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Keeping it together: Protecting entanglement from decoherence and sudden death

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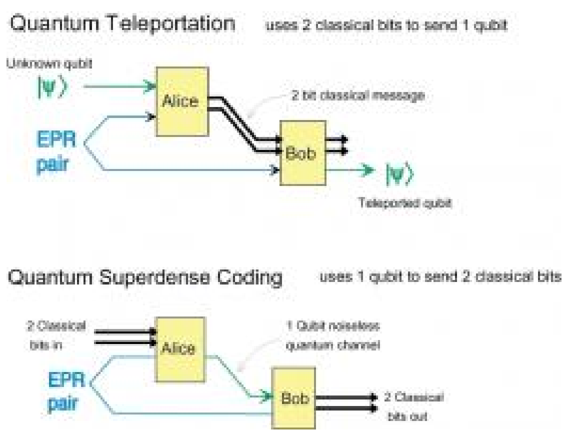

Quantum Entanglement. Two related tasks that require quantum entanglement as a resource. In quantum teleportation, Alice receives a qubit in an unknown state, and destroys it by performing a Bell measurement on that qubit and a member of an entangled pair of qubits that she shares with Bob. She sends a two-bit classical message (her measurement outcome) to Bob, who then performs a unitary transformation on his member of the pair to reconstruct a perfect replica of the unknown state. In superdense coding, Alice receives a two-bit classical message, transmits the message by performing a unitary transformation on a member of an entangled pair that she shares with Bob, and then sends that qubit to Bob. Thus one qubit suffices to carry two classical bits of information. Source: National Science Foundation Workshop on Quantum Information Science

(PhysOrg.com) -- Decoherence can be metaphorically seen as a quantum fall from grace: When quantum bits, or qubits, are in superposition - such as a single qubit simultaneously having both 1 and 0 values - they're said to be in a state of coherence. Any coupling with the environment - whether intentional (as in an observation or measurement) or accidental - causes the superposition to collapse into a state of decoherence in which only one of all possible coherent states exists. When two or more objects - be they subatomic particles, atoms, molecules, or even small but macroscopic diamonds - are in a state of entanglement, a change in a property of one instantaneously appears as the inverse change in the same property of the other, and does so instantaneously - i.e., no time elapses - regardless of the distance between the two entangled objects. Since entanglement is critical factor in quantum information, and decoherence can degrade or terminate entanglement (the latter referred to as entanglement sudden death), preserving coherence is vital to the development of quantum computing, quantum cryptography, quantum teleportation, quantum metrology and other quantum information applications. Recently, scientists in the Department of Physics at Pohang University of Science and Technology (POSTECH) have devised a way to protect entanglement by mitigating decoherence using weak measurement and quantum measurement reversal.

Led by Yoon-Ho Kim, the research team - which also included Yong-Su Kim, Jong-Chan Lee and Osung Kwon - faced a series of challenges in protecting entanglement from decoherence. "In the past," Yoon-Ho Kim tells *PhysOrg.com*, "we've worked on experimental demonstrations of suppressing decoherence for a single-qubit state. We therefore knew that the effect of decoherence can be suppressed by using weak measurement and reversing measurement for a single-qubit. In the current study, our initial question was whether this general approach - that is, using weak and reversed measurements - could work for entangled states."

Since their approach makes use of quantum measurement, which is often destructive and entanglement-breaking, their initial intuition was that it might not. "In some sense," Kim explains, "the main challenge was overcoming this mental barrier of intuition at first sight and getting ourselves to actually formulate the problem mathematically. Quite often in quantum physics, intuition based on daily experience is not always correct, because more often the quantum effects are counter-intuitive."

However, once their theoretical studies convinced the researchers that the approach would work for entangled states, making it possible to protect entanglement from decoherence using weak measurement and quantum measurement reversal, they focused on a clear way to demonstrate the effect experimentally. "The challenge here," Kim notes, "was to be able to vary the amount of decoherence and the strengths of weak and reversing measurements precisely so that the essence of the protocol could be clearly demonstrated. We were able to develop a linear optical method to precisely control the amount of decoherence based on a displaced Sagnac interferometer." A Sagnac interferometer uses counter-propagating light beams to measure its own angular velocity with respect to the local inertial frame.

There are other innovations possible, notes Kim. "In this work, we demonstrated a way to protect two-qubit entanglement from a particular type of decoherence. However, the general approach to use weak measurement and reversing measurement for suppressing the effect of decoherence should be valid for other types of decoherence and for multipartite entangled states. Decoherence is often unavoidable in real life - and to date, several attempts to directly reduce decoherence have been made without much success. I think, in the future, we might battle decoherence using the protocol described in our work, since it's a much more subtle and potentially effective way to battle decoherence. If we find weak and reversing measurements appropriate for a given type of decoherence," Kim adds, "practically all real-world quantum information implementations could benefit by utilizing the protocol."

Not surprisingly, then, the next steps in the team's research involves ways of performing weak measurement and reversing measurement for other types of decoherence. "In particular," Kim tells PhysOrg, "we're interested in a realistic quantum communication scenario - so we're hoping to find ways to perform weak measurement and reversing measurement for the types of decoherence often found in fiber and free-space quantum channels." They're also working on apply their protocol to solid-state (or superconducting) qubits, and atomic qubits (such as trapped ions), because the particular type of decoherence considered in their study is directly responsible for loss of coherence in such systems. "We're actively discussing such experimental possibilities," he adds, "with colleagues working on solid-state physics and atomic physics."

Kim also describes how their findings may make it possible to effectively handle decoherence in quantum information by combining your scheme for protecting entanglement from decoherence with entanglement distillation, a protocol essential in long-distance quantum communications. "Let's consider a simple quantum communication scenario in which entangled photon pairs are distributed through quantum channels with decoherence," Kim illustrates. "Alice prepares the entangled qubit pairs and sends one qubit to Bob and the other qubit to Charlie. Ideally, Bob and Charlie share an entangled-bit, or e-bit, which can be used for many quantum information tasks. However, all practical quantum channels cause a certain level of decoherence to the quantum states being distributed through the channel. If the decoherence is too big, initially entangled qubit pairs end up losing the entanglement." As a result, Bob and Charlie now share two qubits with no entanglement, and which are therefore of no use in quantum information.

"However," Kim explains, "using our protocol, Bob and Charlie can still share two qubits with some amount of entanglement even through a quantum channel with severe decoherence. The amount of entanglement that Bob and Charlie share depends on the strengths of weak and reversing measurements. Bob and Charlie can now repeat the process until they accumulate sufficient numbers of qubit pairs with less-than-maximum entanglement. Now, to produce a single maximally entangled qubit pairs, Bob and Charlie perform an entanglement distillation protocol on multiple pairs of less-than-maximum entanglement." In other words, by using their protocol and combining it entanglement distillation, Bob and Charlie can share maximally entangled qubit pairs even through quantum channels with strong decoherence.

Specifically addressing the study's impact on quantum information applications, Kim first notes that quantum teleportation requires that two parties share maximally-entangled qubit pairs. "In realistic situations, due to decoherence in real quantum channels, sharing maximally entangled qubit pairs over long distances would not be possible, thus preventing quantum teleportation between two parties with a very large separation. Of course, Kim points out, "these two parties could use quantum memory devices to store the qubits and then move apart, but all quantum memory devices have a certain storage time, after which it is not possible to extract the identical qubit. Furthermore, a practical quantum memory device adds decoherence to the quantum state being stored. Thus, our protocol will allow long-distance quantum teleportation possible even if the quantum channel is not ideal."

Secondly, a quantum computer needs to operate coherently until the results are measured and read out. "In implementing a quantum computer," notes Kim, "a qubit and/or many entangled qubits must undergo unitary transformations before decoherence affects the qubit states. In other words, each qubit is said to have a certain characteristic decoherence time. If an operation cannot be done within that decoherence time, it becomes meaningless as it no longer represents a unitary transformation. By using our protocol, it should be possible to prolong the effective decoherence time of a qubit, thus making the qubit less vulnerable to external perturbation."

Finally, in quantum cryptography, as in quantum teleportation, it is often essential pure state qubits must be sent from one party to another. "If the channel between Alice and Bob adds decoherence," says Kim, "even if Alice sends a pure state, Bob doesn't receive a pure state. If this should happen, the quantum bit error rate, or QBER, of the quantum cryptography system will rise - and if it rises above a certain threshold value, it becomes impossible to generate secure keys. Clearly, our protocol will have a unique position for practical quantum cryptography if a practical quantum channel is to be considered."

More generally, Kim tells PhysOrg, the team's research paves the way for dealing with decoherence in an active way by utilizing weak measurement and reversing measurement. "The general approach of using a non-projective quantum measurement, also known as a Positive Operator Valued Measure, or POVM" - a measure whose values are non-negative self-adjoint operators on a Hilbert space - "has been shown to have interesting and important practical applications in quantum information. In this work, we demonstrated that such generalized measurements can be used to actively battle decoherence - and I think it should be possible to find other practical applications of this approach," envisions Kim.

"Another aspect I wish to mention is something more fundamental," Kim concludes. "So far, measurement in quantum optics and quantum information has nearly always meant projective, or von Neumann, measurement. Our work suggests that there could be other interesting and important applications of weak measurement and reversing measurement, not only for quantum information, but also for precision measurement, atomic optics, cavity quantum electrodynamics, mesoscopic physics, and many other areas."

More information: *Protecting entanglement from decoherence using weak measurement and quantum measurement reversal*, *Nature Physics* 8, 117 - 120 (2012), doi:10.1038/nphys2178.

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