Physicists show coherence of Bose-Einstein condensates extends to spin state of atoms

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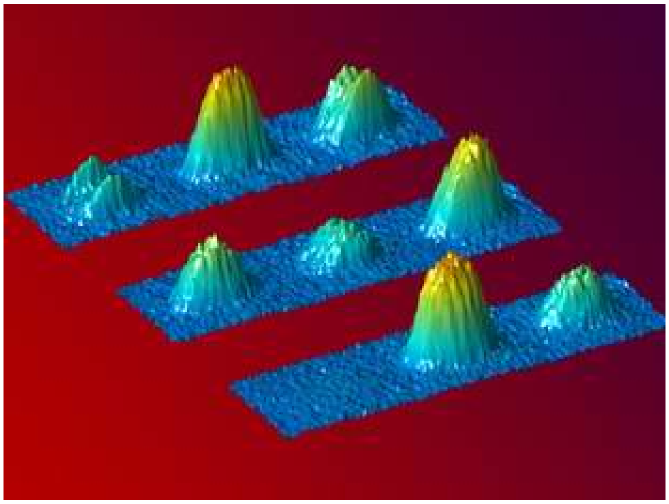

New research shows that the unique properties of atomic Bose-Einstein condensates extend to the internal spin states of the atoms from which the condensates are formed. Bose-Einstein condensates are an unusual form of matter in which all atoms exist in the same quantum state.

Image: Graphic represents how the population of rubidium atoms changed over time. Lower row shows the starting state, which contained only atoms with 0 and -1 spin states.

Beyond fundamental physics interest, the work could provide a foundation for future research with potential implications for quantum information systems.

Bose-Einstein condensates are formed by cooling gas atoms to a fraction of a degree above absolute zero. At that temperature, the atoms all drop into the same quantum state. That makes them coherent, all possessing the same quantum wave function, a state comparable to that of photons in laser systems.

In a paper published in the November issue of the journal Nature Physics, researchers at the Georgia Institute of Technology reported experimental evidence that this coherence also extends to the internal spin degrees of freedom in condensate atoms, which in this case had three different spin states, denoted by 1, 0 and -1.

"The question had been whether the coherence of Bose-Einstein condensates extended to what was going on in the internal states of the atoms," explained Michael Chapman, a professor in Georgia Tech's School of Physics. "The major message of our work is that it does. We have seen manifestation that this Bose-Einstein coherence extends to the spin degrees of freedom. This gives us a much richer system to study."

The research was sponsored by the National Science Foundation and NASA.

Coherence in condensate spin states had been predicted theoretically, and research teams – including Chapman's – had been seeking experimental confirmation. While the results have no immediate practical applications, they provide a foundation for future experiments that could ultimately have important real-world uses.

Chapman plans to use the experimental system to study how relatively small condensates – those containing between 10 and 100 atoms –

interact in a quantum way. Researchers understand the quantum behavior of small numbers of atoms, while semi-classical physics explains how large atomic ensembles work. Chapman wants to learn about the behavior of atomic groups in between those two size extremes.

"We are really interested in this regime in which quantum yields to classical," he explained. "The interest is similar to that of nanotechnology because we're asking the same basic questions. It's fundamentally interesting because while we can write down the exact quantum solution for one or a few atoms and the semi-classical approximations for a large group of atoms, we can't specify what will happen for this in-between region."

Chapman also hopes the small-scale condensate systems will be useful to understanding the atomic analogue of quantum optics or quantum atom optics, where physicists are interested in the behavior of just a few atoms. In condensates containing a million atoms, adding or removing one atom doesn't make a difference. But in groups containing only a hundred or so atoms, theory suggests that adding or removing one atom would make a substantial difference to the properties of the condensate.

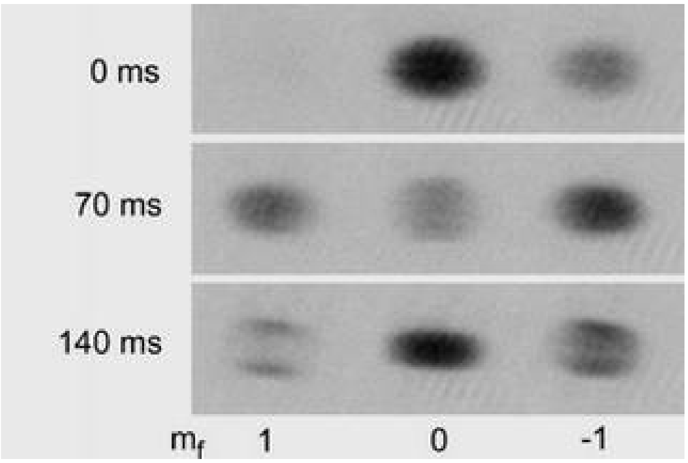

Image: Images of atomic clouds show the change in population distribution over time for rubidium atoms in three different spin states. The system began (at time 0) with only atoms in 0 and -1 spin states. Image: Ming-Shien Chang

Chapman notes that internal spin degrees of freedom can exhibit quantum entanglement in a phenomenon known as "spin squeezing." Understanding that effect in Bose Einstein condensates could be useful to researchers studying quantum information systems and quantum computing.

"Quantum entanglement is the bread-and-butter of quantum information and quantum computing," he said. "From the first time that people realized you could make a condensate that has spin degrees of freedom, people knew that would be interesting because if it really behaves this way, we could use this entanglement to make systems that might have applications to quantum information."

Experimentally, Chapman's research team – which included Ming-Shien Chang and Qishu Qin along with theoretical collaborators Wenxian Zhang and Li You – began with hundreds of millions of atoms of rubidium gas in a magneto-optical atomic trap that was overlapped with an optical trap. From this large number, they loaded a smaller group of atoms into the optical trap.

By applying magnetic fields to condensates created in the optical trap, they created condensates in different spin states and chose rubidium atoms with a -1 spin state to begin the experiment. Into that group, they injected microwave energy, which caused some of the atoms to transition from their original state to a spin 0 state. They then observed as atoms in the condensate collided with one another.

Some – but not all – collisions produced a change in state among the atoms. For instance, when two spin -1 atoms collide, their spin orientations remain unchanged because angular momentum must be conserved. However, when two spin 0 atoms collide, the result can be one spin -1 and one spin +1 atom. Over time, these collisions created quantities of the third spin state (+1) that did not exist in at the start of the experiment.

"We created a spin state that didn't exist in the original form," Chapman said. "That spin state was created by the other spin states that were coherently interactive in the condensate."

The researchers periodically turned off the atomic trap and applied a magnetic field gradient that pulled apart the different spin states, allowing measurement of the number of atoms at each spin state. With that information, the researchers charted spin-state population fluctuations through as many as a dozen oscillations.

The dynamics the researchers observed are analogous to Josephson oscillations in weakly connected superconductors and represent a type of matter-wave four-wave mixing. Beyond the evidence of coherent interaction between the atoms, the research demonstrated the ability to control the evolution of the rubidium system by magnetically applying differential phase shifts to the spin states, Chapman noted.

Source: Georgia Institute of Technology

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