Garching, 14 April 2013

Press Release

Press & Public Relations
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"Spooky action at a distance" in the quantum world shortly before final proof

Physicists succeed in closing last *local realistic loophole* for systems of entangled photons.

In everyday life it is only natural that the properties of objects exist independent of being observed or not. The quantum world on the other hand is ruled by other laws: the property of a particle may be defined not until the instant it is being measured, and two entangled particles seem to be connected in a non-local way over large distances. Various experiments worldwide have proven this fundament of quantum theory. However, up to now last doubts could not be ruled out completely. Advocates of "local realism" by which the classical world is governed refer to several "loopholes" in order to save their world view. Now physicists from the group of Prof. Anton Zeilinger at the Institute of Quantum Optics and Quantum Information (IQOQI) in Vienna, Austria, have closed an important loophole in photonic experiments which use quantum entanglement to rule out a local realistic explanation of nature. The work got theoretical support from Dr. Johannes Kofler from the group of Prof. Ignacio Cirac at the Max Planck Institute of Quantum Optics (MPQ) in Garching, Germany, and experimental assistance from researchers at the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig Germany, as well as the National Institute of Standards (NIST) in Boulder, USA. The results are published this week in *Nature* (14.04.2013, AOP, DOI: 10.1038/nature12012).

"Local realism" is a world view in which the properties of physical objects exist independent of whether or not they are observed by anyone (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, the Irish physicist John Bell proved theoretically that local realism is in contradiction with the predictions of quantum mechanics, and that the decision between these philosophically so radically different world views can be made by experiment. A certain inequality, the now famous "Bell inequality", can be used for an experimental test. Quantum mechanics can violate the inequality, whereas local realism cannot.

In a Bell test, pairs of particles, 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 Bob. They each make a choice which physical property they want to measure, e.g. which direction of their photon's polarization. For pairs that are quantum entangled, the correlations of Alice's and Bob's measurement outcomes can violate Bell's inequality. Quantum entanglement – a term coined by the Austrian physicist Erwin Schrödinger – means that neither photon taken by itself has a definite polarisation but that, if one party measures the polarisation of its photon and obtains a random result, the other photon will always show a perfectly correlated polarisation. 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

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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 or atoms. However, in experimental tests "loopholes" arise which 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 world view falling back on three such experimental 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 the local realistic properties of the particle pairs. With a lot of effort, these two loopholes have already been closed in photonic experiments by separating Alice and Bob over large distances in space and enforcing precise timing of the photon pair creation, Alice's and Bob's choice events and their measurements. Then superluminal signals would be needed to explain the measured correlations. But influences which are faster than light are not allowed in the local realistic world view.

The third escape hatch for the local realist is called "fair-sampling loophole". It works in the following way: If only a small fraction of all 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 ones was able to violate Bell's inequality. (Think of randomly flipping many fair coins, where those coins with heads up tend to hide and thus have a smaller probability of being observed than the ones with tails up. By having only access to the actually measured coins, it wrongly appears as if the coins had a special, i.e. unfair, distribution with more tails than heads up.) 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. As yet, this has not been accomplished for photons but only for other physical systems, e.g. atoms, for which, however, the other two loopholes are very hard to close and indeed have not been closed yet.

The reported Vienna experiment now has, for the first time, closed the fair-sampling loophole for photons. "It employed a novel high-quality source of entangled pairs, low-loss transmission techniques, and state-of-the-art high-efficiency superconducting detectors," Dr. Johannes Kofler explains. In total, the researchers were able to measure about 75% of all entangled photons. "This is actually not sufficient for a test of the original Bell inequality. However, about two decades ago, the physicist Philippe Eberhard from the Lawrence Berkeley Laboratory (USA) proposed a new form of the inequality that explicitly includes also undetected events and requires an efficiency of only two thirds. Therefore, the efficiency of the Vienna experiment is high enough to rule out all local realistic explanations using the recourse of unfair sampling," says Kofler. This 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. It is not clear yet whether such an experiment will be achieved first for photons or atoms or some other quantum systems. If 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 its formulation, the endgame for local realism clearly has begun.

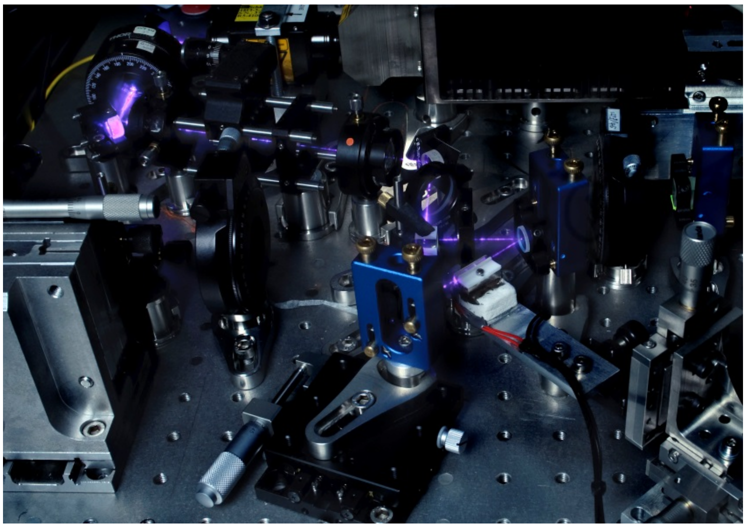

Figure: Quantum optical setup used in the experiment.
(Image: IQOQI Vienna, Jacqueline Godany 2012.)

Original publication:

Marissa Giustina, Alexandra Mech, Sven Ramelow, Bernhard Wittmann, Johannes Kofler, Jörn Beyer, Adriana Lita, Brice Calkins, Thomas Gerrits, Sae Woo Nam, Rupert Ursin, and Anton Zeilinger

Bell violation using entangled photons without the fair-sampling assumption
Nature, 14 April 2013, Advance Online Publication, DOI: 10.1038/nature12012
e-print: http://arxiv.org/abs/1212.0533

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