Breakthrough in Nanoscale Imaging: IBM Scientists Directly Detected the Faint Magnetic Signal from a Single Electron

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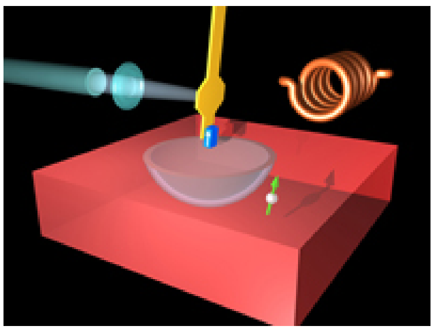

IBM scientists have achieved a breakthrough in nanoscale magnetic resonance imaging (MRI) by directly detecting the faint magnetic signal from a single electron buried inside a solid sample. This achievement is a major milestone toward creating a microscope that can make three-dimensional images of molecules with atomic resolution. Success in this quest should have major impact on the study of materials -- ranging from proteins and pharmaceuticals to integrated circuits and industrial catalysts -- for which a detailed understanding of the atomic structure is essential. Knowing the exact location of specific atoms within tiny nanoelectronic structures, for example, would enhance designers' insight into their manufacture and performance. The ability to directly image the detailed atomic structure of proteins would aid the development of new drugs.

"Throughout history, the ability to see matter more clearly has always enabled important new discoveries and insights," says Daniel Rugar, manager of nanoscale studies at IBM's Almaden Research Center in San Jose, California. "This new capability should ultimately lead to fundamental advancements in nanotechnology and biology."

Rugar leads the team of scientists who for more than a decade have been making pioneering advancements in the nanoscale MRI method called magnetic resonance force microscopy (MRFM). His team has improved MRI sensitivity by some 10 million times compared to the medical MRI devices used to visualize organs in the human body. The improved sensitivity extends MRI into the nanometer realm. (A nanometer is a billionth of a meter, the length spanned by about 5-10 atoms.)

IBM Research has a distinguished history in developing microscopes for nanoscale imaging and science. Gerd Binnig and Heinrich Rohrer of IBM's Zurich Research Laboratory received the 1986 Nobel Prize in Physics for their invention of the scanning tunneling microscope, which can image individual atoms on electrically conducting surfaces. Binnig later invented the atomic force microscope (AFM), which used the attraction between a cantilever and surface features on non-conducting surfaces. Scientists at IBM and elsewhere modified and extended the AFM design to image surface forces such as magnetism, friction and electrostatic attraction with nanometer resolution. MRFM combines concepts from both AFM and MRI to allow nanometer resolution of features up to 100 nanometers deep inside a sample.

The IBM team of Rugar, John Mamin, Raffi Budakian and Benjamain Chui published its single-electron results in the July 15 issue of the scientific journal Nature. This research is funded in part by the Defense Advanced Research Projects Agency.

Technical details
The central feature of an MRFM is a microscopic silicon "microcantilever" that looks like a miniature diving board 1,000 times thinner than a human hair. It vibrates at a frequency of about 5,000 times a second, and attached to the cantilever tip is a tiny but powerful magnetic particle.

Isolated ("unpaired") electrons and many atomic nuclei behave like tiny bar magnets. These fundamental units of magnetism are often called "spins." Just as two bar magnets can attract or repel each another, the MRFM's magnetic tip is attracted or repelled by the spins in the sample. By tuning an oscillating high-frequency magnetic field to the natural precession frequency of the spin being imaged, its magnetic orientation flips back and forth as the cantilever vibrates. Although the magnetic force between the magnetic tip and the spin is exceedingly small (less than a millionth of a trillionth of a pound), the cantilever is so sensitive that the flipping of the spin causes a detectable change in the cantilever's vibration frequency.

While medical MRI looks at groups of at least 1 trillion proton spins, the IBM researchers have just detected the much fainter signal of a single electron spin. The researchers also demonstrated rudimentary (one-dimensional) imaging with 25-nanometer resolution, about 40 times better than the best conventional MRI-based microscopes.

Rugar's future research is aimed at further improving the sensitivity, resolution and speed of the MRFM technique so it can detect single protons and other nuclei, such as carbon-13, that can be used to reveal molecular structures. (The magnetic signal of a single electron is about 600 times stronger than that of a single proton.)

Applying MRFM to protein structures would be particularly far-reaching. The biological activity of a large protein molecule is determined by its intricately folded atomic configuration. But since such a structure is currently impossible to determine directly, scientists must use indirect methods such as the scattering of x-rays by crystallized proteins, or computer simulations. Advanced MRFMs may also be able to serve as detectors of quantum information in future spin-based quantum computers.

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