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Experimental test of Selleri's variable photodetection-probability model

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Selleri's model of photodetection based on variable detection probability is analyzed. The results of an experiment that discriminates between the predictions of Selleri's model and quantum mechanics are presented [*Bell's Theorem and the Foundations of Modern Physics*, edited by A. van der Merwe, F. Selleri, and G. Tarozzi (World Scientific, Singapore, 1992); in *Wave-Particle Duality*, edited by F. Selleri (Plenum, New York, 1992)].

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In recent years several experiments have been performed to test the validity of de Broglie's and Einstein's ideas on the foundations of quantum mechanics. Most of these were based on coincidence detection of photon pairs in different branches of a particular experimental setup, for which the predictions of quantum mechanics and the de Broglie theory or Einstein locality are in conflict. Correlated photons emitted in an atomic cascade were used in the first of these experiments, but in recent years the photons were produced in the parametric down-conversion process instead. With this source, some interesting experiments have been performed in order to test quantum optics, the Einstein-Podolsky-Rosen (EPR) paradox, semiclassical radiation theory, and de Broglie's empty wave theory.

In particular, the reality of the wave associated with each photon in de Broglie's [1] model has been tested experimentally [2] following a proposal of Croca, Garuccio, Lepore, and Moreira [3]. In the experiment (Fig. 1) a parametric down-converter pumped by uv laser light produces pairs of linearly polarized photons. The two photons are generated simultaneously, and following different paths, form two beams, the signal and idler beams. The beams pass through a modified Mach-Zehnder interferometer with three semitransmitting mirrors, and the optical path length is varied by moving the mirror Q. The experiment consists of counting the events in which the idler photon, after traversing BS_3 and BS_1, is detected by the photomultiplier D_1, and the signal photon is detected simultaneously by the photomultiplier D_2 after passing BS_1 and BS_2. The measured coincidence counting rate is proportional to the joint-detection probability for D_1 and D_2. If we assume the reality of de Broglie's wave, this joint detection probability should exhibit modulation as a function of the optical path difference between the two paths P-R-U-D_1 and P-Q-U-D_1, while quantum mechanics predicts a probability independent of these optical lengths. The difference is due to the fact that at U there is an overlap of the idler wave with the empty wave generated by the signal photon passing BS_1 and BS_2. The results of the experiment are in agreement with quantum mechanical predictions and contradict what is expected on the basis of the de Broglie pilot wave theory.

A different interpretation of these results has been proposed by Selleri [4,5], based on the idea of a variable detection probability for the photodetectors. From a realistic and causal point of view, it is possible to develop variable probability detection models that divide the set S of detected objects into a number of subsets S_i with probabilities P_i to be detected, so that the overall detection probability is the average over i, $P=\langle P_i\rangle$. These models agree with quantum mechanics for the single channel counting rates. However, since the average of a product is in general different from the product of the averages, it is in two-particle detections that one might expect a departure from de Broglie's assumption about the detection probability.

In particular, the model discussed by Selleri (a) reproduces single photon physics, (b) explains the observed violation of Bell-type experiments, (c) is consistent with the results of the performed two-photon experiments, and (d) is compatible, within experimental errors, with the Wang, Zou, and Mandel experiment [2].

It has been shown that a simple experiment can test

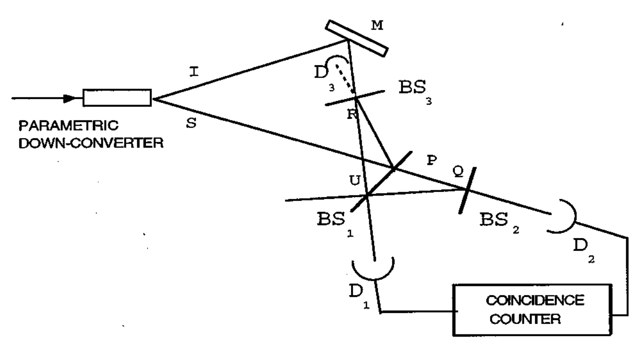

FIG. 1. The Wang-Zou-Mandel experimental setup. The alignment is critical because it is necessary to ensure the spatial superposition at BS_1 of the empty wave and of the full wave associated with the idler photon.

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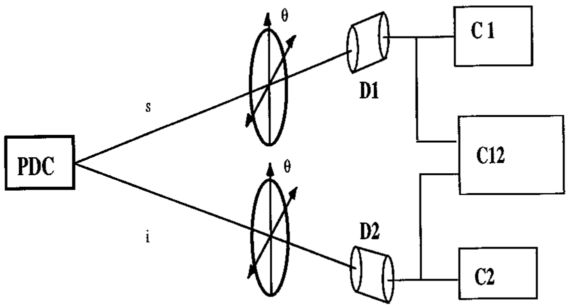

FIG. 2. The conceptual setup for testing the Selleri detection model.

Selleri's model against quantum mechanics [6]. Let us consider a photon pair produced in a parametric down-converter (Fig. 2), in which the two photons have the same linear polarization (viz., along the z axis) and travel in the xy plane. The signal and idler beams impinge on different linear polarizers oriented along the same direction, each making an angle θ with the z axis. The angle θ is allowed to vary, but it is always identical for the two polarizers. Two detectors D_1 and D_2 detect the photons passed through the polarizers; the outputs of the photodetectors are collected by two counters C_1 and C_2 and by a coincidence counter C_{12}. The quantity of interest is the ratio of the number of coincidence detections n_{12} to the product of the number of single photon detections $n_1 n_2$ as a function of the angle θ of both polarizers.

According to Selleri's model the probability for a single emitted photon to be detected is the product of the probability of transmission through the polarizer $T(\theta)$ and a variable detection probability D. The latter depends both on a variable μ, which, for simplicity, is assumed to have value $+1$ or -1 with equal probability, and on the amplitude at the detector of a normalized photonic wave ψ

$$D(\mu)=\eta[1+\mu(1-\eta)(1-2|\psi|^2)], \qquad (1)$$

where η is the (average) measured quantum efficiency of the photodetectors.

If the apparatus is lossless, the photonic wave may be normalized with respect to the ensemble of photons impinging on the polarizer; i.e., we may take $|\psi|^2=\cos^2\theta$ in (1). It follows from formula (1), after averaging over μ and assuming that the Malus law holds for $T(\theta)$, that the probability of detection for a photon that impinges on a polarizer set at angle θ is

$$p(1)=p(2)=\langle T(\theta)D(\mu)\rangle=\cos^2\theta\langle D(\mu)\rangle=\eta\cos^2\theta, \qquad (2)$$

while the joint probability of two-photon detection is

$$p(1,2)=\eta^2\cos^4\theta[1+(1-\eta)^2\cos^2 2\theta]. \qquad (3)$$

The ratio of the joint detection probability to the product of the single detection probabilities is therefore

$$r=p(1,2)/p(1)p(2)=[1+(1-\eta)^2\cos^2 2\theta], \qquad (4)$$

and the measured ratio of the coincidence counting rate to the product of the single channel rates is $R=kr$, where k is a factor depending on the geometrical collecting efficiencies of the apparatus and on the emission rate of the source, which will be discussed in the analysis of the experimental data.

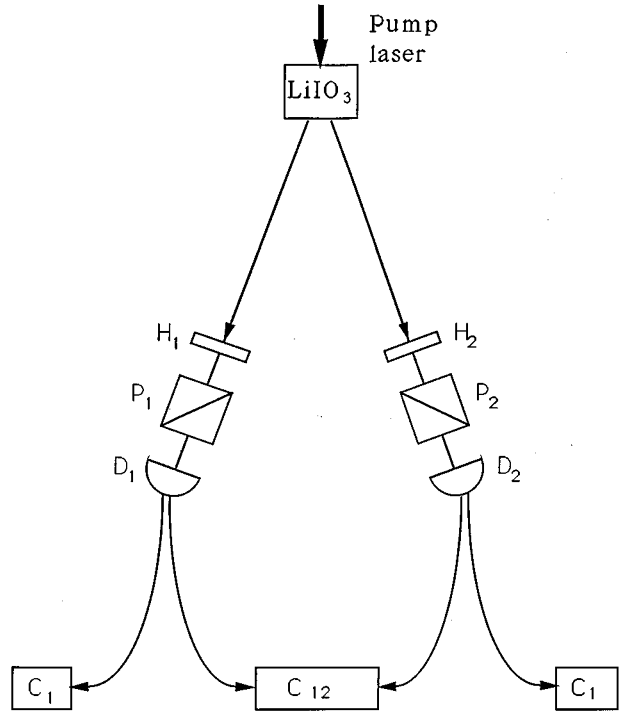

FIG. 3. Outline of the present experiment. The half wave plates H_1 and H_2 are rotated through the same angle $\theta/2$ during the experiment in order to rotate the polarization orientation of both beams through the angle θ. The axes of polarizers P_1 and P_2 do not rotate during the experiment and remain parallel to the initial polarization plane of the photon pair.

The formula (4) exhibits an oscillation of amplitude proportional to $\cos^2 2\theta$, while quantum mechanics predicts r to be constant and equal to 1. Moreover this formula predicts an enhanced joint detection probability, which, for the case $\theta=0$ and $\eta=0.2$, for example, is 65% larger than the quantum mechanical prediction. The two theories predict the same value of r for $\theta=45°$.

An experiment to determine the ratio of the joint detection probability to the product of the single detection probabilities in parametric down-conversion has been performed in the past without polarizers [7]. However, because the correlation between the two detected beams was not known, the results are not immediately applicable to Eq. (4).

We have therefore carried out a new experiment to test Selleri's model with the help of a $LiIO_3$ crystal pumped by an argon-ion laser at 351.1-nm wavelength. The crystal acts as a down-converter (Fig. 3) and emits two optical photons (signal and idler) at 702.2 nm with identical polarizations, each traveling at an angle of 5° with respect to the pumping beam. Along each path a half wave plate was inserted before the polarizer, rather than changing the polarizer's orientation; this was done to prevent misalignment of the beams during the experiment as the polarizers are optically thick, while the wave plates are thin. Both the plates were rotated through the same angle $\theta/2$ during the experiment. Each de-

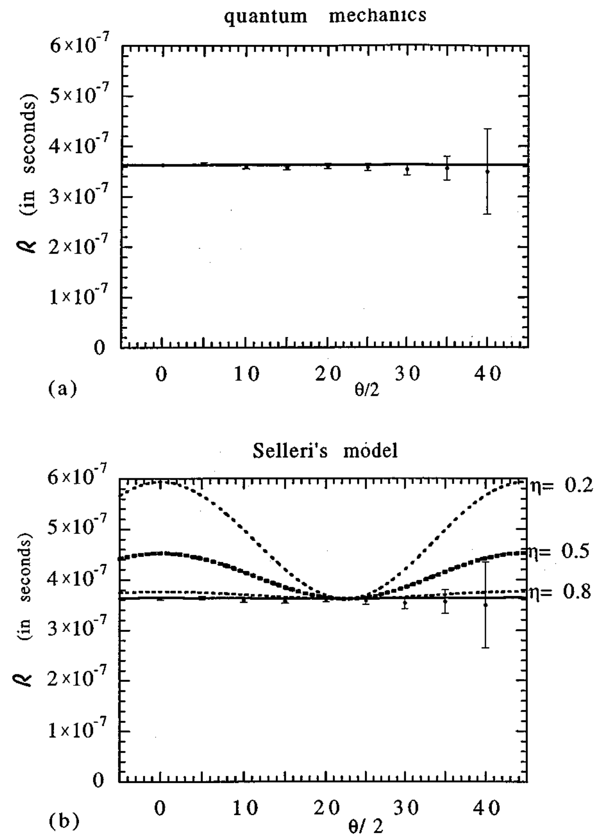

FIG. 4. Measured value of R as function of the rotation angle $\theta/2$ of the half wave plate: (a) The continuous line represents the quantum mechanical expectation for the experimental data. (b) The dotted lines are the predictions of Selleri's model for a quantum efficiency $\eta=0.2$, 0.5, and 0.8. The continuous line in (b) is the best fit of Eq. (4) to the experimental data.

tector consisted of a Thompson polarizer followed by an avalanche photodiode detector with intrinsic detection efficiency of about 50%. The single channel counts and the coincidence counts were registered by a computer.

Figures 4(a) and 4(b) show the experimental results for R as a function of $\theta/2$. The straight line of Fig. 4(a) represents the quantum mechanical prediction. In Fig. 4(b) we display Selleri's predictions (dotted lines) for R based on Eq. (4) and for quantum efficiencies of 20%, 50%, and 80%. The continuous line represents the best fit of the experimental data with Selleri's equation (4); the fit in this case is based on a 0.93 quantum efficiency of the photodetectors.

Since a normalized photonic wave is used in Selleri's theory, it may appear that our results are in conflict with this model because of our choice of normalization. To explore the role of the normalization in Selleri's theory, we now consider the approach of normalizing with respect to the emitted photon pairs.

Let N be the number of emitted photon pairs per second; since the optical devices inserted between the source and the detectors (mirrors, filters, pin holes, lenses, etc.) are lossy, not all the emitted photons impinge on the detectors. Let us call α_1 the fraction of signal photons impinging on detector D_1 when the half wave plate is set at angle zero (this is conceptually equivalent to removing the polarizer), α_2 the fraction of idler photons impinging onto detector D_2 when

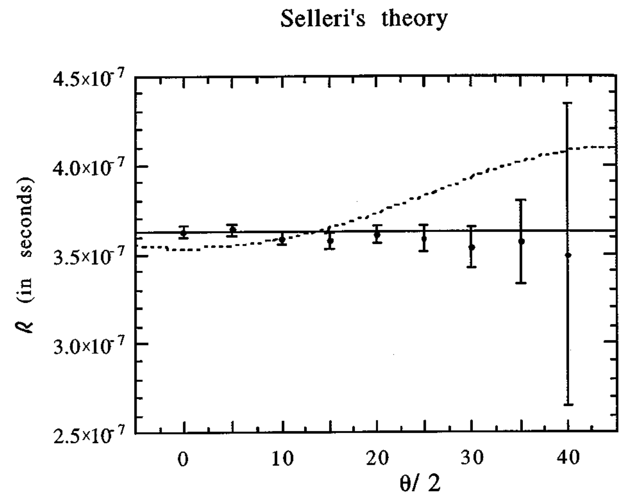

FIG. 5. Comparison of the measured values of R with Eq. (7). The dotted line corresponds to a detection quantum efficiency $\eta=0.5$. The continuous line is based on a quantum efficiency of 0.93 and gives the best fit with the experimental data.

the half wave plate is set at angle zero, and let γ be the fraction of photon pairs that impinge on the two detectors at the same time.

The single channel detection rates are then given by

$$R_1=N\cos^2\theta\alpha_1\eta_1=N\cos^2\theta\eta_{\mathrm{tot1}}, \tag{5}$$

$$R_2=N\cos^2\theta\alpha_2\eta_2=N\cos^2\theta\eta_{\mathrm{tot2}},$$

where $\eta_{\mathrm{tot1}}=\alpha_1\eta_1$ and $\eta_{\mathrm{tot2}}=\alpha_2\eta_2$ represent the overall collection efficiencies for the two channels. We measured these quantities independently and obtained for each channel a value near $\eta_{\mathrm{tot}}=0.11$. As the two detection efficiencies are nearly equal, we then conclude that $\alpha_1=\alpha_2=\alpha\eta_{\mathrm{tot1}}/\eta$, and that the coincidence rate is given by [setting $|\psi|^2=\alpha\cos^2\theta$ in (1)]

$$R_{12}=\gamma N\eta^2\cos^4\theta\{1+(1-\eta)^2[1-2(0.11/\eta)\cos^2\theta]^2\}. \tag{6}$$

The ratio R then becomes

$$R=(\gamma/N)[\eta/(0.11)^2]\{1+(1-\eta)^2[1-(0.22/\eta)\cos^2\theta]^2\}. \tag{7}$$

Figure 5 shows the experimental data superimposed on the curve corresponding to the formula (7). Even in this case, Selleri's model fits the experimental data well (continuous line) only for a high photodetector quantum efficiency. The dotted line represents the theoretical prediction for the actual value $\eta=50\%$ of the quantum efficiency. In this case the experimental data correspond to the value of $\chi^2\approx55$ and the disagreement between Selleri's theory and the experimental data is highly significant [8]. However, this last result also shows that the predictions of the Selleri model depend strongly on the choice of normalization of the ψ function.

This is an unsatisfactory feature of the theory that does not permit a conclusive experimental test.

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