recombination) into 50- to 100-kilobase pieces in yeast cells, and these pieces then being used to replace natural sequences inside the target organism (by selectable recombination methods). Standardization of methods will enable steps to be automated and more research groups to enter the field. Genome minimization and codon reduction are just the first uses of this new technology, which could one day give us functionally reorganized genomes and genomes that are custom designed to direct cells to perform specialized tasks. ■

**Benjamin A. Blount** *and* **Tom Ellis** *are at the Imperial College Centre for Synthetic Biology and the Department of Bioengineering, Imperial College London, London SW7 2AZ, UK.* **T.E.** *is also at the Wellcome Trust Sanger Institute, Hinxton CB10 1SA, UK.*
*e-mails: b.blount@imperial.ac.uk; t.ellis@imperial.ac.uk*

1. Richardson, S. M. *et al. Science* **355**, 1040–1044 (2017).
2. Hutchison, C. A. III *et al. Science* **351**, aad6253 (2016).
3. Fredens, J. *et al. Nature* **569**, 514–518 (2019).
4. Pósfai, G. *et al. Science* **312**, 1044–1046 (2006).
5. Lajoie, M. J. *et al. Science* **342**, 357–360 (2013).
6. Wang, K. *et al. Nature* **539**, 59–64 (2016).
7. Ostrov, N. *et al. Science* **353**, 819–822 (2016).
8. Lau, Y. H. *et al. Nucleic Acids Res.* **45**, 6971–6980 (2017).

ATOMIC PHYSICS

# Quantum gases show flashes of a supersolid

**Supersolids are highly sought-after structures whose atoms can simultaneously support frictionless flow and form a crystal. Hallmarks of a supersolid have now been observed in three experiments that involve quantum gases of dipolar atoms.**

LODE POLLET

Sixty years ago, the theoretical physicist Eugene Gross suggested that a substance could have properties of both a solid and a liquid at the same time, provided that the liquid is a superfluid[1]. A superfluid is a state of matter that can flow without friction and is known to exist[2,3] in helium-4 at temperatures below 2 kelvin. Gross's putative substance was called a supersolid. But despite this theoretical simplicity, supersolids in the purest sense of the term have evaded experimental detection[4]. Now, Tanzi *et al.*[5], writing in *Physical Review Letters*, and Böttcher *et al.*[6] and Chomaz *et al.*[7], writing in *Physical Review X*, report transient signatures of supersolidity in quantum gases of atoms that have strong magnetic dipole moments.

In Gross's proposal, a supersolid is pictured as the superposition of a liquid and a periodic density variation. In other words, a supersolid comprises liquid droplets that consist of many atoms and that form a periodic structure (Fig. 1). Each droplet can be described by its number of atoms and a property known as a quantum-mechanical phase. In a supersolid, unlike in an ordinary solid, each droplet retains the same phase. Such phase rigidity requires the exchange of atoms between the droplets and is possible only if the droplets are sufficiently close to each other.

Historically, supersolidity was sought in solid helium-4 using an apparently different, but formally equivalent, concept[8]. In this picture, a supersolid is a mostly crystalline substance in which certain defects enable a flow of adjacent atoms, which in turn sets the neighbours of these atoms in motion. This process continues until the whole crystal develops a fluid component. Despite some initial excitement[9,10], pure supersolidity is not observed in solid helium-4. However, in this substance, related phenomena such as giant quantum plasticity[11] are measurable and there is mounting evidence of frictionless flow along line-type defects[12] called dislocations, as was first proposed by theorists[13].

Over the past decade, cold-atom systems have shifted the focus back to Gross's picture, because of the controllability and lack of defects and impurities in these systems. When atoms are cooled to temperatures near 0 K, they can form a state of matter called a Bose–Einstein condensate, which gives rise to frictionless flow. The difficulty in producing a supersolid then lies in imposing a periodic density variation that is set by the intrinsic interactions of atoms in these extremely dilute systems. This imposition takes place through a mechanism known as roton softening.

A roton is a minimum in the energy–momentum spectrum of a superfluid's excitations. This minimum is located at a value of the momentum that is equal to the inverse of the average spacing between atoms. When the energy of the roton hits zero, the superfluid becomes unstable and forms a structure that has a periodic density variation. This structure could be, for instance, a supersolid or an ordinary solid. By contrast, alternative approaches for observing signatures of supersolidity have depended on external perturbations from lasers[14–16], rather than intrinsic properties of the system.

In the current experiments, Tanzi *et al.* and Böttcher *et al.* used dysprosium-162 atoms, whereas Chomaz *et al.* used dysprosium-164 and erbium-166 atoms. All of these atoms have intrinsically strong magnetic dipole moments. The interactions of these atoms have the theoretically required ingredients for supersolidity: a repulsive, tunable short-range (contact) component and an attractive, long-range (dipolar) component. Previously, some of the authors of the Böttcher *et al.* paper and their colleagues succeeded in producing

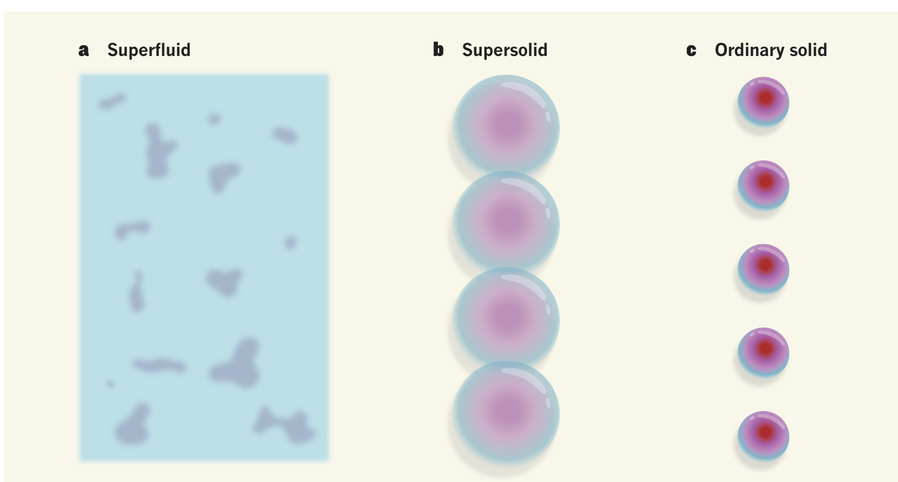


**Figure 1 | Density distributions of three states of matter.** **a**, A superfluid is a substance that can flow without friction. The density of a superfluid is uniform, apart from small fluctuations (as shown in this snapshot). **b**, Three papers[5–7] report experimental evidence for a supersolid — a spatially ordered material that has superfluid properties. A supersolid comprises droplets that contain many atoms and that are coupled to each other. **c**, In these experiments, an ordinary solid consists of isolated droplets. The colours in **a**–**c** represent the atomic density from low (light blue) to high (dark red).



© 2019 Springer Nature Limited. All rights reserved.

a periodic density variation in a system of dysprosium-164 atoms[17,18]. But the droplets in the resulting state were too distant from each other, leading to the loss of frictionless flow.

However, it has been worked out theoretically[19] that, under certain conditions, there is a narrow window in the ratio of dipolar-interaction strength to contact-interaction strength for which the droplets are situated close enough to each other to retain phase rigidity. By tuning an external magnetic field, which changes the way in which atoms scatter when they collide, the authors of the current papers reduced the strength of the contact interaction, bringing all three experiments into the desired parameter regime. The researchers then released the gases from the traps in which they were formed and allowed the matter waves associated with the atoms to interfere with each other. The resulting interference patterns contained a double-peak structure that is a hallmark of supersolidity.

In all the experiments, the peaks were transient phenomena because of three-body losses — losses of atoms that occur when a pair of atoms forms a bound molecular state with the aid of a third collision partner. The lifetimes of the supersolid properties ranged from a few tens of milliseconds for dysprosium-162 and erbium-166 atoms to 150 ms for dysprosium-164 atoms. For the latter atoms, the contact-interaction strength is smaller than the dipole-interaction strength. This feature makes a technically advantageous cooling protocol possible that avoids unwanted excitations and dynamics.

Current limitations of the studies are that each of the experiments involves only a handful of droplets, as well as a complex interplay between the droplets and the axially elongated (cigar-shaped) traps. Future studies should address these issues, aim for a direct manifestation of phase rigidity and study the excitations of a supersolid. Another convincing proof of supersolidity would involve letting a superfluid flow through a prospective supersolid — a situation that is not possible for ordinary fluids and solids. ■

**Lode Pollet** *is in the Faculty of Physics, Ludwig Maximilian University of Munich, 80333 Munich, Germany.*
*e-mail: lode.pollet@physik.uni-muenchen.de*

1. Gross, E. P. *Phys. Rev.* **106**, 161–162 (1957).
2. Kapitza, P. *Nature* **141**, 74 (1938).
3. Allen, J. F. & Misener, A. D. *Nature* **141**, 75 (1938).
4. Boninsegni, M. & Prokof'ev, N. V. *Rev. Mod. Phys.* **84**, 759–776 (2012).
5. Tanzi, L. *et al. Phys. Rev. Lett.* **122**, 130405 (2019).
6. Böttcher, F. *et al. Phys. Rev. X* **9**, 011051 (2019).
7. Chomaz, L. *et al. Phys. Rev. X* **9**, 021012 (2019).
8. Andreev, A. F. & Lifshitz, I. M. *Sov. Phys. JETP* **29**, 1107–1113 (1969).
9. Kim, E. & Chan, M. W. H. *Nature* **427**, 225–227 (2004).
10. Kim, E. & Chan, M. W. H. *Science* **305**, 1941–1944 (2004).
11. Haziot, A. *et al. Phys. Rev. Lett.* **110**, 035301 (2013).
12. Ray, M. W. & Hallock, R. B. *Phys. Rev. Lett.* **100**, 235301 (2008).
13. Boninsegni, M. *et al. Phys. Rev. Lett.* **99**, 035301 (2007).
14. Baumann, K., Guerlin, C., Brennecke, F. & Esslinger, T. *Nature* **464**, 1301–1306 (2010).
15. Léonard, J., Morales, A., Zupancic, P., Esslinger, T. & Donner, T. *Nature* **543**, 87–90 (2017).
16. Li, J.-R. *et al. Nature* **543**, 91–94 (2017).
17. Kadau, H. *et al. Nature* **530**, 194–197 (2016).
18. Wenzel, M., Böttcher, F., Langen, T., Ferrier-Barbut, I. & Pfau, T. *Phys. Rev. A* **96**, 053630 (2017).
19. Roccuzzo, A. M. & Ancilotto, F. *Phys. Rev. A* **99**, 041601 (2019).

PHYSICAL CHEMISTRY

# A twist in the tale of the structure of ice

**A classic study found that crystalline ice adopts an amorphous form when compressed. Experiments now find that alternative phase transitions can occur — with implications for theories about water's structure.** See Letter p.542

JOHN S. TSE

Water is not a simple compound — it exhibits many anomalous physical behaviours that defy adequate explanation. Any fresh information on the structure of water in its various condensed forms is therefore welcome. On page 542, Tulk *et al.*[1] report a study of water under high pressure. They find that it passes through a sequence of crystalline phases rather than forming an amorphous solid, as had been reported by previous studies.

The melting point of ordinary crystalline ice decreases with increasing pressure. This observation inspired a landmark study in 1984, which sought to determine whether such ice would 'melt' when compressed at low temperatures to form a solid that has a disordered molecular structure resembling that of liquid water[2]. Indeed, the study showed that ice compressed at 77 kelvin collapses into a dense form known as high-density amorphous (HDA) ice, which can be recovered at low temperatures under ambient pressure. Remarkably, when heated at ambient pressure, HDA ice transforms into a low-density amorphous (LDA) form instead of reverting to its original crystalline state[3].

Measurements made under conditions of successive compression and decompression have shown that the change in volume associated with the interconversion between HDA ice and LDA ice is discontinuous, and that the transition between these two forms of ice is reversible and does not seem to involve the formation of any intermediate phases[4]. The observations suggest that the interconversion might belong to a class of process known as thermodynamically first-order transitions. If so, this could have important consequences for the phase diagram of water, which relates the temperatures and pressures at which thermodynamically distinct phases of water occur.

The details of the phase diagram of water are not yet fully understood. One possibility is that the boundary between the HDA ice and LDA ice phases extends into, and terminates in, a region of the diagram where water is supercooled (a phase in which water is liquid, despite being below its freezing point). The end of the boundary is known as a critical point. Above the critical point, water would be a mixture of two distinct liquids that have different densities. A feature of this 'two-liquid' model is that compressed ice would form two amorphous solid phases of very different densities that are related to the two liquid waters[5]. Intense experimental and computational efforts have been made to find evidence to support the two-liquid model, including proof of the existence of different amorphous phases in compressed ice.

In general, when a crystalline solid is compressed under 'hydrostatic' conditions that allow thermodynamic equilibrium to be reached, it is expected to transform into another crystalline phase. The formation, instead, of a metastable amorphous phase suggests that an energy barrier has inhibited the transformation of the solid into the second crystalline structure. Such a barrier can be breached if the solid is compressed slowly, which gives time for the structure to relax and for thermodynamic equilibrium to be attained[6]. In this scenario, the formation of the amorphous phase would be described as a kinetic effect, because it depends on the amount of time that is given for a transition to occur.

Ice and the minerals $\alpha$-quartz and berlinite were the archetypal examples of crystalline solids that become amorphous under pressure. The latter two compounds, however, are now known to transform into crystalline structures when compressed under uniform (isotropic) pressure[7,8]. The pressure-transmitting media used to compress $\alpha$-quartz and berlinite isotropically are incompatible with water at high pressures; no other suitable pressure transmitter has been available. One study[9] generated quasi-hydrostatic conditions using a pressure



© 2019 Springer Nature Limited. All rights reserved.