HIGH-TEMPERATURE SUPERCONDUCTORS

Vortices wiggled and dragged

The ability to manipulate an individual superconducting vortex represents a powerful tool for studying the dynamics of vortices and the superconductors that support them. It could also lead to the development of a new class of fluxon-based electronics.

Charles Reichhardt

When a sufficiently strong magnetic field is applied to a superconductor, some of the field can pierce it through the generation of magnetic vortices, each of which contains a quantized amount of magnetic flux. Although the superconducting state of the material outside each vortex is maintained (and destroyed within each vortex), the interaction of vortices with a current passing through the material can cause them to move, dissipating energy and thereby generating a source of electrical resistance. The consequent breakdown in the lossless transmission of electrical current creates problems for applications in which superconductors are used. But studying the dynamics of vortices to develop new ways in which to minimize, or even exploit, their effects is not easy. On page 35 of this issue[1], Auslaender *et al.* show that they can grab hold of a single vortex using the tip of a magnetic force microscope (MFM), and, by observing its response as they drag it back and forth through a superconductor, can probe both the dynamic behaviour of the vortex and the properties of the superconductor itself.

A vortex in a superconductor is a line-like structure that extends all the way from one side of a superconducting sample to the other. The most effective means found so far for limiting the movement of these vortices (as a result of thermal fluctuations or the passage of an electrical current) is to introduce defects into a superconductor's microscopic structure, which serve to 'pin' the vortices in place. Such pinning is not perfect, but attempts to understand and better control the processes involved have been limited by the fact that it has only been possible to study them through bulk measurements of the average behaviour of thousands of vortices across a sample.

Auslaender *et al.*[1] address this limitation by developing a technique that enables them to both image and manipulate a single vortex using the probe of an MFM, which consists of a very sharp magnetic tip attached to the end of a flexible cantilever.

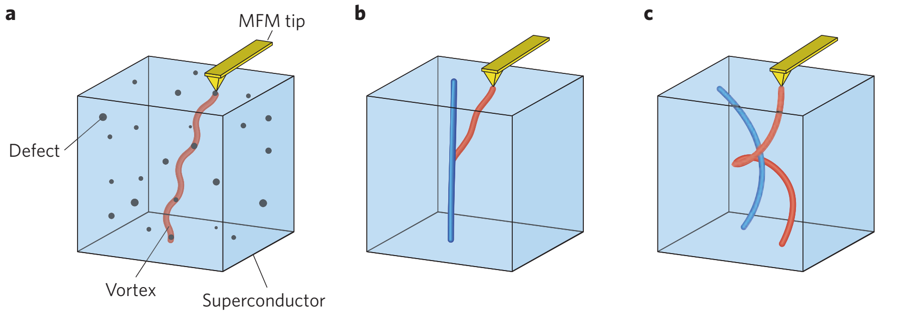

Figure 1 | The ability to grab the end of an individual vortex in a superconductor using the tip of a magnetic force microscope (MFM) provides the opportunity to study many more vortex phenomena than is possible by conventional bulk measurement techniques. **a**, To demonstrate one such possibility, Auslaender *et al.*[1] use this technique to measure the anisotropy of the pinning force as a vortex is dragged through a random distribution of point-like defects. The technique should allow the study of other phenomena such as **b**, the behaviour of a pinned vortex as it is peeled from a line-defect created by ion-beam damage, and **c**, the interaction of multiple vortices twisted around each other.

When this tip is brought close to a sample, the presence of magnetic features at the surface of the sample will cause it to be deflected. By measuring the deflection of the tip as it is scanned across a surface, images of these features can be constructed. This is the basic principle of magnetic force (and, indeed, conventional atomic force) microscopy. But the MFM tip will also exert a force on these features, the magnitude of which can be controlled by the distance of the tip from the surface. Auslaender *et al.* find that they can use this force to grab hold of, and drag, the portion of the vortex line nearest to the surface of the sample, while the remainder of the vortex deeper in the bulk remains pinned (Fig. 1a). Moreover, they find that by 'wiggling' the MFM sideways (perpendicular to the dragging direction), they can move the vortex over a much larger distance than is possible without such wiggling — similar in effect to trying to disentangle a power cable from a mass of other cables behind your computer.

The ability to manipulate individual vortices should help answer a number of open questions that could not be resolved with bulk measurements. For example, to what extent does a vortex line behave like an elastic string? How does a vortex de-pin from different defect topologies, such as a line-like pinning site generated with ion irradiation (as in Fig. 1b)? Does the vortex begin to unzip from top of the defect like a zipper, or form a break-away loop vortex[2]? There is also the question of whether vortices in the glass or liquid phase can entangle around each other, as in a glassy polymer system, or whether they can freely cut through each other[3]. It should now be possible to answer these questions by, for example, dragging a vortex off a line defect or artificially wrapping one vortex around another (Fig. 1c).

Already, the authors observe that the pinning force on the vortices they probe is anisotropic, which may mean that the defects in the sample responsible for pinning the vortices are clustered oxygen defects. And because the vortices couple to inhomogeneities in the sample, moving individual vortices may also be useful for shedding light on the intrinsic superconductivity mechanism underlying high-temperature materials. For example, by measuring the force required to drag a vortex, it may be possible to determine whether the vortex is moving over stripe, checkerboard or fluctuating charge-ordered structures of the type predicted in some theories[4].

The ability to manipulate individual vortices might also lead to the realization of new types of flux-line-based devices, called fluxtronics. There have been proposals for devices using vortices as the elementary units in classical logic devices[5], as well as proposals to manipulate individual spins or charges by coupling the vortex to these objects and then manipulating the vortex line[6]. Similar techniques for moving individual line-like objects could be used in other systems, such as dragging or shaking individual domain walls in magnets, or moving dislocation lines in materials to create specific patterns that will enhance the mechanical properties of the material.

Individual particle manipulation has been widely developed as a tool in systems with larger-scale objects, such as in biological matter where DNA strands are mechanically manipulated[7], or in soft-matter systems where grabbing and shaking a single colloid can be used as a microrheological probe[8]. The work of Auslaender *et al.*[1] points to the feasibility of using many of these ideas on a much smaller scale, not only for vortex systems, but also for a wider class of solid states. One can imagine using multiple probe tips to create a nanorheological probe for vortex or quantum glasses. These local probe techniques may usher in a new era where the individual manipulation of quantum objects could be used to explore local and non-local responses, quantum entanglement, many-body effects and the role of heterogeneities in determining the sample behaviour. ❐

Charles Reichhardt is in the Los Alamos National Laboratory, T-13, MS B213, Los Alamos, New Mexico 87545, USA.
e-mail: charlesr@cnls.lanl.gov

References

1. Auslaender, O. M. *et al. Nature Phys.* **5,** 35–39 (2009).
2. Kafri, Y., Nelson, D. R. & Polkovnikov, A. *Phys. Rev. B* **76,** 144501 (2007).
3. Olson Reichhardt, C. J. & Hastings, M. B. *Phys. Rev. Lett.* **92,** 157002 (2004).
4. Kivelson, S. A. *et al. Rev. Mod. Phys.* **75,** 1201–1241 (2003).
5. Hastings, M. B., Olson Reichhardt, C. J. & Reichhardt, C. *Phys. Rev. Lett.* **90,** 247004 (2003).
6. Berciu, M., Rappoport, T. G. & Janko, B. *Nature* **435,** 71–75 (2005).
7. Bustamante, C., Bryant, Z. & Smither, S. B. *Nature* **421,** 423–427 (2003).
8. Levine, A. J. & Lubensky, T. C. *Phys. Rev. Lett.* **85,** 1774–1777 (2000).

MATTER WAVES

Cloaking matters

The idea of an invisibility cloak — a device capable of bending light, keeping whatever is inside safe from prying eyes — is one that was always destined to capture the public imagination. Over the past few years it has developed from sci-fi mainstay to experimental fact (albeit only under certain conditions), and the excitement in the popular press has just kept growing.

As quantum mechanics blurs the boundaries between the properties of particles and those of waves, such as light, it is not outrageous to wonder — as Allan Greenleaf and colleagues do (*Phys. Rev. Lett.* **101,** 220404; 2008) — whether these same cloaking ideas can be applied to matter.

How does a particle react to a potential barrier of a certain size and shape? It is a standard question posed to undergraduate students when introducing Schrödinger's equation. But Greenleaf *et al.* have turned this problem on its head: what type of barrier will act on a particle with a specific energy to recreate the cloaking effect. Thinking in two dimensions, they propose a series of rings, each with a different potential, that together mask whatever is within from a probing matter wave.

The idea of a cloak for matter waves is not new, however, construction via the approach published previously Shuang Zhang and colleagues (*Phys. Rev. Lett.* **100,** 123002; 2008) is likely to be difficult in practice. Greenleaf *et al.* hope that their concept will offer an easier path.

Its simplicity comes at a price — the cloaking is not perfect — but even this drawback has its advantage: particles at an energy at which the device doesn't work can be trapped within the cloak. Such traps have already proved a boon for fundamental research on atomic physics, and a novel approach is always likely to come in handy.

The matter cloak may be a long way from fruition, but it is a further example of how optical phenomena can be translated to matter waves. The idea complements proposals to use graphene as a Veselago's lens for electron beams and 'extraordinary' transmission of rubidium atoms through an array of sub-de Broglie-wavelength slits.

DAVID GEVAUX