

Pan is particularly keen to probe interactions between quantum mechanics and gravity. “We’ve established a quantum optics laboratory with an effective lab space of a million square kilometers,” he says. “We can experiment at distances and velocities that were inaccessible on the ground.”

Ashley G. Smart

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Quantum gases cooled to long-range antiferromagnetic order

The observation of a checkerboard pattern in a lattice of ultracold atoms is a sign of even more exciting experiments to come.

In the spring of 1986, Georg Bednorz and Alex Müller of IBM Zürich Research Laboratory discovered that a certain copper oxide ceramic became a superconductor at a temperature T_c of 30 K, some 10 K higher than any previously studied material. The finding was immediately recognized as a game changer: It won the pair a Nobel Prize the very next year (see *PHYSICS TODAY*, December 1987, page 17) and launched a frenzied new research field that quickly turned up other families of cuprates with critical temperatures well above 100 K.

Thirty years later, despite intense theoretical and experimental study, high- T_c superconductivity remains largely mysterious. It’s known that the superconductivity occurs in particular lattice planes and depends sensitively on the charge-carrier density, or doping, which can be controlled by tweaking the material composition. Still unknown are the mechanism by which electrons pair up to condense into a superfluid, why the normally insulating ceramics become superconducting at all, and how best to search for new superconductors with even higher T_c , possibly as high as room temperature.

New insights may be on their way from an unlikely source. Cold-atom researchers are hoping to capture the physics of high- T_c superconductors by mimicking the electrons with neutral atoms in an array of optical traps. If they succeed, they’ll be able to study the inner

workings of the superconducting and related phases in a way that’s otherwise inaccessible to either theory or experiment. Trapped atoms can be interrogated and manipulated one by one. Electrons in a solid can’t.

In realizing that hope, the main challenge is temperature. Though at just tens of nanokelvin they are ultracold by any absolute standards, state-of-the-art atomic experiments act like solids with temperatures of hundreds of kelvin, far from the most enticing parts of the cuprate phase diagram. Now Harvard University’s Markus Greiner and colleagues have taken a step into uncharted territory.¹ They’ve cooled their system of lithium-6 atoms far enough to see antiferromagnetic order—the checkerboard pattern in figure 1—across their entire 80-site two-dimensional lattice. “Interesting states like high- T_c superconductivity are often found in the vicinity of antiferromagnetism,” says Greiner. So although the experiments haven’t turned up any new physics just yet, it may not be long before they do.

Theory follows experiment

Although seemingly unrelated, solid-state and cold-atom systems are connected by the Hubbard model, which was proposed in 1963 as a stripped-down theoretical description of the electrons in a solid. (John Hubbard himself died in 1980, so he never had the chance to consider the model’s applicability to

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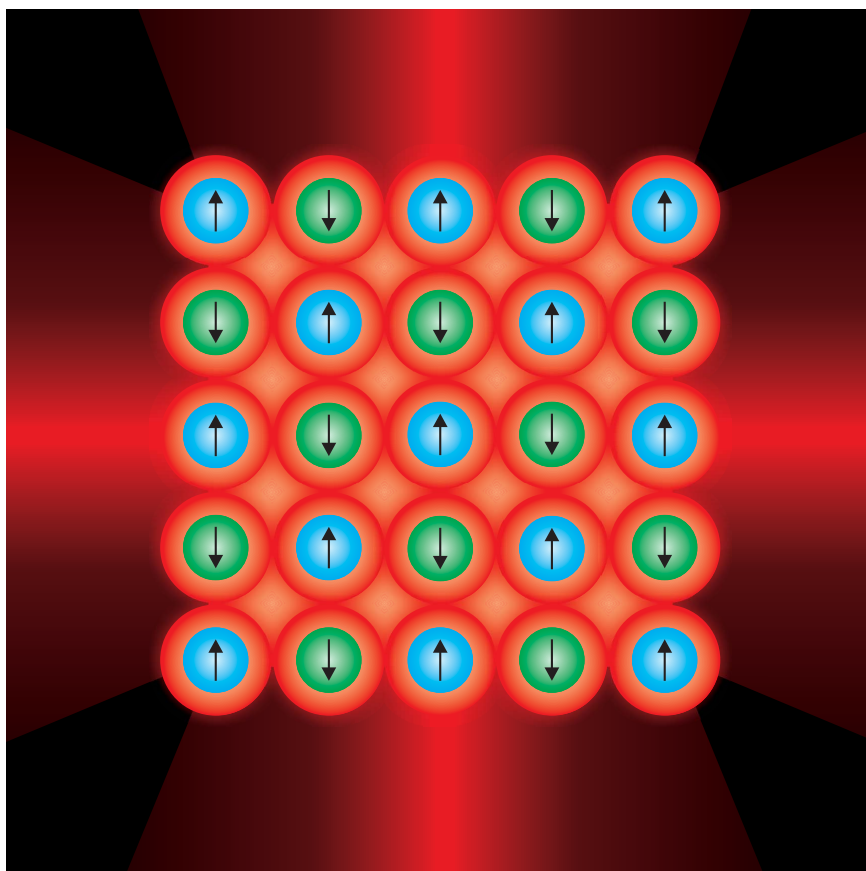


FIGURE 1. ANTIFERROMAGNETIC ORDER in a two-dimensional lattice of optical traps. At low enough temperatures, trapped atoms (blue and green for different spin states) arrange themselves into a checkerboard pattern—even though atoms on different lattice sites don't directly interact.

high- T_c superconductivity; that association came later.)

The model is deceptively easy to state. Quantum particles, whether fermions or bosons, sit on the nodes of the discrete lattice. They can hop from node to node with kinetic energy t , and two particles on the same node have an interaction energy U , which can be positive or negative to represent repulsive or attractive interactions. Particles on different nodes don't interact at all, and if the particles are endowed with spin, their spin states cannot change. When the particles are spin- $\frac{1}{2}$ fermions and U is both positive and much greater than t , the solution to the Hubbard model is thought to have all the same phases as a high- T_c superconductor when the doping (essentially the difference between the number of nodes and the number of particles) and the temperature are varied. Figure 2 shows the predicted phase diagram for a hole-doped system.

Despite the simplicity of its Hamiltonian, the Fermi-Hubbard model is nearly impossible to solve, even numerically, for all but the simplest cases. The difficulty stems from the so-called sign problem: Because swapping any two fermions changes the sign of the overall wavefunction, the multidimensional integrals involved in solving the model each have a lot of positive and negative components that fall just short of canceling out. An accurate numerical evaluation of such an integral requires extremely dense sampling of its domain, so the computational effort to solve the model increases exponentially with the number of particles.

At zero doping, the sign problem goes away, so theorists have a good handle on how the model behaves there. When the temperature is higher than the interaction energy U , particles move freely around the lattice, despite the energy penalty of doubly occupied nodes.

At temperatures below U , they freeze into a so-called Mott insulating state, with one particle immobilized on each node. So far, that behavior is consistent with classical intuition: When particles lack the energy to share a node, they don't.

But at lower temperatures still—on the order of $4t^2/U$ —the system's quantum nature takes center stage as the particles enter a state of antiferromagnetic order. In conventional models of magnetism, such as the Ising and Heisenberg models, ordered states arise because the models explicitly include an interaction between spins and their neighbors. But in the Hubbard model, particles interact only when they occupy the same node—and in the Mott insulating state, they never occupy the same node. So how do they know how to order?

The answer lies in virtual exchange. Even when two neighboring particles don't have enough energy to overcome their mutual repulsion and move to the same node, one can virtually tunnel to the other node, and the two can end up either swapping places or returning to their starting points. The possibility of exchange lowers the total energy of the two-particle state—but only if the particles have different spins. If they have the same spin, the Pauli exclusion principle forbids them from ever occupying the same node, even virtually. As a result, particles have an energetic preference to surround themselves with those of opposite spin, and antiferromagnetic order spreads across the lattice.

Away from zero doping, the sign problem forestalls the same level of certainty. Theorists have developed approximate methods that they can use to make predictions, including that the Fermi-Hubbard phase diagram should be similar to a high- T_c superconductor's. But without any computational or experimental benchmarks, the validity of those approximations and predictions is an open question.

Experiment follows theory

Cold-atom experiments, designed to mimic not the high- T_c superconductor but the Fermi-Hubbard approximation of it, could provide that benchmark. The model's lattice becomes an array of optical traps with spacing of about 500 nm, which can be created by the interference pattern of pairs of counterpropagating

lasers. Fermionic atoms prepared in different hyperfine states play the part of model particles of different spin: Neighboring atoms in different states can undergo virtual exchange, but ones in the same state cannot.

The Mott insulating phase of cold fermionic atoms was first observed in 2008 by Tilman Esslinger and colleagues at ETH Zürich in Switzerland and by Immanuel Bloch and colleagues at the Max Planck Institute of Quantum Optics in Garching, Germany.² Short-range antiferromagnetic correlations—extending only over a lattice site or two—were observed in 2013 by Esslinger’s group and in early 2015 by Randall Hulet’s group at Rice University.³

Those results were all based on indirect measurements of the atomic system. Esslinger and colleagues used a multistep process to determine whether nearest-neighbor pairs of atoms formed spin singlets (which must have antiparallel spin) or triplets (which can be parallel). Hulet and colleagues used Bragg scattering to deduce the ordering of their sample.

An appealing alternative would be to image the lattice with single-site resolution—as Richard Feynman put it, to “just

look at the thing.” Indeed, quantum gas microscopes with just that capability have been around since 2010, developed by Bloch and Stefan Kuhr in Garching and by Greiner’s group at Harvard. The microscopes probe the occupancy of each lattice site by looking for atomic fluorescence. (See *PHYSICS TODAY*, October 2010, page 18.)

But those microscopes worked only for rubidium-87. Atoms in the microscope must be laser cooled at the same time as they’re trapped and imaged, or else the energy imparted to them by the imaging laser would knock them out of the trap. Thanks to its high mass and exceptionally well resolved hyperfine structure, ⁸⁷Rb is one of the easiest atomic species to cool, even as it’s cycled between its ground and excited states for fluorescence imaging. But not only is ⁸⁷Rb a boson—Rb doesn’t even have any stable fermionic isotopes.

The only naturally occurring fermionic isotopes of alkali atoms are lithium-6 and potassium-40, and they both have their difficulties. The low mass of ⁶Li makes it hard to trap, and the densely tangled hyperfine states of ⁴⁰K make it hard to cool. Those challenges were overcome in 2015

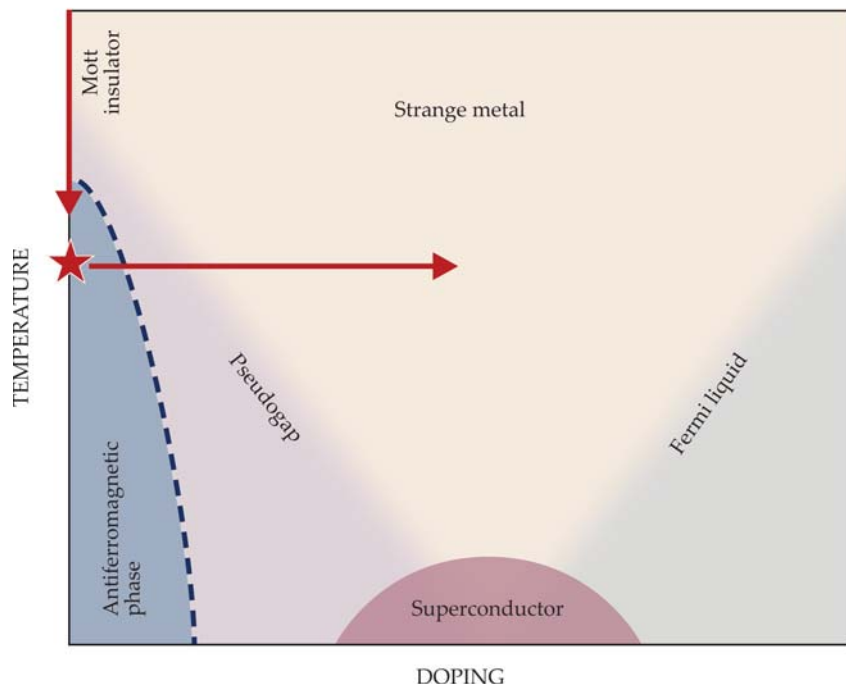


FIGURE 2. PREDICTED PHASE DIAGRAM of the hole-doped Fermi-Hubbard model. New experiments by Markus Greiner and colleagues follow the path shown by the red arrows: Lowering the temperature at zero doping brings the system into a state (starred) of long-range antiferromagnetic order, and doping the system at low temperature destroys that order. (Adapted from ref. 1.)

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when five groups independently developed fermionic quantum gas microscopes.⁴ Greiner's and Bloch's groups worked with ^6Li , and Kuhr's (now at the University of Strathclyde in the UK), Martin Zwierlein's (MIT), and Joseph Thywissen's (University of Toronto) used ^{40}K .

With microscopes built, reaching the antiferromagnetic regime was primarily a matter of trying different techniques to push the system to ever lower temperatures. Greiner and colleagues found success with a scheme that had been proposed in 2009 by theorists Jason Ho and Qi Zhou.⁵ They engineered their optical potential so that the core of the system was surrounded by an even more dilute gas. Adiabatic expansion of the outer gas pulled the most energetic atoms out of the central core and lowered the core entropy.

To detect the antiferromagnetic state, Greiner and colleagues used a laser to dislodge all the atoms of one spin state. Then they imaged the atoms that remained. Figure 3 shows raw and processed images of their lattice, with and without the spin removal. "With the microscope, we

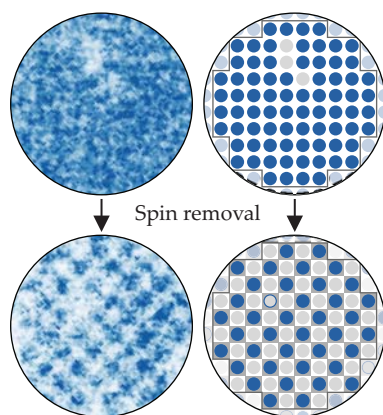


FIGURE 3. QUANTUM GAS MICROSCOPE IMAGES of an antiferromagnetic state. The images on the left show the raw, spatially resolved atomic fluorescence, both before (top) and after (bottom) the atoms in one of the two spin states are removed. The images on the right show the corresponding lattice occupancy. (Adapted from ref. 1.)

don't have any complicated signals to interpret," says Greiner. "We just see a checkerboard."

The microscope also comes in handy for studying the regime of nonzero doping by making it possible to engineer

the potential landscape so that the gas loaded into the lattice has a known homogeneous density. The Harvard researchers found that when they doped their system with holes, the antiferromagnetic order went away, just as the phase diagram in figure 2 suggests that it should.

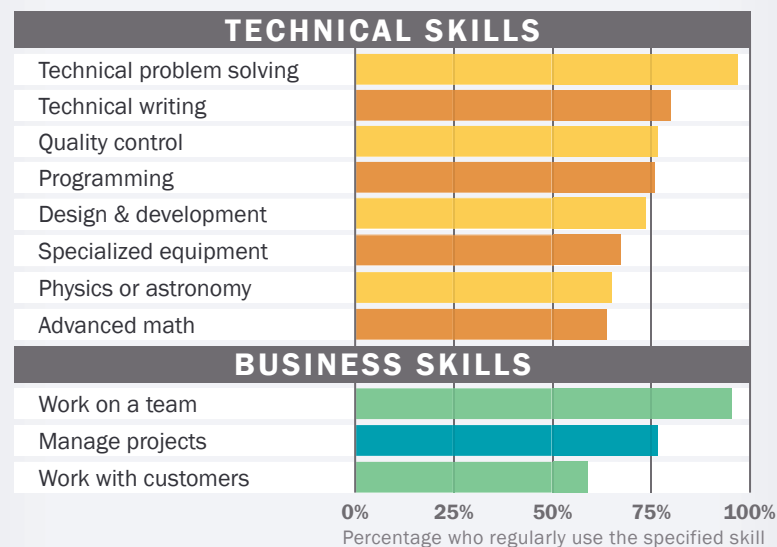
Further exploring the phase diagram will require cooling the lattice to even lower temperatures, which is an outstanding challenge. If it can be met, experiments will show whether the Fermi-Hubbard model really does support a superconducting phase—or perhaps some other equally exotic strongly coupled phase—and they'll be able to probe it at the single-particle level.

But there's also rich physics to be found in the parts of the phase diagram that are accessible now. The pseudogap phase, in which there's a gap in the energy spectrum of charge-carrier states in some directions but not others, is especially tantalizing because of the possible relationship between the mechanism that gives rise to the pseudogap and the mechanism of superconductivity. (See PHYSICS TODAY, August 2013, page 12.)

Even the antiferromagnetic phase itself is interesting, and Greiner and colleagues are eager to explore its transport properties and nonequilibrium dynamics. "With the microscope, we can create a hole at a particular location," says Greiner, "and we can watch where it goes." Intuitively, a single hole can't move around the lattice without disrupting the antiferromagnetic order—but a pair of holes moving in tandem can. "Is the correlated motion of two holes related to the mechanisms of Cooper pairing?" asks Greiner. "That's pretty much impossible to calculate."

Johanna Miller

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