Solid Helium-4 in Bulk Doesn’t Go With the Flow

New observations of an apparent superfluid component close loopholes in an earlier experiment, but present their own set of mysteries.

Suppose you could freeze the water in a washing machine while it was operating. Once the water had solidified, the machine’s agitators would cause the entire icy mass to oscillate—until the motor burned out. In January of this year, Eun-Seong Kim and Moses Chan, both at Pennsylvania State University, reported an experiment[1] that has some of the flavor of the washing-machine fantasy, but which yielded a surprising result (see PHYSICS TODAY, April 2004, page 21). They introduced liquid helium-4 into a torsional oscillator, solidified the liquid at high pressure, and lowered the temperature. When the temperature fell below about 175 mK, the period of the resonant oscillation also began to fall. About 1% of the ^{4}He in the oscillator appeared not to move with the bulk oscillation; it behaved as a superfluid would.

The ^{4}He, though, was embedded in Vycor glass, a highly porous material with a pore size just several nanometers across. That porous structure, with its large surface area, complicated the interpretation of the decrease in oscillation period. A conceptually cleaner experiment would use a torsion oscillator that contains an annular channel filled with solid ^{4}He. Kim and Chan have now done that bulk-helium experiment,[2] and the results are much like those of the earlier Vycor work and a subsequent similar experiment with porous gold. “Kim and Chan are clearly seeing something really fascinating,” says Robert Hallock of the University of Massachusetts Amherst. “I’m not sure what it means yet, but I trust their observations.”

Getting in the groove

In their bulk-helium experiment, the Penn State researchers introduced liquid ^{4}He into a narrow annular channel near the outside of the torsional oscillator illustrated in figure 1, and solidified the ^{4}He at high pressure. They then electrically drove the oscillator and measured the resonant period as they lowered the temperature of the solid; by changing the driving voltage, Kim and Chan adjusted the oscillation amplitude and thus the maximum speed of the channel.

As figure 2 shows, the resonant period began to decrease as the temperature fell below about 250 mK. The period drop was most pronounced for small maximum speeds and seemed to saturate below 5 μm/s or so. The drop in period indicates a corresponding drop in the moment of inertia of the material in the cell’s annular channel. Presumably, some of the solid material had decoupled from the bulk. That so-called supersolid was not participating in the overall oscillatory motion. When a magnesium barrier was introduced into the oscillator to block the annular channel, the change in period was reduced by a factor of about 60.

The observation of an apparent decoupling in the bulk solid answers a major concern that had been raised about the earlier experiments with porous media. Particularly in the tiny-pored Vycor, it was not clear what formed in the pores. One possibility was that a fluid layer lined the pore surfaces and was masquerading as a supersolid. Such a fluid layer may have been present in the bulk experiment too, but with a thickness of just an atom or two, it couldn’t have been responsible for the observed drop in period.

Conversely, the results in Vycor strengthen the interpretation that the bulk-helium observations were caused by the decoupling of a solid component from the bulk. The University of Alberta’s John Beamish points out that, absent the Vycor results, the decoupling might have had a more conventional explanation because solids are not entirely rigid and sometimes can deform. If one rotates a cup of coffee back and forth, Beamish points out, the coffee—a conventional viscous liquid, not a superfluid—does not rotate as quickly in the center of the cup as it does near the edge. If a similar effect were to occur with the solid ^{4}He in the oscillator’s annular channel, it could mimic decoupling. But that explanation is not compatible with the observed decoupling in the small pores of Vycor; all the coffee confined within a thin capillary will rotate together.

The drop in the bulk helium’s moment of inertia can be explained without invoking macroscopic supersolid flow. Anthony Leggett of the University of Illinois at Urbana-Champaign notes that one can’t rule out the possibility that Kim and Chan are observing a nonequilibrium phenomenon with a

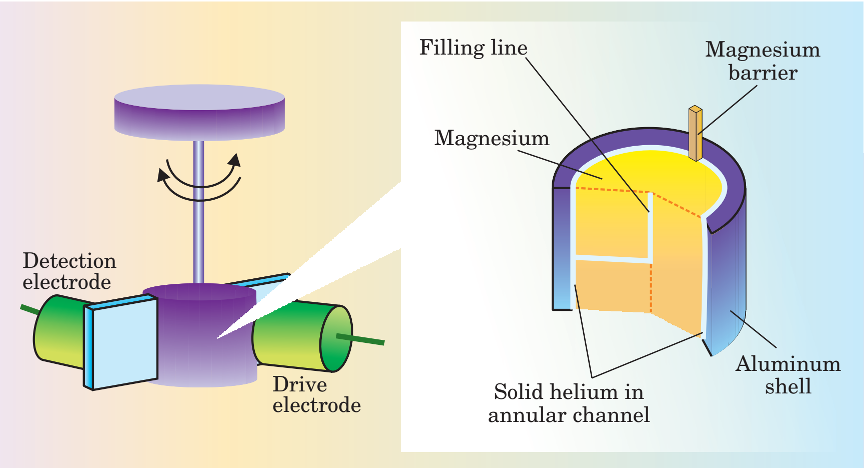

Figure 1. Torsion oscillator. Solid helium occupies a 1-cm diameter annular channel in a cylindrical cell suspended by a torsion rod. With the help of the electrodes attached to the side of the cell, a lock-in amplifier can keep the oscillator in resonance. The superfluid behavior observed in the cell goes away when a magnesium barrier blocks the channel. (Courtesy of Eun-Seong Kim and Moses Chan.)

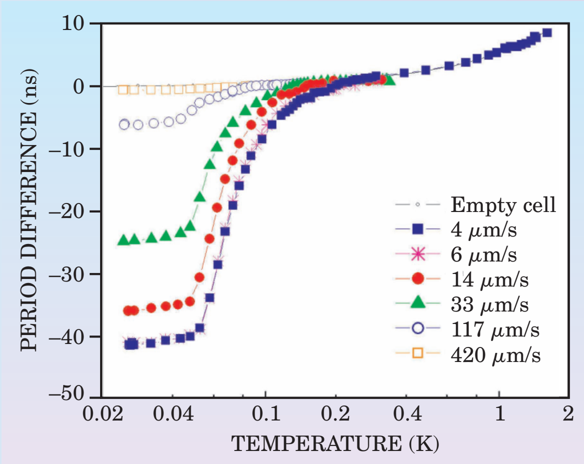

Figure 2. A decrease in period at low temperature. When an oscillator with an annular groove containing solid helium is cooled below 250 mK, the period decreases. (The period difference is defined relative to the period at 300 mK.) That decrease implies a drop in the moment of inertia—apparently some of the solid is not participating in the general oscillation. At lower temperatures, the drop in period increases as the maximum speed of the helium decreases. For this experimental run, the pressure of the helium was 5.1 MPa. Experiments at a variety of pressures suggest that the period drop saturates below about 5 μm/s. (Courtesy of Eun-Seong Kim and Moses Chan.)

relaxation time greater than the 1 ms period of their oscillator. And Nikolay Prokof'ev and Boris Svistunov (both at UMass) have suggested that the material that decouples is restricted to the crystalline boundaries that form as ^{4}He freezes.

But a supersolid component in the bulk is a plausible interpretation of the Kim and Chan observations. What can be responsible for the decoupling of a solid component? In an article commenting on the bulk-helium experiment, Leggett offers three possibilities—vacancies, large defects such as dislocations, and quantum-mechanical exchange associated with atomic wavefunction overlap.[3] All three possibilities have their problems.

No support from pressure

A 2002 experiment conducted by John Goodkind at the University of California, San Diego, inspired Kim and Chan's explorations. That experiment was interpreted in terms of a Bose–Einstein condensate (BEC) in solid, bosonic ^{4}He, mediated by vacancies or dislocations that were thermally activated at temperatures above 200 mK. Some 30 years earlier, Alexander F. Andreev and I. M. Lifshitz and, independently, Geoffrey Chester had raised the possibility of a condensation of zero-point vacancies or defects.

Kim and Chan reasoned that if they solidified ^{4}He in Vycor, the incommensurate shapes of crystal lattice and small pore would enhance the number of vacancies and so increase the chances of seeing a supersolid component. According to that logic, one would expect the amount of supersolid behavior to decrease when the ^{4}He was frozen in the larger pores of porous gold, and to be still less evident in bulk ^{4}He. But that was not the case. Moreover, it is experimentally and theoretically far from clear that bulk ^{4}He at low temperatures has enough vacancies (or dislocations) to support supersolid flow.

On the other hand, notes Beamish, the Vycor and Goodkind experiments were very sensitive to ^{3}He contamination. (Kim and Chan plan to investigate whether the bulk-helium system behaves similarly.) Since dislocations can be pinned by very small impurity concentrations, the ^{3}He may be providing a clue that dislocations are important after all.

The possibility of atomic exchange arises because solid ^{4}He has an unusually large zero-point motion: The root-mean-square displacement of an atom at absolute zero is 30% of the crystal lattice spacing. Significant wavefunction overlap could lead to neighboring atoms swapping positions. If the exchange is frequent and extensive enough, decoupling could result. "That's the most intriguing possibility of all," says Leggett, "though I'd bet against it."

Intuitively, one might expect that the effects of vacancies, dislocations, and exchange would depend significantly on pressure. Thus, one of the mysteries of the bulk-helium experiments is that the low-temperature limit of the supersolid fraction exhibits no discernible dependence on pressure. Figure 3 presents the evidence. Kim and Chan are working to reduce the scatter in their current data. They hope that more uniform cooling of the ^{4}He will do the trick.

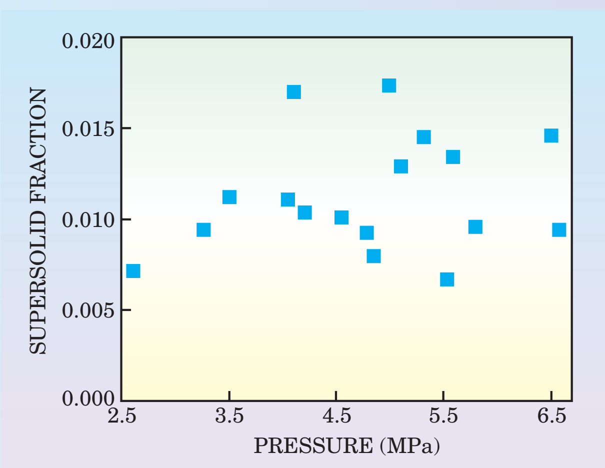

Figure 3. No trend. The fraction of helium-4 that behaves as a supersolid in the low-temperature limit shows no evident dependence on pressure. That's surprising if the supersolid behavior results from vacancies, dislocations, or atomic exchange in the ^{4}He lattice. (Courtesy of Eun-Seong Kim and Moses Chan.)

BEC or friction free?

Supersolid motion could be manifested as a metastable persistent flow or as a genuine equilibrium phenomenon sometimes called nonclassical rotational inertia. According to Leggett, the jury is out on whether the latter inevitably implies the existence of a BEC; the link between metastable flow and Bose–Einstein condensation is more tenuous. Instead of having the long-range correlations of a BEC, the system could simply have a small component of the ^{4}He somehow snaking without friction through the rest of the possibly deformed lattice.

The 5 μm/s critical velocity below which decoupling saturates hints that the supersolid may have long-range order. If the supersolid ^{4}He going around an annulus has such order, its speed will be an integral multiple of a characteristic speed determined by the atomic mass of ^{4}He and the radius of the annulus. For Kim and Chan's setup, the quantization speed is a bit over 3 μm/s. Thus, one possible explanation for the saturation is that the ^{4}He is a BEC and when the annular speed increases beyond a few micrometers per second, vortices (that is, states with nonvanishing speed quantum number) kick in and reduce the observed decoupling. To test that interpretation, Kim and Chan plan to repeat their experiment, but with a torsional cell containing ^{4}He in two concentric annuli. If the interpretation is correct, they should see different saturation speeds for the two annuli.

The nature and microscopic causes of what Kim and Chan have observed in bulk ^{4}He remain unresolved. The explanations that seem most natural have their deficiencies, which is just fine with Hallock. "Anytime somebody sees something that challenges what we know," he says with relish, "man, that's what it's all about!"

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References

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3. A. J. Leggett, *Science* **305**, 1921 (2004).

New Experiments Demonstrate Quantum Optics on a Chip

Researchers achieve coherent coupling between a superconducting quantum bit and a single microwave photon.

Reaching the limit where a single atom couples strongly enough with a single photon to exhibit coherent behavior has been a major focus in quantum optics for much of the past two decades. That strong coupling limit is hard to achieve because photons and atoms interact so weakly in general. But by placing an atom inside a small optical cavity bounded by mirrors that are reflective enough to trap a photon for hundreds or thousands of roundtrips before it escapes, researchers can strengthen the interaction.

According to quantum electrodynamics (QED), the vacuum field of the cavity fluctuates, polarizing the atom that enters it; in return, the induced atomic dipole fluctuates, polarizing the cavity field, an interaction that prompts the exchange of a photon. As a result, an excited atom placed within an optical cavity tuned to the frequency of the atomic transition can repeatedly emit and reabsorb a photon at a characteristic rate known as the vacuum Rabi frequency.

In 1992, a group led by Jeffrey Kimble of Caltech observed strong coupling in the splitting of the eigenvalue spectrum from this oscillatory exchange of energy between single atoms and an electromagnetic cavity mode.[1] Kimble and his collaborators passed a dilute, thermal stream of atoms through the cavity so that only one, on average, would contribute to the interaction. Since then, cavity-QED researchers have gradually prolonged the dwell times of individual atoms in their cavities by using laser-cooling techniques (see PHYSICS TODAY, January 2004, page 16). Exploiting such advances, for example, Gerhard Rempe and colleagues at the Max Planck Institute for Quantum Optics in Garching, Germany, recently reported probing the energy spectrum and splitting from a single trapped atom interacting with the cavity field.[2]

Meanwhile, condensed matter researchers have refined their own techniques by customizing mesoscopic structures like semiconducting dots, wells, and gates, and superconducting junctions that can behave like atoms. Two separate research groups—one at Yale University and one at Delft University of Technology—now report observations of strong coupling in all-solid-state implementations of the cavity-QED concept using circuit elements that play the role of a two-level atom and cavity. The notion of quantizing electrical circuits has been around for a half century, but the technology required to minimize the dissipation in mesoscopic objects millions of times larger than a single atom has matured only in the past few years.

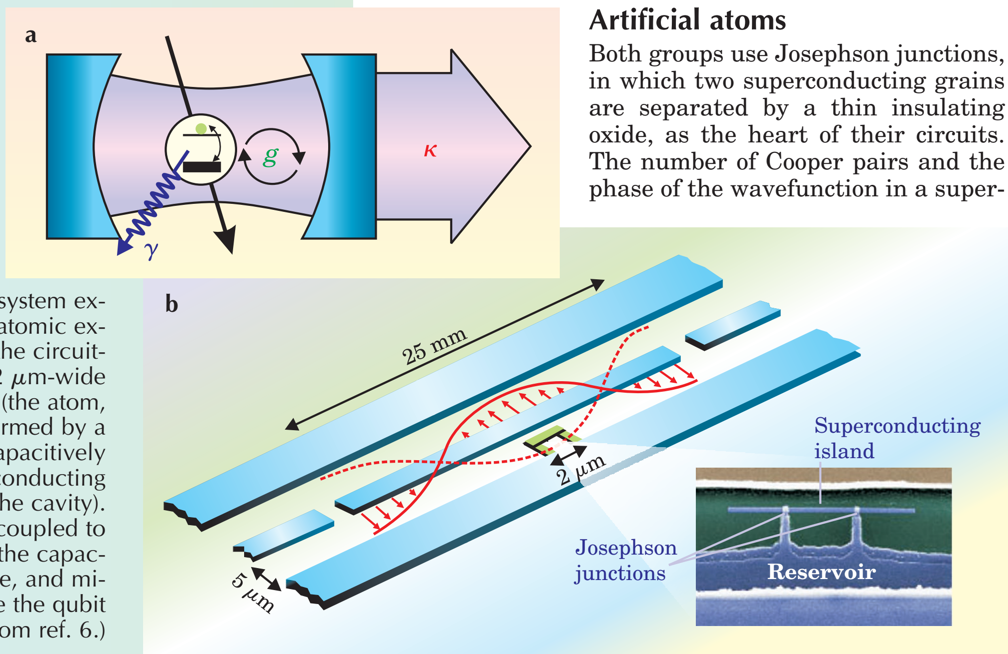

Figure 1. In cavity QED, an atom dropped through a pair of mirrors **(a)** strongly couples for a brief time with a single mode of the electromagnetic field. The coherent rate of interaction (g) is higher than both the rate at which photons leak through mirrors (κ) and the rate of spontaneous decay (γ). The system exists as a superposition of an atomic excitation and photon. **(b)** In the circuit-QED analog, a 2 μm-wide Cooper-pair-box qubit (the atom, green) sits in the antinode formed by a standing microwave in a capacitively coupled section of a superconducting transmission waveguide (the cavity). Input and output signals are coupled to the waveguide resonator via the capacitive gaps in the center line, and microwave pulses manipulate the qubit state. (Adapted from ref. 6.)

Artificial atoms

Both groups use Josephson junctions, in which two superconducting grains are separated by a thin insulating oxide, as the heart of their circuits. The number of Cooper pairs and the phase of the wavefunction in a super-