Towards a Long Distance Bell-Experiment with Independent Observers

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(May 3, 1996)

Abstract

More than 60 years after the paper by Einstein, Podolsky, and Rosen and 35 years after Bell's formulation of his famous inequality, nonlocality is still a fundamental issue in quantum mechanics. We discuss an experiment, presently in preparation at our laboratory in Innsbruck, which will for the first time perform a test of Bell's inequality with truly independent observers. The experiment will measure the polarization correlations between two entangled photons created in the process of type-II parametric down-conversion. It will rule out any possibility of subluminal communication which might inform the photon or the detector station on one side about which measurement will be performed on the other side of the experiment. For that purpose, the orientation of the polarizers will be determined by a purely random physical process and the photons will be registered with accurate time tags separately at each detector before any information can be communicated from the other side. Optical fibers will help to cover the necessary long distances. The correlations, which constitute Bell's inequality, will be calculated afterwards from the independent classical records.

I. INTRODUCTION

The counter-intuitive properties of entangled quantum systems have assumed a central position in the scientific and philosophical interest of Abner Shimony, as evidenced by numerous papers published by him on the subject. (For an early review by him and John Clauser, see Ref. [1].) Most importantly, Abner Shimony has always kept close contact with experiment on the one hand by proposing novel experiments [2,3] and on the other hand by encouraging experimentalists to do increasingly better tests in order to eventually close all existing loopholes in tests of Bell's inequalities. We therefore dedicate this paper, in which we discuss features of one such experiment, which is in progress in our laboratory at Innsbruck University, to Abner Shimony on the occasion of his sixty-fifth birthday.

In 1935, Albert Einstein, Boris Podolsky, and Nathan Rosen (EPR) suggested that the description of physical reality by quantum mechanics cannot be considered complete [5]. In the last sentence of their paper, they even express the expectation that a more complete theory is possible. It is crucial to realize that a premise of the EPR reasoning is the assumption of locality, which they expressed in the sentence: *'[...], since at the time of measurement the two systems no longer interact, no real change can take place in the second system in consequence of anything that may be done to the first system.'* While it is certainly possible and thinkable that hitherto unknown interactions between the two systems might exist, it is generally accepted that spacelike separation of the *decision* what to measure on either side from the *detection* of a particle on the other side would exclude any conceivable mutual physical influence and thus justify the above assumption.

Based on the reasoning of Einstein, Podolsky, and Rosen, 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 [6] 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. [1]

While at that time the attitude of many physicists was that the mere fact of a predicted discrepancy between quantum mechanics and a local-realistic theory dooms the latter unviable, it came as a great surprise that then no experimental evidence existed [1] which would have made it possible to discriminate between the two world views. After the discovery that the polarization correlations between photons emitted in certain atomic cascade decays can lead to viable experimental tests [2], a large series of such experiments was performed and provided a significant body in support of quantum mechanics [7–9].

While the experimental support of quantum mechanics appears to be rather striking – in a recent experiment [10] it was possible to obtain a violation of Bell's inequality by more than 100 standard deviations in a measurement time of less than five minutes using a novel down-conversion source – there are certainly still possibilities open for advocates of local realistic theories to argue their case. These so-called loopholes are essentially based on two different problems in existing experiments. One problem, as has first been pointed out by Pearle [11], is that it is at least thinkable that the subset of pairs detected in such an experiment is not representative for all pairs emitted by the source. Thus, it is possible to assume that, while the observed coincidence count rates agree with quantum mechanics and thus violate Bell's inequalities, observation of all pairs would result in data consistent with local realism. It can easily be shown that such an argument will not be viable with sufficiently efficient detectors. A first proposal to close this so-called detection efficiency loophole was made by Lo and Shimony [3] suggesting the observation of spin correlations between atoms originating from dissociated molecules. An experiment along these lines is presently in progress at Texas A&M University [4].

The second loophole in all past tests of Bell's inequalities is that no experiment has

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[1] If, for example, the property to be tested is polarization, the different measurements are detector clicks behind a polarizer with various orientations on either side.

succeeded in enforcing Einstein locality. The only experiment that has tried to tackle the problem was performed by Aspect, Dalibard, and Roger [9]. In this experiment the analyzer orientation was changed very rapidly with the intention that no information about the orientation on one side could propagate to the other side with luminal or subluminal velocity. 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 [12].

Our aim is to perform an experiment, in which only local and intrinsically random physical processes control the settings of the analyzers. It is evident that random switching is the basic ingredient to a Bell-experiment in which the two remote observers can be considered independent. 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. To be more precise, we believe that in order to test the nonlocality of quantum mechanics, the whole measurement sequence beginning with the choice of the random analyzer orientation up to the classical signal indicating the detection of a photon, must be outside the backward lightcones of all these processes on the other side of the experiment. To perform a clear experiment it is then necessary to keep track of all relevant events involved in the measurement. These events include at least the times at which the individual random numbers were produced and all detection times.

In the following section we are going to explain how these requirements will be fulfilled in our proposed experiment.

II. THE PROPOSED SETUP

A general setup for an experiment to test Bell's inequalities consists of three separate parts: a source emitting entangled particle pairs and two experimental stations, to analyze the entangled property and detect each particle. As a source we will use our recently developed source of entangled particles, the type-II down-conversion process in a χ^2-nonlinear crystal, e. g. BBO [10].

In the process of type-II down-conversion a UV-photon inside a nonlinear crystal may split with very low probability spontaneously into an ordinarily and an extraordinarily polarized photon in the visible to infrared range. As energy is conserved in this process the sum of the frequencies of the down-conversion photons is equal to the pump frequency. In the degenerate case photons of equal wavelength are selected, which means that the wavelength of the down-conversion photons is just twice the wavelength of the pump. As opposed to the case of production of entangled photon pairs in atomic cascades, the emission directions of the down-conversion photons are well defined being governed by phase matching i.e. two-body momentum conservation. It follows from the specific form of the dispersion law inside the crystal that each of the photons, once the frequency is defined, may be emitted into any direction along a cone (Fig. 1). Into which direction along its cone a specific photon will be emitted is quantum mechanically uncertain, but the photons will always be found pairwise, one on each cone, such that the in-crystal momenta add up to the momentum of a pump photon. While the two photons in general can be distinguished by their polarization, this is not the case along the two directions, where the cones intersect. There, the polarization of neither photon is well defined, in fact, it is quantum mechanically maximally uncertain. What is defined is the property that the polarizations of these two photons in a pair have to be orthogonal. Evidently, this implies the momentum entangled state shown in Fig. 1 since the coherence of the pump is so large that all processes in the crystal are coherent. With this source one can easily achieve singles count rates of up to $2 \cdot 10^5\,\mathrm{s}^{-1}$ and coincidence rates of more than $10^4\,\mathrm{s}^{-1}$ depending, of course, on detection and collection efficiencies. 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 questions in our proposal is the minimum distance between the analyzers that is necessary to prevent subluminal communication. As shown in Fig. 2, we must first know how long it takes to create a random number and switch the analyzer according to this number until the detection of the photon. We are only allowed to use physical generators to obtain true random numbers. Any reading of the random numbers from a pre-existing list or even calculation of the random numbers using a pseudo-random generator could not enforce locality because in both of these cases the information about which numbers will be generated and possibly used for analysis is already present at the beginning of the experiment. In an early version of the experiment, we will use a classical source of random numbers, for example, the noise at an electronic resistor. In a later version, we will employ a quantum random process, for example, a radioactive source, an atomic transition, the distribution of individual photons after beam-splitters, or any other source of quantum fluctuations. Even for such truly random sources, one has to be sure to avoid any short time correlations which might occur on a time scale comparable to the photon flight time. To avoid such correlations, the source should produce elementary events at a rate considerably higher than the desired rate of generation of random numbers [13]. We think that if the rate of registering these individual events at the random number generator is larger by at least a factor of ten, short-time correlations will sufficiently be ruled out. Possible specific implementations might involve actively quenched avalanche photodiodes or photomultipliers, either looking at the two output ports of a beam splitter or at a scintillator acting as a radioactivity detector, best with the radioactive samples built in, in order to gather as many of the events as possible.

In general it appears that the highest count rates that can be achieved with a single detector are less than $2 \cdot 10^7\,\mathrm{s}^{-1}$. On the basis of this count rate we obtain $1/(10 \cdot 2 \cdot 10^7\,\mathrm{s}^{-1}) = 500\,\mathrm{ns}$ as a safe upper limit for the time needed to produce a random number, where yet no delays in the electronics have been taken into account. We have also not accounted for delays in the switch which physically sets the direction of polarization analysis or in the detectors, as we shall see, that these can be kept at least one order of magnitude smaller. 500 ns times the vacuum speed of light gives a straight distance of $l = ct = 150\mathrm{m}$ between the analyzers or equally a distance of 75 m between analyzer and source if we use a setup in which all three parts form a straight line.

The complete setup is shown in Fig. 3. Photons are guided over such a distance most easily by single-mode optical fibers although the use of telescopes and vacuum tubes have also been considered. It is well known that depolarization in a single-mode fiber can be neglected for distances on the order of several hundred meters. However, a change in the state of polarization must be compensated for in the outputs [14]. This task can be performed using manual polarization controllers or even by periodic automatic stabilization. We would like to remark that it is not possible to use polarization maintaining fibers; because of their high birefringence they tend to guide one state of polarization better than the orthogonal one and the giant phase-shift between the two polarizations could not be compensated for.

Once the photons have been coupled into a fiber one can take advantage of any available fiber integrated component. The direction of polarization analysis will be chosen using fiber integrated Pockels-cells followed by polarization-beamsplitters. The Pockels-cell would be used as a switchable $\lambda/2$-plate at an angle of 22.5° to change the basis of analysis from $(0^\circ, 90^\circ)$ to $(45^\circ, 135^\circ)$, which yield the strongest violation of Bell's inequalities. Detection of both outputs of each polarizing beamsplitter gives the values h or v when the basis of analysis is set at $(0^\circ, 90^\circ)$ and x or y for $(45^\circ, 135^\circ)$. Fiber-optic integrated $\mathrm{LiNbO_3}$ switches have bandwidths on the order of GHz and need only a few volts of driving voltage. We therefore expect only delays of less than 10 ns which is small compared to the time it takes to produce a random number.

Turning now to the problem of registering the entangled photons, the best commercially available single photon detectors regarding background and efficiency are silicon avalanche photodiodes. To be able to use these we will have to work with wavelengths of less than 850 nm. Unfortunately the optimum wavelengths for fiber transmission are 1310 nm and 1550 nm but a band around 850 nm is also widely used in fiber technology. A powerful pump for downconversion in this frequency range is the 413 nm line of a $\mathrm{Kr^+}$-laser.

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. To make this independence evident we will avoid any additional communication channels as for example cables for coincidence measurements or clock synchronization. Instead, all detected events will be 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 various models or check the counting statistics or randomness of the switching using the raw detection data. This system requires a high time-resolution of at least about 1 ns over a measurement period of 100 s to make a precise calculation of the coincidence windows possible. It does, however, not make sense to have much better time resolution because the detectors have an intrinsic jitter of the same order of magnitude. Reliable measurement of these times over a period of 10 s to 100 s can only be achieved with a precision time-base such as an oven controlled crystal oscillator (OXCO) or even an atomic clock. Synchronization of the two clocks at the two detector stations will be achieved by direct reference to GPS satellites which are in turn referenced to UTC. GPS time transfer with the so called 'common view' method [15] – both stations synchronize their clocks to the onboard frequency standards of three or four satellites – between identical receivers can yield absolute time differences of less than 5 ns with a maximum drift of 120 ns/h, which is stable enough for measurement periods of 100 s.

III. OUTLOOK

We plan to realize the whole setup step by step. Currently we are developing the random number source and the switch. In parallel we are trying to couple down-conversion photons from the BBO-source into a single-mode fiber and perform a simple test measurement of Bell's inequalities at the fiber outputs to determine the combined coupling- and detection efficiency. Bringing these activities together will lead to the first test of Bell's inequalities with randomly switched analyzers. After a subsequent laboratory test of the complete system with the long fibers on coils, the detection systems will be moved away from the source to perform the final experiment with spacelike separation, where we will also try out all possible sorts of time order between the detections on either side. In a parallel activity collaborators[2] are embarking on beating the so-called detection-efficiency loophole using high quantum-efficiency detectors and non-maximally entangled states which have been shown to reduce the efficiency requirement significantly [16]. We hope that one day our efforts will be combined leading to a once and forever definitive test of Bell's inequalities.

Nonlocality is still a striking feature of quantum mechanics, contributing to the fundamental problem of measurement. These questions are heavily discussed in the physics community, and therefore a clearcut experiment, avoiding the standard loopholes is necessary to settle discussions on the viability of certain kinds of local deterministic and thus more complete descriptions of nature.

IV. ACKNOWLEDGEMENTS

A. Z. would like to thank Abner Shimony for numerous discussions on the foundations of quantum mechanics and on issues related to the experimental program proposed here. G. W. acknowledges a doctoral fellowship of the Austrian Academy of Sciences. This work is supported by the Austrian Science Foundation (FWF), Project No. S6502 and by the US National Science Foundation, Grant No. PHY92-13964.

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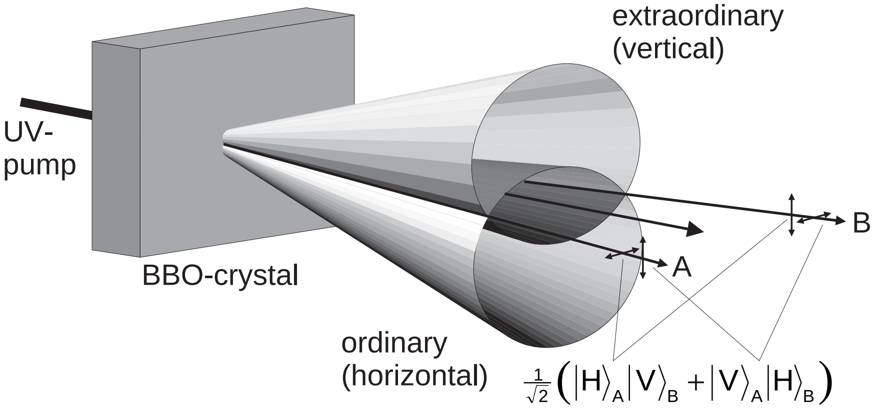

FIG. 1. Type-II downconversion in BBO. Ordinarily and extraordinarily polarized photons are emitted into two different cones. If we select the beams A and B we obtain a polarization entangled two-photon state. In our experiment these two beams will be coupled into optical fibers in order to propagate the photons over long distances.

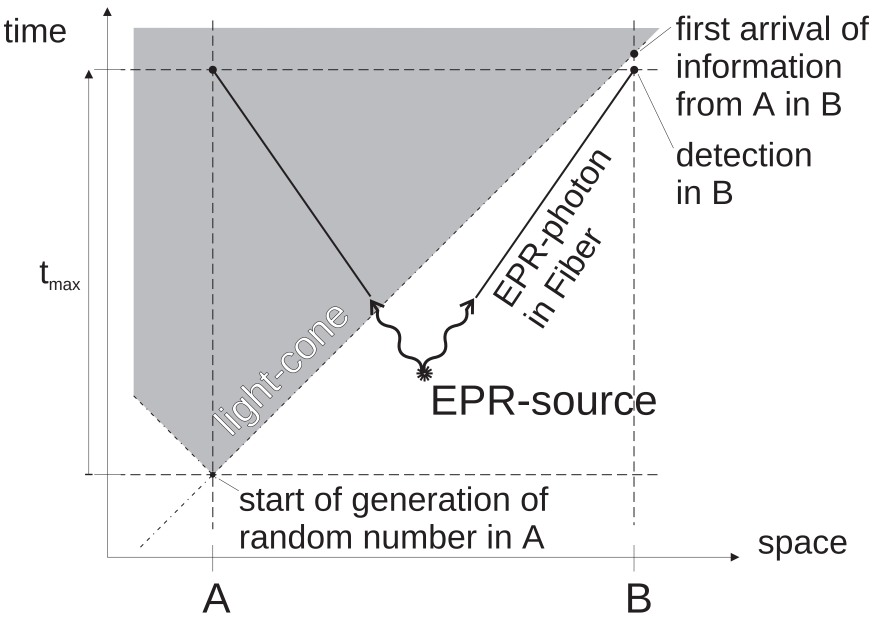

FIG. 2. Spacetime-diagram of a Bell-experiment. The graph visualizes the relation between the maximum switching time and the (straight) distance between the analyzers. To prevent any subluminal communication between the two observers, the generation of a random number and subsequent switching of the analyzers must be accomplished in a time shorter than $t_{\rm max} = \overline{\rm AB}/c_0$, where c_0 is the vacuum speed of light.

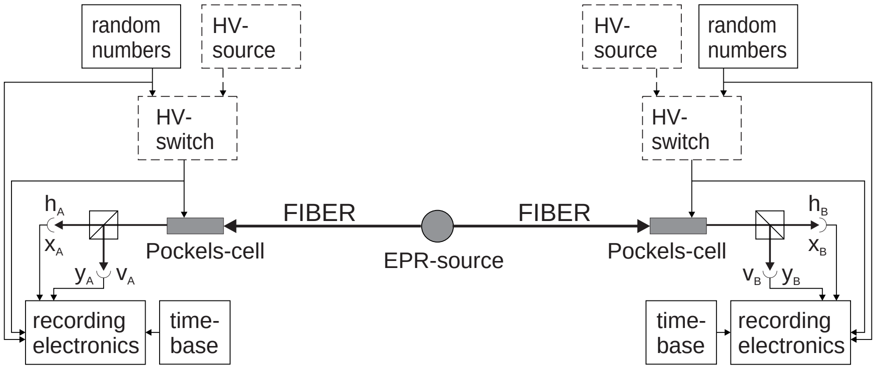

FIG. 3. The proposed setup for a Bell-experiment with independent observers. The main components source, transmission, switches, detectors, and electronics are discussed in the text. The high voltage sources and switches would be needed for macroscopic Pockels-cells but not for fiber integrated ones.