Solidified helium appears to flow without any resistance. How that happens is anything but crystal clear

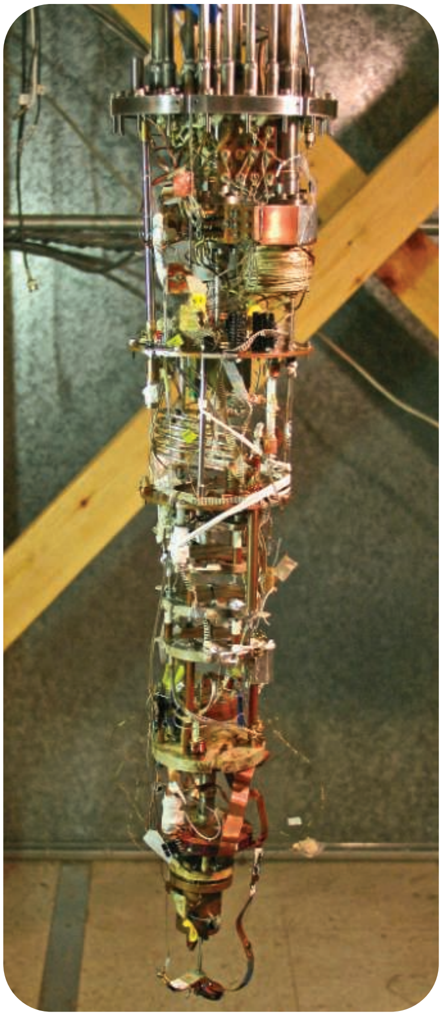
Flowing Crystals Flummox Physicists

University Park, Pennsylvania—The gizmo could be mistaken for an artifact from a science museum or a custom-made part for your old VW Beetle. An aluminum cylinder 13 millimeters wide and 5 millimeters tall sits atop a slender post of beryllium copper. From its sides, two flaps protrude like large ears on a small boy's head, and fine wires festoon the top of the can. As Eunseong Kim, a postdoc here at Pennsylvania State University (Penn State), cradles it in his palm, the device hardly looks like the heart of a breakthrough physics experiment. Yet it produced perhaps the weirdest stuff ever made.

Last year, while Kim was a graduate student, he and physicist Moses Chan used the can to squeeze ultracold helium into a crystalline solid that appears to flow without resistance—like a liquid with no viscosity. For decades physicists had mused about such a bizarre "supersolid," and others had searched for and failed to find it. So Kim and Chan's results have touched off a flurry of activity among experimenters and a debate among theorists as to whether it's even possible for a perfect crystal to flow. They are rejuvenating helium physics, a small field that has played a large role in shaping modern physics (see sidebar, p. 39).

Kim and Chan had previously seen signs of such "superfluid" flow in solid helium crammed into the pores of a spongelike glass. But on 3 January 2004 they saw the first clear evidence that it could occur in a pure crystal. "That was an exciting moment," the soft-spoken Kim recalls as he sits at his desk in the subbasement of Osmond Hall. "That morning Moses came into my lab and I said to him, 'Maybe you'll get the Nobel Prize.' "

Many others agree. "If verified, the discovery of supersolid helium will be one of the most important results in solid state physics—period," says Jason Ho, a theorist at Ohio State University in Columbus, who has come to Penn State to discuss his theory of the phenomenon. Anthony Leggett, a theorist at the University of Illinois, Urbana-Champaign, says the observations challenge the widely held belief that a well-ordered crystal cannot enter a free-flowing supersolid "phase." "I would have bet quite strongly against such a phase," says Leggett in a phone interview from his office. "It looks like the experiments will make me rethink that."



Cool! When running, Kim and Chan's cryostat hides inside a container of liquid helium.

Kim and Chan's results must still be confirmed, however. And physicists must deduce whether the helium crystal itself is flowing, or whether the effect arises from the superfluid flow of liquid helium in cracks and crevices in the crystal—a less mind-bending alternative that wouldn't count as supersolidity. To make the call, researchers are tackling new experiments that should challenge even helium physicists, who enjoy a reputation as expert tinkerers who can squeeze every drop of information out of a thimbleful of helium.

Letting go

Prone to burst into effusive laughter, Moses Chan talks fast and forcefully. But when discussing solid helium, he chooses his words carefully. "I think it's safe to say we've done all the possible control experiments," he says. "And though it sounds weird, I think the simplest explanation is that we see superfluidity in a solid." It's a big claim. Chan is saying that a material structurally similar to rock salt oozes through itself unimpeded. Yet other physicists agree with his assessment of the situation. Of course, they're used to the perversity of helium.

Since it was first liquefied nearly a century ago, physicists have puzzled over ultracold helium. Every other element freezes at some temperature, but unpressurized helium remains a liquid all the way down to absolute zero. Below 2.17 kelvin, however, the most common helium isotope, helium-4, undergoes a stranger transformation: It becomes a superfluid that flows without any resistance. That happens because, compared with other atoms, light and lively helium atoms act a bit less like billiard balls and a bit more like quantum waves. At low enough temperatures, many collapse into a single quantum wave that resists disturbances, in a process known as Bose-Einstein condensation.

Theorists have long speculated that something similar might happen in solid helium-4, which can be made by squeezing the liquid to 25 times atmospheric pressure. In 1969, Russian theorists A. F. Andreev and I. M. Lifshitz proposed that missing atoms, or vacancies, within the helium crystal could condense to form a free-flowing fluid of their own, which would mimic the flow of atoms through the liquid. But no one had seen any sign of a flowing solid until now.

To spot the stuff, Kim and Chan set their little can twisting back and forth on its shaft. The frequency of oscillation depends on the stiffness of the shaft and the inertia of the can, which in turn depends on the amount of

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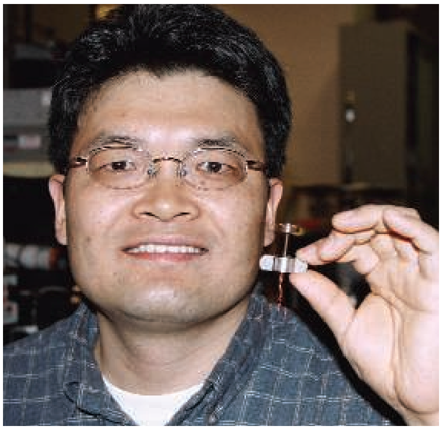
helium stuck to it. At pressures ranging up to 145 times atmospheric pressure, the frequency began to rise suddenly as the temperature sank below about 0.2 kelvin. Those upswings indicated that as much as 1% of the helium was letting go of the oscillator and standing stock-still while the rest of the crystal twisted back and forth, as Kim and Chan reported online on 2 September 2004 in *Science*. That strange behavior implies that some of the helium glided through the crystal without resistance.

In principle, the experiment is simple. In practice, it's a challenge, as a glimpse of the guts of one of Chan's refrigerators, or "cryostats," suggests. The assemblage of tubes, wires, coils, and myriad handmade gadgets hangs like a mechanical stalactite from a platform supported by four great wooden legs. The whole thing stands inside a metal box the size of a small room, which Chan installed to block out radio interference from a nearby campus police station. From the tip of the stalactite hangs the oscillating can; when the can is twisting, its flaps move as little as a single atom's width. Kim and Chan measure changes in the oscillator's frequency to part-in-a-million precision.

Kim and Chan performed a series of experiments that slowly built the case for supersolid helium. For example, they replaced the helium-4 with the isotope helium-3, the atoms of which cannot crowd into a single quantum state because of the way they spin. That implies solid helium-3 should not flow, which is what the experimenters observed. "Moses was very careful and asked all the questions that he could ask with the kind of apparatus he had," says experimenter Richard Packard, from his office at the University of California, Berkeley. "And all the answers indicate that something lets go" in helium-4.

But although researchers agree that the experiments are sound, they disagree on how to explain them. And no one knows whether a crystal really can flow.



Twister. Eunseong Kim holds oscillator that first hinted at flow in "bulk" helium.

CREDITS (TOP TO BOTTOM): *NATURE* **141**, 243-244; A. CHO/*SCIENCE*

The Quirks and Culture of Helium

Ordinarily an inert gas so light it floats off into space, helium might seem to hold little interest for condensed-matter physicists. But since it was liquefied by Dutch physicist Heike Kamerlingh Onnes in 1908, the odd stuff has revealed much about the physics of liquids and solids. "Throughout history, it has provided a variety of new paradigms," says Jason Ho, a theorist at Ohio State University in Columbus.

Font of insight. Liquid helium has inspired key concepts in condensed-matter physics.

Since 1938, physicists have known that below 2.17 kelvin the most common isotope of helium, helium-4, becomes a "superfluid" that flows without resistance, as about 9% of the atoms crowd into a single quantum wave. In 1972, physicists discovered that helium-3 also becomes a superfluid at just a few thousandths of a kelvin. Because of the way they spin, helium-3 atoms cannot pile into a single quantum wave. Instead, they form pairs that glide without resistance, as electrons do in superconductors.

Experiments with helium-3 validated much of the "Fermi liquid theory" that also describes electrons in metals. The superfluid transition in helium-4 provided the primary test bed for the theory of "second-order phase transitions," which describes, for example, the onset of magnetism in materials.

While helium has helped theorists develop key concepts, experimenters working with ultracold helium have developed a reputation for old-fashioned ingenuity. Their experimental devices are usually mechanical contraptions that shake, spin, and squeeze helium to produce subtle but telling signals. By tradition, "you don't buy your instrumentation; you invent it," says John Goodkind, an experimenter at the University of California, San Diego. "You make it, you leak-check it, and you fix it."

Helium physicists are also known for seat-of-the-pants problem solving, slathering their refrigerators with soap and glycerin to plug elusive leaks so small only superfluid helium squeezes through, or using a condom to regulate the flow of gas.

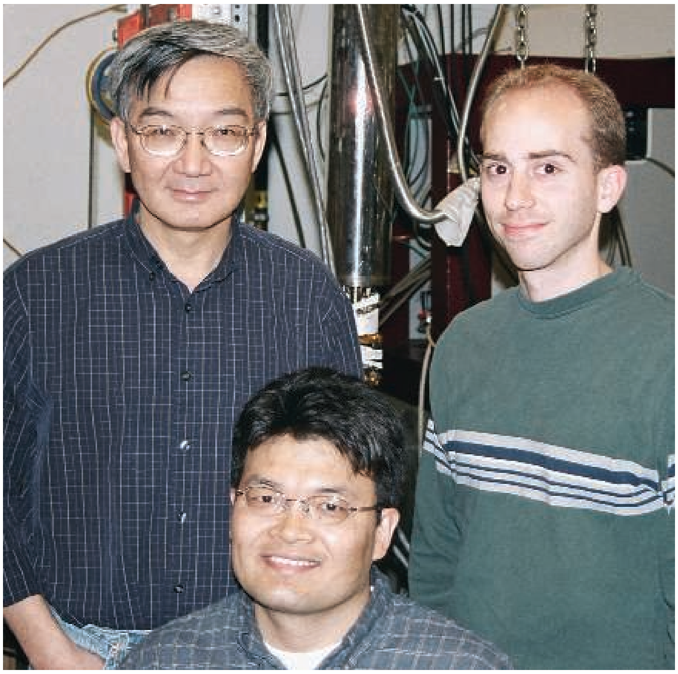
Never very big, the field of helium physics has contracted since its heyday in the 1970s. But researchers trained in helium physics have become leaders in high-temperature superconductivity, nanomechanical devices, two-dimensional electron systems, and other areas. "The people in the field are willing to take risks," says Richard Packard, an experimenter at the University of California, Berkeley. "They aren't afraid of making new devices, and when they go out into other fields, that same state of mind goes with them." –A.C.

Exchange, grains, and defects

Ohio State's Ho has no doubt that it can. He has come to Penn State to discuss the theory he is developing, which assumes that supersolid flow occurs and attempts to explain how swirls resembling smoke rings reduce the flow as the temperature increases. In a conference room on the third floor of Davey Hall, Ho stands beside a viewgraph projector and gestures at the screen with a length of half-inch threaded steel rod. "If it gets too complicated, then I apologize," he says. He's been talking for 90 minutes and will go on for another hour. He's covered blackboards on two walls with equations. It seems supersolidity has no easy explanation.

Theorists have already advanced several ideas, but most run afoul of the data in one way or another. For example, Andreev and Lifshitz's notion of a quantum wave of vacancies jibed nicely with the results of Kim and Chan's experiments with helium in porous glass, reported in January 2004 in *Nature*. It seemed plausible that, cramped by the nanometer-sized pores, the crystals would be riddled with vacancies. But this scheme appears less likely in the "bulk" crystal, as experimental evidence suggests that pure solid helium has very few vacancies. And if the vacancies are mobile, then they should quickly wander to the edge of the crystal and vanish, anyway.

If vacancies don't explain the flow, then perhaps some of the helium atoms themselves undergo Bose-Einstein condensation within the crystal. Leggett and others explored that idea in the 1970s. At first it sounds absurd: In a crystal, each atom is ordinarily confined to a specific site in the three-dimensional "crystal lattice," whereas in the quantum wave of a Bose-Einstein condensate it's impossible to say precisely where any particular atom is. But thanks to their quantum-wave nature, neighboring helium atoms have a tendency to swap places spontaneously in a process called "exchange." If they trade places often enough, then in principle some of them may be able to collapse into a single wave and flow in a way that leaves the pristine crystal structure unsullied.



Shaking things up. Moses Chan (left) and colleagues Eunseong Kim (center) and Anthony Clark have theorists debating whether a crystal can flow.

In actuality, that scenario may be unlikely, however. Leggett originally calculated that the amount of free-flowing helium would be tiny. And computer simulations suggest that a perfectly orderly helium crystal does not undergo Bose-Einstein condensation, as theorists David Ceperley of the University of Illinois, Urbana-Champaign, and Bernard Bernu of Pierre and Marie Curie University in Paris, France, reported in October 2004 in *Physical Review Letters*. "There's been a lot of speculation that somehow you can get a flow of atoms in a solid," Ceperley says in a phone interview. "I just don't think that's possible."

Some theorists have suggested that supersolid helium is really superslushy helium, with the flow occurring in liquid seeping between tiny bits of solid. Boris Svistunov and Nikolay Prokof'ev of the University of Massachusetts (UMass), Amherst, note that solid helium undoubtedly consists not of a single large crystal but of many smaller interlocking crystalline grains. They calculate that more conventional superfluid liquid flowing between the grains might account for Kim and Chan's data, as they reported this April in *Physical Review Letters*. But that explanation would require a multitude of micrometer-sized grains, whereas data indicate that helium tends to form fewer, larger grains.

The secret to supersolidity could lie in the conceptual middle ground between a flowing crystal and liquid flowing between crystal grains, says theorist Burkhard Militzer from his office at the Carnegie Institution of Washington, D.C. The flow could occur within the crystal, he speculates, but along elongated, immobile defects called "stacking faults," which resemble missed stitches in a piece of fabric. Simulations show that atoms swap places easily along the faults, Militzer says, but they do not yet prove that such faults account for Chan's observations.

More data, please

To sort things out, physicists are planning a variety of experiments designed to confirm the observation—and to explain why others had failed to spot the effect before.

In 1981, researchers from Cornell University in Ithaca, New York, and Bell Telephone Laboratories in Murray Hill, New Jersey, saw no evidence for supersolidity in torsional oscillator experiments similar to Chan's. But the researchers may have been foiled by bad luck and a bit of helium-3. The experiment most comparable to Chan's was contaminated with several parts per million of helium-3, says Cornell's John Reppy in a phone interview. "That would have been enough to wipe out the signal, according to Moses's [data]," he says. "I'm willing to believe it." Reppy and colleagues at Cornell are running yet another torsional oscillator experiment to try to reproduce the effect.

Others have searched for supersolidity by trying to squeeze solid helium through tiny holes. If the crystal is free-flowing then it might seep through, just as superfluid liquid helium will flow through openings so small they stop ordinary liquid helium dead. But the fact that solid helium cannot perform this trick may mean only that supersolid and superfluid helium respond to pressure differently, says John Beamish, an experimenter at the University of Alberta in Edmonton, Canada: "If it is a supersolid—and we're not saying it isn't—it doesn't flow as you would naively expect."

Curiously, over the past decade, experimenters studying the propagation of sound and heat in solid helium did see signs of a "phase transition." But they interpreted them very differently. John Goodkind and colleagues at the University of California, San Diego, found that the speed of sound in solid helium increases suddenly as the temperature drops below 0.2 kelvin, and the rate at which the waves die away peaks at that temperature. Goodkind interpreted these and other signs as evidence that some sort of defect proliferates as the temperature of the crystal increases and that these "defectons" undergo Bose-Einstein condensation *above* a critical temperature.

Goodkind hopes to resume his experiments, and Haruo Kojima, a physicist at Rutgers University in Piscataway, New Jersey, has begun sound experiments of his own. If supersolidity exists, then it should be possible to generate a sound wave in which only the free-flowing helium moves, explains Kojima, who has come to Penn State to discuss the experiments with Chan. But the experiments may be tricky, he warns, because researchers aren't sure precisely what signals they should expect to see.

For his part, Chan is devising an elaborate experiment to determine just how many vacancies, grain boundaries, and defects exist in a helium crystal. He plans to run a torsional oscillator in the beamline of a synchrotron x-ray source and to alternately shake the crystal and shine x-rays through it. The sloshing of the oscillator will tell how many atoms are in the crystal, while the scattered x-rays will reveal how many lattice sites there are in it. Only if the crystal is perfect will the two numbers be equal. The experiment may be the key to cutting through the confusion, says UMass's Svistunov in a phone interview: "To answer, how perfect is the crystal? In my opinion, that is the most important question in the field."

Meanwhile, in the sunless subbasement of Osmond Hall, Chan's young colleagues continue their work. Kim is taking data with a bigger oscillator that twists at lower frequencies. Graduate student Anthony Clark is studying solid hydrogen. In March, at the American Physical Society meeting in Los Angeles, California, Clark presented preliminary data that suggest hydrogen may also become a supersolid (*Science*, 8 April, p. 190). "I want to be completely confident," Clark says, "and we've been doing a lot of control experiments."

Both Kim and Clark say they feel intense pressure working on such potentially groundbreaking experiments. Chan takes the hubbub in stride, however. "Nobel Prize or no Nobel Prize, that doesn't matter. What's really nice is that [our work] has attracted so much attention" from other researchers, he says. "We have already had more fun than we deserve." He smiles wryly, like a magician who has pulled off a particularly clever trick. Only this time, not even the conjurer knows precisely how the trick works.

–ADRIAN CHO

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