# Evidence for high temperature superfluidity in cold 'fermion' gas

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A new study has disclosed perhaps the strongest evidence to date for superfluidity in an exotic gas that mimics extreme behavior in Nature -- ranging from high temperature superconductivity to the behavior of fundamental particles in the Big Bang, when the universe is believed to have begun in a huge burst of energy within a very small space. Although the gas was trapped by a laser beam within billionths of a degree of absolute zero, the lowest possible temperature, researchers said it behaved like a superfluid flowing at high temperatures.

In a report published in the Thursday Jan. 27, 2005, Science Express, the online version of the research journal Science, experimentalists from Duke University and theorists from the University of Chicago noted a striking change in the ability of this "strongly interacting Fermi gas" to take in heat energy.

That change suggests the gas of lithium-6 atoms had undergone a phase change into a novel superfluid state -- bolstering previous evidence for the observation of this state of frictionless flow. A phase change is a drastic alteration in properties of a sample of matter when it transitions from one form to another -- for example, the changing of liquid water into steam.

"The temperature at which we were seeing this abrupt change is very close to where the Chicago group predicted there ought to be a transition to a superfluid," said John Thomas, the Fritz London Distinguished Professor of Physics at Duke, in an interview. "And the behavior of the gas closely corresponded with their predictions of what would occur when the energy was added."

The report's principal author is Joe Kinast, a doctoral student in Thomas' Duke laboratory. Other authors include Thomas, his postdoctoral research associate Andrey Turlapov, University of Chicago physics professor Kathryn Levin, her post-doctoral associate Qijin Chen and her former graduate student Jelena Stajic.

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A Fermi gas is one composed of "fermions," a class of standoffish atoms known for keeping more of a distance from each other than the other gregarious class of atoms known as "bosons," Thomas said.

Boson atoms readily condense as single particles into a superfluid, a medium that flows without friction. Superfluids made of bosonic atoms can exhibit properties that seem straight out of science fiction. If placed in an open container, for example, such superfluid matter would spontaneously rise up the sides and flow over the top.

Fermions, in contrast to bosons, cannot become a superfluid made of single particles. But scientists have found evidence that fermionic atoms can join in pairs analogous to the weakly bound electron pairs that conduct current without resistance in conventional superconductors. Such fermion pairs effectively behave as bosons that, in turn, can transition into a superfluid.

However, the novel superfluid state this study described is special, because the lithium-6 atoms appear to form very tightly bound pairs. "Both theory and experiment suggest that the superfluidity the (Duke) group detected is different from what has been seen in the past," said Levin. "In this particular gas the interactions are so strong that the fermions like to have partners – to pair up into bosons – even when they are not a superfluid."

This kind of superfluidity can be used to model long-sought superconductors that could conduct electricity without resistance at room temperatures or higher, Thomas said. It could model such "hot" superconductivity even though the superfluid carries no electrical current as a real superconductor would. "But, in an analogous way, the particles flow without friction," he added.

For several years, evidence has been mounting that the unique Fermi gas the Duke and Chicago groups studied can exist as a superfluid.

In a previous November, 2002 report in Science Express, Thomas's group reported the first observation of this unique strongly interacting lithium-6 gas. It also described a startling lopsided "shape-shifting" when the gas was released from confinement.

Instead of expanding uniformly, the gas expanded in a lopsided manner. In that study, the researchers used a laser beam trap to confine and cool lithium-6 atoms to a "degenerate" state well below their "Fermi temperature."

The Fermi temperature is the point where antisocial fermion atoms begin to approach each other as closely as laws of physics allow. They reach a degenerate state on further cooling. When a magnetic field of a certain value is applied at low temperatures, these maximally squeezed atoms become "strongly interacting," meaning that they can influence each other over exceptionally large distances.

In the earlier experiments, when the Duke scientists released the gas from its laser trap at temperatures estimated at only 50 billionths of a degree warmer than absolute zero, they observed the gas rearranging itself in an unusual way. It exploded outward in one direction while not changing its shape in the other. www.dukenews.duke.edu/news/new … p=all&id=958&catid=2

In 2002, theorists at the University of Trento in Italy suggested that this "anisotropic" shape change could provide evidence for the fermion atoms achieving superfluidity.

Another April, 2004 report by Thomas's group in the journal Physical Review Letters found further evidence for superfluidity in the wiggling, jelly-like behavior of the confined gas.
www.dukenews.duke.edu/news/superfluid_0404.html

In their new Science Express report, Kinast and his fellow researchers noted that the previously observed lopsided expansion mimics the "elliptical flow" of quark-gluon plasmas under study at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory. Such exotic plasmas of charged and colossally-heated fundamental particles are theorized to have existed a split second after the Big Bang.

The new report by the Duke and Chicago groups examined with unprecedented precision how a cooled and laser trapped swarm of strongly interacting lithium-6 Fermi gas responds to measured additions of heat energy.

In the latest study, the researchers began with temperatures so cold "that the energy of the strongly interacting gas behaves much like that of a non-interacting gas, where the behavior is well understood," Thomas said. Using this idea, the Duke group then learned how to "put in a very precisely controllable amount of energy that could be smoothly varied," he added.

They added heat energy in repeated stages by "turning off the laser trap to let the gas expand just a tiny bit, then turning the trap on again," he said. After energy was added, they measured an approximate temperature that was later calibrated. This calibration technique related specific temperatures to the shape and size of the gas cloud as predicted by the Chicago group.

The Duke experimenters noted a sharp modification in the gas's heat absorption capacity at a shape-estimated temperature of about 30 percent of the Fermi temperature. The gas's Fermi temperature itself is about 2 millionths of a degree above absolute zero.

The findings are "the most direct experimental evidence ever for a phase transition in these cold fermionic gases," Levin said. "This is what is particularly exciting about these new experiments. And the phase transition temperature is just where the theory says it ought to be."

A superfluid transition at 30 percent of the Fermi temperature in a gas would correspond to very high-temperature superfluidity in a solid, Thomas said. A typical Fermi temperature in a metal is ten thousand degrees. A superfluid transition at 30 percent of such a high temperature would correspond to a superconductor functioning at thousands of degrees.

Thomas said the heat capacity change in the supercold fermion gas also showed similarities to the "Lambda transition" first measured in 1932 in liquid helium 4 -- a fluid of "sociable" bosons. The significance of that transition was explained by the late Duke physicist and chemist Fritz London, who showed in 1938 that it signaled the onset of superfluidity in helium-4.

Overall, the experimenters' study spanned an estimated temperature range from near the Fermi temperature down to 4 percent of the Fermi temperature. The lowest reading was estimated to be just 80 billionths of a degree above absolute zero.

According to the Chicago group's theoretical guidelines, atomic behavior would change over that temperature range between "free atoms," "strongly-bound pairs" and "superfluid pairs," he said.

The theoretical approach that the University of Chicago group used to explain the lithium-6 atoms' behavior was originally created to study high temperature superconductors. The scientists said the close agreement between prediction and experimental measurement in the lithium-6 study suggests that there may be an "intimate connection" between this behavior and high temperature superconductivity.

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