SUPERCONDUCTIVITY

Controlling the motion of quanta

Solid-state devices that mimic biological motors can be built using magnetic flux quanta, or vortices. A new proposal describes how to transfer energy between two interacting vortex systems in a superconductor without having to physically 'sculpt' the host material.

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On page 179 of this issue, Savel'ev and Nori[1] suggest several innovative ways to control the motion of quantized magnetic flux inside a high-temperature superconductor. This opens a new chapter in the fascinating story of devices inspired by molecular 'brownian motors'. Their groundbreaking idea is to apply a current or magnetic fieldthat is asymmetric in time, rather than space, in order to guide the motion of quantized magnetic flux inside layered superconductors. This remarkable proposal makes it possible to create asymmetric flux motion, which should inspire experimentalists to build a new generation of superconducting devices for controlling magnetic flux quanta. Most importantly, such control is achieved without having to resort to cumbersome electron-beam lithography or irradiation techniques, which were previously needed to pattern structural defects into the host material.

Consider a simple example of a molecular motor: a very small object subject to both thermal noise and a spatially asymmetric periodic potential — known as a ratchet potential[2]. Owing to thermal noise the object can overcome the nearby potential barriers, but the probability of moving forwards or backwards is equal, and if the overall system is in thermal equilibrium, then, on average, the object does not move. Now imagine rocking the potential back and forth, for example by applying an alternating electric or magnetic field. This alternating field drives the system out of equilibrium and, moreover, produces an average directed motion, even against an opposing externally applied force. Nature uses molecular 'brownian motors' of this type for intracellular transport and other important biological functions[3,4].

Are such devices '*perpetua mobilia*'? In other words: is heat or noise converted into work? Obviously not, because extra energy is pumped in, in this case by periodically rocking the ratchet potential, and the overall system is out of equilibrium. These devices simply transfer energy from an unbiased random or periodic field, into a directed or biased output. The second law of thermodynamics is therefore not violated[5]. Nevertheless, such devices are fascinating because, as long as the underlying microscopic agitation is maintained and there is some extra energy input (such as an alternating field), they can produce useful work.

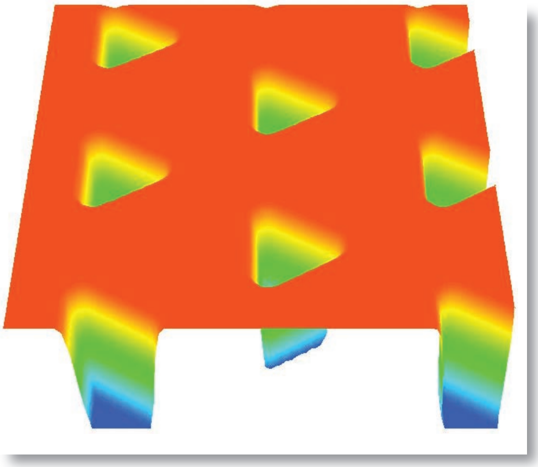

Figure 1 Potential energy landscape felt by vortices in an artificially patterned superconductor[10]. These asymmetrically- shaped defects can be used to transform the unbiased (that is, zero averaged) motion of flux quanta inside a superconductor into a biased, or directed, motion. But these potential energy traps are fixed and unchanging. Moreover, they require cumbersome sample processing, such as lithography or irradiation. Savel'ev and Nori[1] propose a new method that avoids these problems (Fig. 2).

Solid-state devices inspired by simple biological motors have been proposed for specific technological applications, for example to separate small particles according to their sizes, or to control the motion of electrons in semiconductor devices, and so on[6]. In particular, devices using superconducting materials have been suggested, for instance, to remove undesirable vortices that produce noise and degrade performance. A type-II superconductor placed in a large enough external magnetic field and cooled below its superconducting transition temperature, T_c, is permeated by an array of line-like mesoscopic objects, called fluxons or vortices. These quantized magnetic flux lines can be pushed around by thermal noise and electric currents. Also, the vortices can be trapped by structural defects in the host superconducting

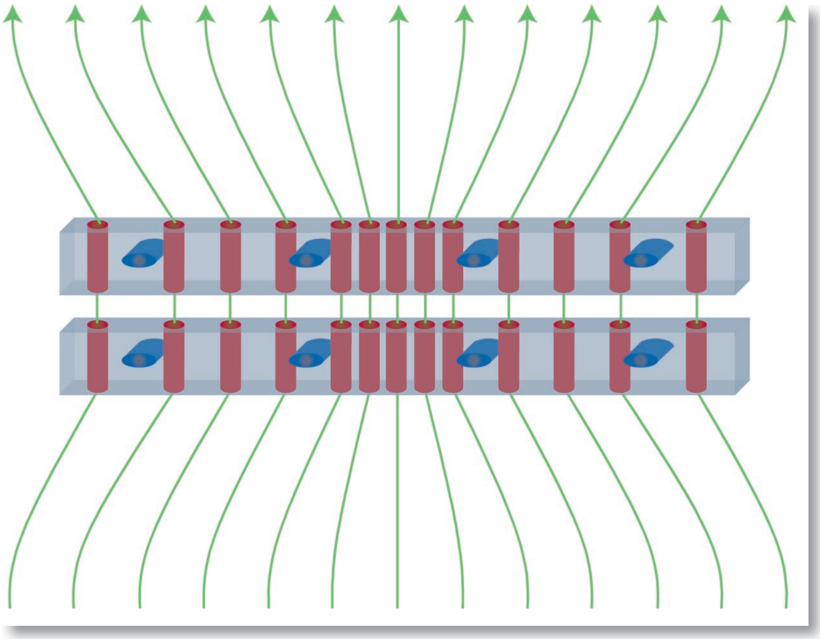

Figure 2 Magnetic flux inside a superconductor configured as a 'vortex lens', which is one of several devices proposed by Savel'ev and Nori[1]. A strongly anisotropic superconductor placed in a magnetic field inclined with respect to the layered structure, is permeated by two interpenetrating vortex lattices: a pancake-vortex lattice (red) and a Josephson-vortex lattice (blue). By applying a time-asymmetric alternating magnetic field, Savel'ev and Nori[1] show that the fluxons can be accumulated or removed from the centre of the device. The unbiased (or zero averaged) time-asymmetric alternating magnetic field is translated into biased fluxon motion by exploiting the complex interactions between the two lattices. (Figure adapted from Nori *et al.*, unpublished work.)

material, such as inhomogeneities, grain boundaries, surface scratches or irradiation defects.

Here we have all the ingredients for building microscale devices capable of extracting work from non-equilibrium fluctuations. Such devices involve biasing, or rectifying, the motion of the vortices by using an unbiased (that is, zero averaged or undirected) alternating field to induce fluxon motion whose direction is determined by a spatially asymmetric potential, which is moulded or 'printed' directly onto the material (Fig. 1). In this way a solid-state device can mimic the working principles of biological molecular motors, with the fluxons playing the role of the brownian object. Several of these devices have been proposed[7–10], including ratchet-type systems with asymmetric channel walls, modulated pinning densities or anisotropic pinning traps. With such systems, experimentalists can build vortex pumps, diodes and lenses, which can be used, for instance, to remove undesirable vortices from superconductors. But these 'vortex devices' are only a first generation. One still needs to 'sculpt' the material using controlled irradiation or electron-beam lithography, or other ways of engineering the desired potential, which remains permanently fixed after the sample is processed.

Savel'ev and Nori[1] propose a second generation of vortex devices based on a completely new approach. They show that an alternating field that is asymmetric in time is sufficient to produce biased vortex motion if the anisotropy of high-temperature superconductors is brought into play. In highly anisotropic superconductors, such as layered copper oxides, applying a magnetic field at an angle to the layered structure generates two populations of interpenetrating vortex lattices: 'Josephson' vortices, aligned parallel to the layers, and 'pancake' vortices, perpendicular to the layers (Fig. 2). The two vortex sub-systems interact with each other, such that one sub-system can 'trap' the other. During slow vortex motion both vortex lattices move together, but during fast motion, they do not. So, for a time-asymmetric field having cycles with fast and slow parts, the result is a 'conveyor belt' transporting vortices in a controlled manner. In essence, one vortex lattice can grab the other during the slow part of the cycle and move it to a desired location. Afterwards, during the fast portion of the driving cycle, the pancake vortex lattice uncouples from the Josephson vortex lattice leaving it behind.

Savel'ev and Nori propose several ingenious second-generation devices for controlling flux motion at the microscale. For instance, one device acts like a convex (or concave) lens, allowing the creation of a changeable magnetic landscape inside the material (Fig. 2). These and other proposals should stimulate new experiments, with potential technological applications in mind. But the authors are keen to stress that their idea is more general — namely, that an external force applied to only one subset of objects in a complex system, can influence the dynamics of another subset that does not itself interact with the external field. The first subsystem transfers the action of the external field to another subsystem. This means that you could indirectly manipulate or control the motion of one species of particles by using another subspecies — imagine, for example, different types of colloidal particles, nanoparticles with different magnetic moments or different electric charges or dipolar moments. The possibilities of controlling the motion of all these different particles may engender an entirely new species of amazing devices.

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