Spin entanglement in supramolecular systems.

G. Lorusso\textsuperscript{1,2}, F. Troiani\textsuperscript{1}, V. Bellini\textsuperscript{1}, A. Ghirri\textsuperscript{1} A. Candini\textsuperscript{1}, S. Carretta\textsuperscript{1,3}, P. Santini\textsuperscript{1,3}, G. Amoretti\textsuperscript{1,3}, W. Wernsdorfer\textsuperscript{4}, G. Timco\textsuperscript{5}, R.E.P. Winpenny\textsuperscript{5}, M. Affronte\textsuperscript{1,2}

\textsuperscript{1}CNR-Institute of nanoSciences S3, via G. Campi 213/a, 41100 Modena, (Italy).
\textsuperscript{2}Dipartimento di Fisica, Università di Modena e Reggio Emilia, via G. Campi 213/a, 41100 Modena, Italy
\textsuperscript{3}Dipartimento di Fisica, Università di Parma and Unità CNISM di Parma, via Usberti 7/a, 43100 Parma, Italy.
\textsuperscript{4}Institut L. Néel CNRS, BP166, 25 Av des Martyrs, 38042 Grenoble, France.
\textsuperscript{5}School of Chemistry, University of Manchester, Oxford Road, Manchester M139PL, United Kingdom.

E-mail: giulia.lorusso@unimore.it

Abstract. Entanglement is an intriguing property of quantum systems that is essential for the implementation of quantum information processing. We review recent results on the establishment of magnetic coupling and spin entanglement between molecular clusters of Cr\textsubscript{7}Ni antiferromagnetic rings. We firstly present the magnetic features of the molecular building blocks and the strategy to link them without altering their properties. A systematic study of the magnetic interaction in (Cr\textsubscript{7}Ni)\textsubscript{2} dimers through different heteroaromatic linkers is then reported. Finally, for the dimer with strongest coupling, the entanglement is directly investigated both theoretically and experimentally.

1. Introduction

Entanglement is a peculiar property of quantum mechanics. Given a composite system, entanglement is established when the states of the parts are so highly correlated each other that it is impossible to describe one quantum component without the knowledge of the rest of the system [1, 2]. Consequently, having two entangled qubits, if we carry out an experiment and we measure one of them, we have information about the state of the other qubit. This property is a great resource for fields like quantum cryptography, teleportation, information and computation [3].

The interest for the exploitation in quantum information science, together with the appeal of quantum entanglement itself, has stimulated intensive research activity for the controlled generation of entanglement between nanoscaled objects. For photons [4] or cold atoms, as well as for a few solid state systems [5], entanglement is largely investigated, both theoretically and experimentally trying to unveil both its qualitative and quantitative aspects [1, 2].

For what concern the entanglement in magnetic systems there is an extensive theoretical literature [6, 7, 8, 9, 10, 11] but very few experiments [12, 13] and the latter are referred to collections of spin systems. Thus, the problem of measuring entanglement in finite spin systems is still very open. Molecular spin clusters represent a suitable test bed in this context. In fact, they represent complex but finite systems whose structural and physical features can be tailored
at synthetic level and whose properties can be predicted by microscopic, albeit demanding, models. Recent achievements in supramolecular chemistry, experiments and modeling appear extremely encouraging in this field [14, 15, 16].

Here we review some results recently obtained, enlightening the steps needed to establish and measure entanglement between spins in supramolecular structures. In the following, Cr$_7$Ni molecular spin clusters are firstly introduced showing that they are good building blocks with well defined state. Afterwards, the problem of establishing magnetic coupling between the units is discussed analyzing how the propagation of spin information at the supra-molecular (nanometer) scale works in four purple-Cr$_7$Ni dimers that differs each other only for the heteroaromatic linker between the rings. Finally, for a particular molecular dimer the entanglement is experimentally measured and theoretically quantified.

2. Molecular spin clusters and Cr$_7$Ni.
Molecular spin clusters are ideal test bed for the study of nanoscale magnetic phenomena. These systems are molecules of few nanometers, constituted by a magnetic nucleus surrounded by organic chemical groups. The magnetic core is typically constituted by transition metals, rare-earth ions or even organic radicals, while the organic bridges comprise light elements like carbon, oxygen, hydrogen and nitrogen. The deep level of control achieved at synthetic level allows to produce collections of identical non-interacting molecules, embedded in crystals and oriented along specific crystallographic directions. Although the final product of synthesis appears as bulk crystals or powders, i.e. macroscopic samples, we can assume these materials as statistical ensembles of quantum systems. Thus, solid state experimental techniques, like the measurements of thermodynamic properties, reflect mainly ensemble properties of the single molecule. Moreover, the experimental conditions needed to reveal the quantum behavior are easily achievable in laboratory: molecular spectra are well resolved at liquid helium temperatures, while level crossings can be observed at few teslas fields. All these reasons contributed to the success of molecular magnets in the last 20 years.

Structural and physical features of molecular magnets can be tailored at synthetic level and a huge variety of molecules can be produced. One possible classification is based on their different magnetic properties: single molecules magnets (SMM), photomagnetic and spin-cross-over derivatives, ferromagnetic or antiferromagnetic (AF) chains and rings.

SMM is a wide class of molecules with high spin. Among them, Mn$_{12}$-acetate has spin $S = 10$ and high anisotropy barrier [17, 18, 19] and it is one of the first ones that has been extensively studied and probably also the most popular. Together with Fe$_8$, for Mn$_{12}$-acet key experimental results were obtained like: tunneling of magnetization [20, 21, 22, 23, 24], the observation of
quantum phase interference (Berry phase) [25] and coherent quantum oscillations of spin between two energy minima [26].

In this review paper the attention is focused on another interesting subclass of molecules, that of AF spin rings. These, differently to the SMM, are low spin systems and with lower dipolar interaction, that are advantages, as discussed later, for applications in quantum information processing. The first AF rings synthesized were homometallic and based on trivalent metals. As examples, there are rings based on Fe$^{3+}$ ($s = 5/2$), like Fe$_6$ [27, 28], F$_{10}$ [29, 28], Fe$_{12}$ [30] and Fe$_{18}$ [31]; those on Cr$^{3+}$ ($s = 3/2$), like Cr$_8$[32, 33] and Cr$_{10}$ [34]; and finally those based on V$^{3+}$, like V$_8$ and V$_{10}$ [35]. These even-membered AF rings have a fully compensated total spin and singlet ground state at low temperature. More recently an extra spin was introduced, in order to break the compensation and control the total spin of the AF wheels. This strategy was used for the Cr-based cyclic systems to synthesize heterometallic molecular wheels in which one Cr ion is substituted with a divalent transition metal M[36]. If M = Ni$^{2+}$ with $s = 1$, the spin balance gives an effective total $S = 1/2$ to the molecule; two examples are Cr$_9$Ni[37], obtained from Cr$_{10}$, and Cr$_7$Ni, obtained from Cr$_8$.

The structure of Cr$_7$Ni is depicted in Fig. 1: the seven Cr$^{3+}$ ($s = 3/2$) ions and the extra Ni$^{2+}$ ($s = 1$) are disposed in a symmetric octagonal planar structure, with the spins antiferromagnetically coupled. This molecule, synthesized in 2003 [36], has been deeply investigated by specific heat and torque [38], nuclear magnetic resonance [32], neutron scattering [39] and micro-SQUID magnetization at very low temperature [40] measurements. The experimental results were fitted by spin-Hamiltonian calculations [41] founding that Cr$_7$Ni is an effective two-level system with $S = 1/2$ ground state well separated from $S = 3/2$ first excited state. Cr$_7$Ni has been then proposed as a molecular qubit, suitable candidate for Quantum Information Processing (QIP) [38, 42]. This proposal has been corroborated by very promising theoretical [43] and experimental [44] studies of coherence. The time of coherence measured for the molecule of Cr$_7$Ni results indeed about 3 µs at 2 K, at least two order of magnitude greater than the time needed for spin manipulation. Finally, successful grafting of isolated molecules on surfaces was achieved, with only minor changes in the magnetic features from the bulk-material [45, 46, 47, 48].

3. Linking the rings

To have entanglement between molecular magnets, we firstly need to establish inter-molecular magnetic interaction in a controlled way. The easiest strategy is by chemical linkers. Examples of supramolecular dimers of single-molecule magnets (SMM) were already reported in the early 1990s by Christou group [50], but the magnetic coupling of the linked Mn$_4$ cages through C–H···Cl hydrogen bonds were found much later in 2002 [51]. In this case, the possibility to change the type of linker is not simple, using diketonates [52]. Aromatic groups could be suitable linkers to realize supramolecular systems with tailored and controlled intermolecular interactions. One critical point in their use at synthetic level, is the risk of obtaining polymeric networks with long-range magnetic order; in the case of Mn$_4$ linked through dicyanamide N(CN)$_2$ the SMM were collected into a 3-dimensional polymer[53]. The crucial factor to avoid this problem is having molecules with small dipolar interaction. In this respect, the Cr$_7$Ni rings offer an unique opportunity.

The first attempt to bind together Cr$_7$Ni rings was realized in 2005 [49]; the link was organo-metallic and it was attached to the Cr$_7$Ni wheels via hydrogen-bonds between F-bridges of the cage and the terminal H–N groups of the link (see Fig. 2(a)). Unfortunately, this type of connection is not magnetically efficient [37], indeed it was shown that no significant exchange of spin can be achieved through this link. Progresses were achieved linking the rings via the external carboxylates at the Ni edge, where appreciable spin density resides. Examples are the dimer structures represented in Figs. 2(b) and (c) where the magnetic coupling between the
Figure 2. Crystallographic structures of the first Cr$_7$Ni dimers synthesized. In a) the organo-metallic link is connected at the centers of the wheels via hydrogen-bonds (from [49]); in b) and c) the link is still organo-metallic but connected via the carboxylate bridge at the Ni edge (from [14]). Moreover, in c) the magnetic coupling can be permanently coupled switched on and off through Cu$_2$ dimer (from [14]).

In 2008 a new derivative of Cr$_7$Ni, hereafter called purple-Cr$_7$Ni, was synthesized [55]. In this new derivative, with respect to the original green-Cr$_7$Ni ring [36], five bridging fluorides are substituted by alkoxides. The replacement of fluoride with alkoxide within the coordination sphere of the majority of Cr$^{3+}$ ions causes a change in color of the crystals from dark green to purple, from this the names. This also affects the Cr -Cr exchange coupling and consequently magnetic levels of each ring [15]. Most importantly, thank to the presence of a terminal ligand, purple-Cr$_7$Ni offers an ideal opportunity to link the rings anchoring directly onto the Ni sites organic linkers with or without metal ions (see Fig. 3(a)). Finally, exploiting faster chemical reaction at Ni site, it is possible to systematically change the aromatic linker, thus tuning the degree of conjugation.

In Figs. 3(b)-(e) four representative linkers of purple-(Cr$_7$Ni)$_2$ dimers are depicted, respectively: $L=4,4'$-bipyridyl (bipy, in short), $trans-1,2-\textit{bipyridylethene}$ (bipyet), $\textit{bipyridyltetrazine}$ (bipyz) and $\textit{bidimethylpyrazolyl}$ (bipz). The structures of the individual rings in the molecular dimers such synthesized do not vary between the derivatives, and in each case the nitrogen from a di-imine is coordinated to nickel, giving the nickel a 2F, 3O, 1N coordination sphere. Chemical synthesis and structure information of these molecules are reported in Refs. [55, 54].

Low temperature specific heat for the four derivatives, taken in presence of an external 1 T magnetic field, is reported in Fig. 4. Data, relative to microcrystalline samples, are plotted as a function of temperature and normalized to the gas constant $R$. For comparison, specific heat multiplied by two of the single purple-Cr$_7$Ni ring that constitutes each dimer (black triangles) and spin-Hamiltonian calculations [15] of its magnetic contribution (dashed line) are reported. The curves of the four compounds superimpose each other almost perfectly, reproducing the
behavior of the single ring at moderate field (1 T). This demonstrates that the pattern of the lowest lying states of the single purple-Cr$_7$Ni rings is preserved also in the supramolecular systems. In particular the presence of well defined Schottky anomaly below 1 K shows that energy split between $S = 1/2$ and $S = 3/2$ states is conserved in spite of inter-molecular interaction that should be in energy scale below 1 K.

Evidence of the coupling between the rings can emerge from the specific heat measurements in zero magnetic field. In the inset of Fig. 4 we present the comparison between the single ring and (Cr$_7$Ni)$_2$-bipy dimer. A Schottky anomaly around 4K is visible for both the derivatives, this is due to the energy gap between the ground and excited states. Conversely, at low temperature the shape of the curves is different. In the case of the single ring (black circles) the specific heat goes to zero, as expected for a Kramers doublet, while for (Cr$_7$Ni)$_2$-bipy (red circles) there is an upturn below 0.5 K due to the energy level splitting in the ground state multiplet.

To explicitly reveal the presence of inter-rings interaction, micro-SQUID magnetization measurements at 40 mK have been performed. In Fig. 5 the resulting curves are plotted for all the derivatives; data are normalized to the saturation value $M_S$ (in correspondence of about $H = 1$ T) and measured with a sweeping rate $dH/dt = 0.28$T/s. The magnetization curves referred to bipy and bipyz dimers present inflection points that can be related to the energy gap between $S = 0$ and $S = 1$ states. As depicted in the inset indeed, if $S = 0$ state is the ground state in zero-field, it should be possible to see a spin-state crossing by increasing the field, with one sub-level of $S = 1$ state falling in energy as field increases. As evident from magnetization curves, the level crossings occur at $H = \pm 0.05$ T for bipy and at $H = \pm 0.04$ T for bipyz. For the other two compounds (bipyz and bipz), the magnetic coupling is too small (must be weaker than 100 mK), and no inflection points are visible in the curves. These results are fully consistent
Figure 4. Specific heat at $H = 1T$ for the four purple-(Cr$_7$Ni)$_2$ dimers discussed in the text: bipy (red), bipyel (blue), bipyetz (green) and bipz (orange). The curves are compared to the signal for the single purple-Cr$_7$Ni ring [15] multiplied by two (black). Data are normalized to the gas constant $R$. (Dashed line) simulation of magnetic contribution of the single ring calculated using the eigenvalues of the microscopic spin-Hamiltonian and multiplied by two. (Inset) specific heat at zero field for single purple-Cr$_7$Ni ring multiplied by two (black circles) and (Cr$_7$Ni)$_2$−bipy dimer (red circles). Theoretical magnetic (lines) contributions are reported. The common bump at higher temperatures is the Schottky anomaly due to the main energy splitting between the ground doublet and the first excited state, while the Schottky at lower temperature, present only for the dimer, is the energy splitting arising from the inter-ring coupling. Measurements were performed on thin pellets (∼2 mg) of polycrystalline sample by a $^3$He cryostat and by using the two-tau method.

with EPR data [54] and spin-Hamiltonian calculations [15, 54]. Finally, Density Functional Theory calculations explain how the magnetic coupling is established through the conjugated linkers [54].

In summary, both experimental and theoretical evidences indicate that, among the supramolecular dimers investigated, the strongest coupling between the rings is achieved through bipy linker. Thus, this is the ideal system in which explore also the presence of entanglement.

4. Entanglement between molecular spins
Experimental detection and quantification of entanglement is a demanding task [56]. Formally a state is entangled if its wavefunction cannot be factorized. This definition is not helpful, because, in general, telling whether a state of $n$ parties is separable or not is a non trivial mathematical problem. In theory, to reconstruct experimentally the overall density matrix it is necessary to measure the correlations between the observables of all the parties. This approach can be used if a small number of particles are involved, as in the case of photons [4]. Conversely, for magnetic bulk systems, i.e. ensemble of the order of Avogadro’s number of spins, one may not refer to individual properties of every constituent of a solid sample or correlation between them. Fortunately, an alternative and much simpler experimental approach exists to certify if a certain state is entangled directly. This tools are the so-called entanglement witnesses. An entanglement witness (EW) is a Hermitian operator which is able to detect entanglement in a state. The basic idea is that the expectation value of the EW for the state $\rho$ under consideration exceeds certain


Figure 5. Micro-SQUID magnetization for the four purple-(Cr$_7$Ni)$_2$ dimers discussed in the text. The curves are normalized to the saturation values $M_S$. The experiments were performed at 40 mK and with a magnetic field sweeping rate $dH/dt = 0.28$ T/s. To enlighten the transitions, we have zoomed in a region around zero field and only data with decreasing field are shown, the complete loops are reported in Ref. [54]. (Inset) schematic representation of the magnetic field dependence for $S=0$ and $S=1$ spin levels resulting from two interacting $S=1/2$ and taking into account axial anisotropy.

bounds only when $\rho$ is entangled [1, 2]. The limits of $EW$ approach are essentially two: it gives only a sufficient condition for entanglement and it is poor in quantitative information. For the cases in which it is possible to know the eigenvalues of the Hamiltonian a quantification of the entanglement can be done theoretically by the calculation of the concurrence ($C$)[1, 2, 56]. By definition[2] the concurrence is a monotonous function of the entanglement of formation and it can assume values comprised between zero and one, which represent the extreme situations of a not entangled or maximally entangled state, respectively.

Recently, the magnetic susceptibility, insofar as sum over all microscopic spin correlation functions, has been proposed as entanglement witness by Wiesniak et al. [57]. Using the complementary principle for the components of the susceptibility $\chi_z$, $\chi_y$, $\chi_z$, measured along three perpendicular direction, it can then be demonstrated [57] that a magnetic system is entangled if:

$$EW = \frac{1}{3} \left( \frac{\chi_x}{g_x^2} + \frac{\chi_y}{g_y^2} + \frac{\chi_z}{g_z^2} \right) - \frac{N_A \mu_B^2 S}{k_B T} \leq 0$$

where $g_x$, $g_y$ and $g_z$ are the components of gyromagnetic factors, $N_A$ is Avogadro’s number, $\mu_B$ the Bohr magneton, $k_B$ is the Boltzmann constant and finally $S$ is the spin of the systems taken into account. As visible from Eq. 1, the entanglement witness depends on the temperature $T$, meaning that the same system can be entangled for certain temperature ranges and not entangled in others. This is a direct consequence that entanglement is a property of the state of the system. Moreover, this enlightens the distinction between entanglement and simple interaction that, being related to the Hamiltonian of the system, is instead independent from the temperature.

In the specific case of (Cr$_7$Ni)$_2$−bipy dimer, we have estimated the entanglement witness described in Eq. 1 considering: $\chi_z = \chi_{\perp}$, $\chi_x = \chi_y = \chi_{||}$, $g_z = g_{\perp}$ and $g_x = g_y = g_{||}$. $\chi_{||}$ is the component perpendicular to the largest surface of the crystal; while $\chi_{\perp}$ refers to the directions within the crystal plane. Rotation of magnetic field within this plane does not evidence changes in the magnetic response. The susceptibility components were obtained as $dM/dH$ by derivative
of micro-SQUID magnetization on single crystals. Measurements were performed with very small magnetic field and for different temperatures [15]. The result is plotted in Fig. 6: for \( T \lesssim 50 \) mK \( EW < 0 \), thus providing a direct experimental evidence of entanglement between the two \( \text{Cr}_7\text{Ni} \) rings at this temperature range. This result is in agreement with concurrence calculations obtained using an effective two-qubit picture (see Ref. [15]). Furthermore, the concurrence gives quantitative estimation of entanglement founding the dependence of the entanglement also on the magnetic field. At vanishing temperatures, a sharp transition is found from maximum entanglement to not entangled state for magnetic fields that exceeds the value of crossing field between \( S = 0 \) and \( S = 1 \) states.

It should be noted that the expression (1) is valid in the condition \( [H, H_1] = 0 \), where \( H \) is the Hamiltonian of the system, and \( H_1 \) the part of the Hamiltonian that describes the interaction with magnetic field [57]. In the present case, the coupling between the effective spins \( S_\alpha \) includes an anisotropic contribution \( (D_{AB} \neq 0) \). However, for small enough values of \( D_{AB}/J_{AB} \), with \( J_{AB} \) exchange constant between the clusters, the difference between the susceptibility and the entanglement witness is negligible with respect to the threshold, as the case presented here (see Ref. [16] for the complete calculations).

5. Conclusions
In summary, \( \text{Cr}_7\text{Ni} \) appears to be a molecular two-level system very promising for qubit encoding. The magnetic coupling between the molecular rings in the \( \text{(Cr}_7\text{Ni})_2 \)-dimers were experimentally characterized in detail by heat capacity, micro-SQUID magnetization and EPR. Finally, for the dimer with the strongest coupling, \( \text{(Cr}_7\text{Ni})_2 - \text{bipy} \), spin entanglement between the rings is experimentally demonstrated below 50 mK using magnetic susceptibility as entanglement witness, in agreement with concurrence calculations.

Acknowledgments
This work has been carried out supported by FP7-ICT FET MolSpinQIP project, Contract No. 211284 and by the PRIN project of the Italian Ministry of Research and by the EPSRC (UK).

References
[1] R. Horodecki, P. Horodecki, M. Horodecki, and K. Horodecki. Rev. Mod. Phys., 81:865, 2009.
[2] L. Amico, R. Fazio, A. Osterloh, and V. Vedral. Rev. Mod. Phys., 80(2):517–576, 2008.
[3] M. A. Nielsen and I. L. Chuang. volume 10. Cambridge: Cambridge University Press, 2000.
[4] D. Bouwmeester et al. Phys. Rev. Lett., 82(7):1345–1349, 1999.
[5] J. R. Petta et al. Science, 309:2180, 2005.
[6] T. Roscilde, P. Verrucchi, A. Fubini, S. Haas, and V. Tognetti. Phys. Rev. Lett., 93(16):167203, 2004.
[7] M. C. Arnesen, S. Bose, and V. Vedral. Phys. Rev. Lett., 87(1):017901, 2001.
[8] A. Osterloh, L. Amico, G. Falci, and R. Fazio. Nature, 416:608, 2002.
[9] T. J. Osborne and M.A. Nielsen. Phys. Rev. A, 66(3):032110, 2002.
[10] G. Vidal, J. I. Latorre, E. Rico, and A. Kitaev. Phys. Rev. Lett., 90(22):227902, 2003.
[11] F. Verstraete, M. Popp, and J. I. Cirac. Phys. Rev. Lett., 92(2):027901, Jan 2004.
[12] S. Ghosh, T. F. Rosenbaum, G. Aeppli, and S. N. Coppersmith. Nature, 425:48, 2003.
[13] A. M. Souza et al. Phys. Rev. B, 77(10):104402, 2008.
[14] G. Timco et al. Nature Nanotec., 4(3):173–178, 2009.
[15] A. Candini, G. Lorusso, F. Troiani, A. Ghirri, et al. Phys. Rev. Lett., 104(3):037203, 2010.
[16] F. Troiani, V. Bellini, A. Candini, G. Lorusso, and M. Afronte. Nanotechnology, 21:274009, 2010.
[17] T. Lis. Acta Crystall. B, 36:2042, 1980.
[18] A. Caneschi et al. J. Am. Chem. Soc., 113:5873–5874, 1991.
[19] J. R. Friedman, M. P. Sarachik, J. Tejada, and R. Ziolo. Phys. Rev. Lett., 76(20):3830–3833, 1996.
[20] R. Sessoli, D.Gatteschi, A. Caneschi, and M. A. Novak. Nature (London), 365:141, 1993.
[21] L. Thomas, F. Lonti, R. Ballou, D. Gatteschi, R. Sessoli, and B. Barbara. Nature, 383:145, 1996.
[22] L. Thomas and B. Barbara. J. Low Temp. Phys., 113:1055–1060, 1998.
[23] D. Gatteschi and R. Sessoli. Angew. Chem. Int. Ed., page 268, 2003.
[24] S. Carretta et al. Phys. Rev. Lett., 79(24):4645–4648, 1997.
[25] W. Wersdorfer and R. Sessoli. Science, 284:133, 1999.
[26] F. Luis, F. L. Mettes, J. Tejada, D. Gatteschi, and L. J. de Jongh. Phys. Rev. Lett., 85(20):4377–4380, 2000.
[27] G. L. Abbati et al. Inorg. Chem., 36:6443, 1997.
[28] M. Afronte, J. C. Lasjaunias, A. Cornia, and A. Caneschi. Phys. Rev. B, 60(2):1161–1166, 1999.
[29] K. L. Taft et al. Journal of the American Chemical Society, 116(3):823–832, 1994.
[30] G. L. Abbati, A. Caneschi, A. Cornia, A. C. Fabretti, and D. Gatteschi. Inorg. Chim. Acta, 297:291, 1999.
[31] J. R. Petta et al. Phys. Rev. Lett., 97(26):267204, 2006.
[32] S. Carretta et al. Phys. Rev. B, 67(9):094405, 2003.
[33] D. M. Low et al. Chem.-Eur. J., 12:12385, 2005.
[34] R. H. Laye et al. Chem.-Eur. J., 9:6215, 2003.
[35] F. K. Larsen et al. Angew. Chem. Int. Ed., 42:101, 2003.
[36] M. Afronte, F. Troiani, A. Ghirri, S. Carretta, et al. Dalton Trans., pages 2810–2817, 2006.
[37] F. Troiani, A. Ghirri, M. Afronte, S. Carretta, et al. Phys. Rev. Lett., 94(20):207208, 2005.
[38] R. Caciuffo, T. Guidi, G. Amoretti, S. Carretta, E. Livioiti, P. Santini, C. Mondelli, G. Timco, C. A. Muryn, and R. E. P. Winpenny. Phys. Rev. B, 71(17):174407, 2005.
[39] W. Wernsdorfer, D. Mailly, G. A. Timco, and R. E. P. Winpenny. Phys. Rev. B, 72(6):060409, 2005.
[40] S. Carretta, P. Santini, G. Amoretti, M. Afronte, et al. Phys. Rev. B, 72(6):060403, 2005.
[41] M. Afronte, F. Troiani, A. Ghirri, A. Candini, V. Evangelisti, M. Corradini, S. Carretta, P. Santini, G. Amoretti, F. Tuna, G. Timco, and R. E. P. Winpenny. Single molecule magnets for quantum computation. J. Phys. D: Appl. Phys., 40:2999, 2007.
[42] Arzhang Ardavan et al. Phys. Rev. Lett., 98(5):057201, 2007.
[43] F. Troiani, V. Bellini, and M. Afronte. Phys. Rev. B, 77(5):054428, 2008.
[44] V. Corradini, A. Ghirri, U. del Pennino, R. Biagi, et al. Dalton Trans., 39:4928, 2010.
[45] A. Ghirri, V. Corradini, C. Cervetti, A. Candini, et al. Adv. Funct. Mat., 2010.
[46] V. Corradini, F. Moro, R. Biagi, V. De Renzi, et al. Phys. Rev. B, 79(14):144419, 2009.
[47] V. Corradini, R. Biagi, U. del Pennino, V. De Renzi, et al. Inorg. Chem., 46:4937, 2007.
[48] M. Afronte, I. Casson, M. Evangelisti, A. Candini, et al. Angew. Chem. Int. Ed., 44:6496, 2005.
[49] D. N. Hendrickson, G. Christou, E. Schmitt, E. Libby, et al. J. Am. Chem. Soc., 114:2455, 1992.
[50] Wolfgang Wernsdorfer, Nria Aliaga-Alcalde, David N. Hendrickson, and George Christon. Exchange-biased quantum tunnelling in a supramolecular dimer of single-molecule magnets. Nature, 416:406, 2002.
[51] E. C. Sanudo, T. Cauchy, E. Ruiz, R. H. Laye, et al. Inorg. Chem., 46:9045, 2007.
[52] H. Miyasaka, K. Nakata, K.-I. Sugiura, M. Yamashita, and R. Clerac. Angew. Chem., 116:725, 2004.
[53] T. Faust, V. Bellini, G. A. Timco, G. Lorusso, A. Candini, S. Carretta, F. Tuna, G. Whitehead, E.J.L. McNamn, R.G. Pritchard, S.J. Teat, W. Wernsdorfer, M. Afronte, and R.E.P. Winpenny. submitted, 2010.
[54] G. A. Timco, E. J. L. McInnes, R. G. Pritchard, F. Tuna, and R. E. P. Winpenny. Angew. Chem. Int. Ed., 49:17
47(50):9681–9684, 2008.

[56] F. G. S. L. Brandão. Phys. Rev. A, 72:022310, 2005.

[57] M. Wieśniak, V. Vedral, and Č. Brukner. N. J. Phys., page 258, 2005.