Feat of experimental acrobatics leads to first synthesis of ultracold molecules

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Achievement could benefit fields of superchemistry, quantum computing

A research team that in 2003 created an exotic new form of matter has now shown for the first time how to arrange that matter into complex molecules.
The experiments--conducted by Cheng Chin, now at the University of Chicago, and his colleagues under the leadership of Rudolf Grimm at Innsbruck University in Austria--may lead to a better scientific understanding of superconductivity and advance a growing new field called superchemistry. In the long term, they may also provide a strategy that could aid the development of quantum computers.

"In this field, it's hard to predict what's going to happen, because none of this was possible before 2003," said Chin, an Assistant Professor in Physics. Chin, Grimm and five colleagues will report their findings in a future issue of journal Physical Review Letters.

The new form of matter that the Innsbruck University team produced in 2003 is called a Fermion superfluid, which exists only at temperatures hundreds of degrees below zero. Superfluids exhibit characteristics distinctively different from the solids, liquids and gases that dominate everyday life. Most notably, superfluids can flow ceaselessly without any energy loss whatsoever. Science magazine named this work one of the top 10 breakthroughs of 2004.

In creating the Fermion superfluid, the team extended the work that earned the Nobel Prize in Physics for Eric Cornell, Wolfgang Ketterle and Carl Wieman in 2001. Those scientists had succeeded in creating the first Bose-Einstein condensate. Building on the work of Satyendra Nath Bose, Albert Einstein predicted in the 1920s that a special state of matter would form when a group of atoms collapsed into their lowest energy state. In this state now named for them, all of the atoms behave as if they are all one giant atom.

Cornell, Ketterle and Wieman created their Bose-Einstein condensate out of bosons, one of the two major categories of subatomic particles. Bosons carry force, while the other category of particles, fermions, comprise matter. Chin and the Innsbruck team showed in 2003 that, with some difficulty, fermions--in this case, lithium atoms--also can be coaxed into a Bose-Einstein condensate.

"Atoms themselves cannot become condensed. They are not bosons," Chin said. "But once they are paired they become bosons, and you can go to this superfluid state."

The laws of quantum mechanics forbid fermions from condensing. Chin and his colleagues used a technique called Feshbach resonance to bind two atoms into a simple molecule that behaves like a boson. The process is carried out in a magnetic field and resembles the type of electron pairing that causes superconductivity--the unimpeded flow of electricity at temperatures near absolute zero (minus 459.6 degrees Fahrenheit)--in solids.

This type of electron pairing is called Cooper pairing. Cooper pairings are the long-distance marriages of the subatomic world, where electrons are bonded at distances far greater than usual. "We have discovered a handle to adjust the interactions between atoms and between molecules, which allows us to synthesize complex quantum objects," Chin said.

Approximately two years ago, the Innsbruck scientists found a deep and unexpected connection between Bose-Einstein condensates and the bonding of Cooper pairs. They learned that they could use a pair of atoms to simulate the electrons of a Cooper pair. And more importantly, they could control the interactions of the atoms.

In their latest achievement, Chin and his colleagues have learned how to use Feshbach resonance as the control that binds the simple molecules made of cesium atoms into even larger clusters at temperatures near absolute zero.

"Since 2003, the controlled synthesis of simple molecules made of two atoms has opened up new frontiers in the field of ultracold quantum gases," said Rudolf Grimm, a professor of experimental physics at Innsbruck University and a co-author of the Letters article. Their present work now shows that ultracold simple molecules can be merged to form more complex objects consisting of four atoms, he said.

An important feature of this synthesis process is its tenability, Chin said. "In a magnetic field you can experimentally adjust it to any value, so we can control the process."

The synthesis of ultracold molecules is so new, it is difficult to predict potential applications, Chin said. But it puts a new field called superchemistry on a firm experimental footing. In superchemistry, scientists are able to precisely control the pairings and interactions of the atoms and molecules in Bose-Einstein condensates.

"We are physicists, but now our field's starting to overlap with chemistry," Chin said.

As ultracold molecules are synthesized into complex quantum objects, phenomena hidden at the subatomic scale will now become visible almost to the naked eye. "These objects may open up completely new possibilities to study the rich quantum physics of few-body objects, including chemical reactions in the quantum world," Grimm said.

Control of quantum objects may ultimately lead to the realization of a quantum computer, Chin said. Although possibly still decades from fruition, a quantum computer would work much faster than today's computers. The idea would be to use atoms in ultracold gas as bits, the basic units of information storage on a computer, with Feshbach resonance controlling their interactions to perform computations.

Chin now is setting up his laboratory at the University of Chicago and plans to continue studying quantum manipulation and computation based on cold atoms and molecules in collaboration with Grimm's Innsbruck team.

"Based on the speed of progress in this field, I think there probably will be more surprises," Chin said.

Source: University of Chicago

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