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Biphoton double-slit experiment

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In this paper we present a double-slit experiment where two indistinguishable photons produced by type-I parametric down-conversion are each sent to a well-defined slit. Data about the diffraction and interference patterns for coincidences are presented and discussed. An analysis of these data allows a test of standard quantum mechanics against the de Broglie–Bohm theory.

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INTRODUCTION

Double-slit experiments are textbook proof of the complementarity principle in quantum mechanics and have represented a very important test bench of this theory [1].

Particularly interesting examples of double-slit experiments have been realized by using biphoton fields produced in parametric down-conversion (PDC), a phenomenon where an incident high-frequency photon is converted, inside a nonlinear crystal, into a pair of highly correlated photons (usually dubbed *idler* and *signal*) fulfilling the condition, known as phase-matching condition, that the produced pair is such that the frequencies of the produced photons sum up to the frequency of the pump photon (energy conservation), and the wave vector of the pump photon is the vectorial sum of the wave vectors of the produced photons (impulse conservation). Among these experiments, a first class was devoted to the study of the effect on the correlations of a double slit inserted *in one of the paths*, i.e., on the idler or the signal-photon direction [2]. A second class was addressed to study the effect of a double-slit inserted on the paths of both idler and signal [3] showing the highly nonclassical aspects of PDC emission.

In our experiment we have realized a rather different configuration where two degenerate identical photons produced in PDC reach a well-defined slit of a double slit at the same time. As idler and signal-photons have no precise phase relation [4] and each photon crosses a well-defined slit, no interference appears at single-photon detection level. When the coincidence pattern is considered, path indistinguishability is established since the photodectector 1 (2) can be reached either by the photon which crossed slit *A* or by the one that went through slit *B* and vice versa. Thus, even if no second-order interference is expected, a fourth-order interference modulates the observed diffraction coincidence pattern.

The main result of our experiment is that our scheme realizes the configuration recently suggested by two theoretical groups [8–10] to test the de Broglie–Bohm (dBB) theory against standard quantum mechanics (SQM). The dBB theory [11] is a deterministic theory where the hidden variable (determining the evolution of a specific system) is the position of the particle, which follows a perfectly defined trajectory in its motion. The evolution of the system is given by classical equations of motion, but an additional potential must be included. This ‘‘quantum’’ potential is related to the wave function of the system and thus is nonlocal. The inclusion of this term, together with an initial distribution of particle positions given by the quantum probability density, successfully allows the reproduction of *almost* all the predictions of quantum mechanics. Nevertheless, a possible discrepancy between SQM and dBB in specific cases has been recently suggested in Refs. [8–10]. Although this conclusion is still somehow subject to discussion [12], we think that our results, in agreement with SQM predictions but at variance with dBB ones (see Ref. [5] for further discussion), represent a relevant contribution to the debate about the foundations of quantum mechanics urging a final clarification for its validity.

DESCRIPTION OF THE EXPERIMENT

In our setup (see Fig. 1) a 351-nm pump laser of 0.5 W power is directed into a lithium-iodate crystal, where correlated pairs of photons are generated by type-I parametric down-conversion (i.e., the two photons have the same polarization). The pairs of photons are emitted at the same time within femtoseconds, while the correlation time is some orders of magnitude larger, and on a well-defined direction for a specific frequency. By means of an optical condenser and within two correlated directions, both corresponding to 702-nm emission (the degenerate emission for a 351-nm pump laser), the produced photons are sent on a double slit (obtained by a niobium deposition on a thin glass by a photolithographic process) placed just before the focus of the lens system. The two slits are separated by 100 μm and have a width of 10 μm. They lie in a plane orthogonal to the incident laser beam and are orthogonal to the table plane (see Fig. 2 where the x axis is parallel to the pump beam and the x-y plane is parallel to the optical bench). The orthogonality to the UV laser has been checked by looking at the diffraction and interference patterns of the laser by the double slit.

Two single-photon detectors are placed at 1.21 m and at

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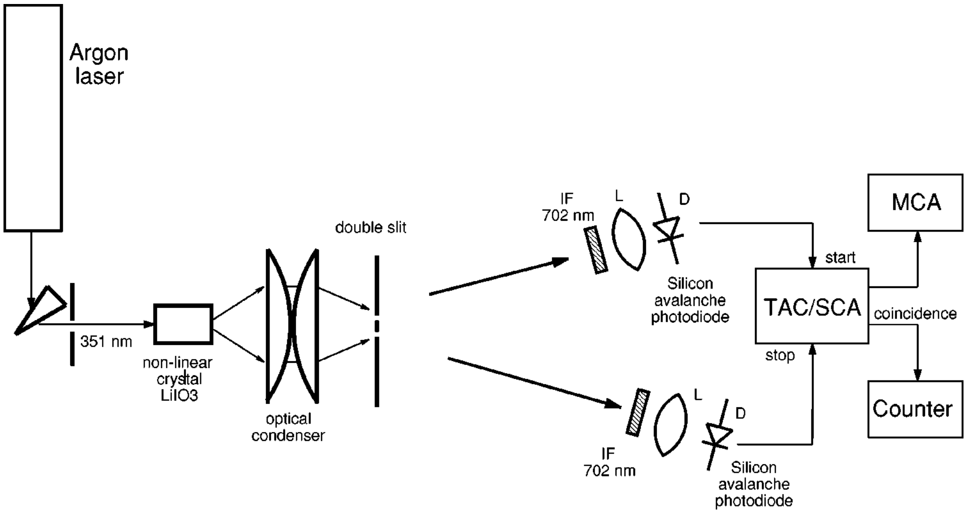

FIG. 1. The experimental apparatus. A pump laser at 351 nm generates parametric down-conversion of type I in a lithium-iodate crystal. Conjugated photons at 702 nm are sent to a double slit by a system of two plane-convex lenses in such a way that each photon of the pair crosses a well-defined slit. The first photodetector is placed at 1.21 m and the second one at 1.5 m from the slit. Each single-photon detector (D) follows an interferential filter (IF) at 702 nm and a lens (L) of 6 mm diameter and 25.4 mm focal length. Signals from the detectors are sent to a time-to-amplitude converter and then to the acquisition system (multichannel analyzer and counters).

1.5 m from the slits after an interferential filter at 702 nm, whose full width at half height is 4 nm, and a lens of 6 mm diameter and 25.4 mm focal length. As a preliminary step, we have also evaluated the efficiency of the detection apparatus (including losses into the crystal, filters, and lenses) by using the method described in Ref. [13]; the result is about 30%.

The output signals from the detectors are routed to a two-channel counter, in order to have the number of events on a single channel, and to a time-to-amplitude converter (TAC) circuit, followed by a single-channel analyzer, for selecting and counting the coincidence events.

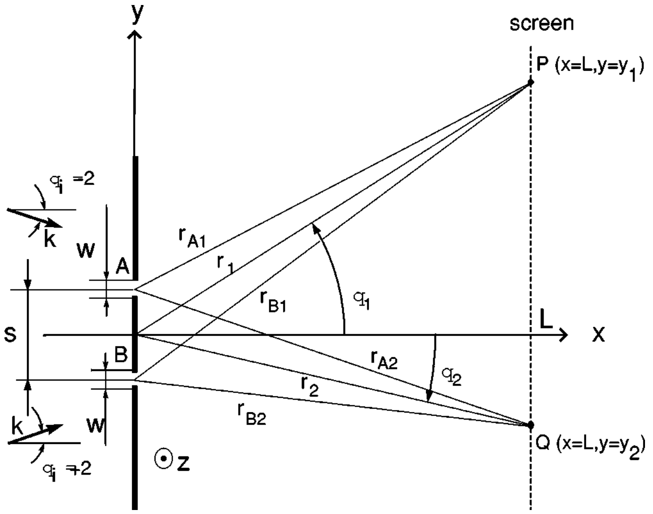

FIG. 2. Reference system. Two photons with wave vector k cross the slits A and B of width $w=10\ \mu$m separated by $s=100\ \mu$m and are detected by the photodetectors P and Q. The x axis is parallel to the pump beam and the x-y plane is parallel to the optical bench.

In order to check that the two degenerate photons crossed two different slits, we have alternatively closed one of them by means of two sharp blades positioned on a micromovimentation, leaving the other open; correspondingly, the coincidence peak disappeared and the coincidence signal dropped to background level. Furthermore, the signal on the related detector dropped as well, confirming the correct position of the double slit.

CALCULATION OF THE COINCIDENCE PATTERN PREDICTED BY QUANTUM MECHANICS

As discussed in Ref. [6], a satisfactory description of the PDC light is given by the wave function

$$|\Psi\rangle = |\mathrm{vac}\rangle + \int d\omega_i d\omega_s \Phi(\omega_i,\omega_s)|\omega_i\rangle\omega_s\rangle. \tag{1}$$

In the Fraunhofer region, after selection with narrow-band interferential filters (centered at the idler and signal frequencies ω_i and ω_s respectively), the diffracted field is described by

$$\Phi(\omega_i,\omega_s) = g(\theta_1,\theta_i^A)g(\theta_2,\theta_i^B)e^{-i(k_A r_{A1}+k_B r_{B2})} + g(\theta_2,\theta_i^A)g(\theta_1,\theta_i^B)e^{-i(k_A r_{A2}+k_B r_{B1})}, \tag{2}$$

where k_A and k_B are the wave vectors of the photon A (idler) and B (signal), respectively, r_{ai} is the vector from the slit a (A or B) to the detector i (1 or 2) (see Fig. 2). $\theta_{1,2}$ is the diffraction angle of the photon observed by detector 1 or 2, θ_i^a the incidence angle of the photon on the slit a (A or B), and

$$g(\theta,\theta_i^a) = \frac{\sin(kw/2[\sin(\theta)-\sin(\theta_i^a)])}{kw/2[\sin(\theta)-\sin(\theta_i^a)]} \tag{3}$$

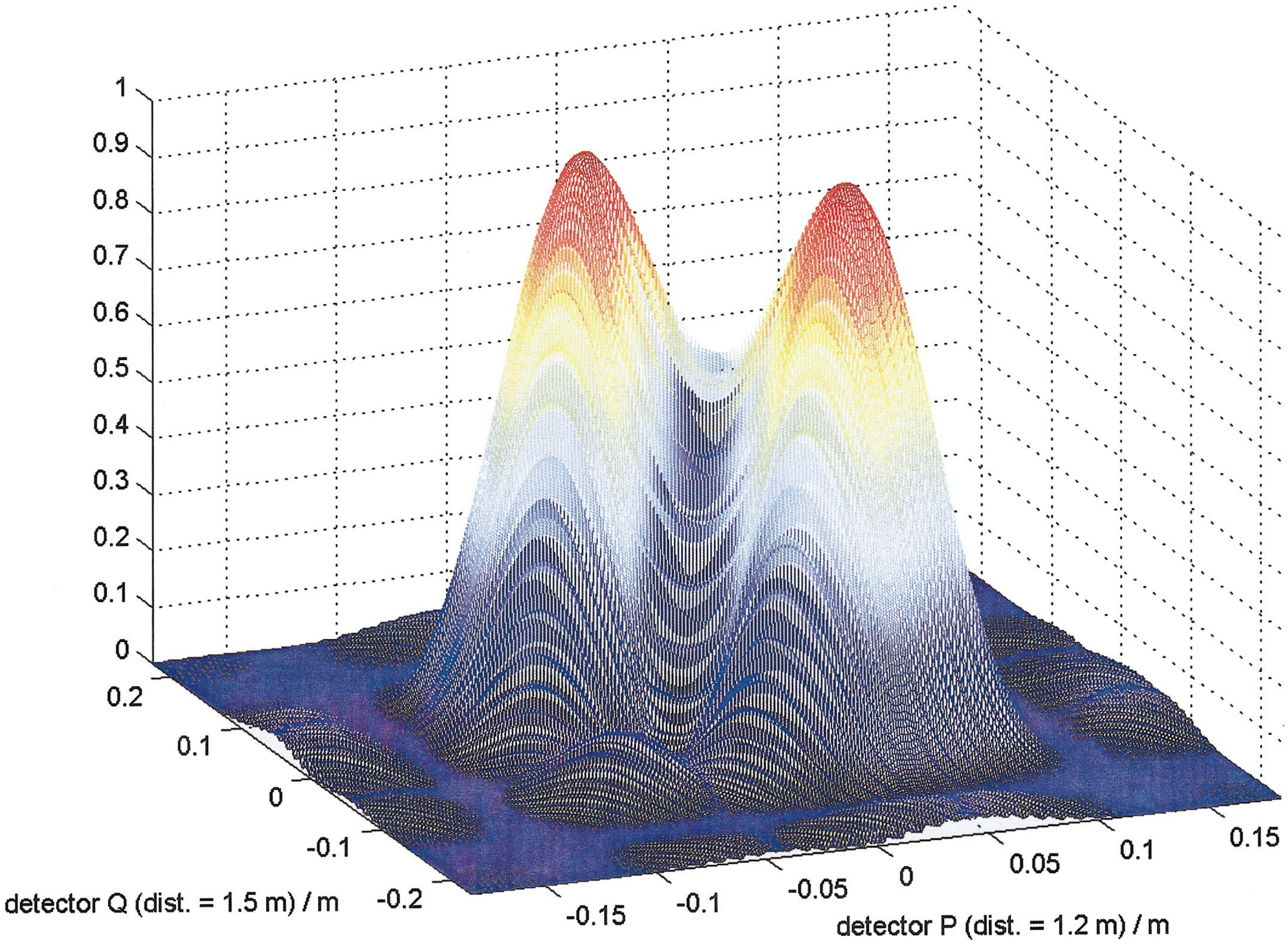

FIG. 3. (Color) Tridimensional plot of coincidences pattern (in arbitrary units) as a function of the positions of the two photodetectors.

takes into account diffraction (k is the wave vector, s the slits separation, and w the slit's width). The coincidence pattern that follows from Eq. (2) is

$$\begin{aligned} C(\theta_1,\theta_2) &= |\Phi(\omega_i,\omega_s)|^2 \\ &= g(\theta_1,\theta_i^A)^2 g(\theta_2,\theta_i^B)^2 + g(\theta_2,\theta_i^A)^2 g(\theta_1,\theta_i^B)^2 \\ &\quad + 2g(\theta_1,\theta_i^A) g(\theta_2,\theta_i^B) g(\theta_2,\theta_i^A) g(\theta_1,\theta_i^B) \\ &\quad \times \cos[ks(\sin\theta_1 - \sin\theta_2)]. \end{aligned} \tag{4}$$

The expected coincidence pattern in terms of the position of the two photodetectors (for photons with a 2° incidence angle) is shown in Fig. 3.

In Fig. 4 we show the section obtained from the previous figure when the second detector is positioned at -1 cm (here and in the following the positions are relative to the symmetry axis of the double slit, with a minus sign for looking at the crystal from the left). The diffraction peak clearly appears modulated by the interference. The same graph as Fig. 4 but with the second detector positioned at -5.5 cm is reported in Fig. 6: now a smaller interference is predicted with respect to the previous one, but a larger coincidence

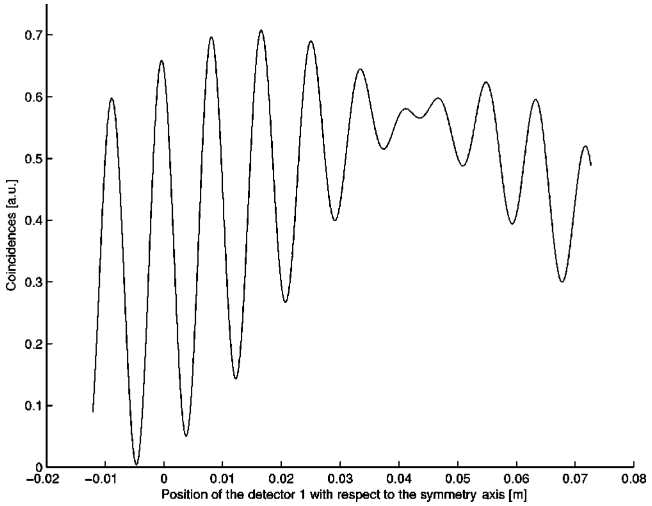

FIG. 4. Plot of coincidences pattern (in arbitrary units) as a function of the positions of the first photodetector when the second one is kept fixed at -1 cm from the symmetry axis.

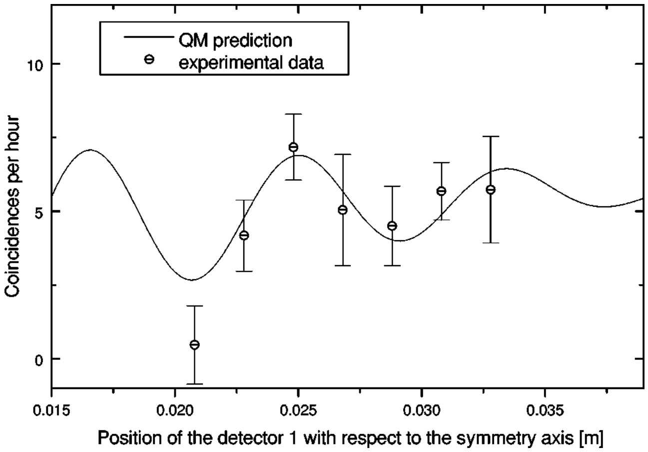

FIG. 5. Coincidences data (with a 2-mm iris) compared with quantum-mechanics predictions (solid curve). On the *x* axis we report the position of the first detector with respect to the median symmetry axis of the double slit. The second detector is positioned at -0.01 m (out of scale). The leftmost region of the data is inaccessible since the two detectors overlap, while on the right a rather flat behavior for coincidences is predicted.

signal is predicted when the two detectors are in the same semiplane; therefore this configuration is well suited for realization of the experiment suggested in Refs. [8–10] (see the following discussion).

We have also taken into account the effect of the nonperfect monochromaticity of the PDC radiation by calculating the convolution of Eq. (4) with a Gaussian transfer function describing the effect of an interferential filter. We have also introduced a small angular dispersion (1 nm/rad) of the photon pairs. The results of such a simulation show that for a filter with a 4 nm full width at half maximum (corresponding to the one used in the experiment) no substantial effect appears (a detailed discussion of these effects can be found in Ref. [7]).

SUMMARY OF dBB CALCULATION OF REFS. [8–10]

Let us now summarize (simplifying a bit) the results of Refs. [8–10] concerning the dBB prediction for our double-slit experiment. Using wave function 2 we can calculate the Bohmian velocities $\vec{v}_i=\vec{j}_i/\Psi^*\Psi$ of particles $i=1$ and $i=2$ (where $\vec{j}_i$ is the current of particle i). The result of this simple calculation implies that

$$v_{1y}+v_{2y}=0. \tag{5}$$

This implies that

$$y_1(t)+y_2(t)=y_1(0)+y_2(0). \tag{6}$$

Thus, if the initial positions of the two particles are chosen to be symmetrical about the line of symmetry ($y=0$), i.e., if $y_1(0)+y_2(0)=0$, we must have

$$y_1(t)+y_2(t)=0 \tag{7}$$

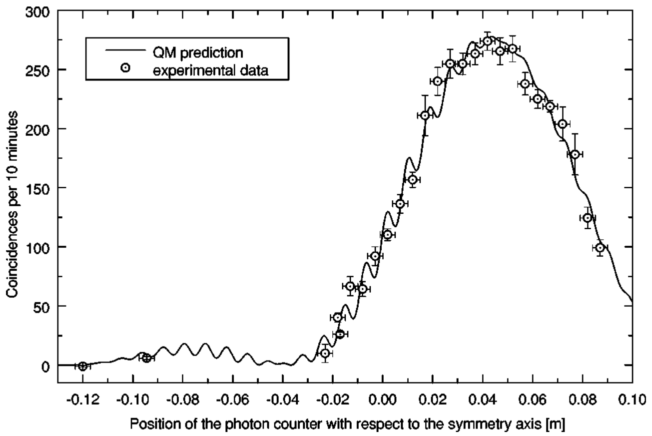

FIG. 6. Coincidence data (with a 6-mm iris) compared with quantum-mechanics predictions (solid curve). On the *x* axis we report the position of the first detector with respect to the median symmetry axis of the double slit. The second detector is kept at -0.055 m. The *x* error bars represent the width of the lens before the detector. A correction for laser power fluctuations is included.

for all times, i.e., the trajectories will always be symmetrical about this line. This implies that the two particles can, in fact, never cross the line of symmetry, in our case represented by the median axis of the double slit, and being observed in the same semiplane (for a precise explicit calculation of trajectories see Ref. [9], where it is also discussed that the difference between SQM and dBB theory is related to the fact that the latter can be nonergodic). This is the main source of incompatibility between dBB theory and SQM according to Refs. [8–10], a result that we will test in the following.

EXPERIMENTAL RESULTS

In order to scan the coincidence pattern, we have kept one detector fixed to a specific position and moved the second one. As the signal is rather low, a long acquisition time is required. This implies some problems since the power of the laser drifts over an acquisition time of several days (as we have directly verified). Also the crystal, pumped with a high-power UV laser, slowly deteriorates. This effect has been clearly observed by monitoring the observed signal of the fixed detector. In order to compensate this effect, we plot the average of the ratio of the coincidence signal (after background subtraction) over the signal of the fixed detector multiplied for the average of the fixed detector signal. The background to coincidences is evaluated shifting the delay between the start and stop TAC inputs of 16 ns. In this way we collect the accidental coincidences far from the coincidence peak. The acquisition window for coincidences is set at 2.5 ns.

As a first comparison of theoretical predictions of Eq. (4) with our data, in Fig. 5 we report the ones (with ten acquisitions of 1 h for each point) obtained when the first detector scans the diffraction pattern, while the second is positioned at -1 cm from the symmetry axis. The iris in front of the first detector is of 2 mm. Even if the data have large uncertainties there is a good indication of the fourth-order interference: the interference pattern predicted by SQM fits the data with a reduced χ^2 of 0.9. By comparison, a linear fit (absence of interference) gives $\chi^2=12.6$ (with five degrees of freedom) and is therefore rejected with a 5% confidence level.[1]

In Fig. 6 we report the swept with a larger iris (6 mm) scanning the whole diffraction peak. The data are obtained by averaging seven points of $30'$ acquisition each. The fixed detector now is placed at -5.5 cm from the symmetry axis. The pattern predicted by SQM significantly agrees with the data. A clear coincidence signal is observed also when the two detectors are placed in the same semiplane with respect to the double-slit symmetry axis and a small signal, 41 ± 14 coincidences per hour with 17 acquisitions of 1 h, is even observed in correspondence to the second diffraction peak (the area without data between the two peaks is due to the superposition of the two photodetectors).

This last result is at variance with the dBB prediction for coincidences calculated in Refs. [8–10], where the coincidence signal is predicted to be strictly zero when the two detectors are in the same semiplane with respect to the double-slit symmetry axis (this configuration was purposely chosen since it has the largest coincidence signal for this case), as discussed above. In particular, when the center of the lens of the first detector is placed -1.7 cm after the median symmetry axis of the two slits (recall the minus means to the left of the symmetry axis when looking towards the crystal) and the second detector is kept at -5.5 cm, with 35 acquisitions of $30'$ each we obtained 78 ± 10 coincidences per 30 min after background subtraction, ruling out a null result at nearly eight standard deviations. Thus, if this theoretical prediction is confirmed, this experiment will pose a strong constraint on the validity of the de Broglie–Bohm theory, which represents the most successful example of a nonlocal hidden variable theory.[2]

CONCLUSIONS

In conclusion, we have realized a double-slit experiment where two identical photons produced in type-I PDC are sent each to a well-defined slit at an identical time. Our data clearly show a good agreement with quantum-mechanics predictions. By contrast, our data contradict the predictions made in Refs. [8–10] for the de Broglie–Bohm theory, stating that no coincidences should be observed when detectors are in the same semiplane with respect to the symmetry axis of the double slit. Thus, if the theoretical predictions of Refs. [8–10] is confirmed, our results will represent a first negative test of the de Broglie–Bohm theory.[3]

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[1] On the other hand we have checked that, as expected, the single-channel signal does not show any variation in the same region: the measured ratio between the mobile and the fixed detector is essentially constant (within uncertainties) in this region.

[2] Local hidden variable theories can be tested using Bell inequalities [14]. Many experiments performed up to now [15] have substantially confirmed SQM, although some doubts remain due to their small detection efficiency [16].

[3] This allows us to exclude also some nonconventional quantum calculation model based on special versions of the dBB theory [17]. Incidentally, we would like to appreciate some previous experiments addressed to test versions of the dBB theory where the empty wave has physical effects [18].

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