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# Synthesis and structures of fluoride-bridged dysprosium clusters: influence of fluoride ions on magnetic relaxation behaviors†

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The synthesis of fluoride-bridged tri-( $[(Cp'_2Dy)_{\mu-F}]_3$ -tol, **1Dy**,  $Cp' = C_5H_4Si(CH_3)_3$ ; tol = toluene), tetra- $([\{Cp'_2Dy(\mu-F)_2\}_2\{(Cp')(THF)Dy(\mu-F)\}_2]\cdot hex, \ \textbf{2Dy}, \ THF = tetrahydrofuran; \ hex = n-hexane), \ and \ hepta-hexane, \ hexane, \ hexane,$ nuclear (3Dy) dysprosium complexes is reported here and a hydroxy-bridged dinuclear dysprosium complex [Cp'<sub>2</sub>Dy(μ-OH)]<sub>2</sub>(**4Dy**) is synthesized for comparison. The nucleation number of the fluoridebridged complexes highly depends on the reaction solvents and the molar ratio of the dysprosium and fluoride precursors. The three Dy ions in 1Dy are arranged in a triangular fashion and the tetranuclear 2Dy displays a butterfly shape geometry. 3Dy shows a much more complicated structure with three types of fluoride bridges. 1Dy and 2Dy exhibit slow relaxation of magnetization with the energy barriers of 95 K and 98 K, respectively, while the dinuclear and heptanuclear dysprosium complexes barely show any behaviors of molecular nanomagnets. Ab initio calculations demonstrated that the thermo-assisted relaxation of magnetization of 1Dy and 2Dy originated from the {Cp'2Dy} fragment. Analysis of magneto-structural correlation revealed that the fluoride ions had a great influence on the orientation of the easy axis of magnetization and the exchange interactions.

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## Introduction

Recently, polynuclear lanthanide clusters possessing diverse structures and topologies have attracted increasing interest in coordination chemistry, owing to not only the fundamental pursuit of complicated and novel structures but also the challenging synthesis, interesting physical properties and potential applications.<sup>1-4</sup> Compared with transition metal ions, the orbital angular momentum of 4f metal ions is largely conserved due to the localization of 4f electrons near the nucleus and hence there is no significant perturbation from the ligand field.<sup>5</sup> Thus, the 4f metal ions exhibit much stronger spinorbit coupling. The large magnetic anisotropy of lanthanide ions makes them ideal candidates for synthesizing singlemolecule magnets (SMMs).6-10 With respect to the molecular nanomagnets, great efforts have been made in understanding and fine-tuning the uniaxial magnetic anisotropy and exchange interactions in order to generate high barriers for spin-reversal. So far, the highest barriers and blocking temperatures have been realized in dysprosium single-ion magnets (Dy-SIMs). 11-15 In light of the lack of progress in multinuclear Dy-SMMs, we explore the effect of the nucleation number and exchange interactions on the magnetic relaxation of Dy-SMMs in this work.

A panoply of lanthanide clusters with a variety of core motifs and nucleation numbers have been successfully synthesized with widely used bridging ligands such as carboxylates,16-18 phosphates,19 sulfonates,20 nitronylnitroxide radicals, 21-24 halides, 25-29 etc. 30 It is known that the fluoride ion possesses a smaller ionic radius and larger electronegativity than the N and O atoms. Therefore, the F ion in the terminal Dy-F bond is believed to provide stronger crystal field splitting and stabilize the  $|M_I| = 15/2$  ground state of Dy, as

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<sup>†</sup>Electronic supplementary information (ESI) available: Additional computational details and magnetic and crystallographic data are provided in the ESI. CCDC 2121103, 2121109, 2121120 and 2121121 for compounds 1Dy-4Dy. For ESI and crystallographic data in CIF or other electronic format see DOI: https:// doi.org/10.1039/d1qi01422f

predicted by Liviu Ungur and co-workers.31 The recent work by Norel and co-workers<sup>28</sup> rationalized this theoretical prediction by showing that the terminal fluoride complex [Dy(Tp<sup>py</sup>)F (dioxane)](PF<sub>6</sub>) (Tp<sup>py</sup> = tris(3-(2-pyridyl)pyrazolyl)hydroborate) exhibits a high spin-reversal barrier of 432 cm<sup>-1</sup>. We are also curious about the effects of fluoride ions on the magnetic properties of multifluorido lanthanide complexes where small F bridges can also shorten the distance between two Dy ions and may reinforce the magnetic interactions between them. However, pure fluoride-bridged lanthanide complexes are very limited because the highly insoluble LnF3 can be easily formed. Most of the reported fluoride-bridged complexes are transition metals and 3d-4f species. The synthesis of fluoridebridged lanthanide clusters needs careful control of multifluorido lanthanide cores to avoid the formation of LnF3. Besides, the introduction of fluoride ions using suitable fluoride precursors is also challenging as most of the fluoride salts are insoluble in organic solvents. The fluoride precursor Et<sub>2</sub>N·HF caught our attention as it can dissolve in THF easily. It also provides good reactivity with lanthanide metallocenes. In this work, we chose [Cp'3Dv] to react with Et3N·HF and obtained several clusters with varied numbers of Dy ions through changing different solvents or different molar ratios of reactants. The hydroxide-bridged complex 4Dy was also prepared using a similar method to compare the effects of hydroxide and fluoride bridges on their magnetic properties.

## Results and discussion

### Synthesis and structural characterization

The synthesis of fluoride-bridged dysprosium clusters was performed by adding an equivalent of Et<sub>3</sub>N·HF into a cold THF solution of [Cp'<sub>3</sub>Dy] very slowly. After filtering and removing the solvent, the raw products crystallizing in toluene and hexane could result in two different complexes 1Dy [Cp'2Dy(µ-F)]<sub>3</sub>·tol and 2Dy[ $\{Cp'_2Dy(\mu-F)_2\}_2\{(Cp')(THF)Dy(\mu-F)\}_2\}$ ·hex. The reaction is promoted by the protonation of the Cp' anion. The protonation degree depends highly on the crystallizing solvent and molar ratio of Et<sub>3</sub>N·HF and [Cp'<sub>3</sub>Dy] (see the ESI<sup>†</sup> Experimental section). An X-ray diffraction experiment indicated that 1Dy and 2Dy crystallize in the space group of  $P\bar{1}$  and P21/c, respectively. Their molecular structures are shown in Fig. 1 and 2, respectively.

Complex 1Dy possesses a typical cyclic trimer structure. The three [Cp'<sub>2</sub>Dy]<sup>+</sup> motifs are connected by μ-F bridges in a triangular manner. Each motif possesses very similar structural parameters, as listed in Table S2.† Each DyIII ion is coordinated by two Cp' anions and bridged by two fluoride ions with the other two DyIII ions. The Dy-F bond lengths fall in a narrow range of 2.194(2)-2.204(2) Å. The Dy-C bond lengths are in a relatively broader range of 2.630(5)-2.721(5) Å. The Dy<sup>III</sup> ions and F<sup>-</sup> ions are almost within a plane. The structurally related 4Dy is a dinuclear complex, wherein the [Cp'2Dy]<sup>+</sup> motifs are connected by two hydroxide bridges (Dy-O: 2.232

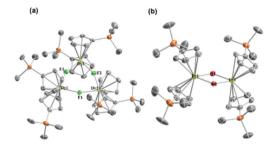


Fig. 1 Molecular structures of 1Dy (a) and 4Dy (b). Co-crystallized THF and toluene and hydrogens are omitted for clarity. Color code: C, grey; Dy, yellow; Si, light orange; O, red; and F, green.

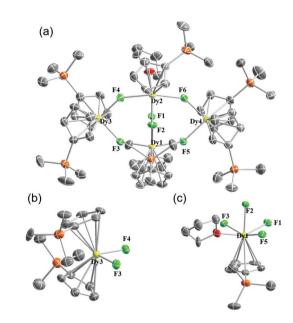
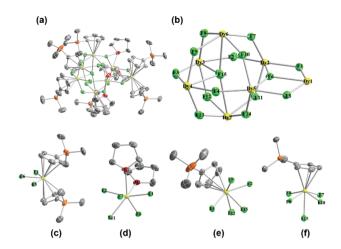


Fig. 2 Molecular structures of 2Dy. Co-crystallized THF and toluene and hydrogens are omitted for clarity. Color code: C, grey; Dy, yellow; Si, light orange; O, red; and F, green.

(2)-2.261(2) Å). The specific bond length and bond angle information is listed in Table S5.†

Complex 2Dy is obtained in the hexane solution and crystallizes with a highly disordered hexane molecule in the unit cell. The tetranuclear complex adopts a chair-like structure, in which the DyIII ions can be divided into two kinds. In 2Dy, there are four DyIII ions and four fluoride ions composed of an eight-membered ring. Dy3 and Dy4 ions are coordinated by two Cp' anions (Dy-C: 2.64(1)-2.69 Å) and two bridging fluoride ions (Dy-F: 2.172(5)-2.199(6) Å). The angles for F3-Dy3-F4 and F5-Dy4-F6 are 90.6° and 88.4°, respectively, which are slightly larger than those in 1Dy (85.9°-87.5°). Within the Dy3 and Dy4 metallocenes, one of the Dy-F bonds shows a smaller distance. Both Dy1 and Dy2 ions coordinate with only one Cp' ring, one THF (Dy-C: 2.68(1)-2.72(1) Å), Dy-O: 2.396(7)-2.409(6) Å) and four bridged fluoride ions (Dy-F: 2.204(5)-2.267(5) Å). Dy1 and Dy2 are further bridged by two fluoride ions.



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Fig. 3 Molecular structures of 3Dy (a) and the core of 3Dy (b); the local coordination environments for Dy1, Dy2, Dy3 and Dy4 are shown in (c) (d), (e) and (f), respectively. Co-crystallized THF and toluene and hydrogens are omitted for clarity. Color code: C, grey; Dy, yellow; Si, light orange; O, red; and F, green.

When the molar ratio of [Cp'3Dy] and Et3N·HF was changed to 1:1.5, a structurally more complicated heptanuclear dysprosium core 3Dy (C<sub>64</sub>H<sub>110</sub>Dy<sub>7</sub>F<sub>15</sub>O<sub>4</sub>Si<sub>6</sub>·hex) was obtained. Five DyIII ions and five fluoride ions form a ten-membered ring with two DyIII ions locating on the two sides of the plane. The DyIII ions in the heptanuclear core can be divided into four kinds (Fig. 3). The Dy1 motif (Fig. 3c) is composed of two Cp' anions (Dy-C: 2.671(5)-2.690(5) Å) and three fluoride ions (Dy-F: 2.268(3)-2.340(2) Å). Dy2 and Dy5 ions are coordinated only by fluoride ions (Dy-F: 2.182(2)-2.308(3) Å) and THF molecules (Dy-O: 2.370(5)-2.402(4) Å) without Cp' rings. Dy3, Dy4, Dy6 and Dy7 ions are all capped by mono-Cp' anions (Dy-C: 2.629(6)-2.696(6) Å). The difference lies in the central F15 ion being closer to Dy3 and Dy4 (2.515(3) and 2.550(3) Å for Dy3-F15 and Dy4-F15; 2.813(2) and 2.695(2) Å for Dy6-F15 and Dy7-F15). As can be seen, through fine-tuning the reaction and crystallizing conditions in the {Cp'<sub>3</sub>Dy + Et<sub>3</sub>N·HF} system, we can obtain well-defined Cp'-Dy-F clusters with various numbers of Dy ions. The diverse structures also highlight the versatility of fluoride ions as bridging ions to offer rich coordination chemistry.

#### **Magnetic properties**

The variety of dysprosium cores provides a good platform to investigate the impact of fluoride ions on their magnetic properties. The direct current (dc) magnetic susceptibility measurements were performed between 2 K and 300 K under a 1 kOe applied dc field. At room temperature, the  $\chi_{\rm m}T$  values for the four complexes are 28.93, 42.34, 57.19 and 101.29 cm<sup>3</sup> mol<sup>-1</sup> K, as shown in Fig. 4, which are in good agreement with the calculated values for the uncoupled Dy<sup>3+</sup> ions (for one free Dy the value is 14.17 cm<sup>3</sup> mol<sup>-1</sup> K). Upon cooling, the  $\chi_{\rm m}T$ values of the four complexes decrease slowly and begin to decrease rapidly below 25 K. At 2 K, the  $\chi_{\rm m}T$  values are 13.07,

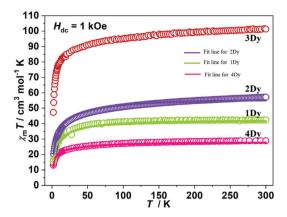


Fig. 4 Susceptibility temperature product  $\chi_m T$  as a function of temperature recorded on samples of 1Dy, 2Dy, 3Dy and 4Dy in an applied field of 1 kOe. The solid line represents the simulation from CASSCF POLY ANISO calculated results

15.28, 20.19 and 47.31 cm<sup>3</sup> mol<sup>-1</sup> K, respectively, which are all less than half of their initial values at room temperature. Such a decrease is probably caused by the thermal depopulation of the Stark levels. The intramolecular antiferromagnetic interaction could also lead to a decrease of  $\chi_{\rm m}T$  values and would be more predominant below 25 K. Field-dependent magnetization data were collected from 0 to 50 kOe at selected temperatures (see ESI Fig. S1-S4†). At 2 K, the magnetization values for the four complexes increase steeply at low fields and finally reach 10.51, 15.76, 20.34 and 37.96 Nβ at 50 kOe, respectively, which are comparable to the magnetization value per DyIII ion (4.7–5.3 N $\beta$ ). The non-superposition of the *M versus HT*<sup>-1</sup> plots suggests the presence of magnetic anisotropy.

To further investigate the effects of fluoride ions on the slow magnetic relaxation, alternating current (ac) susceptibility measurements were performed in the frequency range of 100-10 000 Hz. For 1Dy, measurements of ac susceptibilities conducted in the absence of a dc field showed frequencydependent signals between 2 K and 10 K (Fig. 5a). This result clearly indicates the slow relaxation of magnetization, a behavior of the SMMs. It is worth noting that below 4 K (Fig. S5†),  $\chi''_{\rm m}$  surges up to significantly high values, suggesting a very fast relaxation rate above 104 Hz. This fast relaxation behavior was also previously observed in a cyclic dysprosium tetramer<sup>32</sup> and was possibly caused by thermally assisted quantum tunneling of magnetization (QTM) via the low-lying exchangecoupled excited states. Above 4 K, Cole-Cole plots confirmed a single thermo-related relaxation in the experimental temperature range, with a relatively narrow distribution of relaxation time ( $\alpha$ : 0.29-0.08) (see ESI Fig. S8†). The plots of extracted relaxation times  $\tau$  versus  $T^{-1}$  show the nonlinearity in the measured temperature range (Fig. 6). Such curvature is probably caused by the low-temperature QTM and other processes. Therefore, Arrhenius fitting cannot be applied to obtain the effective energy barrier. Therefore, the Orbach, Raman and QTM process fitting is introduced to the experimental data points, that is, the fitting formula (1),  $\tau^{-1} = 1/\tau_0 \times e^{-U_{\text{eff}}/T} + CT^n$ 

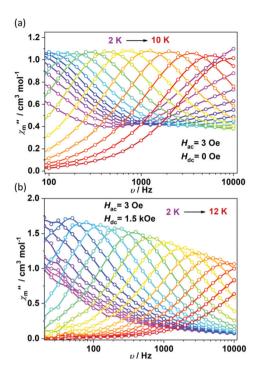


Fig. 5 Plots of out-of-phase susceptibilities  $(\chi''_m)$  versus frequency  $(\nu)$ for 1Dy, under a zero applied dc field (a), and under a 1.5 kOe dc field, with an ac field of 3 Oe (b).

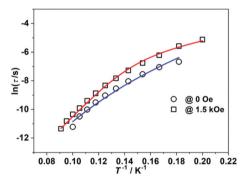


Fig. 6 Plots of the natural logarithm of relaxation time  $ln(\tau)$  vs.  $T^{-1}$  for 1Dy in a zero static field (circle) and 1.5 kOe dc field (square). The solid lines represent the best fit according to the Arrhenius law in the thermally activated regime.

+  $1/\tau_{\text{tunneling}}$ , yielded an effective energy barrier of  $U_{\text{eff}}$  = 87 K, a pre-exponential factor  $\tau_0 = 3.22 \times 10^{-9} \text{ s}, n = 7.49, C = 0.0017$ s<sup>-1</sup> K<sup>-n</sup> and  $\tau_{\text{tunneling}} = 4.23 \times 10^{-5}$  s. To suppress the quantum tunneling, a 1.5 kOe dc field was applied. As shown in Fig. 6 and Fig. S6,† the relaxation rates decreased to some extent. Fitting the data set with eqn (2),  $\tau^{-1} = 1/\tau_0 \times e^{-U_{\text{eff}}/T} + CT^n$ , yielded an effective energy barrier of  $U_{\rm eff}$  = 95 K, a pre-exponential factor  $\tau_0 = 2.27 \times 10^{-9}$  s, n = 4.27 and C = 0.186 s<sup>-1</sup> K<sup>-n</sup>. The obtained  $\tau_0$  is in the typical range expected for molecular nanomagnets. The relatively small value of *n* is more likely due to the second-order Raman process for Kramers dysprosium ions. The theoretically calculated magnetization blocking

barrier is 80 K (55.8 cm<sup>-1</sup>) (see ESI Table S6 and Fig. S12†), which is close to the experimental results.

Ac susceptibility measurements on 2Dy indicate the characteristic SMM behavior below 10 K under zero dc field (Fig. 7 and Fig. S7†). The relaxation of magnetization for 2Dy occurs in a similar temperature range to that for 1Dv (Fig. S9†). The magnitudes of  $\chi''_{m}$  are also comparable with those of 1Dy. The plot  $\ln \tau$  versus  $T^{-1}$  still deviates from linearity even in a higher temperature region (Fig. 8). Similarly, using the Orbach, Raman and QTM processes for fitting, we obtained  $U_{\text{eff}} = 89 \text{ K}$ ,  $\tau_0 = 4.47 \times 10^{-9} \text{ s}, n = 8.61, C = 0.00015 \text{ s}^{-1} \text{ K}^{-n} \text{ and } \tau_{\text{tunneling}} =$  $2.21 \times 10^{-5}$  s. A 2 kOe applied dc field can suppress the fast relaxation process effectively and reduce the relaxation rate.

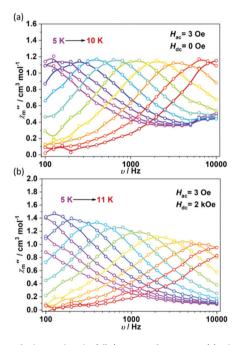


Fig. 7 Out-of-phase signals  $(\chi''_m)$  versus frequency  $(\nu)$  plots for 2Dy, under a zero applied dc field (a), and under a 2 kOe dc field, with an ac field of 3 Oe (b).

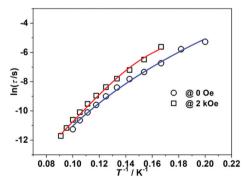


Fig. 8 Plots of the natural logarithm of relaxation time  $ln(\tau)$  vs.  $T^{-1}$  for 2Dy in a zero static field (circle) and a 2 kOe dc field (square). The solid lines represent the best fit according to the Arrhenius law in the thermally activated regime.

The fitting with eqn (1) gives  $U_{\text{eff}} = 97 \text{ K}$ ,  $\tau_0 = 1.38 \times 10^{-9} \text{ s}$ , n =3.87 and  $C = 0.268 \text{ s}^{-1} \text{ K}^{-n}$ , similar to the results for 1Dy. The results of the theoretical calculations of the magnetization blocking barriers for the four Dy(III) ions in compound 2Dy are shown in ESI Fig. S13.† The theoretically calculated magnetization blocking barriers for Dy3 and Dy4 (ESI Fig. S13c, d and Table S6†) are 162 K (112.9 cm<sup>-1</sup>) and 166 K (115.7 cm<sup>-1</sup>), which are quite different from the experimental results of 97 K. This may be due to the influence of weaker magnetic coupling in the system.

For the heptanuclear 3Dy, no frequency-dependent resonant  $\chi''_{m}$  peaks were observed in any applied fields (see ESI Fig. S10†). As mentioned earlier, the magnetic properties of these compounds mainly depend on the structure of [Cp<sub>2</sub>Dy]<sup>+</sup> motifs. This is rational as the introduction of additional fluoride ions using Et<sub>3</sub>N·HF in the coordination spheres of Dy would undermine  $[Cp_2Dy]^+$  motifs, which are the origin of the observed magnetic relaxation in 1Dy and 2Dy (vide infra). For the hydroxide-bridged complex 4Dy, no frequency-dependent in-phase  $(\chi'_m)$  and out-of-phase susceptibilities  $(\chi''_m)$  were observed in the measured temperature range under zero dc field. When a 2.5 kOe dc field was applied, the out-of-phase components showed broad resonant peaks below 3 K (see ESI Fig. S11†). Thus, extracted relaxation times are not restricted due to the lack of well-defined resonant peaks. It can be seen from Fig. S14† that there is an obvious QTM process between the ground double states. The relatively high possibility of QTM between the ground state doublets will quench (accelerate) the relaxation at the initial stage. As a result, compound 4Dy does not exhibit obvious slow magnetic relaxation behavior under zero field.

#### Theoretical analysis

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Previous study has demonstrated that ancillary ligands within the equatorial plane can greatly affect the slow magnetic relaxation behavior of dysprosium metallocenes.<sup>33</sup> A weak ancillary ligand field would help stabilize the Ising type ground doublet of dysprosium metallocenes. Because of the larger electronegativity and the smaller radii of F than those of O, the interaction between DyIII ions and F ions would induce more significant transverse components. However, an ac susceptibility study reveals that 1Dy and 2Dy are SMMs while the hydroxidebridged 4Dy does not show slow magnetic relaxation behavior

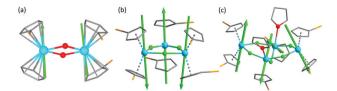


Fig. 9 Ab initio calculated (green) magnetic main axes for 4Dy, 1Dy, and 2Dv.

within the frequency measurement range of the instrument. To further elucidate the influence of fluoride and hydroxide bridges on their energy levels and magnetic properties, complete-active-space self-consistent field (CASSCF) calculations on individual DyIII fragments for the three complexes on the basis of X-ray determined geometries have been performed with MOLCAS 8.0 and SINGLE\_ANISO programs.

The eight lowest spin-orbit energies and the corresponding g tensors of complexes 4Dy, 1Dy and 2Dy are shown in Table S6.† The calculated ground  $g_z$  values of the individual Dy<sup>III</sup> fragments of 4Dy are close to 20, and the  $g_{x,y}$ values are not negligible. The orientations of easy axes for the cyclic trimer are nearly perpendicular to the plane consisting of the Dy<sub>3</sub>F<sub>3</sub> core (Fig. 9b and Fig. S15†), in agreement with the previously reported dysprosium metallocene SMMs. For 2Dy, the orientations of the two types of DyIII fragments are very different. The Dy3 and Dy4 fragments supported by two Cp' anions exhibit similar orientations of the easy axis to that in 1Dy, while the easy axes for Dy1 and Dy2 fragments supported by mono-Cp' are almost perpendicular to the Cp ring, orienting towards the bridging F2 ion (Fig. 9c and Fig. S16†).

Despite the DyIII fragments except Dy1 and Dy2 in 2Dy having some deviations from 20, the Lines model was applied to estimate the exchange interactions in 4Dy, 1Dy and 2Dy using the POLY\_ANISO55,13,34-39 program. All parameters in Table 1 were calculated with respect to the pseudospin  $\hat{\mathbf{x}} = \frac{1}{2}$ of the DyIII ions corresponding to the Hamiltonian representation in eqn (1)-(3). For complexes 4Dy, 1Dy and 2Dy, the total coupling parameters J (dipolar and exchange) were included to fit the magnetic susceptibilities. The calculated and experimental  $\chi_{\rm m}T$  versus T plots of complexes 4Dy, 1Dy and 2Dy are shown in Fig. 4, where the fit for both 4Dy and 1Dy is close to

Table 1 Fitted exchange coupling constant  $J_{\text{exch}}$ , the calculated dipole-dipole interaction  $J_{\text{dip}}$  and the J between Dy<sup>III</sup> ions in 4Dy, 1Dy and 2Dy  $(cm^{-1})$ . The intermolecular interactions zJ' of the three compounds were set to  $-0.00 \text{ cm}^{-1}$ ,  $-0.06 \text{ cm}^{-1}$  and  $-0.20 \text{ cm}^{-1}$ , respectively

	4Dy			1Dy			2Dy		
	$J_{ m dip}$	$J_{ m exch}$	J	$J_{ m dip}$	$J_{ m exch}$	J	$J_{ m dip}$	$J_{ m exch}$	J
$J_1$	-2.95	-0.25	-3.18	-1.90	-0.10	-2.00	-1.13	-1.50	-2.63
$J_2$				-1.86	-0.14	-2.00	-1.10	-1.50	-2.60
$J_3$				-1.89	3.89	2.00	-0.86	-1.50	-2.36
$J_4$							0.99	-1.50	-0.51
$J_5$							5.45	-1.25	4.20

the experimental data. For 2Dy, however, the fit appeared a little deviated from the experimental data since the individual Dy<sup>III</sup> fragments of Dy1 and Dy2 cannot be treated as an ideal Ising type considering their ground  $g_z$  being relatively far from 20 (see in ESI Table S6†). As seen in Table 1, the Dy...Dy interaction in complex 4Dv within the Lines model 40-42 is antiferromagnetic. For 1Dy, the Dy1...Dy2 and Dy1...Dy3 interactions are both antiferromagnetic, while the Dv2-Dv3 interaction is ferromagnetic. For 2Dy, the Dy1-Dy3, Dy1-Dy4, Dy2-Dy4 and Dy2-Dy3 interactions are all antiferromagnetic, while the Dy2-Dy1 interaction is ferromagnetic. The exchange energies and the main values of  $g_z$  for the lowest two exchange doublets for all complexes are given in Table S7.† The  $g_z$  values of the ground exchange state for 4Dy, 1Dy and 2Dy are 38.04, 18.48 and 29.75, respectively. Both the experimental and theoretical results demonstrate that introducing more fluoride ions would impair the uniaxial anisotropy of the dysprosium metallocene SMMs. It is more obvious when we refer to the Dy1 fragment in 3Dy wherein three fluoride ions coordinated to a DyIII ion within the equatorial plane result in the fast relaxation of magnetization.

$$\hat{H}_{\text{exch}} = -J_1 \hat{S}_{\text{Dv}1} \hat{S}_{\text{Dv}2} \tag{1}$$

$$\hat{H}_{\text{exch}} = -J_1 \hat{S}_{\text{Dy}1} \hat{S}_{\text{Dy}2} - J_2 \hat{S}_{\text{Dy}1} \hat{S}_{\text{Dy}3} - J_3 \hat{S}_{\text{Dy}2} \hat{S}_{\text{Dy}3}$$
(2)

$$\hat{H}_{exch} = -J_1 \hat{S}_{Dy1} \hat{S}_{Dy3} - J_2 \hat{S}_{Dy1} \hat{S}_{Dy4} - J_3 \hat{S}_{Dy2} \hat{S}_{Dy3} -J_4 \hat{S}_{Dy2} \hat{S}_{Dy4} - J_5 \hat{S}_{Dy1} \hat{S}_{Dy2}$$
(3)

## Conclusions

In summary, through systematically tuning the crystallizing solvents and molar ratios of reactants we can obtain three fluoride-bridged tri-, tetra-, and hepta-nuclear Cp-based Dy-F clusters along with a related hydroxy-bridged dinuclear dysprosium complex. The tri- and tetra-nuclear compounds can exhibit slow magnetic relaxation with almost identical energy barriers of 95 and 97 K, while the hydroxide-bridged dinuclear and F-bridged heptanuclear clusters barely display any SMM behavior. Ab initio calculations demonstrated that the thermoassisted relaxation of magnetization arises from the [Cp'<sub>2</sub>Dy(μ-F)<sub>2</sub>] motifs. Through this work on Dy-F clusters, it is rationalized that the fluoride ions mainly affect the orientation of the easy axis and the exchange interactions. In short, for a highperformance single-molecule magnet, the suppression of quantum tunneling through the magnetic interaction of the metal center is an important means to improve the magnetic properties. However, for lanthanide ions, it is also crucial to improve local symmetry.

### Conflicts of interest

There are no conflicts to declare.

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## Notes and references

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