Quantum experiment preludes the endgame for local realism – photonic Bell violation closes the fair-sampling loophole

Johannes Kofler[1], Sven Ramelow[2,3], Marissa Giustina[2,3], Rupert Ursin[2,3], Anton Zeilinger[2,3]

[1] Max Planck Institute of Quantum Optics (MPQ), Hans-Kopfermannstr. 1, 85748 Garching/Munich, Germany.
[2] Institute for Quantum Optics and Quantum Information – Vienna (IQOQI), Austrian Academy of Sciences, Boltzmanngasse 3, 1090 Vienna, Austria.
[3] Quantum Optics, Quantum Nanophysics, Quantum Information, University of Vienna, Faculty of Physics, Boltzmanngasse 5, 1090 Vienna, Austria.

Using photons, a recent experiment in Vienna closed a loophole in the arguments against local realism and now makes photons the first quantum system for which all major loopholes have been closed in separate experiments. This is good news for a final experiment closing all loopholes simultaneously.

"Local realism" is a world view in which the properties of physical objects exist independent of whether or not they are observed (realism), and in which no physical influence can propagate faster than the speed of light (locality). In 1964, in one of the most important works in the history of the foundations of quantum theory [1], the Irish physicist John Bell proved theoretically that local realism is in contradiction with the predictions of quantum mechanics. With his now famous "Bell inequality", he showed that it is possible to determine experimentally which of the two radically different world views actually governs reality. The terms in the inequality are the correlations of measurement results. Bell's inequality is satisfied by the predictions of any local realistic theory, whereas quantum mechanics predicts measurement outcomes that can violate it.

In a Bell test, pairs of systems, e.g. photons, are produced. From every pair, one photon is sent to a party usually called Alice, and the other photon is sent to another party known as Bob. They each choose which physical property they want to measure, for instance, a direction of their photon's polarization. For pairs that are quantum entangled, the correlations of Alice's and Bob's measurement outcomes can exceed the correlations predicted by any local realistic theory and thus violate Bell's inequality. Quantum entanglement – a term coined by the Austrian physicist Erwin Schrödinger – means that no photon taken by itself has a definite polarization, but that if one party measures the polarization of its photon, the other photon will always show a perfectly correlated polarization. Albert Einstein called this strange effect "spooky action at a distance".

In addition to its preeminent importance in foundational physics, quantum entanglement and Bell's inequality also play a quintessential role in the modern field of quantum information. There, individual quantum particles are the carriers of information, and the entanglement between them promises absolutely secure communication as well as enhanced computation power compared to any conceivable classical technology.

In the last decades, Bell's inequality has been violated in numerous experiments and for several different physical systems such as photons and atoms. However, in experimental tests, "loopholes" arise that allow the observed correlations – although they violate Bell's inequality – to still be explained by local realistic theories. The advocates of local realism can defend their worldview falling back on essentially three such loopholes. In the "locality loophole" the measurement result of one party is assumed to be influenced by a fast and hidden physical signal from the other party to produce the observed correlations. Similarly, in the "freedom-of-choice" loophole the measurement choices of Alice and Bob are considered to be influenced by some hidden local realistic properties of the particle pairs. These two loopholes have already been closed in photonic experiments [2-4] by separating Alice and Bob by large distances, and enforcing precise timing of the photon pair creation, Alice's and Bob's choice events, and their measurements. The local realist would then need superluminal signals to explain the measured correlations, but influences which are faster than light are not allowed in the local realistic world view.

The third way out for the local realist is called the "fair-sampling loophole" [5]. It works in the following manner: if only a small fraction of the produced photons is measured, a clever advocate of local realism can conceive a model in which the ensemble of all produced photons as a whole follows the rules of local realism, although the "unfair" sample of the actually measured photons was able to violate Bell's inequality. (Think of randomly flipping many fair coins but looking at only some of them, where the coins showing heads tend to hide and thus have a smaller probability of being observed than those showing tails. When looking at only this incomplete and "unfair" subset of the coins, it wrongly appears as if the coins had a special distribution with more showing tails than heads.) This type of loophole has even been explicitly exploited in an experiment faking Bell violations without any entanglement [6]. The way to close the fair-sampling loophole is to achieve a high detection efficiency of the produced particle pairs by avoiding losses and using very good measurement devices. Until now, this has been accomplished for particles with mass such as ions and atoms [7,8], but never for photons. However, for such particles, the other two loopholes are very difficult to close and indeed have not yet been closed.

A recent experiment has, for the first time, closed the fair-sampling loophole for photons [9]. It employed a significantly optimized source of entangled pairs achieving excellent fiber coupling efficiencies and state-of-the-art high-efficiency superconducting detectors to reach the necessary total detection efficiency. The researchers were able to measure about 75% of all photons in each arm. This rules out all local realistic explanations that rely on unfair sampling using a form of Bell's inequality developed about 20 years ago by the American physicist Philippe Eberhard, which requires an efficiency of only two thirds [10]. The recent experiment makes the photon the first physical system for which all three loopholes have been closed, albeit in different experiments.

Although most scientists do not expect any surprises and believe that quantum physics will prevail over local realism, it is still conceivable that different loopholes are exploited in different experiments. It is this last piece in the history of Bell tests which is still missing – a final and conclusive experiment violating Bell's inequality while closing all loopholes simultaneously [11]. It is not yet clear whether such an experiment will be achieved first for photons or atoms or some other quantum system, but if it can be successfully performed, one needs to accept at least one of the following radical views: there is a hidden faster-than-light communication in nature, or we indeed live in a world in which physical properties do not always exist independent of observation. Almost 50 years after the formulation of local realism, its endgame clearly has begun.

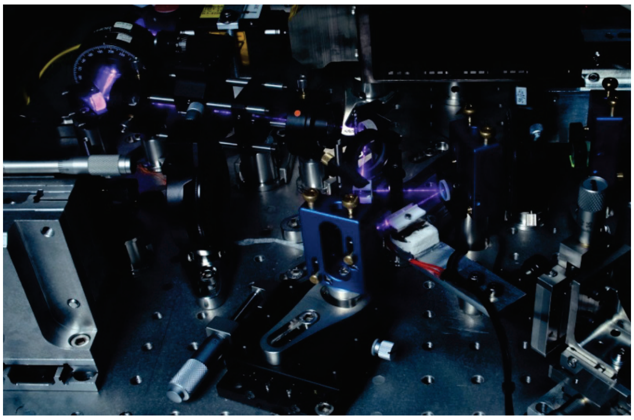

Figure: Optical setup used in the quantum experiment. (Image: IQOQI Vienna, Jacqueline Godany 2012.)

References

[1] J. S. Bell, *On the Einstein Podolsky Rosen Paradox*. Physics (NY) **1**, 195 (1964).

[2] A. Aspect, J. Dalibard, and G. Roger, *Experimental test of Bell's inequalities using time varying analyzers*. Physical Review Letters **49**, 1804 (1982).

[3] G. Weihs, T. Jennewein, C. Simon, H. Weinfurter, and A. Zeilinger, *Violation of Bell's Inequality under Strict Einstein Locality Conditions*. Physical Review Letters **81**, 5039 (1998).

[4] T. Scheidl, R. Ursin, J. Kofler, S. Ramelow, X. Ma, T. Herbst, L. Ratschbacher, A. Fedrizzi, N. Langford, T. Jennewein, and A. Zeilinger, *Violation of local realism with freedom of choice*. Proceedings of the National Academy of Sciences **107**, 19708–19713 (2010).

[5] P. M. Pearle, *Hidden-Variable Example Based upon Data Rejection*. Physical Review D **2**, 1418 (1970).

[6] I. Gerhardt, Q. Liu, A. Lamas-Linares, J. Skaar, V. Scarani, V. Makarov, and C. Kurtsiefer, *Experimentally Faking the Violation of Bell's Inequalities*. Physical Review Letters **107,** 170404 (2011).

[7] M. A. Rowe, D. Kielpinski, V. Meyer, C. A. Sackett, W. M. Itano, C. Monroe, and D. J. Wineland, *Experimental violation of a Bell's inequality with efficient detection*. Nature **409**, 791 (2001).

[8] J. Hofmann, M. Krug, N. Ortegel, L. Gérard, M. Weber1, W. Rosenfeld, and H. Weinfurter, *Heralded Entanglement Between Widely Separated Atoms*. Science **337**, 72 (2012).

[9] M. Giustina, A. Mech, S. Ramelow, B. Wittmann, J. Kofler, J. Beyer, A. Lita, B. Calkins, T. Gerrits, S. W. Nam, R. Ursin, and A. Zeilinger, *Bell violation using entangled photons without the fair-sampling assumption*. Nature **497**, 227 (2013).

[10] P. H. Eberhard, *Background Level and Counter Efficiencies Required for a Loophole-Free Einstein-Podolsky-Rosen Experiment*. Physical Review A **47**, 747 (1993).

[11] Z. Merali, *Quantum Mechanics Braces for the Ultimate Test*. Science **331**, 1380 (2011).