

Entangled quantum memories for a quantum repeater: A step closer to the Quantum Internet

ICFO researchers report in Nature on having achieved, for the first time, entanglement of two multimode quantum memories located in different labs separated by 10 meters, and heralded by a photon at the telecommunication wavelength.

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During the 90s, engineers made major advances in the telecom arena spreading out the network to distances beyond the cities and metropolitan areas. To achieve this scalability factor, they used repeaters, which enhanced attenuated signals and allowed these to travel farther distances with the same features such as intensity or fidelity. Now, with the addition of satellites, it is completely normal to be in the middle of a mountain in Europe and talk with your loved ones living in the other part of the world.

In the road towards building the future Quantum internet, quantum memories play the same

role. Together with sources of qubits, they are the building blocks of this novel internet, acting as quantum repeaters of data operations and using superposition and entanglement as the key ingredients of the system. But to operate such system at a quantum level, the entanglement between quantum memories had to be created over long distances and maintained as efficiently as possible.

All together in one

In a recently published study in Nature, ICFO scientists Dario Lago, Samuele Grandi, Alessandro Seri and Jelena Rakonjac, led by ICREA Prof at ICFO, Hugues de Riedmatten, have achieved scalable, telecom-heralded matter-matter entanglement between two remote, multimode and solid-state quantum memories. In simpler words, they were able to store, for a maximum of 25 microseconds, one single photon in two quantum memories placed 10m apart.

The researchers knew that the photon was in one of the two memories, but they did not know in which one, which emphasized this counter-intuitive notion that we have of nature, which allows the photon to be in a quantum superposition state in the two quantum memories at the same time but, amazingly, 10 meters apart. The team also knew that the entanglement was created with the detection of a photon at telecom wavelength, and it was stored in the quantum memories in a multiplexed fashion, i¿½a feature akin to allowi g several messages to be sent at the same time in a classical channeli¿½. These two key features have been achieved together for the first time and define the stepping ston in extending this scheme to much longer distances.

As Dario Lago, a PhD student at ICFO and first author of the study, enthusiastically pinpoints i¿½So far, several of the milestones achieved in this experiment were done by other group , like entangling quantum memories or achieving storage of the photons in quantum memori s with a very high efficiency and high rates. But, the uniqueness about this experiment is th t our techniques achieved very high rates and can be extended to longer distances.i¿½

Setting up the experiment

Achieving this landmark took its effort and time. During the course of several months, the team setup the experiment, where they used a rare-earth doped crystal as a quantum memory for the basis of their test.

Then, they took two sources generating correlated pairs of single photons. In each pair, one photon, named idler, is at a 1436nm (telecom wavelength), and the other, named signal, is at a wavelength of 606nm. The single signal photons, were sent to a quantum memory, made up of millions of atoms all randomly placed inside a crystal, and stored there via a protocol called atomic frequency comb. Alongside, the idler photons, also called heralding or messenger photons, were sent through an optical fiber to a device called beam-splitter, where the information about their origin and path was completely erased. Samuele Grandi, postdoctoral researcher and co-first author of the study, comments, i¿½We erased any sort f feature that would tell us where the idler photons were coming from, let it be source 1 or , and we did this because we did not want to know any information about the signal phot n and in which Quantum Memory it was being stored ini¿½By erasing these features, the signal photon could have been stored in any of the quantum memories, which means that entanglement was created between them.

Every time that the scientists saw on the monitor a click of an idler photon arriving at the detector, they were able to confirm and verify that there was, in fact, entanglement. This entanglement consisted in a signal photon in a superposition state between the two quantum memories, where it was stored as an excitation shared by tens of millions of atoms for up to 25 microseconds.

As Sam and Dario mention, i¿½The curious thing about the experiment is that it is n t possible to know if the photon was stored in the quantum memory in the lab 1 or in Lab , which was more than 10 meters away. Although this was the principal feature of o r experiment, and one that we kind of expected, the results in the lab were sti l counter-intuitive, and even more peculiar and mind-blowing to us is that we were capable f controlling it!i¿½

The importance of heralded photons

Most of the previous studies that have experimented with entanglement and quantum memories used herald photons to know whether or not the entanglement between quantum memories had been successful. A heralding photon is like a messenger dove and the scientists can know upon its arrival that the entanglement between the quantum memories has been established. When this happens, the entanglement attempts stop and the entanglement is stored in the memories before being analyzed.

In this experiment, the scientists used a heralding photon in the telecom frequency, confirming that the entanglement being produced could be established with a photon that is

compatible with existing telecom networks, an important feat since it allows entanglement to be created over long distances and, even more so, enables these quantum technologies to be easily integrated into the existing classical network infrastructures.

Multiplexing is key

Multiplexing is the capability of a system to send several messages at the same time through only one channel of transmission. In classical telecommunications, this is a frequent tool used to transmit data over the internet. In quantum repeaters, such technique is slightly more complex. With standard quantum memories, one has to wait for the message heralding the entanglement to come back to the memories, before one can try again to create entanglement. But with the use of the atomic frequency comb protocol, which allows this multiplexing approach, the researchers were able to store the entangled photons at many different times in the quantum memory, without having to wait for a successful heralding event before generating the next entangled pair. This condition, called i¿½tempor
l multiplexingi¿½ is a key feature that represents a major increase in the operational time of the system, leading to an increment in the final entanglement rate.

Future Steps

As Prof. ICREA at ICFO Hugues de Riedmatten enthusiastically remarks i¿½This idea w
s conceived more than 10 years ago and I am thrilled to see that it has now succeeded in t
e lab. The next steps are to bring the experiment outside of the lab, to try and link differe
t nodes together and distribute entanglement over much larger distances, beyond what
e currently have now. In fact, we are in the midst of achieving the first quantum link of 35k
, which will be done between Barcelona and ICFO, in Castelldefelsi¿½.

It is clear that the future quantum network will bring many applications in the near future. This achieved landmark proves and confirms that we are in the correct pathway towards developing these disruptive technologies and beginning to deploy them into what will be a new way of communicating, the Quantum Internet.

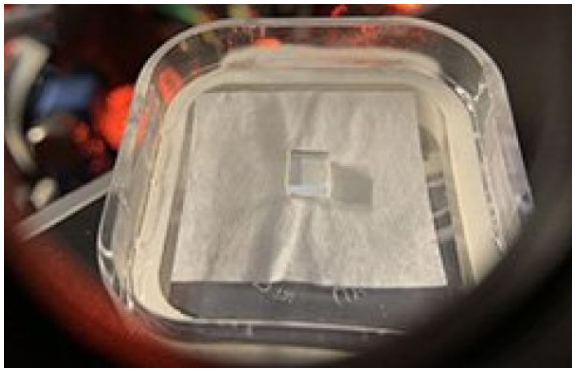
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Acknowledgements:

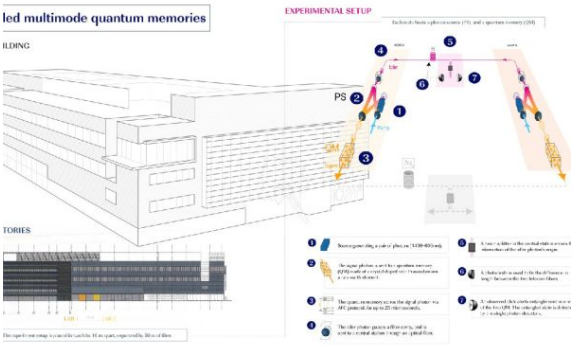
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Reference:

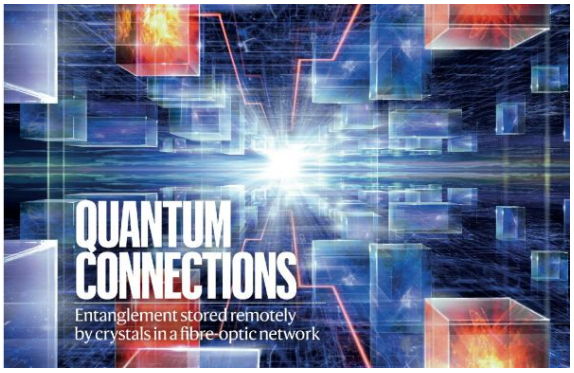
Telecom-heralded entanglement between multimode solid-state quantum memories, Dario Lago-Rivera, Samuele Grandi, Jelena V. Rakonjac, Alessandro Seri, and Hugues de Riedmatten, Nature, 2021, https://www.nature.com/articles/s41586-021-03481-8



Close-up image of a rare-earth doped crystal used as a quantum memory. ©ICFO



Schematic illustration of the experimental setup and the location of the labs in the ICFO building



Study on the cover of Nature magazine - June 3rd Issue