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Indistinguishable photons from dissimilar atomic quantum nodes

ICFO researchers have obtained a world record degree of indistinguishability between two photons coming from two dissimilar quantum nodes when no detections are discarded. These results pave the way towards future heterogeneous quantum networks.

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The development of a quantum internet is a remarkable endeavor running parallel to the pursuit of practical quantum computers. This quantum network aims to facilitate the exchange of quantum bits of information (called qubits) between quantum processors, allowing for unprecedented levels of secure communication and computational power.

A key objective of a quantum network is to create remote entanglement between two distant processing units, which can then be utilized for specific applications. To achieve this, researchers are exploring a new technology called the quantum repeater, which facilitates the generation and transmission of entanglement between two intermediate stations, known as quantum nodes. However, the physical systems used as quantum repeaters may differ significantly from those used in quantum computers. Therefore, developing an interface between these diverse platforms is crucial.

The interface between these systems typically involves sending single photons from each and making them interfere. The quality of this quantum interference determines how effectively entanglement can be distributed across the network. Achieving high-quality interference is challenging because the photons must be **indistinguishable**, and when quantum nodes are based on different technologies, making them emit indistinguishable photons is particularly difficult. A common solution to this problem is to select only a small part of the emitted photons, which increases the indistinguishability, but this comes at the expense of a strong reduction in detection rate.

In this context, ICFO researchers **Dr. Felix Hoffet**, **Dr. Jan Lowinski**, **Dr. Lukas Heller**, **Dr. Auxiliadora Padron-Brito** led by **Prof. ICREA Hugues de Riedmatten** have succeeded in producing **highly indistinguishable photons from dissimilar quantum nodes without discarding any detection, achieving a world record degree of indistinguishability** in the field of hybrid quantum networks under such conditions. The results have recently been published in Physical Review X Quantum.

How to obtain indistinguishable photons out of quantum nodes

In order to check the indistinguishability of the emitted photons, the team first needed to
re-create the typical basic unit of a quantum network: two quantum nodes with different
technologies. In their case the two nodes were based on cold Rubidium atoms. One of the
was based on a fully blockaded cold Rydberg ensemble (sometimes called a Rydber
superatom). This system enables quantum processing capabilities and, in this experiment
generated on-demand single photons. The other one was a quantum repeater node based o
an emissive quantum memory and emitted heralded single photons
The researchers used the quantum memory to synchronize the emission of the two photons
In the emissive memory, several generation trials are made until the detection of a photo
heralds the presence of a photon in the memory. The photon is then stored in the quantu
memory while a classical signal is sent to the Rydberg node, used as a trigger to generat
another single photon in a quasi-deterministic fashion. Finally, the first photon is release
from the quantum memory at a precise time, and the two photons are mixed on a bea
splitter where a quantum interference takes place. The quality of this quantum interferenc
then depends on the indistinguishability between the two photons.
? To achieve the reported milestone, the researchers had to develop some new technique
. First, they tailored the temporal waveforms of the emitted single photons to match ea
h other, which is already an important result. They accomplished this by modulating the lase
s used to read out the atomic excitation
. Next, since these quantum nodes operate independently, they are subject to non-correlat
d experimental fluctuations. This typically results in numerous problems, as it can make t
e photons distinguishable, thereby disrupting quantum interference within a few minutes. Th
s issue is critical because quantum nodes need to maintain their quantum properties ov
r extended periods, spanning several days. To address this limitation, the researche
s developed new stabilization techniques. They periodically measured atomic resonances a
d dynamically adjusted the experiments based on the results, **ensuring consistent quantum
performance over tens of hours**.

One step closer to the quantum internet

This challenging experiment provided a fertile ground for observing non-linear effects that had been predicted by theory but never experimentally confirmed. Overall, this experiment demonstrates that cold atomic systems are promising candidates for scaling up quantum networks. The researchers now aim to reuse the techniques they developed and extend their experimental setup to show that distributing entanglement between hybrid systems is feasible.

According to Dr Felix Hoffet, researcher at ICFO and first author of the study: ï¿½**Cold atoms are interesting for this kind of experiments because, unlike other systems, each atom is**

identical. I am optimistic that this subtle distinction will prove beneficial in the long term for connecting quantum processors with quantum repeaters. Furthermore, given the rapid progress in both research fields, I believe it is now important to bridge the gap between these different platforms and consider larger-scale integration already. I am happy to contribute initial insights to this endeavour¡¿?

. Hugues de Riedmatten, ICREA professor at ICFO concludes **"It is likely that future quantum networks will combine different quantum nodes made of different physical systems and with different functionalities. Creating an interface enabling the distribution of entanglement between disparate quantum systems is an outstanding challenge. Our work is a step in th s direction, but there are many more challenges ahead, the first of which will be to interfa e quantum nodes made of different atoms"**

Reference: Near-unity indistinguishability of single photons emitted from dissimilar and independent atomic quantum nodes, Felix Hoffet, Jan Lowinski, Lukas Heller, Auxiliadora Padron-Brito, and Hugues de Riedmatten, PRX Quantum (2024)
https://doi.org/10.1103/PRXQuantum.5.030305

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Glass cell in the experimental setup.