

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.

Barbara Goss Levi

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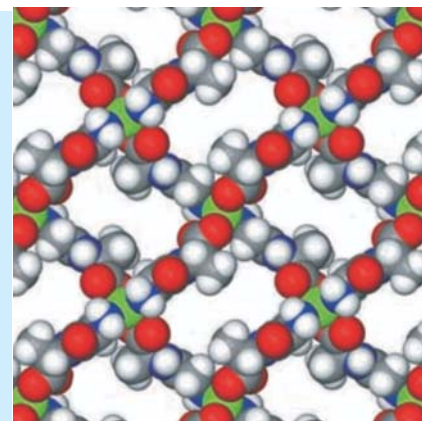
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physics update

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

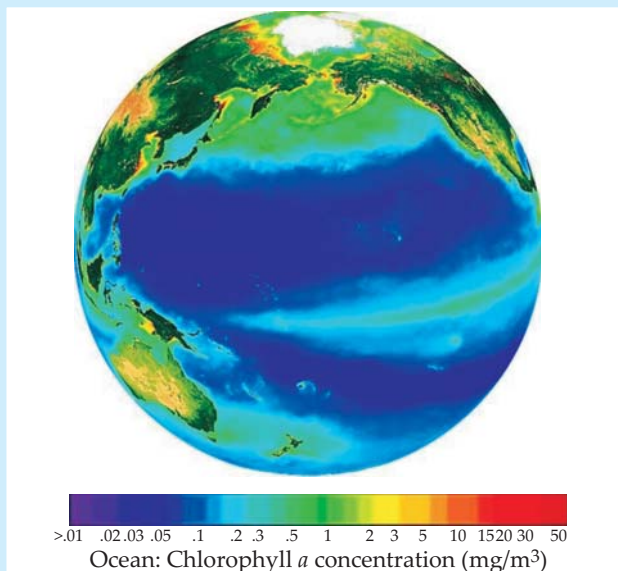
other naturally occurring amino acids are characterized by side chains that are polar, nonpolar, positively charged, or negatively charged. Given that variety, the Liverpool experiment suggests that peptide-based MOF materials might find uses as expandable sponges for a wide range of molecules. (J. Rabone et al., *Science* **329**, 1053, 2010.) —CD



● Zn ● C ● N ● O ● H

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-

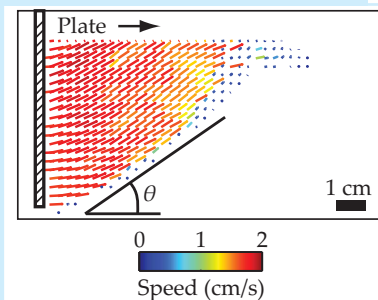
tic weather phenomena known in the Atlantic region as hurricanes and in the Pacific as typhoons or tropical cyclones (see the Quick Study on hurricane formation by Kerry Emanuel in *PHYSICS TODAY*, August 2006, page 74). A new model from a research collaboration led by Anand Gnanadesikan at the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey, shows how strongly correlated the sea surface temperature (SST) is to the ocean's color. The image depicts average concentrations (in mg/m^3) of chlorophyll—the green pigment in phytoplankton—from 1997 to 2000 in the Pacific Ocean, where more than half of the reported typhoon-force winds (greater than 32 m/s) occur. Considering an extreme scenario, the researchers set the concentration of chlorophyll to zero and then studied the evolution of cyclones in the North Pacific Ocean. Without chlorophyll to absorb much of the solar radiation, SSTs drop. Air over the colder water sinks, dry-



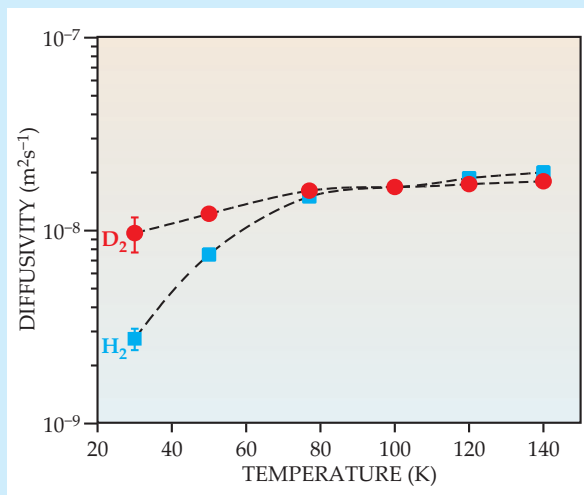
ing the atmosphere and increasing wind shear, which quenches typhoon formation. Although typhoon frequency increased by 20% along the equator in that scenario, the simulation predicted an overall drop in the region—up to 70% for areas beyond 15 degrees north of the equator—and a decrease in frequency of the most intense cyclones. (A. Gnanadesikan et al., *Geophys. Res. Lett.*, in press.) —JNAM

Plowing through a granular medium. Children frolicking in a sandbox probably don't think about the drag forces exerted on their limbs as they displace grains of sand. But physicists Nick Gravish and Daniel Goldman (Georgia Tech) and Paul Umbanhowar (Northwestern University) do think about such forces. Now they have conducted a systematic study of how the drag force on a vertical plate partially submerged in sand-sized glass beads depends on the beads' packing fraction ϕ . Their study reveals a surprising phenomenon: For a dense packing—that is, when ϕ exceeds a critical value ϕ_c —the drag force oscillates as the plate moves horizontally. The crucial physics, argue the authors, hinges on the phenomenon of dilatancy: densely packed beads can become less dense when sheared. Dragging a plate through a dense packing creates a "shear plane" that runs from the bottom edge of the plate to the surface of the beads and makes an angle θ with the horizontal. Particles near the shear plane tend to move parallel to it, toward the surface; particles beyond the plane hardly move at all (see the figure). Shear

forces arising at the plane cause the local packing fraction to decrease, which makes it easier to move the plate. When the packing fraction dips to ϕ_c , the shear plane remains stationary at the surface even as its bottom edge moves with the plate; thus θ increases, which causes the drag force to also increase. Once the drag force is high enough, a new low- θ , high- ϕ shear plane forms, and the cycle repeats. Sandboxes, it seems, have pleasures to offer physicists and children alike. (N. Gravish, P. B. Umbanhowar, D. I. Goldman, *Phys. Rev. Lett.*, in press.) —SKB



Quantum effects turn pore diffusion on its head. Separating isotopes is difficult business: Because an element's various isotopes share similar size and shape, separation methods such as thermal diffusion and centrifugation tend to be time and energy intensive. Now, however, a team led by Suresh Bhatia (University of Queensland, Australia) has shed new light on what may prove an attractive alternative—nanoporous materials known as molecular sieves. Normally, molecular sieves aren't particularly effective isotope separators. Take diatomic hydrogen and its isotopic relative deuterium. As one would expect, the lighter H_2 molecules diffuse through the porous molecular sieve faster than the heavier D_2 , but the difference is slight. That picture changes, though, if the temperature is low enough—and the pores small enough—for quantum effects to set in. If the pore size is on the order of the molecules' de Broglie wavelength, the molecules' zero-point energy becomes the important barrier for pore diffusion and small mass becomes a disadvantage. Not only does D_2 then diffuse faster than H_2 , it can do so by a substantial margin. Using quasi-elastic neutron scattering and carbon



molecular sieves with 3-Å-diameter pores, Bhatia and company directly measured those diffusivities, which differed by nearly an order of magnitude at the coldest temperatures. Although quantum sieve effects—first predicted nearly 15 years ago—had been previously seen in equilibrium adsorption experiments, the research team's findings represent the first microscopic observations of the kinetic phenomenon. (T. X. Nguyen, H. Jobic, S. K. Bhatia, *Phys. Rev. Lett.* **105**, 085901, 2010.) —AGS ■