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Toward an experimental test for the finite-time wave function collapse

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ABSTRACT

In spite of recent conceptual and experimental advances, the ultimate nature of the wave function in quantum theory remains nebulous. Is it a mathematical device that describes our knowledge on a physical system or is it a physical field in any tenable sense? In this work we report on significant experimental steps toward a test on the reality of the wave function, which does not address the duality "epistemic *versus* ontic" in the usual way. Instead of considering inequalities derived from the partial indistinguishability of non-orthogonal states, we focus on the possibility of discriminating instantaneous reduction from finite-time wave function collapse. The former can only be associated with a Bayesian update, while the latter would be compatible with realistic interpretations. We employ non-maximally entangled photons which must be finely synchronized before detection. The required partial entanglement of the pairs is characterized by the violation they produce in the Clauser–Horne–Shimony–Holt inequality and the synchronization is obtained via time-scan measurements. This realization allows us to better understand the necessary instrumental conditions to the execution of a final, conclusive test.

1. Introduction

The recent discussions on the ontological character of the wave function illustrate the difficulties to place the metaphysical question "Does the quantum state exist?" in physically reasonable terms, i.e., amenable to experimental tests.

Presently, the discussion is dominated by a dichotomy: either the quantum state ψ is epistemic or it is ontic. If the former is true, ψ represents the knowledge on some aspects of reality, while the latter implies that ψ directly represents the microscopic state of affairs. As one would expect, it is possible to defend each of these two interpretations, depending on the adopted premises. There is, however, a recent tendency in favor of the ontic view, supported by theoretical [1,2] and experimental [3–5] results. However, it must be clear that each approach relies on different assumptions. For instance, in [1], it is assumed that any system has a "real physical state" objective and independent of the observer. Therefore, the epistemic-versus-ontic issue still stands as an open problem. Whether or not an uncontroversial answer to this question provides a satisfactory response to the question posed in the first paragraph is yet another nontrivial matter.

In this work we report on advances toward tests on the reality of the wave function with a distinct, conceptually independent approach. Rather than investigate the referred dichotomy, what is usually done via inequalities arising from the impossibility to fully distinguish non-orthogonal states, we intend to explore the intimate connection between the reality of the wave function and the nature of its collapse. We will address this problem in the spirit proposed in [6] as a proof of principle and, later, in more realistic terms in [7]. It goes as follows. If the wave function represents only information on some aspects of the underlying physical reality, then an instantaneous collapse is not problematic, since it would represent a Bayesian informational update. On the other hand, if ψ is a physical field in any reasonable sense, then, the collapse should not be instantaneous. Within the model proposed in [7] it is possible to experimentally distinguish this time scale from the time required for the macroscopic specification of the results of a measurement (when the pointer goes to a determined position). It turns out that this distinction is indirect, inferred from the statistical distributions of polarization (or spin) measurements in entangled pairs. Here we will be concerned with polarization-entangled photon pairs.

Let us briefly introduce some key features of the reduction models that we will address [7], and discuss why a non-instantaneous collapse would slightly modify the standard statistical predictions of quantum mechanics, under special conditions. In [7] the experimental fact that any actual measurement has a finite duration, Δt, is explicitly considered. In addition, it is assumed that a microscopic event, a

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"hit", precedes the macroscopic outcome resulting from a measurement. More specifically, it is assumed that the collapse is a process initiated by a "random hit" whose occurrence time is taken as a stochastic variable obeying a probability distribution, which, in the present case, is identified with the temporal intensity profile of the photon wave packet. A third assumption is that the quantum state takes a short time ($\delta t \ll \Delta t$), starting from the hit, to complete its reduction. We do not make any specific statements about this nonunitary time evolution. Now, if we consider, e.g., the state of polarization of two photons, which are sent to different detectors, and the two polarizations are measured during the same time window in the laboratory frame, then there is a small, but finite probability that the two hits (one for each detector) occur within a time interval shorter than δt. In these rare occasions, the second hit may change the outcome toward which the initial collapse would lead to. This would slightly change the frequencies of the measured polarizations, thus being experimentally accessible. For details on the model we refer to [7].

Apart from the fact that entanglement is required, there are not much similarities with Bell tests. In the first place, maximally entangled states are not useful for the present investigation, and it is necessary to produce unbalanced entangled states in a controlled way. In the polarization basis, we should have then states like $|\psi\rangle = \alpha|HV\rangle + \beta|VH\rangle$, with $\alpha \neq \beta$ and H (V) standing for horizontal (vertical) polarization. This has been accomplished with the use of twin photons, generated by parametric down conversion, passing through a Sagnac interferometer [8]. Secondly, the two parties have to measure the *same* observable, say σ_z, and the two measurements have to be finely synchronized in the laboratory reference frame. This synchronization requirement, absent in Bell tests, poses technical difficulties which are addressed here.

Finally, it is important to note that, what is proposed in [7] is not a detailed model for the wave-function collapse, but rather, a way to check the time scale of the reduction assuming that some stochastic mechanism starts it, without making detailed assumptions on the primary mechanisms and dynamics. Several other models are possible and have similarities with the assumptions in [7]. One well known model is the GRW spontaneous collapse theory [9] (for a more recent account including experimental investigations see [10]). In reference [11,12], the collapse is considered as a real physical process, however, without intrinsic stochasticity, with the probabilistic character of Born's rule coming from unknown initial conditions. We refer to experiments investigating the state vector collapse as described in [7] as tests for Finite-Time Wave Function Collapse (FTWFC).

In the following we report a significant step in the implementation of the experimental test for FTWFC, as we perform the required synchronization procedure between two detectors using the necessary asymmetric states under our current best experimental conditions. In this way, we are now able to better estimate the conditions that need to be met for the final test of the proposal, and to conceive a detailed experiment for its implementation. Of course, the experimental setup and procedure that arise from this analysis is considerably more complex and demanding than the picture originally proposed in [7]. For example, Ref. [7] provides an analysis for a variable delay between two detection events, but assumed perfect synchronization of other auxiliary detections. In practice, all detections have to be synchronized and three delay lines will be required for the final test of the FTWFC, spanning a much larger set of time delays. As no specific experimental setup is assumed in Ref. [7], another difference is the absence of a discussion concerning the accumulation of systematic and random errors when compared to the expected statistical errors coming from projective measurements. In order to observe the statistical differences in detection probabilities predicted for FTWFC, the statistical errors have to prevail over all other sources of errors in the system, leading to strong constraints to be met by the experimental apparatus. In the end, we conclude that the final experimental test of FTWFC will be challenging, requiring state of the art performance of all elements in the setup, but it is still feasible with currently available technology.

In the next section we give a detailed account of the experimental setup employed in the present analysis. In Section 3 we characterize the two-photon polarization states in our experiment through their Bell nonlocality, via standard Clauser–Horne–Shimony–Holt tests [13]. Section 4 presents our main experimental results of time-scan measurements. In Section 5 we discuss the results of Section 4 in light of the requirements to test the proposal of Ref. [7]. We also introduce in this section the new, more detailed proposal for the test of FTWFC. Our conclusions are presented in Section 6.

2. Experimental setup

The experimental apparatus used in the present investigation of the FTWFC is introduced schematically in Fig. 1. A mode-locked titanium-sapphire (Ti:S) laser with pulse duration $\tau_p \approx 100$ fs, repetition frequency $f_{rep} \approx 82$ MHz, and centered at $\lambda_c \approx 800$ nm is used to generate correlated photons via Parametric Down Conversion (PDC). The laser is frequency doubled by Type-I second-harmonic generation in a 500 μm barium borate (BBO) crystal. The beam at $\lambda_{SH} \approx 400$ nm is used as a pump for the entangled photons source. A dichroic mirror is used to separate λ_{SH} from the fundamental Ti:S laser beam at λ_p. A half-wave plate (HWP) and a quarter-wave plate (QWP) are used to control the polarization of the pump in order to manipulate the quantum state of the entangled photons.

A Sagnac interferometer with a periodically poled KTP crystal (PPKTP) is used as a source of entangled photons [14]. The PPKTP is grown for collinear, degenerate type II spontaneous parametric down conversion (SPDC) [15,16]. Such crystal has proven itself to be a highly efficient source for SPDC with no transverse walk-off between horizontal and vertical polarizations, due to the phenomenon of quasi-phase matching [17]. The pump beam is weakly focused to a beam waist of 92(2) μm at the crystal center, and has power of 22 mW before entering the Sagnac interferometer.

Inside the Sagnac, two optical elements are used for polarization control: a dual-wavelength (800 nm/400 nm) HWP (Casix) and a broadband polarizing beam splitter (PBS). The PBS is used to couple light in and out of the interferometer. The dual HWP has two functions. The first is to rotate the pump polarization in order to satisfy phase matching conditions in the crystal for both directions, clockwise and counterclockwise, see the Sagnac insert in Fig. 1. The second is to rotate the counterclockwise down-converted photon polarizations and in this manner ensure that the clockwise and counterclockwise idler photons exit the interferometer through the same output port (1 or 2), and the signal photons exit through the other one [8].

Once exiting the source, the entangled photons are sent through a polarization analysis module, composed of a HWP and a PBS. We detect both the reflected and transmitted beams from the PBS separately. Interference filters, centered at 800 nm and with FWHM of 10 nm (40 nm) are placed at the beams transmitted (reflected) by the two PBS, ensuring symmetry for the polarization analysis on output ports 1 and 2 of the Sagnac. For further spectral filtering, we use dichroic mirrors and long-pass color glasses.

Telescopes are placed in all detection channels to improve the coupling of the entangled photons to single-mode fibers. The fibers are connected to single-photon Si detectors (Perkin-Elmer SPCM). The photons from the Sagnac output ports 1 and 2, which are transmitted through the PBS analyzers, are coupled to 30 cm long fibers, while the reflections are coupled into 200 cm long fibers. A micrometric delay line is placed in the path of the Sagnac output port 1 transmission in order to perform the time-resolved measurements necessary to investigate the effects of FTWFC. As discussed in detail in Section 4, the size of the small fibers is an important ingredient to determine how much the delay line needs to be scanned. Note that it is not our goal here to synchronize the four detection outputs, as would be required to test the proposal of Ref. [7]. For that, it would be necessary to introduce delay lines and small fibers in the two reflection outputs of the PBS analyzers.