Super-solid helium state confirmed in beautiful experiment

Enlarge / Computer artwork of the nucleus of a helium atom, or an alpha particle given off during radioactive decay. The nucleus consists of two positively charged protons (red) and two neutral neutrons (green) surrounded by a quantum cloud of gluons, a type of subatomic particle.
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In recent months, I've mentioned super-solids a couple of times, which is a bit unusual for something we haven't been sure actually exists. However, a recent paper seems to offer some quite strong confirmation that super-solids are real. That means it is time to delve into the weird and wonderful world of low-temperature helium.

Helium is, without a doubt, the Universe's weirdest material, beating out molecular hydrogen by a rather long nose. The key to helium's strangeness is that it is normally a boson: a helium-4 atom consists of two protons, two neutrons, and two electrons, which sums to an even number, making a composite boson.

Helium is confusing

What does all that mean? It means that when cold enough, a group of helium atoms can enter the same quantum state. Even though they are spread out over a whole vessel, they all know something about the condition of their distant neighbors. This enables the helium atoms to flow without resistance, a state called a superfluidity. It’s good company among other weird and wonderful properties of helium.

There is another type of helium that only has a single neutron (so two protons, one neutron, and two electrons), which means that it is not a composite boson. Instead, it is a fermion. When cold, these helium atoms cannot enter the same quantum state, so they don’t become superfluid. But, cool them enough, and two helium atoms can pair up to create a composite boson. At that very low temperature, superfluidity also emerges in helium-3.

Neither helium-3 nor helium-4 can become solids at atmospheric pressure. Instead, they become solids at 20-40 atmospheres. As a solid, at the right temperature, there are predictions that helium-4 can enter the super-solid state, while helium-3, which is not a boson, will not. The problem is that the super-solid is also very hard to detect. It hides among other changes to the elastic properties of solid helium.

What is a super-solid?

A super-solid makes its presence known by flowing without resistance. However, what does it mean to say that a solid flows?

When helium (either type) becomes a solid, it crystalizes. That means that all the atoms hold themselves in a fixed arrangement with each other—to give one example, atoms can line up so that they’re at the corners of a cube. As solids

form, however, some positions that should have atoms do not. Others are out of position. When pressure is applied, atoms can move into these vacant positions, creating new vacant positions. As the atoms shuffle along, the solid flows.

To flow, the atoms have to have sufficient energy to leave their current location before they can move to new locations. As the temperature goes down, atoms have less energy and can no longer move. That means that the rate of flow should decrease with temperature.

If a material is in a super-solid state, however, then atoms can move from hole to hole because the quantum properties of the superfluid state tell the atoms where the holes are (so to speak) and allow them to move. These quantum effects get *stronger* with reduced temperature, so the rate of flow increases with decreasing temperature.

Increasing flow with reduced temperature has been observed in Helium-4. Unfortunately, it was not quite the smoking gun that the researchers were looking for, because the elastic properties of the solid also play a role. As the temperature decreases, there is competition between reduced movement of the atoms because they have less energy and increased movement because the solid as a whole is more able to transmit any applied force to a sensor. Maybe the increased flow was actually a change in elastic properties?

Helium-3 to the rescue

To make the case for super-solidity, researchers turned to a form of helium that does not turn into a super-solid: helium-3.

The researchers repeated their experiments with solid helium-3 and observed that the rate of flow decreased with decreasing temperature, exactly as expected for a normal solid. And, because the elastic properties of helium-3 are nearly

identical to that of helium-4, the researchers were able to eliminate that as an effect.

Indeed, the researchers were able to distinguish the elastic motion of the solid and the flow of the solid via atomic motion between vacancies. They showed that flow proceeds quite differently for helium-4 compared to helium-3.

Then came the surprise. At the lowest temperatures, the flow rate of helium-3 stopped decreasing. It didn’t exhibit super-solid properties, but it also stopped behaving like a normal solid.

If you recall from above, helium-3 can become a superfluid at very low temperatures, because the individual atoms can pair up to create bosons. It should also be possible for this to occur for solid helium-3. The researchers were not at a low-enough temperature to expect a helium-3 super-solid. But the temperature was low enough that maybe, just maybe, some pairing was occurring, which was allowing some super-solid properties to start to become apparent.

That last conclusion is a bit speculative in my opinion. However, the contrast between the behavior of helium-3 and helium-4 is quite stark. That alone makes the case for the existence of the super-solid state much stronger.

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