Study unveils a new supersolid phase in dipolar Bose-Einstein condensates

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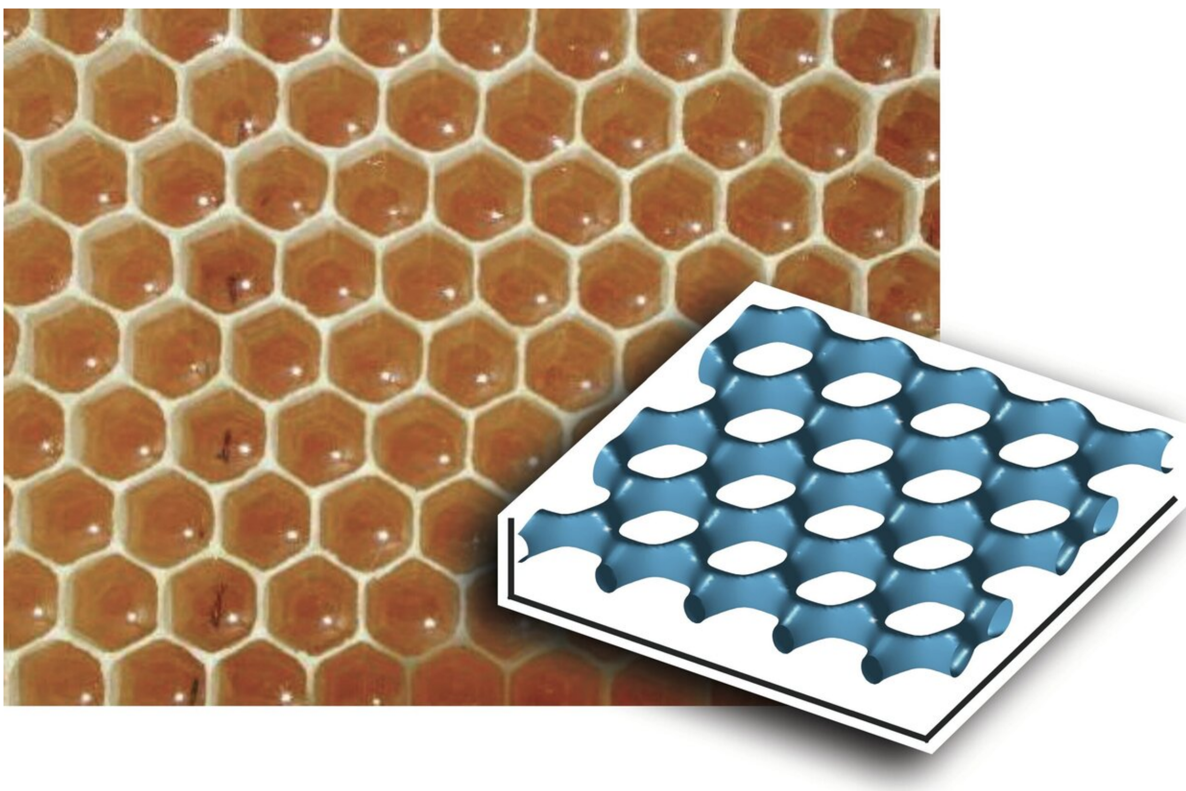

This image shows a typical honeycomb in the background and the calculated condensate density as the inset (showing the same shape). Credit: Zhang, Maucher & Pohl.

Generally, matter exists in three distinct forms: as a solid, a liquid or a gas. Past physics research, however, has unveiled other curious states of matter, one of which is supersolidity. In a supersolid state, particles are arranged into a rigid crystal and can nonetheless flow through the solid without any friction. Although this may appear contradictory, this state is allowed by the laws of quantum mechanics.

A team of researchers at Aarhus University in Denmark has recently carried out a study exploring supersolidity in dipolar Bose-Einstein condensates (BEC), states of matter in which separate atoms cooled to near absolute zero unite into a single quantum mechanical entity. Their study, featured in *Physical Review Letters*, unveiled a critical point at which crystallization occurs, and a new supersolid phase emerges, which is characterized by a regular honeycomb pattern with near-perfect superfluidity.

"Conjectured more than 50 years ago, supersolidity has remained elusive to observations until recently, where new promise is given by experiments with very dilute gases of atoms that are cooled and trapped by laser light at temperatures near absolute zero," Thomas Pohl, one of the researchers who carried out the study, told Phys.org. "Under such extreme conditions, the atoms can collectively form a so-called Bose-Einstein condensate, which is a quantum state that represents an ideal frictionless superfluid. However, one would naturally not expect that such a dilute, free-flowing liquid can crystallize. Fascinated by the bizarre nature of the supersolid state, we wanted to understand whether this might nevertheless be possible if the atoms interacted in a suitable way."

In the early 2000s, researchers proposed dipolar Bose Einstein condensates formed by particles that, just like little magnets, can attract and repel each other over substantial distances. In their study, Pohl and his colleagues Yongchang Zhang and Fabian Maucher observed that quantum fluctuations in such dipolar condensates can lead to crystallization at a critical point (i.e., a point in the phase diagram where two phases of a substance become indistinguishable).

This essentially means that dipolar condensates can, in fact, be supersolid, which is what the researchers had hoped for when they began their investigation. Their calculations, however, yielded further surprises, specifically related to the way in which the quantum fluid crystallized.

"When we put an ice cube into a glass of water, it will take some time until it is fully melted," Zhang told Phys.org. "In other words, water can coexist in liquid and solid form during its melting or freezing, and this behavior is typical for many other substances. To our surprise, we found that our supersolid freezes in a peculiar way, whereby the atoms are either fully liquid or completely solid, and the fluid and crystal become virtually identical right at the point where the two phases transform without coexistence."

The analyses carried out by Pohl, Zhang and Maucher unveiled a new kind of supersolid that was quite different from what they had originally anticipated. Instead of atoms arranging on a typical lattice, the dipolar quantum fluid was found to form a honeycomb-shaped structure of canals.

Yet contrarily to honey, which is a viscous fluid, in this structure, the dipolar atoms can move freely along the ridges of the superfluid "honeycomb." The researchers found this peculiar form of matter, in which particles can flow across a regular network held together purely by the liquid itself and at virtually zero viscosity, extremely fascinating.

"Our theoretical study was based on the analysis and numerical simulation of the macroscopic quantum mechanical wave function that describes the state of the dipolar atoms in the Bose-Einstein condensate," Fabian Maucher, another researcher who carried out the study, told

Phys.org. "As pointed out in previous work, a particularly important aspect is to include quantum mechanical correlations and quantum fluctuations in the description. In fact, it turns out that the honeycomb solid and its unusual freezing behavior are facilitated by such quantum fluctuations, and would not exist otherwise."

The study carried out by Pohl, Zhang and Maucher introduces a new type of supersolid state, which, as their findings suggest, could be traced back to the effects of quantum fluctuations in dipolar condensates. In the future, they plan to investigate these findings further and carry out more studies focusing on dipolar Bose-Einstein condensates. Meanwhile, other research teams are also exploring the behavior of dipolar quantum fluids, both in theory and experiments.

"Very recently, three experimental groups from the University of Stuttgart, the University of Florence and the University of Innsbruck have independently observed the formation of supersolid micron-scale quantum droplets lined up on regular arrays," Zhang said. "These experimental achievements provide a promising outlook, and it will be an important question to clarify under which conditions our theoretical predictions can be observed with dipolar atoms. Surely, dipolar quantum fluids have become an exciting new platform for supersolid behavior that will continue to challenge our understanding and reveal surprises and new insights about this fascinating quantum state of matter."

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