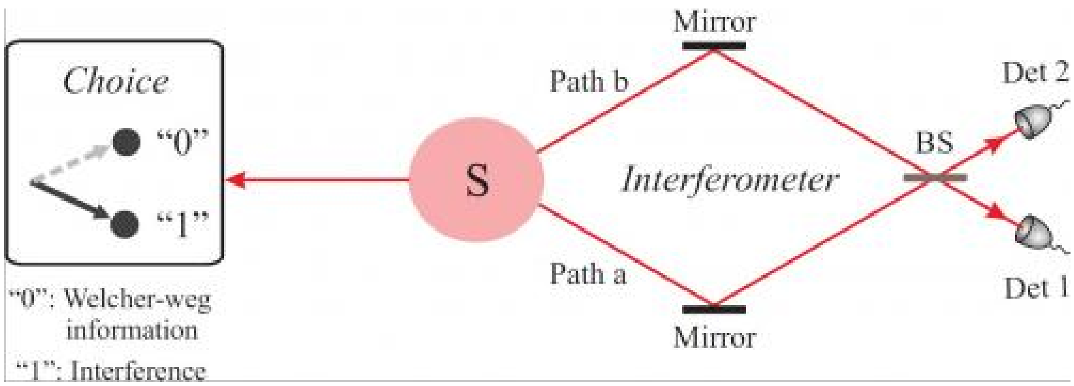
Of Einstein and entanglement: Quantum erasure deconstructs wave-particle duality

January 29 2013, by Stuart Mason Dambrot



Concept of our quantum eraser under Einstein locality conditions. Hybrid entangled photon-pair source, labeled as S, emits path-polarization entangled photon pairs. System photons are propagating through an interferometer (Right) and the environment photons are subject to polarization measurements (Left). Choices to acquire welcher-weg (which-path) information or to obtain interference of the system photons are made under Einstein locality so that there are no causal influences between the system photons and the environment photons. Copyright © PNAS, doi:10.1073/pnas.1213201110

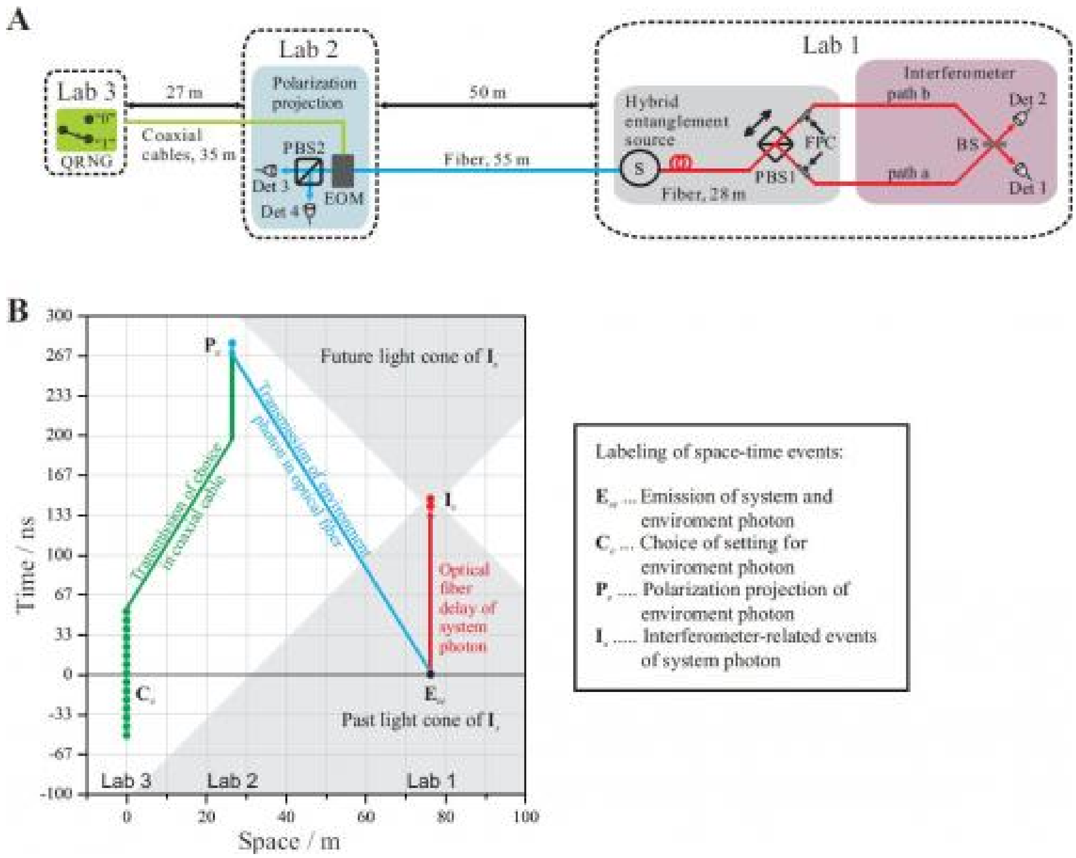
(Phys.org)—Quantum physics presents several counterintuitive features, including entanglement, tunneling and – as demonstrated in double-slit experiments – wave-particle duality. When studying wave-particle duality, however, so-called *interferometric quantum eraser* experiments – in which wave-like behavior can be restored by erasing path information – allow researchers to perform differential measurements on each of two entangled quantum systems. (Double-slit experiments not involving quantum erasure utilize superposition of single particles, while in quantum eraser experiments two particles are entangled.) Specifically, the particle feature's *welcher-weg* (*which-path*) information is erased (or not) from one system, and interference-based measurements in the other system are used to observe (or not, as the case may be) its wave feature.

While previous quantum eraser experiments made the erasure choice before or (in *delayed-choice* experiments) after the interference – thereby allowing communications between erasure and interference in the two systems, respectively – scientists in Prof. Anton Zeilinger's group at the Austrian Academy of Sciences and the University of Vienna recently reported a quantum eraser experiment in which they prevented this communications possibility by enforcing Einstein locality. They accomplished this using hybrid path-polarization entangled photon pairs distributed over an optical fiber link of 55 meters in one experiment and over a free-space link of 144 kilometers in another. Choosing the polarization measurement for one photon decided whether its entangled partner followed a definite path as a particle, or whether this path-information information was erased and wave-like interference appeared. They concluded that since the two entangled systems are causally disconnected in terms of the erasure choice, wave-particle duality is an irreducible feature of quantum systems with no naïve realistic explanation. The world view that a photon always behaves either definitely as a wave or definitely as a particle would require faster-than-light communication, and should therefore be abandoned as a description of quantum behavior.

What does this mean for scientists describing a quantum state without relying purely on mathematics? One way, says Dr. Xiao-Song Ma, lead author of the paper, is that the quantum state can be viewed, as Erwin Schrödinger wrote[1], as an *expectation-catalogue* or *sum of knowledge* – that is, a probability list for all possible measurement outcomes. Whether the outcome of each individual measurement is wave, particle or their superposition depends on the state and measurement context.

Ma also discussed the challenges he, Prof. Anton Zeilinger and their colleagues faced in conducting their research with *Phys.org*. "The main challenge of our quantum eraser experiment is the arrangement of the individual events such that various space-time configurations, including Einstein's locality condition, were fulfilled," Ma says. Achieving that required separate labs, a quantum random number generator, a very fast electro-optical modulator, precise optical and electrical delays, and other sophisticated techniques.

Another challenge was employing hybrid path-polarization entangled photon pairs distributed over the optical fiber and free-space links. "In order to implement the quantum eraser," Ma continues, "we maintained the entanglement between the path and the polarization of two photons and kept the phase and polarization stable over the measurement duration."



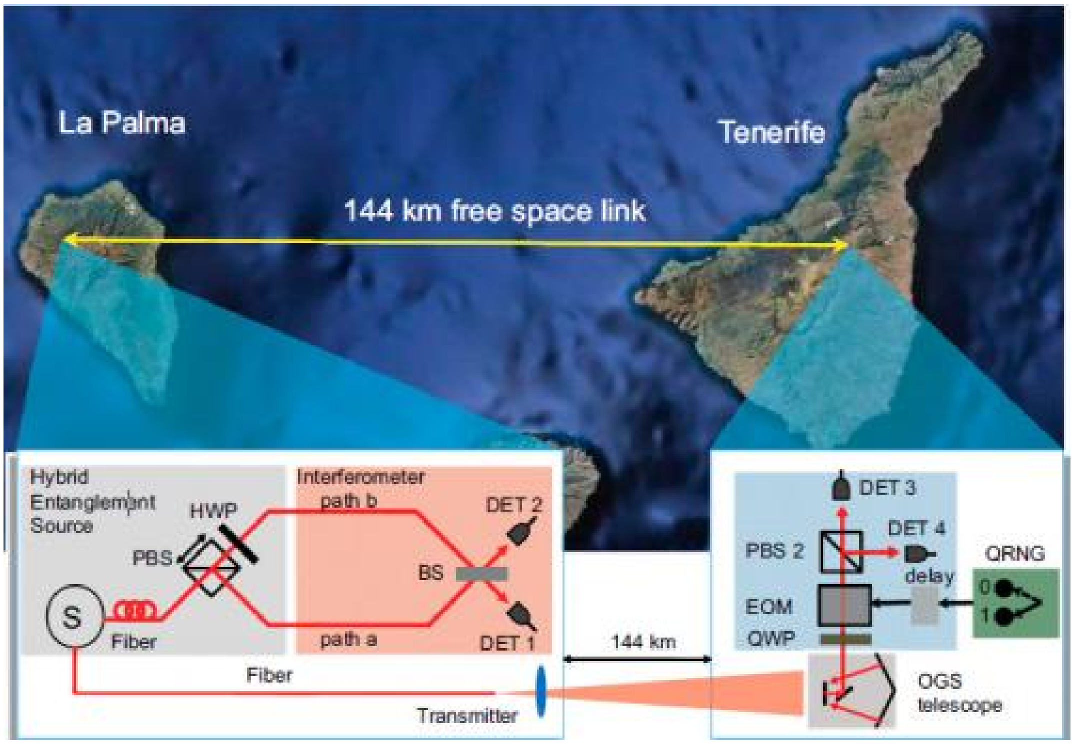
(A) Scheme of the Vienna experiment: In Lab 1, the source (S) emits polarization entangled photon pairs, each consisting of a system and an environment photon, via type-II spontaneous parametric down-conversion. Good spectral and spatial mode overlap is achieved by using interference filters with1-nm bandwidth and by collecting the photons into single-mode fibers. The polarization entangled state is subsequently converted into a hybrid entangled state with a polarizing beam splitter (PBS1) and two fiber polarization controllers (FPC). Interferometric measurement of the system photon is performed with a single-mode fiber beam splitter (BS) with a path length of 2 m, where the relative phase between path a and path b is adjusted by moving PBS1's position with a piezo-nanopositioner. The polarization projection setup of the environment photon consists of an electro-optic modulator (EOM) and another PBS (PBS2). Both photons are detected by silicon avalanche photodiodes (DET 1–4). The choice is made with a QRNG (44). (B) Space–time diagram. The choice-related events Ce and the polarization projection of the environment photon Pe are space-like separated from all events of the interferometric measurement of the system photon Is. Additionally, the events Ce are also space-like separated from the emission of the entangled photon pair from the source

Ese. Shaded areas are the past and the future light cones of events Is. This ensures that Einstein locality is fulfilled. BS, beam splitter; FPCs, fiber polarization controllers; PBS, polarized beam splitter. Copyright © PNAS, doi:10.1073/pnas.1213201110

Addressing these challenges meant doing things differently than all quantum eraser experiments performed to date, in particular by establishing strict Einstein locality between the relevant events. "We achieved this by implementing independent active choices that were space-like separated from the interference," Ma explains. "These choices were made by a quantum random number generator and then implemented by an electro-optical modulator."

When two events are separated by a space-like interval, not enough time passes between their occurrences for there to exist a causal relationship crossing the spatial distance between the two events at or below the speed of light. While the two events can be observed to occur at the same time, there is no reference frame in which the two events can occur in the same spatial location or where they can occur in each other's future or past.

To maintain entanglement between the path and the polarization of photon pairs, Ma points out that the researchers first produced bright highly-entangled polarization pairs using a spontaneous parametric down-conversion process. "We converted the polarization states of the system photon into its path states in an interferometer via a polarizing beam splitter and polarization controllers, while maintaining the polarization state of the environment photon. By carefully adjusting these components, we eliminated the polarization distinguishablity of the path states of the system photon and generated hybrid entangled photon pairs. In order to maintain this hybrid entanglement, we paid exceptional attention in keeping these photons away from decoherence."



Satellite image of the Canary Islands of Tenerife and La Palma and overview of the experimental setup (Google Earth). The two laboratories are spatially separated by about 144 km. In La Palma, the source (S) emits polarization entangled photon pairs, which subsequently are converted to a hybrid entangled state with a PBS (PBS1) and a half-wave plate oriented at 45°. The interferometric measurement of the system photon is done with a free-space BS, where the relative phase between path a and path b is adjusted by moving PBS1's position with a piezo-nanopositioner. The total path length of this interferometer is about 0.5 m. The projection setup consists of a quarter-wave plate (QWP), an EOM, and a PBS (PBS2), which together project the environment photon into either the H/V or +/− basis. Both the system photon and the environment photon are detected by silicon avalanche photodiodes (DET 1–4). A QRNG defines the choice for the experimental configuration fast and randomly. A delay card is used to adjust the relative time between the choice event and the other events. Independent data registration is performed by individual time-tagging units on both the system and environment photon sides. The time bases on both sides are established by global positioning system (GPS) receivers. Copyright © PNAS,

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Specifically, for the polarization states, they had to compensate the polarization rotation and depolarization caused by optical fibers via various tubing and frequently monitoring the polarization transmission fidelity. "For the path states," Ma illustrates, "we had to isolate the system photon from phase noises, which reduce interference visibility." In order to achieve that, they used home-made acoustic-isolation surroundings to protect the interferometer.

In future experiments, notes Ma, the scientists are planning to develop a brighter photon-pair source, low-noise single-photon detectors, faster optical modulators with higher duty cycles, and more precise clock synchronization. "In our experiment, another practical challenge is limited signal-to-noise ratio" says Ma. "This is because most quantum phenomena are very fragile to noise and can be easily washed away." To overcome this problem and demonstrate the counterintuitive features of quantum mechanics, the researchers have to increase the signal and/or reduce the noise.

"To increase the signal," Ma continues, "we have to generate more photons. Therefore, a brighter photon-pair source will be certainly helpful. Additionally, more precise clock synchronization will also improve our results: It will allow us to use a much smaller coincidence window and hence reject the false coincidence stemming from noise. This is possible because time-energy entanglement allows the intrinsic uncertainty of the generation time of photon pairs to be much smaller than the timing jitter of the present remote clock synchronization techniques – for example, the GPS system used in their current study.

Finally, Ma points out that noise is mainly from the *dark counts* of single-photon detectors. Therefore, it is very crucial to reduce these dark counts, which is possible by using some advanced cooling techniques. "All these improvements can be evaluated by using photon counting and entanglement verification."

Ma also says that quantum communication and quantum information processing may benefit from their findings. "Our experiment is important for foundations of quantum mechanics as well as quantum information processing, especially quantum communication. The architecture of our experiment could be used for a satellite-to-ground station quantum communication prototype and hence provide the basis for a worldwide information network, in which quantum mechanical effects enable the exchange of messages with greater security and the ability to perform certain calculations more efficiently than is possible with conventional technologies."

More information: Quantum erasure with causally disconnected choice, *PNAS* January 22, 2013 vol. 110 no. 4 1221-1226, doi:10.1073/pnas.1213201110

Related:
[1]The Present Situation in Quantum Mechanics: A Translation of Schrodinger's "Cat Paradox" Paper, translated by John D. Trimmer, originally published in *Proceedings of the American Philosophical Society*, 124, 323-38 (1980)

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