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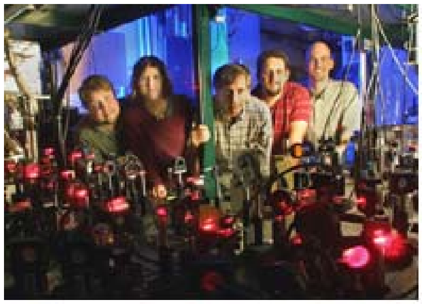

John Thomas and his research team have excited the physics world with their discovery of strange Fermi gas behavior. Photo: Jim Wallace

Ultracold Gas Shows Strange Behavior

When a Duke physics team chilled "fermion" atoms to unprecedented levels in a laser trap, strange effects hinted the possibility of a never-before-seen kind of superfluidity

Thursday, November 07, 2002 | DURHAM, N.C. -- Duke University researchers have created an ultracold gas that has the startling property of bursting outward in a preferred direction when released. According to the researchers, studying the properties of the "lopsided" gas will yield fundamental insights into how matter holds itself together at the subatomic level.

Also, the research team leader said their data suggests the possibility that the gas is exhibiting a never-before-seen kind of superfluidity -- a property in which matter at extremely low-temperatures behaves in unusual ways. However, the researchers emphasized that they cannot completely rule out other mechanisms.

The findings, by a research team led by Duke Professor of Physics John Thomas, were posted online Nov. 7, 2002, on "Science Express," the web counterpart of the journal Science. The work was supported by the Department of Energy, the National Science Foundation, the Army Research Office and NASA.

In their experiments, Thomas and his colleagues Thomas Lab used a "bowl" of laser light to confine a cloud of lithium-6 atoms to a cigar-shape between three and four millionths of a meter in diameter -- and then cooled the cloud to 50 billionths of a degree above absolute zero. Absolute zero, which is -273.15 Centigrade, is the temperature at which theoretically all atomic motion stops.

Ordinarily, a gas cloud -- even a cigar-shaped one -- behaves in a predictable way when released in a vacuum. "It expands and quickly becomes spherical because it moves at equal speeds in all directions," said Thomas.

"This new gas does something radically different," Thomas said in an interview. "In the direction that it was initially tightly confined the gas explodes rapidly outwardly. And in the other

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direction it doesn't move at all.

"So you see an incredible change in shape from being a cigar in one direction to becoming a big ellipse in the other. This gas, which is not being held by anything in empty space, is under its own interaction completely changing its shape.

"It's something that is very weird that you would not normally see, and that has not been observed before in this type of system," said Thomas.

As reported in "Science Express," Thomas's group explains this behavior as a sign that the lithium atoms are both cold enough and sufficiently strongly attractive to become what is known as a "strongly interacting, highly degenerate Fermi gas" -- the first time such a gas has been produced, they said.

A Fermi gas is one composed of "fermions," a class of atoms constrained by a quantum mechanical property from getting too close to each other. Lithium-6 is an example. That property contrasts with the other class of atoms, called "bosons," which prefer closeness. Helium-4 is an example of a boson.

A Fermi gas is "degenerate" when at a very low temperature, known as the Fermi temperature, its atoms approach their closeness limits. Thomas' lab has been a leader in developing optical traps for cooling-down fermions to well below their Fermi temperature, using a carbon dioxide laser trap he likens to an "optical bowl."

To create a strongly interacting gas of fermions, the Duke team had to fill the optical bowl with lithium atoms whose subatomic constituents are in two different states of "spin," or rotation. Those two fermion types can be induced to approach each other unusually closely in the presence of an applied magnetic field.

His group's latest achievement, chilling the trapped atoms to about 50 billionth of a degree above absolute zero, means "we're getting down to the very lowest temperatures anybody has ever seen in a Fermi system," he said.

Such a low temperature means the Duke team had reduced the gas's temperature to much below the temperature at which the atoms first become degenerate.

The fact that the gas is both strongly interacting and highly degenerate means each atom's "range of interaction becomes larger than the distances between each atom," Thomas said. "There's this tremendous interaction that is reaching out to attract the atoms to one another. Some theorists have predicted that the whole gas should implode and be unstable. We suggested that's probably not the case. And our experiments show it is probably not the case."

This special strongly interactive state has great research relevance, he added. That relevance stems from the fact that interacting fermions are the building blocks of all matter -- bosons actually being composites of fermions.

The new atomic gas could thus interest scientists studying such unresolved high-energy physics questions as how fundamental units of matter called quarks are held together within larger subatomic particles. Quarks themselves cannot be separated for study because the powerful force holding them together grows ever stronger as they try to diverge.

"The newest theories about quarks are about ways of dealing with the superstrong interactions within quark matter," he explained. "There are theorists working on new calculation techniques that treat strongly interacting systems in new ways.

"I'm not claiming our atomic system interacts in exactly the same way as quarks do. But it can test the same calculation methods. Our system provides a model for studying strongly interacting systems."

Bosons, being a comparatively "gregarious" class of atoms that can approach each other much closer than fermions, can enter a superfluid state when they become degenerate at very cold temperatures.

When certain bosons, such as helium, become superfluids in frigid liquid form they can exhibit bizarre behavior. Losing their normal randomness, superfluids can, for example, flow up the walls of a cup.

In 1996, Cornell physics professor Robert Richardson, who received his Ph.D. at Duke, shared the Nobel Prize for discovering that helium-3 becomes a superfluid at 1.9 thousandths of a degree above absolute zero.

In 2001 three other United States scientists won the Nobel Prize for inducing bosons to form "Bose-Einstein condensates" at very low temperatures. In such a compact state the atoms not only exhibit superfluidity but also seemingly merge into a single superatom.

Physicists have predicted that an atomic gas of fermions could also become superfluid at temperatures lower than their Fermi temperatures. And experimentalists have been trying to observe such superfluidity in a Fermi gas since about 1995, Thomas said.

There are possible signatures of superfluidity in the data obtained by the Duke group, said Thomas. For one thing, the experiments produced the conditions recently predicted for this type of superfluid. Those predictions suggest that mixtures of fermionic gases of the type used by the Duke group should be able to attain a special kind of very high temperature superfluidity when they are strongly interacting.

Furthermore, the theoretical group of Sandro Stringari of the University of Trento in Italy predicted that a fermionic gas exhibiting superfluidity should show "an anisotropic expansion of the type we're observing," Thomas added. "Our observations fit very closely to this theory."

Yet Thomas and his group remain reluctant to propose that they have observed superfluidity. The introduction to their "Science Express" report said only that "superfluidity is plausible" from their data. "We're not able to claim that we've observed a superfluid," said Thomas. "We're basically asking the question: is this superfluidity?"

The researchers are reluctant to definitively conclude that they have observed superfluidity because they have identified an alternative explanation for the data, said Thomas. The gas may be in a new regime of collisional dynamics, he said. While collisions do not seem to adequately explain the data, the Duke researchers will have to carefully address this possibility in additional experiments.

If this oddly behaving gas is a superfluid, Thomas said it is of a special type that would be an "analog of a very, very high temperature superconductor" were it in solid form.

Superconductors are substances that conduct electricity without resistance. Experimental superconductors can now only exhibit that behavior at the frigid temperatures of liquid nitrogen or colder.

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