Alkyl linker effects on the coordination topology of ditopic di(2-pyridylmethyl)amine carboxylate ligands with ZnII and CuII: polymers vs. macrocycles†

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A series of ditopic ω-di(2-pyridylmethyl)amine carboxylic acid ligands incorporating a range of n-alkyl linkers (CnCOOH, n = 3–5, 7, 10 and 11) have been synthesised. Solution phase studies showed a 1:1 coordination stoichiometry between the ligands and M(ClO4)2·6H2O (M = ZnII or CuII) in all cases. The ZnII and CuII complexes were subsequently crystallised by liquid–liquid diffusion and the solid-state structures investigated by X-ray crystallography. The crystal structures obtained are entirely consistent with the 1:1 metal–ligand ratio of the solution-phase adducts. However, the coordination geometries and complex topologies are dependent on the alkyl chain length of the ligand CnCOOH. The ZnII and CuII complexes of the short alkyl chain ligands (n ≤ 5) exhibit 1D coordination polymeric structures with somewhat different conformations for ([Zn(C2COO)2(H2O)]2(ClO4)·3.5H2O)8 (1), ([Zn(C4COO)2(H2O)]2(ClO4)·1.5H2O)8 (2), ([Zn(C5COO)(H2O)][ClO4]·5H2O)8 (3), ([Cu(C2COO)(H2O)]2(C4COO)·MeOH)8 (4), ([Cu(C4COO)(H2O)]2(ClO4)·2H2O)8 (5) and ([Cu(C5COO)(H2O)][ClO4]·2H2O)8 (6). In contrast, the ligands with longer alkyl chains (n ≥ 7) participate in Zn2L2 metallomacrocyclic structures ([Zn(C8COO)(H2O)][ClO4]·2.5H2O)8 (7), [Zn2(C10COO)2(H2O)2][ClO4]·2H2O·MeOH (8) and ([Zn2(C11COO)2(H2O)2][Zn(C11COO)2]2(ClO4)·2H2O)8 (9). The formation of metallomacrocycles instead of the 1D coordination polymers is a persistent trend and, with identical crystal growth conditions and a non-coordinating anion employed, appears to be an effect of the longer alkyl chain.

Introduction

Crystal engineering of organic–inorganic hybrid architectures has become the subject of particularly intriguing research, due in part to their convenient preparation and ease of structural modification.2 Careful ligand design facilitates the desired propagation of metal–ligand units in coordination polymers. In particular, a well-known strategy is to design a bridging ligand with terminal X-donor atoms (typically X = N, O, P, S).3 Ditopic bridging ligands containing terminal pyridine or carboxylate groups have been widely utilised as good candidates for the construction of coordination polymers due to the efficient coordination abilities of their multiple donor moieties.4 In addition, CuII and ZnII ions are considered two of the most interesting divalent transition metals which can provide novel chemical and physical properties from a coordination perspective.5 In light of the observations above, we have prepared a series of di(2-pyridylmethyl)amine-appended carboxylate ligands (Scheme 1) with an alkyl chain tether of variable length (n = 3–5, 7, 10, 11) as ligands to react with CuII and ZnII ions. In addition, the metal–ligand coordination ratios have been investigated by solution studies prior to growing crystals for solid-state characterisation.
In examining the solid-state coordination topology of the ligands by X-ray crystallography, particular attention can be focused on the effects of varying the chain length of the alkyl linker connecting the tertiary amine nitrogen atom and the carboxyl group. By keeping the metal–ligand ratio, the counterranion and the crystallisation solvent constant ensures that that the effect of the these parameters on the coordination topology is uniform. As the size of the flexible alkyl linker is increased, greater conformational freedom allows for more structural possibilities but with a concomitant decrease in control of the ultimate product structure.

To date, the majority of coordination polymers utilising di(2-pyridylmethyl)alkylamine-appended carboxylate ligands have been reported to form one-dimensional (1D) structures. Furthermore, it should be noted that within these reports, only ligands containing short carboxylate-pendant arms with an alkyl chain of five or fewer carbon atoms were employed. In the present study, ZnII and CuII coordination complexes formed using di(2-pyridylmethyl)amine-appended carboxylate ligands (ligands denoted herein as $C_n$COOH, as per Scheme 1) of $C_3$COOH, $C_4$COOH and $C_5$COOH are revisited with all solid-state structural determinations at low temperature (92–100 K). However, this work extends further to include an investigation of the effect of longer alkyl arms on the coordination behaviour of the ligands $C_3$COOH, $C_4$COOH and $C_5$COOH. The longer alkyl chain length ligands are more entropically unfavourable for coordination interactions and ligand solubility is limited in the polar solvents most compatible with metal salt precursors. Accordingly, the attainment of X-ray diffraction-quality crystals of complexes from long alkyl ligands is a challenging problem; nevertheless we report success in this endeavour. Moreover, our X-ray crystal structure data of these complexes reveals topological variation beyond the 1D chains observed for $C_3$COOH, $C_4$COOH and $C_5$COOH, in particular structures involving metallomacrocycles. Most ditopic ligands with flexible linkers that have previously been employed in studies of structurally diverse coordination architectures are symmetrical with identical functionality at both termini. To the best of our knowledge, the metallomacrocycles reported herein are the first examples obtained from the use of bifunctional ditopic ligands with an alkyl chain of extended length, as distinct from macrocycles obtained from the use of symmetrical ligands with mono or bidentate termini.

### Experimental

**Materials and methods**

Unless otherwise stated, all reagents are commercially available and were used without further purification. Pyridine-2-carboxaldehyde was purchased from Alfa Aesar and further purified by short path distillation (80 °C) on a Kügelrohr before use. Elemental analyses were performed by the Campbell Microanalytical Laboratory, University of Otago; reported elemental percentages (C, H, N, Cl) are accurate to within ±0.4%. $^1$H and $^{13}$C NMR spectra were obtained at 25 °C on either a Varian 400-MR or Varian 500 MHz AR spectrometer. Chemical shifts are reported relative to solvent signals ($^1$H NMR: 7.26 ppm, $^{13}$C NMR: 77.36 ppm). Electrospray mass spectrometry (ESI-MS) was carried out on a Bruker microOTOF-Q in positive mode. Sampling was averaged for 2 min over a $m/z$ range of 50 to 3000 amu. The mass was calibrated using sodium formate clusters, with 15 calibration points from 90 to 1050 amu, using a quadratic plus HPC line fit. ESI-MS spectra were processed using Compass software. Infrared (IR) spectra were recorded on a Bruker Alpha FT-ATR IR spectrometer with a diamond anvil Alpha-P module.

**General method for the preparation of $\omega$-[di(2-pyridylmethyl)amino]alkanoic acid ($C_n$COOH)**

Pyridine-2-carboxaldehyde (2 mole equiv.) was added to a mixture of $\omega$-aminoalkanoic acid (1 mole equiv.) and sodium triacetoxorbornhydride (2.5 molar equiv.) in dichloroethane (20 mL). The suspension was stirred at room temperature for 12 h. The mixture was quenched with water, and chloroform (100 mL) was added. The organic layer was separated and dried over anhydrous Na$_2$SO$_4$. After removal of the solvent under reduced pressure, the residue was purified via column chromatography on silica (DCM/MeOH = 9:1) to obtain the desired product.

$C_3$COOH. Yield 69%. Anal. calcd for C$_{16}$H$_{19}$N$_3$O$_2$: C, 67.35; H, 6.71; N, 14.73%. Found: C, 67.52; H, 6.59; N, 14.94%. $^1$H NMR (CDCl$_3$): $\delta$ 10.85 (1H, br), 8.54 (2H, d), 7.71 (2H, t), 7.46 (2H, d), 7.22 (2H, t), 3.86 (4H, s), 2.67 (2H, t), 2.35 (2H, t), 1.68–1.59 (2H, m). $^{13}$C NMR (CDCl$_3$): $\delta$ 177.73, 156.59, 150.44, 145.78, 130.57, 128.73, 58.86, 56.38, 33.67, 24.51. MS (ESI): $m/z$ calcd for C$_{16}$H$_{20}$N$_3$O$_2$: [M + H]$^+$ 286.1539, found 286.1539. Selected IR (ATR) $\nu$/cm$^{-1}$: 2954 (m, C–H str), 1717 (s, C=O str), 1556 (m, C=–N str), 756 (m), 447 (w).

$C_4$COOH. Yield 71%. Anal. calcd for C$_{17}$H$_{23}$N$_3$O$_2$: C, 68.20; H, 7.07; N, 14.04%. Found: C, 68.55; H, 7.35; N, 14.28%. $^1$H NMR (CDCl$_3$): $\delta$ 10.77 (1H, br), 8.51 (2H, d), 7.64 (2H, t), 7.51 (2H, d), 7.13 (2H, t), 3.78 (4H, s), 2.54 (2H, t), 2.26 (2H, t), 1.66–1.57 (4H, m). $^{13}$C NMR (CDCl$_3$): $\delta$ 177.63, 159.58, 149.27, 138.00, 125.24, 122.84, 59.95, 54.73, 35.08, 24.59, 24.25. MS (ESI): $m/z$ calcd for C$_{17}$H$_{22}$N$_3$O$_2$: [M + H]$^+$ 300.1712, found 300.1712.
M^2+: C_4H_2COOH solutions (2:1 ratio). Solutions (2:1 ratio) were prepared similarly to those used for the 1:2 ratio, except 0.060 M M(ClO_4)_2·6H_2O and 0.030 M C_2H_3COOH were used.

Job’s method of continuous variations

100 mL stock solutions of 0.010 M C_4H_2COOH (n = 3–5, 7, 10 and 11) in 0.100 M HClO_4 and 0.010 M Cu(ClO_4)_2·6H_2O in 0.100 M HClO_4 were prepared. These solutions were used to prepare mixtures with systematically varied mole fractions of the ligand and metal (details in Table S2†). The absorbances of these solutions were measured at 650 nm and plotted against mole fraction of the ligand C_4H_2COOH.

General synthesis of coordination polymers/macrocycles from C_4H_2COOH

M(ClO_4)_2·6H_2O (M = Zn^{2+} or Cu^{2+}, 0.100 mmol) was dissolved in water (2.0 mL) and carefully layered with a methanolic solution of C_4H_2COOH (0.100 mmol in 2.5 mL). Crystals suitable for X-ray analysis were obtained within 2 days and were isolated, dried in air and weighed.

M[Cu(C_4H_2COO)](H_2O)[ClO_4]·1.5H_2O_{n} (5). Yield 64%. Anal. calecd for C_{19}H_{23}ClCuN_3O_6Cu: C, 42.59%; H, 4.63%; N, 8.77% Cl, 7.40%. Found: C, 42.75%; H, 4.72%; N, 8.49; Cl, 7.59%. Selected IR (ATR) ν/cm⁻¹: 2965 (m, C–H str), 1724 (m, C=O str), 1563 (m, C=O str) 1078 (s, ClO_4⁻), 764 (m).

{[Cu(C_4H_2COO)](H_2O)[ClO_4]·2H_2O}_{n} (6). Yield 66%. Anal. calecd for C_{20}H_{24}ClCuN_3O_7Cu: C, 45.91%; H, 5.39%; N, 8.03%; Cl, 6.77%. Found: C, 43.12; H, 5.48; N, 7.87; Cl, 6.52%. Selected IR
Flack parameter 0.00(13) 0.49(3) × Crystal size (mm) 0.60
Z Cl, 5.91%. Found: C, 50.29; H, 6.37; N, 7.20; Cl, 6.33%. Selected IR (ATR) ν/cm⁻¹: 2979 (m, C–H str), 1737 (m, C=O str), 1572 (m, C=N str), 1082 (s, ClO₄⁻), 771 (m).

X-ray crystal structure determinations

Crystallographic data collection, processing and refinement details for 1–9 are reported in Table 1. Data were collected on either a Bruker Kappa APEX diffractometer (sealed tube Mo,

Table 1 Summary of crystallographic data for 1–9

|  | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Formula | C₁₆H₂₃Cl₂CuN₄O₁₀.₅Zn | C₁₈H₂₈ClN₄O₉Zn | C₁₈H₂₃Cl₂CuN₄O₉Zn | C₁₇H₂₂ClCuN₄O₇ | C₁₈H₂₄Cl₂Cu₂N₆O₁₆ |
| M | 530.23 | 1951.81 | 495.22 | 479.37 | 994.76 |
| Radiation | Mo Kα | Cu Kα | Mo Kα | Mo Kα | Cu Kα |
| T (K) | 92(2) | 100(1) | 93(2) | 100(1) | 100(1) |
| Crystal system | Monoclinic | Orthorhombic | Orthorhombic | Monoclinic | Orthorhombic |
| Space group | P2₁/n | Pmna | Pbcn | Pbca | Pnma |
| α (Å) | 9.0642(10) | 17.5644(3) | 15.7577(10) | 10.3753(3) | 14.1032(2) |
| b (Å) | 19.594(2) | 34.1856(4) | 15.1427(9) | 8.3153(9) | 17.7710(2) |
| c (Å) | 12.6956(15) | 13.3564(2) | 16.8380(10) | 23.5131(11) | 15.8872(2) |
| α (°) | 90 | 90 | 90 | 90 | 90 |
| β (°) | 104.058(6) | 90 | 102.275(4) | 90 | 90 |
| γ (°) | 90 | 90 | 90 | 90 | 90 |
| V (Å³) | 2182.7(4) | 8019.7(2) | 4017.3(4) | 1982.0(13) | 3981.90(9) |
| Z | 4 | 4 | 4 | 4 | 4 |
| Crystal size (mm) | 0.44 × 0.20 × 0.06 | 0.18 × 0.13 × 0.08 | 0.55 × 0.42 × 0.35 | 0.44 × 0.09 × 0.03 | 0.30 × 0.15 × 0.10 |
| μ (mm⁻¹) | 1.306 | 3.359 | 1.403 | 1.282 | 3.256 |
| θmin, θmax (°) | 2.4979, 30.3364 | 3.31, 76.63 | 2.74, 30.54 | 3.151, 28.423 | 3.73, 74.16 |
| Reflections measured | 38578 | 55998 | 86630 | 19827 | 16594 |
| Independent reflections | 6661 | 14452 | 6140 | 4477 | 6950 |
| Parameters/restraints | 379/249 | 1115/902 | 277/3 | 270/161 | 598/105 |
| R₁[I > 2σ(I)] | 0.0392 | 0.0626 | 0.0309 | 0.0562 | 0.0564 |
| wR₂[I > 2σ(I)] | 0.1410 | 0.1652 | 0.0806 | 0.1456 | 0.1542 |
| GOF | 1.177 | 1.033 | 1.037 | 1.072 | 1.045 |
| Residual extrema (e Å⁻³) | -0.815, 0.869 | -0.983, 2.217 | -0.467, 0.527 | -1.214, 1.256 | -1.004, 0.797 |
| Flack parameter | 0.00(13) | 0.00(13) | 0.00(13) | 0.00(13) | 0.00(13) |

| 6 | 7 | 8 | 9 |
|---|---|---|---|
| Formula | C₁₆H₂₃Cl₂CuN₄O₉ | C₁₈H₂₈ClN₄O₉Zn | C₁₈H₂₃Cl₂CuN₄O₉Zn | C₁₇H₂₂ClCuN₄O₇ |
| M | 529.42 | 523.27 | 1198.78 | 2299.50 |
| Radiation | Mo Kα | Cu Kα | Mo Kα | Synchrotron |
| T (K) | 100(1) | 100(1) | 100(1) | 100(1) |
| Crystal system | Orthorhombic | Tetragonal | Triclinic | Monoclinic |
| Space group | Pca₂₁ | I₄₁/a | P | Cc |
| a (Å) | 13.0446(3) | 16.9390(2) | 9.4210(17) | 36.788(7) |
| b (Å) | 8.8181(2) | 16.9390(2) | 22.221(5) | 8.669(2) |
| c (Å) | 19.3686(5) | 33.5981(6) | 29.851(7) | 33.481(7) |
| α (°) | 90 | 90 | 90 | 90 |
| β (°) | 90 | 90 | 90 | 90 |
| γ (°) | 90 | 90 | 90 | 90 |
| V (Å³) | 2227.94(9) | 9640.3(2) | 8509(2) | 10433(4) |
| Z | 4 | 4 | 4 | 4 |
| Crystal size (mm) | 0.60 × 0.43 × 0.22 | 0.34 × 0.24 × 0.24 | 0.36 × 0.13 × 0.10 | 0.20 × 0.03 × 0.03 |
| μ (µm⁻¹) | 1.155 | 2.820 | 0.987 | 1.091 |
| θmin, θmax (°) | 3.886, 28.758 | 4.73, 74.85 | 0.73, 22.56 | 1.17, 25.03 |
| Reflections measured | 20122 | 18903 | 35674 | 81232 |
| Independent reflections | 4893 | 4814 | 15134 | 17724 |
| Parameters/restraints | 295/121 | 467/569 | 1164/1281 | 1304/56 |
| R₁[I > 2σ(I)] | 0.0173 | 0.0863 | 0.1558 | 0.0452 |
| wR₂[I > 2σ(I)] | 1.023 | 1.064 | 1.016 | 1.040 |
| GOF | 0.857 | 0.994 | 0.857 | 0.994 |
| Residual extrema (e Å⁻³) | -0.537, 0.972 | -0.999, 0.819 | -0.749, 3.341 | -0.857, 0.994 |
| Flack parameter | 0.009(19) | 0.009(19) | 0.009(19) | 0.009(19) |
graphite monochromated; 1, 3, 8); an Agilent SuperNova with Atlas CCD using mirror monochromated micro-focus Mo or Cu-Kα radiation (2, 4–7); or at the MX2 beamline of the Australian Synchrotron (λ = 0.7180 Å). The data processing was undertaken with SAINT and XPREP (1, 3, 8), CrysAlisPro (2, 4–7) or XDSS (9), and included a numerical or analytical absorption correction over a face-indexed model and/or a multiscan empirical correction, except the data for 9 which was not corrected for absorption. All structures were solved by direct methods with SHELXS-97 (ref. 18) (1-5, 8-9), Superflip (6) or SIR-97 (ref. 20) (7) and were extended and refined against all F2 data with SHELXL-97 (ref. 18) using the X-Seed interface. The non-hydrogen atoms in the asymmetric unit were modelled with anisotropic displacement parameters. Hydrogen atoms were placed in calculated positions and refined using a riding model with fixed C–H distances (sp2-CH 0.95 Å, sp3-CH3 0.98 Å, sp3-CH2 0.99 Å) and isotropic displacement parameters estimated as \( U_{iso}(H) = 1.2U_{eq}(C) \), except for CH3 where \( U_{iso}(H) = 1.5U_{eq}(C) \). Where significant residual electron density peaks were observed, oxygen-bound hydrogen atoms were included and refined with O–H restraints (0.84 Å) and \( U_{iso}(H) = 1.5U_{eq}(O) \). Special conditions/variations to the general procedure are given in the ESI.

**Powder X-ray diffraction**

Crystals were dried, ground to a fine powder and data collected at room temperature with Cu-Kα radiation (λ = 1.5418 Å) on a PANalytical X’Pert-Pro MPD PW3040/60 XRD with Rapid RTMS X’Celerator Detector in the Department of Geology, University of Otago. The samples were scanned at 40 kV and 30 mA from 3–80° 2θ using a step size of 0.0080° and a scan step time of 4.03 s. Data were collected and processed using PANanalytical HighScore Plus, Version 4.

**Results and discussion**

**Preparation of \( \omega \)-[di(2-pyridylmethyl)amino]alkanoic acid ligands (CnCOOH)**

A homologous series of the ligands CnCOOH has been prepared according to a literature procedure with minor modifications. The general reductive amination synthetic approach employed in the syntheses involves Schiff base formation between the primary amine group of the amino-alcanonic acid and the aldehyde group of pyridine-2-carboxaldehyde, and subsequent reduction of the resulting imine. This method gave the desired products as pale yellow oils in good yields (68–75%) and employs milder conditions than dialkylation of an aminoalkanonic acid with 2-picolyl chloride hydrochloride which requires heating at reflux, as described in alternative procedures.

**Solution studies of metal–ligand coordination stoichiometry**

High resolution ESI-MS was used to investigate the metal–ligand coordination stoichiometry of Zn\(^{II} \) or Cu\(^{II} \) with the CnCOOH ligands in solution. In particular, the ratio of metal ion to ligand in solution was varied between 1:2, 1:1 to 2:1, and freshly-prepared solutions were subsequently analysed. Despite different ratios of the metal ion and ligand being used, ESI-MS data in all cases presented similar mass distributions with matching isotopic patterns. The major signal essentially corresponds to a singly-charged ion assigned to metal–carboxylate \([M(\text{CnCOOH})]^+\) as the only significant peak, with good agreement between the experimental and calculated m/z values and isotopic pattern. This suggests that a 1:1 coordination stoichiometry is preferred for the complexation and does not depend upon the metal–ligand ratio in solution or length of the alky linkers. The mass spectrometry data of the metal–ligand solutions with different ratios are listed in Table S1.† Note that \([M(\text{CnCOOH})]^+\) can arise from 1:1 metal–ligand polymeric structures in the solid-state. However, polymeric species are typically not detected by ESI-MS due to low stability, although steric constraints caused by the poly-methylene linkers while in solution may also be a factor.

The method of continuous variation (Job’s method) was also used to determine the stoichiometry of the reactants at chemical equilibrium. In order to confirm the metal–ligand ratios, plots of absorbance vs. mole fraction of CnCOOH in solutions with Cu\(^{II} \) are shown in Fig. S2.† As is seen for all cases, the plots exhibit a maximum absorbance at a 0.5 mole fraction of CnCOOH. Therefore, the derived stoichiometric ratios of the complexes in solution are 1:1 in all cases.

The results from the Job method agree well with the results from solution studies by ESI-MS, which also suggest a 1:1 stoichiometry for the most stable species, irrespective of the molar ratios used.

**Synthesis of coordination polymers/macrocycles from CnCOOH**

In accordance with the 1:1 metal–ligand complex stoichiometries which were identified from the solution studies by ESI-MS and Job’s method, possible linear/macroyclic coordination structures are shown in Fig. 1.

To investigate the actual coordination structures in the solid-state, a 1:1 metal–CnCOOH ratio was subsequently applied to grow crystals of Zn\(^{II} \) and Cu\(^{II} \) complexes. Slow diffusion of a methanolic solution of CnCOOH into an aqueous solution of \( \text{M(ClO}_{4})_{2} \cdot 6\text{H}_{2}\text{O} \) (M = Zn\(^{II} \) or Cu\(^{II} \)) afforded colourless and blue crystalline solids, respectively. Infrared spectral data of the complexes show evidence of coordination of the ligand CnCOOH by their carboxylate group. All the free ligands display strong absorption bands in the range 1723–1735 cm\(^{-1} \) which are assigned to \( \nu(\text{C=O}) \) of the carboxyl group. However, the decreasing intensity of these C=O bands which are observed as medium bands in the spectra of their complexes, indicate that C=O stretching vibration is reduced due to the carboxylate oxygen atoms being coordinated to the metal ions.
metal centre is ZnN₉O₂. As shown in Fig. 2a, the central ZnII is ligated by three nitrogen donors of one ligand molecule and one carboxylate oxygen atom from the adjacent ligand. The pentacoordination is completed through ligation by an aqua ligand. The [Zn(C₆COO)(H₂O)]⁺ units are linked by the ditopic coordination of C₆COO⁻ to form a 1D coordination polymer with an intrapolymer Zn⋯Zn separation of 6.8563(9) Å. It is interesting to note that the second carboxylate oxygen (O2) does not coordinate to the ZnII metal centre but participates in a hydrogen bond with a ZnII-bound water (O3⋯O2 2.683(3) Å; Fig. 3). The polymeric chain has a wave topology due to the intramolecular hydrogen bonds described above, supported by an intermolecular hydrogen bond chain between the second aqua ligand hydrogen (H32), lattice water molecules O91, O92 and the ZnII-bound carboxylate oxygen O1 (Fig. 3).

The ZnII-tertiary amine bond distance (Zn1–N3 2.170(3) Å) is longer than the analogous bond distances involving the pyridyl nitrogen atoms (Zn1–N1 2.111(3), Zn1–N2 2.109(3) Å). The N1–Zn–N3 and N2–Zn–N3 bite angles of the five-membered chelate rings are 79.09(11)° and 79.19(11)°, respectively. According to Addison et al., an index of geometry (τ) of 0 and 1 are identified as ideal square pyramidal and trigonal bipyramidal geometries, respectively. The ZnII centre of 1 displays a distorted square pyramidal geometry (τ = 0.10) which is similar in geometry to a previously reported structure involving the same ligand and metal. As evidence of phase purity, powder X-ray diffraction measurements (Cu-Kα, room temperature) from crystals of 1 (also for 3, 4, 6) are shown in Fig. S2–S5. Insufficient material was available for powder diffraction studies on the other complexes.

[Zn(C₆COO)(H₂O)]₄(ClO₄)₄·1.5H₂O (2) also has 1D polymeric chain structure (Fig. 2b). The coordination polymer 2, crystallises in the orthorhombic space group Pna2₁, and the asymmetric unit consists of four independent [Zn(C₆COO):(H₂O)]⁺ units connected together, along with four perchlorate anions, and one and half water molecules. The coordination environment of each ZnII metal centre is ZnN₉O₉ with a distorted octahedral geometry. The apical positions are occupied by the two pyridyl nitrogen atoms, while the tertiary

**Fig. 2.** ORTEP diagrams of the ZnII coordination polymers (a) 1 (n = 3), (b) 2, (n = 4), and (c) 3 (n = 5). All hydrogen atoms, perchlorate anions and solvent have been omitted for clarity. For bond lengths, angles and coordination geometries see Table S3.† Symmetry code: (i) x, 1/2 – y, 1/2 + z.

**Fig. 3.** Detail of hydrogen bonding interactions for 1. Intramolecular H-bonding interactions are shown in red and intermolecular interactions in orange: O3⋯O2 2.683(3), O3⋯O91 2.703(8), O91⋯O92 2.649(8), O92⋯O1 2.823(5) Å. Symmetry codes: (i) 1/2 + x, 1/2 – y, 1/2 + z; (ii) –1/2 + x, 1/2 – y, –1/2 + z.
niten, the aqua ligand and the neighbouring carboxylate oxygen atoms coordinate to the central ZnII in the equatorial plane. The asymmetric unit repeats itself in a head-to-tail arrangement with intramolecular Zn⋯Zn distances of 9.848(2), 10.132(2), 10.063(2), 10.196(2) Å.

The 1D polymeric chain structure and carboxylate ligand binding mode of \([\{\text{Zn}((\text{C}_3\text{COO})\text{(H}_2\text{O})\}\text{ClO}_4\}]_n\) (3) is similar to 2, as illustrated in Fig. 2c. The coordination polymer 3 crystallises in the orthorhombic space group \(\text{P}b\text{ca}\). The asymmetric unit contains one \([\text{Zn}((\text{C}_3\text{COO})\text{(H}_2\text{O})\}]\) unit accompanied by one perchlorate counterion but no solvent. The ZnII metal centre also adopts a distorted octahedral ZnN_3O_3 coordination environment through bonding to three nitrogen donors of one ligand, two oxygen atoms from the neighbouring carboxylate bridge and a metal bound water. A similar crystal structure, prepared in refluxing water followed by recrystallization from acetonitrile/water, was studied at room temperature.\(^8\)

CuII coordination polymers (4–6). For the X-ray crystal structures of the ZnII complexes derived from the short alkyl chain length ligands (C\(_n\)COOH, \(n \leq 5\)), only 1D coordination polymeric chains are observed. To compare this behaviour with the analogous CuII complexes, their crystal structures were also investigated. The CuII complexes also provide 1D coordination polymers, albeit with an intriguing carboxylate coordination mode in the structure containing C\(_3\)COO.\(^{2980}\)

\([\{\text{Cu}((\text{C}_3\text{COO})\text{ClO}_4)\text{MeOH}\}]_n\) (4) crystallises in the monoclinic space group \(\text{P}2_1/n\), and the asymmetric unit contains one CuII metal centre, carboxylate ligand, a perchlorate counterion, and a lattice methanol. As shown in Fig. 4a and 5a, each CuII exhibits a CuN_3O_3 coordination environment; the CuII centre is coordinated by three nitrogen donor atoms and one carboxylate oxygen atom (O2) from the same ligand. The remaining two coordination sites are occupied by oxygen atoms belonging to the carboxylate group of the neighbouring ligand. Consequently, one \{CuOCO\} ring, two five-membered chelate rings of \{CuNCCN\} and a seven-membered \{CuN(CH\(_2\))\text{CO}\} ring are generated in this configuration. Of the chelate Cu–O bonds of the carboxylate bridge, one (Cu1–O1\(^{\dagger}\) 1.982(2) Å) has a bond length which is comparable to those of the ZnII coordination polymers, whereas the remaining bond (Cu1–O2\(^{\dagger}\) 2.622(2) Å) is significantly longer.

Polymer 4 is dissimilar to all the ZnII polymers 1–3 in that the carboxylate ligand folds back in a “scorpion-like” fashion, giving rise to mini cyclic subunits along the polymeric chain; the carboxylate ‘tail’ exhibits a short O2–Cu1 bond (2.181(3) Å) to the same metal chelated by the N\(_3\) head group (Fig. 5a). Furthermore, the carboxylate oxygen atom O2 bridges a neighbouring CuII metal centre through a long Cu1–O2 bond (2.622(2) Å) and occupying the sixth coordination site of the CuII ion. Overall, the ligand can be described as a tetradentate ligand toward one CuII metal centre and as a bidentate ligand toward an adjacent metal centre forming a dense 1D polymeric chain with an intramolecular Cu⋯Cu distance of 4.4251(7) Å, significantly shorter than the Zn⋯Zn distance (6.8563(9) Å) in 1.
The hexa-coordinated CuII metal centre of 4 can be considered as having a distorted octahedral geometry (Fig. 5a), which is significantly different to the previously reported penta-coordinate \([\text{Cu(C}_3\text{COO)}(\text{H}_2\text{O})]\text{[ClO}_4\text{]}\text{3H}_2\text{O})_n\). In this polymer the carboxylate group is monodentate and an aqua ligand occupies the axial site of a distorted square pyramid, resulting in a more open zig-zag polymer (CuII) with a greater similarity in topology to the ZnII polymers 1–3 than 4. The coordination geometry of these two structures is likely to be influenced by the crystallisation solvent and/or temperature; structure 4 (from methanol/water at room temperature) contains a lattice methanol, while \([\text{Cu(C}_3\text{COO)}(\text{H}_2\text{O})]\text{[ClO}_4\text{]}\text{3H}_2\text{O})_n\) was recrystallised from hot water/acetonitrile and contains three lattice water molecules that participate in extensive hydrogen bonding.

\[\text{[Cu(C}_3\text{COO)}(\text{H}_2\text{O})]\text{[ClO}_4\text{]}\text{2H}_2\text{O})_n\] (5) crystallised in the orthorhombic space group \(Pna2_1\). The asymmetric unit contains two crystallographically-independent 1D polymeric chains of \([\text{Cu(C}_3\text{COO)}(\text{H}_2\text{O})]\text{[ClO}_4\text{]}\text{2H}_2\text{O})_n\), aligned parallel to each other with opposing orientations (Fig. 4b). For each chain the three nitrogen atoms of the \(d(2\text{-pyridylmethyl})\)amine terminus coordinate to one copper site, while the oxygen atoms of each carboxylate terminus coordinate unsymmetrically to an adjacent site, giving rise to the 1D connectivity.

The CuN₃O₃ coordination geometry of each CuII centre is distorted octahedral wherein the axial positions are occupied by two pyridyl nitrogen atoms, while the equatorial positions are occupied by the tertiary nitrogen, a water molecule and both of the carboxylate oxygen atoms from the adjacent ligand. The structure is related to those previously described for penta\(^{ab}\) and hexa\(^{ab}\) coordinated structures, differing in the metal geometry and the identity of the counterion, respectively.

The polymer \([\text{Cu(C}_3\text{COO)}(\text{H}_2\text{O})]\text{[ClO}_4\text{]}\text{2H}_2\text{O})_n\) (6) was found to crystallise in the orthorhombic space group \(Pca2_1\). The asymmetric unit is composed of similar components as observed for 5, albeit with \(\text{C}_3\text{COO}^-\) in the place of \(\text{C}_4\text{COO}^-\). The CuN₃O₃ coordination environment of the CuII metal centre is best described as possessing a distorted octahedral geometry. The 1D zig-zag chain structure is shown in Fig. 4c. Another structure of CuII with \(\text{C}_4\text{COOH}\) has previously been reported but with a different geometry, namely a distorted square-pyramid around the CuII metal centre for crystals obtained from hot water/acetonitrile.\(^{ab}\)

Based on these low temperature structural studies of the ZnII and CuII complexes of the short chain ligands (\(\text{C}_n\text{COOH}, \ n \leq 5\)), all are 1D coordination polymers with a similar coordination mode. Notably, an interesting difference in the
carboxylate bonding in the ZnII and CuII coordination polymers of the short C_nCOOH ligand has been observed. An intramolecular H-bonding interaction folds the alkyl chain back in the Zn example, whereas the carboxylate coordinates back to the same metal ligated by the bis(IJ-pyridylmethyl)amine in the CuII complex. The latter could be described as a "scorpion-like" coordination mode of the short ditopic ligand. ZnII macrocycles (7–9). In contrast to the polymeric ZnII complexes of the short chain ligands (C_nCOOH, n ≤ 5), the structures with the longer analogues C_7COOH, C_10COOH and C_11COOH are dominated by metallomacrocycles. Moreover, the coordination geometry of the tridentate di(IJ-pyridylmethyl)amine moiety adjusts to facilitate macrocycle formation. Efforts to grow X-ray quality crystals of CuII complexes with the longer alkyl chain ligands proved unsuccessful and only the ZnII complexes are reported herein.

The crystal structure of [(Zn(C_7COO)(H_2O))(ClO_4)]_2 (7) reveals the formation of a dimetallic M_2L_2 macrocycle (Fig. 6). The complex crystallises in the tetragonal space group I41/a. The asymmetric unit contains half of the macrocycle 7 with the other half generated by a 2-fold rotation about the...
centre of the macrocycle. Each ZnII metal atom is coordinated by three nitrogen atoms of one ligand, a carboxylate oxygen from the second ligand and an aqua ligand. Each pentacoordinate ZnII centre displays a distorted trigonal bipyrimidal geometry ($\tau = 0.63$) such that the nitrogen donor atoms are in a facial (fac) coordination mode with the amine nitrogen (N3) in an axial site. The fac-N3 coordination here contrasts with a meridional geometry for the shorter alkyl chain coordination polymers. The ZnII centres, linked by two bridging ligands, have a Zn⋯Zn separation of 11.853(1) Å.

As is seen for the polymers 1-3, hydrogen bonds involving the aqua ligand are important interactions driving the molecular packing. Fig. 7a shows a four molecule motif at an inversion centre of the structure 7 where each aqua ligand acts as a double hydrogen bond donor. A non-ligating carbonyl oxygen from a neighbouring macrocycle points toward the water as a hydrogen bond acceptor of H32, an interaction that is repeated fourfold about the c-axis (dashed orange line, Fig. 7a). These are relatively strong interactions$^{27}$ with O3⋯H32⋯O2 1.79(6), O3⋯O2 2.597(6) Å. The second hydrogen of each water ligand is donated to one of two perchlorate anion sites (Cl2, disordered) that sit above and below the plane defined by the macrocycles (dashed blue lines, Fig. 7a); these

![Fig. 10 Packing diagram of the ZnII macrocycles 8 (a) viewed down the a-axis and (b) b-axis with each crystallographically independent macrocycle shown in a different colour (Zn1 blue, Zn2 light green, Zn3 light blue, Zn4 green). The perchlorate anions and disordered solvent are omitted for clarity.](image1)

![Fig. 11 Packing diagram of the ZnII macrocycles 8 (a) viewed down the a-axis and (b) c-axis showing the nanosegregation of the aromatic (blue highlight) and aliphatic (yellow highlight) components of the ligands. Not all perchlorate anions and disordered solvent could be located in the model.](image2)

![Fig. 12 ORTEP diagram of the ZnII macrocycle and polymer 9. All hydrogen atoms, perchlorate anions and solvent have been omitted for clarity. For bond lengths, angles and coordination geometries see Table S5.† Symmetry codes: (i) x, 1 − y, 1/2 + z; (ii) x, 1 − y, z − 1/2.](image3)
are weaker interactions, O₃–H₃₁⋯O₂₁ 2.26(6), O₃⋯O₂₁ 2.964(2) Å, but act cooperatively. A second region of disordered perchlorate anions (Cl₁) is adjacent to the alkyl chains (Cl₁). The hydrogen-bond directed packing extends in the ab-plane to give layers of macrocycles that stack along the c-axis (Fig. 7b).

\[
\text{[Zn₂(C₁₀COO)₂(H₂O)₂][ClO₄]·2H₂O-MeOH} \quad \text{(8)}
\]

was obtained from the crystallization of the C₁₀COOH ligand with Zn(ClO₄)₂·6H₂O. The small crystals diffracted weakly and the low resolution data (P-1) were heavily restrained during refinement. Nevertheless, the data were sufficient to reveal an asymmetric unit containing four macrocycles (Zn₁–Zn₄), each lying about an independent inversion centre, as well as one unit-occupancy and two half-occupancy perchlorate anions. The remaining contents of the asymmetric unit (2ClO₄−, 4H₂O, 2MeOH) are highly disordered and could not be modelled, their contribution accounted for using SQUEEZE. The electron count and volume of the voids are consistent with the missing anions and solvent combination given above, supported by elemental analysis of crystals grown under the same conditions. Each macrocycle has the dimetallic formulation Zn₂(C₁₀COO)₂H₂O₂+ with a similar head-to-tail bridging coordination at ZnII as for the macrocycle 7 (Fig. 8). The ZnII ions display a distorted octahedral geometry in two out of four macrocycles, while the ZnIII ions of the remaining macrocycles exhibit a highly distorted square pyramidal geometry (τ = 0.49 Zn2, 0.44 Zn4) tending towards octahedral with a weak carboxylate O⋯Zn interaction; the N₃ donor atoms adopt a fac-coordination in all cases.

Examination of the packing shows again that hydrogen bonding with the water ligands dominate the intermolecular...
interactions (Fig. 9). In particular, the complexes are arranged in a crossed fashion that places the metal centres in close proximity; this allows each Zn-bound water to interact with a neighbouring complex giving rise to a chain of hydrogen bonds that zig-zag along the a-axis. In addition, a perchlorate anion located in the void adjacent to the metals weakly hydrogen bonds to aqua ligands at Zn2 and Zn4. The elongated macrocycles stack along the a-axis in an alternating, criss-crossed arrangement (Fig. 10) with a separation of ca. 4.71 Å. There are two crystallographically-independent columns (blue and green in Fig. 10) that interlock at the ligated metal regions, stabilised through hydrogen bonding (as discussed above) and aromatic embrace motifs involving both edge-to-face and offset face-to-face π–π interactions of the pyridyl rings. The interlocking of the macrocycle columns along the c-axis gives sheets with cationic metal centres at the interface and regularly packed alkyl chains sandwiched at the centre; this arrangement has similarities with the arrangement of charged surfactant molecules in bilayer structures. The counteranions here are mostly located at the interface between the layers, although as shown in Fig. 9, a small channel of ca. 3 Å running parallel to the column axis accommodates anions (and solvent), stabilised through hydrogen bonding. Fig. 11 further emphasises the nanosegregation of the metal centres, surrounded by aromatic-rich groups (blue highlight), from the densely packed aliphatic regions (yellow highlight).

Crystallization of Zn(ClO3)2·6H2O with the longer C11COOH ligand affords the monoclinic (Cc) structure \([\{Zn_2(C_4H_3COO)_2(H_2O)_4\}\{Zn_2(C_4H_3COO)_3\}(ClO_3)_n\cdot 6H_2O]_n\) (9) which includes both polymeric and macrocyclic elements (Fig. 12).

The \([Zn_2(C_4H_3COO)_2(H_2O)_2]^{2+}\) unit has a discrete Zn2L2 macroscopic structure, whereas the \([Zn_2(C_4H_3COO)_3]^{3+}\) unit is a double stranded or ‘ribbon’ coordination polymer with carboxylate groups bridging a Zn4 dimer. Both of the ZnII centres in the discrete dimetallic macrocycle exhibit a ZnN3O3 octahedral geometry, with the third oxygen donor being an aqua ligand. Each ZnII of the ribbon polymer displays a distorted square pyramidal geometry with a ZnN3O2 coordination environment \((\tau = 0.21 \text{ Zn3, 0.24 Zn4});\) the nitrogen atoms of the di(pyridylmethyl)amino group and one carboxylate oxygen atom occupy the equatorial sites, while an oxygen atom a second carboxylate ligand occupies the axial sites for each metal. The polymer can alternatively be described as Zn2L2 macrocycles, as was seen for 8, linked via the second carboxylate oxygen that ligates the neighbouring Zn11 centre. It is noted that all O–Zn bonds for the bridging carboxylates fall within the range 2.009(3)–2.056(3) Å, indicative of a relatively symmetrical binding mode.

The discrete metallomacrocycles sit across the polymeric ribbon in a crossed “X-like” orientation (Fig. 13 and 14) as is seen for the macrocyclic structure 8. Following the trend seen for the macrocyclic structures with aqua ligands, the hydrogen atoms of the water ligands in 9 interact with a neighbouring carbonyl oxygen. The pair of hydrogen bonds (O13–H132⋯O21 1.86(5) Å and O23–H231⋯O11 1.82(4) Å, dashed orange lines, Fig. 13) at each end of the macrocycle are relatively short and strong, and give rise to H-bonded ribbons of macrocycles (blue, Fig. 14) that weave through the coordination polymer chains (red). The second hydrogen of the aqua ligands is donated to a perchlorate oxygen atom (O13–H131⋯O83 2.04(4) Å and O23–H232⋯O72 2.08(4) Å, dashed blue lines, Fig. 13). These hydrogen bond distances are typical of their respective types. The nanosegregation of the aromatic and aliphatic regions of the ligands is illustrated in Fig. 15; the pyridyl/ionic domains are highlighted in blue and the crossed alkyl domain in yellow.

Alkyl chain conformation
As the length of the alkyl chain increases, the number of potential conformations grows exponentially giving access to widening range of coordination polymers on moving from C4COOH to C11COOH. The conformation about the n-1 carbon–carbon bonds in the alkyl backbone may be characterised as trans/anti (T, torsion angle ca. 180°) or gauche (G). and the ligand conformation of each independent CnCOOH ligand in 1–9 has been analysed (Table 2).

The lowest energy all-T conformation places the two metal binding sites at the greatest separation and it is the T arrangement that dominates in this series, especially in complexes of the longer ligands (7–9). The all-T chains pack efficiently side-by-side (as exemplified in Fig. 14 & 15) and the ligands of 7–9 exhibit, at most, one bond with a G conformation. Notably, where a ligand contains a G unit, it is the second C–C bond from the amine nitrogen and the partner
Table 2  Alkyl chain conformations of the carboxylate ligands in 1–9 and related structures with perchlorate anions

| Ligand CₙCOO⁻ | Alkyl linker conformation (OOC → N₃)⁹ |
|--------------|-----------------------------------|
| n M = Zn     | M = Cu                             |
| 3            | GT (1)                             |
| 4            | GT (CSD: YACYUK)⁹                  |
| 5            | TTTT (3)                           |
| 7            | TTTT (CSD: HAYIXP)⁹d              |
| 10           | TTTTTTGT [Zn1, Zn3] (8)           |
| 11           | TTTTTTTTGT GTTT (CSD: NEDSZ)⁹b     |

* T = trans (anti), G = gauche.

structures 7–9 display intriguing coordination architectures: a discrete Zn₅L₂ metallomacrocycle (7, n = 7), four independent Zn₅L₂ macrocycles that arrange themselves into interlocked stacks (8, n = 10), and a tightly woven network consisting of macrocycles, linked by hydrogen and coordinate bonds along the a- and c-axes, respectively (9, n = 11). Note that metallomacrocores are only observed with the longer alkyl chain ligands, and this behaviour is accompanied by a shift in N₃ coordination geometry of the di[pyridylmethyl]-amino head group from meridional in the short polymers to facial in the macrocycles (n = 7, 10). In all cases the perchlorate anions are non-coordinating and are thought to have minimal effect of the coordination topology.³⁻ It appears that the longer alkyl chain linkers, by virtue of their greater conformational freedom and ability to engage in efficient close packing with each other in the solid-state, give rise to entropically-favoured macrocyclic coordination topologies. For n = 7 and 10, macrocycle formation is accompanied by a facial arrangement of the N₃-donors, but for n = 11 a geometry closer to meridional is now possible without compromising steric hindrance or packing effects. The short linkers are not able to stabilise M₃L₂ macrocycles due to steric constraints, and in the absence of mitigating intermolecular interactions in the solid-state, adopt the expected catenated structures.

Conclusions

The reaction of M(ClO₄)₂·6H₂O (M = Zn¹¹ or Cu¹¹) with unsymmetrical, ditopic di[pyridylmethyl]amino carboxylate ligands (CₙCOOH) affords species with a 1:1 metal–ligand ratio, both in solution phase and solid-state studies. Reaction conditions (solvents, temperature, concentrations) were kept consistent throughout crystal growth experiments, the only variable being the number of methylene units in the alkyl linker thus allowing the effect of the alkyl chain to be probed. It is apparent that the alkyl linker length has an impact on solid-state coordination topologies with CₙCOOH, ranging from 1D coordination polymers to metallomacrocycles.

Six coordination polymers of short alkyl chain ligands (CₙCOOH, n ≤ 5; Zn¹¹ complexes: 1–3 and Cu¹¹ complexes: 4–6) were isolated and investigated by X-ray crystallography. Of note is the Zn¹¹ coordination polymer 1 (n = 3) which displays intramolecular hydrogen bonding that leads to a wave topology, whereas the Cu¹¹ coordination polymer 4 of the same ligand has an unusual polymeric structure where a carboxylate oxygen atom bridges two Cu¹¹ metal centres of the polymer backbone. The carboxylate ligand in 4 folds back in a “scorpion-like” fashion giving rise to mini cyclic subunits along the polymeric chain. The presence of a methanol solvate molecule appears crucial in the constitution of 4 as a more conventional polymeric structure with lattice water molecules is obtained when other crystallisation solvents are utilised.⁹c

Novel head-to-tail Zn¹¹ macrocycles were formed from the longer alkyl chain ligands (CₙCOOH, n ≥ 7). Crystal

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