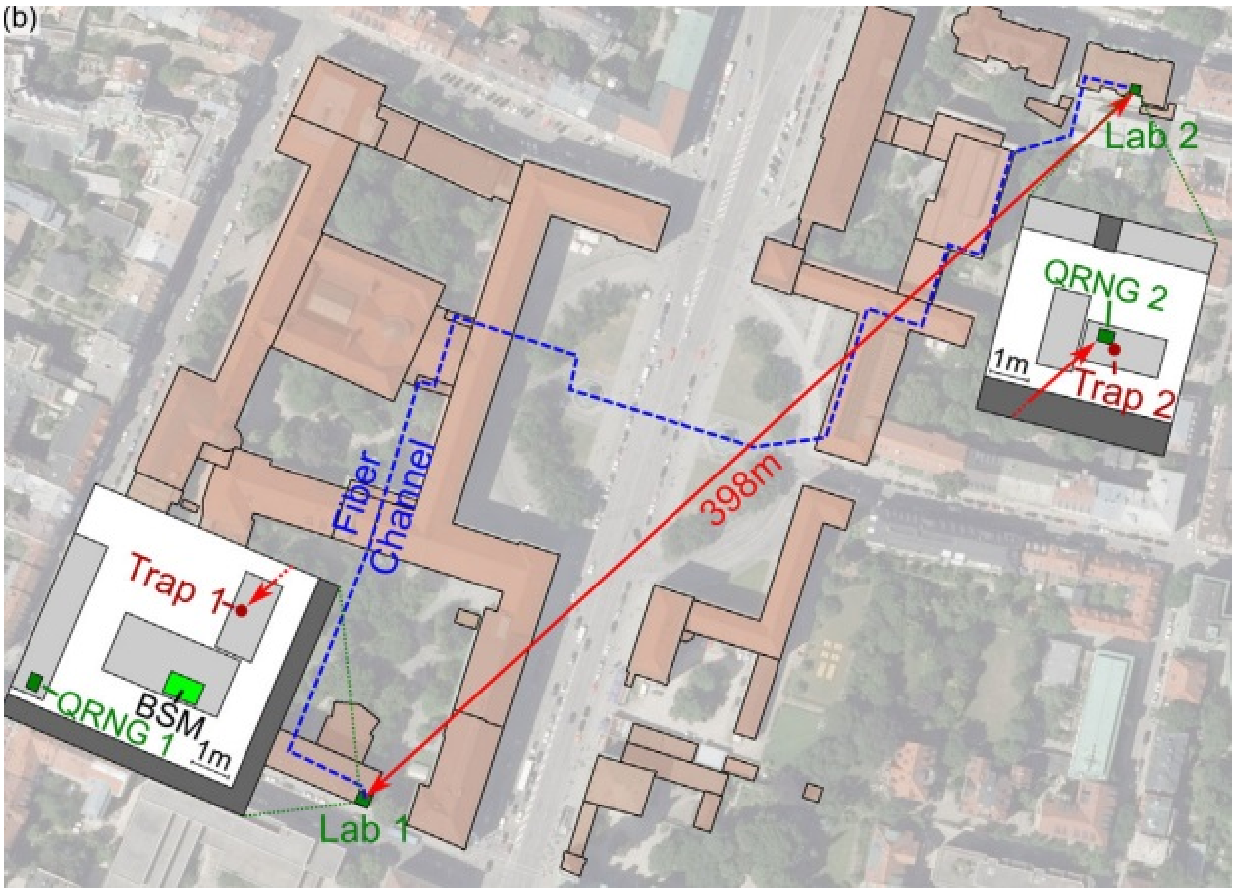
PHYS.ORG

Probability that the quantum world obeys local realism is less than one in a billion, experiment shows

July 20 2017, by Lisa Zyga



The experiment was performed on the Ludwig Maximilian University campus in Munich, Germany. Trap 1 is located in the basement of the physics building, and trap 2 is in the basement of the economics building, 398 meters away. Credit: Rosenfeld et al. Published by the American Physical Society

(Phys.org)—Physicists have reported some of the strongest evidence yet that that the quantum world does not obey local realism by demonstrating new evidence for the existence of quantum entanglement. By performing an essentially loophole-free Bell test, they have shown that two atoms separated by a distance of a quarter of a mile share correlations that should be impossible under the hypothesis of local realism, and are most likely explained by quantum entanglement.

The new Bell test was performed by a group of researchers led by Harald Weinfurter at the Ludwig Maximilian University of Munich and the Max Planck Institute for Quantum Optics, both in Germany.

The probability that the observed correlations can be explained by local realism due to some unknown "hidden variables" rather than entanglement is less than one in a billion, the physicists write in their paper published in *Physical Review Letters*. By accounting for all of their accumulated data, taken over the course of seven months, that probability drops even further, down to about one in ten quadrillion (the number 1 followed by 16 zeros). This means that the quantum world violates either locality (that distant objects cannot influence each other in less than a certain amount of time) or realism (that objects exist whether or not someone measures them), or possibly both.

Three Bell tests

The test reported here is the latest loophole-free Bell test: one that simultaneously closes the two biggest loopholes, the locality loophole and the detection loophole. Closing both loopholes is vital for excluding any alternative explanations, such as the possibility that two entangled objects are secretly sharing information (locality loophole) or that the particles being detected are not representative of the whole sample but rather form a special subset that skews the data (detection loophole).

The first loophole-free Bell test, reported in 2015 by a team led by Ronald Hanson at the University of Delft, demonstrated entanglement between the electron spins of nitrogen-vacancy (NV) centers in diamond. Shortly after, other loophole-free Bell tests reported entanglement between photons. The Bell test reported here demonstrates entanglement between a third type of system: the spin states of atoms.

"In my opinion, the greatest significance of this work is the definite ruling out of local realism," coauthor Wenjamin Rosenfeld, at the Ludwig Maximilian University of Munich and the Max Planck Institute for Quantum Optics, told *Phys.org*. "It is good that similar experiments were performed with different systems (photons, NV centers) essentially at the same time, so all results together can be taken as truly conclusive. Now it is no more a matter of belief whether nature can or cannot be described in a local-realistic way, but a matter of fact. (However, the freedom-of-choice problem still needs to be solved.)"

Experimental setup

The new experiment involved trapping one rubidium atom in the basement of the physics building at the Ludwig Maximilian University of Munich and trapping a second rubidium atom in the basement of the economics building, about 400 meters away. An optical fiber connected the two measurement sites.

In their tests, the scientists excited the atoms, causing them to emit photons at precisely defined times. The photons then travelled through the optical fiber and interfered with each other. This quantum interference, in theory, causes the atoms to become entangled. To detect this entanglement, the researchers performed measurements on the photons, repeating the measurements over and over for tens of thousands of photon pairs. The results showed overwhelmingly that the distant photon pairs were indeed entangled.

Last loophole

One of the last remaining possible loopholes for most Bell tests concerns the choice of measurement made on the atoms. Since these measurements can be performed in multiple ways, it's important to confirm that the experimenter is free to choose which particular measurement to make, and that hidden variables are not influencing the choice of measurement and somehow allowing the atoms to synchronize their properties. This possibility is called the free-will or freedom of choice loophole.

To attempt to close this loophole, the researchers used a high-speed quantum random number generator that chooses measurement settings that are truly random—almost. The problem is that there is a very slight possibility that the random number generators could have communicated with each other or the rest of the experiment before the experiment began. This could allow the atoms to know the random numbers, and consequently the measurements to be performed, in advance, allowing them to synchronize their properties.

The physicists explain that the only way to completely close this loophole is to use an extraterrestrial random number generator, such as the inherently random photon emission from stars located millions of light-years away. The vast distance between the stars and an Earth-based experiment would make it practically impossible for any covert communication to occur, since it would mean that such communication would have had to take place before the light left the stars, millions of years ago. Several physics labs are currently developing extraterrestrial random number generators for this purpose.

Secure communication

Since quantum entanglement is likely to be an important resource in future secure quantum technologies, closing these loopholes helps to increase the security of future applications at the most fundamental level. The researchers expect that the methods used in this study will also contribute to new developments in quantum information systems and quantum repeater networks, which are used for communicating quantum information over long distances. They plan to further investigate this application in the future.

"Apart from further fundamental questions considering the freedom-of-choice problematic, there is a lot one can work on here," Rosenfeld said. "On the one side one can try to push the system further (especially the fidelity of the entangled state) to be able to perform so-called 'device-independent' protocols. These would allow to obtain a secure cryptographic key even from devices which are potentially not trusted (provided by a third party). Here, Bell's inequality provides the possibility to test, whether the devices were somehow prepared in advance to produce a key which is known to an adversary. Moreover, the techniques for generating entanglement between distant objects are important for quantum networks enabling secure communication over long distances."

More information: Wenjamin Rosenfeld et al. "Event-Ready Bell Test Using Entangled Atoms Simultaneously Closing Detection and Locality Loopholes." *Physical Review Letters*. DOI: 10.1103/PhysRevLett.119.010402