Flux Lattice Melting

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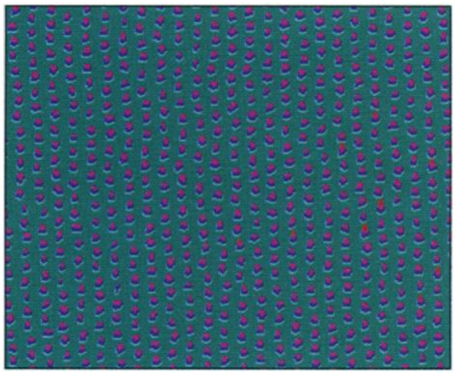
This year is the 10th anniversary of the discovery (*1*) of the first high–transition temperature (T_c) superconducting compounds. Since then, these materials have taught us much new physics. Few issues have been as hotly debated as the controversy about flux lattice melting. Two recent papers (*2*) by Kes and co-workers at the University of Leiden drive right to the heart of this issue.

The superconducting state, in general, does not like magnetic fields. To avoid the presence of a magnetic field in its interior, a superconductor responds in interesting ways. There are two important critical fields for a superconductor that define its response. The first is the lower critical field H_{c1}; for fields less than this value, superconductors expel the applied field (the Meissner effect). The second is the upper critical field H_{c2}; for fields above this value, superconductivity is destroyed. The high-T_c superconductors are examples of what are called "strongly type II" materials, those for which $H_{c2} >> H_{c1}$. All of the technologically important superconductors are of this type, and so their study is essential if applications are to be realized.

Type II materials with fields applied between H_{c1} and H_{c2} enter a mixed state in which the field is admitted into the interior of the sample in the form of quantized bundles of magnetic flux. Each of these bundles contains exactly the same amount of field, and as the applied field is changed, the density of lines changes. In the absence of disorder, these lines form a triangular lattice, the flux line lattice. This lattice can be thought of as a solid in the same sense that the piece of paper you are holding is a solid: it has a finite shear modulus. Liquids and gases do not have a finite shear modulus, although they do have a shear viscosity. The finite shear modulus is an important defining characteristic of a solid.

The figure shows an example of what is perhaps the easiest way to image the lattice. One can cool the superconductor to below its transition temperature, apply a field, and then evaporate magnetic particles onto the surface, which will decorate the magnetic vortices. Subsequent examination with a scanning electron microscope yields vortex lattice images like the one shown.

Soon after the high-T_c superconductors were discovered, the vortices were found to behave in ways not expected from the study of the low-T_c superconductors. It is now known that the flux lattices in the high-T_c materials can melt into a state of matter called a flux liquid. In these materials, the thermal fluctuations are much stronger, partly because of the higher transition temperatures (*3*). These fluctuations can cause the flux line lattice, which is a solid at low temperatures, to melt into a liquid at a transition temperature well below T_c. This idea was very controversial when first suggested (*4*) as an explanation for the unusual behavior of the high-T_c superconductors and has only been widely accepted after nearly a decade of debate.



Magnetic vortices free of topological defects in a superconducting single crystal. The hexatic order, apparent as well-correlated rows, indicates an ordered ground state in the flux line lattice and hence a phase transition between this state and the high-temperature liquid state. (Courtesy of P. L. Gammel, Bell Laboratories, Lucent Technologies)

Flux line lattices might seem like merely an interesting sandbox for academic research, but it turns out that their study is of real importance in the quest for applications for superconductivity. The behavior of the magnetic vortices is intimately related to the most important defining characteristic of the superconducting state: its ability to carry an electrical current without loss.

Each magnetic vortex line consists of a microscopic circulating current: a current vortex. When a macroscopic current is applied to the sample, it puts a force on each vortex line at right angles to both the magnetic field and the current. If the flux line is free to move, then it dissipates some of the energy in the flowing current, and the sample effectively has a finite resistance. It is not superconducting anymore. However, if the lines are not free to move (if they are "pinned"), then no energy is dissipated, and the current flows without loss. The type of vortex structure can be important to having a nonzero critical current. If one has a vortex solid, then a few pins can hold it in place much like a carpet can be held in place by a few nails because of its finite shear modulus. If, however, the flux lattice is a liquid with no shear modulus, then pinning it might require a very different strategy. If I tell you there is some water in the next room and ask you to restrict its movement, you would need to know its state: liquids, solids, and gases require very different objects to hold them.

The experiments of Kes and co-workers have been crucial in this debate about the existence of flux lattice melting and of a flux liquid. They have directly measured the shear modulus of the solid flux line lattice and the shear viscosity of the flux liquid. These measurements are important microscopic evidence for the state of the vortex matter in the various regimes. Their experiments are challenging because vortex matter is soft and squishy stuff. For example, the shear modulus they measure (*2*) is roughly 10 orders of magnitude smaller than that of the chair you are sitting on. This requires a delicate probe of the vortex matter.

Their technique involves the use of superconducting samples with weak pinning channels sandwiched between strong pinning regions. The latter hold the vortices in place while the vortices in the weak pinning channels are forced to shear along the channels by the application of a current. The critical current in such a sample is a measure of the maximum shear strength of the vortex matter in the weak pinning channels. In this way, they were able to measure the shear modulus of the vortex lattice, watch it go to zero at the flux lattice melting transition, and measure the shear viscosity of the liquid.

In the early days of the controversy, the "absence of proof" was often confused with the "proof of absence." For example, it was typical for experimenters to try to probe the system with forces that destroyed the object they were looking for and then claim it did not exist. Vortex matter is very delicate stuff, easily affected by the measurements. Experiments such as those done by the Leiden group are setting new standards for experimental techniques in this field.

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