atoms[10]. Adding to the perspectives, one can think of quantum gases or liquids whose properties could be dramatically varied by manipulating the properties of giant few-body subsystems.

On a personal note, I well remember the time when the giant trimers made outstanding physicists raise their eyebrows. It has been heartening to witness the evolution of this miracle of quantum mechanics from questionable to pathological to exotic to being a hot topic of today's ultracold physics. The fairytale is becoming a reality.

Vitaly Efimov is in the Department of Physics, University of Washington, Seattle, Washington 98195, USA.
e-mail: efimov@u.washington.edu

References

1. Efimov, V. *Phys. Lett. B* **33,** 563–564 (1970).
2. Kraemer, T. *et al. Nature* **440,** 315–318 (2006).
3. Zaccanti, M. *et al. Nature Phys.* **5,** 586–591 (2009).
4. Braaten, E. & Hammer, H.-W. *Ann. Phys.* **322,** 120–163 (2007).
5. Ottenstein, T. B., Lompe, T., Kohnen, M., Wenz, A. N. & Jochim, S. *Phys. Rev. Lett.* **101,** 203202 (2008).
6. Huckans, J. H., Williams, J. R., Hazlett, E. L., Stites, R. W. & O'Hara, K. M. *Phys. Rev. Lett.* **102,** 165302 (2009).
7. Gross, N., Shotan, Z., Kokkelmans, S. & Khaykovich, L. Preprint at <http://arxiv.org/abs/0906.4731v1> (2009).
8. Barontini, G. *et al. Phys. Rev. Lett.* (in the press); preprint at <http://arxiv.org/abs/0901.4584v1> (2009).
9. von Stecher, J., D'Incao, J. P. & Greene, C. H. *Nature Phys.* **5,** 417–421 (2009).
10. Ferlaino, F. *et al. Phys. Rev. Lett.* **102,** 140401 (2009).

SUPERSOLID HELIUM

Stiffer but flowing

There is growing evidence that solid helium-4 possesses superfluid properties, but the nature of this paradoxical phenomenon remains mysterious. The finding that helium-4 in its 'supersolid' form is stiffer than the normal solid adds to the enigma.

Sébastien Balibar

Supersolidity describes the coexistence of solid and superfluid properties in a quantum crystal. The phenomenon was discovered in 2004 by Eun-Seong Kim and Moses Chan[1,2] when they measured the resonance period of a small cylindrical box oscillating around a torsion rod. The box contained solid helium-4, and below about 100 mK, the oscillation period decreased as if 1% of the helium mass had ceased moving with the box. The same method had been widely used for the detection of superfluidity in a liquid — in the absence of viscosity, the liquid in the box remains at rest while the box walls move. To find this property in a solid was rather surprising, but the experiments have now been reproduced by six other groups. Some single crystals had a superfluid fraction as small as 0.01%, whereas in quench-frozen samples, this fraction could be as high as 20% (for a review, see ref. 3).

Naively, one would think that, if solid helium-4 flows without friction, the elastic shear modulus, μ, of this solid should decrease, as it would resemble a liquid in some sense. But in 2007, James Day and John Beamish found the opposite[4]: at the temperature where the rotational anomalies are observed, μ increases by a large amount, about 10%, as one would expect if the atoms were less mobile. Moreover, both the temperature variation of μ and its dependence on the amount of helium-3 impurity seemed to be very similar to that of the rotational inertia. The results showed that there had to be a correlation between stiffening and mass flow. To understand this connection,

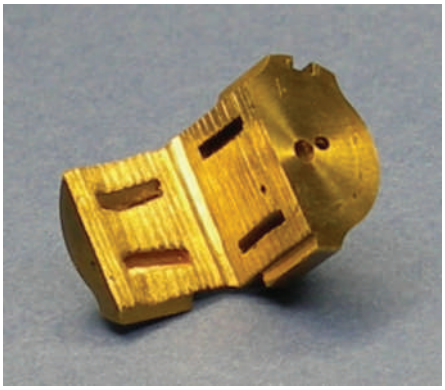

Figure 1 | Strong evidence. The 'strong' beryllium-copper cell used by West *et al.*[5] to demonstrate that supersolidity exists in solid helium-4, but not in solid helium-3. The cell has been cut to show the free annular space inside, which is filled with helium at low temperature and high pressure. The diameter of this annular space is 1 cm. Image courtesy of Joshua West.

the groups of Chan and Beamish now joined forces. On page 598 of this issue, Joshua West and colleagues[5] report a series of measurements that demonstrate that in solid helium-4, the mass is indeed far from being localized, and that there really is quantum superflow.

The experiments of West *et al.*[5] answer an important question that arose in the community following the first observation of unexpected stiffening in helium-4 (ref. 4): could the crystal stiffening mimic a decrease in rotational inertia, given that the oscillator period depends not only on the inertia but also on the total stiffness of the oscillator? West and co-workers have made careful measurements of both rotation and elastic properties[5] and show that this is not the case. More specifically, West *et al.* show that the stiffening results from the binding of impurities to defects in hexagonal crystals (in cubic crystals, no stiffening has been seen); and also that the stiffening cannot explain rotational anomalies that have a quantum nature. This was demonstrated by using an extremely strong cell (Fig. 1) where the contribution of the helium stiffness to the oscillator period is negligible. The rotational anomalies, therefore, must be due to a decrease in rotational inertia — a signature of supersolidity. Furthermore, when West *et al.* filled the strong cell with helium-4 (a Bose system), they observed both stiffening and a rotational anomaly, whereas when filled with solid helium-3 (a Fermi system), they detected stiffening but no rotational anomaly.

The work of West *et al.*[5] shows that the change in rotational inertia is really due to quantum motion of the helium-4 atoms. These experiments complement earlier observations that the mass flow is macroscopic (as it disappears in a cell that is blocked along its diameter[6]) and that the specific heat shows a peak in its temperature variation[7], which signals the existence of a true phase transition where the rotation and elastic anomalies take place.

Supersolidity exists. But the origin of this phenomenon is more mysterious than ever. The early experiments showed that disorder (in the form of dislocations in single crystals, grain boundaries in polycrystals, and glassy regions in quenched samples) has an important role in supersolidity[3]. But what kind of disorder leads simultaneously to a stiffening and to a macroscopic mass flow through the solid matrix? And how? To behave collectively as in a superfluid, atoms need to be able to exchange their positions. Without vacancies in the crystal, exchange seems impossible[8]. Defects can be considered as regions where there are vacancies, and numerical studies have found mass superflow inside dislocations, grain boundaries and glassy regions[9–11]. For macroscopic flow to take place, these defects need to be connected together. Is it possible that, at low-enough temperature, impurities bind to dislocations and prevent them from moving? This would explain the stiffening. Could the binding of impurities promote the connection of dislocations that then form a three-dimensional network and allow superflow? Perhaps, but one needs a very large dislocation density to explain the amplitude of the flow and the temperature at which supersolidity appears. Could fluctuations enhance supersolidity? Are they modified by the binding of impurities? And why should a theory based on dislocations apply to polycrystals where grain boundaries are already connected, and to porous media where similar effects have been observed?

Evidence for glassy behaviour in quench-frozen samples was found recently[12]. In my opinion, the mechanism is not the same as in single crystals or in polycrystals. In other recent work, Phil Anderson[13] has reiterated that supersolidity does not necessarily need disorder to take place, because the ground state of solid helium-4 may contain vacancies. This statement is in absolute contradiction of numerical studies. To me, it now seems important to check experimentally whether disorder is really necessary for supersolidity, or if it only enhances it. I'm no longer so sure. ❒

Sébastien Balibar is in the Statistical Physics Laboratory, Ecole Normale Supérieure and CNRS, 24 rue Lhomond, 75231 Paris, France.
e-mail: balibar@lps.ens.fr

References

1. Kim, E. & Chan, M. H. W. *Nature* **427,** 225–227 (2004).
2. Kim, E. & Chan, M. H. W. *Science* **305,** 1941–1944 (2004).
3. Balibar, S. & Caupin, F. *J. Phys. Condens. Matter* **20,** 173201 (2008).
4. Day, J. & Beamish, J. *Nature* **450,** 853–856 (2007).
5. West, J. T., Syshchenko, O., Beamish, J. & Chan, M. H. W. *Nature Phys.* **5,** 598–601 (2009).
6. Rittner, A. S. & Reppy, J. D. *Phys. Rev. Lett.* **101,** 155301 (2008).
7. Lin, X., Clark, A. C., Cheng Z. G. & Chan, M. H. W. *Phys. Rev. Lett.* **102,** 125302 (2009).
8. Prokof'ev, N. *Adv. Phys.* **56,** 381–402 (2007).
9. Boninsegni, M. *et al. Phys. Rev. Lett.* **99,** 035301 (2007).
10. Pollet, L. *et al. Phys. Rev. Lett.* **98,** 135301 (2007).
11. Pollet, L. *et al. Phys. Rev. Lett.* **101,** 097202 (2008).
12. Hunt, B. *et al. Science* **324,** 632–636 (2009).
13. Anderson, P. W. *Science* **324,** 631–632 (2009).

LUNAR SCIENCE

In the Moon's wake

In November 1998, when the annual Leonid meteor shower coincided with the New Moon, astronomers working in Texas noticed an unexpectedly high concentration of sodium atoms localized above the Earth. This 'Na spot' was identified as a stream of atoms escaping from the Moon. Now, a comprehensive study by Majd Matta and colleagues of the brightness of this spot over 31 consecutive lunar months has provided clues as to how sodium atoms escape the Moon's surface (*Icarus* http://dx.doi.org/10.1016/j.icarus.2009.06.017; 2009).

The Moon is known to have a thin and transient atmosphere made up of atoms that have been released from the lunar surface. One of the species detected so far is sodium, which can be picked up using Earth-based spectroscopic techniques. These measurements have shown that the sodium atmosphere extends to about 8,700 km — five times the lunar radius, R_M — on the side of the Moon closest to the Sun and to about 20 R_M on the dark side. This comet-like sodium tail is attributed to solar radiation pushing the sodium atoms away from the Sun.

All-sky observations made between 18–20 November 1998 at the McDonald Observatory in Fort Davies, Texas, revealed an intense spot of 589 nm light — the same wavelength as sodium D

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lines — in a 3° × 3° area of the night sky. This Na spot was seen near the antisolar point and only on the three nights of the New Moon, when the Earth is roughly aligned with the Sun and the Moon. The explanation was that the Moon's sodium tail was being focused by the Earth's gravitational field. It was also postulated that the spot was made particularly bright by an increase in the rate of sodium escape from the Moon's surface during the Leonid meteor shower, which had been at its most intense a couple of days earlier (it takes the sodium atoms roughly two days to travel the distance between the Moon and the Earth).

Matta and colleagues, using the El Leoncito Observatory in Argentina, spent almost two and a half years (from April 2006 to September 2008) monitoring how the intensity of this spot varies. Their aim was to determine whether increases in intensity coincided with any other form of astronomical activity, and thereby provide a better understanding of the mechanism by which the sodium atoms escape from the lunar surface.

Contrary to what was first thought, the team found little correlation between meteoric activity at the Moon and the lunar-tail brightness. There was also little connection between the Na-spot intensity and the flux of either solar-wind protons, which are thought to sputter sodium atoms from the surface, or solar photons, which could lead to photon-stimulated desorption. Matta *et al.* suggest that no single mechanism drives sodium expulsion exclusively, but stress that the ambiguity may be due to the absence of any appreciable meteor storms in the period of the study.

DAVID GEVAUX