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Exchange Interactions at the Origin of Slow Relaxation of the Magnetization in \{TbCu_3\} and \{DyCu_3\} Single-Molecule Magnets

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Supporting Information

ABSTRACT: New \{TbCu_3\} and \{DyCu_3\} single-molecule magnets (SMMs) containing a low-symmetry Ln^{III} center (shape measurements relative to a trigonal dodecahedron and biaugmented trigonal prism are 2.2–2.3) surrounded by three Cu^{II} metalloligands are reported. SMM behavior is confirmed by frequency-dependent out-of-phase ac susceptibility signals and single-crystal temperature and sweep rate dependent hysteresis loops. The ferromagnetic exchange interactions between the central Ln^{III} ion and the three Cu^{II} ions could be accurately measured by inelastic neutron scattering (INS) spectroscopy and modeled effectively. The excitations observed by INS correspond to flipping of Cu^{II} spins and appear at energies similar to the thermodynamic barrier for relaxation of the magnetization, ~15–20 K, and are thus at the origin of the SMM behavior. The magnetic quantum number M_{tot} of the cluster ground state of \{DyCu_3\} is an integer, whereas it is a half-integer for \{TbCu_3\}, which explains their vastly different quantum tunneling of the magnetization behavior despite similar energy barriers.

INTRODUCTION

Single-molecule magnets (SMMs) display slow relaxation of the magnetization of purely molecular origin and have remained a hot topic because of their fundamental physics and potential applications.¹ The majority of SMMs have been molecular 3d transition-metal complexes,² but in recent years, lanthanide-containing molecules have gained prominence.³ 3d–4f complexes are also good candidates for SMMs: very large single-ion magnetic anisotropies have been observed for Tb^{III} and Dy^{III}, and ferromagnetic coupling is commonly observed between Cu^{II} ions and Ln^{III} ions such as Gd^{III}, Tb^{III}, and Dy^{III}. In comparison to polynuclear Ln^{III}-based SMMs,³⁶ there are relatively few Tb^{III}Cu^{II} SMMs, these using Schiff base or macrocyclic ligands, and even fewer Dy^{III}Cu^{II} SMMs.³⁷ Furthermore, the origin of slow relaxation of the magnetization in 3d–4f SMMs needs more detailed investigation. The main interactions governing magnetic properties in 3d–4f SMMs are the crystal-field interactions of the lanthanide ions and the exchange interactions between lanthanide ions and transition-metal ions. We report a new family of \{LnCu_3\} complexes (Ln = Gd^{III}, Tb^{III}, Dy^{III}), of which the Tb^{III} and Dy^{III} analogues show slow relaxation of magnetization. We have determined the exchange interactions in \{TbCu_3\} and \{DyCu_3\} with inelastic neutron scattering (INS) spectroscopy, a powerful technique often used to measure crystal-field and exchange splittings in molecular clusters,⁸ with pioneering work on lanthanide-containing clusters done by Furrer, Güdel, and co-workers.⁹ Despite its obvious potential, especially for Ln clusters, very few Ln-containing SMMs have thus far been studied with INS spectroscopy.¹⁰ We found that the fundamental INS excitations correspond to Cu^{II} spin flips, which have energies similar to the barriers for magnetization reversal that we determined using ac magnetic susceptibility measurements. These findings indicate the importance of these spin flips for the magnetic relaxation and therefore of the 3d–4f exchange interactions. Furthermore, the nature of the ground state (M_{tot} = integer or half-integer) determines the effectiveness of quantum tunneling of the magnetization (QTM).

EXPERIMENTAL SECTION

Syntheses. \[\text{[Cu}_2(\text{H(edte)})_2]\text{[NO}_3\text{]}_2. \] To a solution of 2,2',2''-(ethane-1,2-diyldinitrilo)tetraethanol (H_{4}edte; 12.68 g, 53.68 mmol) in

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100 mL of MeCN was slowly added a solution of Cu(NO$_3$)$_2$·3H$_2$O (6.65 g, 27.52 mmol) in 100 mL of MeCN with vigorous stirring. The reaction mixture was stirred at room temperature overnight to yield a blue precipitate, which was collected by filtration, washed with MeCN, and then air-dried. Yield: 95% based on Cu. Vapor diffusion of redissolved precipitate in MeOH with Et$_2$O produced blue-green plates suitable for X-ray diffraction. Anal. Calcld for C$_{30}$H$_{66}$Cu$_3$TbN$_9$O$_{21}$: C, 29.09; H, 5.37; N, 10.18. Found: C, 29.04; H, 5.41; N, 9.91. Selected IR peaks (cm$^{-1}$): 3200 (br), 2974 (w), 2947 (w), 2897 (w), 2843 (w), 2794 (w), 1747 (w), 1456 (m), 1453 (m), 1453 (m), 1431 (m), 1383 (m), 1354 (m), 1313 (s), 1259 (m), 1234 (m), 1170 (w), 1110 (w), 1107 (w), 1078 (s), 1057 (s), 1033 (s), 1014 (s), 985 (m), 922 (m), 908 (m), 893 (m), 883 (m), 869 (m), 844 (w), 825 (m), 817 (m), 756 (m), 725 (m), 675 (m), 646 (m), 605 (w).

$\text{[GdCu}_2(\text{H}_2\text{edte})\text{][NO}_3\text{][NO}_3]\text{[GdCu}_3\text{]}$. To a stirred solution of [Cu$_2$(H$_2$edte)$_2$][NO$_3$]$_2$ (0.4 g, 0.55 mmol) and NEt$_3$ (0.21 mL, 1.5 mmol) in MeOH (20 mL) was added Gd(NO$_3$)$_3$·6H$_2$O (0.112 g, 0.25 mmol). The reaction mixture was stirred at room temperature overnight to yield a blue precipitate, which was collected by filtration, washed with EtOH, and then air-dried. Yield: 89%. Vapor diffusion of redissolved precipitate in MeOH with THF produced blue plate-like needles suitable for X-ray diffraction. Anal. Calcld for C$_{20}$H$_{46}$Cu$_2$N$_6$O$_{14}$: C, 55.60; H, 5.26; N, 9.12. Selected IR peaks (cm$^{-1}$): 3200 (br), 2974 (w), 2947 (w), 2897 (w), 2843 (w), 2794 (w), 1747 (w), 1456 (m), 1453 (m), 1453 (m), 1431 (m), 1383 (m), 1354 (m), 1313 (s), 1259 (m), 1234 (m), 1170 (w), 1110 (w), 1107 (w), 1078 (s), 1057 (s), 1033 (s), 1014 (s), 985 (m), 922 (m), 908 (m), 893 (m), 883 (m), 869 (m), 844 (w), 825 (m), 817 (m), 756 (m), 725 (m), 675 (m), 646 (m), 605 (w).

$\text{[TbCu}_2(\text{H}_2\text{edte})\text{][NO}_3\text{][NO}_3]\text{[TbCu}_3\text{]}$. To a stirred solution of [Cu$_2$(H$_2$edte)$_2$][NO$_3$]$_2$ (0.4 g, 0.55 mmol) and NEt$_3$ (0.21 mL, 1.5 mmol) in MeOH (20 mL) was added Tb(NO$_3$)$_3$·6H$_2$O (6.65 g, 27.52 mmol) in 100 mL of MeCN with vigorous stirring. The reaction mixture was stirred at room temperature overnight to yield a blue precipitate, which was collected by filtration, washed with EtOH, and then air-dried. Yield: 89%. Vapor diffusion of redissolved precipitate in MeOH with THF produced blue plate-like needles suitable for X-ray diffraction. Anal. Calcld for C$_{30}$H$_{66}$Cu$_3$TbN$_9$O$_{21}$: C, 29.13; H, 5.38; N, 10.19. Found: C, 29.0; H, 5.41; N, 9.91. Selected IR peaks (cm$^{-1}$): 3200 (br), 2898 (w), 2835 (w), 2686 (w), 1465 (m), 1440 (m), 1383 (m), 1338 (m), 1301 (s), 1263 (m), 1170 (w), 1151 (w), 1139 (w), 1078 (s), 1057 (s), 1016 (s), 987 (m), 970 (m), 918 (m), 904 (m), 891 (m), 877 (m), 848 (w), 827 (m), 819 (w), 798 (w), 760 (w), 736 (m), 721 (m), 696 (w), 669 (w), 663 (m). In all three {LnCu$_3$} compounds, the nitrate counterion molecule (H$_2$edte)$_2$·3H$_2$O was also constrained to take standard values.

$\text{[GdCu}_3(\text{H}_2\text{edte})\text{][NO}_3\text{][NO}_3]\text{[GdCu}_3\text{]}$. To a stirred solution of [Cu$_2$(H$_2$edte)$_2$][NO$_3$]$_2$ (0.4 g, 0.55 mmol) and NEt$_3$ (0.21 mL, 1.5 mmol) in MeOH (20 mL) was added Dy(NO$_3$)$_3$·6H$_2$O (0.112 g, 0.25 mmol). The reaction mixture was stirred at room temperature overnight to yield a blue precipitate, which was collected by filtration, washed with EtOH, and then air-dried. Yield: 88%. Vapor diffusion of redissolved precipitate in MeOH with THF produced blue plate-like needles suitable for X-ray diffraction. Anal. Calcld for C$_{20}$H$_{46}$Cu$_2$N$_6$O$_{14}$: C, 55.60; H, 5.26; N, 9.12. Selected IR peaks (cm$^{-1}$): 3200 (br), 2974 (w), 2947 (w), 2897 (w), 2843 (w), 2794 (w), 1747 (w), 1456 (m), 1453 (m), 1453 (m), 1431 (m), 1383 (m), 1354 (m), 1313 (s), 1259 (m), 1234 (m), 1170 (w), 1110 (w), 1107 (w), 1078 (s), 1057 (s), 1033 (s), 1014 (s), 985 (m), 922 (m), 908 (m), 893 (m), 883 (m), 869 (m), 844 (w), 825 (m), 817 (m), 756 (m), 725 (m), 675 (m), 646 (m), 605 (w).

$\text{[DyCu}_2(\text{H}_2\text{edte})\text{][NO}_3\text{][NO}_3]\text{[DyCu}_3\text{]}$. To a stirred solution of [Cu$_2$(H$_2$edte)$_2$][NO$_3$]$_2$ (0.4 g, 0.55 mmol) and NEt$_3$ (0.21 mL, 1.5 mmol) in MeOH (20 mL) was added Dy(NO$_3$)$_3$·6H$_2$O (0.109 g, 0.25 mmol). The reaction mixture was stirred at room temperature overnight to yield a blue precipitate, which was collected by filtration, washed with EtOH, and then air-dried. Yield: 76%. Vapor diffusion of redissolved precipitate in MeOH with THF produced blue plate-like needles suitable for X-ray diffraction. Anal. Calcld for C$_{20}$H$_{46}$Cu$_2$Cu$_3$[Dy$_3$]: C, 29.01; H, 5.36; N, 10.15. Found: C, 28.66; H, 5.49; N, 9.80. Selected IR peaks (cm$^{-1}$): 3200 (br), 2974 (w), 2947 (w), 2897 (w), 2843 (w), 2794 (w), 1747 (w), 1610 (w), 1465 (m), 1453 (m), 1431 (m), 1383 (m), 1354 (m), 1313 (s), 1259 (m), 1234 (m), 1170 (w), 1110 (w), 1107 (w), 1078 (s), 1057 (s), 1033 (s), 1014 (s), 985 (m), 922 (m), 908 (m), 893 (m), 883 (m), 869 (m), 844 (w), 825 (m), 817 (m), 756 (m), 725 (m), 675 (m), 646 (m), 605 (w).
complexes, here using a similar ligand to perform a CuII starting material, \([\text{Cu}_2(\text{H}_3\text{edte})_2][\text{NO}_3]_2\) (H$_4$edte = 2,2′,2″,2‴-(ethane-1,2-diyldinitrilo)tetraethanol). This dimeric CuII precursor can be prepared in 95% yield (see the Experimental Section and the Supporting Information), where the dicationic complex is structurally similar to that found in the previously reported compound \([\text{Cu}_2(\text{H}_3\text{edte})_2][\text{ClO}_4]_2\). Subsequent reaction of \([\text{Cu}_2(\text{H}_3\text{edte})_2][\text{NO}_3]_2\) with Ln(NO$_3$)$_3$·xH$_2$O in MeOH in the presence of NEt$_3$ yields \([\text{LnCu}_3(\text{H}_2\text{edte})_3(\text{NO}_3)]^−[\text{NO}_3]_2·0.5\text{MeOH}\) (Ln = GdIII, TbIII, DyIII) in >70% yield (Table 1).

The \([\text{LnCu}_3]\) complexes consist of a central eight-coordinate LnIII ion surrounded by three bidentate \([\text{CuH}_2\text{edte}]\) metaloligands and one bidentate nitrate ligand (Figure 1). The LnIII ion is in a distorted environment (Figure 2) and shape measurements relative to a trigonal dodecahedron ($D_{3d}$) or biaugmented trigonal prism ($C_{3v}$) are the best match at 2.2–2.3 (see the Supporting Information, Table S1). The next best match is for the Johnson-biaugmented trigonal prism ($C_{2v}$) at 2.9–3.3. In \([\text{LnCu}_3]\), the steric properties of the \([\text{CuH}_2\text{edte}]\) metaloligands will play a key role in determining the shape of the LnIII coordination sphere, encouraging further study into the utilization of flexible metaloligands to isolate rare or unusual LnIII coordination geometries in 3d–4f complexes. Incorporation of a 3d metal ion such as CuII as the central ion of the metaloligand increases the flexibility further, due to its range of typical coordination environments from [4] to [4 + 2]. The CuII centers in \([\text{LnCu}_3]\) are in a distorted [4 + 1] environment $\{\text{N}_{30}\text{O}_{28}\\text{O}_{30}\}$, each encapsulated by a H$_2$edte$^{2−}$ ligand. For each ligand, two arms are deprotonated and form alkoxide bridges between the CuII ion and the central LnIII ion \([\text{Cu}−\text{O}−\text{Ln} = 96.71(13)−101.08(15)°]\). Two arms remain protonated: one fills the axial position (Cu−O = 2.203(4)–2.272(4) Å) and the other remains

### Table 1. Crystal Data and Structure Refinement Parameters

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<th></th>
<th>[Cu$_2$(H$_3$edte)$_2$][NO$_3$]$_2$</th>
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<th>[TbCu$_3$]</th>
<th>[DyCu$_3$]</th>
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<td>15.9760(6)</td>
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Figure 1. Structure of \([\text{TbCu}_3(\text{H}_2\text{edte})_3(\text{NO}_3)]^−[\text{NO}_3]_2\)\(^{2−}\). Atom colors: Tb, cyan; Cu, orange; N, blue; O, red. All hydrogen atoms except ligand OH groups are omitted for clarity.

Figure 2. Core of \([\text{TbCu}_3]\), highlighting the distorted environment at TbIII. Atom colors: Tb, cyan; Cu, orange; N, blue; O, red.
unbound, hydrogen bonded to adjacent \{Cu,Ln\} complexes and lattice nitrate anions.

**Static Magnetic Properties.** In the magnetic susceptibility data for \{LnCu_3\} (Figure 3a), at low temperature the upturn in

\[ \chi_T \]

\[ \text{Figure 3. (a) Temperature dependence of } \chi T \text{ for } \{\text{LnCu}_3\} \text{ from 300 to } 1.8 \text{ K in a 1000 G field. (b) Magnetization versus field at 2 K for } \{\text{GdCu}_3\}. \text{ The solid lines in (a) and (b) correspond to fits of the data with the parameters given in the text.} \]

\[ \chi_T \text{ data is consistent with ferromagnetic exchange between Ln}^{III} \text{ and Cu}^{II}. \text{ Gd}^{III} \text{ has a spin-only ground state (} S_{\text{Gd}} = 7/2). \text{ Therefore, the } \chi_T \text{ data for } \{\text{GdCu}_3\} \text{ can be fit,}^{22} \text{ using a spin Hamiltonian with a single parameter } J \text{ describing the exchange interaction between } S_{\text{Gd}} \text{ and the three Cu}^{II} \text{ spins } (S_i = 1/2): \]

\[ H = -J \sum_{i=1}^{3} (S_{\text{Gd}}S_i) + \mu_B g_H (S_{\text{Gd}} + \sum_{i=1}^{3} S_i) \]

(1)

The second term in eq 1 is the Zeeman interaction, with \(\mu_B\) being the Bohr magneton and \(H = 1000 \text{ G the magnetic field. The best-fit result between 10 and 280 K yields the parameters } g = 2.04(3) \text{ and } J = 2.9(3) \text{ cm}^{-1}, \text{ consistent with an } S = 5 \text{ ground state of } \{\text{GdCu}_3\} \text{ (the small decrease at low temperature may be due to antiferromagnetic intercluster interactions or a small zero-field splitting and was excluded from the fit). This } g \text{ value seems quite reasonable, considering that Gd}^{III} \text{ has } g = 7/2 = 2.0 \text{ and the Cu}^{II} \text{ ions are expected to have a } g \text{ value slightly larger than } 2, \text{ giving credibility to this fit. These parameters also model the low-temperature magnetization versus field data for } \{\text{GdCu}_3\} \text{ very well, as can be seen in Figure 3b. N.B.: throughout this paper we adopt the notation } J \text{ for total angular momentum and } \tilde{J} \text{ for the exchange interaction parameters.} \]

For \{\text{TbCu}_3\} \text{ and } \{\text{DyCu}_3\} \text{ the crystal-field splitting of their respective } F_g \text{ and } ^4H_{15/2} \text{ ground states is as important for the magnetic properties as the exchange interactions with the Cu}^{II} \text{ spins. The lanthanide ion in each complex is in a low-symmetry environment (Table S1, Supporting Information). Therefore, many crystal-field terms (e.g., in the form of extended Stevens operators } \sum_{i=1,2,4,6} \sum_{j=-L}^L B_l(j) \text{ are allowed by symmetry and their parameters are not correlated. This large number of parameters makes it virtually impossible to unequivocally model the featureless high-temperature magnetic susceptibility. At low temperatures, the susceptibilities of } \{\text{TbCu}_3\} \text{ and } \{\text{DyCu}_3\} \text{ increase due to the ferromagnetic exchange interactions between the lanthanide ion and the Cu}^{II} \text{ ions, which impedes the determination of the low-energy crystal-field states from the magnetic susceptibility.} \]

The magnetization data of \{\text{TbCu}_3\} \text{ at } 2 \text{ and } 4 \text{ K and of } \{\text{DyCu}_3\} \text{ at } 2, 4, \text{ and } 6 \text{ K in Figure 4 show a steep increase at low}

\[ \text{Figure 4. Magnetization curves of } \{\text{TbCu}_3\} \text{ at } 2 \text{ and } 4 \text{ K (a) and of } \{\text{DyCu}_3\} \text{ at } 2, 4, \text{ and } 6 \text{ K (b). The solid lines are fits based on the effective model (eq 2) with exchange parameters from INS, as described in the main text.} \]
\[ H = -\sum_{i=1}^{3} J_{op}(\hat{S}_{i}^x \hat{z}_{ax} + \hat{S}_{i}^y \hat{z}_{ay}) - \sum_{i=1}^{3} J_{ix}(\hat{S}_{i}^x \hat{z}_{ix} + \hat{S}_{i}^y \hat{z}_{iy}) \]

\[ + \mu_B \hat{H}(g_{\|}(\hat{S}_{i}^x + \hat{S}_{i}^y) + g_z \hat{S}_{i}^z + g_{Cu} \sum_{i=1}^{3} \hat{z}_{i}) \]

(2)

where \( J_{op}, J_{ix}, \) and \( J_{ix} \) are the effective parameters describing the anisotropic exchange interactions between \( S^+ \) and the Cu\(^{2+} \) spins \( s_i = 1/2 \). The solid lines in Figure 4 are fits of the magnetization to this data, whereby the exchange parameters were taken from the INS measurements (vide infra). In such an effective model \( g_{\|} = g_{\|}(2\alpha M_j + 2\beta M_j^2 + ...), \)

where the parameters \( \alpha, \beta, ... \) describe the contribution of different \( M_j \) states to the wave function \( | \Psi_M \rangle = M_j| \Psi_M \rangle + M_{j-2}| \Psi_M \rangle + ... \) of the Ln\(^{3+} \) ground state and \( g_{\|} \) values are the intrinsic Ln\(^{3+} \) g factors for a given \( J \) multiplet.

For \{TbCu\(_3\}\}, the maximum \( g_{\|} \) is therefore given as \( g_{\|}^{\text{max}} = 2M_{j=\pm 1}^{\text{max}}g_{\|} = 18 \) \( g_{\|} = 3/2, M_{j=\pm 1}^{\text{max}} = J = 6 \), which was set as the upper limit for the fit. The following fit parameters were determined: \( g_{\|} = 0(3), g_{\|} = 18(2), g_{\|} = 2.4(3) \) with the exchange parameters \( f_{\|} = 16.6 \) cm\(^{-1} \) and \( f_{\perp} = 26.7 \) cm\(^{-1} \) (INS; vide infra). The magnetization of \{DyCu\(_3\}\} at 2, 4, and 6 K could be fit the same way, but with an upper limit of \( g_{\|}^{\text{max}} = 2M_{j=\pm 1}^{\text{max}}g_{\|} = 20 \) \( g_{\|} = 4/3, M_{j=\pm 1}^{\text{max}} = J = 15/2 \). The best fit parameters are \( g_{\|} = 0(1), g_{\|} = 16.9(6), g_{\|} = 2.2(1) \) with the INS exchange parameters \( f_{\|} = 13.1 \) cm\(^{-1} \) and \( f_{\perp} = 27.7 \) cm\(^{-1} \) (vide infra).

For both \{TbCu\(_3\}\} and \{DyCu\(_3\}\} the fits yield reasonable values for the Cu\(^{2+} \) g factor with the deviation between the two samples within the errors of the fit. The transverse g factor of the lanthanide ions \( g_{\perp} \) is 0 in both cases, but with rather large error bars, indicating that its effect on the magnetization is marginal (see also contour plots of square of differences vs \( g_{\|} \) and \( g_{\perp} \) in the Supporting Information). From the values of \( g_{\|} \) we can estimate the main \( M_j \) contribution to the lowest doublet of the crystal-field split states. In \{TbCu\(_3\}\} the maximum \( g_{\|} = 18(2) \) is found in the fit, which yields \( M_j = \pm 6 \) as the main contribution to the ground doublet wave function. For \{DyCu\(_3\}\} \( g_{\|} = 16.9(6), \) which is quite close to the value 82/3 expected for \( M_j = \pm 13/2, \) and we thus conclude that the ground doublet of Dy\(^{3+} \) in \{DyCu\(_3\}\} is best described by \( M_j = \pm 13/2 \). Approximating the coordination geometry of the Ln\(^{3+} \) ions in \{LnCu\(_3\}\} as square antiprismatic (shape measurements relative to \( D_{4h} \) are 3.16 and 3.03 for \{TbCu\(_3\}\} and \{DyCu\(_3\}\}, respectively) allows comparison to mononuclear Ln\(^{3+} \) SMMs with that geometry,\(^{23,30} \) where it was found that the Tb\(^{3+} \) ion has a maximum \( M_j = \pm 7 = \pm 6 \) ground state, and for Dy\(^{3+} \) the lowest Kramers doublet is characterized by \( M_j = \pm 13/2 \), in good agreement with the magnetization fits for \{TbCu\(_3\}\} and \{DyCu\(_3\}\}.

**Single-Molecule Magnetism.** Both \{TbCu\(_3\}\} and \{DyCu\(_3\}\} display frequency-dependent (\( \nu \)) slow magnetic relaxation in low-temperature ac susceptibility measurements (Figures 5 and 6), with \{TbCu\(_3\}\} showing distinct peaks in \( \chi'' \) vs \( T \), without application of a dc field. For the Arrhenius analysis \( (\tau = \tau_0 \exp(\Delta E/k_B T)) \) in Figure 7 \( \ln(1/\tau) \) was plotted as a function of 1/\( k_B T \) with \( \tau = 1/(2\pi\nu) \) and \( \tau_{\text{max}} \) is the peak position from Lorentzian fits of the peaks in \( \chi'' \) vs \( T \). For \{TbCu\(_3\}\} in zero applied dc field \( \Delta E/k_B = 17.3(4) \) K (\( \Delta E = 12.0(3) \) cm\(^{-1} \)), and \( \tau_0 = 2.2(3) \times 10^{-7} \) s (Figure 7) could be deduced from linear fits. Application of a small dc field \( H_{dc} = 1.0 \) kG leads to a 12% increase in the effective anisotropy barrier (\( \Delta E/k_B = 19.3(1) \) K (\( \Delta E = 13.4(1) \) cm\(^{-1} \)), and \( \tau_0 = 1.4(1) \times 10^{-7} \) s. \{DyCu\(_3\}\}, on the other hand, shows only a small frequency dependence in zero applied dc field, while application of \( H_{dc} = 1.5 \) kG allows observation of distinct peaks in \( \chi'' \) vs \( T \), giving \( \Delta E/k_B = 16.2(4) \) K (\( \Delta E = 11.2(3) \) cm\(^{-1} \)) and \( \tau_0 = 1.8(3) \times 10^{-7} \) s, following the above analysis. While the magnetic ground state of \{TbCu\(_3\}\} is characterized by half-integer cluster \( M_{tot} \) states \((M_{tot} = (\sum M_{tot})/2 \text{if } \sum M_{tot} \text{ is even}) \), \{DyCu\(_3\}\} has integer cluster \( M_{tot} \) states (vide infra), leading to more effective QTM in \{DyCu\(_3\}\} that is strongly suppressed by the application of a dc field in the ac susceptibility experiment.

The higher rate of QTM in \{DyCu\(_3\}\} in comparison to \{TbCu\(_3\}\} is confirmed in the low-temperature, single-crystal magnetization vs field curves shown in Figures 8 and 9. \{TbCu\(_3\}\} shows SMM-typical sweep-rate-dependent hysteresis curves with nonzero coercivity (Figure 8), and only at low enough sweep rates and high enough temperatures can the coercivity be suppressed. For \{DyCu\(_3\}\}, on the other hand, there is very little dependence of the magnetization curves on the sweep rate, and there is no coercivity at all temperatures (Figure 9), only a very small hysteresis at fields close to saturation of the magnetization ("butterfly" hysteresis). The lack of coercivity paired with the fast relaxation at \( H_{dc} = 0 \) and slow relaxation at \( H_{dc} = 1.5 \) kG are clear indications that \{DyCu\(_3\}\} is an SMM with very effective ground-state QTM, in agreement with an integer \( M_{tot} \) ground state. Application of a small dc field removes the ground-state degeneracy and thus suppresses the tunneling, thereby uncovering the thermal activation energy for spin relaxation of \( \Delta E/k_B = 16.2(4) \) K.

**Exchange Interactions.** Inelastic neutron scattering (INS) experiments were performed on ~2 g of \{TbCu\(_3\}\} and on ~1 g of \{DyCu\(_3\}\} in the temperature range 1.4–30 K on the time-of-
flight spectrometer FOCUS (Figures 10 and 11). These spectra show the scattering intensity integrated over \(Q\) (\(\sim 0.4 < Q < 2.6\) Å\(^{-1}\)) at \(\Delta E = 0\). The \(Q\) dependence of the intensity of the INS transitions is practically featureless, apart from a small decrease with increasing \(Q\) in comparison to the rising background, and could therefore not be used for further analysis. The reason for the diffuse, structureless \(Q\) dependence and the rising background is most probably incoherent scattering due to the many hydrogen atoms in the sample.

\{TbCu\(_3\}\) was measured with two initial neutron wavelengths, 4.3 and 5.5 Å. At 4.3 Å a clear peak labeled II is observed at \(\sim 13\) cm\(^{-1}\) at all three temperatures (1.4, 10, and 30 K; see Figure 10a).

Additionally, a shoulder on the elastic line at \(\sim 7\) cm\(^{-1}\) (I) can be seen in Figure 10a. Both features decrease in intensity with increasing temperatures and thus correspond to transitions from the ground state to different excited states. Peak II is quite broad, and the high-resolution measurement at 5.5 Å reveals that it indeed consists of multiple components. Because of the expected larger crystal-field splitting of the Tb\(^{III}\) ion, the splitting observed by these excitations has to originate from the exchange interactions between the Tb\(^{III}\) ion and the Cu\(^{II}\) ions. These interactions can be approximated to the interactions of the Tb\(^{III}\) ground \(M_J\) doublet, described as a pseudospin \(S' = 1/2\), and the three Cu\(^{II}\) spins using the effective Hamiltonian:

\[
\mathcal{H} = -\sum_{i=1}^{3} J_{ij} (S'_{ix} \hat{\sigma}_{ix} + S'_{iy} \hat{\sigma}_{iy}) - \sum_{i=1}^{3} J_{ij} \hat{S}_{ix} \hat{\sigma}_{ix}
\]

i.e. eq 2 without the Zeeman terms. The three Tb\(^{III}\)–Cu\(^{II}\) exchange interactions are unrelated by symmetry, and a maximum of six parameters could be used in this effective model, as the anisotropy of the lanthanide ions due to their crystal-field splitting is absorbed into the effective exchange parameters (also an isotropic model yields two transitions with an energy ratio of 4:1, incompatible with the data). Six parameters is clearly too many for the number of observed peaks, and in a first approximation the same parameters \(J'_{xy}\) and \(J'_{xz}\) were used to describe all three interactions. The dotted line in Figure 10a depicts the calculated spectrum at 1.4 K for \(J'_{xy} = 16.6(2)\) and \(J'_{xz} = 26.7(2)\) cm\(^{-1}\). This simple model fails to capture the small splitting of peak II but

**Figure 6.** Magnetic ac susceptibility of \{DyCu\(_3\}\} in \(H_{ac} = 0\) (a) and in \(H_{ac} = 1.5\) kG (b). \(\chi'\) and \(\chi''\) are the in-phase (real) and out-of-phase (imaginary) contributions, respectively.

**Figure 7.** Arrhenius fits for \{TbCu\(_3\}\} in \(H_{ac} = 0\) (red ●) and 1.0 kG (red ○) and \{DyCu\(_3\}\} in \(H_{ac} = 1.5\) kG (blue □). For details, see the main text.
otherwise yields a reasonable description of the experimental spectrum (and these parameters were therefore used for the magnetization fits; vide supra). A calculated spectrum where peak II is split into multiple components can be obtained by varying the parameters for the three different TbIII–CuII exchange interactions. Peak II only splits into two components, even for six completely different exchange interaction parameters, and peak I does not split at all. Therefore, we limited the number of parameters by assuming a constant ratio $J_0/|J_0|$ and a symmetric variation of the three exchange parameters: $J_{1xy} - J_{2xy} = J_{3xy} = J_{4xy}$. The best agreement with the measured spectra was achieved for $J_{1xy} = 16.6(2)$ cm$^{-1}$, $J_{2xy} = 14.8(1)$ cm$^{-1}$, $J_{3xy} = 18.4(1)$ cm$^{-1}$, and $J_{4xy} = 1.61(3)$ (solid line in Figure 10a). Substituting the real quantum number $M_0 = \pm 6$ for $S'$ allows construction of the cluster wave functions, best described with the total magnetic quantum number $M_{tot} = \langle J_{tot}M_{tot}\rangle J_{tot}/|J_{tot}|^2$. The ground state of $\{\text{TbCu}_3\}$ has $M_{tot} = \pm 15/2$, and the INS excitations are to the $\pm 13/2$ states, in agreement with the INS selection rules ($\Delta M_{tot} = 0, \pm 1$), shown in Figure 10b. Due to the ferromagnetic exchange interactions, the cluster ground state $\pm 15/2$ arises from a parallel alignment of the TbIII moment and the CuII spins, and the INS excitations are CuII spin flips.

Figure 9. Single-crystal magnetization versus field hysteresis loops for $\{\text{DyCu}_3\}$: (a) with a constant field-sweep rate of 0.14 T/s at different temperatures between 0.03 and 5 K; (b) at a constant temperature of 0.03 K with different sweep rates between 0.004 and 0.280 T/s.

For $\{\text{DyCu}_3\}$ a thinner sample had to be used due to the large neutron absorption cross section of Dy, and it was thus not possible to measure at a wavelength of 5.5 Å, where the neutron flux is lower and the neutron absorption of the sample higher. The INS spectra of $\{\text{TbCu}_3\}$ recorded with a wavelength of 4.3 Å are depicted in Figure 11a. At 1.4 K clear peaks at $\sim 10$ and $\sim 14$ cm$^{-1}$ are observed, which decrease in intensity with increasing temperature. These excitations are also expected to arise from the exchange interactions between the central DyIII ion and the three CuII spins, as the crystal-field splitting of the DyIII ion is expected to be larger than the measured energy range. Calculating the spectra for the best fit of peak position to the calculated energies yields the dotted line in Figure 11a for $J_{1xy} = 13.1(1)$ and $J_0 = 27.7(1)$ cm$^{-1}$. However, in $\{\text{DyCu}_3\}$ as in $\{\text{TbCu}_3\}$, peak II is broadened and may be best assumed to consist of multiple components. The same analysis as for $\{\text{TbCu}_3\}$ yields the parameters $J_{1xy} = 12.5(2)$ cm$^{-1}$, $J_{2xy} = 11.1(1)$ cm$^{-1}$, $J_{3xy} = 13.9(1)$ cm$^{-1}$, and $J_0/|J_0| = 2.20(5)$ for $\{\text{DyCu}_3\}$ and the solid line in Figure 11a. The low-energy spectrum as a function of the total magnetic quantum number $M_{tot}$ is visualized in Figure 11b. The ground state can be described as $M_{tot} = \pm 8$ with excitations to states with $\pm 7$. As in $\{\text{TbCu}_3\}$, the observed INS excitations in $\{\text{DyCu}_3\}$ correspond to CuII spin flips.

The energies of the fundamental excitations in the $\{\text{TbCu}_3\}$ and $\{\text{DyCu}_3\}$ SMMs are comparable to the energy barriers found in the ac susceptibility, as is shown in Figures 10b and 11b. Therefore, it is safe to assume that the thermal relaxation goes via these excited states, which, as noted above, correspond to CuII spin flips.

In order to compare the values of the exchange interactions to the exchange interactions in e.g. $\{\text{GdCu}_3\}$, conversion into
with a TbIII ground state not pure. We presume that we used the dominant linear combinations of wave functions with different \( \Delta M_J \) components in the effective calculations. The LnIII ground state wave functions in our model.

**CONCLUSIONS**

In summary, we have presented two new 3d–4f SMMs, \{TbCu\} and \{DyCu\}, assembled using a step-by-step approach and provided three more examples with ferromagnetic LnIII–CuII exchange interactions. Despite the somewhat similar barriers for the two SMMs (for \{TbCu\} in zero applied dc field \( \Delta E/f_B = 17.3(4) \) \( K \); for \{DyCu\} in 1.5 \( K \) applied dc field \( \Delta E/f_B = 16.2(4) \) \( K \)), strikingly different ac susceptibility and magnetic hysteresis curves are observed. The main reason for these differences lies in the different ground states, \( M_{\text{tot}} \) being a half-integer for \{TbCu\} and \( M_{\text{tot}} \) an integer for \{DyCu\}, and the associated more efficient ground state quantum tunneling of the magnetization (QTM) in \{DyCu\}. This highlights how the often strong QTM associated with lanthanide ions can be modulated by using 3d–4f exchange interactions. For \{TbCu\} and \{DyCu\}, the ferromagnetic exchange interactions between the central LnIII ion and the three CuII ions could be accurately measured by inelastic neutron scattering (INS) spectroscopy and modeled effectively. The excitations observed by INS correspond to flipping of CuII spins and appear at energies similar to the thermodynamic barrier for relaxation of the magnetization, \( \sim 10–20 \) \( K \), which we determined using ac susceptibility measurements. The CuII spin flips and hence the 3d–4f exchange interactions are thus at the origin of the SMM behavior in these exchange-coupled systems, where CuII spins coupled to the highly anisotropic LnIII ion form an anisotropic cluster ground state with large \( M_{\text{tot}} \) which can relax from one orientation to the other via CuII spin flips. This suggests that controlling and increasing the d–f exchange is essential in order to increase the blocking temperature of d–f SMMs and that, to be effective, this has to be done alongside careful control over the position of each magnetic center within the complex.

**ASSOCIATED CONTENT**

5 Supporting Information

Figures, a table, and CIF files giving crystallographic data and IR spectra for \{Cu\}, \{H3edt\}, \{H2edt\}, \{NO3\}, \{GdCu\}, \{TbCu\}, and \{DyCu\}, shape measurements of \{LnCu\}, diffuse reflectance spectra, and contour plots. This material is available free of charge via the Internet at http://pubs.acs.org.

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NOTE ADDED AFTER ASAP PUBLICATION

Due to a production error, this paper was published on the Web on August 7, 2014, with errors in equations 2. The corrected version was republished on August 11, 2014.