Constructing [Co$_6^{I I}$] hexagon-centered heterometallic {Ln$_6$Co$_6$} (Ln = Y, Eu and Dy) clusters with a calix[8]arene ligand†

Haitao Han,$^{a,b}$ You-Song Ding, $^{c}$ Xiaofei Zhu, $^{a}$ Tian Han, $^{c}$ Yan-Zhen Zheng $^{b,c}$ and Wuping Liao $^{d,*}$

Three isostructural 3d–4f polynuclear clusters {(Ln$_6^{II}$Co$_6^{II}$)(C8A)$_3$} (Ln = Y (CIAC-248), Eu (CIAC-249), Dy (CIAC-250)); C8A = p-tert-butylcalix[8]arene) were synthesized under solvothermal conditions. These three compounds feature some tripod-like entities in which three Ln$_2$-C8A secondary building units acting as the legs bolster a [Co$_6$] hexagon. Magnetic study indicated that the complex {(Eu$_6^{II}$Co$_6^{II}$)(C8A)$_3$} (CIAC-249) exhibits spin glass behaviour at $\approx 9$ K, and the complex {(Dy$_6^{II}$Co$_6^{II}$)(C8A)$_3$} (CIAC-250) shows slow relaxation of magnetization.

Introduction

Heterometallic 3d–4f clusters have attracted considerable attention due to their fascinating structures, interesting magnetic properties such as single-molecule magnet (SMM) behaviour, and potential applications in high-density information storage and quantum computing.$^1$–$^3$ Commonly, the syntheses of these types of clusters are based on some shielded or multi-dentate ligands which can act as the magnetic coupling mediator. Calixarenes have been proven to be excellent multi-dentate ligands to construct single-molecule magnets due to their polyphenolic nature, which can not only induce ferromagnetic or antiferromagnetic coupling efficiently but also assume diverse coordination modes. To date, there have been some reports on the construction of paramagnetic molecular clusters with calixarenes. For example, Dalgarno and Brechin,$^4$–$^7$ applied methylene-bridged calix[4]arene in the construction of SMMs and magnetic coolers. We,$^8$–$^{13}$ and others$^{14}$–$^{16}$ used thia- and sulfonyl-bridged calix[4]arenes for the preparation of polynuclear clusters possessing interesting magnetic properties. However, to the best of our knowledge, polynuclear clusters based on larger calixarenes such as p-tert-butylcalix[8]arene with SMM properties and ferromagnetic ordering behaviours are rare.$^{14}$–$^{16}$ Compared to calix[4]arene, calix[8]arene, which has more coordination sites, variable conformation and higher flexibility, may generate novel materials with interesting properties.$^{17}$–$^{18}$ In addition, a carbonate anion is also a good bridge due to its various bridging modes, such as $\mu_2$-CO$_3$$^{2-}$,$^{19}$–$^{20}$ $\mu_1$-CO$_3$$^{2-}$,$^{21}$–$^{22}$ $\mu_3$-CO$_3$$^{2-}$,$^{23}$–$^{24}$ and $\mu_6$-CO$_3$$^{2-}$.$^{25}$–$^{27}$ Furthermore, we found that calix[8]arene adopting a double cone conformation can form a Ln$_2$-C8A secondary building unit (SBU) when reacting with lanthanide ions and the Ln$_2$-C8A SBUs can bond some transition metals (TM) to form heterometallic 3d–4f clusters. Here, we present the crystal structures and magnetic properties of three {(Ln$_6^{II}$Co$_6^{II}$)(C8A)$_3$} compounds (Ln = Y (CIAC-248), Eu (CIAC-249), Dy (CIAC-250)); C8A = p-tert-butylcalix[8]arene) incorporating a central $\mu_6$-carbonate anion. These compounds exhibit ferromagnetic long-range ordering or SMM properties.

Experimental

Starting materials

All starting materials were of analytical reagent grade and used as received without further purification. p-tert-Butylcalix[8]arene was prepared according to the literature method.$^{28}$

Syntheses of compounds CIAC-248–250

{(Y$_6$Co$_6$)(C8A)$_3$(CH$_3$OH)$_6$(CH$_3$COO)$_2$}·23H$_2$O, 0.35CH$_3$OH[(C$_6$H$_5$)$_2$NH] (CIAC-248). Blue block crystals were obtained by the solvothermal reaction of a mixture of

‡These authors contributed equally.
C8A (0.065 g, 0.04 mmol), Co(CH3COO)2·4H2O (0.038 g, 0.15 mmol), Y(CH3COO)3·6H2O (0.04 g, 0.39 mmol), CH3OH (6 mL), triethylamine (1.1 mL) and several drops of DMF in a 20 mL Teflon-lined autoclave which was kept at 150 °C for 3 days and then slowly cooled to room temperature at about 4 °C h−1. The crystals were isolated by filtration and washed with methanol and dried under air. Yield: 36% with respect to Y. Elemental analysis (%): calcd for [C292H390Y6Co6N6O45] (excluding disordered solvent molecules): C, 62.73; N, 1.50; H, 6.98. Found: C, 62.23; N, 1.31; H, 6.31. FT-IR (KBr pellet, cm−1): 3527(w), 2955(s), 1650(s), 1569(w), 1454(s), 1387(m), 1360(m), 1293(s), 1212(s), 1125(w), 1044(m), 909(w), 875(w), 822(m), 754(m), 674(w).

\[\text{([(Eu}_{6}\text{Co}_{6})(\text{C}_{8}\text{A})_{3})(\text{CH}_{3}\text{OH})_{5}(\text{CH}_{3}\text{OO}^{-})(\text{DMF})_{6}(\text{CH}_{3}\text{COO}^{-})_{3}]_{2}\text{H}_{2}\text{O} \cdot [(\text{C}_{2}\text{H}_{5})_{3}\text{NH}^{+})] \text{(CIAC-249)}} \]

The procedure was similar to the synthesis of CIAC-249 except that Y(CH3COO)3·6H2O was substituted with Eu(CH3COO)3·6H2O. The crystals were isolated as blue block crystals in 32% yield based on Eu. Elemental analysis (%): calcd for [C292H390Eu6Co6N6O45] (excluding disordered solvent molecules): C, 62.23; N, 1.31; H, 6.31. FT-IR (KBr pellet, cm−1): 3527(w), 2955(s), 1650(s), 1569(w), 1454(s), 1387(m), 1360(m), 1293(s), 1212(s), 1125(w), 1044(m), 909(w), 875(w), 822(m), 754(m), 674(w).

\[\text{([(Dy}_{6}\text{Co}_{6})(\text{C}_{8}\text{A})_{3})(\text{CH}_{3}\text{OH})_{5}(\text{CH}_{3}\text{OO}^{-})(\text{DMF})_{6}(\text{CH}_{3}\text{COO}^{-})_{3}]_{2}\text{H}_{2}\text{O} \cdot [(\text{C}_{2}\text{H}_{5})_{3}\text{NH}^{+})] \text{(CIAC-250)}} \]

The procedure was similar to the synthesis of CIAC-248 except that Y(CH3COO)3·6H2O was substituted by Dy(CH3COO)3·6H2O. The crystals were isolated as blue block crystals in 32% yield based on Dy. Elemental analysis (%): calcd for [C292H390Dy6Co6N6O45] (excluding disordered solvent molecules): C, 58.76; N, 1.41; H, 6.54. Found: C, 58.49; N, 1.32; H, 6.65. FT-IR (KBr pellet, cm−1): 3528(w), 2953(s), 1656(s), 1466(s), 1396(m), 1358(m), 1293(s), 1217(s), 1125(w), 1027(m), 908(w), 876(w), 821(m), 754(m), 674(w).

Results and discussion

Single-crystal X-ray diffraction analysis reveals that compounds CIAC-248–250 are isostructural and feature a tripod-like unit composed of a wrapped \{Co6\} hexagon and three LnII-C8A SBUs (Fig. 1). So compound CIAC-250 is described in detail as an example. Complex CIAC-250 crystallizes in the monoclinic system with the space group C2/c. In the structure, three p-tert-butylcalix[8]arene molecules adopt the double cone conformation. Each conic subunit of the calix[8]arene molecule binds a Dy atom through its oxygen atoms at the lower rim so that a Dy2-C8A secondary building unit (SBU) is formed, which is a common unit found in the compounds of 4f/5f metals and calix[8]arene. Six adjacent Co atoms are bonded to the same \(\mu_6\)CO32− anion in situ generated from the decomposition of DMF to form a \{Co6\} hexagonal plate. Furthermore, this hexagon is bolstered by three Dy2-C8A SBUs to form a tripod-like \([(\text{LnIII}_{6}\text{Co}_{6})(\text{C}_{8}\text{A})_{3}]_{2}\) entity (Fig. 2 and 3). It should be noted that all three calix[8]arene molecules in an isolated entity are nearly perpendicular to the planar \{Co6\} hexagon (Fig. S3†). The extended structure of compound CIAC-250 is stacked by these dodecanuclear heterometallic units through supramolecular interactions (Fig. S4†).

For the \(\text{LnII}_{6}\text{Co}_{6}\) core, there are twelve crystallographically independent metal sites which have three types of coordination. Each Co atom is five coordinated in a distorted trigonal bipyramid coordination geometry. The coordination geome-

Fig. 1 Molecular structure of compound CIAC-250. Hydrogen atoms and solvent molecules are omitted for clarity. Blue: Co atoms; green: Dy atoms; red: O atoms; gray: C atoms.
It is noted that the 3d\textsuperscript{2.18} complexes was measured up to 7 T at low temperatures (Fig. S6). The variable-temperature direct current (dc) magnetic susceptibility \(\chi T\) value at 300 K (31.10 emu K mol\(^{-1}\)) is much larger than that of CIAC-248. Such a large value is due to a certain amount of magnetic moment from the excited states (e.g., \(7F_1\)) of the Eu(III) ion. The \(\chi T\) value is about 1.87 emu K mol\(^{-1}\) for each Eu ion at room temperature based on complex CIAC-248, which is close to the reported value.\(^\dagger\) The \(\chi T\) values decrease slowly as the temperature decreases to 12.56 emu K mol\(^{-1}\) at 22 K, followed by a sharp increase to a maximum value of 26.81 emu K mol\(^{-1}\) at 8.7 K, which indicates ferromagnetic interactions in the \(\{\text{Eu}_6\text{Co}_6\}\) cluster, and then drop to 10.03 emu K mol\(^{-1}\) at 2 K. The field dependence of magnetizations for CIAC-249 gives a small value of 5.98 \(\mu_B\) at 2 K and 7 T, which is close to those of CIAC-248, in accordance with the diamagnetic ground state of Eu(III) ions.

For CIAC-250, the \(\chi T\) value at room temperature (97.56 emu K mol\(^{-1}\)) is consistent with the expected value of six uncoupled Dy(III) ions \(S = 5/2, L = 5, g = 4/3, {^4}\text{H}_{15/2}\) and six isolated Co(II) ions. The \(\chi T\) value is smaller than the expected value with the orbital angular momentum from Co(II) ions, owing to the antiferromagnetic coupling between Dy(III) and Co(II). The \(\chi T\) values decrease gradually from 300 to 50 K and much rapidly below 50 K. At 2 K, the \(\chi T\) value is 34.55 emu K mol\(^{-1}\) and the maximum \(M\) value is 34.82 \(\mu_B\) at 7 T. This unsaturation \(M\) value indicates the presence of magnetic anisotropy and/or low-lying excited states in the system. The program PHI was used to fit the magnetic susceptibility of CIAC-248 with a minimal model (eqn (1)),\(^3\) which can reproduce the temperature-dependent susceptibility at the temperature range from 50 K to 300 K (Fig. 4) and provide a reasonable estimate of the intramolecular magnetic exchange coupling \(J\) between the Co(II) ions. The best simulation gives \(J = -3.15\) cm\(^{-1}\) with \(g = 2.73\). Attempts for fitting the lower temperature data failed, probably due to the interplay and competition of spin-orbital interactions of the Co(II) centers and possible antiferromagnetic coupling between Co(II) ions. The magnetization for CIAC-248 increases slowly with the field and reaches a maximum value of 6.30 \(\mu_B\) at 2 K and 7 T.

For CIAC-249, although the Eu(III) ion \(J = 0, {^7}\text{F}_0\) possesses a diamagnetic ground state, the \(\chi T\) value at 300 K (31.10 emu K mol\(^{-1}\)) is much larger than that of CIAC-248. Such a large value is due to a certain amount of magnetic moment from the excited states (e.g., \(7F_1\)) of the Eu(III) ion. The \(\chi T\) value is about 1.87 emu K mol\(^{-1}\) for each Eu ion at room temperature based on complex CIAC-248, which is close to the reported value.\(^\dagger\) The \(\chi T\) values decrease slowly as the temperature decreases to 12.56 emu K mol\(^{-1}\) at 22 K, followed by a sharp increase to a maximum value of 26.81 emu K mol\(^{-1}\) at 8.7 K, which indicates ferromagnetic interactions in the \(\{\text{Eu}_6\text{Co}_6\}\) cluster, and then drop to 10.03 emu K mol\(^{-1}\) at 2 K. The field dependence of magnetizations for CIAC-249 gives a small value of 5.98 \(\mu_B\) at 2 K and 7 T, which is close to those of CIAC-248, in accordance with the diamagnetic ground state of Eu(III) ions.

For CIAC-250, the \(\chi T\) value at room temperature (97.56 emu K mol\(^{-1}\)) is consistent with the expected value of six uncoupled Dy(III) ions \(S = 5/2, L = 5, g = 4/3, {^4}\text{H}_{15/2}\) and six isolated Co(II) ions. The \(\chi T\) value is smaller than the expected value with the orbital angular momentum from Co(II) ions, owing to the antiferromagnetic coupling between Dy(III) and Co(II). The \(\chi T\) values decrease gradually from 300 to 50 K and much rapidly below 50 K. At 2 K, the \(\chi T\) value is 34.55 emu K mol\(^{-1}\) and the maximum \(M\) value is 34.82 \(\mu_B\) at 7 T. This unsaturation \(M\) value indicates the presence of magnetic anisotropy and/or low-lying excited states in the system. The program PHI was used to fit the magnetic susceptibility of CIAC-248 with a minimal model (eqn (1)),\(^3\) which can reproduce the temperature-dependent susceptibility at the temperature range from 50 K to 300 K (Fig. 4) and provide a reasonable estimate of the intramolecular magnetic exchange coupling \(J\) between the Co(II) ions. The best simulation gives \(J = -3.15\) cm\(^{-1}\) with \(g = 2.73\). Attempts for fitting the lower temperature data failed, probably due to the interplay and competition of spin-orbital interactions of the Co(II) centers and possible antiferromagnetic coupling between Co(II) ions. The magnetization for CIAC-248 increases slowly with the field and reaches a maximum value of 6.30 \(\mu_B\) at 2 K and 7 T.

The \(\chi T\) plots for CIAC-248, 249 and 250 under a 1 kOe dc field. The solid line is the best fit.

---

Fig. 2 Scheme of the assembly of compound CIAC-250.

Fig. 3 Arrangement of the metal ions of compound CIAC-250.

---

The variable-temperature direct current (dc) magnetic susceptibility data for all compounds were collected under a 1 kOe applied field at the temperature range of 2–300 K (Fig. 4), and the field \(H\) dependence of the magnetizations \(M\) for these three complexes was measured up to 7 T at low temperatures (Fig. S6–S8). The \(\chi T\) value for CIAC-248 is 19.88 emu K mol\(^{-1}\) at room temperature, which is larger than the spin-only value (11.25 emu K mol\(^{-1}\)) expected for six uncoupled Co(II) ions \(S = 3/2, g = 2.0\), owing to the contribution from the orbital angular momentum. Upon cooling, the \(\chi T\) value decreases slowly and reaches 5.75 emu K mol\(^{-1}\) at 2 K, presumably corresponding to the depopulation of higher Kramers doublets.
coupling and magnetic interactions. The alternating current (ac) susceptibility measurement of CIAC-248 at the frequency of 1488 Hz with a zero dc field displays a paramagnetic property (Fig. S9†), thus showing neither magnetic ordering nor slow relaxation of the magnetization above 2 K.

$$\hat{H} = -2J\left(\sum_{i=1}^{5} S_i S_{i+1} + S_6 S_1\right) + g\mu_B \sum_{i=1}^{6} S_i H \quad (1)$$

As complex CIAC-249 shows a peak at 8.7 K in its $\chi T$--$T$ plots, further magnetic investigation was performed. The zero-field cooled (ZFC) and field-cooled (FC) magnetic susceptibility for CIAC-249 was recorded under a field of 50 Oe. Both the peak of the ZFC curve and the divergence of the ZFC and FC curves appear at about 9.2 K (Fig. 5), indicating a transition from a paramagnetic state to either a long-range ordering, a spin-glass state or a superparamagnetic state. Magnetic hysteresis measurements show a clear hysteresis loop at 2 K with a coercivity field of 580 Oe and a remnant magnetization of 0.38$\mu_B$, and a closed hysteresis loop at 9 K, indicative of a magnet behavior (inset in Fig. 5 and Fig. S13†).

Ac magnetic susceptibility measurements for CIAC-249 were further carried out under a zero dc field. Wide peaks of the in-phase ($\chi '$) and out-of-phase ($\chi ''$) signals were observed between 8 K and 10 K with a very weak frequency dependence, supporting the existence of spin glassy behavior (Fig. 6). The parameter $\phi = (\Delta T_p/T_0)/(\log f)$ was estimated as 0.02, which falls into the range of a spin glass and excludes a superparamagnet. We tried to fit the relaxation times at various temperatures via the Arrhenius law ($\tau = \tau_0 \exp(U_{\text{eff}}/k_B T)$, where $\tau_0$ is a pre-exponential factor and $U_{\text{eff}}$ is the energy barrier), and obtained $\Delta E = 1176$ K and $\tau_0 = 2.43 \times 10^{-57}$ s (Fig. S10†). This rather fast $\tau_0$ also excludes the possibility of an SMM. Those behaviours are similar to other Co clusters with spin glass behaviours. For CIAC-249, the spin glassy behavior probably is attributed to the weak magnetic moment from Eu(III) ions that modified the magnetic coupling between Co(II) ions. Every Eu$_2$ C8A SUB bridges two Co(II) ions (Co$_2$ dimer), and three Co$_2$ dimers result in a triangular structure. Such a triangular geometry often leads to spin frustration with spin-glass ground state.

The magnetic dynamics for CIAC-250 was studied using ac magnetic susceptibility measurements under a zero dc field. As shown in Fig. 7, $\chi '$ signals diverge at nearly 30 K without reaching the maximum (except for high frequencies) and splitting tails of $\chi ''$ signals were observed above 2 K, indicating the slow relaxation of magnetization, a characteristic SMM behaviour, but with the existence of fast quantum tunneling of magnetization (QTM). The parameter $\phi$ is calculated as 0.51, which is larger than the value for a spin glass, but close to a superparamagnetic behaviour. The relaxation times ($\tau$) at different temperatures for CIAC-250 are evaluated from variable-frequency data via a generalized Debye model (Fig. S11 and S12†). The obtained ln($\tau$) values remain linear between 5.4 and 3.5 K, showing a thermally activated process, which can be fitted by the Arrhenius law, giving $U_{\text{eff}} = 41.5$ K and $\tau_0 = 8.50 \times 10^{-57}$ s.

Fig. 5 $\chi T$ plots of CIAC-249 under field-cooled (FC) and zero-field-cooled (ZFC) conditions with a field of 50 Oe. Inset: Field-dependent magnetizations for complex CIAC-249 from 0 to 50 kOe at 2 K.

Fig. 6 Temperature dependence of the in-phase ($\chi '$) and out-of-phase ($\chi ''$) ac susceptibility signals under a zero dc field at the indicated frequencies for CIAC-249.

Fig. 7 Temperature dependence of the in-phase ($\chi '$) and out-of-phase ($\chi ''$) ac susceptibility signals under a zero dc field at the indicated frequencies for CIAC-250. The lines are visual guides only. Inset: Plots of ln($\tau$) versus 1/$T$ for CIAC-250. The solid line is the best fit.
10^{-8} \text{ s (inset in Fig. 7). A slight deviation occurs as the temperature further decreases, which could be attributed to strong QTM at low temperature.}

To suppress the QTM, ac magnetic susceptibilities were measured under a dc field of 500 Oe from 2 K to 12 K (Fig. 8), which was fitted with a generalized Debye model (Fig. 9). The \( \alpha \) parameters range from 0.50 to 0.64, indicating a wide contribution for the relaxation times. The obtained \( \ln(\tau) \) values remain linear above 6 K and with slight curvatures at low temperature, but do not become temperature independent. The linear regime at high temperature is often known as the Orbach relaxation process, while for low temperature it can be regarded as the Raman relaxation process because it is not temperature independent. So the Orbach process was combined with the Raman process to fit the relaxation times, giving \( C = 3.0(5) \text{ s}^{-1} \text{ K}^n, n = 2.6(1), \tau_0 = 3(2) \times 10^{-6} \text{ s and } U_{\text{eff}} = 56(9) \text{ K} \) (Fig. 9).

**Conclusions**

In conclusion, we have synthesized \( \{\text{Ln}^{III}_{6}\text{Co}^{II}_{6}\} \) \( \text{C8A}_3 \) clusters featuring a wrapped [Co6] hexagon linked to three calix[8]arene molecules in a double-cone conformation. Interestingly, the \{Eu6Co6\} cluster shows spin glass behaviours below \( \approx 9 \text{ K} \), while the \{Dy6Co6\} cluster exhibits SMM behaviour with \( U_{\text{eff}} \) of 41.5 K under a zero dc field (56(9) K under a 500 Oe dc field). This result emphasized that larger calix[n]arene \((n = 6, 7, 8)\) with more coordination sites and larger molecules will provide further opportunities for controlling the self-assembly and tuning of the magnetic properties. Exploration of another transition metal, Ln, and mixed transition-metal/Ln clusters supported by methylene-bridged calix[8]arenes is underway to generate other novel functional materials.

**Conflicts of interest**

There are no conflicts to declare.

**Acknowledgements**

We thank the National Natural Science Foundation of China (no. 21971233, 21620102002, 21503155 and 21473129), the Science and Technology Development Plan of Jilin Province (2015052009JH), the “National 1000 Young Talents” Program, and the Wuhan National High Magnetic Field Center (2015KF06).

**Notes and references**


Research Article

Inorganic Chemistry Frontiers


21 B. Das, M. Bhadhbhade, A. Thapper, C. D. Ling and S. B. Colbran, A new trinuclear Cu-carbonate cluster utilizing \(CO_2\) as a Cl-building block -reactive intermediates, a probable mechanism, and EPR and magnetic studies, Dalton Trans., 2019, 48, 3576.

22 W. Meng, H. F. Ye, S. Liu, F. Xu and W. J. Xu, Emergence of complex chiral coordination clusters \(\{Cu_{16}^{II}Na_{12}\}\) by using multiple ligands under oxidizing conditions, Dalton Trans., 2019, 48, 3204.

23 E. Guarda, K. Bader, J. V. Slagerenb and P. Alborés, \(\{Ni_{4}^{II}Ln^{III}_{6}\}\) (Ln=Gd, Dy) rod-like nano-sized heteronuclear coordination clusters with a double carbonate bridge skeleton and remarkable MCE behaviour, Dalton Trans., 2016, 45, 8566.


29 G. M. Sheildrick, SHELXS-97, A computer program for the solution of crystal structures, PC version, University of Göttingen, Göttingen, Germany, 1997.


34 N. A. Chernova, Y. N. Song, P. Y. Zavalij and S. W. Whittingham, Solitary excitations and domain-wall


