Physicists find quantum coherence and quantum entanglement are two sides of the same coin

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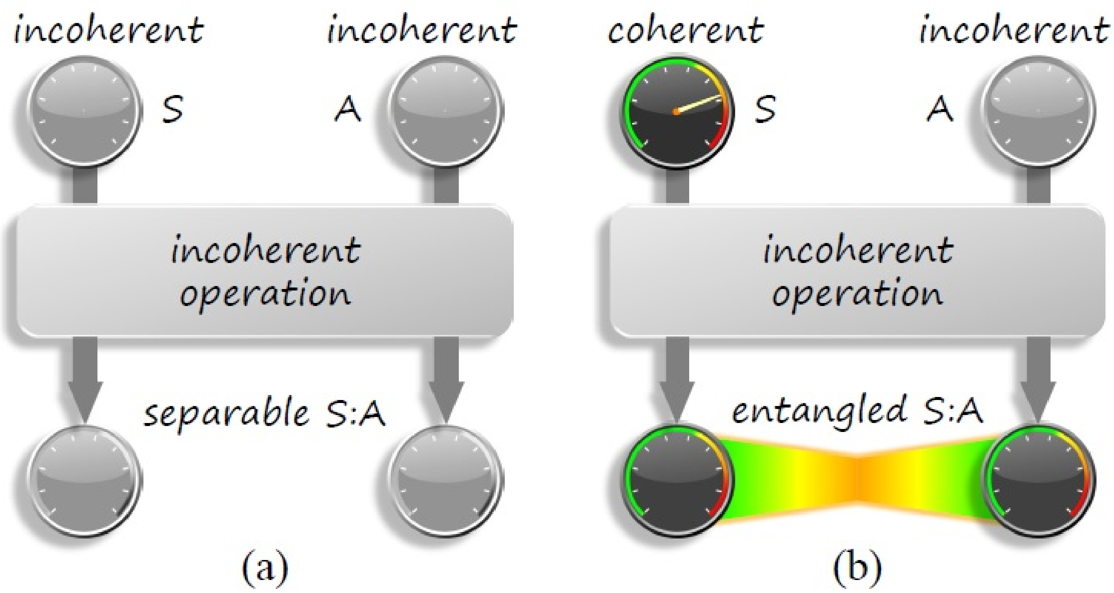

(a) Input states that are fully incoherent (S and A) cannot be converted to entanglement via incoherent operations. (b) On the other hand, when the input state of S has any nonzero coherence, the coherence can be converted to entanglement via incoherent operations. The new results show that, in such a scenario, the input coherence and the output entanglement are quantitatively equivalent. Credit: Streltsov, et al.

(Phys.org)—Quantum coherence and quantum entanglement are two landmark features of quantum physics, and now physicists have demonstrated that the two phenomena are "operationally equivalent"—that is, equivalent for all practical purposes, though still conceptually distinct. This finding allows physicists to apply decades of research on entanglement to the more fundamental but less-well-researched concept of coherence, offering the possibility of advancing a wide range of quantum technologies.

Close relatives with the same roots

Although physicists have known that coherence and entanglement are close relatives, the exact relationship between the two resources has not been clear.

It's well-known that quantum coherence and quantum entanglement are both rooted in the superposition principle—the phenomenon in which a single quantum state simultaneously consists of multiple states—but in different ways. Quantum coherence deals with the idea that all objects have wave-like properties. If an object's wave-like nature is split in two, then the two waves may coherently interfere with each other in such a way as to form a single state that is a superposition of the two states. This concept of superposition is famously represented by Schrödinger's cat, which is both dead and alive at the same time when in its coherent state inside a closed box. Coherence also lies at the heart of quantum computing, in which a qubit is in a superposition of the "0" and "1" states, resulting in a speed-up over various classical algorithms. When such a state experiences decoherence, however, all of its quantumness is typically lost and the advantage vanishes.

The second phenomenon, quantum entanglement, also involves superposition. But in this case, the states in a superposition are the shared states of two entangled particles rather than those of the two split waves of a single particle. The intrigue of entanglement lies in the fact that the two entangled particles are so intimately correlated that a measurement on one particle instantly affects the other particle, even when separated by a large distance. Like coherence, quantum entanglement also plays an essential role in quantum technologies, such as quantum teleportation, quantum cryptography, and super dense coding.

Converting one to the other

In a paper to be published in *Physical Review Letters*, physicists led by Gerardo Adesso, Associate Professor at the University of Nottingham in the UK, with coauthors from Spain and India, have provided a simple yet powerful answer to the question of how these two resources are related: the scientists show that coherence and entanglement are quantitatively, or operationally, equivalent, based on their behavior arising from their respective resource theories.

The physicists arrived at this result by showing that, in general, any nonzero amount of coherence in a system can be converted into an equal amount of entanglement between that system and another initially incoherent one. This discovery of the conversion between coherence and entanglement has several important implications. For one, it means that quantum coherence can be measured through entanglement. Consequently, all of the comprehensive knowledge that researchers have obtained about entanglement can now be directly applied to coherence, which in general is not nearly as well-researched (outside of the area of quantum optics). For example, the new knowledge has already allowed the physicists to settle an important open question concerning the geometric measure of coherence: since the geometric measure of entanglement is a "full convex monotone," the same can be said of the associated coherence measure. As the scientists explained, this is possible because the new results allowed them to define and quantify one resource in terms of the other.

"The significance of our work lies in the fact that we prove the close relation between entanglement and coherence not only qualitatively, but on a quantitative level," coauthor Alex Streltsov, of ICFO-The Institute of Photonic Sciences in Barcelona, told *Phys.org*. "More precisely, we show that any quantifier of entanglement gives rise to a quantifier of coherence. This concept allowed us to prove that the geometric measure of coherence is a valid coherence quantifier, thus answering a question left open in several previous works."

While the results show that coherence and entanglement are operationally equivalent, the physicists explain that this doesn't mean that are the exact same thing, as they are still conceptually different ideas.

"Despite having the same roots of origin, namely quantum superposition, coherence and entanglement are conceptually different," said coauthors Uttam Singh, Himadri Dhar, and Manabendra Bera at the Harish-Chandra Research Institute in Allahabad, India. "For example, coherence can be present in single quantum systems, where entanglement is not well-defined. Also, coherence is defined with respect to a given basis, while entanglement is invariant under local basis changes. In all, we believe coherence and entanglement are operationally equivalent but conceptually different."

Future quantum connections

The operational equivalence of coherence and entanglement will likely have a far-reaching impact on areas ranging from quantum information theory to more nascent fields such as quantum biology and nanoscale thermodynamics. In the future, the physicists plan to investigate whether coherence and entanglement might also be interconverted into a third resource—that of quantum discord, which, like entanglement, is another type of quantum correlation between two systems.

"Our future plans are diverse," Adesso said. "On the theoretical side, we are working to construct a unified framework to interpret, classify and quantify all different forms of quantum resources, including and beyond entanglement and coherence, and highlight the interlinks among them from an operational perspective. This will allow us to navigate the hierarchy of quantumness indicators in composite systems with a common pilot, and to appreciate which particular ingredients are needed in various informational tasks.

"On the practical side, we are investigating experimentally friendly schemes to detect, quantify, and preserve coherence, entanglement and other quantum correlations in noisy environments. More fundamentally, we hope these results will inspire us to devise scalable and efficient methods to convert between different quantum resources for technological applications, and bring us closer to understanding where the boundaries of the quantum world ultimately lie in realistic scenarios."

More information: Alexander Streltsov, et al. "Measuring Quantum Coherence with Entanglement." *Physical Review Letters*. To be published.
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