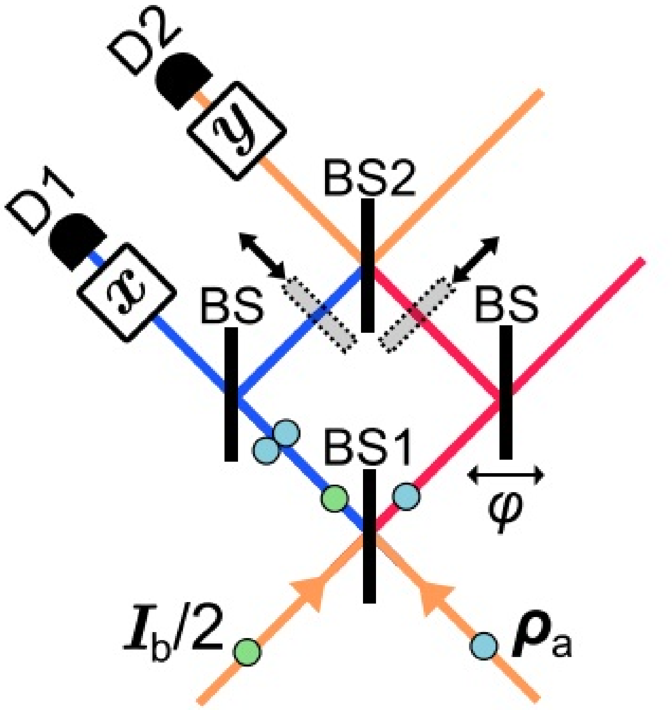
Physicists measure complementary properties using quantum clones

August 16 2017, by Lisa Zyga



Schematic of the experimental setup, in which complementary properties x and y are jointly measured. Credit: Thekkadath et al. ©2017 American Physical Society

(Phys.org)—In quantum mechanics, it's impossible to precisely and simultaneously measure the complementary properties (such as the position and momentum) of a quantum state. Now in a new study, physicists have cloned quantum states and demonstrated that, because the clones are entangled, it's possible to precisely and simultaneously measure the complementary properties of the clones. These measurements, in turn, reveal the state of the input quantum system.

The ability to determine the complementary properties of quantum states in this way not only has implications for understanding fundamental quantum physics, but also has potential applications for quantum computing, quantum cryptography, and other technologies.

The physicists, Guillame S. Thekkadath and coauthors at the University of Ottawa, Ontario, have published a paper on determining complementary properties of quantum clones in a recent issue of *Physical Review Letters*.

As the physicists explain, in the classical world it's possible to simultaneously measure a system's complementary states with exact precision, and doing so reveals the system's state. But as Heisenberg theoretically proposed in 1927 when he was beginning to develop his famous uncertainty principle, any measurement made on a quantum system induces a disturbance on that system.

This disturbance is largest when measuring complementary properties. For instance, measuring the position of a particle will disturb its momentum, changing its quantum state. These joint measurements have intrigued physicists ever since the time of Heisenberg.

As a way around the difficulty of performing joint measurements, physicists have recently investigated the possibility of making a copy of a quantum system, and then independently measuring one property on each copy of the system. Since the measurements are performed separately, they would not be expected to disturb each other, yet they would still reveal information about the original quantum system because the copies share the same properties as the original.

This strategy immediately encounters another quantum restriction: due to the no-cloning theorem, it's impossible to make a perfect copy of a quantum state. So instead, the physicists in the new study investigated the closest quantum analog to copying, which is optimal cloning. The parts of the clones' states that share the exact same properties as those of the input state are called "twins."

Whereas theoretical perfect copies of a quantum state are uncorrelated, the twins are entangled. The physicists showed that, as a consequence of this entanglement, independently measuring the complementary properties on each twin is equivalent to simultaneously measuring the complementary properties of the input state. This leads to the main result of the new study: that simultaneously measuring the complementary properties of twins gives the state (technically, the wave function) of the original quantum system.

"In quantum mechanics, measurements disturb the state of the system being measured," Thekkadath told *Phys.org*. "This is a hurdle physicists face when trying to characterize quantum systems such as single photons . In the past, physicists successfully used very gentle measurements (known as weak measurements) to circumvent this disturbance.

"As such, our work is not the first to determine complementary properties of a quantum system. However, we've shown that a different strategy can be used. It is based on a rather naïve idea. Suppose we want to measure the position and momentum of a particle. Knowing that these measurements will disturb the particle's state, can we first copy the particle, and measure position on one copy and momentum on the other? This was our initial motivation. But it turns out that copying alone is not enough. The measured copies must also be entangled for this strategy to work.

"This is what we showed experimentally. Instead of determining the position and momentum of a particle, we determined complementary polarization properties of single photons. You would intuitively expect this strategy to fail due to the no-cloning theorem. However, we showed that is not the case, and this is the greatest significance of our result: measuring complementary properties of the twins directly reveals the quantum state of the copied system."

As the physicists explain, one of the most important aspects of the demonstration is working around the limitations of the no-cloning theorem.

"In our daily lives, information is often copied, such as when we photocopy a document, or when DNA is replicated in our bodies," Thekkadath explained. "However, at a quantum level, information cannot be copied without introducing some noise or imperfections. We know this because of a mathematical result known as the no-cloning theorem. This has not stopped physicists from trying. They developed strategies, known as optimal cloning, that minimize the amount of noise introduced by the copying process. In our work, we go one step further. We showed that it is possible to eliminate this noise from our measurements on the copies using a clever trick that was theoretically proposed by Holger Hofmann in 2012. Our results do not violate the no-cloning theorem since we never physically produce perfect copies: we only replicate the measurement results one would get with perfect copies."

In their experiments, the physicists demonstrated the new method using photonic twins, but they expect that the ability to make precise, simultaneous measurements of complementary properties on twins can also be implemented with quantum computers. This could lead to many practical applications, such as providing an efficient method to directly measure high-dimensional quantum states, which are used in quantum computing and quantum cryptography.

"Determining the state of a system is an important task in physics," Thekkadath said. "Once a state is determined, everything about that system is known. This knowledge can then be used to, for example, predict measurement outcomes and verify that an experiment is working as intended. This verification is especially important when complicated states are produced, such as the ones needed in quantum computers or quantum cryptography.

"Typically, quantum states are determined tomographically, much like how the brain is imaged in a CAT scan. This approach has the limitation that the state is always globally reconstructed. In contrast, our method determines the value of quantum states at any desired point, providing a more efficient and direct method than conventional methods for state determination.

"We experimentally demonstrated our method using single photons. But, our strategy is also applicable in a variety of other systems. For instance, it can be implemented in a quantum computer by using only a single quantum logic gate. We anticipate that our method could be used to efficiently characterize complicated quantum states inside a quantum computer."

More information: G. S. Thekkadath, R. Y. Saaltink, L. Giner, and J. S. Lundeen. "Determining Complementary Properties with Quantum Clones." *Physical Review Letters*. DOI: 10.1103/PhysRevLett.119.050405, Also at arXiv:1701.04095 [quant-ph]

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