Magnetism under the microscope

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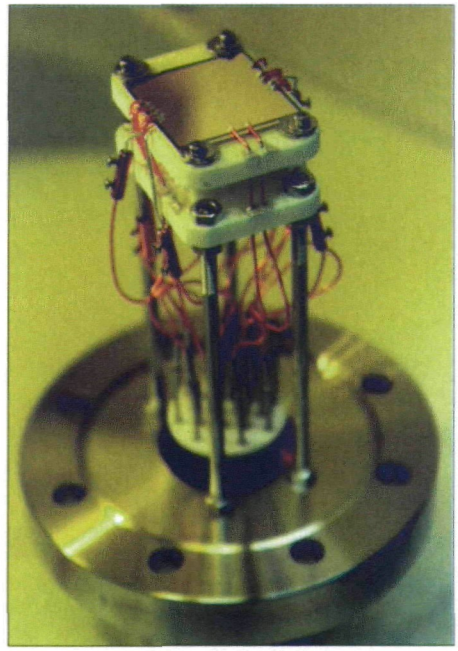
in principle, greatly outperform a classical or conventional computer.

As an example, imagine an atom tube that splits in two, then joins up again further on. When atoms travel through this diamond-shaped structure, the quantum-mechanical wavefunction that describes their position also splits and recombines. The waves interfere constructively or destructively, depending on the phases they accumulate as they travel along the two paths. The result is a set of interference fringes in which the number of atoms that reach the output varies. If the two paths are separated by a few millimetres then this atom interferometer could be extremely sensitive to gravity and rotations – and could be a valuable tool in fields ranging from mineral prospecting to navigation.

Quantum computing is another fascinating possibility because each atom floating above an atom chip can store a quantum bit or "qubit" that can have both 0 and 1 logical values at the same time. The ability of atoms to exist in two or more quantum states at the same time means that a quantum computer can calculate many possibilities simultaneously, in principle allowing it to solve problems that are impossible for any classical computer.

The basic operation for quantum computers is the controlled-NOT (CNOT) operation, which acts on two qubits at a time – a control and a target qubit. The state of the target qubit is reversed if the control qubit is in state 1, and left unchanged if the control qubit is in state 0. Earlier this year Peter Zoller and co-workers at Innsbruck in collaboration with our group at Sussex showed that the CNOT operation could be accomplished with a pair of neutral atoms that were carefully controlled by an atom chip (T Calarco *et al.* 2000 *Phys. Rev.* **A61** 22 304).



A close-up of the atom chip used at Innsbruck to control the movements of cold atoms. The atoms were guided a few tens of microns above the surface by the magnetic fields produced by thin U-shaped gold wires.

For all such quantum manipulations it is important to have control over the phase of the wavefunction, which means that the atoms must not be allowed to bounce from side to side in the guide. This motion can be reduced by making the thermal energy kT (where k is the Boltzmann constant and T is the temperature) smaller than the quantum of vibration hf, where h is the Planck constant and f is the frequency of the vibrations. This requires extremely thin magnetic guides of about 100 nm in diameter, in which atoms would vibrate at high frequencies of around 100 kHz, and low atom temperatures of around 1 μK.

Several groups have been working towards this vision over the last few years. In 1998 Claus Zimmerman's group at Eberhard-Karls University in Tübingen, Germany, showed that atoms could be captured outside a small current-carrying wire, while this year our own group transported atoms magnetically down the centre of a hollow optical fibre. The idea of using integrated circuits – which was first suggested in 1995 by Ken Libbrecht of Stanford University – was demonstrated for the first time late last year by Ted Hänsch and colleagues at the Max Planck Institute for Quantum Optics in Munich using rubidium-87 atoms. And a few weeks later, Dana Anderson's group at the JILA laboratory in Colorado showed that rubidium atoms travelling at speeds of around 10 $m\,s^{-1}$ could be guided round corners using a chip.

Now the Innsbruck group has succeeded in loading lithium atoms onto a chip with the smallest guiding tubes to date. At the moment, their atoms have temperatures around 1 mK, which is still far too hot for quantum manipulations, but the work brings us one step closer to the dream of having atoms so cold that they occupy only one quantum-mechanical state of transverse vibration as they travel in the guide. The race for quantum atomic-chip devices is on.

Magnetism under the microscope

From **Ivan K Schuller** in the Department of Physics, University of California at San Diego, US

In 1935 the fictional detective Dick Tracy predicted that "the nation that controls magnetism will control the universe". In accordance with these prophetic words, the field of magnetism has experienced an incredible expansion in both basic and applied research over the past 15 years. Much of this interest has been motivated by a number of factors: the ever-increasing demand for miniaturization; the ability to make nanometre-scale features; the desire for novel materials that exhibit properties not encountered naturally; and by applications such as magnetic sensors, memories and recording heads.

Materials in which the atoms are confined to one or two dimensions have a range of interesting physical properties and applications, especially when they are in contact with other materials. To understand complex magnetic materials in detail, we need to understand the behaviour of surfaces and interfaces as a function of their electrical and magnetic properties.

The most important issues relate to the magnetic structure at these surfaces, the unavoidable effects of structural and chemical roughness, and the changes in the magnetic properties when the atoms are confined to one or two dimensions. The presence of so-called proximity effects due to the magnetic layer touching other materials, and competing phenomena like superconductivity, also need to be understood.

Now two groups have developed independent techniques to image the magnetic structure of surfaces and interfaces in great detail (S Heinze *et al.* 2000 *Science* **288** 1805, F Nolting *et al.* 2000 *Nature* **405** 767). The methods promise to greatly improve our understanding of magnetism at the nanometre scale.

Naively it might be thought that the magnetic field next to the surface of a material made from magnetic atoms can simply be inferred from its physical and chemical structure using well known theories. However, this is not the case and there have been many notable surprises. For example, it was discovered 15 years ago that the variations of the magnetic field along a magnetic–nonmagnetic interface is much smaller than that expected from the structural profile of this interface.

Ideally, we would like to be able to simultaneously characterize the physical, chemical and magnetic properties at the atomic or nanoscale level. However, the main problem with realizing this task is that nanostructured magnets have inherently small volumes, meaning that very sensitive probes are needed.

A particularly interesting phenomenon that is still not fully understood, even though it has been studied extensively in magnetic bilayers, is the so-called exchange bias. Bilayer structures consist of two materials that exhibit different magnetic properties, such as

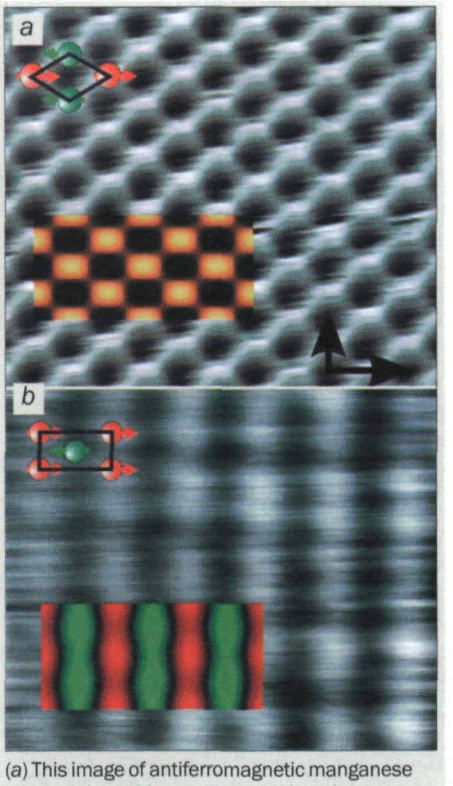
ferromagnetism and antiferromagnetism. In a ferromagnet, the spins of all the individual atoms line up in the same direction, while the neighbouring atoms in an antiferromagnet point in opposite directions.

In a ferromagnet, the hysteresis loop – a plot of the magnetization versus the applied magnetic field as the field is increased and decreased – is symmetric about the zero-field line. However, when the same material is placed in contact with an antiferromagnet, the hysteresis loop shifts away from zero. The origin of this exchange bias, and its dependence on properties including the spin orientation and surface roughness, is currently not understood. It is not even known whether there are one or more mechanisms at work.

Many theoretical models have been developed to understand this phenomenon, and several can explain some of the features found experimentally. However, they all assume that the magnetic structure of the interface is the same as the bulk material. Clearly an experimental determination of the magnetic structure is essential to advance the theory further.

There are essentially three major ways to image magnetic materials at the atomic level: neutron and electron scattering; direct imaging using scanning probe microscopy; and interactions with polarized electromagnetic radiation. Although neutron scattering is ideal for this purpose, it has only been used sporadically because large areas of material are needed for measurements. The two recent studies have used the other complementary techniques to determine the structure of a much smaller area of the surface of an antiferromagnet, and the relative orientation of the spins at the interface between a ferromagnet and an antiferromagnet.

Matthias Bode and co-workers at the University of Hamburg and the Institute for Solid State Research in Germany used scanning probe microscopy to image the physical and magnetic structure of a single layer of manganese atoms deposited on a tungsten substrate. First they moved a sharp non-magnetic tungsten tip across the antiferromagnetic manganese surface. Electrons tunnel from the tip to the surface to reveal the location of the atoms. They then repeated the experiment using a tip coated with iron, which allowed them to image the magnetic structure of the surface (see figure). The findings show that the magnetic structure has twice the periodicity of the physical structure, a result that is in good agreement with earlier theoretical predictions.



(*a*) This image of antiferromagnetic manganese atoms, taken with a scanning probe microscope and using a non-magnetic tungsten tip, shows the positions of the atoms. (*b*) The magnetic structure was determined by using a tip coated with iron. In both cases the results agree with the theoretical structures shown in the insets. The images are 2.7 nm×2.2 nm in size.

In the second study, Frithjof Nolting of the Lawrence Berkeley National Laboratory and co-workers from the US and Switzerland used polarized X-rays to study the spins at a magnetic interface. The X-rays interact with the magnetic moment of the atoms and can thus be used to image the magnetic domains. If the X-ray wavelength can be tuned, as it can in a synchrotron, the radiation can also be used to selectively image a single element. The Swiss–US team used this combination of techniques, known as X-ray magnetic dichroism spectromicroscopy, to selectively image the magnetic orientation of a layer of ferromagnetic cobalt on top of an antiferromagnetic film of lanthanum iron oxide.

At 20 nm, the spatial resolution is short enough to resolve the relative orientation of the antiferromagnetic and ferromagnetic domains. The results show that the spins of the ferromagnetic atoms are aligned parallel or antiparallel to those of the antiferromagnet. This relative orientation gives rise to a local exchange bias even though there is no such bias for the material as a whole in the absence of a magnetic field.

The latest research shows that a number of complementary techniques can now be used to image the magnetic structure of interesting materials at nanometre scales. It will not be long before we can make detailed experimental measurements that will constrain theoretical models. Theorists beware.

Table-top laser produces X-ray beams

From **Greg Tallents** in the Department of Physics, University of York, UK

Since the invention of the maser, which amplifies radiation at microwave frequencies, a great deal of research has been aimed at reducing the operating wavelength of lasers. The energy density needed in a lasing material increases rapidly as the wavelength is reduced, so below about 50 nm the lasing medium must be a plasma.

Lasers operating in the visible or near-infrared are typically used to create the plasmas needed for short-wavelength laser studies, although discharge plasmas have also been used. In the laser experiments, a line of plasma is produced by focusing the light onto a solid target (figure 1). The solid evaporates and ionizes, and then expands rapidly away from the surface of the target. X-ray lasing can occur along this plasma line for a short time (typically 2–100 picoseconds) in regions where the plasma temperature and density conditions are correct. This usually happens between 10 and 100 μm from the target. The lasing, which does not require mirrors, results from the amplification of spontaneously emitted photons by stimulated emission.

A number of large optical-laser systems around the world have been used to "pump" X-ray lasers at wavelengths from 3.5 nm to 30 nm. For almost a decade, researchers have succeeded in generating intense beams of X-rays by maximizing the efficiency of the laser – so-called saturated operation. Currently, the shortest wavelength reached in a saturated laser is 5.9 nm, an achievement made by the UK X-ray laser consortium using the VULCAN laser at the Rutherford Appleton Laboratory. However, lasers like VULCAN, which can provide 90 J of energy for X-ray laser experiments, are very large and occupy several rooms. Now Jim Dunn and co-workers at the Lawrence Livermore National Laboratory in the US have produced a saturated laser that emits X-rays in the 14–20 nm wavelength range using only 5–7 J of energy from a compact optical laser. This system, called the CMT laser (pronounced "comet"), occupies a single optical bench, so the arrangement is referred to as a "table-top X-ray laser" (J Dunn *et al.* 2000 *Phys. Rev. Lett.* **84** 4834).

Two major developments have made this possible. In the mid-1990s, several groups discovered that more intense radiation could be produced by irradiating a target with two short pulses of infrared light, rather than a single long pulse.