First entanglement between light and optical atomic coherence

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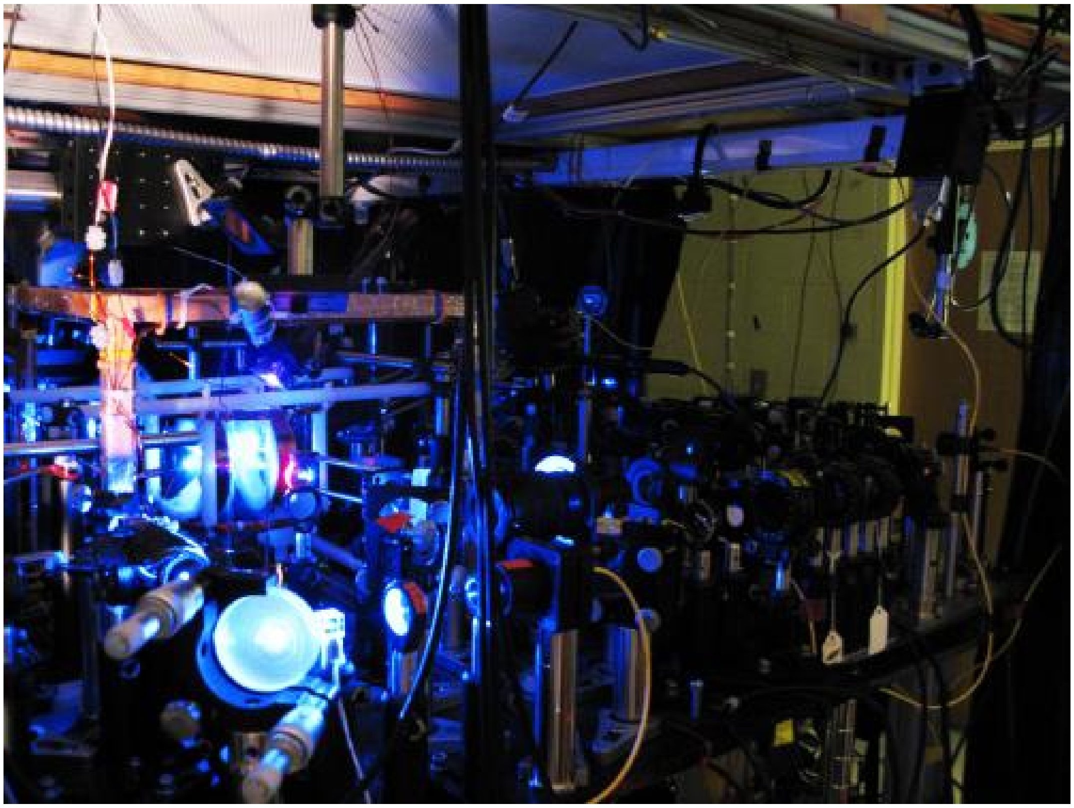


This is the experimental setup used to measure the entanglement between light and an optical atomic excitation in the laboratory of Alex Kuzmich. Credit: Kuzmich Physics Lab

Using clouds of ultra-cold atoms and a pair of lasers operating at optical wavelengths, researchers have reached a quantum network milestone: entangling light with an optical atomic coherence composed of interacting atoms in two different states. The development could help pave the way for functional, multi-node quantum networks.

The research, done at the Georgia Institute of Technology, used a new type of optical trap that simultaneously confined both ground-state and highly-excited (Rydberg) atoms of the element rubidium. The large size of the Rydberg atoms – which have a radius of about one micron instead of a usual sub-nanometer size – gives them exaggerated electromagnetic properties and allows them to interact strongly with one another.

A single Rydberg atom can block the formation of additional Rydberg atoms within an ensemble of atoms, allowing scientists to create single photons on demand. Georgia Tech professor Alex Kuzmich and collaborators published a report on the Rydberg single-photon source in the journal *Science* in April 2012, and in a subsequent *Nature Physics* article, demonstrated for the first time many-body Rabi oscillations of an atomic ensemble.

In the new research, the state-insensitive trap allowed the researchers to increase the rate at which they could generate photons by a factor of 100 compared to their previous work.

"We want to allow photons to propagate to distant locations so we can develop scalable protocols to entangle more and more nodes," said Kuzmich, a professor in Georgia Tech's School of Physics. "If you can have coherence between the ground and Rydberg atoms, they can interact strongly while emitting light in a cooperative fashion. The combination of strong atomic interactions and collective light emissions results in entanglement between atoms and light. We think that this approach is quite promising for quantum networking."

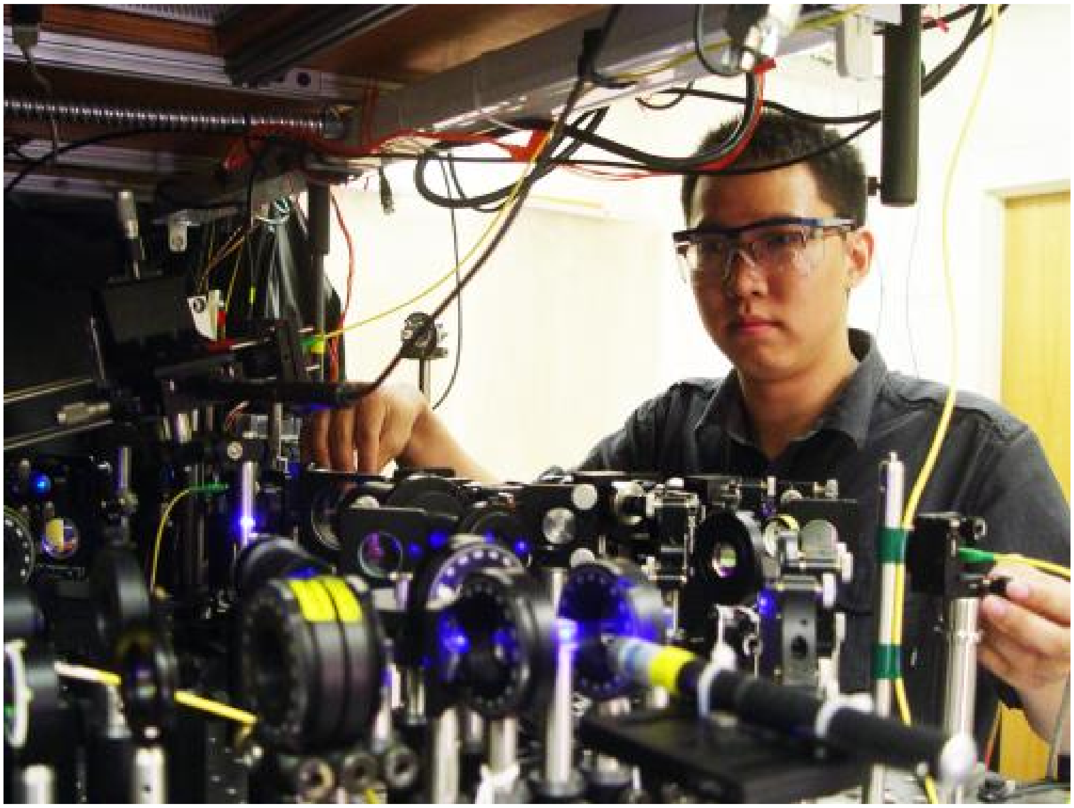
The research was reported June 19 in the early edition of the journal *Nature*. The research has been supported by the Atomic Physics Program

and the Quantum Memories Multidisciplinary University Research Initiative (MURI) of the Air Force Office of Scientific Research, and by the National Science Foundation.

Generating, distributing and controlling entanglement across quantum networks are the primary goals of quantum information science being pursued at research laboratories around the world. In earlier work, ground states of single atoms or atomic ensembles have been entangled with spontaneously-emitted light, but the production of those photons has been through a probabilistic approach – which generated photons infrequently.

This spontaneous emission process requires a relatively long time to create entanglement and limits the potential quantum network to just two nodes. To expand the potential for multi-mode networks, researchers have explored other approaches, including entanglement between light fields and atoms in quantum superpositions of the ground and highly-excited Rydberg electronic states. This latter approach allows the deterministic generation of photons that produces entanglement at a much higher rate.

However, until now, Rydberg atoms could not be excited to that state while confined to optical traps, so the traps had to be turned off for that step. That allowed the confined atoms to escape, preventing realization of atom-light entanglement.



Georgia Tech graduate student Lin Li adjusts the optics on equipment being used to measure the entanglement between light and an optical atomic excitation in the laboratory of Alex Kuzmich. Credit: Kuzmich Physics Lab

Based on a suggestion from MURI colleagues at the University of Wisconsin, the Georgia Tech team developed a solution to that problem: a state-insensitive optical trap able to confine both ground-state and Rydberg atoms coherently. In this trap, atoms persist for as much as 80 milliseconds while being excited into the Rydberg state – and the researchers believe that can be extended with additional improvements. However, even the current atomic confinement time would be enough to operate complex protocols that might be part of a quantum network.

"The system we have realized is closer to being a node in a quantum network than what we have been able to do before," said Kuzmich. "It is certainly a promising improvement."

Key to the improved system is operation of an optical trap at wavelengths of 1,004 and 1,012 nanometers, so-called "magic" wavelengths tuned to both the Rydberg atoms and the ground state atoms, noted Lin Li, a graduate student in the Kuzmich Laboratory.

"We have experimentally demonstrated that in such a trap, the quantum coherence can be well preserved for a few microseconds and that we can confine atoms for as long as 80 milliseconds," Li said. "There are ways that we can improve this, but with the help of this state-insensitive trap, we have achieved entanglement between light and the Rydberg excitation."

The rate of generating entangled photons increased from a few photons per second with the earlier approaches to as many as 5,000 photons per second with the new technique, Kuzmich said. That will allow the researchers to pursue future research goals – such as demonstration of quantum gates – as they optimize their technique.

Experimentally, the research works as follows: (1) an ultra-cold gas of rubidium atoms was confined in a one-dimensional optical lattice using lasers operating at 1,004-nanometer and 1,012-nanometer wavelengths. The atomic ensemble was driven from the collective ground state into a single excited state; (2) By applying a laser field, an entangled state was generated. The retrieved field was mixed with the coherent field using polarizing beam-splitters, followed by measurement at single-photon detectors; (3) The remaining spin wave was mapped into a field by a laser field.

According to Kuzmich, the success demonstrates the value of collaboration through the MURI supported by the Air Force Office of Scientific Research, which in 2012 awarded $8.5 million to a consortium of seven U.S. universities that are working together to determine the best approach for creating quantum memories based on the interaction between light and matter.

Through the MURI, a team of universities is considering three different approaches for creating entangled quantum memories that could facilitate long-distance transmission of secure information. Among the collaborators in the five-year program are Mark Saffman and Thad Walker at the University of Wisconsin, Mikhail Lukin of Harvard, and Luming Duan of the University of Michigan, who at the beginning of this century made pioneering proposals which formed the basis of the approach that Kuzmich, Li and colleague Yaroslav Dudin used to create the entanglement between light and the Rydberg excitation.

More information: Lin Li, Yaroslav Dudin and Alexander Kuzmich, "Entanglement between light and an optical atomic excitation," *Nature*, 2013. dx.doi.org/10.1038/nature12227

Provided by Georgia Institute of Technology

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