

LA-UR-

08-8012

Approved for public release;
distribution is unlimited.

Title: Vortices Wiggled and Dragged

Author(s): Charles Reichhardt/170260/LANL/T-4

Intended for: Nature Physics



Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the Los Alamos National Security, LLC for the National Nuclear Security Administration of the U.S. Department of Energy under contract DE-AC52-06NA25396. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

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 Reichardt

When a sufficiently strong magnetic field is applied to a superconductor, some of the field can pierce the superconductor 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 XXX of this issue¹, 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. When this tip is brought close to a sample, the presence of

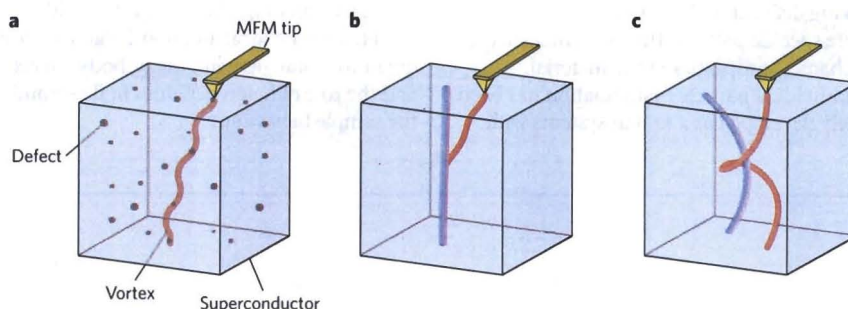


Figure 1 | The ability to grab the end of an individual vortex in a superconductor using the tip of a magnetic force microscope (MFM) provides the opportunity to study many more vortex phenomena than is possible by conventional bulk measurement techniques. a, To demonstrate one such possibility, Auslaender *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. Other phenomena it should allow the study of include 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.

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 (ref. 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 other³. 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 since the vortices couple to inhomogeneities [AU: heterogeneities? (see final line)] 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 theories⁴.

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 utilizing vortices as the elementary units in classical logic devices⁵, as well as proposals to manipulate individual spins or charges by coupling the vortex to these objects and then manipulating the vortex line⁶. 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 manipulated⁷, or in soft-matter systems where grabbing and shaking a single colloid can be used as a microrheological probe⁸. 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**, XXX-XXX (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).