over Greenland. Much of the vast island has been mapped with radar, including the sites of several ice cores.

To analyze these data, Fahnestock and Waleed Abdalati of NASA headquarters have developed a sophisticated computer program that matches the radar-observed reflection layers at one of the ice core sites with the time-tagged layers in the core itself. Thus calibrated, reflection layers, which rise and fall depending on the local snow accumulation rate and other factors, can be followed away from the core along the flight paths. The result is a direct measurement along each flight path of what glaciologists call an age–depth relation, a key probe of ice models.

Modeling the flow of ice is challenging. Glacial ice is a non-Newtonian fluid. The harder you push it, the softer it gets. Moreover, its properties depend not only on its current temperature, but on its thermal history. The Greenland ice sheet still "remembers" the colder temperatures from the last Ice Age.

Despite these complications, elementary models have been successful at capturing basic ice-sheet rheology. In the simplest model, devised in the 1950s by John Nye, accumulation is balanced by horizontal flows that thin the ice in such a way that vertical strain is constant with depth and the sliding occurs only at the bed. In Greenland, where most of the ice is stuck to the bed, Willi Dansgaard and Sigfus Johnsen found they had to modify the Nye model. Their 1969 revision incorporates a shearing zone just above the bed where the vertical strain rises from zero to a constant.

Dansgaard and Johnsen's model yields the age of a layer in terms of the annual accumulation rate, the height above the bed, and the thickness of the sheet and the shearing layer. Having already measured the age–depth relation, Fahnestock and company inverted the model to derive the thickness of the shear layer. This technique gives sensible values for the shearing layer thickness along most of the radar tracks, but not everywhere. At certain locations, layers appear to collapse toward the bed, as if the underlying layers had been knocked from under them. Applying the Dansgaard–Johnsen model to the disturbed layers yields negative values for the shearing layer thickness.

To account for the disturbed layers, Fahnestock made a simple adjustment to the model. He replaced the shearing layer with a term that removes ice at a constant rate from the bed, presumably by melting. As a result, the amount of thinning that horizontal flows would have to produce for a given ice load is reduced. This simple model fits the data from the disturbed layers well and, as the figure on page 17 shows, can be used to map the basal melting rate along the radar tracks.

Comparing the basal melt map with the disposition of the northeast Greenland ice stream proved especially revealing. Ian Joughin of NASA's Jet Propulsion Laboratory, another of Fahnestock's collaborators, had mapped the ice stream using space-based radar interferometry. As the figure shows, the head of the ice stream coincides with an area of intense basal melting—strongly suggesting that meltwater loosens the ice's hold on the bedrock and sets the stream in motion.

Over the volcano

According to the radar data, a layer tens of centimeters thick turns to water each year beneath the ice stream. Melting that much ice requires nearly a watt per square meter of thermal power—20 times more than what Greenland's ancient bedrock typically puts out. Only an unusually concentrated heat source, such as a volcano or some other magmatic structure, can do the job.

Does a volcano lurk under the ice? Indirect evidence suggests the answer is yes. John Brozena of the Naval Research Laboratory, another of Fahnestock's collaborators, has surveyed the gravitational and magnetic fields in the ice-stream region. Close to the region of rapid basal melting, there appears to be a structure whose gravitational signature is reminiscent of the huge caldera in Yellowstone National Park. And not far away is an area of stronger than normal magnetization of the sort expected when magmatic rock cools and crystallizes.

If confirmed, the Greenland caldera won't be the first volcano implicated in basal melting. In 1993, a team led by Don Blankenship of the University of Texas at Austin uncovered evidence of a volcano under the West Antarctic Ice Sheet, close to the source of one of the ice streams that feed the Ross Ice Shelf. Water is certainly necessary for ice streaming to occur, but in West Antarctica, where the snow pack lacks easy-to-measure layering, it's unclear how much meltwater underlies the streams. Also uncertain in the case of the West Antarctic ice streams is the role played by glacial till, a soft muddy mixture of clay, sand, pebbles, cobbles, and boulders that lies between the ice and the bedrock. Till could act either as a lubricant or as a soft, easily deformed shearing layer.

Perhaps the most intriguing implication of the Greenland discovery is that the crust beneath Greenland is warm in places, rather than cold and dead throughout. Greenland lies hundreds of miles from the Mid-Atlantic Ridge, the closest seismically active zone. But, points out Caltech geophysicist Don Anderson, the Greenland crust is likely to be under tension, a condition that could make it vulnerable to a magmatic hemorrhage. **Charles Day**

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From Superfluid to Insulator: Bose–Einstein Condensate Undergoes a Quantum Phase Transition

> The atoms in a BEC assemble gregariously into a coherent whole, but in a periodic potential that's sufficiently strong, they can separate into an array of isolated atoms.

Bose–Einstein condensates (BECs) have opened yet another promising avenue of experimental research. This time, the road leads to an opportunity to study quantum phase transitions in a very clean and controlled manner. Specifically, researchers from the Max Planck Institute for Quantum Optics in Garching, Germany, and the University of Munich have shown that they can take a dilute gas of cold atoms from a superfluid to an insulator—and back again—simply by varying the intensity of a laser beam.[1] Daniel Kleppner of MIT said it was "breathtaking" to witness a quantum fluid move back and forth between its superfluid and insulating phases.

Matthew Fisher, a condensed matter theorist from the University of California, Santa Barbara, was excited to see BECs getting into the regime in which interactions between the bosonic atoms are driving qualitatively new effects. He is eager for experimenters to gain similar control over degenerate fermions as well. Aside from its intrinsic appeal, the capability demonstrated by the recent experiment might lead to such applications as controlled chemical reactions and quantum computation.

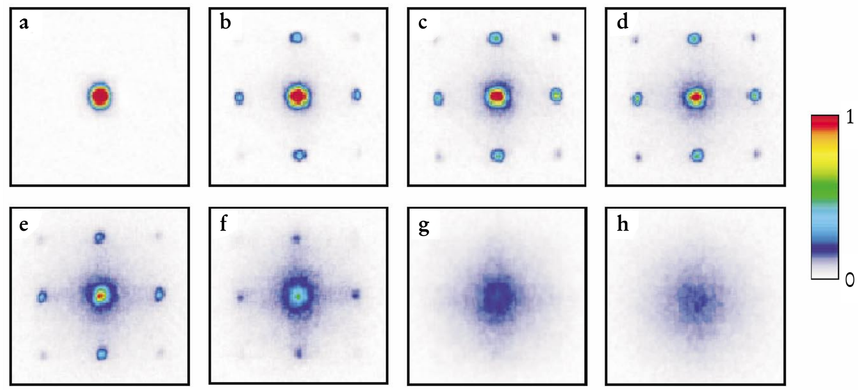

FIGURE 1. INTERFERENCE PATTERNS in absorption images (gauged by scale on right) result when a gas of cold atoms in a three-dimensional optical lattice is in its superfluid phase; no interference is seen in a Mott insulating phase. The depth of the potential wells in the lattice is systematically increased from 0 at (**a**) to 20 E_r at (**h**), where E_r is a reference energy. The phase transition occurs somewhere between (**f**) and (**g**). (Adapted from ref. 1.)

Phase transitions

Classical phase transitions are well known, the most obvious example being the melting of ice. At the melting point, thermal fluctuations drive the system from the liquid to the solid phase, or vice versa. A quantum phase transition is one that occurs at absolute zero: Thermal fluctuations are absent and the system is instead governed by quantum fluctuations.[2] Only in the past decade or two have theorists begun to study in earnest such quantum phase transitions, and it's been difficult to find experimental systems that bear close resemblance to the idealized models.

One example of a quantum phase transition is that between a superfluid and a Mott insulator. In a superfluid, the atoms move in phase with one another, all part of a single macroscopic wavefunction. In a Mott insulator, each atom occupies its own separate quantum well, unaffected by any of its neighbors. As different as these two phases are, they are described by the same Hamiltonian and are characterized by the competition between two interactions: the tendency of the particles to hop into adjacent wells, and the interparticle forces that keep them in separate wells. Depending on the relative strengths of these two interactions, the system can go from a superfluid to an insulator and back again, much as ice melts and refreezes as the air gets warmer or cooler.

A transition to a Mott insulator becomes possible when a superfluid like a BEC is placed in a periodic potential. In 1989, theorists used a Bose–Hubbard model, which describes interacting bosons in a periodic potential, to study transitions in a system like superfluid helium-4 absorbed in a porous medium.[3] Their predictions could not be unambiguously validated because of the imprecisely known interactions and the presence of disorder, or imperfections, in the confining lattices.

Three years ago, a team of theorists from the University of Innsbruck in Austria and from Victoria University in New Zealand used the same model to analyze the phase transition of an ultracold, dilute gas of bosonic atoms placed in a periodic optical potential created by interfering pairs of laser beams.[4] This team recognized that, with such a system, unlike in the porous ^{4}He gels, experimenters had control over the relative strengths of competing interactions. Furthermore, disorder was unlikely to be present in such precisely made optical lattices.

The experiment

At the time of the Innsbruck–Victoria paper, experimenters were able to make optical lattices in one, two, and three dimensions, but they had not been successful in getting atoms to occupy more than a small percentage of the lattice sites. (To picture an optical lattice, think of the two-dimensional case, which is simply an egg-carton potential.) In 1998, Mark Kasevich and his group at Yale University loaded a BEC into an optical lattice to get many atoms in each well of a 1D lattice. For the recent experiment, the Munich group used the same approach in 3D. Participating in the experiment were Immanuel Bloch, Theodore Hänsch, Markus Greiner, Olaf Mandel, and Tilman Esslinger (now at ETH Zürich).

Bloch and company had to find room for the three pairs of lasers needed to create a 3D lattice, so they magnetically steered the ultracold atoms from a magneto-optic trap, which already has six lasers for cooling, to a separate trap (see the cover of this issue), where they formed a BEC and imposed the optical lattice.

With an average occupancy of one to three atoms per lattice site, the Munich group was able to vary the relative strength J of the tunneling between adjacent sites and the (repulsive) interaction energy U between two atoms. U is nearly fixed, but J gets weaker as the potential wells (whose heights are controlled by the laser intensities) get deeper. Think of the situation in 2D as one in which the potential is a landscape of peaks and valleys. In the superfluid phase, these undulations are small, and atoms move as a single coherent wavefunction, oblivious to the ripples below them. As the experimenters deepen the valleys by upping the intensity of the laser beams composing the lattice, the atoms at first remain in the coherent phase. But when the valleys become just a bit too deep, the atoms get localized in them, and the system enters the Mott insulating phase.

To find out what phase is present, the Munich researchers released the atoms from their trap and let them expand freely. They looked for the interference that's present when the atoms are in phase and absent when they are not. The interference pattern seen in panels a through f of figure 1 signals the superfluid phase. For the deeper wells shown in panels g and h, a Mott insulator has formed, as suggested by the disappearance of the interference pattern.

Amazingly, experimenters can take the atoms back and forth between these two phases. The phase coherence that's lost when the atoms enter the insulating state is promptly restored when the system re-enters the superfluid. The transition is rather sharp as a function of well depth and comes at a value that agrees with the predictions of the Innsbruck–Victoria group. Peter Zoller, an Innsbruck member of that team, said, "We are proud that our theoretical prediction was realized in the lab in an incredibly beautiful way."

Although the quantum phase transition technically occurs only at absolute zero, the atoms in the Munich experiment are sufficiently cold that the quantum fluctuations still dominate the thermal ones.

Number-squeezed states

A year ago, Kasevich, together with coworkers from Yale and the University of Tokyo had done a similar experiment, in one dimension: They formed a BEC, loaded it into a 1D optical lattice and saw the presence and absence of interference patterns as a function of well depth.[5] The emphasis of their experiment was different, however, so that they had far more atoms—on the order of 1000—per lattice site. Kasevich and his coworkers are working on precision interferometry and want to have the large number of atoms to gain greater sensitivity.

In both the Yale–Tokyo and the Munich experiments, the Mott insulating phase was in what is known as a number-squeezed state. That is, one could know with a very high degree of certainty how many atoms occupied each site. The price for such certainty, as dictated by the uncertainty principle, was that the phase was completely unknown. In the present case, the superfluid and Mott insulating phases are characterized by extreme cases of two conjugate parameters: In a superfluid, the phase is known but the number of atoms per site is undetermined, and in a Mott insulator the atom number is known but the phase is completely randomized.

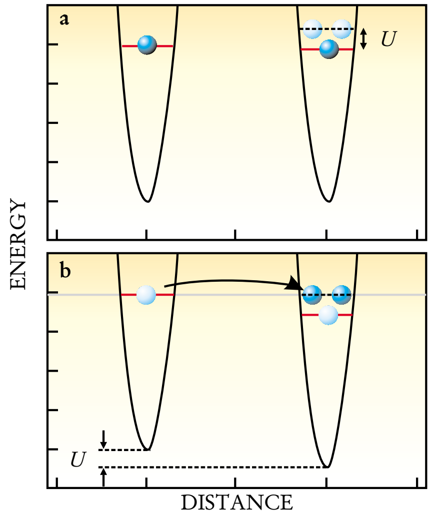

FIGURE 2. INTERSITE INTERACTION. (**a**) Two atoms (dark blue balls) occupy neighboring potential wells. *U* is the energy cost for them to be in the same well (pale blue balls). (**b**) Lowering one well relative to the other allows atoms originally in separate wells (light blue) to occupy the same well (dark blue). (Adapted from ref. 1.)

One prediction of the theory is that the formation of a Mott insulator should be accompanied by the opening of an energy gap in the excitation spectrum; as shown in the top panel of figure 2, it costs an energy *U* to move an atom from the left-hand to the right-hand well. Bloch and his colleagues came up with a clever way to measure this energy gap. With the system in its insulating phase, they applied an energy gradient to the potential wells, which in 2D would be like tilting the egg carton. The effect is shown in the bottom panel of the figure: Once the energy gradient has raised the relative energy of the left-hand well by an amount *U*, the left-hand atom can hop, and both atoms end up on the same site. The tilt threshold that results in such tunneling tells experimenters the value of the energy gap *U*.

As for applications, Zoller said that the Mott insulator should allow interesting chemistry to happen. For example, "One might load exactly two atoms per lattice site and engineer the formation of molecules by way of a photoassociation process." Zoller and Ignacio Cirac (Max Planck Institute for Quantum Optics) have also proposed a scheme to entangle atoms for quantum computation using cold, controlled collisions.[6,7] Zoller views the Mott insulator as an ideal starting point for their scheme.

BARBARA GOSS LEVI

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Ultracold Neutrons Exhibit Quantum States in the Earth's Gravitational Field

Quantization imposes a lower limit on the energy of a neutron trapped in a gravitational potential well.

Quantum mechanics is thought to be universal. It ought to apply to particles trapped in the Earth's gravitational field just as it does to electrons trapped in the electric field of an atom. Like atomic electrons, very cold neutrons sitting in a gravitational potential well ought to have quantized energy levels. The experimenter's problem, of course, is that the gravitational force on a neutron at sea level is 19 orders of magnitude weaker than the Coulomb force on an electron in the ground state of the hydrogen atom. Whereas the low-lying hydrogen energy eigenstates are separated by electron volts, the analogous neutron states in a gravitational well would be separated by only picoelectron volts (1 peV = 10^{-12} eV).

More than 20 years ago, Vladislav Luschikov and Alexander Frank at the Joint Institute for Nuclear Research in Dubna, near Moscow, suggested that one might exploit the then-new technology of ultracold neutrons to exhibit these gravitationally bound quantum states. Now, at last, a group at the Laue–Langevin Institute (ILL) in Grenoble seems finally to have pulled off this difficult trick. Valery Nesvizhevsky and coworkers report, in a recent paper, that they have clearly demonstrated the 1.4-peV neutron ground state in a gravitational well and have also found hints of the first few excited quantum levels.[1]

It's not just a matter of verifying quantum mechanics in a new observational realm. The techniques developed in this very challenging experiment may eventually be applied to searches for a nonvanishing neutron charge or violation of the equivalence of inertial and gravitational mass. The present experimental upper limit on the neutron's charge is about $10^{-21}\,e$.

At the Laue–Langevin

Nestled in the French Alps, the ILL, with its high-flux research reactor, is a particularly prolific source of