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Direct imaging captures the crystalline vibrations of a supersolid made of atoms and light

For the first time ICFO researchers, in collaboration with scientists from UAB, have directly imaged a spin-orbit-coupled supersolid. The team has observed quantum fluids of atoms forming stripes whose spacing oscillates in time, as the spacing of a crystal does. These results, published in Science, demonstrate unequivocally the dual superfluid and crystalline nature of such systems.

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The 20th century was marked by the discovery of exotic states of matter. First, liquid helium was observed to flow without friction at extremely low temperatures, a phase now known as superfluid. Soon after, it was also discovered that, under appropriate external conditions, some materials can conduct electricity without resistance; these materials were therefore named superconductors. Later, in the 1960s, scientists added the idea of supersolids to the list: in this state of matter, atoms would flow without friction like a superfluid, while maintaining the periodic spatial order characteristic of a crystal.

Although supersolids were predicted decades ago, researchers have only recently managed to realize them and experimentally explore their dual superfluid and crystalline nature. Many open questions remain about how and if these properties manifest in different platforms.

Now, researchers at ICFO, **Dr. Craig Chisholm**, **Dr. Sarah Hirthe**, **Dr. Vasiliy Makhalov**, **Dr. Ramon Ramos**, and **Dr. Remy Vatre**, led by **ICREA Prof. Leticia Tarruell,** in collaboration with the theoretical physicists **Dr. Josep Cabedo** and **Prof. Alessio Celi** at the **Universitat Autonoma de Barcelona** (UAB), have succeeded in **unequivocally demonstrating supersolidity in ultracold potassium atoms** coupled to light.

For the first time, ICFO researchers have **imaged** the so-called **spin-orbit-coupled supersolids,** providing **compelling evidence of both their solid and superfluid features**. These direct observations, now published in Science, show a cloud of potassium atoms spontaneously forming **stripes** (a crystal-like structure) **whose spacing oscillates in time**, alternately getting closer together and moving farther apart. Through the collaboration with the UAB theorists, the team managed to explain the experimental results by describing the atomic cloud as a mixture of modified atoms that interfere, what they called the **mixture model**. ?

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ï¿½Crystal structures are never perfectly static,ï¿½ explains ICREA Prof. Leticia Tarruell the lead researcher of the study. ï¿½Atoms slightly vibrate around their positions, chang ng the spacing between them. A true supersolid should also share this feature, which is exact y what we saw.ï¿½ The researchers also observed that, as the total cloud size expands or shrinks, new stripes appear or existing ones vanish, respectively, a behavior that is relat d to its superflui

Is a spin-orbit-coupled Bose-Einstein condensate a true supersolid?

Naturally, to take these images, the researchers first had to create the supersolid. By cooling a cloud of potassium atoms to temperatures close to absolute zero, they were slowed down until they became nearly motionless, eventually forming a Bose-Einstein condensate -an exotic phase of matter in which all atoms occupy the lowest-energy state, sharing a single quantum wavefunction and thus behaving collectively.

Next, the researchers sent two laser beams from different directions to couple the atoms' spin state with their momentum. Ultimately, this generated a **spin-orbit-coupled Bose-Einstein condensate** where two atomic states of different momentum interfered with each other. The interference is what produced a pattern in the cloud in the form of stripes, thereby giving rise to a supersolid.

ï¿½Most of the previous work on supersolids was done with magnetic quantum gases, whi e other platforms such as spin-orbit coupled Bose-Einstein condensates had remained large y unexplored,ï¿½ says Prof. Tarruell. As she explains, the question of wheth r a spin-orbit-coupled Bose-Einstein condensate could become a true supersolid had een debated for years, that is, whether a crystal-like structure with its rich dynamics could re lly emerge out of it. ï¿½In previous experiments, one could indirectly infer whether a crystalline pattern aros **we really wanted to see pictures** of it,ï¿½ shares Dr. Sarah Hirthe, one of the first co-autho s of the article. The first direct images of this kind of supersolid have, in fact, settled the deba e surrounding spin-orbit-coupled Bose-Einstein condensates, establishing them as a **excellent new platform for studying supersolidity**. ï¿½Potassium was essential for amplifying he pattern, allowing us to directly observe its dynamics. In earlier experiments with other ato ic species, the stripes' contrast was too low to be seen clearly and could only be inferred, ¿½ the researcher

A glimpse into future exotic states of matter

The team is now already thinking of taking one step further by applying the acquired knowledge to create what they call a ï¿½supersolid liquidï¿½. This hypothetical phas of matter would consist of liquid droplets stabilized by pure quantum effects -such as those discovered by the same ICFO group back in 2017- that also contain an internal crystalline structure. If realized, supersolid liquids would join the family of exotic states of matter, whose

exploration began a century ago.
But, for the time being, the pictures have already marked a milestone for the field by revealing the stripes' dynamics as indicative of both superfluid and crystal behavior.
According to Prof. Tarruell: ï¿½For the first time, **we have really seen the crystal-like structure of a supersolid being truly dynamic, essentially ?breathing', as if it were alive**.ï¿

Reference:
C. S. Chisholm, S. Hirthe, V. B. Makhalov, R. Ramos, R. Vatre, J. Cabedo, A. Celi, L. Tarruell, Probing supersolidity through excitations in a spin-orbit-coupled Bose-Einstein condensate, Science (2026). DOI:

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Single shot experimental image of the in situ density profile of the cloud of potassium atoms measured with matter-wave optics. The vertical fringes show the periodic spatial order reminiscent of the solid-like nature of the supersolid. ©ICFO.

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Optical table used in the experiment. ©ICFO.

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Potassium atoms in the magneto-optical trap, an intermediate stage before the formation of a Bose-Einstein condensate. ©ICFO.