Coordination [Co$^{II}_2$] and [Co^{II}Zn] helicates showing slow magnetic relaxation

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Supporting Information Placeholder

ABSTRACT: The slow magnetic relaxation of Co(II) in the elusive intermediate geometry between trigonal prism and trigonal antiprism has been studied on the new [Co$_2$L$_3$]$^{4+}$ and [CoZnL$_3$]$^{4+}$ coordination helicates (L is a bis-pyrazolylpyridine ligand). Solution paramagnetic ^{1}H-NMR and solid-state magnetization measurements unveil single-molecule magnet behavior with small axial anisotropy, as predicted previously.

Controlling the magnetic states of certain molecules, the so-called single-molecule magnets, SMMs,[1-4] opens wide possibilities for creating new devices for ultrahigh-density information storage.[5-6] SMMs are paramagnetic *d-* or *f*-metal complexes with large magnetic anisotropy, resulting in slow magnetic relaxation of the magnetic moment.[7-14] Among first row transition metal SMMs, cobalt complexes have the largest barrier of magnetization reversal,[15-18] which in the case of a two-coordinate linear cobalt(II) complex[19] approaches the theoretical limit in that environment of 450 cm^{-1}. These complexes and their cobalt(I),[20] iron(I)[21] and iron(II)[22] analogues are, however, unstable, making any possible technological applications extremely challenging.

Among other coordination environments that also ensure large magnetic anisotropy of cobalt(II) while keeping the complex chemically stable, a trigonal prism (TP) recently emerged as an ideal geometry.[17, 23] Despite some recent examples acting as SMMs,[18, 24-25] these compounds remain unusual, as the TP geometry is limited to rather exotic rigid clathrochelate ligands.[26] More common scorpionate-like ligands often lead to trigonal antiprism (TAP) geometries,[27]

where slow relaxation is only observed under an applied magnetic field.[28-30] A distortion from a TP towards a TAP geometry (Bailar twist) reduces further the SMM performance with respect to both ideal polyhedra.[31] It was even predicted[32] that at an angle φ of ca. 40° (φ = 0° and φ = 60° for ideal TP and TAP, respectively) the axial parameter, *D*, of the zero field splitting (ZFS) changes its sign; however, no experimental data on the SMM behavior have been collected for the cobalt(II) complexes with trigonal symmetry and φ between 24 and 57°, which should provide a better understanding of magneto-structural correlations for cobalt(II)-based SMMs.

We have synthesized a new cobalt(II) dinuclear helicate from a new bis(pyrazolylpyridine) ligand (L, 1,3-bis[1-(pyridine-2-yl)-pyrazol-3-yl]benzene),[33] which ensures trigonal geometry, intermediate between the TP and the TAP, around the metal ion. Indeed, the analogous helicates with Fe(II) feature φ ≈ 30.[33-34] Besides the desired coordination geometry, this helicate exhibits two metal centers, which might modulate the SMM properties of the corresponding cobalt(II) ions by exchange bias.[35] We have employed this compound to study the magnetic relaxation of Co(II) in this elusive intermediate geometry. To analyze the mutual effect of the Co(II) ions within the **[Co$_2$]** molecule, we have also prepared the mixed metal **[CoZn]** helicate, as part of a solid solution with the homometallic analogue; **[Zn$_2$]**. For comparison and for further support, the pure **[Zn$_2$]** has been prepared and characterized.
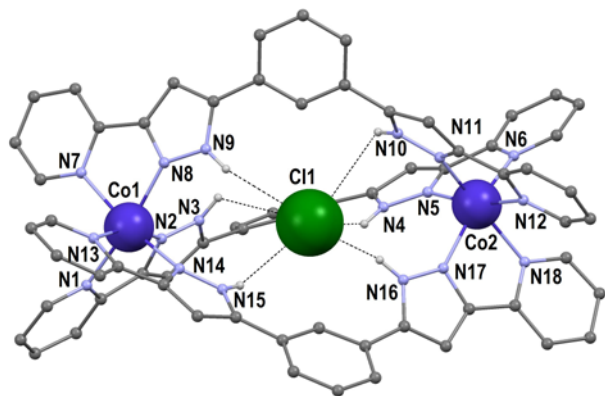
Figure 1. Molecular structure of $(Cl@[Co_2L_3])^{3+}$ in **1**. Only heteroatoms are labelled, with C and H shown in dark and light grey, respectively. Only H atoms that are part H–bonds (dashed lines) are shown.

The triple stranded **[Co₂]** helicate, with formula $Cl@[Co_2L_3]Cl(PF_6)_2$ (**1**), has one of its four anions encapsulated as a Cl⁻ species inside its cavity (see below). Since the helical structure has never been isolated without of a Cl⁻ or a Br⁻ guest, it is likely that the latter acts as a stabilizing template. Empty specimens have been only detected *via* mass spectrometry (MS). Complex **1** forms as orange crystals after mixing stoichiometric amounts of $CoCl_2 \cdot 6H_2O$ and L in MeOH, with two equivalents of NBu_4PF_6, followed by the slow diffusion of diethylether. The analogous procedure using $ZnCl_2$ produces $Cl@[Zn_2L_3]Cl(PF_6)_2$ (**2**) as colorless crystals. The yield of **2** is poorer than **1**, presumably due to its higher solubility.

Crystals of both compounds were suitable for single-crystal X-ray diffraction (SCXRD, see below). To obtain the heterometallic **[CoZn]** analogue, the same synthesis was repeated using an equimolar mixture of the Co and the Zn salts. The MS of the resulting orange crystals revealed only the presence of **[Co₂]**, suggesting a higher propensity of the latter to crystallize over that of any zinc analogue and/or a higher stability in the MS conditions. To force the detection of the **[CoZn]** species, the reaction was performed with Co and Zn in the 1:9 ratio. The MS of the resulting pale orange crystals unveiled the presence of the **[Zn₂]** and **[CoZn]** helicates while **[Co₂]** was detected in a smaller amount. This is consistent with metal analysis and SCXRD (see below), which suggest the formulation $(Cl@[CoZnL_3])_{0.19}(Cl@[Zn_2L_3])_{0.31}Cl(PF_6)_2$ (**3**) and shows that the system does not favor the segregation into homometallic species. Analysis of ¹H NMR data (see below) reveals that the presence of the **[Co₂]** species in (**3**) is in fact marginal, confirming that under the MS conditions, its occurrence is magnified due to a higher stability.

Compounds **1**, **2** and **3** are isostructural if small differences in lattice solvent molecules and crystallographic disorder are not considered, therefore, details will only be provided for **1**. Complete structural information for all three compounds is collected as Supplementary Material. The space group is the tetragonal $I4_1cd$. The asymmetric unit of **1** contains one $(Cl@[Co_2L_3])^{3+}$ species, one Cl⁻ and two PF_6^- disordered anions, together with four molecules of MeOH and one partially occupied (0.25%) molecule of diethylether. The

$(Cl@[Co_2L_3])^{3+}$ ensemble (Fig. 1) is a dinuclear triple-stranded helicate comprising a central axis that contains two Co(II) ions lying 9.771 Å apart. These metals are held together by three L ligands that chelate them through their two pyrazolylpyridyl moieties, furnishing a chiral, distorted trigonal environment that is intermediate between the TP and the TAP, with a distortion angle, φ, of about 38°. This angle is close to that for which the sign of the axial zero field splitting (ZFS) parameter, *D*, is expected to change in six coordinate Co(II) (see above).[32] The chirality around both metals of each molecule is the same, and by symmetry, both possible enantiomers (Δ–Δ and Λ–Λ) are present in equal amounts in the lattice. The three ligands feature a total of six N–H moieties from the pyrazolyl groups, pointing towards the interior of its central cavity, perfectly poised to encapsulate the Cl⁻ guest *via* six [N–H···Cl] hydrogen bonds. The helical ensembles occur approximately in sheets along the *ab* plane, with the PF_6^- anions localized in between them (SI). Several π···π and C–H···π interactions connect the $(Cl@[Co_2L_3])^{3+}$ species within the sheets.

Trigonal symmetry of the $(Cl@[Co_2L_3])^{3+}$ species also follows from ¹H NMR data collected in methanol-d⁴ (Fig. 2a), which is consistent with MS experiments. As expected for an SMM, large paramagnetic shifts are observed.[36-37] However, while large values of axial anisotropy of the magnetic susceptibility tensor at room temperature is often a sign of SMM behavior,[17-18] the assembly $(Cl@[Co_2L_3])^{3+}$ has a very moderate value of $\Delta\chi_{ax} = 0.05$ Å³ (see SI). This is in contrast with other complexes with both the TP $(\Delta\chi_{ax} = 0.26$ Å³)[18] and TAP $(\Delta\chi_{ax} = 0.21$ Å³)[38] geometries. The possible reasons are either the intermediate TP-TAP geometry of the **[Co₂]** assembly or the intramolecular magnetic interaction between both Co(II) ions. To estimate the contribution of the latter, we examined the heterometallic species $(Cl@[CoZnL_3])^{3+}$; the nature of its synthesis leads to an admixture calculated on the ¹H NMR spectrum of 13% of the **[CoZn]** complex and 87% of the **[Zn₂]** one, with detection of only trace amounts of the **[Co₂]** complex.
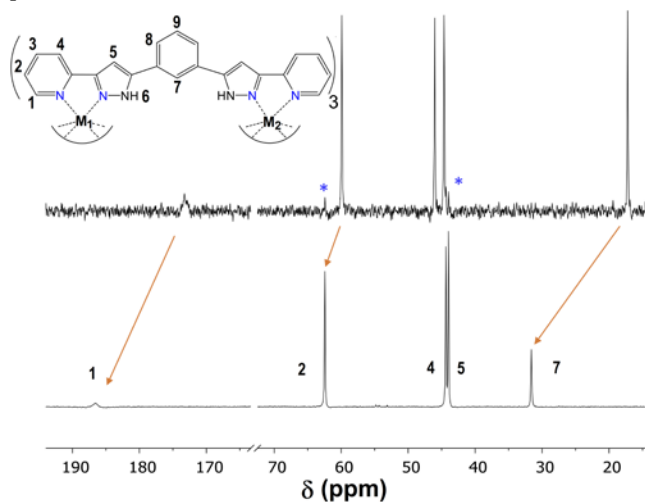

Figure 2. Paramagnetic part of the ¹H NMR spectra of $(Cl@[Co_2L_3])^{3+}$ (bottom) and $(Cl@[CoZnL_3])^{3+}$ (top) in methanol-d⁴ at 290 K and their assignment. The signals of $(Cl@[Co_2L_3])^{3+}$ not detected in the top spectrum are shown by asterisks.

The ^{1}H NMR spectrum of the target complex **[CoZn]** differs significantly from that of the parent **[Co₂]** complex. The signals for the protons close to the Co(II) ion are indeed paramagnetically shifted in a similar manner; however, those close to the zinc(II) ion are not. Moreover, the paramagnetic shift observed for proton **7** (Fig. 2), which is located on the bridging phenyl moiety in between the two metal ions, exhibits a much larger shift in the **[Co₂]** complex than in the heterometallic one, where it only feels one cobalt(II) ion. The value of $\Delta\chi_{ax}$ estimated from the NMR spectrum for **[CoZn]** (0.05 Å³) is virtually the same as the one estimated for the complex **[Co₂]**. Therefore, the low magnetic anisotropy is not caused by intramolecular magnetic interactions but results from the distorted TP-TAP geometry.

To support these findings from NMR spectroscopy, we turned to dc-magnetometry. Molar magnetic susceptibility (χ) measured for a fine crystalline sample of **1** at 2–300 K confirms the Co(II) high-spin state over the entire temperature range (Fig. 3a). At room temperature, the measured χT value (5.7 cm³mol⁻¹K) is larger than the spin-only value for two non-interacting high-spin Co(II) ions (3.75 cm³mol⁻¹K), which indicated the influence of spin-orbit coupling. The decrease in χT observed upon cooling results also from spin-orbit coupling effects. Complex (Cl@[CoZnL₃])³⁺ shows exactly the same behaviour, after accounting for the dilution by the diamagnetic analog (Cl@[Zn₂L₃])³⁺ and the presence of only one cobalt(II) ion. This clearly demonstrates the absence of any significant intra- or intermolecular magnetic interactions in the solid state of (Cl@[Co₂L₃])³⁺.
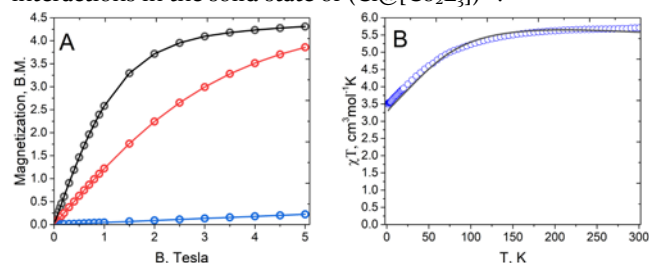
Figure 3. (A) Isothermal magnetization *vs.* field plots of (Cl@[Co₂L₃])³⁺ at 2 K (black), 5 K (red) and 100 K (blue). (B) Variable-temperature magnetic susceptibility under applied d.c. field of 1 kOe (circles). The parameters used to obtain the fits (solid lines) are in Table S4.

By simultaneously fitting the data from dc-magnetometry and temperature-dependent NMR spectroscopy to appropriate Spin Hamiltonians (see SI for details, Table S5), we estimated the energy of the first excited magnetic state in (Cl@[Co₂L₃])³⁺ to be at least 174 cm⁻¹ (Table S6) and established Ising-type magnetic anisotropy. X-Band EPR was used to shed light into the magnetic structure.[39] Interestingly, the spectra of (Cl@[Co₂L₃])³⁺ and (Cl@[ZnCoL₃])³⁺ are quite different from those seen in cobalt(II) complexes with a TAP geometry. Instead of well-resolved EPR spectra with a clear axial component,[40-42] both compounds give the same set of broad lines, indicating a symmetry lower than trigonal and/or as the result of a complicated magnetic behavior (see SI).

To probe the spin dynamics of these complexes, we also performed ac-magnetometry measurements on **1** and **3**. In zero magnetic field, no out-of-phase signal was detected even at 2 K. This agrees with a small anisotropy, as expected from an angle φ close to 40°. Another explanation could be

the presence of fast zero-field tunneling relaxation. Indeed, under a dc field of 100 Oe a signal was observed for both complexes (Figs. S17), revealing slow magnetic relaxation under these conditions.

A fit with the generalized Debye model yielded the field dependence of the relaxation time τ, very similar for both complexes (Fig. 4a); τ initially increases with the magnetic field and drops sharply at higher fields. The latter is a sign of the direct relaxation mechanism, causing τ^{-1} to be nearly proportional to H⁴, as expected for a Kramers system.[43] The small differences between both complexes likely result from larger intermolecular dipolar interactions in **[Co₂]**.

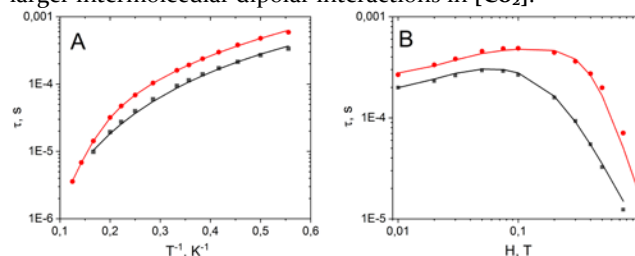Figure 4. (A) Field dependence of τ at 2 K for (Cl@[Co₂L₃])³⁺ (black) and (Cl@[CoZnL₃])³⁺ (red) and (B) its temperature dependence in an optimal field of 1 kOe. Parameters used to obtain the fits (solid lines) are collected in Table S5.

Analyses of temperature-dependent ac-data under an optimal field of 1000 Oe (Fig. S18) produced non-linear Arrhenius plots (Fig. 4b) that are again remarkably similar for both complexes. These dependencies can be reproduced invoking quantum tunneling ($B_1/(1 + B_2H^2)$), direct (AH^nT), Raman (CT^m) and Orbach ($\tau_0 \exp(-\Delta/k_BT)$) relaxation processes (Table S5). The obtained values for the Orbach relaxation barrier (Δ) were significantly smaller than expected from dc-magnetometry and NMR data, which is consistent with the data obtained previously for other Co(II)-based SMMs, where the magnetic relaxation was described using a combination of Raman and direct relaxation pathways with no Orbach contribution,[25, 44-45] or where the Orbach barrier was smaller than predicted by other methods.[46-48]

In conclusion, two new complexes are presented with Co(II) ions in a trigonal geometry intermediate between TP-TAP that reduces the large magnetic anisotropy observed in complexes with either of both geometries, verifying previously published predictions. The TAP geometry facilitates high magnetic anisotropy large contributions from non-Orbach relaxation mechanisms, suggesting the search for complexes with TP geometry. The elusive intermediate coordination polyhedron shown here is intriguing and worth studying. We are now exploring ways of enforcing or tuning it by introducing capping fragments to the pyridine moieties of L or modifying the bridging phenylene to vary the torsion at will.

ASSOCIATED CONTENT

Supporting Information

Synthesis, X-ray crystallography, magnetic measurements, NMR and theoretical calculations are in the SI. This material is available free of charge via the Internet at http://pubs.acs.org."

Author Contributions

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SYNOPSIS TOC The new supramolecular coordination helicates (Cl@[Co$_2$L$_3$])$^{3+}$ and (Cl@[CoZnL$_3$])$^{3+}$ contain Co(II) ions in a coordinate geometry in between trigonal prism (TP) and antiprism (TAP). A combination of solid state and solution magnetic studies unveil the slow relaxation of the magnetization of these ions, despite the low axial magneto-anisotropy, here detected as previously predicted for this geometry.