SUPERCONDUCTIVITY

Fingerprinting Vortices with Smoke

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Ten years ago, the materials now known as high-transition-temperature (high T_c) superconductors were discovered. It was a scientific breakthrough of breathtaking proportions which quickly won the Nobel Prize for discoverers J. Bednorz and K. A. Müller; it appeared to herald an imminent technological revolution. To date, such a revolution has not yet appeared. A reasonable question to ask at the tenth anniversary is, "what happened?"

TECH VIEW

There are many things that influence whether a technology is successful, such as the cost of capital, progress in competing solutions, environmental concerns, and so on. But in the case of the high T_c superconductors, it is fair to say that the single most vexing problem has been the pathological behavior of the magnetic fields, which arrange themselves into lattices of small vortices. These lattices in turn are vitally related to the technological issue of how much current the material can carry. In these materials, the vortices simply do not behave in the way we would have expected, based on our studies of conventional superconductors. This has been a major impediment to successful applications. As a result, the study of magnetic vortices has become an active issue in condensed-matter physics. Because of this extreme interest in the subject, many experimental techniques have been applied to the study of magnetic vortices in type II superconductors. However, no technique is as simple and powerful as magnetic decoration. In this technique, the vortices are visualized by "dusting" them with magnetic smoke in much the same way that fingerprints on a glass are visualized by dusting them with a fine powder. This ability to "see" vortices has been extremely important to the development of the field.

The technique has a long history. Decoration with fine particles was first used by Bitter many years ago to image ferromagnetic domains. Trauble and Essmann (*1*) refined the technique in the 1960s and pioneered its use to image the vortex lattice in the conventional type II materials that were then known. When the high T_c materials were discovered, we resurrected the technique, further refined it (particularly with regard to computer-based image processing), and have used it to study the vortex lattice in many materials in the last 10 years (*2*). The technique is now quite common, and many groups around the world routinely use it to image magnetic vortices (*3–5*).

How do the vortices arise? When a magnetic field is applied to a type II superconductor at low temperatures, one of three things can happen. In the first case, for high fields greater than a critical field called $H_{c2}(T)$, the normal state is regained, where the superconductor behaves like an ordinary metal. For very low fields below $H_{c1}(T)$, the Meissner state is achieved, where all of the magnetic flux is completely expelled from the body of the superconductor. However, for fields between $H_{c1}(T)$ and $H_{c2}(T)$, known as the lower and upper critical fields, respectively, something quite different and interesting happens. In this field range, the magnetic flux enters as quantized flux lines and forms a flux line lattice (FLL). In the simplest case, in the absence of disorder, these flux lines will form a hexagonal lattice. However, as we will show below, there are many cases in which the FLL forms much more interesting and exotic structures.

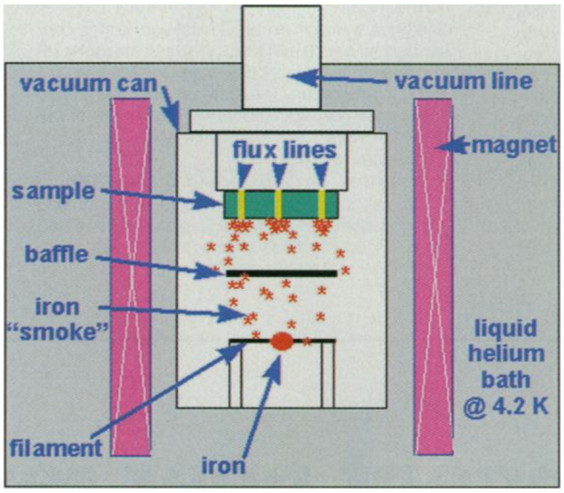

Fig. 1. Magnetic decoration apparatus.

This FLL that forms in a type II superconductor is quite interesting and important. It is important because of the effects that flowing currents have on the magnetic flux lines. The quantized lines of magnetic flux are created by small whirlpools of flowing electrical currents. When a macroscopic current is applied to the sample, a Magnus force is exerted on each flux line, which tends to make it move at right angles to both the current and the applied field. If the flux line is free to move, it dissipates energy as it moves, and energy is lost from the flowing current. There is then a finite resistance and the sample is not "superconducting." However, if the flux line is "pinned" or kept from moving by defects in the sample, then no energy is dissipated in the flowing current, and there is zero resistance, thus making the sample a superconductor. Therefore, the defining characteristic of the superconducting state—zero resistance—requires that the flux lines stay pinned. The maximum amount of current a superconducting sample can carry before the flux lines break free and start to move is the critical current, J_c. Clearly, J_c will depend on the detailed FLL structure, how well pinned it is, whether it is a liquid or a solid, and many other aspects of its character.

In addition to practical importance, the study of the FLL is quite interesting physics. Flux lattices are excellent model systems for studying issues in condensed-matter physics such as phase transitions in the presence of disorder, self-organized criticality, the flow of pinned structures, melting in two dimensions, and hexatic order, to name but a few examples. Because of this, the study of the static and dynamic behaviors of flux line lattices is clearly a growth area in solid-state physics.

Figure 1 shows a typical magnetic decoration apparatus. It consists of a small vacuum can, which contains the sample and an iron filament. Around the outside of the can is wrapped a coil of wire that produces the magnetic field which creates the vortices in the sample. The entire apparatus is cooled by the liquid helium in which it is immersed. When magnetic vortices exit the surface of a sample, they produce a small field gradient which acts like a homing beacon and guides the magnetic particles. In operation, a field is applied to the sample, it is cooled below its transition temperature, and the filament is heated to evaporate a small amount of iron. Because there is a some helium gas in the can, the evaporated material forms a smoke of magnetic particles instead of a metallic film. This smoke diffuses in the gas and is thermalized by it. The roughly 50 Å magnetic particles follow the magnetic field lines

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created by the vortices in the sample and land on its surface where the flux lines are located. The van der Waals force then acts like "atomic glue." This force is extremely strong but quite short-ranged. When the magnetic particles land on the surface of the sample, the van der Waals force holds them firmly in place. The sample can then be warmed up to room temperature and its surface examined with a scanning electron microscope (SEM) to locate the vortices. For many experiments, modern computer-based image processing is then used to extract the physics from the vortex patterns.

nearest-neighbor bond angles are correlated over long distances, while the positions of the vortices have only short-ranged order.

Shown in Fig. 2C is an image of vortex chains in the high T_c superconductor YBCO. This novel vortex structure is a result of the strongly anisotropic nature of these compounds. Under normal circumstances, superconducting vortices repel one another. However, if the field is applied nearly in the *a-b* plane of these materials, a bound state is formed, where the vortices will sit at a fixed distance apart and form a chain like pearls on a string. These chains still repel one another,

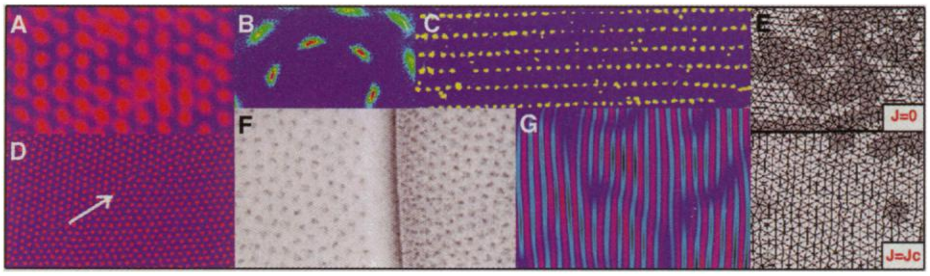

Fig. 2. A variety of vortex images were taken, using the magnetic decoration technique. (**A**) Lattice in the high T_c superconductor BSCCO, (**B**) Fourier transform of a lattice in $NbSe_2$ with hexatic order, (**C**) vortex chain state in YBCO, (**D**) vortex lattice in YBCO near twins, (**E**) the result of applying a current which anneals the lattice, (**F**) lattice moving over a step in the surface which acts like a vortex diode, and (**G**) vortex flow channels.

In addition to being able to image both with dust, vortices are also like fingerprints in that no two are ever exactly alike. This is because the microscopic disorder in every sample's crystal structure is unique. Such things as atomic vacancies, interstitials, dislocation lines, voids, and inclusions act as places where vortices prefer to sit and, hence, as pinning sites for vortex lines. These defects in the crystal, which are always present at some level, disorder the vortex lattice and cause it to never be a perfect hexagonal lattice. An example of this (Fig. 2A) is a decorated image of the FLL in the high T_c superconductor BSCCO taken at 4.2 K and at a field of 20 oersted. The vortices in the image are the red circles. Clearly, the lattice is roughly hexagonal with most vortices having six nearest neighbors, but there is a lot of disorder due to pinning at defects in the underlying crystal lattice. Such images allow one to measure the superconducting flux quantum, study the pinning process, measure the correlation functions of the FLL, see vortex lattice melting, and learn many other things about the FLL.

Figure 2B shows a fairly typical type of analysis we do. The Fourier transform of a vortex lattice in the superconductor $NbSe_2$ is shown. The real-space images are important to see such things as defects, whereas the transforms allow long-ranged, averaged properties to be seen. This transform shows a hexatic vortex lattice or one in which the

and structures are seen in which the distance between chains, but not the density of vortices along the chains, varies with field.

Figure 2D shows a vortex lattice in YBCO near an extended defect: a set of twins. Twins form in YBCO because of the orthorhombic symmetry of the unit cell. Twins are 90° grain boundaries in the crystal where the *a* and *b* directions of the crystal reverse. In the image, the twins meet at right angles (not shown). Studies like this one have shown that the twins act as strong pinning centers for vortices, breaking the rotational degeneracy of the FLL with respect to the crystal lattice and forcing the FLL to line up parallel to the twin. However, there is a problem. It is not possible to pack six-sided objects into a square box without forming defects. In the image, this defect can be seen as an FLL dislocation line (white arrow). As these twins are a ubiquitous feature in this compound, understanding the nature of this pinning process is extremely important, and such images have proven invaluable.

Another type of analysis commonly done is Delaunnay triangulation (Fig. 2E). To create it, decorations as described above are made, and a computer is used to find the locations of all the vortices. Next, the computer draws a line between each vortex and its nearest neighbors; in most cases there are six neighbors, but in some cases there are five or seven. The final step is to shade in the defective neighborhoods or the regions around any vortices which are not six-fold coordinated. These shaded regions are then the topological defects of the vortex lattice. The images shown are for two vortex lattices with a different current history. In the upper image, the sample has been cooled in a field with no current applied. Note that there is a moderate density of defects in the lattice. In the lower figure, the sample has had a current applied, equaling the critical current, which was then rapidly removed. Notice how much more well ordered the lattice is. These types of experiments have shown how in an FLL, flow-induced order can be seen. Such observations have been crucial in helping to understand the microscopic nature of the critical current in a superconductor, one of its most important properties.

The remaining images show two other types of structures formed by flowing vortices. In Fig. 2F, vortices can be seen that are flowing to the left side of the image, but are piling up at a step on the surface of the sample. Such steps can act like "vortex diodes," in that they will impede the flow of vortices flowing up the step but not down it. Figure 2G shows an image of moving vortices flowing in channels. To generate the image, vortices were decorated while they were flowing along the direction of the arrow. A decoration was made, then was Fourier filtered and retransformed back into real space. The picture shows how vortices want to flow in well-defined channels. Such patterns formed by the dynamics of moving vortices are an interesting and important ingredient in our understanding of the current-carrying capability of type II superconductors.

The technique of magnetic decoration is simple, effective, inexpensive, and powerful. In comparison with other methods for imaging vortices such as small-angle neutron scattering, electron holography, atomic force microscopy, scanning tunneling microscopy, and scanned superconducting quantum interference devices, it seems quite primitive. This simplicity not-withstanding, the technique has an impressive list of firsts associated with it, and for the foreseeable future will remain one of the most important tools in our bag of tricks to attack the problem of magnetic vortices in type II superconductors.

References and Notes

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