The collapse of the wave function and the speed of quantum information

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Abstract

We performed a long-distance Bell experiment with simultaneous detection events and the axis between the detectors approximately east–west oriented. Two-photon interferences with visibilities well above the Bell inequality threshold were continuously observed. The rotation of the Earth and the configuration of the experiment allowed us to set a lower bound on the "speed of quantum information" up to four orders of magnitude faster than the speed of light. Moreover, the same experimental setup, with the addition that each detected photon triggered the displacement of a macroscopic mass, was used to test the hypothesis that the measurement time is related to gravity-induced state reduction. The results confirm the non-local nature of quantum correlations.

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Introduction and motivation

Entanglement is one of the most important features of quantum mechanics. According to quantum theory, entanglement is at the origin of the quantum correlations between two distant events that violate the Bell inequalities. A hypothetical alternative explanation would be that a first event influenced the second, through a hypothetical influence that travelled between the two. In this case, the speed of this influence would need to be defined in some privileged reference frame and be greater than the speed of light. Einstein branded it as 'spooky action at a distance'.

To test this possibility, we could perform a Bell experiment where the two detection events are simultaneous in a certain hypothetically privileged reference frame. Because the speed of the influence must be finite, it can not arrive on time and no violation of Bell inequalities should be observed.

In the past, we used the results of previous Bell experiments where quantum correlations were observed, to set a lower bound on this speed (let's call it "speed of quantum information") to 10^7 times the speed of light in the Geneva reference frame (1) and 10^4 in the background radiation reference frame (2). Hence, only two different reference frames were tested.

Note that if the two events are simultaneous in some reference frame, then they are also simultaneous with respect to any reference frame moving in a direction perpendicular to the line joining the two events. So, in a long-distance Bell test performed over a period of 12 hours, with the axis between the detectors (A-B axis) east-west oriented, if the events were simultaneous in the Earth's reference frame, then they would also be simultaneous with respect to all frames moving in the plane perpendicular to the east–west axis. In 12 hours, all possible hypothetically privileged frames would be scanned. If the A-B axis was almost but no perfectly east-west oriented, the

experiment could still be performed over 24 hours (see Figure 1).

At the same time, these experiments also addressed the very difficult and deep question of where (or when) the wave function collapse takes place. In one experiment (3) we assumed that the collapse takes place in the reference frame determined by the massive measuring detectors. The two apparatuses are in relative motion so that both detectors, each in its own inertial reference frame, are first to perform the measurement. We did not observe any disappearance of the correlations, in agreement with quantum mechanics.

In another experiment (4), we used acousto-optic modulators as moving beam splitters and interferometers separated by 55 m. Again, the results are in agreement with quantum mechanics.
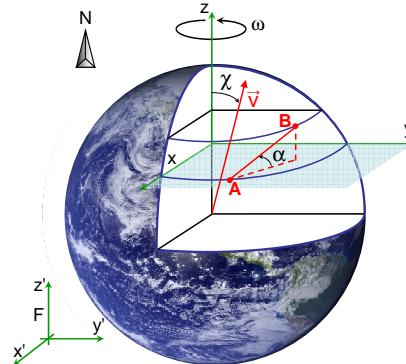

Figure 1: The Earth frame moves with respect to a hypothetically privileged reference frame F at a speed v. The zenith angle X between v and the z axis can have values between 0° and 180°. The A–B axis forms an angle α with the equatorial (x–y) plane. ω is the angular speed of the Earth.

Main achievements

Recently, we performed a Bell experiment (5) between two villages separated by 18 km, approximately east–west oriented, and with the

source located precisely in the middle. We adjusted the lengths of the fibres linking the source with the detectors so the two events were simultaneous.

Two-photon interferences with visibilities well above the Bell inequality threshold were continuously observed. After 24 hours, the rotation of the Earth and the configuration of our experiment allowed us to determine, for any hypothetically privileged frame, a lower bound for the speed of a hypothetical influence travelling between the two detection stations. For instance, if the Earth's speed in this privileged frame is less than 10^{-3} times that of the speed of light, then the speed of the influence would have to be at least four orders of magnitude greater than that of light.

Finally, in another recent experiment (6) the two events are space-like separated and we consider the hypothesis that the measurement time is related to gravity-induced state reduction. This is, the collapse of the wave function only takes place just after a macroscopic mass has moved, modifying its surrounding gravitational field. Two energy-time entangled photons are sent through optical fibres and directed into unbalanced interferometers at two receiving stations separated by 18 km. At each station, the detection of a photon triggers the displacement of a macroscopic mass. The timing ensures space-like separation from the moment a photon enters its interferometer until the mass has moved. Two-photon interference fringes with a visibility of up to 90.5% are obtained, leading once again to the violation of the Bell inequalities.

Conclusions

In all the experiments we performed, the results confirm the non-local nature of quantum correlations. An explanation based on "spooky action at a distance" would have to assume that the hypothetical influence propagates at speeds even greater than the bounds obtained in our experiments.

References

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