Time-resolved measurement of Bell inequalities and the coincidence loophole

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We report an Einstein-Podolsky-Rosen-Bohm experiment with a pulsed source of entangled pairs of photons, recording the time of arrival of the pulses and of the detection of each single photon. This allows varying the parameters of the analysis (as the size of the time coincidence window) at will after the experiment has ended. Among other results, we present the measurement of the time variation of the Clauser-Horne-Shimony-Holt parameter during the pulse. The obtained results close (or at least impose new and tight restrictions to) the last loophole that remains open in the tests of quantum mechanics vs local realism (the so-called coincidence loophole).

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I. INTRODUCTION

Local realism (LR) is, roughly speaking, the intuitive belief that the results of an experiment are generally unaffected by events occurring at remote places and that the physical world is independent of observation. Some predictions of quantum mechanics (QM) are incompatible with this belief [1]. A large number of experiments have been performed with the aim to determine whether QM or LR is valid in nature. Most of them are of the Einstein-Podolsky-Rosen-Bohm (EPRB) type, where for a state of two photons entangled in polarization, the rate of coincident detections is measured after analyzers are set at certain angles. The correlation between the results of the measurements according to QM is larger than allowed by any theory holding to LR. The correlation is usually quantified with an experimentally accessible parameter such as the Clauser-Horne-Shimony-Holt (S_{CHSH}) parameter [1]. The inequality $S_{\mathrm{CHSH}} \leqslant 2$ holds for LR while, according to QM, $S_{\mathrm{CHSH}} = 2\sqrt{2}$. The violation of this often-called Bell-CHSH inequality has been observed and, consequently, QM has been confirmed against LR. However, practical limitations in the experiments leave space to alternative LR theories to survive by exploiting the so-called logical loopholes. It is therefore essential to the foundations of QM to close all the loopholes.

The loopholes can be classified as follows: (i) the *detection* or *efficiency* loophole, which exploits the imperfect efficiency of detection; (ii) the *contextual, locality,* or *timing* loophole, which exploits the possibility that the source of photon pairs is somehow affected by the setting of the analyzers; and (iii) the *coincidence* [2], *trapping* [3], or *memory* loophole [4], which exploits the ambiguity in the definition of a coincident detection due to the arbitrary (but usually fixed) value T_w of the time coincidence window. The LR theories exploiting this loophole (coincidence-loophole theories, CLHT) assume that the analyzer's setting influences the time at which the photon detection occurs. Then, a local detection may be coincident with a remote detection, or not, depending on the angle setting and the size of T_w. The result is that the number of coincidences depends on both settings and that it can be adjusted to fit the QM values, even though the process is completely local. Not a single photon is lost; all that happens is that its detection is shifted in time, in or out the coincidence window. Most CLHT are able to fit the QM values even in ideal setups with 100% efficient optics and detectors, and with random variation of the analyzers' settings.

An experiment using an ion trap closed the detection loophole by reaching nearly 100% efficiency [5], and EPRB experiments using random varying analyzers placed in remote stations closed the contextual loophole [6,7]. The simplest of the CLHT [8] was disproved by recording the time of detection ("time stamping") of the photons produced with a continuous-wave (CW) source [9]. A general test of CLHT requires, in addition, the definition of the time interval where it is expected to detect photons if there is no shifting effect. This time interval is named here the "natural time" for photon detection. As it is detailed later, the statistical properties of the photons detected outside the natural time provide a test of the coincidence loophole. Two setups have been proposed for this purpose [3]: one uses an event-ready source [10], and the other one uses a pulsed spontaneous parametric down-conversion (SPDC) source. Here we choose the second alternative, closely following [3]: "*In the case of pulsed optical experiments…if the pulse is short in comparison with the pulse spacing…(it) will provide a well-defined, pre-determined coincidence window and this will remove the coincidence loophole*" and [4]: "*…one selects just those measurements within an appropriate time interval after a saved "alert" message… It is practically extremely important that this selection may be done after the experiment has run its course.*" Finally, some LR theories suppose that the setup (or some hypothetical ether) "learns" how to reproduce the QM values as photons cross it [11–13]. To test this supposition, it is necessary to measure the time evolution of the correlation.

In this paper, we report the main results of an experiment using a nanosecond-pulsed SPDC source. The "alert" or "trigger" signal is provided by a fast photodiode detecting the pump pulse. The time values of the triggers of all the pump pulses, as well as the time of detection of each single photon, are recorded and saved for further analysis (see Fig. 1). To our knowledge, the realization of an experiment with these features has not been done before.

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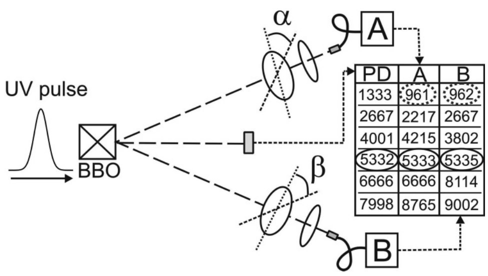

FIG. 1. Sketch of the experimental setup. The time of detection of each photon (A or B) and the arrival of each pulse (PD) are measured and saved with a resolution of 12.5 ns. The natural time for photon detection T_{nat} is an interval of 75 ns (the full pulse duration) synchronous with the PD "trigger" signal. All the delays and time coincidence windows can be varied at will after the experiment has ended. In the first line there is a coincidence ($T_W^{AB} \geqslant 25$ ns) between A and B, but it is outside T_{nat}. A coincidence inside T_{nat} is in the fourth line.

II. EXPERIMENTAL SETUP

Photon pairs are generated by pumping a nonlinear crystal with 355-nm radiation (third harmonic) from an actively Q-switched diode-pumped Nd:YVO_4 laser built in this lab [14]. At a 60-kHz rate, the pulses last 35 ns FWHM, fulfilling the requirement in [3] that the pulse duration must be much smaller than the pulse spacing, and the coherence length is measured to be 18 mm. Two crystals' sets are used: one is a single BBO-II crystal 3 mm long and another one two crossed BBO-I crystals 1 mm long each. The latter demonstrates to be easier to align and produces higher values of S_{CHSH}. The detectors are fiber-coupled silicon avalanche photodiodes (single-photon counting modules, SPCMs) placed after the usual set of optics, filters ($\Delta\lambda = 10$ nm at 710 nm, $T = 55\%$), and analyzers. The time-stamping device is an NI 6602 PCI counter timer with a resolution of 12.5 ns [9].

The saved data can then be thought of as a three-column table of time values (PD, A, and B). Each table, or file, covers ≈54 sec of real time. A typical experimental run accumulates up to seven files for (at least) each of the 16 settings of the angles $\{\alpha,\beta\}$ necessary to measure S_{CHSH}, i.e., more than 300 files.

As said before, an event-ready setup is a proposed alternative. Note that our "trigger" is not an "event-ready" signal. Even if our detectors and optics were perfect, not all triggers would herald a single detected pair, for the field state generated in our setup does not have a well-defined number of photons. An *entanglement swapping* scheme [10] does produce genuine event-ready signals [15]. It involves a mode-locked laser (femtosecond pulses at a rate of ≈90 MHz), four SPCM, and narrow filters. This scheme has been performed with many modifications and a variety of scopes [16]. Yet even in this case, not all event-ready signals herald one detected pair due to the nonideal optics and detectors. Experimental and theoretical complications, as well as the impossibility of measuring the evolution of S_{CHSH} inside a femtosecond pulse (see Fig. 4), make preferable, for the purposes here, using a nanosecond-pulsed SPDC. In our setup, we cannot know with certainty if a pair should be detected, but we do know with certainty the time interval when it should not be detected. With the help of time stamping, this suffices to reveal photons shifted out of their natural time and hence to uncover the mechanism of the coincidence loophole, if it exists.

In the usual QM description of pulsed SPDC [16,17], the pump is written as a superposition of monochromatic waves, so that the output state of the field is an integral over the pulse spectrum: $|\psi_{\mathrm{pulse}}\rangle = \int d^3k\,|\psi[F(k)]\rangle$, where $|\psi[F(k)]\rangle$ is the state for the CW case with wave vector k and field amplitude $F(k)$. In our setup, the pump bandwidth $\Delta\omega_p$ is much smaller than the bandwidth of the SPDC in the crystals [17] and also than the filters' bandwidth $\Delta\omega_f \approx 10^{13}\ \mathrm{s}^{-1}$, so that the probability of detecting one photon of the pair at time t and the other one at t' is

$$P(t,t') \sim \exp\left[-\Delta\omega_f^2(t-t')^2\right]\exp\left[1/2\Delta\omega_p^2(t+t')^2\right]. \quad (1)$$

This means that the time correlation of the detections is defined by the resolution of the filters, while the events can only happen at times dictated by the pump [16]. But the detections according to the CLHT do not follow Eq. (1). They are shifted in a time scale determined by T_w. That is why, to test the coincidence loophole, the value of T_w must be variable at will after the experiment has ended [4].

In EPRB setups in general, a large number of uncorrelated photons (noise) are detected in addition to the entangled ones. Statistically, they produce accidental (spurious) coincidences. Naturally, attaining a high ratio r between the valid and the accidental coincidences is necessary. In the CW pump, this is achieved by using a small T_w. In a pulsed pump this method does not work, because the signal and most of the noise are simultaneous. In this case, r is inversely proportional to p, the probability per pulse of detecting a photon [18]. Typically, $p \leqslant 0.05$ to get a good value of r. Thus, we must adjust the average pump power low (<10 mW), so that most pulses do not generate photons. Be aware that the Fig. 1 may be misleading: there are actually much more PD signals in a file ($\approx 3.2 \times 10^6$) than single detected photons ($<10^5$).

The efficiency of our detectors and optics is (of course) nonideal, and our analyzers' settings are fixed, so that we must assume fair sampling and noncontextuality to violate the Bell-CHSH inequality. Our experiment is, in this sense, complementary to the ones in [5–7]. Each experiment closes one of the three loopholes separately, and in each experiment LR is disproved by assuming that the other two loopholes are closed.

III. TESTING THE COINCIDENCE-LOOPHOLE

The CLHT can be admittedly artificial [2–4,8,19], or be based on a mechanical system [11,12], or follow an information processing approach, where each optical element acts as a logical unit following a simple adaptive program [13]. This list is far from complete. Analyzing the consequences of our experimental data for each of the CLHT would be extenuating. Hence this report does not exhaust the information that can be extracted from our time-stamped data. Nonlinear analysis [20] and studies on deviations from statistical homogeneity [21,22] have been performed on the data of [6], providing new insights many years after the experiment was completed. With this antecedent in mind, we discuss here only the main results for the general reader, and we upload the raw data to the web [23] so that the specialists can carry out their own tests.

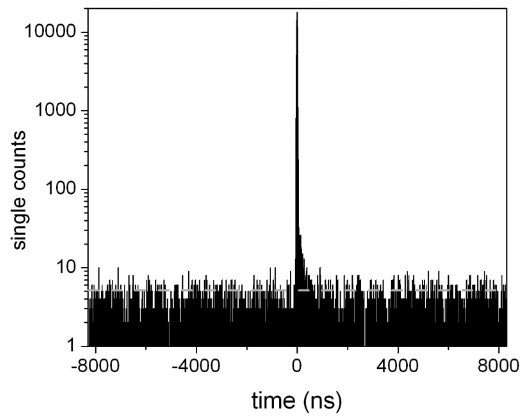

FIG. 2. Histogram of the distribution of the number of single counts; $t = 0$ corresponds to the pump-pulse peak. Note that almost all single counts are within the pump-pulse duration, which defines the "natural time" T_{nat}. The dashed gray line is the average rate outside T_{nat} (file: S7D21943).

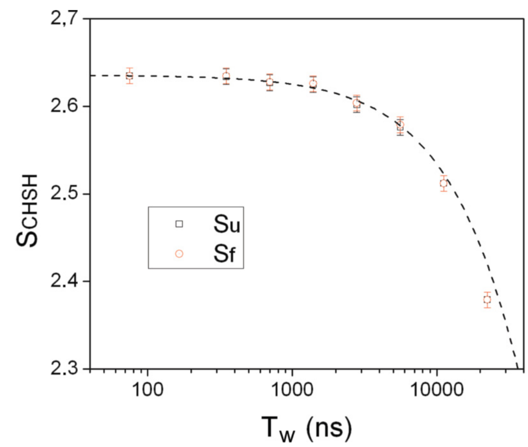

FIG. 3. (Color online) S_{CHSH} vs T_w. In the whole range, $S_u \leqslant S_f$. The measured values fit Eq. (2) (dashed curve), which is obtained by assuming that all the coincidences outside T_{nat} are fully uncorrelated (files' set: BBO-I crystals).

In spite of their diversity, CLHT should be revealed by one or more of the effects described next. The first consequence of shifting the detection of the photons in time is that a certain number of single counts should appear out of the natural time interval, which is defined by the full pump-pulse duration (75 ns $\equiv T_{\text{nat}}$) and the synchronicity with the trigger. For example, according to the simple CLHT in [3], that number should be $3/\sqrt{2}$-1 or $\approx$12.13% of the total. In order to test this effect, histograms of the number of single counts as a function of time are plotted, as the one illustrated in Fig. 2, covering the whole period from one pump pulse to the next. Most single counts are inside T_{nat}. The total number in Fig. 2 is 60,108 and there are only 5170 outside T_{nat}. This is smaller than required by the mentioned CLHT example ($\approx$7290), and besides, it corresponds to a rate $\approx$96 s^{-1}, nearly equal to the rate we measure with the laser blocked and to the dark count rate according to the SPCM's specs.

Other CLHT may survive to this test if the place of a fraction of the dark counts is taken by the shifted photons, but if this effect existed, then the set of coincidences outside T_{nat} should show some correlation (detectable as a variation of its number with $\{\alpha,\beta\}$), for some value of T_w, at least. If the coincidences were caused only by the detectors' dark counts instead, they would be fully uncorrelated. No variation with $\{\alpha,\beta\}$ is observed for any value of T_w, but instead of displaying lots of figures with horizontal lines, we find it more interesting to show the lack of correlation in that set by using the S_{CHSH} parameter as follows.

Let us consider the value of the S_{CHSH} parameter calculated with the coincidences between A and B only, and let us call this value S_u (or an *unfiltered* value). The value of S_{CHSH} calculated with the coincidences in A, B, and the condition of being inside T_{nat} is named S_f (or a *filtered* value). If the CLHT are true, then $S_u > S_f$, because the restriction to T_{nat} removes the degree of freedom that allows the CLHT to fit the QM predictions. If QM is true instead, then $S_u = S_f$ or, at most, $S_u < S_f$ because the restriction removes part of the noise. For example, the CLHT in [3] shifts the detections in or out of T_{nat} so that $S_u = 2\sqrt{2}$. If only the detections inside T_{nat} are taken into account, $S_f = (6\sqrt{2} + 32)/17 \approx 2.38 < S_u$.

As far as we know, our experiment is the only performed to date able to discriminate between S_f and S_u. To process the data, a coincidence between A and B occurs if $|A\text{-}B| \leqslant T_W^{AB}$, between A and PD if $|A\text{-}PD| \leqslant T_W^{APD}$, and between B and PD if $|B\text{-}PD| \leqslant T_W^{BPD}$. The values of T_W^{AB}, T_W^{APD}, and T_W^{BPD} can be chosen at will. In Fig. 3, S_{CHSH} is plotted for $T_W^{AB} = T_W^{APD} = T_W^{BPD} = T_w$ for T_w ranging from T_{nat} until the next pump pulse. The values of S_f and S_u are so close that they are within the error range and they are difficult to separate by the eye, but they all hold to $S_u \leqslant S_f$. For example, for $T_w = \text{T}_{\text{nat}} = 75$ ns, $S_f = \text{S}_u = 2.635 \pm 0.009$, and for $T_w = 5.6\ \mu$s, $S_f = 2.579 \pm 0.009 > S_u = 2.576 \pm 0.009$ (the largest difference between the two values). These and other results (obtained, e.g., with $T_W^{AB} \neq T_W^{APD}$) show $S_u \leqslant S_f$ in all cases, hence confirming the QM prediction.

Besides, the measured $S_{\text{CHSH}}(T_w)$ values fit the curve obtained assuming that the coincidences added to the statistics (as T_w increases) are fully uncorrelated. To see this, consider that the set of data inside T_{nat} has a value of $S_{\text{CHSH}} = S_0 \neq 0$, and assume that the set of data outside T_{nat} are fully uncorrelated ($S_{\text{CHSH}} = 0$). It is observed, from the data files, that the number of coincidences in the second set increases linearly as $q \times (T_w - T_{\text{nat}})$. Therefore

$$S_{\text{CHSH}}(T_w) = S_0[1 + q(T_w - T_{\text{nat}})/N_{\text{nat}}]^{-1}, \tag{2}$$

where N_{nat} is the number of coincidences inside T_{nat}. Equation (2) is plotted as a dashed curve in the Fig. 3, showing an excellent agreement with the measured values. This is evidence that the coincidences outside T_{nat} are fully uncorrelated. The only noticeable difference between the measured and the calculated values is for $T_w = 22.4\ \mu$s, where the window is so large that the next pulse is included. This is because the next pulse contributes an amount of uncorrelated coincidences that is not taken into account in Eq. (2).

It may still be argued (to defend the CLHT) that, for escaping from detection in the intervals between pulses, the shifted photons "jump" to the next pulse [3]. If this effect were real, then there would be some correlation linking the coincidences

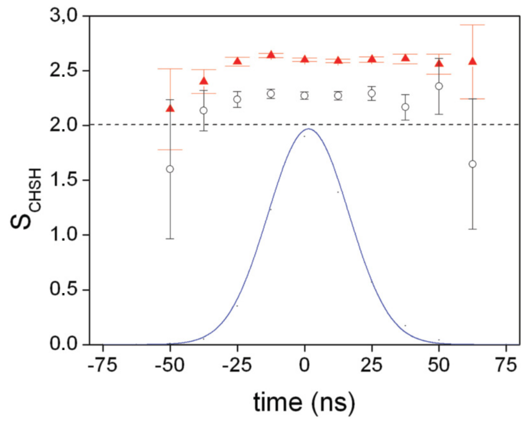

FIG. 4. (Color online) Variation of S_{CHSH} during the pump pulse. Open circles: BBO-II crystal; triangles: $2 \times$ BBO-I crystals. A Gaussian fit to the pump-pulse shape is plotted for comparison.

calculated between the n and the $n+1$ pulses. The measured rate of coincidences ($T_W^{APD} = T_W^{BPD} = 75$ ns $= T_W^{AB}$, with A and B in consecutive pulses) is 12.3 $\pm$ 1 s^{-1}, with no detectable variation with $\{\alpha,\beta\}$. The S_{CHSH} calculated using these coincidences is 0.07 $\pm$ 0.15, then practically equal to zero. Besides, the observed coincidence rate is equal to the estimated accidental rate, 12.5 $\pm$ 1 s^{-1}. These results mean that the coincidences between neighbor pulses are uncorrelated. All the calculations are performed using the same data files, so that, if the shifted photons had escaped detection before by jumping to the next pulse, they would have not been able to pass unnoticed here, and vice versa.

Finally, some theories [11–13] require the experiment to run for some time, or that a certain number of pairs cross the setup, in order for the system (or some hypothetical ether) to "learn" how to reproduce the QM results. If the learning process loses its memory when the source is turned off (say, in the time between pulses) [24], then each pulse is like a fresh start of the process. In consequence, the value of S_{CHSH} would be smaller when it is calculated with the coincidences obtained at the beginning of the pulses than when it is calculated with the ones at their peaks or falling slopes. According to QM instead, there is no predicted variation of S_{CHSH} with time.

The variation of S_{CHSH} inside the pump pulse is plotted in Fig. 4 ($T_W^{AB} = 12.5$ ns; the position of the time window where the coincidence occurs is also recorded). To our knowledge, the time variation of the violation of a Bell's inequality has not been done previously. The profile of the pump pulse is drawn for comparison. The error bars vary because the statistics is smaller at the pulse's edges. The value of S_{CHSH} has no significant variation; note that it is the same at the rising and the falling edges. The interpretations consistent with these results are: (a) there is no such learning process or (b) the learning process has a memory that lives longer than the pulse separation (16.7 μs) and even the time between single detections (0.4–2 ms); or (c) the process learns faster than 12.5 ns (the resolution time), which is much shorter than the minimum average separation between coincidences ($\approx$6 ms) or even between single detections ($\approx$0.9 ms). This implies that the learning time is *not* related to the rate of photon detection (no matter if coincidences or singles), in contradiction with most (if not all) the theories of this class.

IV. CONCLUSIONS

In summary, four different features of the experimental data have been tested: the number of singles in the set outside T_{nat}, the correlation of the coincidences in that set through the relationship between S_u and S_f for any value of T_w, the correlation between coincidences in successive pulses, and finally, the time evolution of S_{CHSH}. No evidence of the coincidence loophole or related effects has been found. The data are available in the web [23] to allow for additional tests. Taking into account that the detection and the locality or contextual loopholes have been closed in separate experiments, it is reasonable to say that our results complete the disproval of LR. However, the history of the QM vs LR controversy demonstrates that space for a counterexample is always found. Hence we prefer to be cautious and say that our results impose tighter restrictions to the theories based on the coincidence loophole. Finally, it must be noted that the three loopholes have been closed in separate experiments. An experiment closing the three loopholes *together* is of course a logical requirement to settle the controversy in a fully satisfactory way.

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[24] It has also been proposed [11] that a flash of light illuminates the setup between measurements in order to reset the hypothetical memory and ensure a fresh start. In our setup, an average of ≈50 pulses illuminates the setup between single recorded photons.