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Intermittently Flowing Rivers of Magnetic Flux

Franco Nori

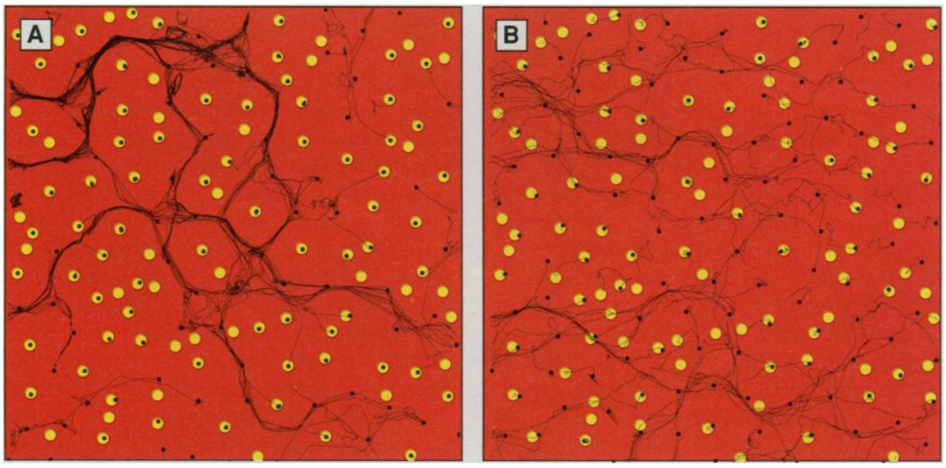
One of the major unsolved puzzles in superconductivity is the nature of the motion of penetrating flux lines. Magnetic flux enters a clean type II superconductor in the form of a regular triangular lattice of quantized magnetic flux lines (also known as vortices because electrical currents whirl around each flux line). When this lattice is forced to move, by application of either an electric current or a varying magnetic field, it maintains its regular periodic structure. The dynamics of this lattice of flux lines become more complicated when it is forced to move inside a disordered sample with pinning sites that can temporarily trap vortices. As the external magnetic field is increased, additional flux lines are forced inside the sample, where their motion is impeded by defects. When pinning is weak relative to the driving force, the array of flux lines flows smoothly, with some minor distortions, and behaves as an elastic medium (that is, like a flowing rubber sheet). If the pinning forces are very strong, the flux lattice remains immobilized. In the poorly understood intermediate regime, when pinning and driving forces are comparable, vortex motion is not expected to remain elastic, but to become plastic, where parts of the flux lattice break loose from the rest.

In this issue of *Science*, Tonomura and collaborators (*1*) present direct evidence of plastic flow of flux lines in a superconductor. Their experiments provide a striking motion picture of the onset of vortex motion that vividly illustrates the existence of flowing "rivers" of quantized magnetic flux that intermittently form, freeze, and reappear at different locations in the sample. These rivers flow around "islands" (or domains) of flux lines that are temporarily trapped by the pinning sites. The shape and size of these temporarily frozen islands abruptly change over time with every loading-unloading cycle. Movies of the phenomena [for figures 5 and 6 on page 1394 of (*1*)] are available from *Science*'s World Wide Web site at URL <http://www.aaas.org/science/beyond htm>.

Flux pinning in superconductors is of both technological and scientific interest (*2*). Practical applications of superconducting materials require that the magnetic flux lines be pinned, because the motion of flux lines dissipates energy and destroys the superconducting state. Therefore, it is important to understand how the trapping and depinning of flux lines occur. The complex nature of this onset of collective motion—with loading and unloading cycles, plastic flow, and intermittent avalanches—is not well understood, and it is the subject of intense investigations on both superconducting materials and a large variety of other systems: granular assemblies, magnetic bubble arrays, electron lattices in semiconductors, charge density waves, water droplets sprayed on a surface, and the stick-slip motion of two rubbing interfaces. These apparently dissimilar systems have interacting moveable objects (such as vortices, electrons, or grains) that repel each other and are pushed toward instability by an external driving force. During the unstable state, particle transport occurs in the form of avalanches or cascades that release accumulated strain in the system and allow the medium to move to a nearby metastable state. The detailed nature of the onset of collective transport in these systems is still hotly debated and continues to be an exciting area of research.

A remarkable feature of the technique used by Matsuda *et al.* (*1*) is the ability to monitor the spatiotemporal dynamics of the vortex lattice while simultaneously imaging the large pinning sites irradiated on the sample. This technique, called Lorentz microscopy, allows the microscopic motion of individual flux lines to be seen directly. Their observation of flux gradient–driven intermittent plastic flow is consistent with previous time-resolved experiments (*3*) and computer simulations (*4*) of vortices forced by an increasing magnetic field. Other studies of plastic flow [for example, (*5, 6*)] focused on the different case where the flux lattice is driven by an applied electrical current, whereas in (*1, 3, 4*), the varying external field provides the pressure that forces the vortices through the sample. Moreover, previous experiments on plastic flow were indirect, because they did not image the spatiotemporal evolution of the vortex lattice.

Several "magnetic snapshots" of the flux lattice are presented in (*1*). These directly show how the flux lattice orders when either the field or the temperature is increased. The main results of (*1*) are summarized in its figure 6, where successive video frames show a vortex lattice with several "frozen" domains (top frame), vortex streets



Branched vortex channels. Computer-simulated trajectories (black trails) of eastbound vortices (black dots) moving inside a superconductor with pinning sites (yellow circles). (**A**) Strong pinning produces a few vortex channels with heavy traffic, whereas (**B**) weak pinning induces a different network of much broader vortex trails. Indeed, in (*1*), the vortex channels also become wider at higher temperatures, when pinning is weaker. A short video clip of this figure is available at URL <http://science-mag.aaas.org/science/feature/beyond >.

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in the following two frames, and a new set of frozen domain structures (bottom frame). This partial flux flow, first described by Kramer (7) more than 20 years ago, was believed to occur in the technically useful strong-pinning superconductors; Matsuda *et al.* (1) provide direct evidence supporting this view.

In order to better understand the factors that control the formation of the vortex rivers observed (1), it is advantageous to analyze computer simulations (see figure), where, unlike in experiments, material parameters can be continuously varied. Indeed, both Lorentz microscopy and computer simulations are valuable tools for the analysis of the microscopic spatiotemporal dynamics of individual flux lines in superconductors, which are not easily observed by other means, lending insight to commonly measured bulk macroscopic quantities such as the magnetization and the critical current. These approaches can help elucidate the topological ordering of a driven plastic lattice interacting with a rigid one, a problem that has recently attracted considerable attention (3–6).

The figure here and figure 6 of (1) show paths through which vortices move, producing dynamically generated flux lattice defects or phase slips. This plastic flow is in contrast to the coherent motion predicted by elastic models. In both the figure here and in (1), the increasing external field provides the pressure that forces the vortices to move into the sample (8). The figure herein shows the top view of a small region of a larger sample. In part A of the figure, where the pinning force is strong, the vortex transport is characterized by trails of interstitial vortices that move around regions with flux lines that are strongly pinned at defects, indicating that the interstitial vortices are flowing through the energy minima created by the strongly pinned flux lines. In part B, where the force is 10 times weaker, vortex transport proceeds in a different manner: pin-to-pin vortex motion, as well as interstitial, is possible, and the previously narrow vortex trails become considerably broader.

Although most experiments only focus on the effects of random pinning distributions, some investigations (9) have used samples with periodic arrays of pinning sites (PAPS). These can greatly enhance pinning when parts of the flux lattice become commensurate with the underlying PAPS. Under such conditions, high-stability vortex configurations are produced that persist in an increasing current or external field. Flux lattice domains attributable to commensurate effects are visible in figures 3 and 4 of (1). Other vortex matching effects also have recently been observed in a variety of different superconducting systems, including Josephson junctions, superconducting networks, and the matching of the flux lattice to the crystal structure of $YBa_2Cu_3O_7$ due to intrinsic pinning. Nonsuperconducting systems also exhibit magnetic field–tuned matching effects, notably in relation to electron motion in periodic structures where unusual behaviors arise as a result of the incommensurability of the magnetic length with the lattice spacing. Commensurate effects also play central roles in many other areas of physics, including plasmas, nonlinear dynamics, the growth of crystal surfaces, domain walls in incommensurate solids, quasi crystals, Wigner crystals, and spin and charge-density waves. The magnetic motion pictures obtained in (1) allow one to easily visualize such commensurate effects, which otherwise can rarely be directly resolved in both space and time.

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The Expanding World of Trinucleotide Repeats

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It is not every day that new kinds of mutations in the genetic material are discovered. Nevertheless, 5 years ago the first examples of mutations resulting from the unstable expansion of trinucleotide repeats were reported in individuals with fragile X syndrome and spinal and bulbar muscular atrophy (1). In both cases, a normally polymorphic triplet of nucleotides (CGG in fragile X syndrome and CAG in spinal and bulbar muscular atrophy) increases in copy number in individuals with these disorders. For fragile X syndrome, this change could be extraordinary; patients can exhibit hundreds and sometimes thousands of the CGG triplet at this site (locus), whereas normal individuals contain only about 30 repeats. Although the normal CAG repeat at the site mutated in spinal and bulbar muscular atrophy is similar in length to the fragile X triplet (about 20 CAGs), in affected individuals the expansion is more modest, exhibiting only a two- to threefold increase (38 to 66 repeats). Ten additional human loci are now known to have alleles with expanded trinucleotide repeats of either the massive or modest variety (2) (see figure). Although at some of these loci expansion is benign (except causing a chromosomal variation called a fragile site), most result in disease, including such disorders as Huntington's disease, myotonic dystrophy, and a number of hereditary ataxias. There are certain similarities among these repeats that have implied some simplifying generalizations. The most recent addition to this growing list of genetic diseases caused by trinucleotide repeat expansion, Friedreich's ataxia, reported by Campuzano and co-workers in this issue, now shows that some of these generalizations may have been premature (3).

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Before this most recent discovery, all the known expansion loci contained either CGG or CAG repeats, although they have been reported in permutations that vary with strand and frame. When expansion results in disease, the disorder transmits as a dominant trait with the repeats found within the exons of their respective genes (although they may or may not be coding for amino acids). Furthermore, the repeats at these loci, despite being stably transmitted in normal families, exhibit marked instability when abnormally expanded, with siblings often showing unique repeat lengths distinct from that of the transmitting parent. In addition, these "dynamic mutations" show a predilection for gaining repeat units when transmitted through subsequent generations. Concomitant with this increase in repeat number with subsequent generations is an increase either in disease severity, frequently revealed by decreasing age of onset, or in penetrance. This phenomenon is called genetic anticipation and is considered a hallmark of such dynamic mutations.

These similarities have become viewed as mechanistically significant points. The relatively high CG content of the repeats appeared pertinent, and a number of models were proposed in which such trinucleotide repeats assumed hairpin or triple helical