Japanese Researchers Push Electron Holography

Rarely used in this country, the technique could become a powerful tool for high-temperature superconductivity studies

Tokyo

"WATCH!" SAYS AKIRA TONOMURA, the slight, gray-haired man who is chief researcher at the Hitachi Advanced Research Laboratory here. His finger traces snakelike black and white bands undulating on the dark screen of his modified electron microscope, a 3-meter steel tower he customized himself. The pattern looks a bit like 1960s psychedelic art. In fact it is the microscopic image of tiny threads of magnetic field, captured just as they arc outward into empty space from the surface of a superconducting metal—in this case, lead at 4 K. Theorists have long known that these field lines have to be there. But Tonomura is the first researcher ever to image them directly, thanks to a 20-year-old tool known as electron holography.

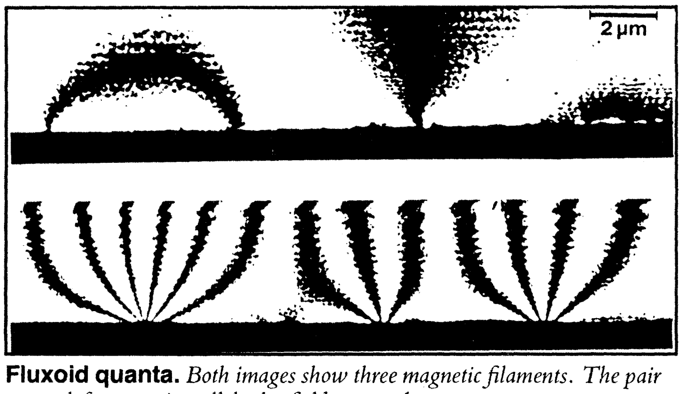
The significance is more than merely theoretical. Although electron holography is still largely unexplored in U.S. and European laboratories, Tonomura's innovative applications of it in such areas as microscopic magnetic field mapping and ultramicroscopic thickness measurements are beginning to draw the attention of researchers around the world. The technique is particularly intriguing for its potential in the study of high-temperature superconductors, where the behavior of these magnetic threads—"fluxoid quanta"—is thought to set fundamental limits on the materials' ability to *be* superconductors.

"What Tonomura's doing is pretty impressive," says Stephen Gregory, who studies superconductivity at the Bell Communications Research Laboratory in New Jersey. "It's essential work."

The Japanese government clearly thinks so. Tokyo recently announced a 5-year, $13.8-million program to develop the technique and apply it to a variety of problems in both physics and biology. Titled the Tonomura Electron Wavefront Project, it starts this month and will be administered by the Exploratory Research for Advanced Technology (ERATO) program, a government effort that teams young Japanese researchers from academia, industry, and government in multidisciplinary 2- to 5-year projects with their counterparts overseas.

Just as the electron microscope is a higher resolution version of the optical microscope, says Tonomura, electron holography is the high-resolution counterpart of laser holography. Indeed, the basic concept goes back to Dennis Gabor, whose invention of holography in 1947 won him the 1971 Nobel Prize.

Gabor recognized that you could theoretically take a beam of electrons and split it into two parts. You could then direct one beam at a specimen so that the electrons would be scattered, either as they passed through the sample or as they were were reflected from it. Next, you could recombine the scattered particles with those of the second beam, which had propagated unchanged. If the original beam was coherent—that is, if the electrons started out as well ordered and as organized as the photons of laser light—then the combined beams would produce a holographic image.



Akira Tonomura

Fluxoid quanta. *Both images show three magnetic filaments. The pair at top left are antiparallel: the field arcs and reenters.*

That was the theory, but the trick was to make that coherent beam. "[This] only became possible with the field-emission electron cathode developed by A. V. Crewe and his associates in 1968," says Tonomura. Otherwise, the technology required is pretty much that of the standard electron microscope—which makes Hitachi's interest a natural one: the company is a leading manufacturer of these instruments.

As one side effect of this technology, Tonomura can easily demonstrate the fundamental wave-particle duality of quantum mechanics. Once the beam is split he just brings it back together on a fluorescent screen. Each individual particle forms a dot—but the dots accumulate into a pattern of bands characteristic of interacting waves.

Of Tonomura's more practical results, meanwhile, his magnetic field imaging is easily the most intriguing. "The development of practical high-temperature superconductors has been delayed by difficulty in creating compounds which can handle high current, and which maintain their superconductive state in the presence of a strong external magnetic field," he says. And that difficulty traces right back to those thin, twisting fluxoid quanta.

Bellcore's Gregory has made a specialty of this problem. At high temperatures, he says, "fluxoid quanta are like spaghetti: They move about in the bowl." And when flux lines move in this way, they disrupt the current flowing through the material, destroying its ability to superconduct. "However, if you place several forks in the bowl at key places," he says, "you might be able to keep all the spaghetti from moving." In much the same way, the addition of certain impurities to the material can "pin" the fluxoid quanta and minimize the disruption.

Unfortunately, says Gregory, finding the right impurities to use has largely been a matter of trial and error, not least because there has been no good way to see what the fluxoid quanta were actually doing.

Enter electron holography. Tonamura's approach is to let the image beam of his device skim the surface of a superconductor. Anywhere a fluxoid quanta touches the surface, its magnetic field will jet out into space and deflect the electrons, thus producing an image.

Tonomura is the first to admit that his images are still snapshots, and not yet motion pictures. Nor, for that matter, has he worked directly with the high-temperature superconductors themselves. Nonetheless, the principle has been established, and Tonomura can see several ways in which further work could remove these limitations. Indeed, by using higher energy electron beams, he may even be able to image the filaments inside the material. That, in turn, should help researchers quickly evaluate new pinning substances, and thus determine whether a new compound is a good candidate for commercial viability.

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