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The enigma of supersolidity

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A 'supersolid' is a quantum solid in which a fraction of the mass is superfluid. As a remarkable consequence, it is rigid, but part of its mass is able to flow owing to quantum physical processes. This paradoxical state of matter was considered as a theoretical possibility as early as 1969, but its existence was discovered only in 2004, in ^{4}He. Since then, intense experimental and theoretical efforts have been made to explain the origins of this exotic state of matter. It now seems that its physical interpretation is more complicated than originally thought.

Quantum properties of matter are paradoxical, especially when they show up at the macroscopic level. This is true for superfluidity (Box 1), and even more so for the newly found supersolidity of solid ^{4}He. A solid is rigid because its atoms (or molecules) occupy particular positions in space — they are 'localized' — and are 'distinguishable', which means that an atom at one position can be distinguished from another at a different position. By contrast, a superfluid moves without friction because it is a collective wave of matter in which atoms are indistinguishable and delocalized. Given this, it is not clear how a system can be 'supersolid', which means being solid and superfluid at the same time. In a supersolid, part of the mass flows without friction through the rest, which remains solid, but there is no consensus on how this occurs. As will become evident, the enigma of supersolidity "continues to defy agreed theoretical explanation", as A. J. Leggett said recently[1].

In 2004, Kim and Chan[2,3] found some experimental evidence for this phenomenon in so-called torsional oscillator experiments on solid ^{4}He samples. Since then, several groups have confirmed that anomalies exist not only in the rotation properties[4–9] of solid ^{4}He but also in its elastic properties[10–13] and in its specific heat[14,15]. The whole set of experimental results strongly supports the hypothesis that solid ^{4}He is indeed a supersolid, but the interpretation of the data is probably not as simple as was proposed 40 years ago.

There is some consensus among theorists that supersolidity does not exist in perfect crystals[16,17] and that defects such as dislocations in single crystals, grain boundaries in polycrystals or glassy regions are necessary. However, this consensus is not universal, as Anderson[18–20] believes that supersolidity can be an intrinsic property of ideal crystals that is only enhanced by disorder. The goal of this Review is to summarize the present status of this intriguing field, to offer some possible interpretations of the observed phenomena and to raise some issues whose investigation could help solve the enigma of supersolidity. Three extensive review articles have already been published[16,21,22], but this subject evolves quickly.

From superfluids to supersolids

A classical liquid is made of atoms (or molecules) that move in a random manner such as to make the liquid viscous (Box 1). In a superfluid, however, atoms move coherently because together they form a macroscopic wave of matter. An important consequence of this coherence is that superfluids do not rotate like classical liquids: in a slowly rotating bucket, a superfluid stays at rest; it is not set in rotation by the moving walls. If the rotation speed is increased beyond a critical value, then some rotation appears inside the superfluid in the form of quantized vortices. The same is true for superconductors subjected to magnetic fields: a small field is totally excluded from the superconductor but beyond some threshold it may enter as so-called magnetic flux quanta, which are quantized vortices of electrical charges.

In a classical solid, each individual particle resides on one particular site — a lattice site if the solid is a crystal — and is localized such that the crystal is rigid and responds elastically to shear stress. A classical solid inside a box is forced to rotate with the box walls when the box rotates. However, in a quantum solid, particles fluctuate a lot around their average positions, with the result that atoms may exchange places with their neighbours. If this exchange is easy enough, some of the atoms may flow through the otherwise rigid network and some of the mass may stay at rest while the rest rotates. Eventually, if this flow becomes superfluid, the solid is said to be supersolid. Some of the mass is delocalized and the remainder is localized. The question to be answered is whether this paradoxical state of matter really exists.

Let us start with some early ideas. In 1969, Thouless[23] and, independently, Andreev and Lifshitz[24] considered a quantum crystal in which, at low temperatures, there could be 'vacancies', that is, empty sites where atoms are missing (Fig. 1). These authors further conjectured that such vacancies could behave like mobile quantum particles because they could easily exchange their positions with neighbouring atoms through quantum tunnelling. Anyone who has tried to solve a 16-tile magic-square puzzle knows that exchange is much easier in a lattice if there are empty sites. If the atoms are bosons, mobile vacancies should also obey Bose–Einstein statistics and could therefore undergo Bose–Einstein condensation, thus giving rise to superfluid-like behaviour below a certain temperature (Box 1). Crucially, a flow of vacancies being an inverse flow of mass, it should be possible to observe the coexistence of solid properties (an elastic response to shear stress) and superfluid properties (a fraction of the mass flowing without friction through the lattice). This was the original proposal for the emergence of a new 'superstate of matter' — a supersolid. Shortly after this suggestion, Leggett explained that the rotation of this solid should be anomalous, like that of a superfluid liquid[25]. The problem with this explanation is that it relies on the assumption that there exist vacancies in the zero-temperature limit, and that is far from obvious.

First sighting of supersolidity

The suggestion of a new state of matter was attractive enough that many research groups started looking for it[26], but the first indication of its existence was found in only 2004, by Kim and Chan[2,3]. They used a well-documented method for the detection of anomalous rotation, which had been used with superfluids. The experimental set-up consists of a torsional oscillator containing a cylindrical cell with an annular space filled with a sample material, such as liquid helium, suspended from a torsion rod (Fig. 2a). At resonance, the period, τ, of the oscillator is related to

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Box 1 | Superstates of matter

Superfluidity, superconductivity and now supersolidity — the list of superstates of matter is growing. These quantum states of matter differ significantly from classical ones. In a classical fluid, particles (atoms or molecules) move in a random manner and are distinguishable from each other. Owing to interparticle interactions, a classical fluid has a non-zero viscosity. However, in 1937 in Cambridge, UK, Allen and Misener[49] discovered that below a temperature of 2 K, liquid ^{4}He enters a new state, which moves without friction — a state named 'superfluid' by Kapitza[50], who made similar observations at the same time in Moscow[51]. A few months later, Allen and Jones[52] made spectacular images of fountains of superfluid ^{4}He. The image (courtesy of J. F. Allen, University of St Andrews) shows the famous 'fountain effect' (photographed in 1972). The inviscid flow of superfluid ^{4}He is produced by a small heater below the neck of the glass bottle. This motion could not be explained using the classical laws of thermodynamics and hydrodynamics, and triggered the proposal by London[53] and Tisza[54] that superfluid ^{4}He had to be a quantum fluid in which atoms are indistinguishable and accumulate in the same state in such a way that they all move together in a coherent manner — a phenomenon called Bose–Einstein condensation (BEC) that pertains to bosons. Helium-4 atoms are bosons, and it is now generally accepted that superfluidity is associated with a generalization of BEC that was explained in 1951 by Penrose[55].

There is a close analogy with electrical conductors. In an ordinary metal, electrical resistance is a consequence of the incoherent motion of electrons. However, Kamerlingh Onnes[56] discovered in 1911 (that is, more than two decades before the discovery of superfluidity) that at a sufficiently low temperature, some metals enter a 'superconducting' state in which the electrical resistance vanishes. In 1957, Bardeen, Cooper and Schrieffer explained this phenomenon as being due to the formation of a BEC of electron pairs[57,58] (the so-called BCS theory of superconductivity) — single electrons are fermions obeying Fermi statistics but become bosons when paired up. Similarly, the superfluidity of liquid ^{3}He was discovered near 2 mK by Osheroff, Gully, Richardson and Lee[59,60] in 1972, and it was shown that because ^{3}He atoms are fermions, they also need to form pairs to achieve a superfluid state. During the past two decades, it has also been shown that a similar BEC/BCS type of superfluidity can be realized in bosonic[61,62] and fermionic atom gases. In fermionic atom gases, it has also been shown how the superfluid transition can be tuned continuously from BCS pairing to a BEC of molecules as a function of the intensity of the interactions between the atoms.

As discussed in this Review, the great surprise today has been to find that a quantum solid may also be superfluid — a new state of matter called a 'supersolid'.

the rotational inertia, I, through the relationship $\tau = 2\pi(I/K)^{1/2}$, where K is an elastic constant determined mainly by the rigidity of the rod. The tell-tale sign of the superfluid transition is a shift in the resonance period of the oscillator because the inertia decreases when the material becomes superfluid — the superfluid liquid stays at rest while the walls of the box oscillate. The amplitude of the period shift thus varies with temperature, T, as the fraction of the liquid that is superfluid increases from zero to one as T decreases from the superfluid transition temperature to zero. Furthermore, this period shift is observed only for oscillation velocities smaller than a certain critical velocity (typically of the order of 1 cm s^{-1}), beyond which dissipation starts and superfluidity is destroyed.

The remarkable discovery by Kim and Chan in 2004 was that they observed a similar shift in the oscillator period in solid, not liquid, ^{4}He. At a temperature of the order of 100 mK, the oscillator period decreased (Fig. 2b), a behaviour that was absent in control experiments with either an empty cell or a cell filled with ^{3}He (recalling that ^{3}He atoms are fermions, unlike ^{4}He atoms, which are bosons (Box 1)). This was interpreted as a strong indication of supersolidity. The main difference from superfluid liquid ^{4}He was that, in Kim and Chan's sample, the magnitude of the shift indicated a superfluid fraction of the order of 1% of the total ^{4}He mass, but it seemed that at a sufficiently low temperature, and in agreement with Leggett's prediction, solid ^{4}He did not rotate like a classical solid.

The nature of supersolidity

Kim and Chan's discovery[2,3] triggered a period of intense activity, with several experimental groups trying to reproduce and better understand the data and many theorists trying to explain the observed phenomenon (see, for example, refs 16, 21 and 22). One of the critical issues early on was the question of whether supersolidity could be an intrinsic property of ^{4}He crystals, as originally considered by Thouless[23] and by Andreev and Lifshitz[24], or a phenomenon solely dependent on the presence of defects in the studied samples. The crucial point thus became determining whether there were vacancies in the ground state of a perfect ^{4}He crystal, that is, a crystal in equilibrium near $T = 0$ K, and whether the presence of such vacancies could explain the observed anomalies.

Several theorists looked at the energy cost and gain associated with creating vacancies in a crystal. On the one hand, removing one atom from a crystal lattice costs potential energy because bonds between atoms must be broken. On the other hand, if the vacancies are delocalized, they are shared by all atoms instead of being confined inside a 'cage' made by nearest neighbours (Fig. 1). Heisenberg's uncertainty principle stipulates that a confinement in position space results in a large uncertainty in momentum space and, consequently, in a large kinetic energy. Thus, a delocalization of the vacancies would entail fewer fluctuations of their velocity, meaning less kinetic energy; in short, the vacancies would gain energy by being delocalized. If the energy gain from the delocalization is larger than the potential energy cost of removing one atom from the crystal lattice, the balance is negative and the ground state must contain vacancies. In addition, if vacancies repel each other, they form a dilute gas, which can be superfluid. In such circumstances, the crystal would still be periodic in position space, but the number of atoms would be less than the number of lattice sites; the crystal would be 'incommensurate', and some of its mass, in the form of atoms jumping between the lattice sites owing to the presence of vacancies, could flow without friction. Below some superfluid transition temperature, it would thus become supersolid.

For a long time, the simple vacancy-based model of supersolidity looked possible. However, post-2004 Monte Carlo simulations showed that the above energy balance is positive and large[16,17,27]; it was found that the creation of vacancies costs more than 10 K (at the atomic level, energies are often measured in kelvin, a temperature unit that translates

into energy according to $E = k_B T$, where k_B is the Boltzmann constant). Because 10 K is much larger than 0.1 K, the typical temperature at which supersolidity was observed, the probability of vacancies existing under experimental conditions should be negligible, and they could not be responsible for the observed phenomena.

Importance of disorder

Despite some disagreement[18–20,22] about the validity of the Monte Carlo simulations mentioned above, it was then proposed that supersolidity might instead be caused by the presence of defects in the solid samples under study. Two possible types of defect were suggested, dislocation cores and grain boundaries (Fig. 3). One reason for this conjecture was that these are regions of the crystal where local stresses naturally give rise to the formation of vacancies, thus allowing the exchange of atoms and mass flow. Indeed, theoretical studies predicted[28,29] that part of the mass inside defects could, under the right circumstances, become superfluid and propagate along dislocations and grain boundaries connected in a three-dimensional network, thereby giving rise to the observed supersolid behaviour at the macroscopic level.

At this stage, two types of experiment seemed to confirm that disorder does have a crucial role in the supersolid-like behaviour. One line of experiments continued the exploration of alternating (a.c.) mass flow using torsional oscillators. Although Rittner and Reppy[4,5] reproduced Kim and Chan's findings[2,3], they also found that in annealed samples (heat treatment typically reducing the defect density in crystals) the rotation anomaly called 'non-classical rotational inertia' (NCRI) decreased to below the noise level in the measurements. By contrast, when performing the same type of measurement on quench-frozen samples, that is, in the presence of large disorder, the NCRI was found to be as large as 20% of the total helium inertia. Subsequent experiments by the group of Chan[30] later confirmed that annealing reduces the NCRI. However, this group found that even in their best samples, a very small fraction of the mass, of the order of a few parts in 10^4, still decoupled from the oscillating walls. Annealing did not completely suppress the rotation anomaly.

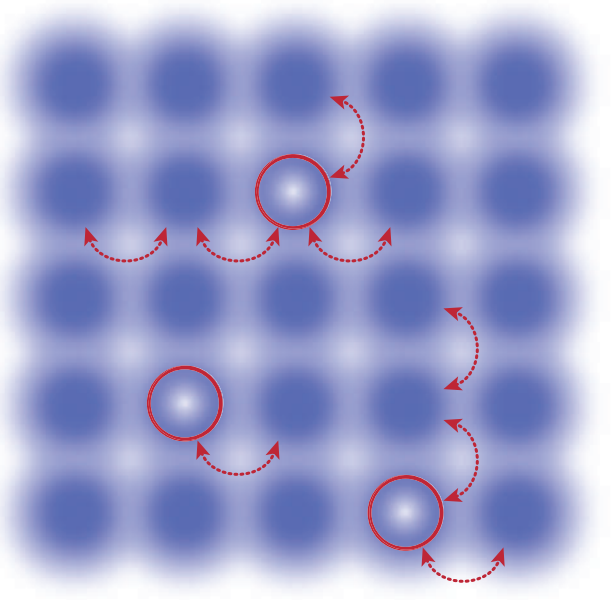

Figure 1 | Quantum tunnelling of vacancies. In the original model of supersolidity, the number of atoms is less than the number of lattice sites. The lattice thus contains vacancies (red circles), which are able to exchange their positions with neighbouring atoms (blue dots) so easily that they are delocalized throughout the whole system. These vacancies are bosons, which at low temperatures may form a Bose–Einstein condensate, that is, a macroscopic wave that extends throughout the system. As a result, the atoms themselves are not localized at particular sites as in a classical lattice. Some of the mass can flow without friction through the rest, which remains a rigid solid.

In any event, it became clear that the magnitude of the supersolid fraction strongly depends on the amount of disorder.

The other type of experiment was pursued by Sasaki *et al.*[31,32], who, instead of investigating a.c. mass flow in torsional oscillator experiments, decided to look for d.c. mass flow through a static, solid sample. To this end, they built a two-part sample cell containing various types of ^{4}He crystals in equilibrium with liquid ^{4}He. Using an optical cryostat, they monitored the respective levels of the liquid–solid interface in the two parts of the cell and measured their relaxation to the same height in the cell. As any level change would necessitate mass flow through the solid because of the different densities of liquid and solid ^{4}He, such an equilibration would signal supersolid behaviour. The experiments indeed provided evidence for superfluid d.c. mass flow, but only in polycrystals containing grain boundaries. No such flow was observed in single crystals. This then seemed to imply that grain boundaries are necessary for supersolidity. However, as indicated below, the lowest temperature that the experiments by Sasaki *et al.*[31,32] reached, 50 mK, today seems not to have been low enough to rule out the possibility of mass flow in single crystals.

Following the experiments by Sasaki *et al.*, more evidence was found that the few atomic layers forming grain boundaries might be supersolid[33]; however, evidence was also found that some mass could flow along liquid channels forming at the interface between grain boundaries and the cell walls or at points where grain boundaries intersect with each other[34,35]. In my opinion, the existence of d.c. mass flow inside single crystals of ^{4}He is not yet firmly established.

As the growth of solid samples at constant volume can lead to the formation of polycrystals with a high density of grain boundaries, in light of the above discussion the question became that of whether the observed supersolid behaviour in torsional oscillator experiments could also be attributed to mass flow along grain boundaries. To answer this question, Chan's group made new measurements[30] using torsional oscillators in which the cell was filled with single crystals of ^{4}He. They found that the period shift is smaller than in the corresponding experiments on polycrystals but is non-zero, indicating the presence of a supersolid fraction of 0.04–0.4%. It is therefore possible that although grain boundaries could be responsible for the supersolidity observed in polycrystals, supersolidity could also be exhibited by single crystals, in which the origin of the vacancy-induced mass flow more probably could be due to dislocations. However, the interpretation of the data was to receive yet another twist.

Pinning at ^{3}He impurities

The first experiments by Kim and Chan[2] had already shown that the phenomenon of supersolidity was very sensitive to the presence of tiny amounts of ^{3}He impurities. Helium-4 is extracted from oil wells where it accumulates owing to the radioactive decay of uranium in the Earth. In natural ^{4}He, there are about 0.3 parts per million (3×10^{-7}) of the light isotope ^{3}He. This may not seem much, but at low temperatures the quantum statistical nature of particles (^{4}He atoms being bosons and ^{3}He atoms being fermions) becomes important. This fundamental difference in quantum behaviour makes ^{3}He behave like a significant impurity in a ^{4}He system, even at such low concentrations.

The concentration of ^{3}He in ^{4}He can be controlled. In fact, it is possible to prepare ultrapure ^{4}He gas in which the concentration of ^{3}He is only one part per billion (10^{-9}). Experiments have found that the supersolid transition temperature depends on the presence of ^{3}He, even at such extremely low concentrations[10,11,36]. Because previous experiments had shown that ^{3}He impurities adsorb on dislocations at low temperatures[37,38], it was then suggested that the whole phenomenon could be attributed to how the properties of defects such as grain boundaries and dislocations, discussed above, are modified by the presence of ^{3}He atoms.

Unexpectedly, measurements in 2007 by Day and Beamish[10] and Day, Syshchenko and Beamish[11] found that the shear modulus, μ, increased at the onset of supersolidity (Fig. 4) — when the mass started to flow, they found that the solid ^{4}He became stiffer. This was surprising, as the naive expectation is that if part of the mass of a crystal starts flowing, the quantum solid should somehow more closely resemble a liquid, such that its shear modulus should decrease, contrary to what was observed.

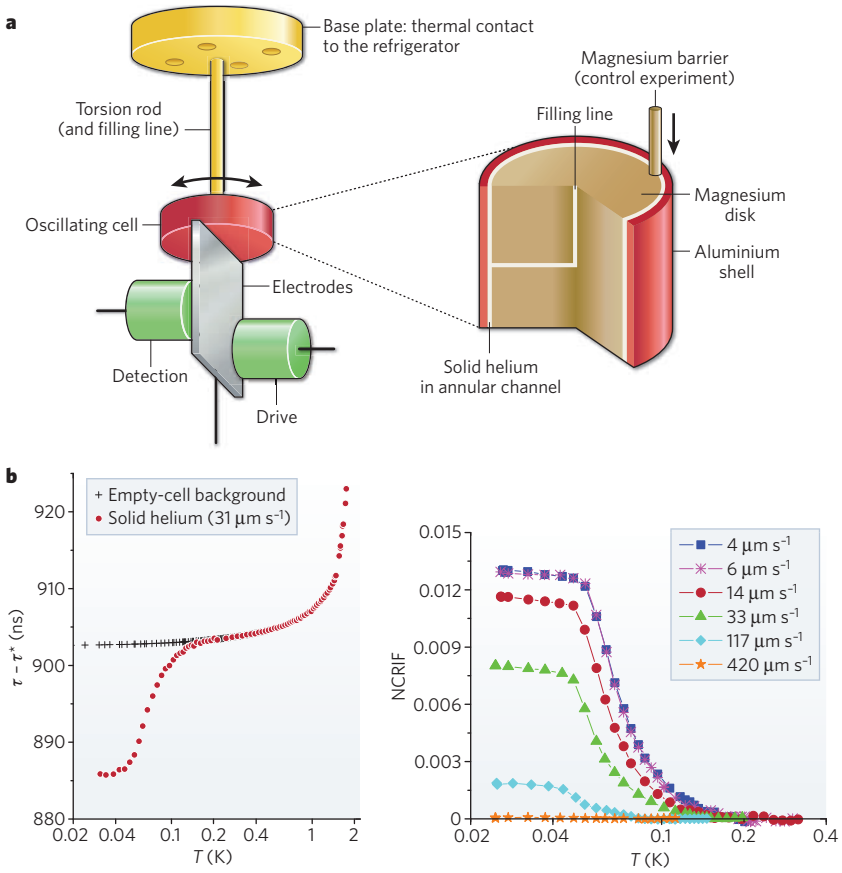

Figure 2 | First experimental evidence of supersolidity in ^{4}He. **a**, Schematic view of the experimental set-up in a typical torsional oscillator experiment by Kim and Chan[2,3]. The oscillating cell contains helium in an annular channel where the circulation can be blocked by inserting a vertical magnesium barrier. The helium is introduced in the cell through a filling line that runs vertically inside the torsion rod. Electrodes are used to drive and detect the oscillation of the cell, and consequently to measure its resonant period. This period is expected to decrease when solid helium becomes supersolid because a fraction of the helium mass stops moving with the oscillating walls of the box. This fraction is found to be 0.01–20%, depending on sample quality. When the magnesium barrier is inserted, the period change disappears. **b**, Left: one of the first measurements by Kim and Chan[2], showing that the period, τ, of their torsional oscillator decreases at temperatures, T, below about 0.1 K when filled with solid ^{4}He, relative to when the empty cell is used. The reference period, τ^*, is chosen as 971,000 ns for convenience. The maximum velocity of the cell rim in the experiment with ^{4}He is as indicated. Right: measurements, made by the same authors[3], where the period change is converted into the non-classical rotational inertia fraction (NCRIF) of the ^{4}He sample. At low temperatures, the NCRIF is of the order of 1%. Its value depends on the maximum velocity of the cell rim (as indicated) when this velocity is greater than 6 μm s^{-1}. (Panel courtesy of M. H. W. Chan, Pennsylvania State University, University Park, Philadelphia.)

These experiments further found that μ increased at temperatures below the same critical temperature at which the rotational inertia began to decrease in Kim and Chan's[2,3] experiments. In fact, the shape of the temperature variation of μ looks exactly the same as that of the NCRI, and even the dependence of the transition temperature on ^{3}He impurity content was found to be the same (Fig. 4).

Thus, these experiments[10,11] showed that the anomalies observed in both the rotational and elastic properties of solid ^{4}He have a common origin, which prompted Day and Beamish[10] to interpret the stiffening as follows. In a quantum crystal, dislocations can be highly mobile because they may have mobile kinks (Fig. 5). Kinks are regions where the dislocation lines shift from one atomic row to the next. Quantum fluctuations may allow kinks to tunnel from one lattice site to the next, and so induce motion of the whole line. Consequently, in measurements of the stiffness the response of the system to an applied stress is the sum of the usual lattice deformation plus a contribution due to the displacement of the dislocations. However, the mobility of dislocations should depend on temperature and on the ^{3}He concentration because ^{3}He impurities should bind to dislocations and pin them locally below a certain temperature. Below this temperature, which could be of the order of 0.1 K, the crystal should therefore be more rigid. This interpretation looked likely to be correct, but it left open an important question, that of the mechanism by which supersolidity is associated to the pinning of dislocations.

Torsional oscillator experiments revisited

In view of the above developments, the very existence of supersolidity was once again questioned. One proposal[39,40] suggested that the anomalies seen in torsional oscillator experiments could in fact be an artefact — it was suggested that the period shift perhaps was not due to a reduction of the inertia, I, in the relationship $\tau = 2\pi(I/K)^{1/2}$, but to an increase in the elastic constant, K. Naturally, the contribution to K of the helium stiffness would have been small in most experiments, but the period shift itself was small. The respective groups of Chan and Beamish collaborated to check this possibility[41]. They built a very strong cell in which the helium contribution to K was negligible. They found a definite period shift that had to be the consequence of a decrease in the rotational inertia[41]. Furthermore, they proved that the rotation anomaly is indeed associated with the quantum statistics of the ^{4}He; they found a similar elastic anomaly in solid ^{3}He, a fermionic system, but did not observe a rotation anomaly there (see ref. 41 for details on the importance of the crystal structure). Supersolidity thus seemed to have been confirmed.

The existence of supersolidity had in fact already been strongly supported by two other types of measurement. One type was the so-called blocked annulus experiment. Kim and Chan[3] and later Rittner and Reppy[42], with more accuracy, compared a torsional oscillator with a free annular space containing solid helium with a similar one in which the annulus was blocked along a diameter so as to interrupt the macroscopic circulation of mass (Fig. 2). In the experiments with a free annulus, a rotation anomaly signalling loss of inertia was found. In the blocked case, however, such an anomaly was not observed. Even though Reppy recently presented some puzzling results from measurements in a more complicated cell geometry[43], I believe that the rotation anomaly observed in torsional oscillator experiments in general is due to a macroscopic superflow. The other supporting experiments were done by Lin and colleagues[14,15]. They found a peak in the specific heat of solid helium at the temperature at which the rotation anomaly occurs. This is a strong indication that the phenomenon is a true phase transition, despite there being discussions about the magnitude of the peak relative to that of the inertia change[44].

At this point, I would like to mention a few interesting results related to the response time and frequency dependence of the torsional oscillator experiments. It has been found that as the frequency of the oscillations is increased, the supersolid transition temperature increases as well[7]. It also seems that the rotation velocity has a role similar to the thermal agitation[9]. Furthermore, Aoki *et al.*[7] and Penzev *et al.*[8] have shown that their oscillators are hysteretic at low temperatures: the

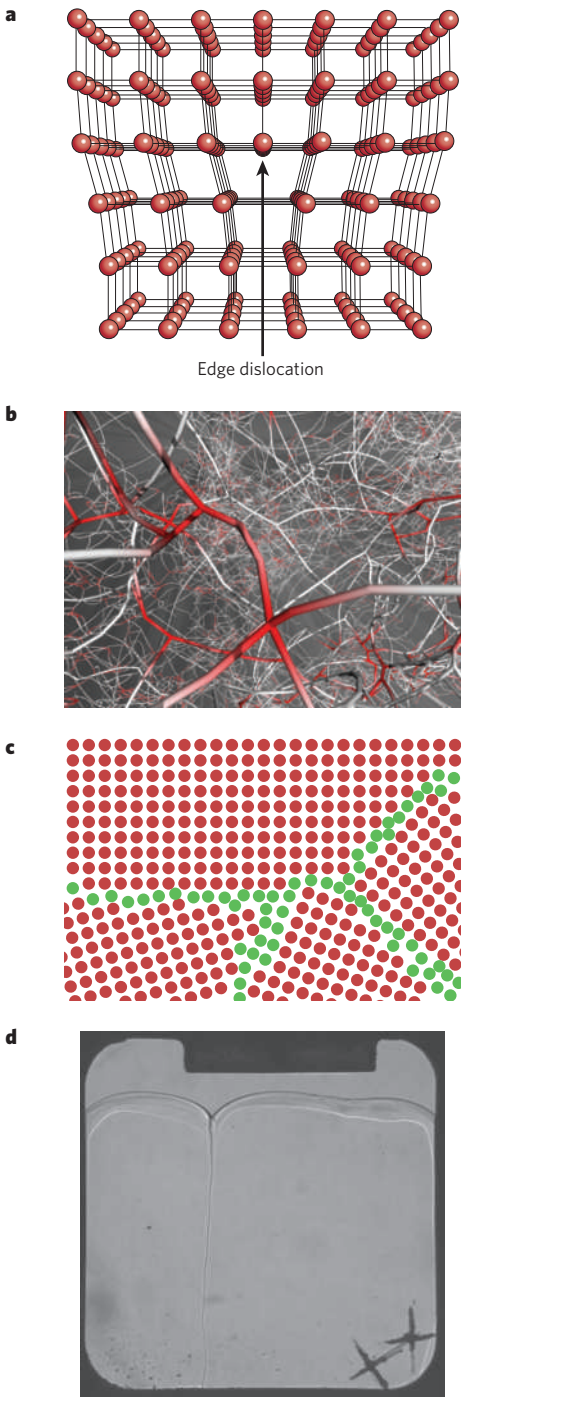

Figure 3 | Various defects in solids. a, In a single crystal, an edge dislocation is the end line of an interrupted lattice plane. **b**, Owing to their mutual attraction, dislocation lines usually organize themselves as three-dimensional networks. For a detailed description, see the ParaDiS project (http://paradis.stanford.edu). (Image courtesy of the ParaDiS project code team: A. Arsenlis, V. V. Bulatov, W. Cai, R. D. Cook, M. Hiritani, M. Rhee and M. Tang, Lawrence Livermore National Laboratory, Livermore, California.) **c**, In polycrystals, the boundaries (green) between crystal grains of different orientations are regions of atomic thickness where atoms are not ordered, owing to the competing influences of the adjacent lattices. **d**, Photograph of a vertical grain boundary between two helium crystals in equilibrium with liquid helium above. The cell height and width are 11 mm. It is enclosed by two glass windows. Two crosses are carved on the bottom right of the front window to help focus the camera. The photograph shows that a grain boundary is not a liquid region[32,34]. Indeed, as explained by Sasaki *et al.*[32,34], the groove it makes where it meets the liquid phase has a non-zero opening angle (of about 30°). As a consequence, grain boundaries may be supersolid (that is, solid and partially superfluid) but not entirely superfluid. (Image reproduced, with permission, from ref. 32.)

period decreases when cooling below 50 mK, but a subsequent warming does not bring the period to its first measured values. This observation leads to many questions, especially about the true value of the critical velocity measured by various groups (which ranges from a few micrometres per second to at least 100 times more). Eventually, Hunt *et al.*[9] showed that their oscillator has a response time that diverges near the transition temperature in a way that, as far as I know, has not been understood either.

It is not known what mechanisms are behind this set of observations. It could be the network of dislocations (or grain boundaries), which relaxes with a T-dependent time, or it could be the diffusion of ^{3}He impurities, which becomes slow at low T. A totally different picture was proposed by Anderson[18–20]. If mass really flows it may form vortices, and Anderson invoked a 'vortex liquid', that is, a tangle of interacting vortices. Because such vortices should interact with the crystal lattice, their proliferation near the supersolid transition temperature might lead to an increase in the rigidity. Furthermore, the properties of a vortex tangle should depend on frequency and temperature, but all these issues are open problems and are difficult to solve, especially if the sample disorder is unknown.

Towards a solution

Given the observations that I briefly describe above, I believe that even if supersolidity remains mysterious, it has really been discovered. It appears to be strongly dependent on disorder, and it seems that the supersolid transition is accompanied by a surprising stiffening of the samples.

To provide a better understanding of this set of observations, some groups have tried to maximize the NCRI by preparing highly disordered samples that in effect might be glassy. In my group, we have chosen an opposite approach that seems promising. Having optical control of the crystal growth[34,45], we know how to prepare polycrystals, disordered single crystals or very high-quality single crystals. The high-quality single crystals have been shown to be free of screw dislocations if grown at 20 mK (ref. 46). Day and Beamish's observations[10,11] of stiffening were done on polycrystals but not interpreted in terms of grain boundaries; to clarify this, we have made new measurements of the elasticity of ^{4}He, this time in single crystals with variable concentration of ^{3}He impurities[13]. Our most interesting result is on ultrapure single crystals (we have discovered a simple method to eliminate all impurities[47]), in which we also observed a stiffening[13], this time below 40 mK. This temperature is lower than has been observed in any other experiment. It is also the temperature below which the search for d.c. mass flow through solid ^{4}He should be repeated. In view of these observations, the pinning of dislocations by ^{3}He impurities cannot be the only mechanism responsible for the stiffening.

Interestingly, a new possible explanation for the observed stiffening in the absence of ^{3}He impurities was proposed by Kuklov and colleagues[48] in 2009. They theoretically predicted that dislocations could change state as a function of temperature. They calculated that at $T = 0$ K, a dislocation is a straight line that is anchored by the lattice and does not fluctuate. However, at a certain finite temperature, a transition occurs to a rough fluctuating state in which the dislocation line becomes mobile because it is invaded by kinks (Fig. 5). This 'roughening transition' could exist in the absence of ^{3}He and thus provide an explanation for the change in stiffness observed in experiments. The sensitivity to the presence of ^{3}He impurities is a consequence of the fact that kinks become dressed with ^{3}He atoms that attach to them (Fig. 5), such that a higher temperature is needed for their creation.

To verify these new ideas experimentally, it is necessary to see whether an ideal crystal free of impurities and dislocations shows stiffening at low temperatures. This experiment is in progress in our group, but it is not easy to observe a single dislocation. In addition, these are very delicate experiments because helium crystals are extremely fragile, probably owing to their quantum nature. If we succeed in showing that perfect, ultrapure crystals show no stiffening, the theory of Kuklov and colleagues[48] will be strongly supported. If the crystals do show stiffening, it will be necessary to search for another origin of the stiffening, which

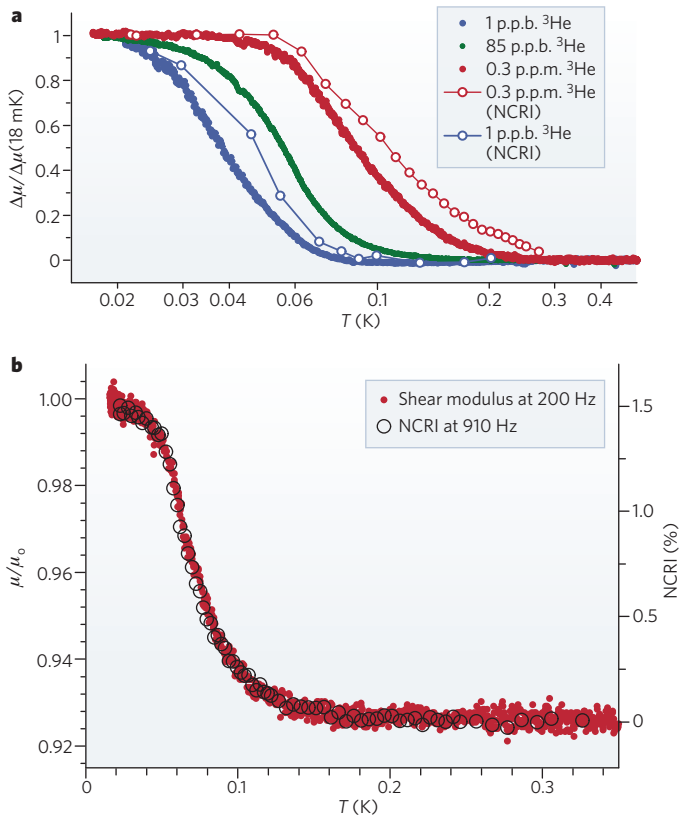

Figure 4 | Stiffness measurements and the role of ^{3}He impurities. a, The original measurements by Day and Beamish[10] of the variation of the stiffness of ^{4}He crystals as a function of ^{3}He impurities. For comparison, measurements by Kim and Chan[3] of the NCRI are shown on the same graph (see key). Both the stiffness and the NCRI are expressed as variation in shear modulus, μ, at temperature T relative to the variation at 18 mK. p.p.b., parts per 10^9; p.p.m., parts per million. (Panel reproduced, with permission, from ref. 10.) **b**, Further measurements have shown an even more striking similarity between the temperature dependences of the shear modulus and the NCRI: after adjustment of the vertical scales, the two sets of data shown coincide (μ_0 is the low-temperature value of the stiffness). This is very strong evidence that the rotation anomaly and the elastic anomaly have a common origin. (Panel courtesy of J. D. Beamish, University of Alberta, Edmonton, Canada.)

could perhaps be explained by Anderson's vortex liquid picture[18–20].

Naturally, we will also have to see whether the same ideal crystals show a rotation anomaly. For this, we need a transparent torsional oscillator to be able to monitor the growth and measure the crystal orientation, which is an important parameter that should be explored. This experiment is also in progress in our group, now in collaboration with J. West and M. H. W. Chan. If the rotation anomaly disappears in ideal crystals, then the dislocation network theory will be strongly supported.

We also have a suggestion for the connection between rigidity and supersolidity: transverse fluctuations of dislocation lines should induce mass currents, which should manifest as phase fluctuations because, in a superfluid, a mass current is the gradient of the phase of the wave function. When dislocations start fluctuating, phase fluctuations could destroy the supersolidity. Conversely, if the dislocation is supersolid, the phase coherence should force the dislocation to be a smooth, non-fluctuating, straight line. If the rotation anomaly disappears in perfect crystals, this theory will receive strong support. Otherwise, the favoured theory will be Anderson's, where supersolidity is an intrinsic crystal property that is only enhanced by disorder, and the elastic anomaly is due to the proliferation of vortices close to the supersolid transition.

In conclusion, I believe that supersolidity is a real phenomenon but that it is not yet understood. The true origin of mass flow inside ^{4}He crystals is unclear, as are the origin of their stiffening at low temperatures and the connection between the mechanical response of these quantum

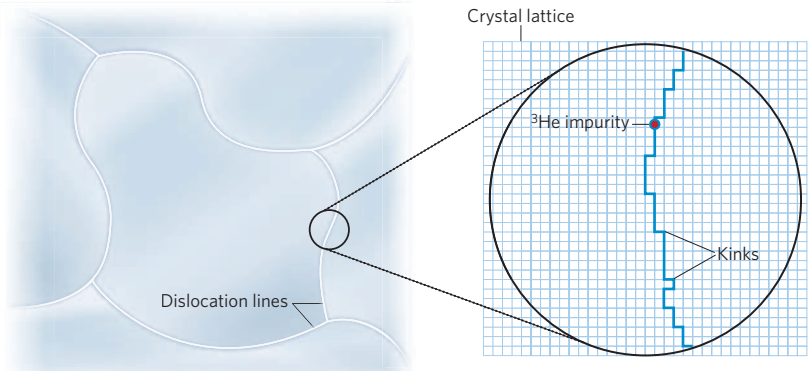

Figure 5 | Dislocation lines. At the atomic scale and at a sufficiently high temperature, dislocation lines show kinks where they shift from one atomic row to the next. In a quantum crystal such as ^{4}He, these kinks may move very easily by quantum tunnelling from one site to the neighbouring one. In this case, the dislocation line itself is a mobile line whose presence reduces the crystal rigidity. However, Aleinikava *et al.*[48] have proposed that below a certain roughening transition temperature, kinks disappear and the dislocation line is straight and immobile, such that the crystal rigidity is greater than it is above the roughening temperature. This roughening process may be at the origin of the stiffness anomaly of ^{4}He crystals. The roughening temperature should depend on the presence of ^{3}He impurities, which are known to bind to the dislocation lines, where they probably dress kinks. Even if this set of hypotheses is correct, the coupling between stiffness and supersolidity remains to be clarified.

crystals and the onset of supersolidity. However, I expect experimental results in the coming year that should help to discriminate between the two main types of interpretation that have been proposed. The most fundamental question remaining to be answered by experiments is whether disorder is necessary for supersolidity to appear in a quantum crystal such as solid ^{4}He. ■

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