Physicists demonstrate new violations of local realism

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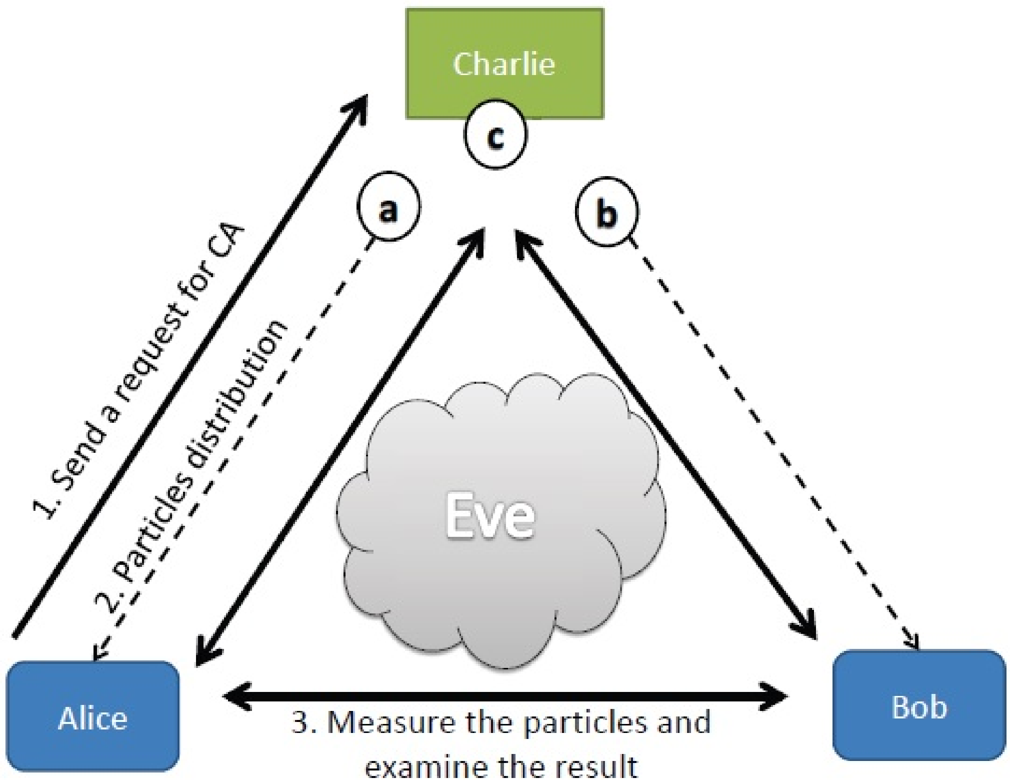

By extending Gisin's theorem from pure states to mixed states that obey a certain property, the results of the new paper could have applications for quantum certificate authorization protocols, like the one shown here. Credit: Chen, et al. ©2015 Nature *Scientific Reports*

(Phys.org)—Erwin Schrödinger once famously stated that quantum entanglement is "*the* characteristic trait of quantum mechanics" that distinguishes it from classical theories. Now in a new paper, physicists have demonstrated a new family of entangled states that violates the principle of "local realism"—an intuitive concept that is a standard feature of classical theories, but disturbingly at odds with quantum theory.

When two objects are entangled, a measurement on one object instantly affects the state of the other, even more quickly than light could travel between them. This instantaneous action goes against our intuition that an object should be affected only by its immediate surroundings, a concept known as locality.

For years, physicists struggled to definitively answer the question of whether or not entangled states truly violate local realism—that is, do they violate either locality or realism, where realism is simply the assumption that objects exist even when they're not being observed?

Although it was long suspected that at least some entangled states violate local realism due to how they seem to instantly influence each other, it wasn't until 1991 that physicist Nicolas Gisin at the University of Geneva quantitatively demonstrated that all pure entangled states must violate local realism. This result is now known as Gisin's theorem.

In quantum mechanics, a "pure" entangled state is one that is clearly defined. However, the vast majority of entangled states are "mixed" to some degree, meaning they consist of a combination of multiple types of pure states. Although Gisin's theorem holds only for pure states, over the years physicists have extended the theorem by showing that some other types of states can also violate local realism.

In a new paper to be published in Nature *Scientific Reports*, Jing-Ling

Chen, et al., from institutions in China and Singapore, have demonstrated that all mixed states that obey a certain steering property must violate local realism. This new family of entangled mixed states that violate local realism may lead to a better fundamental understanding of quantum correlations, as well as simplify the implementation of some quantum information protocols.

"Our enhanced Gisin's theorem is the first time that the theorem has been generalized from pure states to mixed ones, and includes the original Gisin's theorem as a special case," Chen, a physicist at Nankai University in China and the National University of Singapore, told *Phys.org*.

Two distinct concepts

Chen explained the problem in more detail:

"It has long been well-known, starting from Werner's seminal 1989 paper 'Quantum states with Einstein-Podolsky-Rosen correlations admitting a hidden-variable model,' that entanglement and violation of local realism are two distinct concepts. Some entangled quantum states admit a local hidden variable model and hence do not violate local realism. An important question arises. Can we pinpoint a condition that constrains quantum states to those for which entanglement is equivalent to a violation of local realism? A possible condition is purity. Any pure entangled quantum state violates Bell's inequalities. This is known as Gisin's theorem.

"For a more general case of mixed states, however, researchers have been concerned about a lack of such a condition. The more general condition is of great significance not only from the theoretical viewpoint of the need for a deeper understanding of quantum correlations. It is also important in experiments, and for quantum informational applications.

Since a quantum system inevitably interacts with its environment, the quantum states practically always are to some degree 'mixed.' In this work, we address this problem and propose to use the concept of Einstein-Podolsky-Rosen steering as a condition to bridge entanglement and violations of local realism."

Three forms of correlations

As Chen explained, entanglement, steering, and violations of local realism can be thought of as three different forms of quantum correlations that form a hierarchical structure, with violations of local realism being the strongest form. Steering, the intermediate form, takes the correlations of entanglement a step further so that one system can control—or "steer"—the state of its entangled partner.

Here, the physicists demonstrated that, if two observers are able to steer each other's qubits into pure states by making a measurement on their own qubit that spontaneously collapses the state of the other's qubit, then even if the qubits were originally in mixed states, they must violate local realism.

"This proposed condition is more intrinsic, in the sense that Einstein-Podolsky-Rosen steering is by definition a form of quantum correlation that is intermediate between just entanglement and a much stronger one: violation of local realism," Chen explained. "Our result provides an important step forward to solving a long-standing problem of pinpointing a physical condition that automatically implies violation of local realism by an entangled state."

Overall, the findings help establish rigorous criteria for marking the borders between these three highly related yet different concepts.

"In this hierarchical structure of entanglement, steering, and violations of local realism, the former contain the latter as a subset," Chen explained. "[Marking the borders between them] is a nontrivial problem since, in general, it is not easy to reduce a superset [entanglement] to a subset [violations of local realism] by imposing extra constraints, which is just EPR steering in our work."

As the scientists explain, the new family of states that violate local realism could provide a new resource for quantum information tasks by reducing the number of entangled particles needed to perform a task. One example is the Third Man cryptography protocol, also called "secret sharing," in which a third party can control whether two people are allowed to secretly communicate with each other. Previous versions of this protocol required three entangled qubits, but because the fidelity of three-particle entangled states is currently still below about 90%, it is very error-prone. Using the new states, the protocol can be implemented with just two entangled qubits, which has a fidelity of more than 99% and therefore a much lower error rate.

Another potential application is quantum certificate authorization, in which a person sending a confidential message through the internet to another person can ask a third party to verify that person's identity. One way that the third party might do this is by ensuring that both the sender and the receiver can steer each other's qubits into pure states. If they can, the entangled states must violate local realism, which ensures a secure protocol. The physicists plan to use the new family of EPR-steerable mixed states to experimentally realize these protocols in the near future.

More information: Jing-Ling Chen, et al. "Beyond Gisin's Theorem and its Applications: Violation of Local Realism by Two-Party Einstein-Podolsky-Rosen Steering." *Sci. Rep.* 5, 11624; DOI: 10.1038/srep11624. To be published. Also at arXiv:1404.2675 **[quant-ph]**