Fake violations of Bell tests reinforce importance of closing loopholes

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(PhysOrg.com) -- In quantum mechanics, Bell's inequalities serve as a test of nonclassical behavior: if something (such as a light source) violates Bell's inequalities, then it can be considered to involve quantum behavior. Ensuring the nonclassicality of a system is important for applications such as quantum cryptography, in which quantum entangled photons ensure the system's security while non-entangled photons do not. Now in a new study, scientists have shown that they can violate Bell's inequalities using classical light by taking advantage of two loopholes common in some experiments. This "fake violation" emphasizes the importance of closing all loopholes in Bell tests, even if the detection devices appear to be operating normally.

The researchers, led by Vadim Makarov of the Norwegian University of Science and Technology in Trondheim, Norway, and the University Graduate Center in Kjeller, Norway, along with Christian Kurtsiefer of the National University of Singapore, have published their study in a recent issue of Physical Review Letters.

In a typical experimental Bell test, a light source produces a pair of photons, with one photon sent to Alice and one to Bob. Alice and Bob each have a polarizer that they can set to one of four states, and a photon can only enter a polarizer when it's in the same state. After a photon enters the polarizer, a photon detector amplifies a single electron generated by the photon into a large electric current. When this electric current crosses a certain threshold, it reveals the presence of a photon and its polarization. If the photon pair is classical, it must obey local realism so that the measurement of one photon does not influence the polarization of the other photon. But if the photon pair is entangled, then the measurement of one photon will instantaneously affect the other photon's polarization. By repeating the experiment, counting the simultaneous detections (coincidences), and comparing the number of coincidences to what is possible in classical theory, Alice and Bob can determine if the detected photon pairs are entangled.

Many previous studies have investigated how an eavesdropper, Eve, might be able to compromise the security of Alice and Bob's communication channel. In the current study, the scientists showed that Eve can send strong, classical light pulses, with a polarization of her choice, into both Alice and Bob's photon detectors at the same time. This classical light produces photocurrents that are interpreted as photons. Therefore, Alice and Bob are unknowingly measuring classical light pulses, which means that some of the coincidences that they count are not due to quantum entanglement but to Eve's manipulation. Makarov explained in more detail how this experiment works:

"First, we blind the detectors using continuous, moderately bright light," he said. "Just like human eyes in daylight, detectors are overwhelmed by this background, can no longer see single photons and now behave classically (by a crude analogy, human eyes cannot see stars in the day sky, even though the stars are still there!). Then, we send a short, very bright light pulse of a carefully tuned peak power (which to the single photon detector looks like a supernova, which can be visible by the naked eye in the day sky). This very bright pulse causes sufficient photocurrent to cross the detection threshold only in one of the four polarizer settings. In the other three polarizer settings, the polarizer partially blocks light, the photocurrent stays below the threshold and the detector remains blind. Thus, Eve classically controls exactly which of the four polarizations Alice and Bob register. Then she can fake any correlation she pleases."

Theoretically, Alice and Bob should be able to detect Eve's interference, but only when all loopholes are closed. The two loopholes the researchers took advantage of here were the locality loophole and the detection loophole. In the locality loophole, measurement choices on both sides may not be independent, while in the detection loophole, nonclassical behavior can be attributed to shared randomness, rather than entanglement, between the two photons.

The researchers performed three experiments in which they faked the violation of Bell's inequalities by taking advantage of one or both of these loopholes. The implication – that all loopholes must be closed in order to ensure accurate results – is not new to physicists. However, the experiments underscore how ignoring these loopholes can directly compromise the security of quantum communication systems. While the researchers explain that implementing a countermeasure against these attacks would not be difficult, it should not be assumed that quantum systems are fully secure until all loopholes are closed.

"In any kind of quantum cryptography or secure quantum communication, a determined attacker will employ all tricks possible, in principle, to cheat the honest parties," Makarov said. "There we show that users cannot blindly trust their quantum devices unless they see that the devices perform the Bell test with all loopholes closed (i.e., both the locality loophole and the detection loophole).

"For verifying the laws of Nature, the significance is subtler, it is more philosophical there. On the one hand, we have no reason to believe Nature cooperates against our tests in an evil way. On the other hand, until a loophole-free Bell test has actually been done, the principles of quantum mechanics are, strictly speaking, not proven true."

More information: Ilja Gerhardt, et al. "Experimentally Faking the Violation of Bell's Inequalities." *Physical Review Letters* 107, 170404

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The study is also available at arXiv:1106.3224v3 [quant-ph]
arxiv.org/abs/1106.3224