Department of Physics & Astronomy

PHYSICS NEWS FLASH

Small Scale Superconductivity

UT Scientists Find a Powerful Phenomenon in a Quantum System

February 27, 2006

Researchers at The University of Tennessee and Oak Ridge National Laboratory have found that superconductivity can be exceptionally robust at the nanoscale, defying conventional wisdom and opening potential avenues for exploiting this powerful property in systems far too tiny to see with the human eye.

In the March issue of *Nature Physics*, UT Physics Professors Hanno Weitering and Jim Thompson, along with graduate student (and lead author) Murat Ozer, explain how they used quantum mechanics to confine wandering electrons in lead—a soft metal—and consequently stabilize superconductors that are only a few atoms thick.

Superconducting materials (like aluminum or lead) are those that completely lose their electrical resistance at very low temperature—electricity runs through them without friction. Properly harnessed, this phenomenon has tremendous potential. Strong electro-magnets could be the basis for high speed, levitating trains. Power grids would no longer suffer dissipative transmission losses. But while such large scale applications are technically feasible, they still require copious amounts of very expensive cryogenic refrigeration. What UT-ORNL scientists have discovered, however, is that superconductivity could possibly be applied at the nanoscale—systems less than 100 nanometers in size. (Consider that it takes roughly 26 million nanometers to equal one inch). Superconductive nanodevices, for example, could increase the flow of digital information by orders of magnitude and possibly even provide a platform for ultra-fast “quantum computers.”

As Dr. Weitering, who holds a joint UT/ORNL appointment says, “Superconductivity is arguably the most fascinating and useful characteristic a material can possess.”

Break dancing and superconducting coherence

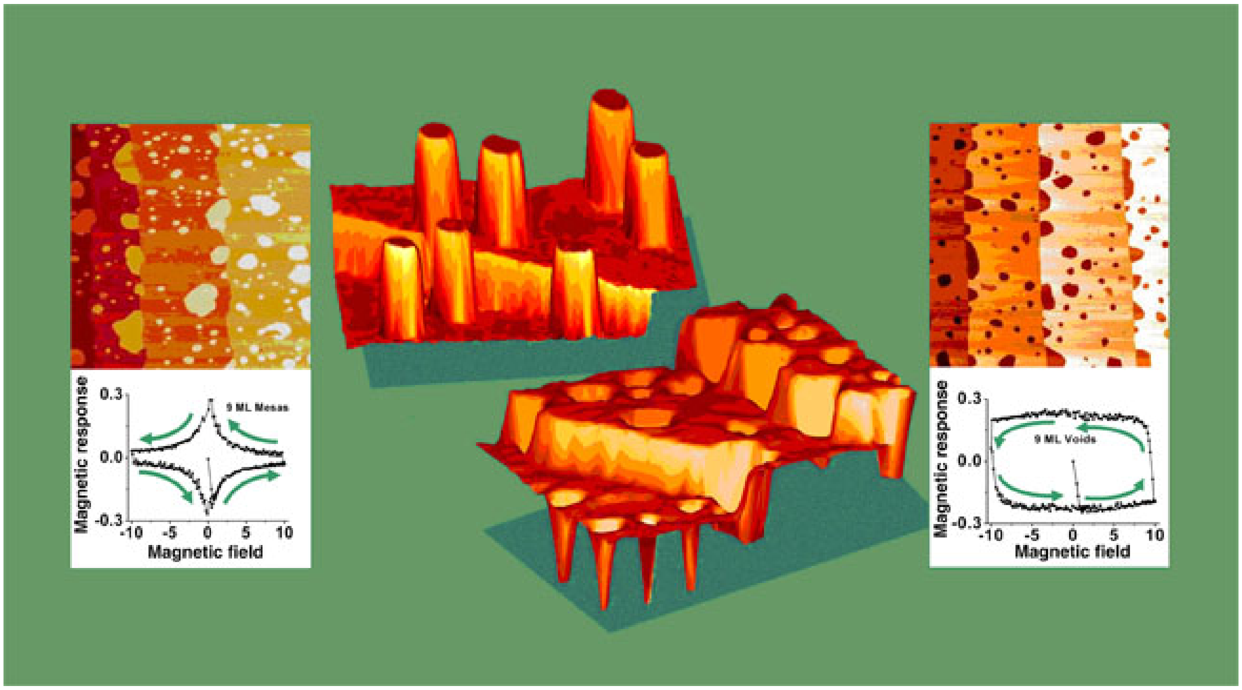
Unfortunately, when superconducting materials are made very small or thin, they lose their ability to “superconduct.” The culprit is entropy which, loosely speaking, refers to nature’s tendency to maximize disorder. In macroscopic superconductors—those visible to the human eye—paired electrons, or “Cooper pairs,” carry the supercurrents. Cooper pairs all have to “dance in step” to make this work, forming a macroscopic quantum mechanical wave. As the superconductor is reduced to the nanoscale, more and more Cooper pairs behave like disorganized “break dancers.” Hence coherence or superconducting order is destroyed and the material generally loses its ability to carry electrical currents without resistance.

The basis for this breakdown in order is the spontaneous generation of up- and downwardly directed magnetic field lines, also known as vortex-antivortex pairs. A vortex has a core, which is essentially a cylinder inside which superconductivity is strongly suppressed. Like a microscopic tornado, the core is surrounded by whirling supercurrents that generate the magnetic field. Vortices and superconductivity coexist in this so-called “mixed state.” The root cause of power dissipation, however, lies in how the vortices move. Superconductors can only maintain their ability to carry large scale, macroscopic supercurrents as long as these vortices remain firmly locked in place.

In the *Nature Physics* article, Tennessee researchers describe how exploiting quantum mechanics can help immobilize these vortices at the nanoscale, resulting in very stable, incredibly small superconductors. The extraordinary morphological stability of these soft quantum films, which is reminiscent of the stability of closed electron shell configuration of the noble gases, was first noticed about six years ago.

Hard supercurrents

Surprisingly, these extremely thin superconductors show no sign of fluctuation-driven suppression of superconductivity. In fact, they actually sustain supercurrents of up to 10 percent of the theoretical limit where superconductivity must break down. For instance, a film that is only nine atom layers thick can sustain amazingly large circulating supercurrents of about 100 milli amperes in a 3 millimeter square film; this corresponds to a supercurrent density of about 2 million amperes per cm2. These currents were measured by sensing the magnetic fields they generate (since all magnetic effects are due to charges in motion). In a typical experiment, one varies both the magnitude and orientation of the applied magnetic field. The measured magnetic signal is proportional to the magnitude of the induced supercurrent circulating along the sample's perimeter. A typical measurement result is shown in the left and right panels of the figure below:



Arrows indicate the direction of the field sweep. The magnetic signal depends strongly on the magnetic history of the sample, revealing magnetic '"hysteresis." In particular, the rectangular loop shown in the right panel implies extreme hysteresis, or "hardness." This tells us that the vortices are strongly pinned.

Quantum phase separation

The magnetic hardness of the critical state is attributed to quantum trapping of vortices. The quantum traps are actually physical depressions inside the films, made visible by a scanning tunneling microscope (see figure). The depressions are exactly two atom layers deep. They are caused by quantum mechanical phase separation in slightly underdosed lead films, resulting in strongly preferred layer thicknesses. (Phase separation is a well-known thermodynamic phenomenon, which is also responsible for familiar phenomena like the separation of phases in a mixture of oil and water.) For the same reasons, overdosed films exhibit two atom-layer tall mesas. These contrasting morphologies, whose origins are thus purely quantum mechanical, are shown in the middle panel of the figure. The vertical height is strongly exaggerated for clarity. Plan view images of the overdosed and underdosed films are shown on the left and right, respectively.

Quantum trapped vortices

Because the large flat area of the underdosed film is only nine atomic layers thick, magnetic flux lines or superconducting "vortices" can significantly reduce their vortex line-energy by positioning themselves inside these nanoscale depressions or voids. This is a very efficient trapping mechanism for the vortices and produces a hard magnetization loop, shown on the right. This, in turn, implies robust or hard superconductivity. In contrast, films that are intentionally overexposed produce a soft magnetization loop, indicating weak pinning (left). In other words, nano-voids attract and pin vortices, whereas nano-mesas repel vortices. Generally speaking, thickness variations in thin film nanostructures are atomically discrete and are of the same order of magnitude as the overall size or thickness. Therefore, strong vortex pinning may be observable in many nanostructures whose size can be controlled with atomic precision, as is the case here. An additional beauty of this work is that the vortex pinning energy can be accurately calculated from the known geometry of the nano-voids. The present study thus paints a conceptually appealing, elegant picture of a model nano-scale superconductor with nicely calculable critical state properties. It furthermore indicates the intriguing possibility of achieving and exploiting superconductivity in the ultimate low-dimensional limit, including precisely engineered quantum structures.

Ali Yazdani reviews this work in his article entitled "Lean and Mean Superconductivity" in the News and Views section of Nature Physics (subscription required).