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A TEST OF BELL'S INEQUALITIES WITH INDEPENDENT OBSERVERS[1]

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In this work we present an experiment which will for the first time test nonlocality with truly independent observers. In the experiment we measure the polarization of individual photons from a type-II parametric down-conversion source at two remote points of observation. The axes of the polarization analyzers will be switched very rapidly between two directions. These directions will be controlled by two independent physical random number generators. All processes which are important in setting the analyzer and detecting a photon will be so fast that no subluminal signal can broadcast any information to the other side of the experiment. This means that the respective events on either side are spacelike separated. Optical fibers guide the photons to the detectors where every detection event is registered with its time and analyzer direction. Correlations can then be extracted from the two classical records. The experiment is currently set up in the laboratory. In the final version the fibers will stretch over several hundred meters.

1. Introduction

Based on the reasoning of Einstein, Podolsky, and Rosen [1] it was shown in 1965 by John Bell that more complete theories, as intended by EPR, which obey a quantified version of the locality assumption, yield experimental predictions which differ from the quantum mechanical ones. The ensuing Bell's inequalities [2] are a quantitative expression of the fact that correlations in local theories are limited and further inspection shows that that limit can be surpassed by quantum mechanics.

While the experimental support of quantum mechanics is rather striking [3, 4, 5, 6] there are still so-called loopholes which make it difficult to clearly refute local realistic theories. The loopholes are essentially based on two different problems in all existing experiments. One problem, as has first been pointed out by Pearle [7], is the low

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detection efficiency of the detectors used. An attempt to close this loophole is presently in progress at Texas A&M University [8].

The second loophole in all past tests of Bell's inequalities is that no experiment has succeeded in enforcing Einstein locality. The only experiment that has tried to tackle the problem was performed by Aspect, Dalibard, and Roger [5]. However, in the experiment, locality was not fully enforced for at least two reasons. One is that the analyzer setting was switched periodically in a predetermined way, the second is that unluckily the dimensions of the apparatus were chosen as not to be able to rule out communication with the speed of light for the given switching frequency [9].

We are setting up an experiment, in which only local and intrinsically random physical processes control the settings of the analyzers. In order to maintain locality switching has to be done so fast that no information on the analyzer orientation on one side can propagate to the other side with luminal or subluminal velocity before both particles are detected. For a detailed timing analysis see Ref. [10].

2. The setup

As a source we are using the type-II down-conversion process in a χ^2-nonlinear crystal, e. g. BBO. From the light emitted by the crystal we are selecting a momentum-polarization entangled state of two photons by interference filters and irises. For a thorough description of this source see [6, 10, 11].

With this source we are achieving coincidence count rates of several hundreds per second. These count rates are orders of magnitude higher than in previous experiments which will greatly improve the statistics and at the same time speed up the measurement thus reducing the requirements on apparatus stability.

One of the most important requirements in our experiment is true random switching in a time as short as possible because this time governs the minimum distance between the analyzers that is necessary to prevent subluminal communication between the two observers. To accomplish this task we have developed random number generators (RNG) based on the randomness of photon emission from an arbitrary coherent source and on the randomness that occurs in the choice of a certain output of a 50/50 beamsplitter for every photon that hits the beamsplitter. Our RNGs are capable of delivering high quality binary random signals with exponentially distributed time intervals [12]. Intervals down to approx. 2 ns can occur. This limit is set by the output pulse width of the photomultipliers we use to detect the photons. No correlations are measured in the outputs of these RNGs for times longer than a few times (≥ 3) the mean RNG switching interval [12].

The complete setup is shown in the figure. The photons are guided from the source to the detectors by single-mode optical fiber cables, which were specialty made to suit our wavelength of 702 nm. The cables are rigid enough to be installed into cable channels. With the effective filter bandwidth of 0.5 nm, which is achieved by the coupling of the down-conversion light to the fiber [13], polarization mode dispersion is small enough to maintain a polarized state over hundreds of meters. The change in the state of polarization is compensated for by manual polarization controllers, which have to be readjusted rarely.

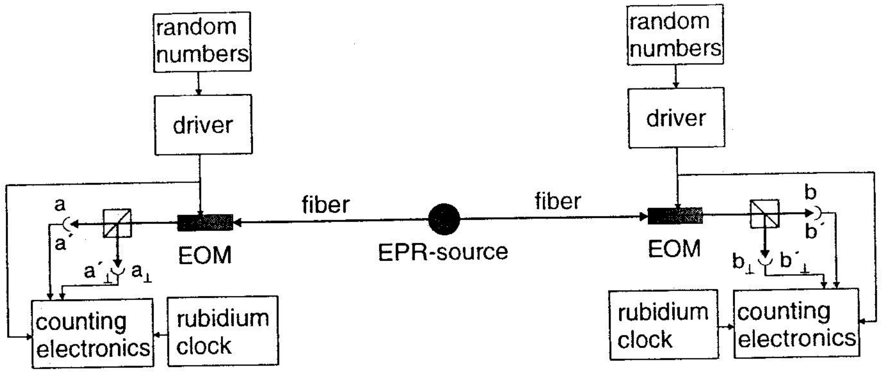

Fig. 1. The setup for a test of Bell's inequalities with independent observers. The main components source, transmission, switches, detectors, and electronics are discussed in the text. "EOM" is short for electro-optic-modulator.

Our polarization analysis system consists of electro-optic polarization switches (transverse electro-optic phase modulators) followed by two-channel calcite polarizers (Wollaston prisms) which provide 10^{-5} extinction for both channels. The switches will be used as a switchable half-wave-plates at an angle of 22.5° with to the respective polarizers in order to change the basis of analysis from $(a, a_\perp) = (0°, 90°)$ to $(a', a'_\perp) = (45°, 135°)$ on one side and from $(b, b_\perp) = (22.5°, 112.5°)$ to $(b', b'_\perp) = (67.5°, 157.5°)$ on the other side. These settings presumably yield the strongest violation of Bell's inequalities [14]. Additionally we are planning to measure various other settings to test whether or not the data behave sinusoidally as a function of the difference angle, as predicted by quantum mechanics.

The switches are not yet installed. Currently we are acquiring "macroscopic" ones that can switch within a few nanoseconds and have 100% switching ratio as well as more than 95% transmission. Still, we are considering the possibility to realize the scheme with fiber-integrated switches operated in the same way as described above. They have the advantage of much higher switching frequencies, but in turn they show much more loss. Most kinds of integrated modulators are even only able to transmit one polarization, which clearly rules these types out for our experiment.

In a test of Bell's inequalities the two remote observers want to compare their detector clicks for the various orientations of the analyzer they chose independently. In our experiment the detector clicks are pulses from silicon avalanche photodiodes. Each pulse corresponds to a single detected photon. These diodes show very little noise (less than hundred dark-counts per second) and rather high efficiency (approx. 30%). The detector time resolution is approximately 500 ps.

To make the independence of the observers evident we are avoiding any additional communication channels as for example cables for coincidence measurements. Instead, all detected events are registered as highly accurate time-tags together with the instantaneous position of the polarization switch. The correlations can then be calculated afterwards and anyone can test their various models using the raw data.

This goal requires a high time-resolution of about 1 ns over a measurement period of 100 s to make narrow "coincidence windows" possible. Of course the "window" is only set by the data evaluation after the experiment has been performed, but in order to be able to do this correlation calculation a precise timescale must be maintained. In our experiment the timebase is given by two rubidium clocks (LPRO by Efratom) with an absolute frequency accuracy of 10^{-11} and a relative stability of 10^{-12} for 100 s, thus eliminating the need for synchronization. These frequency standards serve as clocks for our time-interval analyzers (TIA). The TIAs perform the task of associating a time tag with each detected photon at a resolution of 100 ps, over a time interval that is only limited by the computers memory, in which the time tags are stored.

Currently we have set up the whole system without the fast polarization switches in our laboratory. The optical fibers are still on coils giving an actual detector separation of a few meters. After further tests we will move the whole apparatus out of our laboratory to achieve separations of up to 1 km.

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