SUPERCONDUCTIVITY

Flux lines on video holograms

David Caplin

THE elementary quantum of magnetic flux that appears in superconductivity is large enough that the penetration of magnetic fields into superconductors is sufficiently coarse-grained to be visible with electron microscopy. Pictures of the distribution of discrete flux lines were first obtained more than 20 years ago, but a new electron holographic technique developed by Tonomura and co-workers[1] at Hitachi's Advanced Research Laboratory in Japan allows the flux lines to be imaged dynamically, with an image rate of tens of frames per second. So far, the technique has been applied only to a conventional low-temperature superconductor, lead, but it should be usable also with technologically significant materials, such as the niobium alloys from which high-field magnets are fabricated, and perhaps eventually with the new high-temperature oxide superconductors. Because the crucial parameter of critical current density is controlled by the physical pinning of flux lines, such studies should help to improve their performance.

The flux quantum φ_0, which is the ratio of Planck's constant, h, to twice the electron charge e ($2e$ because superconducting electrons are paired), is equal to 2.07×10^{-15} webers. In the mixed state of a type II superconductor immersed in a magnetic field, the field penetrates in the form of quantized flux lines at an areal density proportional to the magnetic induction B. If the latter is 1 millitesla, there are 5×10^{11} flux lines per square metre, corresponding to a typical spacing between lines of about 1 μm, and so, well within the resolution of electron microscopy.

The earlier method[2] of imaging flux lines was to form a Bitter pattern by evaporating a 'smoke' of submicrometre ferromagnetic particles onto the surface of the superconductor. The particles are attracted to regions of strong field gradient, which in this case are the points at which the flux lines emerge from the surface of the superconductor. Under appropriate conditions, in both conventional[2] and high-temperature[3,4] superconductors, the flux lines have been seen to form a regular lattice.

The drawback of the Bitter method is that, because it requires the formation of a replica of the flux-line pattern, it cannot be used to follow the motion of the flux lines in the superconductor. The Hitachi group's electron-holographic technique overcomes this handicap, and so can distinguish between flux lines that are pinned firmly in place, and those that are comparatively mobile.

As in making any hologram, what is recorded in electron holography is the interference pattern between a reference wave and the object wave; the pattern depends on both the amplitude and phase of the latter wave. The Hitachi group, led by Akira Tonomura, has been developing electron holography for more than 20 years, and have applied it to a wide range of problems[5]. In the new work, it is the magnetic field of the fluxon that alters the phase of the electron wave. This is just the Aharonov–Bohm[6] effect (once a theoretical curiosity in quantum mechanics), in which the induced phase difference, measured in wavelengths, between two paths (Fig. 1) is simply equal to the magnetic flux they enclose, measured in units of h/e. Thus a single flux quantum induces a phase difference of half a wavelength, and so causes destructive interference.

The big advance that has now been made by Matsuda *et al.* is to replace photographic recording of the hologram, which takes several seconds, with much faster video recording. Furthermore, instead of reconstructing the photographic image optically with laser light, the more conventional approach, a fast computer is used to obtain the image by numerical Fourier transform algorithms. This allows the full range of image analysis and enhancement techniques to be deployed, which, because the shape of the fluxon field lines has to obey the laws of classical eletromagnetism, are rather powerful.

In a structurally perfect superconductor, the current-induced Lorentz force on the flux lines would cause them to move easily, dissipating energy, so that the critical current would be essentially zero. In conventional superconductors, dislocations and micrometre-scale precipitates are known to be effective at pinning flux, and so raising the critical current to useful levels. In the new oxide materials, there are good reasons to believe that only much smaller crystallographic defects can be effective; perhaps oxygen vacancies provide strong pinning sites[7], but so far there is really no microscopic evidence to link the position of a pinned flux line to identifiable microscopic changes in structure.

The electron holographic technique may open the way toward microscopic correlation between structure and pinning capability. Simply because the length scales are larger, the task will be easier with the low-temperature niobium-based superconductors. The challenge of applying the technique to the high-temperature materials is daunting, but if successful, could provide the key to using them as practical conductors. □

David Caplin is in the Blackett Laboratory, Imperial College, Prince Consort Road, London SW7 2BZ, UK.

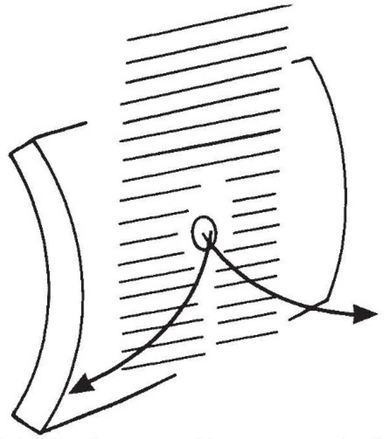
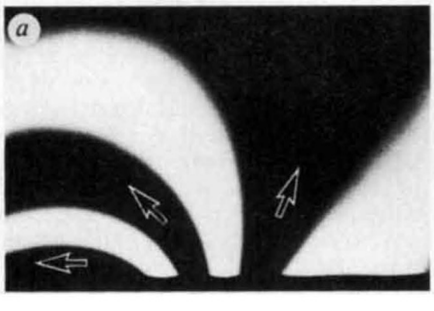


FIG. 1 A flux line trapped in a superconducting film induces phase changes in an electron wave. A single flux quantum, magnitude $h/2e$, gives a half-wavelength phase difference between the wave fronts on either side of it.



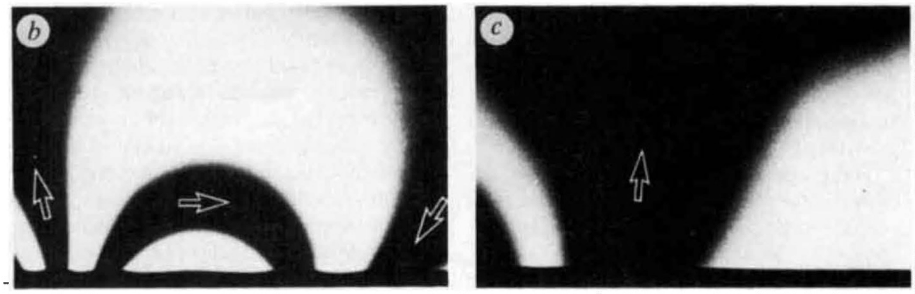


FIG. 2 Flux lines trapped in a superconducting lead film[1] at 5 K, only just below its superconducting transition temperature of 7 K, so that pinning is weak and the flux lines are highly mobile. Initially *a*, three 'up' flux lines are visible in the centre of the frame; *b*, 0.13 s later, two 'down' flux lines have entered from the right, and *c*, at 1.33 s, a pair of 'up' and 'down' flux lines have annihilated. (Courtesy A. Tonomura.)

1. Matsuda, T. *et al. Phys. Rev. Lett.* **66**, 457–460 (1991).
2. Essman, U. & Trauble, H. *Phys. Lett.* **24A**, 526–527 (1967).
3. Gammel, P.L. *et al. Phys. Rev. Lett.* **59**, 2592–2595 (1987).
4. Vinnikov, L. Ya. *et al. Solid State Comm.* **70**, 1145–1148 (1989).
5. Tonomura, A. *Phys. Today* **43**, 22–29 (April 1990).
6. Aharonov, Y. Bohm, D. *Phys. Rev.* **115**, 485–491 (1959).
7. Daeumling, M., Seuntgens, J.M. & Larbalestier, D.C. *Nature* **346**, 332–335 (1990).