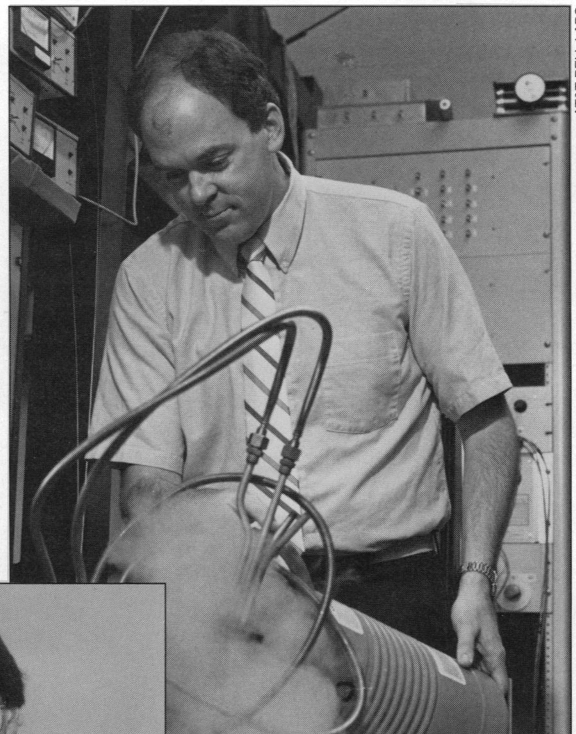
A Sea Change for the New Superconductors?

Restless magnetic field lines play havoc with superconductivity. But new work raises hopes that they can be tamed

WHEN THE DISCOVERY OF HIGH-TEMPERATURE superconductors hit the headlines 4 years ago, scientists and the public alike were enchanted by visions of resistance-free power transmission lines and ultrastrong electromagnets for everything from particle accelerators to floating trains. But such visions soon got a cold dose of reality: Researchers quickly discovered that when a high-temperature superconductor is exposed to a magnetic field, the field lines penetrating the conductor jiggle around due to thermal fluctuations, interfering with the superconductivity. As a result, a high-temperature superconducting magnet might literally turn itself off.

But a new theory, confirmed in a spate of recent experiments described in this issue of *Science* (page 165), suggests this problem may not be a show-stopper after all, at least for one major class of high-temperature superconductors—the yttrium-based compounds. The key is the surprising ability of magnetic field lines wandering within these materials to freeze suddenly as the temperature is lowered, much as water does, into a "glasslike" state that allows a resistance-free flow of current. The discovery of this "vortex glass" phase could speed efforts to convert superconductivity from lab curiosity to industrial and research workhorse—and perhaps even restore some of that early enthusiasm. "This is one of those rare, rich ideas that not only involve fundamental physics, but have important technological implications as well," says Stanford University superconductivity researcher Ted Geballe.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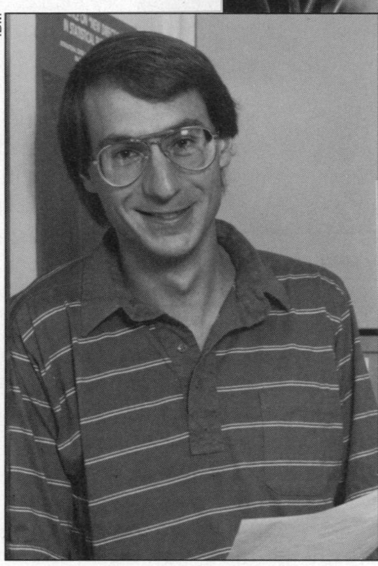
IBM

Experimenter and theorist. *David Bishop* (above) *and collaborators have amassed evidence for the "vortex glass" phase first predicted 2 years ago by Matthew Fisher.*

The magnetic flux problem should not have come as a complete surprise, for physicists have long known that magnetic fields can play havoc with the properties of conventional, low-temperature superconductors. In these materials, a field stronger than 100 kiloGauss—about 100 times the strength of a refrigerator magnet, and on the order of the strength of a conventional superconducting magnet—often prevents the material from slipping into a superconducting state as it is cooled. Researchers had hoped, however, that the new, high-temperature materials would preserve their superconducting abilities in much stronger fields, since they seemed to outdo earlier superconductors in retaining other properties under a broad range of conditions.

But to physicists' consternation, high-temperature superconductors proved even more susceptible to the effects of magnetic fields than their low-temperature brethren. In even moderate magnetic fields, they become painfully sluggish about losing their resistivity. "In fields of 100 kiloGauss some of these materials don't behave anything like a superconductor," says Harvard theorist Daniel Fisher. "Samples that are supposed to go superconducting at 80 degrees K don't even beat out copper until you bring them down to 20 degrees. And it wasn't clear that the resistance goes all the way down to zero at any temperature." That could pose a real problem because, says Fisher, "many of the large-scale applications you would be interested in doing with high-temperature superconductors involve these types of fields." Magnetic fields become a force to reckon with not just in electromagnets but in any conductor carrying a high current—a high-tension power line, for example.

Physicists thought they knew what was going on. According to conventional theory, magnetic field lines piercing any superconductor bundle together in tubes, or "vortices." At high temperatures, the vortices dance around as current flows through the material, dissipating energy and thus impairing conductivity. In low-temperature superconductors, the vortices can be tamed by lowering the temperature: Their cavorting becomes less energetic until individual vortices are "pinned" by higher-resistance impurities and faults in the superconductor. As a result, the material can make a sharp transition into a superconducting state.

In high-temperature superconductors, though, the unruly vortices aren't so easy to control. Because these materials have a layered structure, a vortex pinned in one layer may still be drifting freely in another. The result is a leisurely drop in resistance, spread out over a broad range of temperatures. Since superconductivity is usually marked by a dramatic plunge in resistance over an extremely narrow temperature range, researchers began to suspect that these materials could never become superconducting in the presence of a magnetic field.

But then came a theory that seemed to offer a way out. In 1989 Daniel Fisher's brother, IBM researcher Matthew Fisher (the Fishers are the Flying Wallendas of superconductivity—father Michael was an early contributor to the field), published a theory that described how the flux lines in yttrium-based materials interact with one another. At low enough temperatures, the theory suggested, the interactions can completely overcome the thermal jiggling of the lines, producing a sudden phase transition in which the flux lines freeze. The resulting "vortex glass"—so named because the vortices would be locked in random positions—might very well allow the material to act as a true superconductor.

The theory was far from an overnight sensation, however. For one thing, the model had some gaps that made it difficult to wring predictions from it. For another, some of the predictions it did make about how the materials' resistivity should change with changing temperature and magnetic field were at the limits of voltmeters' sensitivity at the time—though experiments by IBM researcher Roger Koch and collaborators provided a bit of support. "At first," recalls Harvard theorist David Nelson, "there was tremendous resistance to the whole idea."

Since then, theory and experiment have risen to the challenge. Daniel and Matthew Fisher and Bell Labs researcher David Huse carved out a more complete version of the vortex glass model, published last January in *Physical Review B*, that predicts in some detail how high-temperature superconductors' resistivity should vary with changing conditions. Meanwhile, AT&T Bell Laboratory researchers Peter Gammel, David Bishop, and collaborators carried out experiments with a new "picovoltmeter" that, they say, provides data six orders of magnitude more precise than before. Prediction and experimental result jibed nicely. "Now we can say for sure these materials become superconducting in a magnetic field at a finite temperature," says Bishop.

The discovery of the vortex glass state probably won't spark any immediate progress in applications. But at least now physicists know what they're dealing with. "Trying to understand how these materials behave in a magnetic field without knowing about the vortex glass phase transition would be like trying to understand silicon without asking whether it was a liquid, solid, or gas," says Bishop. Next physicists need to determine how well the vortex glass model applies to high-temperature superconductors other than the yttrium-based materials on which most of the work has been focused. "It's not completely clear yet that bismuth-based materials [another broad class of high-temperature superconductors] have this transition, though there is some evidence for it," notes Daniel Fisher. "We need to take a closer look at other materials, too."

But Bishop is confident the efforts will eventually pay off. One likely role for the new insight: guiding researchers who are attempting to tailor the locations and types of impurities and faults in samples—by bombarding them with neutrons or ions, for example—so as to hasten the onset of the vortex glass phase. "I couldn't say for sure that this work will result in a better wire 5 years from now," he notes. "But I have a religious belief that if you have a better understanding of the fundamental principles of these things, you can take advantage of it in engineering." ■ DAVID H. FREEDMAN

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Getting a Handle on Ras Activity

Take a walk around any cell, says protein chemist Henry Bourne of the University of California at San Francisco School of Medicine, and you will inevitably bump into a member of the large superfamily of proteins known as GTPases, which are enzymes that split guanosine triphosphate (GTP) into guanosine diphosphate and phosphate. The members of this family, which seems to grow larger almost every day, act as "on-off" switches in some aspect of almost every cellular activity. But just how those "on-off" signals are converted into changes in cell activities has remained mysterious for most of these proteins. Now comes Bourne with a new proposal about how at least one GTPase, a protein known as Ras, may transmit its signals to the cell interior.

Bourne himself describes his suggestion, which he presented last month at the annual meeting of the American Society for Cell Biology in Boston, as "very preliminary" and "highly speculative." But if it's right it will upset current notions of how Ras controls cellular activities.

How Ras exerts its effects is an especially urgent question. In its normal form, the protein is a key component of the pathways transmitting growth stimulatory signals into cells. If it's mutated, though, its GTPase gets stuck in the "on" position, leading to uncontrolled cell growth and paving the way for cancer development. But researchers haven't been able to figure out what comes next after the Ras GTPase is turned on, Bourne says.

The assumption is that active Ras binds to another cell protein, thereby transmitting the signal to it. But that protein, called an "effecter," hasn't been identified, and, Bourne explains, no one will really know how Ras works until it is. And that won't happen, he says, until biologists locate the precise site where Ras binds the effecter molecule. So the Ras puzzle has become a sort of molecular Catch-22. The effecter can't be identified until its binding site on Ras is known, and the binding site can't be pinned down until the effecter is located.

Although the effecter-binding site hasn't been pinpointed for sure, evidence from several labs suggests that it may be near the known binding site for a second protein that goes by the name GAP (for GTPase-activating protein), which is necessary for turning on the Ras GTPase activity. Indeed, the Ras effecter might even bind to the GAP protein, rather than to Ras itself. What Bourne is now proposing, however, is that the Ras effecter doesn't bind anywhere near GAP, but at the other end of the Ras molecule entirely.

To reach this conclusion, Bourne took advantage of some GTPase family resemblances. While the effecter-binding region of Ras is unknown, its three-dimensional structure has been solved in both the "on" and "off" positions. The exact opposite is true for another GTPase, called G_S. Its functional regions, including its effecter-binding site, have been identified, while its three-dimensional structure has not yet been solved. So Bourne and his colleagues lined up the structurally related regions of the proteins, in effect superimposing the three-dimensional image of Ras over the G_S sequence to find where on the Ras molecule its effecter region might be. This led them to a surprising conclusion: the effecter-binding site is on the "posterior" side of the molecule, near where Ras binds to the cell membrane and well away from the GAP-binding site, which is on the end of Ras that projects into the cell cytoplasm.

Since the effecter should be transmitting signals to the cell interior, that looks like the wrong site for effecter action. Still Bourne says, "I am willing to bet you that the true Ras effecter does not bind to the so-called effecter domain where GAP does bind." But while much of his proposal is "compatible with the data," he concedes that it's not necessarily the only conclusion to draw. Family members, after all, often behave in unpredictable ways. ■ MICHELLE HOFFMAN