Physicists boost 'entanglement' of atom pairs

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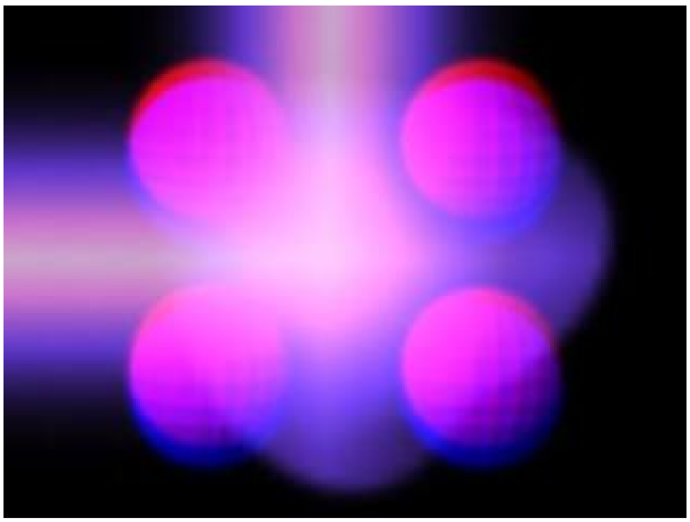

The NIST process for "purifying" an unusual property of quantum physics called entanglement involves illuminating two pairs of beryllium ions (charged atoms) with a series of ultraviolet laser pulses. Credit: Bill Pietsch, Astronaut 3 Media Group Inc.

Physicists at the Commerce Department's National Institute of Standards and Technology have taken a significant step toward transforming entanglement--an atomic-scale phenomenon described by Albert Einstein as "spooky action at a distance"--into a practical tool. They demonstrated a method for refining entangled atom pairs (a process called purification) so they can be more useful in quantum computers and communications systems, emerging technologies that exploit the unusual rules of quantum physics for pioneering applications such as "unbreakable" data encryption.

The NIST work, reported in the Oct. 19, 2006, issue of *Nature*, marks the first time atoms have been both entangled and subsequently purified; previously, this process had been carried out only with entangled photons (particles of light). The NIST demonstration also is the first time that scientists have been able to purify particles nondestructively. Direct measurement would destroy the delicate entangled state of atom pairs; the new experiment gets around this problem by entangling two pairs of atoms and measuring only one pair.

Entanglement is a curious property of quantum physics that links the condition and behavior of two or more particles, such as atoms or photons. Entanglement can occur spontaneously when two atoms interact. For the initial interaction, the atoms have to be in close proximity, but the entanglement may persist even if they are physically moved apart. The quality of the entanglement can be degraded by many environmental factors, such as fluctuating magnetic fields, so the process and the transport of entangled particles need to be tightly controlled in technological applications. The purification process implemented at NIST can clean up or remove any distortions or "noise" regardless of the source by processing two or more noisy entangled pairs to obtain one entangled pair of higher purity.

"We demonstrated entanglement purification with relatively high success rates in an ion trap system that could be scaled up to build quantum computers of a practical size," says Dietrich Leibfried, an author of the paper and designer of the experiment. "It's a more complicated procedure than anything we've demonstrated before, and it will be useful in many contexts once we improve our purification procedures."

The NIST team used ultraviolet lasers to entangle two pairs of beryllium ions (electrically charged atoms) in an electromagnetic trap. A similar process was used to cross-entangle the entangled pairs--that is, to entangle each member of the first pair with its counterpart in the second pair. Then the first pair of ions was measured, and the results were used as an indication of whether the second pair (unmeasured, and thus with its quantum state intact) was entangled with higher purity. Additional tests were performed to verify that the quality of the entanglement had indeed improved.

The reported purification rate is a record (although the entangled state is not yet pure enough for use in a working computer or other device) with more than one success for every three attempts, compared to one in a million in the photon experiments. Theoretically, the NIST process could be enhanced and then repeated as many times as necessary to create a stream of near-perfectly entangled pairs in a computer or network. The NIST team's continuing research aims to substantially improve the purification operations through, for example, improved control of magnetic fields and laser intensity.

The same NIST group previously has demonstrated at a rudimentary level all the basic building blocks for a quantum computer, including key processes such as error correction and, most recently, a mass-producible ion trap. Ions are among the most promising of a dozen or so candidates for quantum bits (qubits) to store, manipulate, and transport quantum information.

Quantum computers, if they can be built, could break today's best public-key encryption systems, used to protect commercial communications. Quantum communications systems, if well designed, provide a new approach to "unbreakable" encryption to keep messages secret. Quantum computers also potentially could be used to optimize complex systems such as airline schedules, accelerate database searching, and develop novel products such as fraud-proof digital signatures.

Entanglement could have many uses in large quantum computers and networks. For example, it is required for "teleportation" of information, a process that could be used to rapidly transfer data between separate locations in quantum computer, or to detect and correct minor operational errors. Entangled photons are used in various forms of quantum cryptography, and are the clear choice for long-distance communication.

Purification is crucial because particles can be entangled initially only when they are close together, and the link degrades as the particles are moved apart. The NIST process could be used, for example, to purify entangled ions before transfer of information to photons in large networks. Most long-distance quantum communication schemes require data transfer from storage qubits to transport qubits. "If someone comes up with an interface for efficiently transferring information from ions to photons, then ions could be used for purification and photons for transport," Leibfried says.

Background: Purifying Entangled Ions

Just as a magnet has a north and south pole, an ion has a “magnetic moment,” which for quantum computing purposes is called the spin (a spinning electrical charge is one way to create a magnetic moment). The values 0 and 1 are represented by the direction of the spin: Spin up is 0, and spin down is 1. In beryllium ions, the spin down state fluoresces when illuminated by a laser beam with a certain wavelength, whereas spin up does not.

Ions can exist in both 0 and 1 states at the same time, a quantum condition known as superposition. A superposition may be closer to 0, about equally positioned between 0 and 1, or closer to 1. When the ion is measured, the superposition “collapses” to either 0 or 1, depending on the superposition at the time. In an equal superposition, the ion would have a 50 percent chance of being measured as 0 and a 50 percent chance of being measured as a 1.

The NIST scientists adapted a theoretical method developed by another research group for purifying entangled particles, as follows:

Step 1—All four ions are prepared spin down (fluorescing).

Step 2—A laser pulse rotates all the ions to place them in equal superpositions of all possible spin states.

Step 3—Two ultraviolet laser beams, positioned at right angles and overlapping the ions, apply an oscillating force to the four ions, to entangle them in two pairs. The lasers are tuned so the difference between their frequencies is very close to the frequency of one of the ions' natural vibrations, a motion of swinging back and forth. The ions are brought into a superposition of standing still while also swinging left and right in unison. The superposition of different motions leaves an imprint on the spin states that has the effect of entangling pairs of ions in a controlled way.

Step 4—A laser pulse undoes the rotation in Step 2. The four ions are now entangled in pairs.

Entangled particles do not necessarily have identical properties, just properties that are linked in predictable ways. The NIST team can establish different forms of entanglement based on the spacing between the ions, the type of ion motion targeted, and the duration of the laser pulses. The purification process was designed so that each pair of entangled ions has a superposition of spin states that are not identical, but rather are mirror images of each other: ↑↓ and ↓↑. This means that, if ion 1 were measured as spin up, for example, then its entangled partner, ion 2, would be certain to be spin down. The individual states of ions 3 and 4 at this point would be unknown.

Step 5—A laser operation similar to Steps 1-4 is used to entangle each ion of the first pair with its counterpart in the second pair, so ions 1 and 3 are entangled and ions 2 and 4 are entangled. The properties of all four ions are now linked.

Step 6—Ions 1 and 2 are measured by illuminating them with a laser pulse and evaluating their overall fluorescence. Very high or low fluorescence levels indicate the two ions are in the same spin state; a mid-range value indicates they are in different states. If ions 1 and 2 have identical values, then an error has occurred somewhere. (They were entangled in a way that should make these results different.) This means that ions 3 and 4 probably are not entangled with higher fidelity. But, if ions 1 and 2 have opposing spins or values, then ions 3 and 4 (unmeasured) have been purified and are now more likely to be entangled with mirror-image superpositions of spin states than before. (That is, ions 3 and 4 are more likely to be in an entangled state of ↑↓ and ↓↑). Ions 3 and 4 would thus be available for use in a quantum computer or communications system.

In a final step to verify their success (this would not be done in a computer or other real device), the NIST scientists used lasers to rotate ions 3 and 4 by various amounts, and measured them at each angle by illuminating them with a laser pulse. The fluorescence resulting from the different rotation angles was compared to known patterns produced by perfectly entangled pairs.

Citation: R. Reichle, D. Leibfried, E. Knill, J. Britton, R.B. Blakestad, J.D. Jost, C. Langer, R. Ozeri, S. Seidelin, and D.J. Wineland. Experimental purification of two-atom entanglement. *Nature*. Oct. 19, 2006.

Source: NIST