Physicists close two loopholes while violating local realism

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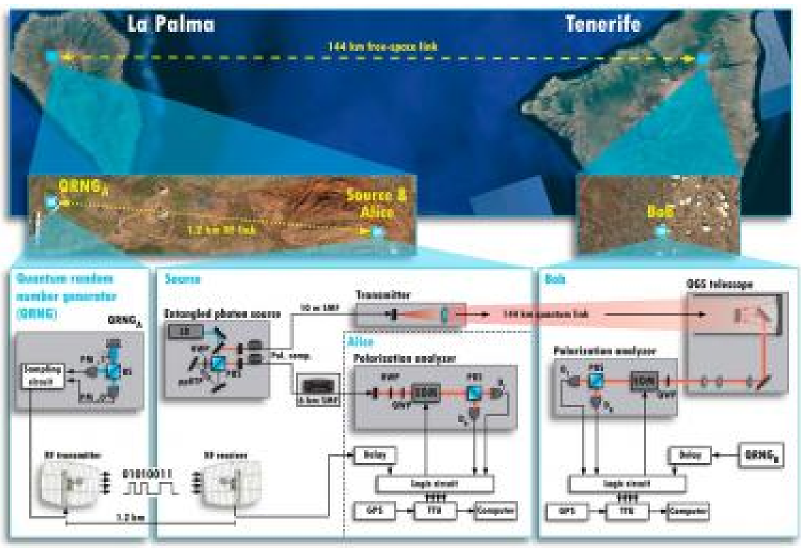

Physicists performed a Bell experiment between the islands of La Palma and Tenerife at an altitude of 2,400 m. Starting with an entangled pair of photons, one photon was sent 6 km away to Alice, and the other photon was sent 144 km away to Bob. The physicists took several steps to simultaneously close the locality loophole and freedom-of-choice loophole. Image credit: Thomas Scheidl, et al. and Google Earth, ©2008 Google, Map Data ©Tele Atlas.

(PhysOrg.com) -- The latest test in quantum mechanics provides even stronger support than before for the view that nature violates local realism and is thus in contradiction with a classical worldview. By performing an experiment in which photons were sent from one Canary Island to another, physicists have shown that two of three loopholes can be closed simultaneously in a test that violates Bell's inequality (and therefore local realism) by more than 16 standard deviations. Performing a Bell test that closes all three loopholes still remains a challenge, but the physicists predict that such an experiment might be "on the verge of being possible" with state-of-the-art technology.

The physicists, who belong to the group of Rupert Ursin and Anton Zeilinger and were all at either the Austrian Academy of Sciences in Vienna or the University of Vienna when performing the experiments in 2008, have published their study on the new Bell test in the early edition of *PNAS*. As they explain in their study, local realism consists of both realism – the view that reality exists with definite properties even when not being observed – and locality – the view that an object can only be influenced by its immediate surroundings. If a Bell test shows that a measurement of one object can influence the state of a second, distant object, then local realism has been violated.

"The question of whether nature can be understood in terms of classical concepts and explained by local realism is one of the deepest in physics," coauthor Johannes Kofler told *PhysOrg.com*. "Getting Bell tests as loophole-free as possible and confirming quantum mechanics is therefore an extremely important task. From a technological perspective, certain protocols of quantum cryptography (which is entering the market at the moment) are based on entanglement and violation of Bell's inequality. This so-called 'unconditional security' must in practice take care of the loopholes in Bell tests."

The physicists explained that, in experimental tests, there are three loopholes that allow observed violations of local realism to still be explained by local realistic theories. These three loopholes can involve locality (if there is not a large enough distance separating the two objects at the time of measurement), the freedom to choose any measurement settings (so measurement settings may be influenced by hidden variables, or vice versa), and fair sampling (a small fraction of observed objects may not accurately represent all objects due to detection inefficiencies).

Previous experiments have closed the first loophole, which was done by ensuring a large spatial separation between the two objects (in this case, two quantum mechanically entangled photons) so that measurements of the objects could not be influenced by each other. Special relativity then ensures that the objects cannot influence each other, since no physical signals can travel faster than the speed of light. In these experiments, classically unexplainable correlations were still observed between the objects, indicating a violation of local realism. (The fair sampling loophole was closed in another earlier experiment using ions, where large detection efficiencies can be reached.)

In the current experiment, the physicists simultaneously ruled out both the locality loophole and the freedom-of-choice loophole. They performed a Bell test between the Canary Islands of La Palma and Tenerife, located 144 km apart. On La Palma, they generated pairs of entangled photons using a laser diode. Then they locally delayed one photon in a 6-km-long optical fiber (29.6-microsecond traveling time) and sent it to one measurement station (Alice), and sent the other photon 144 km away (479-microsecond traveling time) through open space to the other measurement station (Bob) on Tenerife.

The scientists took several steps to close both loopholes. For ruling out the possibility of local influence, they added a delay in the optical fiber to Alice to ensure that the measurement events there were space-like separated from those on Tenerife such that no physical signal could be interchanged. Also, the measurement settings were randomly determined by quantum random number generators.

To close the freedom-of-choice loophole, the scientists spatially separated the setting choice and the photon emission, which ensured that the setting choice and photon emission occurred at distant locations and nearly simultaneously (within 0.5 microseconds of each other). The scientists also added a delay to Bob's random setting choice. These combined measures eliminated the possibility of the setting choice or photon emission events influencing each other. But again, despite these measures, the scientists still detected correlations between the separated photons that can only be explained by quantum mechanics, violating local realism.

By showing that local realism can be violated even when the locality and freedom-of-choice loopholes are closed, the experiment greatly reduces the number of “hidden variable theories” that might explain the correlations while obeying local realism. Further, these theories appear to be beyond the possibility of experimental testing, since they propose such things as allowing actions into the past or assuming a common cause for all events.

Now, one of the greatest challenges in quantum mechanics is simultaneously closing the fair-sampling loophole along with the others to demonstrate a completely loophole-free Bell test. Such an experiment will require very high-efficiency detectors and other high-quality components, along with the ability to achieve extremely high transmission. Also, the test would have to operate at a critical distance between Alice and Bob that is not too large, to minimize photon loss, and not too small, to ensure sufficient separation. Although these requirements are beyond the current experimental set-up due to high loss between the islands, the scientists predict that these requirements may be met in the near future.

“Performing a loophole-free Bell test is certainly one of the biggest open experimental challenges in the foundations of quantum mechanics,” Kofler said. “Various groups are working towards that goal. It is on the edge of being technologically feasible. Such an experiment will probably be done within the next five years."

More information: Thomas Scheidl, et al. "Violation of local realism with freedom of choice." 19708-19713, *PNAS*, November 16, 2010, vol. 107, no. 46. DOI:10.1073/pnas.1002780107