parameters of precession or obliquity. Using cost-effective proxy records instead of marine $\delta^{18}O$ variations is tempting, but as Clemens *et al.* (*7*) show, it may be a misleading stratigraphical tool, particularly when using the lead and lag relations as being diagnostic for the dynamics of a climate system.

Thus, the report of Clemens *et al.* (*7*) is of twofold importance. It highlights the need for increasing the precision of stratigraphical techniques, but also shows that the monsoon is a very complex system, which provides a serious challenge for future modeling efforts if the natural succession of the observed monsoon oscillations is to be reproduced. The realization of both concepts would, however, be an important step in understanding the physical mechanisms of drought and floods in Asia and Africa, past and present.

References

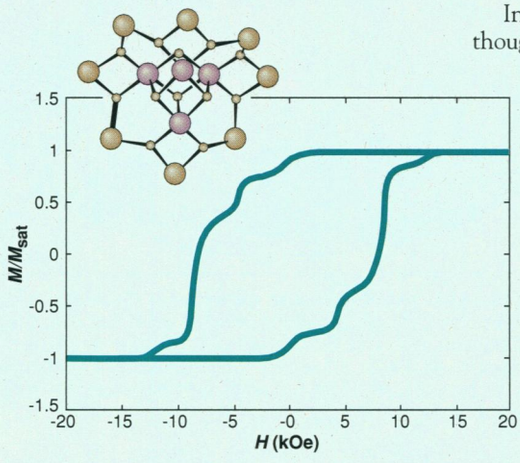
1. W. L. Prell and J. E. Kutzbach, *J. Geophys. Res.* **92**, 8411 (1987).
2. P. B. deMenocal and D. Rind, *ibid.* **98**, 7265 (1993).
3. W. L. Prell and J. E. Kutzbach, *Nature* **360**, 647 (1992).
4. J. Overpeck, D. Anderson, S. Trumbore, W. Prell, *Clim. Dyn.* **12**, 213 (1996).
5. C. R. V. Raman and J. A. Maliekal, *Nature* **314**, 430 (1985).
6. T. P. Barnett, L. Dümenil, U. Schlese, E. Roeckner, M. Latif, in *Teleconnections Linking Worldwide Climate Anomalies*, M. H. Glantz, R. W. Katz, N. Nicholls, Eds. (Cambridge Univ. Press, Cambridge, 1991), pp. 191–225.
7. S. C. Clemens, D. W. Murray, W. L. Prell, *Science* **274**, 943 (1996).
8. F. Sirocko, D. Garbe-Schönberg, A. McIntyre, B. Molfino, *ibid.* **272**, 526 (1996).
9. G. T. Walker, *Mem. Indian Meteorol. Dept.* **24**, 75 (1923).
10. J. Bjerknes, *Mon. Weather Rev.* **97**, 163 (1969).
11. R. S. Bradley, H. F. Diaz, G. N. Kiladis, J. K. Eischeid, *Nature* **327**, 497 (1987).
12. H.-F. Graf, *Clim. Dyn.* **7**, 19 (1992).
13. H. F. Diaz and V. Markgraf, Eds., *El Niño* (Cambridge Univ. Press, Cambridge, 1992).
14. P. Gloersen, *Nature* **373**, 503 (1995).
15. S. Hastenrath and P. J. Lamb, *Phys. Oceanogr.* **10**, 649 (1980).
16. S. Clemens, W. Prell, D. Murray, G. Shimmield, G. Weedon, *Nature* **353**, 720 (1991).
17. J. Haigh, *Science* **272**, 981 (1996).
18. M. Stuiver, T. F. Branziunas, B. Becker, B. Kromer, *Quatern. Res.* **35**, 1 (1991).
19. P. deMenocal, *Science* **270**, 53 (1995).
20. J. Chappellaz *et al.*, *Nature* **366**, 443 (1993).
21. M. R. Rampino and S. Self, *ibid.* **359**, 50 (1992).
22. D. Rind *et al.*, *ibid.* **349**, 500 (1991).

Quantum Hysteresis in Molecular Magnets

Eugene M. Chudnovsky

Magnetic materials are marked by hysteresis: their response to an increasing magnetic field is different from their response to a decreasing field. Elementary science textbooks always show smoothly shaped magnetic hysteresis loops; the stepwise magnetization curve in the accompanying figure is therefore extraordinary. The measurement was made at a temperature below a few kelvin in a crystalline organic compound, Mn_{12} acetate, and the steps are caused by a quantum mechanical effect amplified to a macroscopic level. This quantum magnetic hysteresis has recently been reported by Friedman *et al.* (*1*) and confirmed (*2*, *3*) by several groups. The findings are an important landmark in the search for macroscopic quantum tunneling of the magnetic moment.

The chemical formula of the crystal that exhibits the effect is $[Mn_{12}O_{12}(CH_3COO)_{16}(H_2O)_4]\cdot 2CH_3COOH\cdot 4H_2O$. In chemistry this compound is a teenager (*4*), and intensive research of its physical properties began only a few years ago (*5*). It consists of weakly interacting molecules of spin 10, arranged in a tetragonal lattice. Each molecule is formed by 12 Mn ions of mixed valence, interacting through oxygen bridges (see figure, inset). The four Mn ions of the central tetrahedron have spin $^3/_2$ and form a ferromagnetic cluster of total spin 6. The eight Mn ions of the crown have spin 2 and form another ferromagnetic cluster of total spin 16. The total spin of the molecule results from the antiferromagnetic interaction between the clusters: 16 – 6 = 10. All the interactions are so strong that the Mn_{12} molecule is effectively a single spin 10 object; in magnetic measurements one does not detect the effects of the individual atomic spins. In a Mn_{12} acetate crystal, the symmetry axes of all Mn_{12} molecules are aligned in one direction, making the crystal highly anisotropic: individual magnetic moments have a strong preference to look along the anisotropy axis.



Quantum magnetic hysteresis in Mn_{12} acetate. The inset shows the structure of the Mn_{12} molecule. Only Mn ions (large circles) and oxygen ions (small circles) are shown. [Courtesy of the authors of (*1*)]

According to quantum mechanics, the projection of spin 10 on a certain axis, say the anisotropy axis z of the crystal, can take only discrete values: $m = -10, -9, \ldots, -1, 0, 1, \ldots, 9, 10$. At zero magnetic field the two levels of the minimal energy belong to the two opposite orientations of the spin along the anisotropy axis, with $m = -10$ and $m = 10$, respectively. Other values of m numerate excited levels.

In classical terms, an m level can be thought of as the precession of the magnetic moment of the Mn_{12} molecule about the z axis, with the amplitude of the precession increasing with decreasing $|m|$. At $H = 0$, the energy barrier between the states with $m = -10$ and $m = 10$ is about 60 K in temperature units. This observation can be attributed to the anisotropy of the molecule. The separation between the levels is about 12 K at the bottom of the spectrum and about 0.6 K at the top. Imagine now that the crystal is cooled down to a few kelvin and put in a strong magnetic field applied in the negative z direction. Such a field makes the state with $m = -10$ energetically more favorable than the $m = 10$ state, resulting in the negative magnetization of the crystal. If the field is now quickly removed, most of the molecules will occupy the $m = -10$ level, which corresponds to the lower part of the hysteresis loop in the figure. The negative magnetization of the crystal decays with time as a result of the rotation of individual molecular moments. By absorbing phonons (oscillations of the crystalline lattice), a Mn_{12} molecule can go up the staircase of the excited levels until it reaches the top of the energy barrier. Then, by emitting phonons, it goes down the staircase, finally switching the spin projection from $m = -10$ to $m = 10$. Each phonon can change the m number by 1. Consequently, in zero field, the molecule must

The author is in the Physics Department, City University of New York Lehman College, Bronx, NY 10468–1589, USA. E-mail: chudnov@lcvax.lehman.cuny.edu

absorb 10 phonons before it reaches the top of the barrier at $m = 0$. At high temperature, phonons are in abundance, and the spins of the molecules frequently flip between $m = -10$ and $m = 10$, as in conventional paramagnets. At low temperature, however, phonons are scarce and the decay of the magnetic moment of the Mn_{12} crystal may take a long time (6). Under such conditions another mechanism of the magnetization decay comes into play: quantum tunneling between the m states.

Friedman *et al.* (*1*) found that, in contradiction with a commonsense interpretation, a weak magnetic field applied against the magnetic moment of the crystal slows down the decay of the moment. This remarkable observation helped them to understand the physics behind the stepwise hysteresis loop shown in the figure. According to quantum mechanics, the probability of tunneling must have maxima when the tunneling occurs between the m states of the same energy. This phenomenon is called resonant tunneling. In zero field the states with opposite projections of the spin, m and $-m$, have exactly the same energy, and the tunneling across the barrier occurs with the highest probability. A weak field applied in the positive z direction moves down all levels corresponding to positive m, while moving up all levels corresponding to negative m. This behavior breaks the condition of the resonance and suppresses tunneling. If the field in the positive z direction continues to increase, the positive m levels continue to move down while the negative m levels continue to move up. Quantum mechanics predicts that at about 5 kOe, levels with positive m will again come to resonance with negative m levels. The next resonance will occur at about 10 kOe, and so on. Altogether, there should be 21 resonances on the magnetic field, separated by 5 kOe, as the field sweeps from –100 to 100 kOe. Consequently, every 5 kOe, the rate at which the magnetization changes with time must have a maximum owing to the resonant tunneling. These maxima are responsible for the steps in the figure. Seven steps have been observed so far at the expected values of the field (*1*). As the field goes up, the energy barrier goes down, rapidly increasing the probability of the phonon-induced thermal over barrier transitions. For that reason, at 2.4 K the magnetization curve appears reversible above 15 kOe. Measurements down to 10 mK are needed to make all 21 magnetization steps apparent in high fields.

The possibility of quantum tunneling of a large magnetic moment has been intensively studied after it was suggested (*7*) that in magnetic nanoparticles quantum mechanics can reveal itself on a macroscopic scale. Experimentalists have been trying to manufacture a system of identical nanomagnets that would exhibit this effect (*8*). A crystal of Mn_{12} acetate is an ideal system of that kind: it consists of identical, regularly spaced, uniformly oriented, spin 10 magnets. Their magnetic moment is, however, intermediate between micro- and macroscopic. Being 20 times as great as the electron moment, it is sufficiently large to be treated macroscopically. At the same time, it is small enough to make its quantization noticeable in the magnetic hysteresis. This kind of behavior, which is intermediate between classical and quantum, makes the discovery of Friedman *et al.* (*1*) extremely interesting in the context of macroscopic quantum tunneling. After the finding was reported at the Magnetic Conference in Philadelphia in November 1995, it has been reproduced with high accuracy in other laboratories (*2*, *3*). There are now questions for the theorists. According to quantum mechanics, tunneling between the low-lying levels, such as $m = -10$ and $m = 10$, can occur only in a strong transverse magnetic field, which has not been the case in experiments performed to date. Apparently, much weaker fields resulting from interactions of molecular magnetic moments with each other, with nuclear spins, and so on, are responsible for the effect. In this case, tunneling can occur only from high excited levels for which the barrier height and the change in m are sufficiently small. Because these levels should be thermally populated, the observed Arrhenius-law temperature dependence of the magnetization reversal, which accompanies quantum steps, strongly supports this picture. Quantitative theory that would describe the resonant magnetic tunneling from excited levels is absent, however.

Research on magnetic molecules is in its infancy. As it advances, some practical applications of these systems may develop as well. Mn_{12} molecules have extremely high magnetic anisotropy. Well below 1 K the orientation of the molecular magnetic moment must be very stable. A system like Mn_{12} acetate can, therefore, provide the ultimate limit of high-density magnetic memory. Materials with even higher anisotropy would allow increased operating temperatures. Because molecules of that class can exist in a quantum superposition of "spin up" and "spin down" states, one can also imagine them as potential candidates for elements of quantum computers. In that instance, one could explore the fact that the probability of tunneling can be controlled with a magnetic field. Of course, the feasibility of devising materials and instruments that would allow the ability to read and write information at the molecular level has yet to be determined. The cooperation between chemists and physicists will be of primary importance for this exciting new area of magnetism.

References and Notes

1. J. R. Friedman, M. P. Sarachik, J. Tejada, R. Ziolo, *Phys. Rev. Lett.* **76**, 3830 (1996).
2. J. M. Hernandez *et al.*, *Europhys. Lett.* **35**, 301 (1996).
3. L. Thomas *et al.*, *Nature* **383**, 145 (1996).
4. T. Lis, *Acta Crystallogr. Sect. B* **36**, 2042 (1980).
5. C. Paulsen, J.-G. Park, B. Barbara, R. Sessoli, A. Caneschi, *J. Magn. Magn. Mat.* **140**, 1891 (1995); M. A. Novak, R. Sessoli, A. Caneschi, D.Gatteschi, *ibid.* **146**, 211 (1995).
6. J. Villain, F. Hartman-Boutron, R. Sessoli, A. Rettori, *Europhys. Lett.* **27**, 159 (1994).
7. E. M. Chudnovsky and L. Gunther, *Phys. Rev. Lett.* **60**, 661 (1988).
8. The success reported in ferritin by Gilder *et al.* [*Science* **268**, 77 (1995)] has been questioned [see discussion in *Science* **272**, 424 (1996)].

Lipid A: Target for Antibacterial Drugs

Martti Vaara

Bacteria are dangerously good at developing resistance to antibiotics. Thus the report on p. 980 of this issue by Onishi *et al.* (*1*) of a new antibacterial agent aimed at a previously unassaulted part of the bacteria (lipid A of the outer membrane) is especially welcome.

In the past, we have been able to introduce new antibacterial drugs at a pace sufficient to counter the infections caused by drug-resistant bacteria. Indeed in the 1980s, many people believed that bacterial infections were successfully controlled and that the era of bacterial diseases had passed. Many of the large U.S. and Japanese pharmaceutical companies reduced or stopped their efforts to find new antibacterial agents (*2*) and shifted their focus to antifungal and antiviral compounds. The rate of introduction of new antibacterial drugs with novel modes of action or genuinely different spectra of activity slackened. In the 1990s there was a worldwide resurgence of bacterial diseases, in large part due to the rapid emergence and spread of pathogenic bacteria resistant to multiple antibiotics. Indeed, bacterial strains resistant to all available antibiotics have emerged and

The author is in the Department of Bacteriology and Immunology, University of Helsinki, 00014 Helsinki, Finland. E-mail: martti.vaara@helsinki.fi