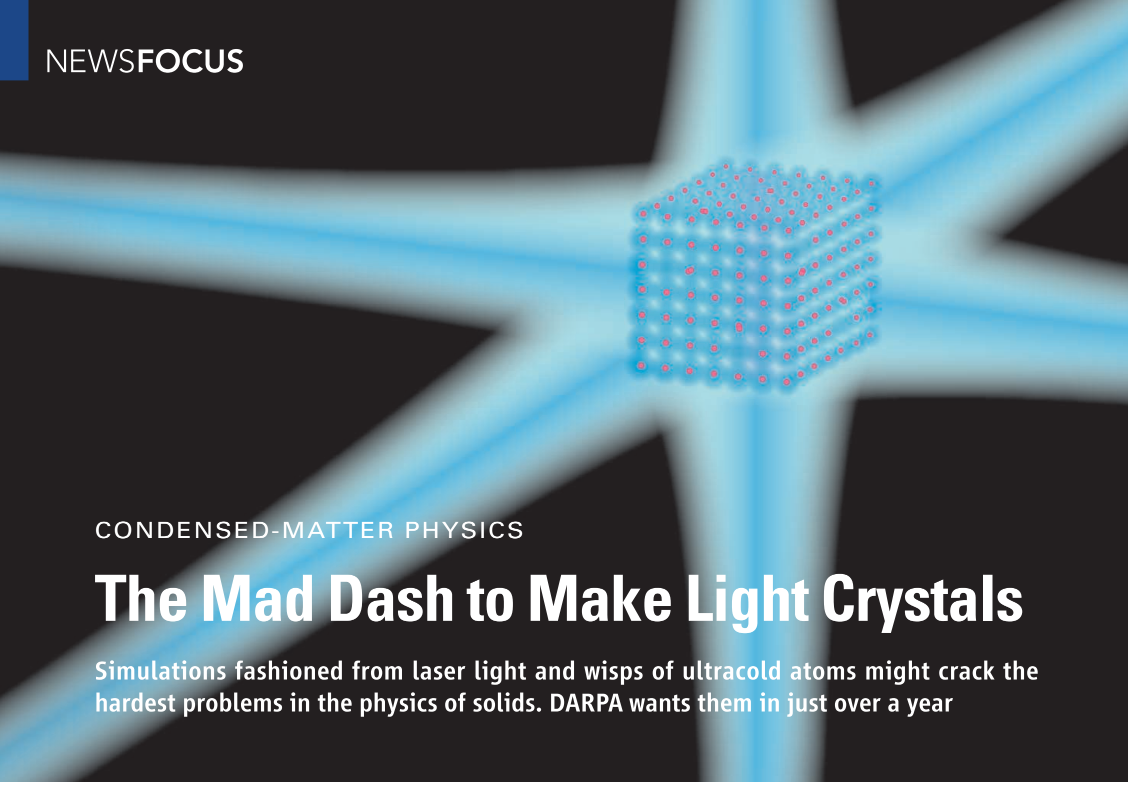

Crystal clear. In an optical lattice, spots of laser light simulate the ions in a crystal. Atoms (red) hopping between the spots simulate the electron in the solid.

CONDENSED-MATTER PHYSICS

The Mad Dash to Make Light Crystals

Simulations fashioned from laser light and wisps of ultracold atoms might crack the hardest problems in the physics of solids. DARPA wants them in just over a year

For more than a century, physicists have developed ever more sophisticated theories of rock-hard solids and the electrons whizzing within them. They've deciphered metals and insulators, concocted the semiconductors that make computers hum, and explained mind-boggling phenomena such as conventional superconductivity, in which some alloys conduct electricity with no resistance at temperatures near absolute zero.

Yet many problems continue to stump theorists. For example, 22 years after high-temperature superconductors were discovered, physicists still don't know how the exotic compounds carry current without resistance at temperatures up to 138 kelvin. Generally, whenever the shoving among electrons grows too strong, physicists find themselves stymied—even if they resort to high-powered numerical simulations. "We know that we can't do these things on a classical computer," says David Ceperley, a theorist at the University of Illinois, Urbana-Champaign (UIUC).

Help may be on the way, and from an unlikely quarter. Atomic physicists have spent 2 decades fiddling with ultracold gases a millionth the density of air. Now they're striving to model weighty crystalline solids with laser light and cold atoms. Interfering laser beams create an array of bright spots called an "optical lattice" that emulates the ions in a crystal; atoms hopping between the spots emulate the electrons. Physicists can tune the lattice's geometry, the rate of hopping, and the push and pull between atoms. So they hope to map the various behaviors of a model solid—superconducting, insulating, and so on—in a portrait called a "phase diagram."

The U.S. Defense Advanced Research Projects Agency (DARPA) has launched a multimillion-dollar program to develop such optical-lattice emulators. They might crack some of the toughest problems in condensed-matter physics or even enable researchers to design materials from scratch. Plans call for the first ones to be running in 15 months.

"The DARPA program is excellent," says Wolfgang Ketterle, an experimenter at the Massachusetts Institute of Technology (MIT) in Cambridge and leader of one of three multi-institution teams receiving funding. "It puts money and resources into an effort that is scientifically superb." But some warn that making the emulators work may be harder than expected. And researchers' goals don't necessarily jibe with DARPA's. Physicists want the phase diagrams. Seeking a tool to design exotic new materials, DARPA wants an automated system that works in just 10 hours.

Abstractions made material

The emulators could bridge the gap between the abstraction of theory and idiosyncrasies of experiments with real solids. Theorists make an educated guess at the physics behind a material's behavior. This "model" is captured in a mathematical expression known as a Hamiltonian, which describes the system's energy. Unfortunately, it's often impossible to "solve" the Hamiltonian to prove it produces the observed behavior. And there is no guarantee that the model doesn't leave out some key detail.

Take, for example, a high-temperature superconductor. It contains planes of copper and oxygen ions arranged in a square pattern along which the electrons pair and glide. At low enough temperatures, the electrons repel one another so strongly they get stuck one-to-a-copper-ion in a traffic jam known as a Mott insulator state. The electrons also act like little magnets, and neighboring electrons point alternately up and down to form an "antiferromagnet." Now, take out a few electrons by tweaking the material's composition. The traffic jam breaks and, perhaps through waves of magnetism, the electrons pair and flow without resistance. Or so many theorists assume.

This scenario is known as the two-dimensional (2D) Fermi-Hubbard model, and nobody can prove it produces superconductivity. Nobody is sure that it captures the essential physics of the messy crystals, either. "The materials are so complicated that you can't look at just the electron-electron correlations," UIUC's Ceperley says. "There are all these other things going on."

But physicists might be able to make a Fermi-Hubbard model by loading cold atoms into a 2D optical lattice that would simulate just these copper-and-oxygen planes. Atoms spinning in opposite directions would hop from bright spot to bright spot. By tweaking the laser beams and applying a magnetic field, physicists would vary the rate of hopping, the repulsion between atoms, and other factors to determine under what conditions if any the model produces superconductivity, says Tin-Lun "Jason" Ho, a theorist at Ohio State University in Columbus. "The goal is to reproduce the model faithfully in an optical lattice and let nature tell you what the solution is," he says.

The next coolest thing

The push marks the next chapter in the short, glorious history of ultracold atoms. Atoms can be sorted into two types—bosons and fermions—depending on how much they spin. Thanks to quantum mechanics, the two types behave very differently. Bosons are inherently gregarious. In 1995, two teams independently chilled bosons to below a mil-

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lionth of a kelvin to coax them into a single quantum wave and produce a state of matter called a Bose-Einstein condensate (BEC) that flows without resistance (*Science*, 14 July 1995, p. 152). That accomplishment netted a Nobel Prize in 2001.

Fermions are loners, as no two identical fermions can occupy the same quantum wave or state. Nevertheless, at very low temperatures fermions can get it together to flow freely. First they have to pair, and then the pairs condense into a quantum wave. This is what happens in superconductors, and in 2004, physicists made fermionic atoms pair and condense in much the same way (*Science*, 6 February 2004, p. 741).

Given those accomplishments, creating an optical-lattice emulator might seem easy. Electrons are also fermions, so it might appear that researchers need only impose an optical lattice on fermionic atoms already trapped by magnetic fields and laser beams. But researchers have several steps to go before they can emulate the Fermi-Hubbard model and other intractable systems. They must achieve the Mott insulator state, which would pin one atom to each lattice site, and then the antiferromagnetic state, in which neighboring atoms spin in different ways.

Physicists have made progress. In 2002, Immanuel Bloch, now at the Johannes Gutenberg University of Mainz in Germany, and colleagues reached the Mott insulator state for bosons by loading a BEC of rubidium-87 into an optical lattice and cranking up the brightness of the laser spots to effectively increase the repulsion between atoms. "That was a landmark," says Randall Hulet, an experimenter at Rice University in Houston, Texas. "That showed that we could do something that was relevant from a condensed-matter perspective."

Last month at an American Physical Society meeting in New Orleans, Louisiana, Niels Strohmaier and Tilman Esslinger of the Swiss Federal Institute of Technology Zurich reported reaching the more elusive Mott state for fermions. "We have a few puzzle pieces, and now we want to put everything together," says Ketterle, who shared the Nobel for BECs.

Emulators, pronto!

The DARPA program aims to do just that. Last July, the agency gave three large teams—led by Ketterle, Hulet, and Christopher Monroe at the University of Maryland, College Park—a few million dollars each (DARPA won't say exactly how much) and 2 years to develop a working emulator. In that first phase, researchers will tackle simpler models for which the Hamiltonian *can* be solved. For example, Hulet's group will study fermions in 1D tubes of light, and Ketterle will aim for the antiferromagnetic state of fermions in a 3D lattice.

If a team's starter emulation works by July 2009, it will be eligible for a 3-year second phase, in which researchers will tackle an incalculable Hamiltonian. Hulet and Ketterle both hope to emulate superconductivity in the 2D Fermi-Hubbard model. Monroe's team is focusing on bosons in both phases, which do not mimic electrons but should still be useful for simulating exotic magnetic materials.

To get to the second phase, the emulators for the first phase must work at lightning speed, however. The machinery must step through a complete phase diagram in 10 hours, not including the setup time. That's roughly how long it takes the best computer simulations to run, says DARPA program manager Air Force Lt. Col. John Lowell. "You're trying to establish a comparison with other computational techniques, and time is the metric," he says.

It sounds like the sort of results-on-demand program that would drive university researchers crazy. However, all voice great enthusiasm for the project. "DARPA really wants you to stay focused on the task at hand, and I find that very productive," Hulet says. "I've got a schedule on my white board of when things have to get done, and it definitely creates some tension in the lab."

Heavy hitters. MIT's Wolfgang Ketterle (*top*) and Rice's Randall Hulet praise DARPA's vision.

CREDITS (TOP TO BOTTOM): DONNA COVENEY/MIT; JEFF FITLOW/RICE UNIVERSITY

The challenges ahead

Making the emulators work won't be easy, physicists say. The biggest hurdle may be getting the atoms cold enough. Researchers may have to chill gases to picokelvin temperatures to emulate the Fermi-Hubbard model. Oddly, they may catch a break getting part of the way there. Theory suggests that if they turn on an optical lattice gently—so as not to add entropy—a gas of fermions should spontaneously cool enough to reach the antiferromagnetic state. But researchers may be underestimating the difficulty of getting even colder to reach the superconducting state, Ohio State's Ho says. "It requires a breakthrough," he says. "Just doing things the way they are doing them now is as good as praying."

Experimenters will also have to devise ways to prove that their emulator is doing what they think it is. A high-temperature superconductor may be messy, but it produces an unambiguous signal that it's working: zero electrical resistance. Atoms in a lattice won't signal so clearly that they have gone superconducting, so proving they have will require subtle new probes.

Then there is the 10-hour time limit—an odd requirement given that physicists would be happy to have the phase diagram for the Fermi-Hubbard model even if it took years to get it. Some predict DARPA officials won't enforce the limit strictly. "Everybody knows it can be tweaked in the end if need be," Monroe says. Don't be so sure, Lowell warns. "I wouldn't have laid this out as a milestone if I didn't think it was doable," he says. "And you wouldn't have signed on to it if you didn't think it was achievable."

Where will it all lead? Even leading physicists doubt that they'll produce a black box capable of deciphering any solid. "I see it as unlikely that in the end there will be this universal machine that solves any problem you would like to solve," says Mainz's Bloch. Some say optical lattices may serve primarily to validate techniques for computer simulation, which will remain the biggest wrench in the theorist's toolbox.

Nevertheless, all agree that making light crystals could be a revolutionary advance. "It's bloody difficult, but it doesn't seem impossible," Ketterle says. "Let's stop talking and start doing." The clock is already running.

–ADRIAN CHO

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