Securely propagating entanglement at the push of a button

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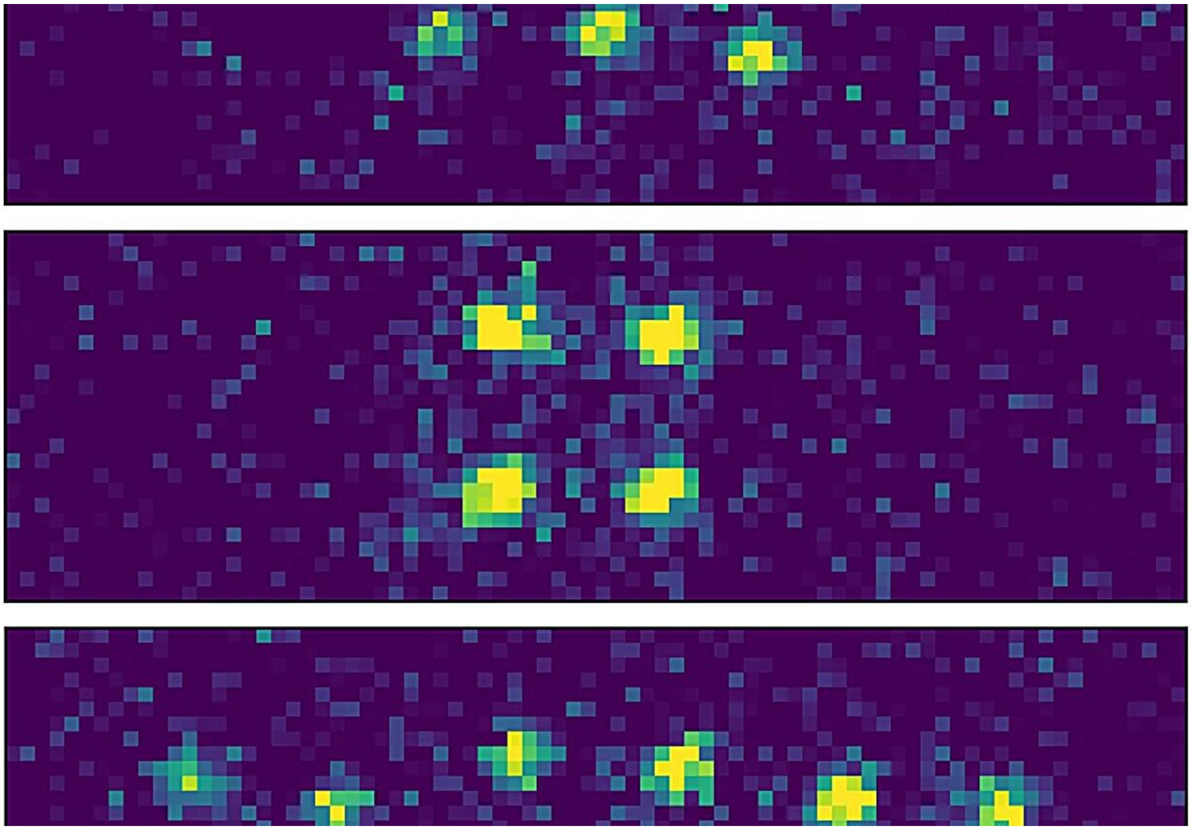

So far, the Garching scientists have been able to manipulate up to six rubidium atoms as quantum bits in the optical resonator with the light tweezers. To make them visible, the atoms are excited to emit light. In theory, the resonator can hold up to 200 atoms—highly effective addressable quantum bits. Credit: Max Planck Society

Entanglement, Einstein's "spooky action at a distance," today is THE tool of quantum information science. It is the essential resource for quantum computers and used to transmit quantum information in a future quantum network. But it is highly sensitive. It is therefore an enormous challenge to entangle resting quantum bits (qubits) with flying qubits in the form of photons "at the push of a button."

A team led by Gerhard Rempe, Director at the Max Planck Institute of Quantum Optics in Garching, Germany, has now succeeded in doing exactly that with atoms connected in parallel. The work was published July 11 in the journal *Science*.

The atoms are sandwiched between two almost perfect mirrors. This setup guarantees reliable interaction with photons as flying qubits—a technique pioneered by Gerhard Rempe. Using optical tweezers, the team was able to individually control up to six atoms and entangle each with a photon.

By applying a multiplexing technique, the scientists could demonstrate an atom-photon entanglement generation with almost 100% efficiency, a groundbreaking achievement for distributing entanglement over a quantum network.

Interfaces between resting qubits and flying qubits come into play whenever quantum information needs to be transmitted over long distances. "One aspect is the communication of quantum information over long distances in a future quantum internet," explains Emanuele Distante, who supervised the experiment as a postdoctoral researcher, and is now a researcher at ICFO in Barcelona.

"The second aspect is the goal of connecting many qubits in a distributed network to form a more powerful quantum computer. Both applications require efficient interfaces between qubits at rest and qubits in motion.

This is why many groups around the world are feverishly researching quantum mechanical light-matter interfaces," says Distante.

Several different technical approaches are being pursued. Gerhard Rempe and his team in Garching have been working for many years on a method that uses ultracold rubidium atoms trapped between two almost perfect mirrors as an optical resonator. The focus is on a future quantum internet.

This approach has an inherent advantage because it allows a trapped atom to interact highly efficiently with a photon, which bounces back and forth between the two mirrors about 20,000 times, like a ping-pong ball.

What's more, because one of the two mirrors is slightly more transparent than the other, the photon leaves in a precisely predetermined direction. This means that it is not lost, but can be reliably coupled into an optical fiber. If this photon is entangled with the atom using a specific protocol of laser pulses, this entanglement is maintained as the photon travels.

Multiplexing to overcome transmission losses

In 2012, the Garching team succeeded in entangling an atom in one resonator with a second atom in another resonator via "photon radio" through a 60-meter-long glass fiber. With the help of the transmitted photon, they formed an extended entangled quantum object from the two atoms. However, the photon must not get lost in the glass fiber along the way, and this is precisely the problem with a longer journey.

The solution, at least for medium distances of a few kilometers, is called "multiplexing." Multiplexing is a standard method used in classical information technology to make transmission more robust. Think of it as a radio link through a noisy area: If you send the radio signal along several parallel channels, the probability that it will reach the receiver via at least one channel increases.

"Without multiplexing, even our current Internet would not work," explains Distante. "But transferring this method to quantum information systems is a particular challenge."

Multiplexing is not only interesting for more secure transmission over longer distances in a future quantum internet, but also for a local quantum network. One example is the distributed quantum computer, which consists of several smaller processors that are connected via short optical fibers. Its resting qubits could be entangled more reliably by multiplexing with flying qubits to form a distributed, more powerful quantum computer.

Laser tweezers for handling atoms

The challenge for the Garching team was to load several atoms into a resonator as resting qubits and to address them individually. Only if the position of the atoms is known can they be entangled in parallel with one photon each in order to achieve multiplexing. Hence, the team developed a technique for inserting optical tweezers into the narrow resonator.

"The mirrors are only about half a millimeter apart," explains Lukas Hartung, Ph.D. student and first author of the paper in *Science*.

The optical tweezers consist of fine laser beams that are strong enough to capture an atom in their focus and move it precisely to the desired position. Using up to six such tweezers, the team was able to arrange a corresponding number of floating rubidium atoms in the cavity to form a neat qubit lattice. Since the atoms can easily remain in the trap for a minute—a little eternity in quantum physics—they could easily be entangled with one photon each.

"This works almost 100% of the time," says Distante, emphasizing the key advantage of this technique: The entanglement distribution works almost "deterministically," i.e., at the push of a button.

Scalable to considerably more qubits

In order to achieve this, the team used a microscope lens objective positioned above the resonator with micrometer precision in order to focus the individual beams of the light tweezers into the narrow mirror cabinet. The tweezer beams are generated via so-called acousto-optical deflectors and can therefore be controlled individually. Precise adjustment of the laser tweezers in the optics requires a great deal of dexterity.

"Mastering this challenge was the cornerstone for the success of the experiment," summarizes Stephan Welte, who helped develop the technology as part of the team and is now a researcher at ETH Zurich.

The current experiment gives hope that the method can be scaled up to considerably more qubits without losses: The team estimates that up to 200 atoms could be controlled in such a resonator. As these quantum bits can be controlled very well in the resonator, this would be a huge step forward. And as the interface even feeds 100% of the entangled photons into the optical fiber, a network of many resonators, each with 200 atoms as resting qubits, would be possible.

This would result in a powerful quantum computer. It is still a dream of the future. But with the laser tweezers, the Garching team now has a considerable part of this future firmly under control.

More information: Lukas Hartung et al, A quantum-network register assembled with optical tweezers in an optical cavity, *Science* (2024). DOI: 10.1126/science.ado6471

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