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Ultra-cold gas makes great magnetometer

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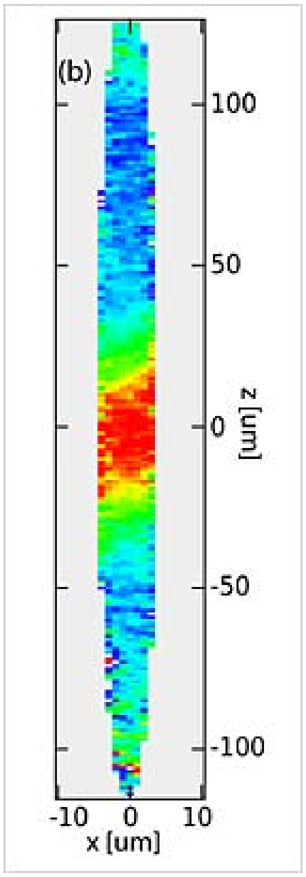
Capturing the coldest atoms in the universe within the confines of a laser beam, University of California, Berkeley, physicists have made a device that can map magnetic fields more precisely than ever before.

Doctors now use sensitive magnetic field detectors called SQUIDS to record faint magnetic activity in the brain, while similar detectors are employed in fields ranging from geology to semiconductor manufacturing. One advantage of the new device, which is based on ultra-cold Bose Einstein condensates (BECs), is that it can measure low-frequency fields, such as slow brain waves, at a very high resolution and with very high sensitivity.



This photo of a Bose-Einstein condensate, only half a millimeter long and 10 microns wide, reveals minute variations in magnetic field across the sample. The ultra-cold gas of rubidium atoms can detect variations in magnetic field as small as one picoTesla, which is 50 million times smaller than Earth's magnetic field. (Stamper-Kurn lab/UC Berkeley)

"This is not a bulk sensor for magnetic fields, but a precision magnetometer that can measure the magnetic field over small length scales, on the order of microns - a thousand times smaller than a millimeter - with a field sensitivity which is comparable to or better than modern scanning-SQUID microscopes," said Dan Stamper-Kurn, UC Berkeley associate professor of physics and faculty scientist at Lawrence Berkeley National Laboratory.

Stamper-Kurn and his colleagues, including postdoctoral researcher Mukund Vengalattore and former graduate student, now post-doc, James M. Higbie, report their results in the May 18 issue of the journal *Physical Review Letters*.

The researchers created their device by cooling a gas of rubidium atoms (rubidium-87) to a mere 50 nanoKelvin - 50 billionths of a degree above absolute zero - to create a so-called spinor Bose-Einstein condensate. This is a quantum fluid that manifests both frictionless flow, making it a superfluid, and also magnetization, as a ferromagnet. By taking repeated pictures of the gas and exploiting its magnetic properties, they were able to detect, within a quarter-second measurement time, magnetic fields as small as 1 picoTesla, 50 million times weaker than the Earth's magnetic field of 50 microTesla.

What truly distinguishes this magnetic microscope, according to Stamper-Kurn, is not the smallness of the detected field, but rather the smallness of the spatial region in which this field was detected: an area only 10 microns by 10 micron, a millionth the area of a postage stamp.

For comparison, in mapping magnetic fields at similar spatial resolution, current devices such as SQUIDs (superconducting quantum interference devices) have, to date, reached sensitivities of only about 30 picoTesla over a one-second measurement time. At present, the BEC magnetometer matches, or even slightly improves upon, the theoretical limits to the sensitivity of a SQUID-based magnetic microscope, and further improvements beyond this limit appear possible, Stamper-Kurn said. He predicts that, as the size and complexity of BEC-producing machines is reduced, BEC magnetometers could replace SQUID magnetometers in many applications, perhaps even for brain wave measurements, providing higher sensitivity at low frequencies and better spatial resolution.

Stamper-Kurn's laboratory focuses on studies and applications of BECs, which are gases so cold that all the atoms collapse into the same quantum state, becoming essentially indistinguishable from one another. Stamper-Kurn was a member of the Massachusetts Institute of Technology team that was among the first to create these supercold systems in 1995, a feat for which his advisor, physicist Wolfgang Ketterle, shared the 2001 Nobel Prize.

Though the first condensates were confined by magnetic fields to keep them from touching the walls of a container and heating up, Stamper-Kurn creates his within an "optical trap," essentially a low-power laser beam. He and his colleagues discovered that using an optical trap rather than a magnetic trap enabled the trapped atoms to respond to very minute magnetic fields. This is possible because, in a magnetic field, the spins of the atoms in a cold optical trap precess, just like the axis of a spinning top, at a frequency determined by the strength of the surrounding magnetic field.

A key element in the researchers' magnetometer is a method they developed for taking snapshot images of the orientation of the spin of the ultra-cold trapped gas. By taking a rapid-fire sequence of such snapshots, the team can record a movie of the spin of the atoms precessing, and then calculate the strength of the magnetic field from the rate of this precession. The point of using a BEC for such sensing is that the atoms in this quantum gas hardly move at all. Atoms at different locations can then be counted upon to sense only the magnetic field at their locale.

This feature provides the magnetic sensor with its impressive spatial resolution. Though some hot-gas systems, such as spin-polarized atomic gases, can be used to measure magnetic fields smaller than those measured using ultra-cold gases, their spatial sensitivity is worse because the hot gases diffuse quickly throughout the centimeter-sized devices.

The laser-trapped BEC cloud is about one-half millimeter long and 10 microns across - about 10 percent the width of a human hair. One run of the magnetic sensor provides a map of the magnetic field across this entire area simultaneously.

"With the BEC's strengths - its stability, its long coherence times, the fact that collisions don't shift the precession frequency - we have all the ingredients we need for a high spatial resolution magnetometer," said Vengalattore.

"The fact that we can take a single picture showing how all the atomic 'compass needles' have been rotated by the local magnetic field is ideal for getting the precise information we need at once, without having to scan slowly over a surface," added Higbie.

"This finally delivers on the promise of using Bose-Einstein condensed atoms for precision measurement," said Stamper-Kurn.

Vengalattore admits that, for the foreseeable future, the magnetometer will be most useful in probing the magnetic properties of small physical systems like those under study in Stamper-Kurn's laboratory. Currently, the group is using this technique of imaging the spin of the atoms to study quantum phase transitions in a BEC. Just as water undergoes a thermal phase transition when the temperature rises, changing from ice to liquid, quantum systems undergo quantum phase transitions as conditions such as pressure and magnetic field change.

The researchers aim to probe such quantum phase transitions using ultra-cold gases confined in a periodic potential called an optical lattice. By studying the magnetic properties of such model systems, they hope to better understand the behavior of more complex magnetic materials.

Source: UC Berkeley

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