Using degrees of freedom to get hyperentanglement

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(PhysOrg.com) -- One of the biggest challenges scientists are grappling with today is the creation of an efficient quantum computer. There are a number of models out there, and hundreds of scientists and researchers around the world are constantly coming up with theories and experiments in an effort to make quantum computing possible. One of the main issues is that of entanglement. Being able to entangle photons has long been thought a necessity of quantum computing.

"It's important to manipulate an increasing number of qubits," Wei-bo Gao tells *PhysOrg.com*. "One way to extend the number of qubits is to be able to entangle a greater number of particles. However, usually it is very difficult. So far, up to eight atoms have been demonstrated. The other way is to create entanglement with more degrees of freedom. It is called hyper-entanglement, and it is vital for efficient quantum computing."

Gao is a scientist in Jian-wei Pan's group at the University of Science and Technology of China, located in Hefei. He has been working with a team of scientists from the University of Science and Technology, as well as scientists from the Österrichische Akademie der Wissenshaften and the Universität Innsbruck in Austria, the Universidad de Sevilla in Spain, and Ruprecht-Karls-Universität Heidelberg in Germany. They have succeeded in demonstrating an optical controlled-NOT gate based on a six qubit cluster state, and the results can be seen in *Physical Review Letters*: "Experimental Realization of a Controlled-NOT Gate with Four-Photon Six-Qubit Cluster States."

"We created a cluster state that is universal for quantum computing," Gao says. "We also show that spatial qubits can help in quantum computing. Our method uses different degrees of freedom, including polarization and spatial modes of photons, to help achieve hyper-entanglement. We have recently done up to 10 qubits, using five photons and two degrees of freedom for each photon, even though this paper only demonstrates six qubits."

Gao and his peers generated the six-qubit state using photons, and then used single qubit measurements to apply the CNOT gate to arbitrary single input qubits, which is thought to be one of the keys to creating universal quantum computation. The team also took care to show that this optical method of quantum computation could not be reproduced using local operations and classical communication techniques.

The next step is to see whether hyper-entanglement can be achieved using even more photons and degrees of freedom. "We'd like to create seven photon entanglement, and use more degrees of freedom," Gao explains. "Now that we have shown that spatial qubits can be used, we'd like to see if arrival time and angular momentum could also be used. This would help increase the number of qubits and provide scalability to quantum computing."

Part of the challenge to increase the number of photons used is the collection process. "We will need to increase collection efficiency so that we can actually get more photons. That will be a bit of a challenge in making efficient optical quantum computers, but it is something that many scientists are working on."

Gao is sure that scalable quantum computing can be achieved at some point in the relatively near future. "With more power, more degrees of freedom, and the developing technique of atomic memory, I am confident that more efficiency in optical quantum computing can be achieved as we have more qubits."

More information: Wei-Bo Gao, et. al., "Experimental Realization of a Controlled-NOT Gate with Four-Photon Six-Qubit Cluster States," *Physical Review Letters* (2010). Available online: link.aps.org/doi/10.1103/PhysRevLett.104.020501