

SOLID HELIUM

Supersolid: crystal or plastic?

The flow behaviour of solid helium at very low temperatures has recently generated as much controversy as excitement. An experiment looking directly at the grain boundaries offers fresh insights.

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The 'supersolid' experiments of Kim and Chan¹ reported in 2004 on solid helium have fascinated scientists to an extraordinary extent. In those torsional-oscillator experiments, a small cylindrical or toroidal sample was oscillated and cooled to low temperature. At the lowest temperature, below 200 mK, the period of the oscillator increased, the simplest explanation being that some of the helium inside is not entrained with the motion of the walls of the container but remains at rest with respect to the laboratory. A superfluid is expected to behave this way — but the helium is under high enough pressure to be a solid. Hence, the claim is that solid helium at low temperature possesses the long-range positional order of a crystal but the response to movement of a superfluid, and it has thus been called a supersolid (which does not mean that it is a very hard material). The microscopic explanation for this observation has been controversial. Now, Sébastien Balibar and colleagues have taken a direct look at the solid helium as it flows (or not), using a barometer setting rather than a torsional pendulum, and, writing in *Science*², suggest that grain boundaries play an important role in the phenomenon.

The supersolid phase was originally proposed by Andreev and Lifshitz³ in 1969, suggesting that any crystal having ground-state vacancies — that is, a mismatch at low temperatures between the number of lattice sites and the number of atoms — would form a Bose condensate and have superfluid properties. However, experiments and computer simulations find that for solid helium such a mismatch is not thermodynamically stable, and thus solid helium in the true ground state should not be a supersolid⁴. To make an analogy with electronic systems, solid helium should be an insulator, with its atoms localized around lattice sites, and if a fluctuation creates a vacancy–interstitial pair, that pair should be bound and quickly disappear without allowing net flow.

There have been several recent experiments indicating that defects may be responsible for the observations of Kim and Chan¹, but not point defects. Chan's group did exquisitely accurate



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Figure 1 A grain boundary in solid helium. In a path integral simulation of a quantum system, each atom is represented as a ring polymer. The grain boundary runs vertically through the centre of the crystal. One can see delocalization of the atoms in the grain boundary, which can lead to the formation of a two-dimensional superfluid.

heat-capacity measurements of solid helium. Bose condensation should have been easily detected as a characteristic 'lambda peak', which, however, was absent. In another torsional-oscillator experiment, Rittner and Reppy⁵ showed that annealing the sample, cycling the temperature up and down near the melting temperature, was sufficient to change an initial 'supersolid' crystal into a normal crystal. This suggests that the sample preparation is crucial to the observation of the supersolid, and that, in agreement with calculations, the better crystals do not show superflow. But such history dependence has not been seen in other laboratories.

In the experiment by Balibar and co-workers², a modern version of the classic barometer was filled with solid helium and immersed in a bath of pressurized liquid helium, so that one could see the liquid–solid interface at two different pressures. By visually measuring their heights, Balibar *et al.* were able to estimate the macroscopic flow resulting from the pressure difference. This was the first experiment in which direct inspection of the crystal was accompanied by measurement of the flow properties. And something surprising was discovered: The 'superflow' was directly related to the presence of grain boundaries at the solid–liquid interface (Fig. 1), which, presumably, extend into the solid. Without grain boundaries, no flow was observed. Balibar *et al.* speculate that grain boundaries are also responsible for the superfluidity in the torsional-oscillator

experiment of Kim and Chan¹. The observed temperature dependence is then the normal fluid–superfluid transition in a two-dimensional network of interfaces within the volume of the oscillator. Furthermore, the striking dependence on ³He concentration — on increasing the ³He concentration from 1 part per billion to 3 parts per million, the superfluid density was found to increase by a factor of 100 — could be explained by its role in creating and stabilizing the grain boundaries during crystal growth.

But the new findings do not resolve the puzzle completely. How do we explain the consistency of the results of Kim and Chan — that is, why do they see the same apparent superflow response in various porous media such as vycor glass, porous gold and bulk helium, and at various pressures? One would expect that the density of grain boundaries would be much greater in porous media. How does the very small amplitude of the oscillator produce such a large

angular momentum in the grain boundaries? Could dislocations, responsible for plastic flow in crystals, play a role? Lacking a measurement on a perfect helium crystal, measurement of crystal quality in the torsional oscillator would help resolve whether extended defects are involved in the superflow response.

What is emerging is that helium, long used as a testbed for ideas on quantum many-body physics including Bose and Fermi superfluidity, quantum crystals and magnetism, may also play a role in understanding the quantum mechanics of extended defects.

REFERENCES

1. Kim, E. & Chan, M. H. W. *Science* **305**, 1941–1944 (2004).
2. Sasaki, S., Ishiguro, R., Caupin, F., Maris, H. J. & Balibar, S. *Science* **313**, 1098–1100 (2006).
3. Andreev, A. F. & Lifshitz, I. M. *Sov. Phys. JETP* **29**, 1107–1113 (1969).
4. Clark, B. K. & Ceperley, D. M. *Phys. Rev. Lett.* **96**, 105302 (2006).
5. Rittner, A. S. C. & Reppy, J. D. Preprint at <<http://arxiv.org/cond-mat/0604528>>(2006).