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Physicist Observe Quantum Magnetism in an Optical Lattice

Cambridge MA, Physicists at Harvard University in Cambridge Massachusetts have succeeded in coaxing ultracold atoms trapped in an optical lattice to self-organize into a magnet, using only the minute perturbations resulting from quantum mechanics. The research, published this week in the journal Nature, is the first demonstration of such a "quantum magnet" in an optical lattice, opening new possibilities for quantum engineering of novel materials like high temperature superconductors.

As modern technology depends more and more upon materials with exotic quantum mechanical properties, we are approaching a stumbling block. "The problem is that what makes these materials useful often makes them extremely difficult to design," explains senior author Markus Greiner, associate professor of physics at Harvard. "They can become entangled, existing in multiple states at the same time. This hallmark of quantum mechanics is difficult for normal computers to represent, so we had to take another approach."

That approach is a so-called "quantum simulator", in which the properties of a quantum material are simulated with an artificial quantum system that can behave similarly, but which is easier to manipulate and observe.

The physicists found that when they applied a force to a crystal formed by ultracold atoms trapped in an optical lattice (a Mott insulator), the atoms behaved like a chain of little magnets that repelled one another, in the presence of an external magnetic field which sought to align them.

"When the external magnetic field was strong, all of the magnets aligned to it, forming a paramagnet," says co-author Jonathan Simon, a postdoctoral fellow in Harvard's Department of Physics. "When we reduced the magnetic field, the magnets spontaneously anti-aligned to their neighbors, producing an antiferromagnet."

While such self-organization is common in everyday materials, it typically depends upon temperature to jostle the system into the new order, like shaking a boggle game to help the dice settle. "But the temperature was so low that thermal fluctuations were absent," explains Simon. "Our fluctuations arose from quantum mechanics."

When quantum mechanics takes over, things get bizarre. "Quantum fluctuations can make the magnets point in multiple directions simultaneously," Greiner says. "This 'quantum weirdness' gives rise to many of the fascinating properties of quantum magnets."

Greiner and his colleagues used their quantum gas microscope to observe individual magnets at temperatures of one billionth of a degree above absolute zero (-273 Celsius). They were able to watch as quantum fluctuations flipped the magnets around, turning a paramagnet into an antiferromagnet and back again.

"Observing quantum magnetism in a cold gas is a crucial first step towards quantum simulation of real magnetic materials," Greiner exclaims. "There remain many exciting questions to answer, and we have only just scratched the surface. By studying the bizarre and wonderful ways that quantum mechanics works, we open new perspectives not only for developing novel high tech materials, but also for quantum information processing and computation."

Greiner and Simon's co-authors in Harvard's Department of Physics are Waseem Bakr, Ruichao Ma, Eric Tai, and Philipp Preiss. Their work was supported by the Army Research Office through the DARPA OLE program, the AFOSR MURI program, and by grants from the NSF.