suggested in 1979 that AGNs were the source. But a crucial test of his theory failed when the spectrum of background x-rays didn't match a spectrum that combined some of the closer quasars and other types of active galactic nuclei. That made it hard to argue that the background and the nuclei were related. Other theories, such as a hot, x-ray emitting gas in intergalactic space, were proposed and later discarded when contradictory evidence emerged.

Researchers, Krolik among them, then returned to Giacconi's idea, realizing the mismatched spectra could have been the result of instrument limitations. Previous measurements of the x-ray background showed that it consists of a wide range of x-ray energies. But the AGN spectrum in the test came from a satellite called HEAO1 that—Krolik suspects—only detected a narrower portion of that range from individual nuclei. The result: The AGN spectrum didn't match the background.

To get a more accurate spectrum, Krolik used better detectors on the Gamma-Ray Observatory and Ginga. He combined spectra from a handful of individual AGN and constructed a model of the x-ray spectrum that would result from millions of these scattered through space. To do that he assumed he had collected a representative sample and then extrapolated to the population at large, using satellite data on AGN population distribution. The data actually show the number of AGN at different red shifts, and to convert that data into a spatial distribution he had to make some assumptions about the distance scale and geometry of space. The model spectrum he got as a result matched up nicely with the spectrum of the background —and met the expectations and approval of some colleagues. "I expect there to be consensus within a year," says Columbia University astronomer David Helfand, who has reached similar conclusions from independent studies of the background.

But while this general idea seems acceptable, NASA-Goddard astronomers Elihu Boldt and Darryl Leiter differ on some details. They argue that Krolik's result ties up too much of the universe's mass in AGNs. Boldt and Leiter, making different assumptions about the geometry of the universe, conclude that in addition to AGNs, another class of sources also contributes to the background. They propose "precursor" AGNs, which shine at us from far out in space and far back in time.

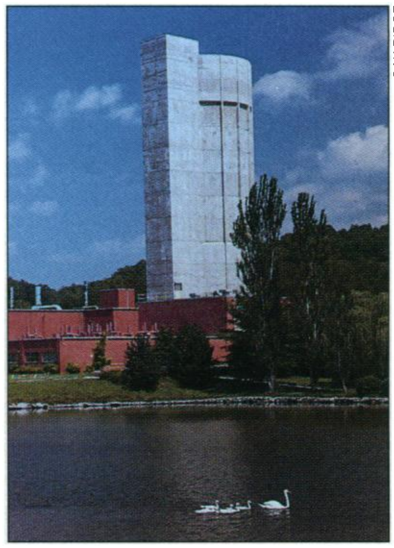
Boldt adds that his idea is just speculation, but it shows that the case isn't solved yet. At one time people proposed that the background came from everything from hot gases to exploding stars. Now it's narrowed down, says Boldt, but there's still room for debate at a more refined level. "The whole thing is in its infancy," he says.

–Faye Flam

MATERIALS SCIENCE

Holding the Lines in High-Temperature Superconductors

George Crabtree, who works on high-temperature superconductors at Argonne National Laboratory, recalls how a former student put his finger on the challenge that is now consuming Crabtree and his colleagues. When it came time for the student to defend his Ph.D. thesis, one of the first to be written on this new class of ceramics that can carry current without resistance at temperatures tens of degrees higher than earlier superconductors, he insisted on discussing magnetic lines of force as though the lines were real. That didn't go over well with the professors on his thesis committee. Unfamiliar with the nuances of superconductivity, they kept trying to explain to this misguided soul that flux lines are only emblems of magnetic field strength and direction. Like the lines on a contour map, they don't really exist.



OAK RIDGE

Big gun. Drilling angstrom-sized holes in superconductors has required massive accelerators, like the Holifield Heavy Ion Facility at Oak Ridge.

The problem is that in high-temperature superconductors, the flux lines *are* real. As magnetic fields penetrate a superconductor, they actually break up into lines: individual vortices, like the swirling whirlpools formed as the water drains out of a bathtub. Each vortex contains one quantum of magnetic flux—the minimum flux nature allows. And when electric currents flow through the material, these vortices can be torn from their moorings. As they move, they waste energy, create resistance, and cause the temperature at which the material loses its superconductivity to "drop like a rock," as physicist David Nelson of Harvard University puts it. Because many of the applications envisioned for these materials—in generators, motors, magnetic resonance imagers, and research magnets, for instance—would expose them to high magnetic fields, that's a major obstacle to realizing their much-heralded potential.

In principle, at least, researchers already have a solution to this problem: bombarding superconducting materials with ions to create holes tens of angstroms across called columnar or track defects. By capturing the vortices and pinning them in place, these defects enable the materials to retain their superconductivity in high magnetic fields at temperatures high enough — above 77° Kelvin—for liquid nitrogen, rather than liquid helium, to suffice as a coolant.

But this solution is far from perfect. Drilling the holes has required accelerators that can hurl heavy ions at energies of half a billion electron volts or more, machines far too rare and expensive to become part of any superconductor production line. By learning more about the physics of columnar defects and borrowing techniques from areas as far-flung as metallurgy and nuclear physics, however, researchers are developing ways to create the defects more cheaply and efficiently. Says Argonne materials scientist Mark Kirk, "It's one of the tricks everyone is trying to do."

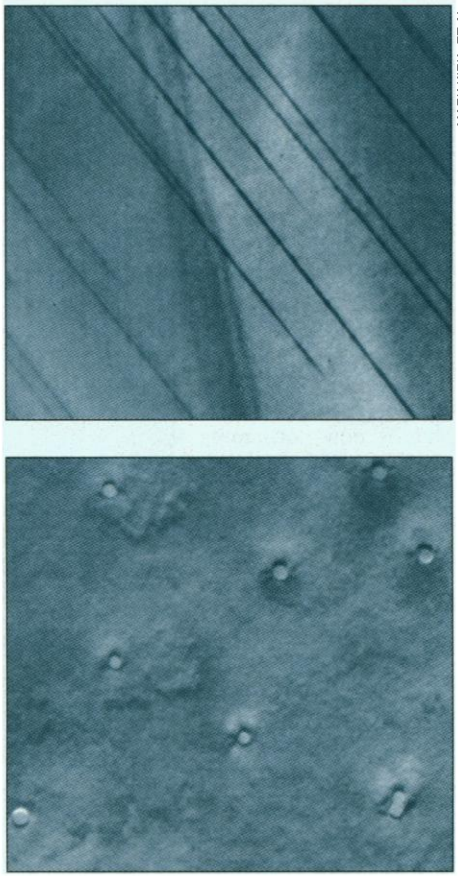
The effort to pin down the flux vortices began when their show-stopping effect was first observed, soon after the 1986 discovery of high-temperature superconductors (*Science*, 26 May 1989, p. 914). The initial question, says James Thompson of Oak Ridge National Laboratory, was simply, How do you immobilize a line of magnetic flux? Because the core of a magnetic vortex isn't superconducting, a vortex is most "comfortable," energetically speaking, when it sits in a non-superconducting region of the material. The obvious approach to pinning the vortices, says Thompson, was to create such defects deliberately—to somehow destroy the superconductivity on a scale of a few tens of angstroms. In 1990, Thompson and colleagues from Oak Ridge and IBM bombarded superconducting crystals with protons, creating what Thompson calls a "rather dense array of random point-like defects"—sites where, say, an atom was dislodged from the crystal lattice.

The result was an order of magnitude increase in the amount of current the materials could carry in weak magnetic fields. At liquid nitrogen temperatures, however, the materials remained far too sensitive to increasing magnetic fields. The pinning just wasn't good enough, says Thompson. "Think of the vortex line as kind of like a rubber band," he explains. "If you have randomly placed point defects...the vortex [can] reach around, stretch, and bend." These contortions consume energy, increasing resistance and hampering superconductivity.

The hole solution. The ultimate solution to the problem was suggested at a Chinese restaurant in Anaheim, California, in March 1990. During an American Physical Society meeting, researchers from the Oak Ridge-IBM collaboration were dining with collaborators from the Ames Laboratory in Iowa, among them John Clem, who runs the electronic journal on superconductors known as the *High-Tc Update*. The physicists were discussing the best way to pin a vortex, and Clem suggested that since a vortex is a linear object, "a really keen way to immobilize it," in Thompson's words, would be to create not a point defect but "a line-like potential well, a line of normal non-superconducting material, a microscopic hole through the superconductor such that the vortex core could sit in it." And the best tool for drilling a hole that could capture a line of magnetic flux, suggested IBM physicist Alan Marwick, was a high-energy ion, which could plow a long track through the material's crystal structure.

Working with Leonardo Civale, an Argentine physicist then at IBM, and the Oak Ridge heavy ion facility, Thompson and his collaborators shot tin ions at very high energies (600 million electron volts) at a single, almost perfect crystal of an yttrium-based superconductor. Thompson calls the results "great." The tin ions carved tracks roughly 60 angstroms in diameter that looked like something, says Thompson, "between a string of beads and a snake that swallowed a nest of eggs." At 77°K, in a magnetic field of 4 tesla (the field strength of a powerful electromagnet), the defect-riddled crystal could carry as much as 100,000 amperes of current in every square centimeter of material. Under the same conditions, the researchers reported in *Physical Review Letters* in 1991, a crystal without defects could carry only immeasurably small currents.

Theorists, in particular Nelson and his colleague Valerii Vinokur of Argonne, immediately set about figuring out the details of binding between vortices and track defects and how these alliances push up the temperature limit of superconductivity. Experimenters were slower to jump in, mainly because of the shortage of accelerators that could deliver ions with sufficient energy; the Oak Ridge facility itself was shut down last year to be rebuilt into a machine that can do radioactive nuclear beam work. Now, however, at Argonne, Canada's Chalk River Laboratories, Indiana University, and Michigan State University, accelerators normally used for nuclear physics are about to give beam time to superconductor work.


MARK KIRK, *ET AL.*

Traps for magnetic flux. Electron micrographs show side *(top)* and end views of the damage tracks left in a high-temperature superconductor by high-energy gold ions.

Crabtree's group is one of three now waiting to bombard materials. He and his colleagues hope to test a proposal Nelson made last month at a conference on low-temperature physics in Eugene, Oregon. Nelson predicted—on the basis of work done with Vinokur, Pierre La Doussal of Rutgers University, and Terence Hwa of the Institute for Advanced Study in Princeton—that the defects would be even more effective at trapping magnetic vortices if they were splayed through the superconductor, with their orientations varying by as much as 20 to 30 degrees, rather than being parallel. "The idea," says Nelson, "is to force vortices to be deliberately tangled and make it very difficult for them to escape, because they'll crash into other vortices if they do that. It should be a very effective way to optimize pinning."

Looking for a better deal. Other researchers, meanwhile, are looking for more economical ways to produce pinning defects. Rather than relying on a heavy ion accelerator, something that "looks like a Midwest silo," says Thompson, these researchers are trying to create equivalent defects by tinkering with the elemental recipe for the superconductor or the way it is processed. "They try to texture the material," says Nelson, "by having this stuff appear naturally. It can be very effective—in principle."

Oak Ridge researcher Dave Christen and his colleagues, for example, have been studying what happens when extra yttrium is added to the recipe for yttrium-based superconductors. The oversupply tends to precipitate out, forming tiny threadlike defects that serve the same purpose as ion tracks, although they are not quite as effective. Researchers at the Texas Center for Superconductivity at the University of Houston, meanwhile, have been compressing yttrium-based compounds at temperatures high enough—950° C—to allow the microscopic grains making up the ceramic to shear and slip past each other, not unlike tectonic plates moving about under California. The slippage, says Kamel Salama, a mechanical engineer at Houston, creates microscopic deformations that resemble line defects. "This technique has been proven to be very strong in improving the current carrying capability in the presence of magnetic fields," says Salama, though it too falls short of pinning by ion tracks.

In the latest work at Houston, physicist Roy Weinstein includes an exotic ingredient in his superconductor recipes: He spikes his superconductor samples with atoms of uranium-235. The material is then exposed to a beam of neutrons from a nuclear reactor. "The thermal neutrons fission the U-235," explains Weinstein, "and that makes two heavy energetic charged ions moving off back to back, which both leave columnar defects." Not only is neutron bombardment "cheap and readily available at any of many reactors," says Weinstein, but the neutrons can process thicker samples than ions because they penetrate much farther—millimeters instead of microns. Indeed, Weinstein has successfully tried his fission-track technique in samples a centimeter square and a millimeter thick.

Weinstein admits that the technique "has a drawback, in that the columns are not oriented in a fixed direction. They're random." But it shows promise of being nearly as effective at pinning the fly-away vortices as heavy ion bombardment. Weinstein says that in a magnetic field of 2 tesla, the fission-tracked samples can carry currents of 85,000 amps per square centimeter at 77°K.

Still, Weinstein knows the lessons of high-temperature superconductors well and says applications may not emerge for years—if ever. In this game, involving materials that are brittle and intractable to start, anything can go wrong. "You have to worry about cracking, quenching, creep, and radioactivity," he says. "It's not a one-dimensional problem." After years of struggling with these balky materials, he adds, "I bet my life on nothing."

–Gary Taubes