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Quantum Entanglement Creates New State of Matter

Half a million ultracold atoms were linked together in the first-ever "macroscopic spin singlet" state

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Physicists have used a quantum connection Albert Einstein called "spooky action at a distance" to link 500,000 atoms together so that their fates were entwined. The atoms were connected via "entanglement," which

Atoms' spins (shown here as black arrows) were connected through quantum entanglement (ribbons), so that if one atom's spin was altered, the spin of its entangled partner would also change.

Credit: Alina Hirschmann/Nerea Grisaleña

...art. The ...s the first ...w state of ...ever before ... of the ...antum ...an eerie instantaneous connection over long distances ...oscopic world (hence Einstein's "spooky" remark). A ...glement where multiple particles' spins—their intrinsic angular momentum—add up to 0, meaning the system has zero total angular momentum.

The experimenters worked with rubidium atoms, which have a constant spin value of 1. (All particles have an unchanging spin value, a quantum characteristic that is always given in numbers without units.) The only way for a group of these atoms to have spins that add up to zero—the requirement for a spin singlet—is if the direction of

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their spins cancel one another out. And once two or more atoms are entangled in a spin singlet, their spins will always equal zero. That means that, bizarrely, if the direction of one atom's spin is altered, its entangled fellows will change their spins accordingly, and instantaneously, to preserve the sum of zero total spin.

Entangling such a large group of atoms in this way was no easy feat. First, the researchers cooled the atoms to 20 millionths of a kelvin—a frigid temperature necessary to keep the atoms almost perfectly still; any collisions between them would disturb their spins. Then, to determine the atoms' total spin, the researchers

learning about a quantum system that avoids altering its state. (This is necessary because active measurements of quantum systems tend to disturb their subjects, irrevocably changing the very thing being measured.)

To make the nondemolition measurement, the scientists sent a pulse of about 100 million photons (particles of light) through the cloud of atoms. These photons had energies that were precisely calculated so that they would not excite the atoms but rather would pass through. The photons themselves, however, were affected by the encounter. The atoms' spins acted as magnets to rotate the polarization, or orientation, of the light. By measuring how much the photons' polarization had changed after passing through the cloud, the researchers could determine the total spin of the cloud's atoms.

Although the measurement didn't change the spin state of the particles, it did have the effect of entangling many of them with one another. The researchers assume the atoms started out with spins pointing in random directions. In some cases, however, the measurement showed that their total added up to zero. When that happened, the measurement "locked in" that net zero result, in a way, ensuring that subsequent measurements would continue to find that the total spin equaled zero. "The measurement itself has somehow created the singlet state," says Naeimeh Behbood of The Institute of Photonic Sciences in Barcelona. "It has created an entangled state from a state without entanglement. How it does this is a deep mystery of quantum mechanics."

The total experiment involved a cloud of about one million rubidium atoms, but the passive measurements could not quantify exactly how many of these atoms became entangled. For the system's total spin to equal zero, however, the quantum limits of

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atoms have been entangled into one macroscopic system with net zero spin. (Previous experiments have done this to photons.) The study was published August 25 in *Physical Review Letters*. "I find it a remarkable result both for fundamental and applied research," says physicist Marco Koschorreck of the University of Bonn, who was not involved in the study. Because the entangled atoms' spins are very sensitive to magnetic manipulation, he says, the macroscopic spin singlet could be used to sense magnetic fields.

In the near future the researchers would like to better understand the new state of matter they created. For example, because they only know the total spin of their cloud, they do not know how individual atoms contribute to it. “For example, which atoms are entangled?” Behbood asks. “Is it nearest neighbors [pairs of atoms right next to one another] or the most distant atoms—or is it random? Do the atoms form singlets in pairs or in larger groups?” Such questions could help the scientists better understand how quantum nondemolition produces entanglement and how to manipulate it for practical purposes. The more we understand entanglement, the less “spooky” it becomes.

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