SUPERCONDUCTIVITY

Conveyor belts for magnetic flux quanta

The successful demonstration that magnetic flux lines in a superconductor can be moved by time-dependent drives instead of spatially asymmetric structures suggests a versatile new approach to control the motion of nanoscale objects.

AKIRA TONOMURA
is at the Hitachi Advanced Research Laboratory, Hitachi Ltd., Saitama 350-0395, Japan
email: tonomura@harl.hitachi.co.jp

A popular stunt consists of rapidly pulling a tablecloth from underneath the dinner plates on top of it. Pull fast enough, and the plates do not move. Pull slowly, and the dishes move together with the tablecloth, which now acts like a 'conveyor belt' for the plates. Now consider these two processes in sequence: a fast pull of the tablecloth to the right followed by a slow motion back to the left. The result is a movement of the plates to the left. When performed repeatedly, this periodic motion of the tablecloth produces a steadily increasing displacement of the plates. Thus, effectively the tablecloth acts like a conventional electronic diode, rectifying a bidirectional alternating drive current (here, the movement of the tablecloth) into a net unidirectional motion (of the plates). The same principles can be applied at microscopic length scales to control the motion of flux quanta, or vortices, in superconductors[1] (Fig. 1). On page 305 of this issue, Cole *et al.*[2] report that they have successfully used this form of rectification to transport and 'focus' superconducting vortices, each carrying a single magnetic flux quantum.

The strongly anisotropic superconducting crystals used by Cole *et al.* have a layered structure like graphite, being composed of vertical stacks of superconducting 'sheets'. A tilted applied magnetic field produces a mixture of two types of magnetic flux quanta in the material: Josephson vortices that are controlled by the horizontal magnetic field component and are trapped between the superconducting layers; and pancake vortices, created by the vertical magnetic field component and oriented perpendicular to the layers[3]. In this system the equivalents of the dinner plates (Fig. 1) are the pancake vortices (red disks in Fig. 1), which are stacked vertically like beads on a string, each string containing a single quantum of magnetic flux. The analogue of the tablecloth is the array of Josephson vortices (blue tubes in Fig. 1). Josephson vortices attract pancake vortices and therefore can be used to drive the pancake vortices back and forth by applying a time-dependent horizontal magnetic field — slowly in one direction, and fast in the other. Thus, these horizontal Josephson vortices behave like an oscillating conveyor belt, dragging around the pancake vortices of the perpendicular lattice. Compressing the horizontal Josephson vortices slowly towards the centre and then rapidly expanding them towards the edges results in a concentration of the pancake vortices at the centre of the sample (Fig. 2). Therefore, as each pancake vortex carries a quantum of magnetic flux, this device effectively operates as a convex lens for the magnetic field. Alternatively, fast compression followed by slow expansion of Josephson vortices

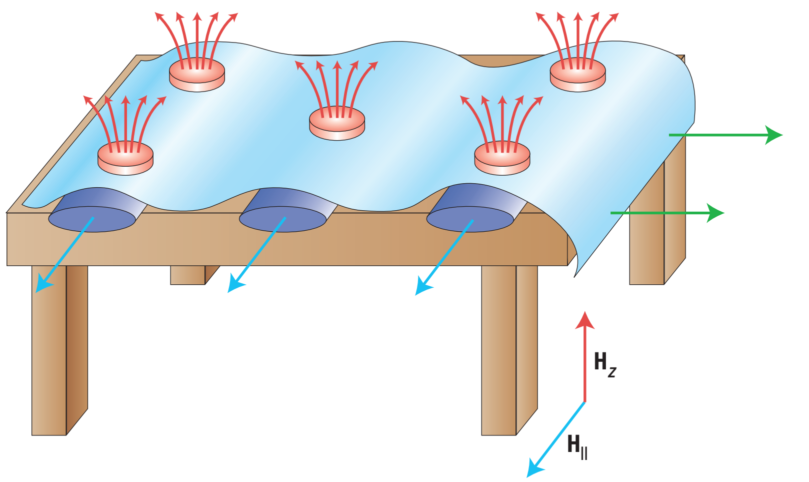

Figure 1 Moving vortices. A tilted magnetic field produces two types of vortices, Josephson vortices (blue tubes) that are trapped between the layers and pancake vortices (red disks) in the layers. Josephson vortices attract pancake vortices, and thus both type of vortices move together when the Josephson vortices are driven slowly (along the direction of the green arrows) by an applied horizontal magnetic field (blue arrows). In contrast, when they are driven fast enough, the Josephson vortices leave the pancake vortices behind — like the plates on a table when the tablecloth is rapidly whisked away.

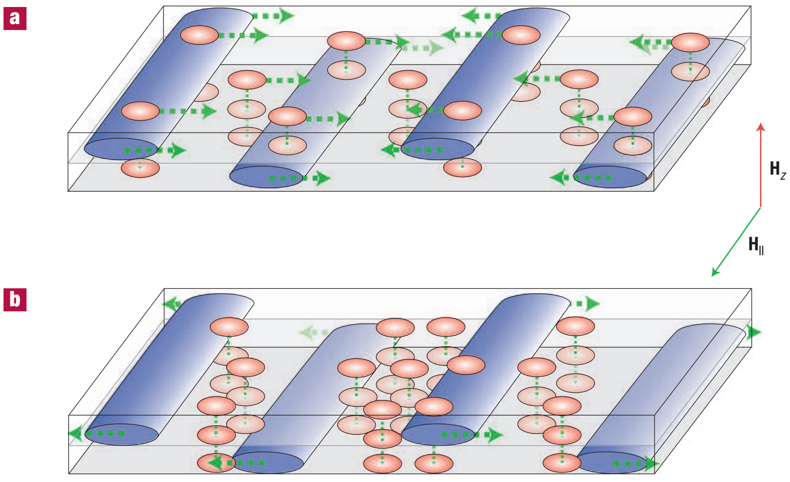

Figure 2 'Conveyor belt' motion in a superconductor. **a**, The slowly driven (blue) Josephson vortices drag vertical 'strings' of (red) pancake vortices towards the sample centre. **b**, Josephson vortices moving rapidly towards the sample edges leave the pancake vortices behind. After several repeated cycles the pancake vortex density at the sample centre is much greater than that at the edges. (Adapted from ref. 2.)

removes flux quanta from the centre of the sample and mimics a concave magnetic lens. In principle, more-complex combinations of compression and expansion allow arbitrarily shaped profiles to be sculpted for the out-of-plane magnetic field.

Apart from showcasing an intriguing effect in superconductors, these devices could be important for applications. Even fields as small as the Earth's magnetic field are sufficient to cause tiny vortices to penetrate into superconductors. Because the location of these vortices will often fluctuate, they create noise in highly sensitive superconducting devices such as tiny magnetometers and high-frequency filters. Hence it is very desirable to find a way to remove the vortices entirely or at least move them out of the way as far as possible from the most noise-sensitive regions of the devices. In a more general context, controlling the motion of objects such as vortices, electrons, ions and colloidal particles is a great challenge because conventional forms of transport cease to be feasible as devices are made smaller and smaller. Many approaches to nanoparticle motion control use spatially asymmetric 'ratchet' substrates[4–10]. For instance, devices that are so tiny that they cannot use wires use triangular 'bumpers' to guide electrons inside a nanoscale 'pinball machine'[8]. Other asymmetric solid-state devices have been developed experimentally to control the motion of vortices[5–7], electrons[8] and colloidal particles[9]. Even the transport of ions within or between cells of our bodies takes place through asymmetric funnel-type ion channels. But this approach fails if one frequently needs to change the direction of the particle flux, as the particle motion is usually fixed by the asymmetric ratchet potential. Several ways to avoid this problem were suggested theoretically a few years ago[1,10]. It is the successful experimental realization of these ideas that distinguishes the work by Cole and colleagues.

There are several advantages to the ratchet effect based on the microscopic conveyor belt: no time-consuming and costly sample nanofabrication is required, and the manipulation efficiency and the direction of nanoparticles can be readily changed by modifying the external asymmetric drive. For instance, one can reverse the direction of the transported particles by simply reversing the polarity of the drive. These advantages, and its simplicity of implementation, should allow the approach to be transferred to different systems with the aim of controlling the motion of other tiny objects such as colloidal particles and electrons.

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