formation. Indeed, all of Boyet and Carlson's terrestrial samples had the same $^{142}Nd/^{144}Nd$ ratio to within a few parts per million, the resolution of their measurement.

But Nd has another radiogenic isotope, ^{143}Nd, the daughter of the much longer-lived ^{147}Sm. Since much of Earth's original ^{147}Sm is still around, geological processes over the whole of Earth's history can and do separate ^{147}Sm and ^{144}Nd, yielding measurably different $^{143}Nd/^{144}Nd$ ratios over a much larger range of about one part per thousand.

If Earth's composition were chondritic, then primitive, undifferentiated mantle material would have a $^{143}Nd/^{144}Nd$ ratio of about 0.5126, the same as that of the chondrites. But since, as Boyet and Carlson found, the accessible part of Earth formed with more ^{146}Sm than the chondrites, it must also have had more ^{147}Sm. The expected $^{143}Nd/^{144}Nd$ for primitive terrestrial mantle thus works out to between 0.5129 and 0.5131.

As shown in the top panel of figure 2, the rocks from Baffin Island and from neighboring West Greenland do fall within the 0.5129–0.5131 range. When Stuart and colleagues measured those values in 2003, they inferred not that the samples were from a primitive reservoir but that they were mixtures of material from two different parts of the mantle, neither of which represented a primitive composition.

Lead

It was Jackson's idea to revisit the Baffin Island samples in light of Boyet and Carlson's ^{142}Nd results, by looking at Pb. Like Sm decaying into Nd, two particular isotopes of uranium decay into two isotopes of Pb through a series of α and β decays: ^{235}U into ^{207}Pb and ^{238}U into ^{206}Pb. All the intermediate elements in each decay chain have short half-lives, so the decay rate is governed by the U half-life: 700 million years for ^{235}U and 4.5 billion years for ^{238}U.

Unlike ^{146}Sm, neither U isotope has entirely decayed away, so the amounts of both radiogenic Pb isotopes, measured with respect to the nonradiogenic ^{204}Pb, can vary considerably from sample to sample. The key to making sense of the measurements is to realize that since the two U isotopes decay at different rates but otherwise behave almost identically, the $^{235}U/^{238}U$ ratio is a function of time but not of position. It follows that on a plot of $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$, a system that's been isolated for a time t will fall somewhere on a line, called an isochron, whose location depends on t. Where on the line it falls depends on the U/Pb ratio that the system started with.

As shown in the lower panel of figure 2, the Baffin and West Greenland samples are clustered around the 4.50-billion-year isochron, as expected for material that's been isolated since shortly after Earth's mantle formed. All of the other high-^3He samples fall well to the Baffin samples' right. That doesn't mean that their ages are given by the isochrons through those points, rather that at some point in their history—possibly during their journey through the mantle to the surface—they mixed with material of different composition.

As the world churns

If the Baffin samples are indeed from an ancient mantle reservoir, how could any part of the mantle have remained undifferentiated for so long? Many geoscientists once thought that the answer was easy. Studies of seismic-wave speeds reveal a pressure-induced phase boundary at a depth of 660 km; that boundary, it was thought, could be a barrier to mixing. If the upper and lower parts of the mantle never mixed, then the lower mantle would have remained pristine.

Subsequent seismic studies, however, have shown that picture to be far too simple. As new oceanic crust is created at the mid-ocean ridges, the old crust sinks, or subducts, beneath the neighboring tectonic plate and into the mantle, as shown in figure 1. The slabs of subducted crust appear to extend far past the 660-km discontinuity almost all the way to the core–mantle boundary. (See PHYSICS TODAY, August 1997, page 17.) Since the oceanic crust regenerates fairly quickly compared to the age of Earth—the time from creation to subduction is usually less than 200 million years—the subducted slabs should induce mixing of the whole mantle.

But it can't be mixed to the point of homogeneity. Even setting aside Jackson and colleagues' new work, the $^3He/^4He$ measurements make it clear that the mantle's composition is not uniform. The challenge for geophysical modelers is to reconcile the seismic measurements with the isotopic ones. Some models show every part of the mantle affected by mixing, but not uniformly.[4] They could explain the high $^3He/^4He$ ratios, but not the preservation of any primitive material.

Other models show primitive material preserved in pockets. For example, if the subducted crust is more than a few percent denser than the surrounding mantle, it sinks to and accumulates around the core.[5] As the dense pools build up, they could trap blobs of uncontaminated mantle material, possibly for billions of years.

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Putting quantum gases under the microscope

Microscopes with single-site resolution are vital for using ultracold atoms to simulate strongly correlated electrons in solids.

Many intriguing behaviors, such as high-temperature superconductivity, result from the strong interactions among particles in a many-body system. Theorists have explored those complex interactions with model Hamiltonians, but real-world defects make physical systems imperfect realizations of the models. And time and memory constraints limit computer simulations of quantum behavior to just a handful of atoms.

A tantalizing alternative is to use small clouds of atoms, typically tens of thousands, cooled to nanokelvin temperatures, to study the complex physics of strongly correlated systems. To simulate the structure of solids, researchers can trap atomic gases in a periodic array of optical potentials created by intersecting laser beams, much as eggs are confined by the corrugations of an egg carton. The optical arrays can be nearly defect free, and particle interactions can be tuned to explore the system behavior. Depending on whether the atom is a fermion or a boson, it might represent an electron or an electron pair. The simulations can possibly be extended to quantum spin systems, such as anti-

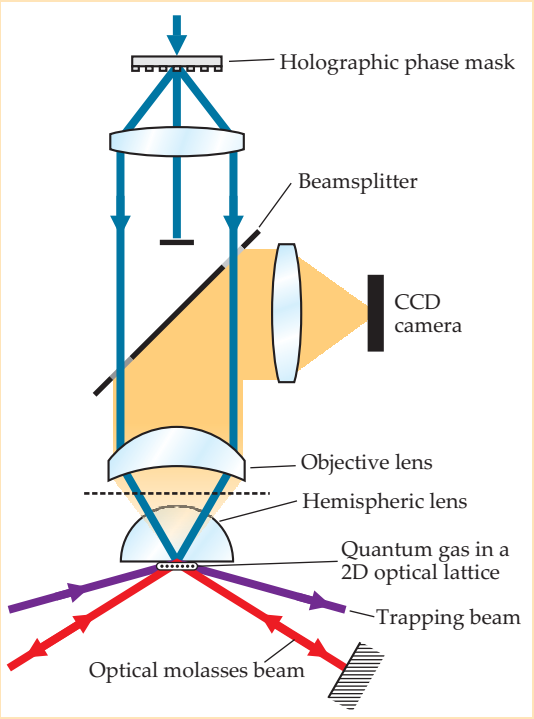

Figure 1. Fluorescent microscope used at Harvard University to image two-dimensional quantum gases of rubidium atoms. Laser light (blue) passing through the holographic phase mask forms an optical lattice to trap a 2D quantum gas. Additional lasers (purple) further confine the gas. Yet others (red) create an optical molasses that cools the gas. Fluorescent light (yellow) scattered off the atoms is focused by the two lenses and reflected by the beamsplitter onto a CCD camera. (Adapted from ref. 5.)

ferromagnetic systems or spin liquids, if experimenters can get down to 100 pK temperatures.

Until recently, however, experimenters could only measure densities averaged over many lattice sites, making it difficult to obtain accurate information about many important system properties such as the equation of state or the temperature. Experimenters lacked the insight that would come from knowing the local properties of each atom. Such insight is now provided by newly published fluorescent-microscope images that give single-site resolution of quantum gases of rubidium atoms in optical lattices. The images from two experiments confirm visually what had previously been inferred indirectly (see PHYSICS TODAY, March 2002, page 18) about the transition from a superfluid phase, such as a Bose–Einstein condensate (BEC), to a Mott insulator (MI) phase. (An MI does not carry current because particle interactions inhibit hopping between sites.) The new experiments were done by Markus Greiner and his colleagues at Harvard University[1] and by a group under the direction of Stefan Kuhr and Immanuel Bloch of the Max Planck Institute of Quantum Optics in Garching, Germany.[2]

Single-atom snapshots

Although images have been made of ions in various kinds of traps and of small numbers of individual atoms, until recently no one had resolved single atoms in a large collection of atoms. Recently, electron beams were used both to address and to make high-resolution images of atoms in a two-dimensional BEC, but each lattice site held up to 80 atoms.[3] In 2007, David Weiss and coworkers at the Pennsylvania State University produced fluorescent images that resolved single atoms sitting in successive planes of a 3D lattice, with 250 atoms total.[4] The team members were motivated by their interest in using atoms in the 3D lattice as qubits for quantum information processing, an application that requires a means both to address and to manipulate single atoms.

To apply fluorescent microscopes to cold-atom simulations of strongly correlated systems, researchers need to resolve lattice sites that are much more closely spaced than in the Penn State experiment (0.5 μm versus 5.0 μm): Only at those shorter distances do particles tunnel and interact strongly. Researchers also had to incorporate the required high-resolution microscope into an all-optical trap designed to produce a very cold, quantum degenerate gas.

Last year Greiner and coworkers introduced a fluorescent microscope of unique design having a resolution on the order of half a micron, roughly the size of the lattices to be studied.[5] Their more recent work, together with that of the Max Planck group, shows unambiguously that atoms, which freely move around within a BEC, freeze in

regions of constant density within an MI.

The high-resolution microscopes have created quite a buzz, especially among those researchers who hope to use quantum gases to explore a variety of model Hamiltonians. Wolfgang Ketterle of MIT likens the new tool's impact to that of scanning probe microscopes on condensed-matter systems: Those probes provide real-space pictures to complement momentum-space measurements.

Fluorescent microscopes

The high-resolution fluorescent microscope designed by the Greiner group is sketched in figure 1. After forming the optical trap with a holographic phase mask, the team controls the state of the gas (BEC or MI) by tuning the depth of the potential wells in the optical lattice. Before taking a snapshot of the atoms in a given phase, the experimenters want to be sure that their subjects don't move during the exposure. Thus, they very quickly deepen the lattice's potential wells a thousandfold to pin each atom in place. They then turn on an arrangement of polarized lasers known as an optical molasses. Atoms in the lattice inelastically scatter the photons in the molasses, producing fluorescence. Typically, one atom will scatter thousands of photons per image.

The scattered light is collected by a high-resolution imaging system consisting of both an objective lens outside the vacuum chamber and a hemispheric lens inside it. The hemispheric lens increases the numerical aperture, a measure of the angle over which a lens can collect light. The resulting large numerical aperture (0.8) contributes to both greater light collection and higher resolution (0.6 μm).

Kuhr, Bloch, and coworkers used a similar apparatus and procedure except that they relied on interfering laser beams rather than on a holographic mask to generate the optical lattice. In addition, the Max Planck team used a single high-quality objective lens with a numerical aperture of 0.68 and a resolution of 0.7 μm.

The fluorescent microscopes actually do not determine the total occupancy of each lattice site, which typically holds more than one atom. That's because the optical molasses beams promote inelastic collisions between pairs of atoms and scatter those pairs out of the trap. As a result, each site is left with one or no atoms, depending on whether it was initially occupied by an odd or even number of atoms. Hence, the images record the parity of the atom number.

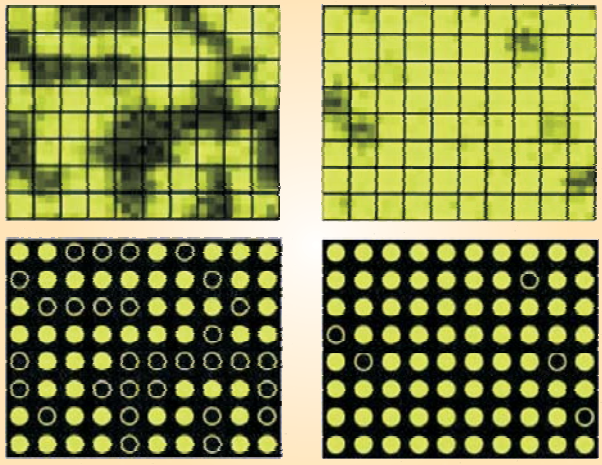

Figure 2. Images of a Bose–Einstein condensate (left panels) and a Mott insulator (right) from a 10 × 8 array of lattice sites within a larger sample. From the image intensity (top panels), an atom detection algorithm determines which sites are occupied or unoccupied (bottom panels). (Adapted from ref. 1.)

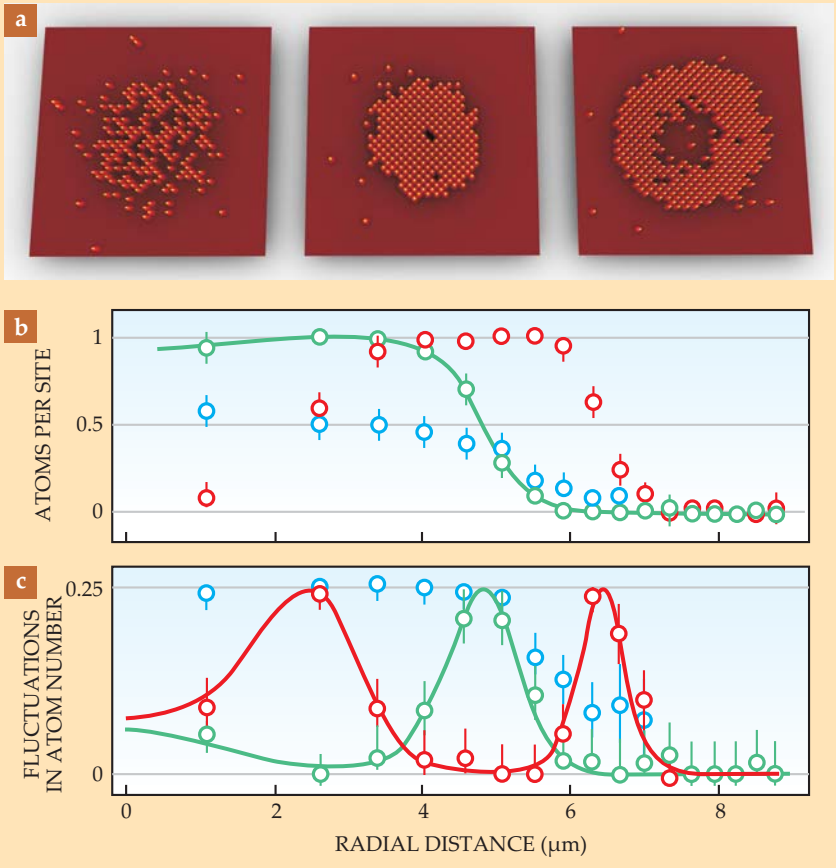

Figure 3. Shell structure of the Mott insulator (MI) is apparent in microscopic images. **(a)** Reconstructed distribution of atoms, or more accurately, the parity p of the number of atoms on each site. Sites in a Bose–Einstein condensate (BEC; left) are randomly occupied. In the MI (center), single atoms occupy a circular core region. For an MI with more atoms (right), doubly occupied sites in the center (shown as $p \sim 0$) are surrounded by singly occupied sites ($p \sim 1$). **(b)** The radial distribution of the average atom number per site is shown for the three phases in panel a: a BEC (blue), a single-shell MI (green), and a two-shell MI (red). **(c)** The radial distribution of fluctuations in the number per site is shown for the same three cases. (Adapted from ref. 2.)

The Mott insulator

The cold-atom lattices studied in the Harvard and Max Planck experiments can be described by the Bose–Hubbard model. According to that model, atoms are governed by only two parameters: the interaction U when two atoms occupy the same site and the strength of tunneling J between lattice sites. The experimenters can control J and hence the ratio U/J by changing the depth of the potential wells in the optical lattice. When the ratio is low as in the superfluid phase, hopping is prevalent. As the ratio increases, atoms are pinned more strongly by the lattice and the system transitions to an MI, with the atoms essentially frozen in place. The recent experiments explored that transition. Although their findings yielded few surprises, "Still they are amazing to see," commented Pierre Meystre at the University of Arizona. "The pictures are gorgeous."

The images in figure 2, taken by the Harvard microscope, show a small region of a quantum gas in both the BEC and the MI phases. Shown are both the direct images and the result of an algorithm that determines which of the 10 × 8 lattice sites are occupied. Because atoms in a BEC freely hop from one site to another, they are delocalized across the entire lattice. On each site then it is equally likely to find an even or an odd number of atoms, hence the average measured site parity p is about 0.5. In the MI phase shown, atoms are fixed in place with all the sites singly occupied, so that p approaches 1 or 0.

Wider fields of view, such as the reconstructed images in figure 3, reveal the shell structure predicted for the MI. Theory predicts that as more atoms are added to the MI, the energy to put an atom in a lattice site outside a certain radius exceeds that for adding a second atom to the inner core. The resulting shell, or wedding cake, structure had been seen before[6–8] but never quite so visually.

The radial atom-number distribution within the observed shells is plotted in figure 3 for the BEC and the two MI phases shown in the top panel. As expected, p is approximately 0.5 for a BEC and approaches either 0 or 1 within an MI region. Also shown is the variance in those number distributions. The BEC is characterized by large fluctuations because atoms are free to hop from site to site. Large fluctuations also show up in relatively narrow regions just outside each MI shell. The low fluctuations in the MI regions indicate that the entropy is close to zero there: Those regions have dumped their entropy into the surrounding shells.

If the images from the Harvard and Max Planck groups offer any surprise, it is the sharpness of the transition region—both in space and in time—between the MI and the superfluid BEC. Spatially, some MI regions are only a few lattice sites wide. Temporally, the system is found to go from a BEC to an MI phase in a few milliseconds. Greiner is amazed that the atoms can arrange themselves so quickly, exactly filling all the right lattice sites.

The transfer of entropy out of the MI regions has given a number of experimenters an idea for further cooling. As explained by Greiner, ejecting those atoms just outside a core MI region can get rid of all that entropy. The new cooling regime might then reach the low enough temperatures for experiments on quantum spin systems.

In addition to trying to get to lower temperatures, the experimenters are working to extend their imaging capabilities to 3D. They are also exploring ways to manipulate the atoms, especially for applications to quantum computing.

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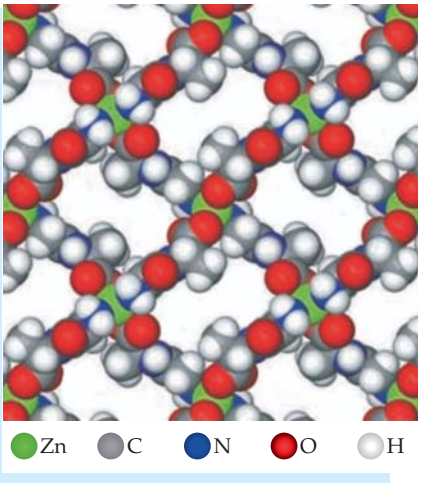
physics update

These items, with supplementary material, first appeared at http://www.physicstoday.org.

An expandable molecular sponge. Zinc ions and some other metal ions can bind to three or four organic molecules at once. If those molecules are long and attach to zinc at both ends, it's possible to create a metal–organic framework (MOF), an open sheet of linked molecules with ions at the vertices. And if those sheets bind to each other and stack in register, the result is a material whose columnar pores can store, catalyze, or otherwise usefully process small molecules. Matthew Rosseinsky and his coworkers at the University of Liverpool in the UK have made a MOF material, but with a new twist. For its linker, the Liverpool team used a dipeptide—that is, two peptide-bonded amino acids (glycine and alanine; see figure). The team made two versions of the material, one incorporating a solvent (a mix of water and methanol) and one not. X-ray diffraction and nuclear magnetic resonance spectroscopy revealed that adding the solvent caused the dipeptide linkers to straighten, widening the pores to accommodate the solvent ions. Glycine, alanine, and the 18 other naturally occurring amino acids are characterized by side chains that are polar, nonpolar, positively charged, or negatively charged. Given that variety, the Liverpool experiment suggests that peptide-based MOF materials might find uses as expandable sponges for a wide range of molecules. (J. Rabone et al., *Science* **329**, 1053, 2010.) —CD



Color-dependent cyclone activity. Under the hot summer sun, the ocean's surface waters become warmer than the atmosphere above them. As the heat is transferred to the atmosphere, it can strengthen low-pressure disturbances and drive the characteris-