside of a ligand forming C-H···π interactions at 2.54 Å, akin to the stacking arrangement found in β-phase clathrates of CTV. The host-guest interactions displayed in complex 4p are opposite to those found in complex 3m, which highlighted a propensity for the quinolyl arm to interact with the [a,d,g]cyclononatriene core. However, whilst the modes of intramolecular interaction may differ, the result in each case is a tetrameric meso-complex that exists as a racemic dimer of dimers.

Each L2p ligand binds to three Pd(II) centres, and the two symmetry related quinolyl groups in the centre of the [Pd4(L2p)6(CF3CO2)12] assembly form phenyl···pyridyl, face-to-face, π-π stacking interactions at a ring centroid separation of 3.75 Å. This is again converse to the coordination stoichiometry found in complex 3m, where only two ligand arms coordinated the metal centres.

Van der Waals dispersion interactions are again present between neighbouring propyl chains, yet to a much lesser extent than for complexes constructed from ligand L1p. This is perhaps due to the numerous aromatic interactions afforded through the quinolyl moieties.
There are two Pd(II) coordination modes within the complex. For two symmetry related Pd(II) cations, the trans quinolyl ligands are not mutually co-planar and are arranged such that their phenyl rings are trans to one another. The other four Pd(II) ions each have a co-planar arrangement of the two coordinating quinolyl moieties, which display mirror-like symmetry and hence a cis arrangement of the phenyl groups. Previously reported examples of M₆L₄ metallo-supramolecular assemblies are Fujita’s [Pd₆(en)L₄]¹²⁺ cages, where en = ethylenediamine,⁵⁴ or variants.⁵⁵,⁵⁶ In these, the metal centres are arranged in an octahedron with flat tripodal ligands, such as tris(4-pyridyl)triazine, bridging between them. The ligands are arranged cis to one another and occupy half of the octahedral faces through vertex sharing, shown in cartoon form in Figure 6a.

Complex 4p can also be understood in terms of an octahedron with half the faces taken up by the tripodal ligand, however the octahedron is significantly compressed, and the ligands are both vertex and edge-sharing, Figure 6b. This is not the first CTV-derived complex that is built on an octahedral framework and we have previously reported the elucidation and solution-phase behavior of a family of [Pd₆L₈]¹²⁺ octomeric assemblies with 4-pyridyl-derived ligands.⁵⁹,⁶⁰

The extended lattice of complex 4p possesses two sites of void space which contain disordered lattice solvent, comprising a head-to-head arrangement of ligands between neighbouring complexes and large, unidirectional channels that run down the crystallographic c-axis (Figure 7). The insolubility of complex 4p meant that its solution-phase behaviour could not be probed. ESI-MS analyses were conducted in DMSO but no peaks corresponding to the complex were observed and it is likely that it undergoes a coordination-induced disassembly.

It is interesting to note that all attempts to form the analogous Pd₆L₄ assembly with methylated ligand L₂m were unsuccessful. Equally, the analogous Ag₆(L₂p), complex was inaccessible, in spite of the linear coordination geometry required. It appears that complexes 3m, 3p and 4p are all
unique and highly specific with respect to their preference for metal salt used.

3. Experimental

General

Chemicals were obtained from commercial sources and used without further purification. Propylated-cyclotriguaiacylene (p-CTG) was prepared according to literature methods from propyl-cycloptriveratrylene (p-CTV). 46,48 Ligands L1m, L1p and L2p were prepared according to known literature procedures. 46,47,48 NMR spectra were recorded by automated procedures on a Bruker DPX 500 or 300 MHz NMR spectrometer. Electrospray mass spectra (ESI-MS) were measured on a Bruker MicroTOF-Q or Bruker MaXis Impact instruments in positive ion mode. Infra-red spectra were recorded as solid phase samples on a Perkin-Elmer FT-IR Spectrometer and microanalyses were performed by the University of Leeds microanalytical service using a Carlo Erba Elemental Analyser MOD 1106 spectrometer. Samples for microanalysis were dried under vacuum prior to analysis.

Preparation of compounds

(±)-2,7,12-Tripropoxy-3,8,13-tris(2-quinolylmethyl)-10,15-di hydro-5H-tribenzo[a,d,g]cyclononene (L2p) A mixture of p-CTG (369 mg, 0.749 mmol) and potassium carbonate (1.24 g, 8.99 mmol) were held at reflux in acetonitrile (150 mL), under argon, for thirty minutes. After which, 2- (chloromethyl)quinoline hydrochloride (0.99 g, 4.49 mmol) was added and the reaction mixture held at reflux for a further 48 hours. The reaction mixture was cooled to room temperature and solvent removed in vacuo. The resultant residue was taken up into dichloromethane (150 mL), washed with water (2 x 50 mL) and brine (50 mL), dried over MgSO4 and concentrated in vacuo. The desired compound was obtained as a white solid through trituration of the impure material with methanol, collected by filtration and dried in vacuo. Yield 863 mg, 89 %. m.p. decomposes > 230 °C; HRMS (ESI): m/z 916.4334 [M+H]+; calculated for C40H33N5O6 916.4326; 1H NMR (300MHz, CDCl3) δ ppm = 8.17 (d, 3H, quin-H1), 8.07 (d, 3H, quin-H4), 7.83 (d, 3H, quin-H8), 7.2 (7.2 Hz), 7.77-7.71 (m, 6H, quin-H2, H6), 7.55 (dd, 3H, quin-H3, J = 7.0, 8.1 Hz), 6.93 (s, 3H, aryl-H), 6.74 (s, 3H, aryl-H), 5.39 (s, 6H, OC6H5-quin), 4.67 (d, 3H, CTG exo-H, J = 13.8 Hz), 3.80 (m, 6H, protyl ΨH, J = 6.4 Hz), 3.43 (d, 3H, CTG endo-H, J = 13.8 Hz), 1.72 (q, 6H, propyl β-H, J = 6.8 Hz), 0.97 (t, 9H, propyl ΨH, J = 7.4 Hz); 13C (1H) NMR (75 MHz, CDCl3) δ (ppm) = 158.7, 147.9, 147.5, 134.7, 136.9, 132.9, 131.7, 129.7, 128.8, 127.8, 127.6, 126.4, 119.1, 116.3, 115.3, 72.7, 70.6, 36.5, 22.6, 10.6; Analysis for L2p 2·(H2O) (calculated, found) C (74.99, 75.20), H (6.49, 6.10), N (4.37, 4.35); Infrared analysis (FT-IR, cm⁻¹) 3400-3100 (broad), 2925, 1600, 1506, 1265, 1140, 1093.

{[Ag(L1p)][Co(C5B11H11)]}·2·(DMF)·(H2O) (complex 1p) Ag[Co(C5B11H11)] (6.43 mg, 0.0149 mmol) and L1p (12.10 mg, 0.0149 mmol) were dissolved in DMF (~ 1 mL) and diethyl-ether vapours were diffused into the solution. Yellow blocks formed after 21 days and were analyzed via single crystal X-ray analysis using a synchrotron source. Yield 7.4 mg. Analysis for {[Ag(L1p)][Co(C5B11H11)]}·2·(DMF)·(H2O) (calculated, found) C (49.00, 49.20), H (6.03, 6.20), N (4.93, 5.05). Infrared analysis (FT-IR, cm⁻¹) 2985, 2810, 1750, 1664, 1504, 1271, 1106, 756.

{[Cd(L1p)][NO3]2}·(H2O)·(DMF)·0.5(EtOH) (complex 2p) Cd(NO3)2·4H2O (6.89 mg, 0.0224 mmol) and L1p (12.10 mg, 0.0149 mmol) were dissolved in DMF (~ 1 mL) and diethyl-ether vapours were diffused into the solution. Colourless needles formed after 21 days and were analyzed via single crystal X-ray analysis. Yield 4.9 mg. Analysis for {[Cd(L1p)][NO3]2}·(H2O)·(DMF)·0.5(EtOH) (calculated, found) C (51.37, 51.55), H (5.35, 5.00), N (7.77, 7.80). Infrared analysis (FT-IR, cm⁻¹) 3400-3150 (broad), 2965, 2914, 1777, 1654, 1509, 1480-1400 (broad), 1261, 758.

{[Ag(L2p)][Co(C5B11H11)]}·1.5(MeNO3) (complex 3p) Ag(cobalt(III)bis(dicarbollide) (6.43 mg, 0.0149 mmol) and L2p (13.60 mg, 0.0149 mmol) were dissolved in a 1:1 mixture of acetonitrile and nitromethane (~ 1.2 mL) and diethyl-ether vapours were diffused into the solution. Small, orange blocks formed after 28 days and were analyzed via single crystal X-ray analysis using a synchrotron source. Yield 6.6 mg. Analysis for {[Ag(L2p)][Co(C5B11H11)]}·1.5(MeNO3) (calculated, found) C (57.04, 56.90), H (5.91, 6.00), N (3.12, 3.00); Infrared (FT-IR, cm⁻¹) 2963, 2551, 1599, 1510, 1255, 1143, 1086, 980, 824, 760.

[Pd(L2p)2(CF3CO2)3]·n(CH3NO2)·n(EtO) (complex 4p) Pd(CF3CO2)2 (6.89 mg, 0.0224 mmol) and L2p (12.10 mg, 0.0149 mmol) were dissolved in a 1:1 mixture of acetonitrile and nitromethane (~ 1 mL) and diethyl-ether vapour was diffused into the solution to give bulk crystalline material. Yield 1.8 mg. Analysis for [Pd(L2p)2(CF3CO2)3]·3(CH3NO2)·7(H2O) (calculated, found) C (53.73, 53.40), H (4.24, 4.15), N (3.52, 3.20); Infrared analysis (FT-IR, cm⁻¹) 2991, 1747, 1650, 1501, 1178 (CF3CO2 anion), 1146 (CF3CO2 anion). 1H NMR resonances of the complex were broad and unassignable and the mass spectra did not highlight any mass peaks corresponding to the molecular ion or its breakdown. Larger crystals grown for single crystal X-ray analysis were isolated using a similar procedure but with a 2:2:1 mixture of acetonitrile:nitromethane:water as the solvent system.

Crystallography

Crystals were mounted on a glass or MiTeGen fibre tip under oil and flash frozen using a stream of cold N2. Data were collected on a Bruker-Nonius X8 diffractometer with an Mo-rotating anode (λ = 0.71073 Å), or on a Rigaku Saturn using synchrotron radiation (λ = 0.6899 Å) at station 119 at Diamond Light Source. Data were
corrected for Lorenzian and polarization effects and absorption corrections were applied using multi-scan methods. The structures were solved by direct methods using SHELXS-97 and refined by full-matrix least-squares on F^2 using SHELXL-97, aside from complex 3p which was refined by block-matrix least-squares, interfaced through the X-seed interface.\(^{59,60}\) Unless otherwise specified, all non-hydrogen atoms were refined as anisotropic, and hydrogen positions were included at geometrically estimated positions. Molecular graphics were obtained using POV-RAY through the X-Seed interface.\(^{60}\) Additional details of data collections and refinements are summarised below and details of disorder treatment are given in Supplementary Information.

\[
\text{[Ag(L1p)](Co(C_2B_9H_11)_2]} \cdot 2.5(\text{DMF}) (\text{H}_2\text{O}) \]

1p: C_{11}H_{73}Ag_{2}B_{36}Co_{2}N_{11}O_{25}, \(M_r = 2880.44\), triclinic, \(a = 10.324(3), b = 18.828(5), c = 21.852(6) \text{ Å}, \alpha = 69.016(6), \beta = 84.428(10), \gamma = 75.039(10) \text{°}, V = 3831.3(18) \text{ Å}^3\), synchrotron radiation, space group \(P-1\), \(Z = 1\), \(\theta_{\text{max}} = 26.57 \text{ °}, T = 100(1) \text{K}, 869\) parameters, 4 restraints, \(R_1 = 0.0807\) (for 13623 data \(I > 2\sigma(I)\)), \(wR_2 = 0.2426\) (all 15549 data). CCDC-988765.

\[
\text{[Cd(L1p)](NO}_3\text{)C}_{2}\text{(DMF)} \cdot 0.5(\text{Et}_2\text{O})\]

2p: C_{100}H_{11}Cd_{9}N_{3}O_{25}, \(M_r = 2344.92\), monoclinic, \(a = 38.700(3), b = 9.6729(10), c = 38.853(4) \text{ Å}, \beta = 111.954(4) \text{°}, V = 13490(2) \text{ Å}^3\), space group \(C2/c\), \(Z = 4\), \(\theta_{\text{max}} = 24.69 \text{ °}, T = 150(1) \text{K}, 736\) parameters, 755 restraints, \(R_1 = 0.1335\) (for 7036 data \(I > 2\sigma(I)\)), \(wR_2 = 0.4291\) (all 11146 data). CCDC-988766.

\[
\text{[Ag(L2p)](Co(C_2B_9H_11)_2]} \cdot 1.5(\text{MeNO}_3)\]

3p: C_{129}H_{163}Ag_{2}Co_{2}Co_{2}N_{11}O_{15}, \(M_r = 2787.94\), monoclinic, \(a = 19.3628(7), b = 43.7924(11), c = 16.6371(6) \text{ Å}, \beta = 90.525(3) \text{°}, V = 14107.7(8) \text{ Å}^3\), synchrotron radiation, space group \(P2_1/c\), \(Z = 4\), \(\theta_{\text{max}} = 22.50 \text{ °}, T = 100(1) \text{K}, 1633\) parameters, 2 restraints, \(R_1 = 0.1128\) (for 15562 data \(I > 2\sigma(I)\)), \(wR_2 = 0.3462\) (all 20256 data). CCDC-988767.

\[
\text{[Pd}_{2}(L2p)]_{2}(\text{CF}_2\text{C}_0\text{O}_2\text{)}_{2]} \cdot (\text{Et}_2\text{O})\]

4p: C_{268}H_{330}F_{36}N_{12}O_{29}Pd_{6}, \(M_r = 5729.07\), monoclinic, \(a = 21.057(5), b = 44.917(9), c = 40.687(8) \text{ Å}, \beta = 97.365(6) \text{°}, V = 38165(14) \text{ Å}^3\), space group \(C2/c\), \(Z = 4\), \(\theta_{\text{max}} = 20.00 \text{°}, T = 150(1) \text{K}, 1368\) parameters, 26 restraints, \(R_1 = 0.0914\) (for 10804 data \(I > 2\sigma(I)\)), \(wR_2 = 0.2572\) (all 17764 data). The SQUEEZE\(^{61}\) routine of PLATON\(^{62}\) was employed on this structure. CCDC-955888.

4. Conclusions

In summary, we have shown how two cyclotrimeratrylene ligand pairs, differing only in the length of alkylx substituents, display dissimilar metal-mediated self-assembly even under analogous conditions. Such sterically and interacionally similar ligand pairs demonstrate how even subtle alterations to the organic building blocks are enough to bias their self-assembly. The self-assembly of a methylated and propylated 4-pyridyl-derived ligand pair, \(L1m\) and \(L1p\), was dependent on aggregation of propyl moieties as a driving force in complex formation, resulting in expansion of a 2-connected 1D polymer, as methylated ligand \(L1m\), to a 3-connected 1D polymer for propylated ligand \(L1p\). This was mirrored in the formation of a 2D net with cadmium(II) centres, featuring two sites of alkyl-alkyl interactions, that was inaccessible with the methylated ligand.

Similar results were found for the 2-quinoly1 ligand pair, \(L2m\) and \(L2p\), whereby the formation of the \([\text{Ag}_{2}(L1m)]_{2}\)\(^{1+}\) tetramer was prevented due to steric; and how the increased solubility of propylated ligand \(L1p\) allows for the elucidation of a new type of compressed, hexameric [Pd\(_2\)(L1p)]\(_{12}\)\(^{16+}\) assembly that is inaccessible with parent, methylated ligand \(L1m\).

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6. Notes and references

School of Chemistry, University of Leeds, Woodhouse Lane, Leeds, LS2 9JT, UK. Email: m.j.hardie@leeds.ac.uk.

† Electronic Supplementary Information (ESI) available: Details of synthetic methodology and further crystallographic details. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/b000000x/.

Graphical Abstract

Propylated cyclotrimeratrylene ligands with N-donor groups form coordination polymers where the propyl groups aggregate or form a Pd₆L₄ cage.