hypothesis came from extensive population time-series analysis from that earlier study[5], which showed beyond reasonable doubt that a mosquito vector species called *Anopheles coluzzii* persists locally in the dry season in as-yet-undiscovered places. However, the data were not consistent with this outcome for other malaria vectors in the study area — the species *Anopheles gambiae* and *Anopheles arabiensis* — leaving wind-powered long-distance migration as the only remaining possibility to explain the data[5].

Both modelling[6] and genetic studies[7] support the idea of long-distance migration to explain the seasonal dynamics of malaria mosquitoes in the Sahel, but many researchers have instead long discounted this phenomenon as being rare, accidental and inconsequential. This entrenched attitude has been difficult to dispel given the challenge of obtaining compelling direct evidence.

Huestis *et al.* met this challenge through aerial sampling of insects using sticky nets tethered to helium-filled balloons stationed in the villages that they studied. Nets suspended at set altitudes ranging from 40 to 290 metres above ground were launched at night (malaria mosquitoes are nocturnal), for about 10 consecutive nights each month over a span of 22–32 months. During a total of 617 sampling nights, 461,100 insects were caught, which included 2,748 mosquitoes. Careful controls by the authors enabled them to conclude that the insects were captured at altitude and not during balloon deployment near the ground.

Among the mosquitoes captured were *A. gambiae* and *A. coluzzii*, as well as four other species of malaria vector. Comparable distributions of species across villages and years, and consistent peaks in insect captures in the mid to late rainy season, indicate that high-altitude migration of malaria vectors is deliberate rather than accidental. Moreover, the annual malaria vector bioflow predicted to cross a hypothetical 100-km line joining the authors' sampling sites exceeds 50 million insects, suggesting that high-altitude migration is common rather than rare. Simulated migratory trajectories for these vectors yield maximal distances of around 300 km, assuming one 9-hour high-altitude journey.

From this work and their previous study[5], Huestis and colleagues have finally resolved in broad outline the 'dry-season paradox' in favour of two non-mutually exclusive strategies: long-distance migration and local persistence. Yet many knowledge gaps remain.

Perhaps the most important of these is whether wind-borne migration includes malaria mosquitoes infected with malaria-causing parasites. The authors make much of the fact that female insects (only females transmit malaria) outnumber males by a ratio of more than 4:1 in the mosquitoes they captured, that more than 90% of the females had taken at least one blood meal before their flight, and that 31% of those meals were from humans, implying possible mosquito exposure to malaria parasites and the potential to spread infection over great distances.

However, the authors failed to detect parasite infections in their aerially sampled malaria vectors, a result that they assert is to be expected given the small sample size and the low parasite-infection rates typical of populations of malaria vectors. A problem with this argument is that the typical infection rates they mention are based on one specific mosquito body part (salivary glands), rather than the unknown but undoubtedly much higher infection rates that would be obtained if whole mosquito bodies were used to test for parasite infection. Further research will be required to flesh out this and many other fundamental issues raised by Huestis and colleagues' study.

If it is confirmed that there are wind-borne mosquitoes infected with the malaria-causing parasite, the implications of this would include the possibility of the reintroduction of disease into places where malaria has been previously eliminated, as well as the potential for the long-distance spread of drug-resistant parasites. Wind-borne malaria vectors, whether or not they are infected with parasites, could also profoundly affect the success of vector-control efforts. For example, migration could foster the long-distance spread of insecticide-resistant mosquitoes, worsening an already dire situation, given the current spread of insecticide resistance in mosquito populations. This would be a matter of great concern because insecticides are the best means of malaria control currently available[8]. However, long-distance migration could facilitate the desirable spread of mosquitoes for gene-based methods of malaria-vector control. One thing is certain, Huestis and colleagues have permanently transformed our understanding of African malaria vectors and what it will take to conquer malaria. ■

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QUANTUM PHYSICS

Sounds of a supersolid

Ultracold gases of dipolar atoms can exhibit fluid and crystalline oscillations at the same time, illuminating the ways in which different kinds of sound propagate in the quantum state of matter known as a supersolid. See Letters p.382 & p.386

SEAN M. MOSSMAN

The quest to realize an exotic state of matter called a supersolid has intrigued researchers since initial theoretical predictions of its existence[1] were made in the late 1960s. A supersolid combines properties of a crystalline solid and a superfluid — a fluid that flows without resistance. After intense debate about a possible observation of supersolidity in solid helium[2], ultracold atomic gases have emerged as a powerful platform for investigating supersolid behaviour[3–5]. Tanzi *et al.*[6] and Guo *et al.*[7], on pages 382 and 386, respectively, and Natale *et al.*[8], writing in *Physical Review Letters*, have now made direct observations of supersolid dynamics. The teams have excited these exotic systems, and tuned in to the sounds of a supersolid for the first time.

To gain an intuitive picture of a supersolid, consider a narrow channel of fluid. Imagine that we turn a dial on our experiment and regularly spaced droplets begin to form — regions of high density that are connected through a background flow of liquid. The emerging droplets have a rigidity in that they tend to hold a fixed spacing, whereas the fluid that comprises them flows between the droplets without resistance. As we continue to turn the dial, this supersolid breaks as the droplets form more tightly until each one is isolated from its neighbours.

Researchers make such a state in the laboratory by using laser beams to suspend a collection of atoms inside a vacuum chamber. They then cool these atoms to some of the lowest temperatures in the Universe — about 50 nanokelvin. At these temperatures, the atoms condense into a single quantum state, a phase of matter known as a Bose–Einstein condensate (BEC). In such BECs, the atoms are superfluid and move in concert as a single quantum object.

The BECs produced for the three current experiments use atoms, such as erbium or dysprosium, that have strong permanent magnetic dipole moments. These atoms interact over long ranges, much as do the atoms in liquid helium[9], allowing for a roton — a kind of excitation that has a particular momentum.

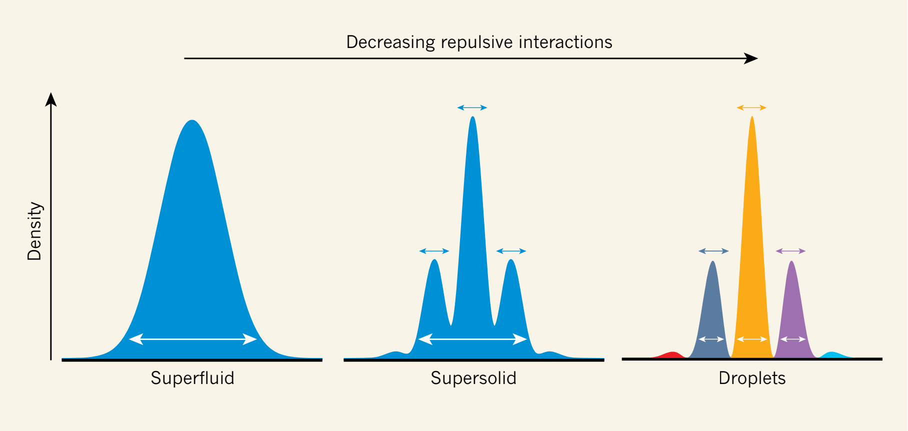

Figure 1 | Density distributions in a superfluid, a supersolid and isolated droplets. Three teams[6–8] report experiments on ultracold gases of magnetically dipolar atoms that exist as a superfluid (a fluid that flows without friction). As repulsive interactions between these atoms are decreased, the superfluid becomes a supersolid — a state of matter in which superfluidity and a crystal structure coexist. As the interactions are further decreased, the system forms a collection of isolated droplets (shown by the differently coloured density peaks). The white arrows indicate the regions over which the fluid can flow; the coloured arrows indicate how the crystal structure can move. In the supersolid, there is flow across the entire fluid that is independent of the crystal-structure motion.

In experiments on dipolar BECs, the energy of this roton can be tuned by using an external magnetic field to adjust repulsive short-range interactions.

Much like the cat in Schrödinger's classic thought experiment, a BEC is a quantum object that can exist in two different quantum states simultaneously — a superposition. The existence of a roton allows a BEC to more easily occupy a superposition of two different momenta, effectively moving left and right at the same time. On average, the BEC is stationary, but owing to the wave nature of quantum mechanics, the left-moving and right-moving parts of the system interfere. This interference generates a diffraction pattern, resulting in a periodic arrangement of atoms. In a supersolid, this superposition is the lowest-energy configuration.

Previous reports of supersolids or supersolid-like states in BECs used external influences to produce such a superposition[3–5,10]. What sets dipolar BECs apart from other cold-atom experiments is that no external influence is needed to generate the roton. The emergent crystalline structure spontaneously breaks translational symmetry — the symmetry that is associated with the system being uniformly smooth — in such a way that the crystal structure is free to move and vibrate. This spontaneous symmetry breaking is associated with the emergence of excitations called Higgs and Goldstone modes, which are of fundamental importance in both condensed-matter and high-energy physics.

Sound at low temperature in these exotic systems is characterized by such symmetry breaking, which underpins much of modern physics. In the early 1960s, it was shown that when a system spontaneously breaks a fundamental symmetry, such as that of translation, long-lived, low-energy excitations (sound modes) emerge[11,12]. In the standard model of particle physics, symmetry breaking has a key role in the emergence of light particles such as pions, which are responsible for nuclear interactions, and in the Higgs mechanism, which is responsible for much of the mass in the Universe.

What makes supersolids interesting is that two symmetries are simultaneously broken, resulting in two Goldstone modes. The nature of these two modes can be understood separately: normal sound in the superfluid is associated with the superfluid flow of the BEC, whereas the supersolid sound mode is associated with oscillation of the crystal structure. In practice, the use of an external trap causes these modes to be coupled and discretized. A supersolid has the necessary character of superfluid flow across the entire fluid, independent of the crystal-structure oscillation (Fig. 1). The main goals of the three current papers were to directly observe the Goldstone mode associated with supersolid formation and to distinguish it from the mode related to superfluidity.

> ***"The experiments show what happens when we shake a supersolid, but what happens when we stir or spin it?"***

Guo and colleagues study the first discrete excitation of the sound modes — the sloshing mode of the supersolid in the authors' bowl-like trap. Unfortunately, this mode has a low excitation energy, and therefore moves so slowly that observing it directly would take longer than the lifetime of the supersolid. However, the reported correlation between superfluid displacement and crystal displacement sampled over many iterations indicates that if the superfluid sloshes one way, the crystal tends to move the other way. This result provides convincing evidence for simultaneous superfluidity and crystalline structure, as contrasted with the case in which the system forms independent droplets and the correlation is absent.

Tanzi *et al.* and Natale *et al.* observe a different discrete Goldstone mode, known as a breathing mode. Like an accordion, a supersolid breathing mode is one in which the superfluid and the crystal compress and decompress, but at different frequencies. The authors extract these two oscillations by monitoring the spacing and relative magnitudes of the density peaks as the system is pushed from the regular superfluid regime into the supersolid one. They show that the two oscillation frequencies grow more disparate as the independent-droplet regime is approached.

These three studies are a major step forward as experiments start to probe the properties of supersolids. At the current stage, the restricted size of the observed density modulation (consisting of about three or four linked droplets) and the limited lifetime of the dipolar supersolids pose challenges. However, experimental efforts are already under way to circumvent these issues. In the future, the study of vorticity (how a superfluid forms tornado-like structures) will shed light on the fluid properties of supersolids. The current experiments show what happens when we shake a supersolid, but what happens when we stir or spin it?

Supersolids are also likely to play a key part in our understanding of pulsars (rapidly rotating stellar remnants called neutron stars), making observation in terrestrial experiments even more valuable. Although hot by human standards, neutron stars are cold on nuclear-physics scales, and are expected to contain several forms of superfluid, from neutron superfluids in their crust to 'colour superconductors' in their core. An exotic type of supersolid mechanism[13] predicted in the 1960s might be needed to explain puzzling observations in pulsars. With this emerging generation of experiments, there is now a solid future for the study of supersolids. ■

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