S. OGDEN

John Reppy holds up a torsional oscillator used in his experiments.

THE SUPERSOLID'S NEMESIS

John Reppy has come out of retirement to question the high-profile discovery of a new kind of quantum matter.

BY EUGENIE SAMUEL REICH

The fourth time he is asked what the dental floss is for, John Reppy seems to hear. He picks up a pair of scissors, and starts snipping away at the plastic strands wound round the shiny beryllium–copper components of his torsional-oscillator experiment. "I want to make a change to it anyway," he says. As he snips, pieces of wire and piping begin to pop out of the neat cylindrical column he has built, making it completely clear what the floss is for: to hold everything down.

The pieces of this experiment, in a basement lab at Cornell University's Clark Hall in Ithaca, New York, span more than half of Reppy's 50-year career studying the behaviour of helium cooled to ultra-low temperatures. Near the top of the metre-long column is a 30-year-old refrigeration unit that Reppy found among the bric-a-brac in his lab a few years after he signed up for retirement. Below that is a torsional oscillator of the type he invented in the 1970s — a cylindrical vessel, just a few centimetres across, that is free to twist back and forth around a rod running down the centre of the cylinder. When the vessel is filled with the isotope helium-4 via pipes wrapped around the column, and when its temperature is gradually lowered, changes in the oscillation frequency reveal changes in the physical properties of the helium. At two-tenths of a degree above absolute zero, for example, the helium-4 condenses into a solid crystal — and may even turn into a 'supersolid', a strange quantum state in which some of the atoms seem to pass through others without friction.

Or it may not. In recent months, the results from his apparatus have led the 79-year-old, semi-retired Reppy to become a vocal critic of a 2004 claim by physicists Moses Chan and Eun-Seong Kim that they had formed a supersolid in Chan's laboratory at Pennsylvania State University in University Park. The stakes are high: other such macroscopic-scale quantum effects, such as superconductivity and superfluidity, have won their discoverers Nobel prizes. And Reppy knows his criticisms are raising hackles in the field. Others have replicated Chan and Kim's results, yet no one has replicated Reppy's contradictory finding. "My result is a bolt out of the blue," he admits.

Nonetheless, as the inventor of the modern torsional-oscillator apparatus, and as Chan's former supervisor, Reppy has a professional stature that makes his views impossible to ignore. "He's come up with a lot of inventive, clever experimental techniques, and always manages to pick out the experiment that reveals what's really going on," says David Lee at Texas A&M University in College Station, one of the winners of the 1996 physics Nobel prize for the discovery of superfluidity in another isotope of helium, helium-3, work done while he was at Cornell.

HEART OF THE MATTER

The roots of the supersolid controversy go back to 1969, when Russian physicists predicted a state of solid matter in which gaps, or vacancies, in a crystal structure could move together as a single quantum wave — a collective motion reminiscent of the frictionless flow of a superfluid.

In 2004, Chan and Kim reported the first experimental evidence consistent with this 'supersolid' behaviour[1,2]. They found that the back-and-forth swings of a torsional oscillator filled with solid helium-4 sped up as the temperature was lowered to below two-tenths of a degree above absolute zero — just as would be expected if a supersolid were forming inside. The idea is that the zero-friction quantum effects predicted by the Russians effectively decouple some of the atoms in the solid and prevent them from oscillating along with the rest of the atoms. This makes the inertia of the oscillator smaller than the total quantity of helium would suggest, which leads to the faster oscillations. Chan and Kim's claim prompted enormous excitement, and about a dozen researchers began building torsional oscillators in a bid to replicate the observation.

Reppy was one of them. When Chan and Kim first reported their results, Reppy was approaching the end of a five-year Cornell programme intended to ease older faculty members into retirement by steadily reducing their hours, teaching responsibilities and lab space. He was looking forward to a retirement spent rock-climbing — a field in which his reputation looms as large as it does in physics. A world-class climber since his student days, Reppy is famous for his invention and promotion of clean-climbing techniques, in which the nuts that hold the rope are wedged into existing, natural cracks in rock faces rather than banged in like pitons. He says he likes the technique not just because it is environmentally friendly, but because it is easy. And safe: when he talks about climbing, he doesn't emphasize the obvious excitement it gives him, so much as his caution. "You always climb with a partner," he says.

But with supersolidity promising a different kind of adventure, Reppy decided to make a comeback from retirement. When he heard that a fellow faculty member at Cornell had taken on a graduate student, Sophie Rittner, to replicate Chan and Kim's experiment, Reppy suggested that she work with him instead: just as in climbing, he needed a partner. Rittner did not immediately jump at the idea of signing on with a retired professor with a lab full of junk and no active research group. But it was obvious that Reppy would be a good supervisor for her work, as he had had a long career developing experimental tricks for studying superfluidity in helium-3. "I came to appreciate the fact that I had an adviser with a huge amount of time. He was super hands-on," says Rittner. Together they ordered the parts for a torsional oscillator, which Rittner constructed. Then every morning, Reppy came into the lab at about 7 a.m. and started the experiment going. He would stay until about 4 p.m.; Rittner came in later in the morning and stayed into the evening.

The pair soon saw the increased oscillation that Chan and Kim had reported. But in February 2006, they tried something new and got a surprise. After one run of recording data, Reppy and Rittner let the frozen helium warm up to just above 1 kelvin, and then lowered the temperature again to repeat the run. The second time around, the speed-up was markedly diminished.

Heating and then recooling a crystal, a process called annealing, is in general expected to remove defects in the crystal structure. To Reppy and Rittner, the implications of their observations were clear: the supersolid signal was not due to an intrinsic quantum behaviour of a pure crystal, but was somehow caused by disorder in the structure, which is why it went away when the defects did.

IN A SPIN

When Rittner presented the results[3] at the March 2006 American Physical Society meeting, there was something of an uproar, she says. "People were saying 'what is this?'" The findings threatened to make supersolidity substantially less interesting, because effects caused by imperfections and impurities often turn out to be impossible for theoretical physicists to calculate exactly. Even now, six years after Chan and Kim's experiment was published, there is still no comprehensive theory of supersolidity. And when Rittner gained her PhD, she decided to move on to a different research field.

Left on his own, Reppy — an inveterate tinkerer — was soon trying to improve his apparatus. Picking up a box containing many of his historical torsional oscillators, he gives it a rattle, selects one and points out an interesting ridge. He loves to shape the metal pieces himself, he says. And with no more administrative duties to distract him, he adds happily: "I can spend all my time in the machine shop."

One of Reppy's first moves after Rittner left was to make a new oscillator vessel, which, instead of holding the helium in a ring-shaped channel

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Craftsman at work: Reppy loves to fashion the parts he needs for his research.

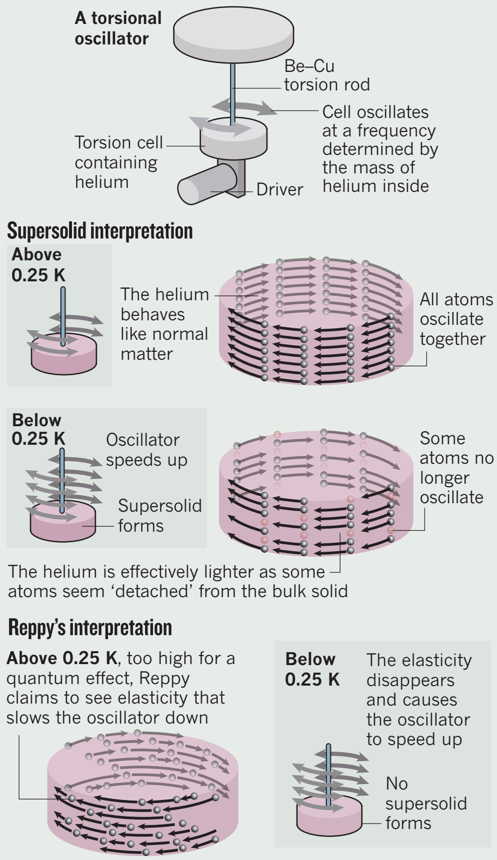
circling the cylinder's rim, also included a channel across the middle. He filled the oscillator with helium-4, ran the apparatus and verified that he saw the faster oscillations attributed to a supersolid. Then he blocked one side of the ring, so that the putative supersolid could flow only through the central channel and the other side of the ring, and found that the signal decreased — just as the supersolid theory would predict. But then he also blocked the central channel to try to stop the supersolid flowing at all, which should have made the signal go away entirely. But it didn't. Thinking that there must be a leak, Reppy tried several variations — including just watching to see if the helium-4 escaped like air out of a balloon. It didn't.

Reppy has never understood this observation, and hasn't published it. But the unexpected behaviour planted a seed of doubt in his mind: was the formation of a supersolid the true explanation for the effects that everyone had seen? There were other discordant findings too. For example, liquid helium-4 ought to be able to flow through a solid helium-4 barrier if that solid contains some supersolid. But neither Reppy and Rittner, nor a group led by John Beamish at the University of Alberta in Edmonton, were able to observe this.

By late 2009, Reppy had tinkered with his apparatus yet again, adding a diaphragm on top that allowed him to deform a sample during a measurement run. Following up on the possibility that disorder was involved in supersolidity, he wanted to see if he could increase the amount of supersolidity in a given sample by using the deformation to introduce more defects. The results of this experiment were totally unexpected: Reppy found no evidence of a supersolid signal at all — at least, not at ultra-low temperatures. Instead, the deformation produced a decrease in the oscillation frequency at higher temperatures — so high that the jiggling of atoms would be expected to destroy any quantum effect such as supersolidity.

SUPERSOLID OR NOT?

Experts disagree on whether helium enters a rare quantum state at very low temperatures



SOLID GROUND?

The publication of these results[4] in June 2010 caused another stir, including a news article in *Science* claiming that the evidence for a supersolid was "slipping away"[5]. In a commentary in *Physics*[6], Beamish suggested that Reppy had discovered a kind of "quantum plasticity", an effect in which solid helium-4 radically increases its softness as its temperature is raised, then stiffens again as the temperature is lowered. That stiffening would cause the frequency of a torsional oscillator to increase and mimic the supersolid signal. Reppy has embraced that idea and interpreted his results as a repudiation of supersolidity — an indication that he, Chan, Kim and everyone else had in fact been seeing the disappearance of the previously undetected quantum plasticity at low temperatures. He insists that he takes no joy in that conclusion. "I'm disappointed that this is turning out to be something other than a supersolid," he says.

But others in the community are not so convinced. Is the evidence for supersolidity really slipping away, or does Reppy just have anomalous equipment? Sebastien Balibar, an expert on helium-4 at the École Normale Supérieure in Paris, says he believes two novel effects have been discovered — supersolidity and a radical change in elasticity, something akin to Beamish's quantum plasticity. Without meaning to, Balibar says, Reppy configured his vessel to be especially sensitive to changes in the elastic properties of the material — perhaps because the stiffer helium-4 at lower temperatures was effectively gluing together parts of his experimental chamber, and producing a heavier oscillator.

Asked about that possibility, Reppy whisks the visitor out of his lab to a blackboard in a breezy corridor, where he chalks out a calculation showing why he feels the gluing hypothesis is extremely unlikely.

Even so, Reppy is having difficulty getting others in the field to share his doubts about the supersolid. Kim and his colleagues have just published additional results[7] showing what they say is conclusive evidence for formation of a supersolid. Reppy has seen Kim's work, and says that he feels the problem presented by his own results hasn't yet been addressed properly. But the field of supersolid helium-4 is too small and collaborative for Reppy's result to be ignored. Chan — for one — naturally bridles at the suggestion that the supersolid interpretation is in trouble, but he has also asked Reppy to collaborate, to gain a better understanding of his equipment. Chan points out that even when Reppy and Rittner replicated the 2004 experiment, they were reporting supersolid fractions of 20% — 20 times greater than the 1–2% measured by other groups. He takes that as evidence that there's a secondary effect at work in Reppy's apparatus that is swamping the supersolid signal. Chan hopes that could be understood by testing the vessel's response when filled with better-studied superfluid helium-3.

Meanwhile, Reppy's latest, unpublished, results are giving him new cause for doubt. These data were taken with a secondary oscillator added to the bottom of his experiment, which allows him to vary the frequency of the vessel's oscillation. His preliminary finding is that the response of the helium-4 sample depends on that frequency — which would not be the case if the helium-4 was a supersolid. But, Reppy wonders, doodling with chalk on a cartoon sketch of his vessel, could this be a way to turn the critiques of his experiment into a bonus? He starts drawing an alternative configuration of the apparatus, in which he could produce the first measurement of the elasticity of helium-4. Asked what light that would shed on the formation — or otherwise — of a supersolid, he shrugs. "I don't know," he says.

Chan says that in a similar situation, with an experiment giving very surprising results, he probably wouldn't have published anything. But researchers in this field are having to feel their way experimentally because of the absence of a guiding theory. And, as tends to happen with a quintessential experimentalist, Reppy's caution inevitably gives way to dogged determination once he is confident that each result is real. "That 20% — he knows it's unusual, but he felt compelled to publish it," Chan says. "Whatever way it turns out, I think respect for him will grow." ■

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Eugenie Samuel Reich *is a reporter for Nature.*

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