Toward the experimental study of indefinite causal order phenomenon

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Abstract

The so-called phenomenon of indefinite causal order has long been studied theoretically and experimentally. Even earlier, the phenomenon of broken causal order (when the effect precedes the cause) was experimentally observed. Both phenomena obviously have a common physical basis. This physical basis is simple and convenient to study experimentally precisely in the broken causal order variant.

Keywords: indefinite causal order, HOM effect, quantum memory, nonlocality, time reversal noninvariance.

In the classical world, physical events always happen in a fixed causal order. However, quantum mechanics allows the occurrence of events without having any definite causal order [1 - 8]. It is supposed that different events are placed in a quantum superposition. This superposition has strong analogy with entangled states.

The physical meaning of such a superposition is not clear. In general, this topic is difficult to understand and confusing. There is more mathematics than physics here. Is it possible to find a physical explanation for this phenomenon? You can. But for this it is better to go from the other side.

Much earlier, experimental results were published, which directly indicate a possible violation of causality [9, 10]. The most surprising thing here is that these fantastic results did not interest neither theorists, nor experimenters. No one continued these experiments.

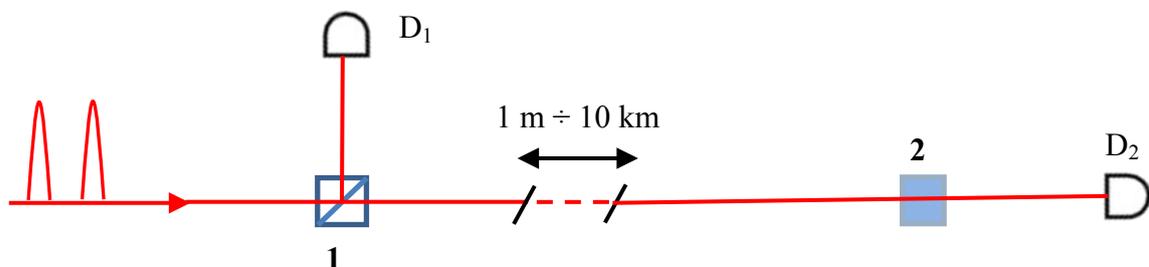Figure 1 shows a simplified scheme of such experiments.

Figure 1. Simplified experimental scheme for the case when the entangled photons delay control device is located after the beam splitter. 1 - beam splitter, 2 - Pockels cell.

Two entangled photons with orthogonal polarization enter to an unpolarized beam splitter (50:50) at slightly different times and then to two single photon detectors (D_1 and D_2). A Pockels cell [9] (or quartz plates [10]) is installed in front of one of the detectors, with the help of which it is possible to change the delay between photons (synchronize their phases). A typical Hong-Ou-Mandel (HOM) effect was observed.

It is fundamentally important here that both the quartz plates and the Pockels cell were located after the beam splitter. This situation looks like a violation of causality. The splitting of photons by a beam splitter (consequence) precedes the cause (Pockels cell or plates manipulation). The photons, coming to the beam splitter, in some mysterious way "know" whether their phases will be synchronized or not, and behave on the beam splitter accordingly.

There is a fairly simple physical explanation here. It is based on the experimental fact of the nonequivalence of forward and reversed processes in quantum physics [11] (mathematicians call this time reversal noninvariance). The concept of the memory of a quantum system about its initial state is directly associated with this nonequivalence. Without such memory it is impossible to distinguish the direct process from the reversed one. We don't know where this memory is stored. It looks like the physical equivalent of entropy.

This nonlocal memory of the quantum system (as a whole) serves as a mystical "knowledge" of photons. Here we can study its nonlocal properties quite simply. If we move the Pockels cell away from the beam splitter at a distance of 1 m ÷ 10 km, then somewhere the observed HOM effect should disappear. This will characterize the degree of nonlocality of the quantum system's memory.

If a high-speed Pockels cell is used to synchronize photons, then in the version of the so-called "delayed choice" [12], the speed of information (memory) propagation in space can be measured.

Thus, broken causal order and indefinite causal order are an illusion of causality violation. Causality persists. In reality, we are dealing with a manifestation of the nonlocal memory of a quantum system about its initial state. The basic properties of this nonlocal memory can be studied in simple experiments.

Conclusion

The experiments discussed should have been carried out 30 years ago. There are a large number of experimenters who have all the necessary equipment for such experiments. We hope that someone will at last carry out these important, interesting and simple experiments [13].

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