Whitworth of the Campden and Chorleywood Food Research Association explained at the meeting. His company has developed a fast, non-destructive technique to measure the amount of bran in flour. The system, known as Branscan, allows millers to mix very pure white flour with flour of lower grade to produce an acceptable overall blend, thereby improving their cost margins.

Existing techniques involve destructive and time-consuming measurements of the mineral content or the colour of the flour. In some cases, the miller takes a sample from the production line, burns it in the lab and then analyses the residue. In other mills, the overall colour of the flour is inspected – a measurement that can take up to two minutes.

In contrast, Whitworth and co-workers have developed an on-line monitoring technique that exploits the fact that flour is pumped pneumatically to move it around the mill. A trapdoor in the duct automatically collects a small sample of flour directly from the pipeline. A series of lower-power light-emitting diodes illuminates the flour in the inspection area so that a camera can take a snapshot of the sample. Image-analysis software then searches for specks of bran, which are much larger and more irregular in shape than the flour, and computes the bran content before releasing the flour back into the pipeline. The whole process takes about 10 seconds, allowing millers to adjust the flour mixture in real time.

Whitworth's group, together with Ricky Wildman and Qasim Saleem at Loughborough University in the UK, is also developing a laser-based technique to measure the strain in biscuits (figure *b*). Most manufacturers package their biscuits shortly after baking. However, the non-uniform moisture content in freshly baked biscuits can lead to a build up of strain, which causes them to crack.

The researchers are monitoring exactly how this strain develops across a biscuit using electronic speckle pattern interferometry (ESPI) – a technique that is more commonly used in the automotive and aviation industry, as well as in art restoration (see "Lasers in art conservation" *Physics World* November 2001 pp37–42).

In ESPI, a laser beam is split into two: one of the beams is focused onto the biscuit, while the other beam is interfered with the reflected light. The resulting interference pattern is recorded in real time with a CCD camera and then subtracted from a reference image. So far, Whitworth and co-workers have detected strains of 10^{-5} and have started making measurements as a function of humidity. The results could eventually lead to improvements in the baking process, and fewer broken biscuits.

Appliance of science

Although machine-vision systems are not at the cutting-edge of physics research, it is clear that the food and drink industry offers some unique challenges for physicists. Transferring equipment from the lab and making sure it can operate almost continually in a factory environment is the real test. So next time you are enjoying a chicken burger or a chocolate biscuit, it is worth giving some thought to the physics that went into producing it.

New vision of magnetic tunnelling

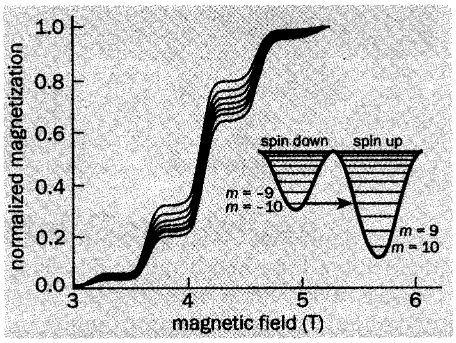
Recent experiments support the idea that crystal defects may be responsible for the quantum tunnelling of magnetic moments in molecular magnets at low temperatures

From **Jonathan R Friedman** in the Department of Physics, Amherst College, Massachusetts, USA

The magnetic moment of a typical bar magnet will never spontaneously reverse direction. However, thermal fluctuations can flip the moment of a magnetic particle just a few nanometres across. The particle can be cooled to nearly absolute zero to suppress this process, but the moment may still find a way to reverse via quantum tunnelling.

Quantum tunnelling of magnetization has been the subject of decades of research. Until a few years ago, however, there had only been circumstantial evidence for the phenomenon. This is because most systems of small magnetic particles are hard to characterize – the particles have a variety of shapes, sizes and other properties, making it difficult to compare data with theory.

Some real progress was made a few years ago through research into high-spin single-molecule magnets. With dimensions of about a nanometre, these magnets are usually composed of a magnetic core that is surrounded by organic complexes. When they crystallize into a regular lattice, the organic ions keep neighbouring magnets well separated so that they interact only weakly. Ideally all the molecules are identical because they have been built chemically, which means that they can be characterized precisely and that any data can be analysed



1 The magnetic moment of single-molecule magnets can tunnel from spin "down" to spin "up" states when an external field brings energy levels on opposite sides of the potential barrier into resonance, as shown in the inset. The magnetization of a sample of Mn_{12} exhibits steps whenever the applied magnetic field brings the system to such a resonance.

quantitatively (see "Magnets, molecules and quantum mechanics" *Physics World* March 1999 pp35–39).

The most studied of these molecules is manganese-12 acetate (Mn_{12}). Within each molecule, the spins of the eight Mn^{3+} ions (each with $S = 2$) are antiparallel to the spins of the four Mn^{4+} ions (each with $S = 3/2$), giving Mn_{12} a total spin of $S = 10$. Or, to put it another way, the magnetic moment of Mn_{12} is 20 times larger than that of the electron. Its spin also likes to point either parallel or antiparallel to a particular crystal axis, the z axis – in other words, Mn_{12} has a large "anisotropy barrier".

The system can be modelled as a double-well potential, where one well corresponds to the case where the spin points "up" and the other to the spin pointing "down" (see the inset of figure 1). The energy levels in the two wells correspond to the $2S + 1 = 21$ allowed values of the magnetic quantum number, m. Applying a magnetic field along the z axis tilts the potential, so that the spin prefers to point up rather than down.

In 1995 my colleagues and I discovered a new phenomenon called resonant magnetization tunnelling in this material (J R Friedman *et al.* 1996 *Phys. Rev. Lett.* **76** 3830). At temperatures below 3 K, we found steps in the hysteresis loops for Mn_{12} (like those in figure 1) whenever the external magnetic field caused the energy levels in opposite wells to line up, allowing the spins to tunnel between the wells. Tunnelling causes molecules with down spins to start pointing up.

Although it was clear that tunnelling was occurring in this material, it was not understood why. Since the intrinsic anisotropy of the molecules and the magnetic field both point along the z axis, the z component of the spin is a conserved quantity, i.e. m is a good quantum number and tunnelling between different m states is forbidden.

Something needs to be added to allow tunnelling – something that points in a different direction from z. This could be a transverse magnetic field due to nuclear spins or dipole interactions with neighbouring molecules. But these effects by themselves turn out to be too weak to account for the observed tunnelling rates.

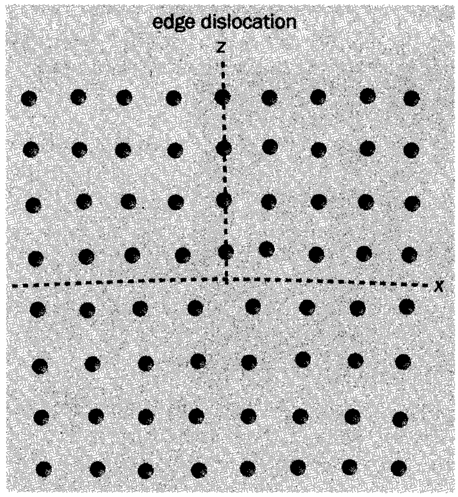
Tunnelling could also be induced by another anisotropy that makes the spin have a slight preference for, say, the x rather than the y direction (although it would still strongly prefer to be aligned along z). But Mn_{12} is a highly symmetric molecule and these effects are thought to be small.

Now Eugene Chudnovsky of Lehman College in New York and Dmitry Garanin of the University of Mainz in Germany have suggested a new mechanism for producing tunnelling in Mn_{12} – defects (*Phys. Rev. Lett.* 2001 **87** 187203). The term "defect" is sullied by its own name, implying something amiss. Yet defects can be a source of rich and varied physical phenomena. Chudnovsky and Garanin propose that defects in the Mn_{12} crystal create distortions in the x–y plane that can induce tunnelling. While the paper was still in preprint form, four experimental groups found evidence to support the notion that defects are responsible for tunnelling in this system.

Chudnovsky and Garanin considered a particular kind of defect called an edge dislocation, in which an extra crystal plane is inserted at some point in the crystal (see figure 2). The distortions created by such a dislocation do not affect all of the Mn_{12} molecules equally. Those molecules near a dislocation are distorted more and can tunnel faster, while those further away tunnel more slowly. Although previously all of the molecules had been thought to be identical, dislocations alter the picture. Instead there is a wide distribution of tunnelling rates.

This idea provides an entirely new interpretation of the resonance steps seen in earlier experiments. Every molecular spin does not have the same chance of tunnelling at a given resonance as every other, as had previously been thought. In the new picture, each resonance step represents the tunnelling of a different set of molecules. At the first step, the barrier is high and only those molecules closest to a dislocation (i.e. the fastest part of the distribution of tunnelling rates) can flip the direction of their spins. At the next step, the barrier is somewhat lower and another part of the distribution can tunnel, and so on. Thus, each step gives us information about a different part of the distribution.

The theory predicts that one should be able to take data from each of the steps and piece them together to form a smooth curve that reflects the underlying distribution of tunnelling rates. This is precisely what Myriam Sarachik's group at the City College of New York has done (K M Mertes *et al.* 2001 *Phys. Rev. Lett.* **87** 227205). The researchers measured the heights of the steps as a function of the magnetic-field sweep rate and,



2 An edge dislocation in a crystal produces distortions that can lead to tunnelling in Mn_{12} molecules. The molecules that are closest to the dislocation have the highest tunnelling rates.

following Chudnovsky and Garanin's recipe, they were able to build a smooth curve from all of the data – a result that is consistent with the picture of dislocation-driven tunnelling. In contrast, they found that no smooth curve could be constructed if one assumes that tunnelling is driven only by a transverse magnetic field.

Meanwhile, Beth Parks at Colgate University in Hamilton, New York, and, independently, a collaboration between researchers at Florida State University and Montana State University have measured the energy separations between the different m levels (B Parks *et al.* 2001 *Phys. Rev.* **B 64** 184426 and K Park *et al.* arxiv.org/abs/cond-mat/0106276). Both groups found that their spectral lines of Mn_{12} were wider than the experimental resolution. This implies that the height of the energy barrier varies slightly from molecule to molecule – an effect that can be explained in terms of dislocations.

Another test of Chudnovsky and Garanin's theory has been performed by Javier Tejada's group at the University of Barcelona (J M Hernández *et al.* arxiv.org/abs/cond-mat/0110515). The researchers induced dislocations in a crystal of Mn_{12} by rapidly cooling it in liquid nitrogen and then rapidly warming it to room temperature again. After this treatment they found that the tunnelling rate for the sample had substantially increased. By creating more dislocations, the thermal treatment increases the number of molecules that are distorted and hence can tunnel faster.

Are defects the whole story of tunnelling in molecular magnets? Certainly not. In some molecular magnets, the mechanism of tunnelling is well understood and defects play only a secondary role. Even in Mn_{12}, nuclear spins and dipole fields still must play some role. What is clear is that if one day we want to use such tiny magnets to store data, the effects of defects will have to be taken into account.

Highlights from PhysicsWeb

Alien atmosphere spotted
Space scientists have detected the atmosphere of an extrasolar planet for the first time. The well known absorption lines of sodium appeared as light from the star, dubbed HD 209548, passed through the atmosphere of the orbiting planet. The findings are likely to spark similar searches among the 80 or so other known extrasolar planets.

Snow goes mobile
Scanning electron micrographs of snow have cast doubt on the theory of bond formation between compressed ice crystals. The discovery of ridges between snow grains suggests that ice migrates throughout the structure, redistributing the mass in packed snow faster than had previously been thought. The same effect may also occur in other materials.

Neutron sources shrink
A new and compact neutron generator could make it easier to probe the structure of materials, ranging from crystals to human tissue. The device, which measures just a few centimetres across, is more efficient and lasts longer than existing commercial neutron generators. The neutrons are produced when deuterium and tritium nuclei fuse on a layer of titanium.

Black hole in one measurement
Astronomers will soon be able determine the masses of thousands of black holes faster and more accurately than ever before. Huge black holes are thought to exist at the heart of every galaxy, but previous techniques to calculate their masses have proved slow and complicated. Now a new relationship has been discovered between the mass of a black hole and the concentration stars that orbit around it, which can be easily measured from snapshots of galaxies.

Microwave tuner
A liquid-crystal device has been developed to control the wavelength of high-frequency microwaves, and could be exploited by satellite communications systems. The device relies on diffraction from a grating made of aluminium sheets and layers of liquid crystal.

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