Studying the excitation spectrum of a trapped dipolar supersolid

August 16 2019, by Ingrid Fadelli

A figure inspired by a roman/Latin ancient God called 'Giano Bifronte' or Jianus. This God condenses in himself two rather antithetical natures, which co-exist in one entity. It is not possible to remove or extract one of the two natures without completely destroying the God. In the context of the study, the two natures are the superfluid and crystal one. Credit: Harald Ritsch and the Erbium team.

Supersolids, solid materials with superfluid properties (i.e., in which a substance can flow with zero viscosity), have recently become the focus of numerous physics studies. Supersolids are paradoxical phases of matter in which two distinct and somewhat antithetical orders coexist, resulting in a material being both crystal and superfluid.

First predicted at the end of the 1960s, supersolidity has gradually become the focus of a growing number of research studies, sparking debate across different scientific fields. Several years ago, for instance, a team of researchers published controversial results that identified this phase in solid helium, which were later disclaimed by the authors themselves.

A key issue with this study was that it did not account for the complexity of helium and the unreliable observations that it can sometimes produce. In addition, in atoms, interactions are typically very strong and steady, which makes it harder for this phase to occur.

Dipolar quantum gases lie at the opposite extreme of structures such as solid helium, as they are made up of ultracold magnetic atoms in the gas phase chilled to nanokelvin temperatures. In these gases, therefore, interactions between atoms are weak, yet they are also long-range and tunable with externally controlled magnetic fields.

Because of their high degree of tunability, a few years ago, quantum gases started appearing more frequently in theory proposals for supersolidity. The first experiments using gases coupled to light fields showed states with supersolid-like properties, but in these states, the solid remained incompressible.

Finally, a few months ago, three research groups investigating ultracold gases of highly magnetic atoms (a German group led by Tilman Pfau, an Italian group led by Giovanni Modugno and a group of researchers based at the University of Innsbruck and Institut für Quantenoptik und Quanteninformation led by Francesca Ferlaino), simultaneously published observations of states with supersolid properties.

"We were able to prove that in particular interaction conditions, the magnetic gas underwent a phase transition to a supersolid state, showing both spontaneous density modulation (i.e., crystal) and global phase-coherence (i.e., superfluid)," the Innsbruck-based researchers told Phys.org via email. "Remarkably, the supersolid properties genuinely arise from the bare interparticle interactions, which have a strong dipole-dipole contribution."

Building on these previous results, the research team led by Francesca Farlaino carried out a new study investigating the excitation spectrum of a trapped dipolar supersolid, gathering interesting new observations. This study is an important step forward in unveiling how the supersolid state of matter responds to excitations.

"To probe supersolidity, it is important to prove that the superfluid and crystal nature of a system respond differently to perturbations," the researchers explained. "More generally, in quantum physics, any system has intrinsic excitation modes characterizing how it responds to a perturbation. For example, a pinched guitar string responds only with a given frequency, making a clear sound, which a trained ear could recognize as a specific note, estimating the string's characteristics. The same holds for a quantum system; its excitation spectrum reveals intimate information on its intrinsic character. Probing the excitations of the supersolid can thus enable new and deeper insight into this intriguing phase."

The responses observed by the researchers match theoretical predictions associated with supersolids, which suggests that they successfully observed a supersolid state. Their paper, published in *Physical Review Letters*, specifically focuses on the spectrum of elementary excitations of a dipolar Bose gas placed in a 3-D anisotropic trap while it is undergoing the transition between superfluid and supersolid.

"We have made an important step forward by studying the response to excitations of systems," the researchers told Phys.org. "The way in which a system responds tells you a lot about the system itself. It is enough to think about an external excitation in which one throws a stone on a system, and how different the response is if one throws this stone to the sea or at a wall. This is merely an example; instead of throwing a stone, we study the compressibility of the system."

In their study, Ferlaino and her colleagues essentially probed the excitation modes of the supersolid state produced from a quantum gas of erbium atoms in a cigar-shaped trap made of light by changing the value of an external magnetic field. In this experimental setup, the density modulation appeared spontaneously along the trap, while the system remained supefluid.

The researchers then globally excited the system by perturbing the trap in the same direction in which the density modulation had appeared. This resulted in the excitation of distinct modes, which they probed by observing the change in the patterns from the matter-wave interference of the gas with itself (obtained by making the gas expand) over time.

"In our work, we identify the different elementary excitation modes by applying a model-free statistical analysis called Principal Component Analysis on the time evolution of the patterns we observed," the researchers said. "Our most meaningful observation was that the simultaneous existence of the two orders –crystal and superfluid- in a supersolid translates into remarkable properties of its spectrum of elementary excitation, which we further investigated in our work."

Past studies suggest that at the thermodynamic limit (i.e., in infinite systems), the existence of both crystal and superfluid properties produces two branches in the excitation spectrum, each of them being associated with one of the orders. This results in modes that are either vibrations of the crystal structure or flow of the superfluid, respectively. In their study, Ferlaino and her colleagues showed, both theoretically and experimentally, that this key feature of the supersolid spectrum occurs in laboratory systems where only a few crystal sites are present.

"Experimentally, we observed that the system's response to our global excitation scheme changes from one to several excited modes when the system transitions from a regular superfluid to a supersolid, reflecting the multiplicity of the excitation branch in the system," the researchers explained. "Importantly, one class of the excited modes has a decreasing energy cost when moving deeper into the supersolid regime, i.e., when the superfluid character of the phase is reduced. Such a behavior characterizes the modes that induce a superfluid flow within the droplet array."

The researchers found that while in the Bose-Einstein condensate regime the system they examined exhibited an ordinary quadrupole oscillation, in the supersolid regime it produced an intriguing two-frequency response. This response is associated with the system's two spontaneously broken symmetries.

The study carried out by Ferlaino and her colleagues provides evidence of the possibility of superfluid flow in the supersolid state, while its solid elasticity is sensitive. To ascertain their observations, however, the researchers would also need to prove the irrotationality of the superfluid flow, for instance by observing vortices. This is one of the many things that they hope to accomplish in their future work.

"The story of supersolid dipolar gas is still an incomplete book and many chapters remain to be written," the researchers said. "For instance, how does the superfluid fraction evolve along the phase diagram? What is the nature of the superfluid flow in such a system and how does the system react to rotation or to a local perturbation? What are the other features that one can catch from the supersolid's excitation spectrum, concerning both its solid elasticity and its superfluid fraction? These are only a few of the exciting directions that we could explore in the future."

More information: G. Natale et al. Excitation Spectrum of a Trapped Dipolar Supersolid and Its Experimental Evidence, *Physical Review Letters* (2019). DOI: 10.1103/PhysRevLett.123.050402