Research paper

New flexible bis-pyridyltetrazole ligands for use in coordination polymer formation: Synthesis and structural studies

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ABSTRACT

In this work, we have further developed the pyridyl-tetrazole ligand systems into bis-tetrazole systems, where the linker introduced to join these moieties was a flexible $(CH_2)_3$ backbone, with the intention of forming frameworks with potential voids. We synthesised three different pyridyl-tetrazoles linked *via* this flexible backbone through the pyridine ring and not the tetrazole rings. Two crystals of ligand **1** were solved by X-ray crystallography and showed interesting polymorphism. No crystals of the copper(II) complexes of the ligands could be obtained, suggesting that they were polymeric in nature.

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1. Introduction

Since the report by Robson in 2008 on the design and construction of coordination polymers (CPs) [1], the occurrence of CPs in the literature has increased enormously and covers a multitude of applications, including luminescence, thin films, adsorption, biomedicine, chemical sensors and catalysts [2–9]. The design, synthesis and applications of CPs based on flexible ligands have so far not attracted as much attention as increased flexibility makes it more difficult to forecast and control the final structures due to different ligand conformations. Deng and co-workers synthesised bis-tetrazole methane *in situ* from malononitrile with the aim of expanding the repertoire of tetrazole based CPs [10]. Solvothermal reactions with $CdSO_4$ and $ZnSO_4$ and a secondary ligand, 2,2′-bipyridine, produced 2-D networks whereas when the secondary ligand was changed to 4,4′-bipyridine, a 3-D architecture was generated. Bis-tetrazoles with more flexible $(CH_2)_n$ backbone linkers have also been employed in the synthesis of coordination polymers. Wang and co-workers improved their rigid tetrazole-based ligands [11–13] by introducing flexible $(CH_2)_4$

backbones, aiming to construct helix/loop subunits in polyoxometalates (POMs) [14]. Their occurrence is rare however, possibly due to the many conformations possible resulting from their conformational freedom [15–18]. Nevertheless, it presents an alluring challenge for supramolecular and materials chemists to harness the benefits of flexible ligands in a way that also produces crystalline predictable structures.

In our previous work, we successfully designed a series of pyridyl-tetrazole ligands with a tethered carboxylate group and introduced them into CP systems, and obtained novel networks and multinuclear clusters [19,20]. Our recent work on bis-tetrazole systems with a rigid pyrazine linker resulted in the formation of a cluster of six water molecules within a copper(II) coordination polymer [21]. We have further developed these systems into bis-tetrazole systems, where the linker introduced to join these moieties is a trimethylene moiety, a flexible linker; hence we aimed to make the ligands (**1–3**) presented in Scheme 1. These ligands would have some conformational freedom, and would allow an investigation into the effect of spacer flexibility on coordination polymer structures.

## 2. Results and discussion

2.1. Synthesis of ligands

The synthesis of **1**, **2** and **3** was achieved using the approach depicted in Scheme 1. Access to these ligands was achieved by

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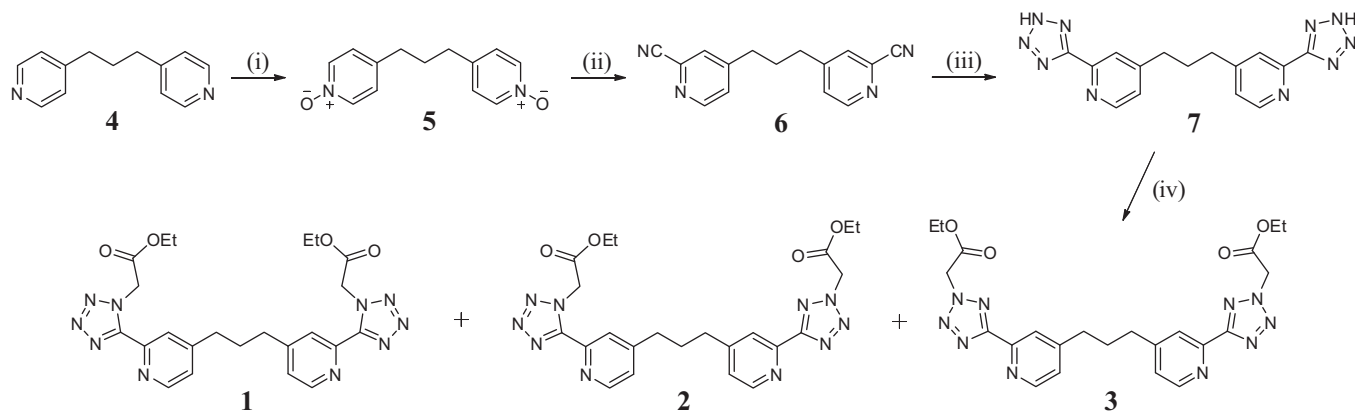
Scheme 1. Reagents and Conditions: (i) H$_2$O$_2$, CH$_3$COOH, 79 °C, 20 h, 75%; (ii) DMCC, Zn(CN)$_2$, DMF, 0 °C, 1 h, 25 °C, 18 h, 34%; (iii) NaN$_3$, NH$_4$Cl, DMF, 110 °C, 10 h, 93%; (iv) K$_2$CO$_3$, BrCH$_2$COOEt, CH$_3$CN, 82 °C, 24 h, 10% (**1**), 16% (**2**), 28% (**3**).

firstly oxidising commercially available 4,4′-trimethylenebipyridine (**4**) to the corresponding 1,3-bis(4-pyridyl)propane-N,N′-dioxide (**5**), following a previously reported procedure [22].

The α-cyanation of **5** has been reported previously by Deng and colleagues, who employed trimethylsilyl cyanide and benzoyl chloride to gain access to the bis-cyano derivative **6** [18]. We undertook α-cyanation of **5** using the conditions of Zn(CN)$_2$ and dimethylcarbamoyl chloride (DMCC) in N,N-dimethylformamide (DMF), since **5** was insoluble in many solvents but it did dissolve in DMF over time. The very reactive acyl chloride can react with DMF to form N,N,N′,N′-tetramethylformamidinium chloride, which are notoriously intractable, dark sticky oils [23–25]. To prevent this undesired reaction from occurring, the acylating agent, DMCC, was added slowly over one hour to a reaction mixture of Zn(CN)$_2$ and **5** in DMF at 0 °C. The reaction was then allowed to slowly warm up to room temperature overnight. After work up and extraction with DCM, the crude mixture was analysed by ^{1}H NMR spectroscopy. The presence of three aromatic signals was observed, indicating successful substitution of the pyridine ring. However, methyl peaks and a singlet at 8.17 ppm were visible in the spectrum, indicating the formation of some N,N,N′,N′-tetramethylformamidinium chloride. The mixture was passed through a silica plug using ethyl acetate and petroleum ether (40–60) as the eluent in a 3:1 ratio. This yielded a white crystalline solid with isolated yields of around 30%. As well as the ^{1}H NMR spectrum displaying three aromatic signals, there was further evidence that a nitrile group was present at the 2-position of the pyridine ring indicated by a sharp peak positioned at 2237 cm^{-1} in the IR spectrum. In the ^{13}C NMR spectrum, a peak concomitant with a nitrile carbon was observed at 117.2 ppm. The collated data acquired for **6** was consistent with that reported by Deng and co-workers [18].

Synthesis of the ligands continued with a 1,3-dipolar cycloaddition using conditions described previously [21]. The product, **7**, was analysed by NMR and IR spectroscopies and HRMS. The IR spectrum of **7** displayed a broad stretch at ∼3386 cm^{-1} which was indicative of the ν(N–H) vibrational mode of the protonated tetrazole. Furthermore, the ν(C≡N) frequency was absent which was anticipated if it had been consumed during the reaction. The presence of two tetrazole rings was also indicated by the ^{1}H NMR spectrum which exhibited five resonances, three aromatic signals and two alkyl chain resonances attributed to the propyl chain protons, which implied a symmetrical system and therefore indicated bis-substitution. The tetrazole quaternary C-5 peak was positioned at 154.9 ppm in the ^{13}C NMR spectrum, which is typical of C-5 resonances of protonated tetrazole rings [26–30]. Finally, HRMS analysis revealed the presence of a molecular ion peak at m/z 335.1476 which

corresponded to a (**7**+H)$^+$ ion. Thus, the data acquired for **7** supported the presence of two tetrazole rings being present.

Alkylation of **7** was then carried out in the presence of base, using ethyl bromoacetate. On analysis of the crude residue by ^{1}H NMR spectroscopy, the spectrum initially appeared complicated. However, it could be deduced that there were three products present in the mixture, most plausibly the N-1, N-1′ (**1**), N-1, N-2′ (**2**) and N-2, N-2′ (**3**) substituted regioisomers. The crude mixture was separated by flash column chromatography using a gradient system. The separated fractions were analysed by NMR spectroscopy and the ^{13}C NMR spectra of the compounds revealed the substitution on the tetrazole rings. The first product to elute was the N-1, N-1′ regioisomer (**1**), as indicated by the single C-5 resonance peak at 152.2 ppm. The second product to elute was the N-1, N-2′ regioisomer (**2**) as indicated by the additional ^{13}C resonances present which supported the presence of asymmetry in the molecule. The ^{13}C NMR spectrum exhibited a C-5 resonance at 164.1 ppm for the N-2 substituted ring and at 151.4 ppm for the N-1 substituted ring. The ^{1}H NMR spectrum also clearly showed that this was the case (Fig. 1). The spectrum showed the same trends as seen in previous alkylated tetrazoles, with the N-1 methylene group being more deshielded in the N-1 substituted tetrazoles than the N-2 substituted tetrazole rings [21,26–30]. The final product that eluted was the N-2, N-2′ regioisomer (**3**) which was confirmed by ^{13}C NMR spectroscopy where the single C-5 resonance for the tetrazole ring resonated at 164.8 ppm.

These ligands would possess distinctive advantages in that they could provide multiple coordination sites by virtue of possessing pyridine and tetrazole N donor atoms and carboxylate O donor atoms. Furthermore, the carboxylate groups could allow for an expansion in dimensionality and the relatively long spacer and the two pyridyl groups can rotate along its C–C bonds to form nine main configurations, thereby enabling the ligand to adopt versatile coordination modes and conformations [18].

2.2. X-ray structures of ligand **1** (orthorhombic and triclinic polymorphs)

Single crystals of **1** were grown and analysed by X-ray crystallography (Figs. 2 and 3) and yielded two polymorphs, one in space group *Pna*2$_1$ (two molecules in the asymmetric unit) and the second in triclinic *P*$\bar{1}$ (No. 2). The plate-like crystal of the *Pna*2$_1$ polymorph was obtained from the mother liquor whilst the block-like crystal of the *P*$\bar{1}$ polymorph was obtained from a methanol solution of **1** with zinc chloride. No zinc complex was obtained from the latter reaction. Molecules A and B of **1** in the *Pna*2$_1$ structure