Physicists add 'quantum Cheshire Cats' to list of quantum paradoxes

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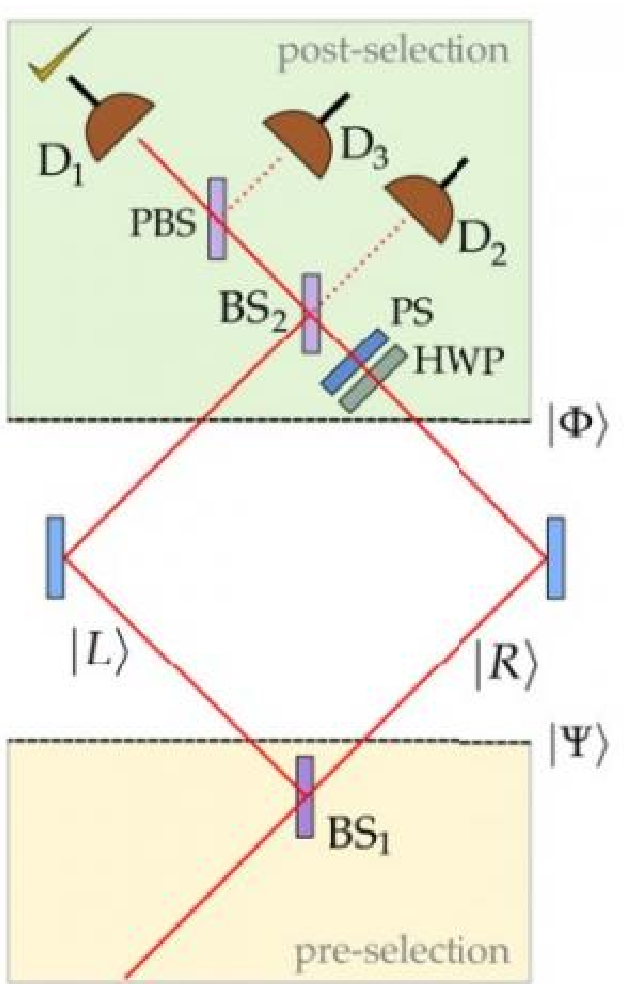

In the proposed experimental set-up, the quantum Cheshire Cat paradox is demonstrated when photons travel through the left arm of the interferometer while photon polarizations travel through the right arm. Some measurements disturb the photons and cause them to travel through the right arm with their polarizations, making the paradox seem to disappear. However, weak measurements that do not cause this disturbance bring the paradox back to life. Credit: Aharonov, et al. ©2013 IOP Publishing Ltd and Deutsche Physikalische Gesellschaft

(Phys.org) —Given all the weird things that can occur in quantum mechanics—from entanglement to superposition to teleportation—not much seems surprising in the quantum world. Nevertheless, a new finding that an object's physical properties can be disembodied from the object itself is not something we're used to seeing on an everyday basis. In a new paper, physicists have theoretically shown that this phenomenon, which they call a quantum Cheshire Cat, is an inherent feature of quantum mechanics and could prove useful for performing precise quantum measurements by removing unwanted properties.

The physicists, Yakir Aharonov at Tel Aviv University in Tel Aviv, Israel, and Chapman University in Orange, California, US, and his coauthors have published a paper on quantum Cheshire Cats in a recent issue of the *New Journal of Physics*.

The physicists begin their paper with an excerpt from Lewis Carroll's 1865 novel *Alice in Wonderland*:

'All right', said the Cat; and this time it vanished quite slowly, beginning with the end
of the tail, and ending with the grin, which remained some time after the rest of it had
gone.

'Well! I've often seen a cat without a grin', thought Alice, 'but a grin without a cat!
It's the most curious thing I ever saw in my life!'

Just as the grin is a property of a cat, polarization is a property of a photon. In their paper, the physicists explain how, "in the curious way of quantum mechanics, photon polarization may exist where there is no photon at all."

Disturbing measurements

In their proposed experimental set-up, the physicists show that a photon will travel through the left arm of an interferometer with 100% certainty, yet its polarization can be detected in the right arm, where there is 0% probability of the photon traveling. That is, the photon is in one place while its polarization is in another.

However, there is a caveat with this experiment: it does not measure the location of the photon and its polarization simultaneously, but instead measures the location of some photons and the polarization of others at different times. This raises the question of whether it is possible that the polarization measurement disturbs the photons, causing them to change course and travel through the right arm.

To address this issue, the researchers proposed two additional variations of this experiment.

In the first variation, the physicists theoretically showed that simultaneously measuring the photon's location and polarization does, in fact, cause the photon to change course and travel through the right arm. That is, the act of measurement changes the outcome, and the paradox seems to disappear. This explanation of measurement-induced disturbance is actually the standard resolution of many paradoxes in quantum mechanics.

Reviving the paradox

Here, however, the physicists take things a step further and show that there really is a quantum Cheshire Cat by proposing another experiment that limits the measurement-induced disturbance. In this proposed experiment, the physicists take advantage of the tradeoff between disturbance and precision by performing a so-called "weak" measurement—one that is not very precise, but causes very little disturbance.

In this proposed set-up, the detectors used in the previous two experiments are replaced by a CCD camera and an optical element, both of which cause very little disturbance. Now, when the photon's location and polarization are measured simultaneously, the results are identical to those of the original experiment: the photon is in the left arm while the polarization is in the right arm.

This finding means that separating a property from its object truly is a feature of quantum mechanics, and not only for photons. The physicists predict that the effect also holds for an electron and its charge or spin, as well as for an atom and its internal energy. Yet while the proposed optical experiment can be implemented with current technology (and the researchers hope it soon will be), realizing the electron version is beyond the reach of current technology.

Wider implications

As the physicists explain, weak measurements can be used to revive other quantum paradoxes besides this one.

"We have many examples in which weak measurements 'bring back' paradoxes; it is in fact a general strategy and it can be applied to all paradoxes that were dismissed until now as simple illusions that would disappear when actual measurements are performed," coauthor Sandu Popescu at the University of Bristol told *Phys.org*.

The physicists have explained this topic in greater detail in a recent paper on Hardy's paradox. They also have applied the same strategy to what is probably the most famous quantum paradox, dating from the early days of quantum mechanics, which is the idea of negative kinetic energy. Kinetic energy is, by definition, a positive quantity, but appears to be negative for particles that have tunneled into a barrier.

"The tunneling example has in fact been used over and over again, in almost all classic quantum mechanics textbooks, to explain how quantum mechanics works, how the paradoxes are nothing more than illusions stemming from the wrong desire to apply classical thinking, and that a 'correct' understanding of quantum mechanics, namely the fact that measurements produce disturbance completely removes the paradox," Popescu said. "What we showed is that this standard way to dismiss paradoxes generates a wrong intuition and misses all that is truly interesting in quantum mechanics, and that the paradoxes are brought back to life if one knows how to look at the problem."

As for the current paradox, the existence of quantum Cheshire Cats opens up many intriguing questions. For example, how will an electron with disembodied charge and mass affect nearby electrons? In an atom with disembodied internal energy, what will the gravitational field look like? Can photons with disembodied polarization impart their polarization to one object and their radiation pressure to another object? The physicists hope that future work will address these questions.

Quantum Cheshire Cats could also have applications for performing precision measurements. For instance, in an experiment in which a particle's charge causes unwanted disturbances, perhaps the charge could be removed by confining it to separate region.

More information: — Yakir Aharonov, et al. "Quantum Cheshire Cats." *New Journal of Physics*. DOI: 10.1088/1367-2630/15/11/113015

— Yakir Aharonov, et al. "Revisiting Hardy's paradox: counterfactual statements, real measurements, entanglement and weak values." *Physics Letters A* 301 (2002) 130–138 www.sciencedirect.com/science/ … ii/S0375960102009866

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