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How to Efficiently Achieve Photonic Multi-Qubit Entanglement

Two-dimensional graph states consisting of a large number of entangled photons are at the heart of measurement-based quantum computation. Researchers have now developed a procedure to efficiently and reliably generate linear graph states with up to 14 entangled photons, all emitted from a single atom. Adding even more photons also seems to be nearly within reach.

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Using the principles of quantum mechanics to process information is a rapidly developing field of research. In addition to engineering efforts to build proof-of-principle systems for quantum information processing (QIP) that can be used for applications in computing and communications, there are numerous studies that focus on crucial resources and components for QIP, and on fundamental quantum effects. Among the key resources are multi-qubit entangled states: they are essential to the experimental realization of quantum algorithms and secure communication protocols alike, and the development of reliable procedures to generate them motivates cutting-edge research in this area.

The various approaches differ in the physical implementation of qubits – photons, trapped ions, cold atoms, or superconducting electrical circuits, notably. But what holds true for all qubit carriers is that entangled states with large numbers of qubits are more challenging to produce and protect from deleterious effects that can hijack their nonclassical properties, such as decoherence.

Photonic qubits among the candidates for quantum information processing applications

In their recent Nature publication "Efficient generation of entangled multiphoton graph states from a single atom," Gerhard Rempe and his team present a promising strategy for photonic multi-qubit entanglement. Optical photons were among the very first physical systems to be used for encoding quantum information, and remain a valid candidate for future QIP applications because they are relatively easy to manipulate and are less sensitive to decoherence than other carriers. Technological innovations such as photonic chips and high-efficiency single-photon detectors have increased their potential even further.

However, photonic QIP is subject to severe limitations. Usually, the creation of entangled states of light relies on a probabilistic process called spontaneous parametric down-conversion (SPDC). In SPDC, the interaction of a specially prepared pump laser field with a nonlinear crystal converts incoming pump photons into pairs of entangled photons. This process has been a workhorse of experimental quantum optics, allowing researchers to generate various prototypical quantum states in the lab – such as heralded single-photon states and squeezed states – and probe fundamental aspects of quantum theory. However, the performance of SPDC sources is greatly hampered by the probabilistic nature of the underlying process, which makes it difficult for researchers to further increase the number of entangled photons. Deterministic sources can, at least in theory, produce photons with high probability at well-defined times and on demand. In contrast, SPDC sources create entangled photons at random times, and the process is characterized by a conversion rate where only about one in a hundred billion pump photons is converted into a photon pair.

The team's publication now offers a new way to overcome these limitations. It reports on the generation of the largest entangled states of optical photons to date, based on a cavity quantum electrodynamics (cQED) platform that leverages entanglement between a single atom and a number of photons emitted by it. In their experiments, the authors created one-dimensional (or linear) cluster states made of 12 photons as well as Greenberger-Horne-Zeilinger (GHZ) states with 14 photons. Both belong to a class of entangled multiparticle states known as graph states. These are parametrized by mathematical graphs identified by a set of N vertices, or nodes, and a set of edges arbitrarily connecting the vertices. Graph states play a fundamental role in measurement-based quantum computation (MBQC), which is one of several formally equivalent models for quantum computing.

The more widely known quantum circuit model, for example, relies on quantum logic gates, implemented by unitary operations on qubits, to process quantum information. In this model, it is only at the end of a computation that the qubits are measured and, consequently, the quantum information is converted into classically readable information. In one-way quantum computing, which is an instance of MBQC, the approach is different. First, the system is prepared in a graph state known as a two-dimensional (2D) cluster state; then, a specific sequence of measurements on the individual qubits of the cluster state realizes a given algorithm. The fact that the graph state can be prepared independently of the algorithm is why the 2D cluster state can be considered a universal resource in one-way quantum computing.

Single-qubit measurements on cluster states don't pose as many challenges as more complex two-qubit logic gates in quantum circuits; consequently, most experimental efforts in one-way quantum computing focus on the generation of the initial quantum state. Rempe's team have now produced graph states with the highest number of entangled photons ever generated in the laboratory. The fact that they didn't reach even higher numbers was largely due to the limited available measurement time in the lab: the more photons are generated, the less likely it becomes that all of them can be detected in a given attempt.

A cyclically repeatable process to create the desired multiphoton states

The team's experimental setup features a rubidium atom – an atomic qubit – trapped at the center of an optical cavity created by highly reflective mirrors. The cavity acts as an efficient light-matter interface to enable atom-photon entanglement. Laser beams propagating orthogonally with respect to the cavity axis allow the manipulation of the atom's state and the emission of photons.

The production cycle of an entangled multiphoton state starts by initializing the rubidium atom through optical pumping and then applying a suitably shaped laser pulse that generates a first photon, entangled in polarization with the atomic qubit, through the vacuum-stimulated Raman adiabatic passage (vSTIRAP) technique.

Subsequently, the authors apply a specific laser pulse to perform a rotation on the atomic qubit. In this context, using different rotations allows them to produce graph states of different types. Another pulse then prepares the atom for another vSTIRAP process, which produces the second entangled photon. To obtain an N-photon state, the authors repeat this sequence of operations N minus 2 times, with the emitted photons being entangled because of the coherence properties of the atom. The process ends with a laser pulse that leads to the emission of photon N and at the same time brings the atomic qubit into a state disentangled from the photonic state.

The entangled photons exiting the cavity are analyzed with superconducting nanowire single-photon detectors that record N-photon coincidences, that is, photon detection events that fall within a predefined temporal interval. In the presented implementation, an experimental run is deemed successful when the detectors reveal N photons in a row, with each photon detected within a 1-microsecond window. The collected data is post-selected to discard detection events that do not correspond to successful experimental runs. As atoms do not stay trapped in the cavity indefinitely and can move away from its center during the experiment, reloading and repositioning operations must also be carried out regularly. Consequently, further post-selection ensures that data points corresponding to an unintended shift in the atom's position inside the cavity are discarded.

Atom-photon entanglement and single-photon generation in cQED setups have been demonstrated before. The novelty of the present work lies in the efficiency of the process: it creates the desired multiphoton states with very high probabilities of success and over short time scales, while its individual steps can be repeated cyclically to obtain photonic quantum states that consist of large numbers of entangled photons. It is an achievement made possible by the unique features of the experimental setup, which include long atom trapping times via fast atom cooling, efficient photon generation via optimized laser pulses, the use of low-loss optics in the photon path to the detectors, and highly efficient photon detection.

Experimental challenges

The linear cluster states and GHZ states considered in the publication by Rempe and his team present specific experimental challenges. A quantum state can be described completely in terms of its density matrix, where the matrix's elements correspond to the state's projections onto a set of basis states. This matrix can be experimentally determined through a technique called quantum state tomography. In turn, experimental knowledge of the density matrix allows the estimation of state fidelity, which quantifies how closely the experimentally generated state matches the desired quantum state. Over the years, state fidelity has established itself as one standard way to evaluate the quality of qubit sources. However, the more non-zero elements in the density matrix – that is, the more complex the structure of the state – , the more difficult its reconstruction and the subsequent fidelity estimation become.

The entangled states produced by Rempe's team are far too large for a full experimental reconstruction of their density matrices, which include over a hundred million terms. In the case of a GHZ state, however, the authors were still able to calculate the fidelity as a function of the photon number N because there are only four non-zero elements in the state's density matrix. They found that the fidelity can be expected to drop below 50 percent – the threshold below which the generated state is considered to be classical – only at N = 44 photons.

For the linear cluster state, calculating the fidelity is much more demanding because of the many non-zero elements in the density matrix. Accordingly, the authors chose a less resource-intensive alternative to demonstrate the successful generation of multiphoton entanglement. They computed what is known as an entanglement witness – an observable that provides a lower bound on the fidelity – and found the latter to be above 50 percent for all values of N up to 12 for the linear cluster state. For the GHZ state, a different witness indicated that the state fidelity for the 14-photon entangled state had a lower bound of 76 percent. In both cases, these findings confirm the presence of genuine quantum correlations in the multi-qubit states produced. Compared to the GHZ state, the fidelity of the linear cluster state seems to decrease much more rapidly as the size of the state increases, but the authors note that here the entanglement witness tends to underestimate the actual fidelity.

High photon generation and detection efficiencies were key to producing 12- and 14-photon entangled states. The probability of success for detecting an N-photon coincidence is a function of both efficiencies, and it scales exponentially with the photon number. In their experiments, the authors were able to draw on an overall single-photon generation-to-detection efficiency of ca. 43 percent; the intrinsic source efficiency, which corresponds to the probability of finding a photon at the output of the optical cavity, was 66 percent, while the efficiency of detection for a single photon in the chain of N light particles was 70 percent.

Future directions: developing the setup into a programmable source of entangled multiphoton states

Potential improvements to the setup range from using higher-quality mirrors for the cavity to reducing the number of free-space-to-optical-fiber couplings in the detection unit. According to the authors, both source and detection efficiencies could surpass 80 percent by doing so.

A notable feature of the source in question is its N-photon coincidence rate, which the authors studied as a function of the photon number N while taking into account the experimental duty cycle – which measures the experimental runtime that is actually allocated to entangled-state production – and data post-selection. For the 14-photon GHZ state, for example, the authors recorded 151 14-photon coincidences in seven hours of experimental runtime. This translates into roughly one coincidence detection event every three minutes, which is orders of magnitude faster than what has been achieved to date with sources of entangled photons based on other platforms.

Most importantly, the authors found that the coincidence rate of their cQED source decayed more slowly for larger numbers of entangled photons compared to sources based on SPDC, quantum dots or Rydberg superatoms. This points to the possibility of scaling up the cQED source to produce even larger graph states. Additionally, the team's ability to perform arbitrary single-qubit rotations on the atom, as part of a photon production cycle, permits the generation of different graph states, making their setup a programmable source of entangled multiphoton states.

A natural albeit challenging extension of this work would consist in weaving a 2D fabric of entangled photonic cluster states from individual 1D chains, hence bringing one-way quantum computing hardware closer to our reach. ●

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