# A non-causal quantum eraser

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This is a long time exposure photography viewing from Tenerife to La Palma. A green laser beam indicates the free-space link between the two laboratories. Credit: IQOQI Vienna

Whether a quantum object behaves like a wave or like a particle depends (according to the Copenhagen interpretation) on the choice of measurement apparatus used for observing the system, and therefore on the type of measurement performed.

Anton Zeilinger's team of physicists at the University of Vienna and the Austrian Academy of Sciences has recently taken this phenomenon further than ever. Whether a certain photon behaves like a particle or like a wave depends on the measurement performed on a second photon.

In the new experiment, this second photon is so far separated from the first photon that no transfer of information whatsoever (the velocity of which can never exceed the speed of light) would be fast enough. Yet, the first photon behaves like a wave or like a particle, still depending on the measurement performed on the second. While the results of such experiments are fully consistent with quantum physics, a clear explanation in terms of causality is impossible, as, according to Einstein's relativity theory, any transfer of information is limited to the speed of light. The science article "Quantum erasure with causally disconnected choice" has appeared in the current issue of the renowned science journal Proceedings of the National Academy of Sciences (*PNAS*).

## The basis: the delayed choice experiment

Gedanken experiments on the foundations of quantum mechanics have a long history. Such thought experiments were developed to play through and discuss the behavior of single particles, which contradict both classical physics and common sense, at least theoretically. One milestone was the 1978 delayed-choice experiment by Einstein's last collaborator John Wheeler. In this gedanken experiment, a single photon has two paths it could take in an interferometer. In its wave character, the photon will take both paths simultaneously. In its particle character, the photon needs to decide which of the two paths it will take. Wheeler proved, in accordance with quantum mechanics, that the decision whether the photon will behave as a wave or as a particle can be taken after even after it has already entered the interferometer.

## The quantum eraser

The so-called quantum eraser, presented in 1982 by Marlan Scully and Kai Drühl, turned out to be another milestone. A quantum mechanically

entangled pair of one photon and one atom is created. The atom can take two paths, emitting the photon in the process. By measuring the photon, it can now be determined which of the two paths the atom has taken. If we now measure the photon in such a way that it becomes fundamentally impossible to determine the atom's path, as a consequence, the information about which path the atom has taken is, so to speak, erased. The atom then exhibits phenomena which can only be explained by its taking both paths, as a wave.

## Vienna quantum physicists turn off the causality factor in experiment

The two ideas, delayed choice and quantum eraser, have been realized in experiment both separately and in combination. In all past experiments, the possibility that the choice of measurement has a causal influence on the actual observation (by transmission of information slower than light) still remained, if only in principle.

In the two new experiments, one of which was performed in Vienna and one on the Canary Islands, this remaining possibility of a causal explanation was now ruled out. The researchers created a pair of photons, one of which was sent through two glass fibers while the other was sent to a different laboratory, 50 meters away in Vienna and 144 km distant on the Canary Islands. The second photon was entangled with the first in such a way that by measuring its polarization (horizontal or vertical), it was possible to determine which path the first one had taken. If the second photon's polarization was measured at 45 degrees, no deduction on the path of the first photon was possible, which then, as a wave, took both paths. The decision of which measurement to perform on the second photon was realized by means of a high-speed random number generator. In both experiments, also in the case of the 144 km long optical free space connection from La Palma to Tenerife across the

Atlantic, the choice of polarization measurement at the Tenerife photon was completely separated causally from its twin in La Palma. And yet, the photon on La Palma behaved like a particle or like a wave, according to the Tenerife measurement.

"This rules out the possibility of any physical signal between the two photons. Introducing this non-causal choice is a substantial step beyond existing quantum eraser experiments, where such communication is still possible in principle", explains Xiao-Song Ma, the first author of the current article.

Consequently, the experiment can be seen as a complete realization of the quantum eraser concept, not via delayed choice (which theoretically might be influenced by past events) but using a causally separated choice (by rendering any causal influence impossible).

"Our work disproves the view that a quantum system might, at a certain point in time, appear definitely as a wave or definitely as a particle. This would require communication faster than light – which is dramatically at odds with Einstein's theory of relativity. And so, I think that this view needs to be abandoned completely. In a certain sense, quantum events are independent from space and time", says Anton Zeilinger.

Provided by University of Vienna