A first experimental test of de Broglie-Bohm theory against standard quantum mechanics

G. Brida, E. Cagliero, G. Falzetta, M. Genovese, M. Gramegna, and C. Novero

Istituto Elettrotecnico Nazionale Galileo Ferraris,
Strada delle Cacce 91, 10135 Torino, Italy

(Dated: March 31, 2022)

Abstract

Quantum Mechanics is a pillar of modern physics, confirmed by a huge amount of experiments. Nevertheless, it presents many unintuitive properties, strongly differing from classical mechanics due to its intrinsic non-epistemic probabilistic nature. Many attempts have been devoted to build a deterministic theory reproducing all the results of Standard Quantum Mechanics (SQM), but where probabilities are epistemic, namely due to our ignorance of some hidden variables. These theories can be local or non-local. The formers are substantially excluded by Bell inequalities experiments. The latter include the de Broglie - Bohm (dBB) one, the most successful attempt in this sense. DBB theory is built in order to reproduce almost all SQM predictions. However, it has recently been shown that different coincidence patterns are predicted by SQM and dBB when a double slit experiment is realised under specific conditions, in particular no coincidence is expected when the two photodetectors are in the same semiplane respect to the median symmetry axis of the double slit. In this letter we present the first realisation of such a double slit experiment with correlated photons produced in type I parametric down conversion. We observe a perfect agreement with SQM prediction and a coincidence peak almost 8 standard deviations above zero, when the two photodetectors are well inside the same semiplane: Thus our results confirm Standard Quantum Mechanics contradicting dBB predictions.

PACS numbers: 03.65.Ta

*Electronic address: genovese@ien.it; URL: http://www.ien.it/~genovese/marco.html
†Dedicated to the memory of our beloved friend and collaborator Carlo Novero.
I..INTRODUCTION

Quantum Mechanics represents a pillar of modern physics: an impressive amount of experiments have confirmed this theory and many technological applications are based on it.

According to its standard interpretation, Quantum Mechanics nature is intrinsically probabilistic, permitting only predictions about probabilities of the occurrence of an event [1]. The state of a system is described by a wave function, whose modulus squared gives the probability density distribution of the system. Of course, in this picture, physical systems do not follow trajectories in their motion because of their position is not perfectly defined. The non-epistemic nature of probabilities in SQM leads to many unintuitive properties of quantum systems and, more badly than that, the transition between the microscopic quantum world and macroscopic deterministic classical world remains unsolved: None of the many attempts to give a solution of macro-objectivation [1] has effectively reached a universal consent in physicists community.

Starting from an Einstein’s [2] work, many attempts have been devoted to build a deterministic theory reproducing all the results of SQM, in which probabilities become epistemic, namely are due to our ignorance of some hidden variables, whose knowledge would in fact make the evolution of the system perfectly determined.

A fundamental paper of Bell [3] showed that local Hidden Variable Theories (HVT) cannot reproduce all the results of SQM. Since then a lot of experiments have been addressed to test local HVT against SQM. All of them [1, 3] confirmed SQM, even though a conclusive experiment is still missing due to the low detection efficiency, which leads to the need of an additional hypothesis stating that the final measured sample is a faithful representation of the initial one (detection loophole) [10].

However, Bell theorem does not apply to non-local hidden variable theories, including the de Broglie-Bohm one [1, 7, 8], the most serious and successful attempt to propose an alternative to SQM. In this theory the hidden variable 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 it is non-local. The inclusion of this term, together with an initial distribution of particles positions given
by the quantum probability density, successfully allows the reproduction of almost all the predictions of quantum mechanics.

Nevertheless, in a series of recent papers [4, 5, 6] it has been shown that under particular conditions (namely when the system is not ergodic [15]) different experimental results are predicted by dBB and SQM, allowing a test of the two theories. In particular, in dBB one expects that [4, 5, 6], due to the non-crossing theorem, in a double slit experiment, where two identical particles cross simultaneously each a precise slit, no coincidence can be measured in the same semiplane respect to the median symmetry axis of the two slits.

II. DESCRIPTION OF THE EXPERIMENT

In order to test this prediction we have realised a novel experimental configuration in which two identical photons reach a double slit at the same time, each one crossing a different slit, according to the configuration proposed in ref. [4, 5, 6]. However, it must be pointed out that only in some versions of dBB theory the photon is described as a particle [4, 5, 8, 11]: therefore our test concerns these versions of the theory, which have the fundamental advantage of describing bosons and fermions on the same ground. If the experiment will be repeated with fermions a conclusive test of dBB will be obtained. In the last years some experiments [12, 13, 14] were performed, in which PDC light was crossing a double slit, but in none of them a median symmetry axis was well defined and a configuration suitable for the present test was realized.

More in details (see fig.1) a 351 nm pump laser of 0.4 W power is directed into a lithium iodate crystal, where correlated pairs of photons are generated by type I parametric down conversion (PDC) [3]. The two photons are emitted at the same time (within femtoseconds, whilst correlation time is some orders of magnitude larger) on a well defined direction for a specific frequency. By means of an optical condenser the produced photons, within two correlated directions corresponding both to 702 nm emission (the degenerate emission for a 351 nm pump laser), are sent on a double slit (obtained by a metal 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 lay in a plane orthogonal to the incident laser beam and are orthogonal to the table plane. Two EG&G single photon detectors are placed at a 1.21 and a 1.5 m distance after the slits. They are preceded by
an interferential filter at 702 nm of 4 nm full width at half height and by a lens of 6 mm diameter and 25.4 mm focal length. 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 analyser, for selecting and counting the coincidence events.

With this experimental set-up, we obtained that a clear signal appeared on the multi-channel analyser when the detectors were placed in the positions where the maximum of coincidences was expected, namely at 2 degrees, in two different semiplanes, respect to the median symmetry axis of the double slit (which is parallel to the incident pump laser). In order to check that the two degenerate photons crossed two different slits, we have alternatively closed one of the slits leaving the other opened: correspondingly, the coincidence peak disappeared and the signal on the related detector dropped to background level, confirming the correct position of the double slit. Then we moved the first detector scanning the diffraction pattern, leaving the second fixed at 5.5 cm from the symmetry axis. We found that the coincidences pattern perfectly followed quantum mechanics predictions, see fig.2. The last ones are given by:

\[
C(\theta_1, \theta_2) = g(\theta_1, \theta_1)g(\theta_2, \theta_2)^2 + g(\theta_2, \theta_1)g(\theta_1, \theta_2)^2 + 2g(\theta_1, \theta_1)g(\theta_2, \theta_1)g(\theta_1, \theta_2)\cos[ks(sin\theta_1 - sin\theta_2)]
\]

(1)

where

\[
g(\theta, \theta_l) = \frac{\sin(kw/2(sin(\theta) - sin(\theta_l)))}{kw/2(sin(\theta) - sin(\theta_l))}
\]

(2)

takes into account diffraction. \(k\) is the wave vector, \(s\) the slits separation, \(w\) the slit width, \(\theta_1, \theta_2\) is the diffraction angle of the photon observed by detector 1 or 2, \(\theta_l\) the incidence angle of the photon on the slit \(l\) (A or B).

Because of finite width of the slit, a partial penetration of trajectories in the opposite semiplane is possible, however this penetration is of the order of the slit width \(\frac{1}{10}\) (10 µm) and thus negligible.

The fundamental result of our experiment is that a coincidence peak is clearly observed (see fig.3) also when the first detector is placed inside enough the same semiplane of the second one. We consider coincidences acquisitions with a temporal window of 2.6 ns, the background is evaluated shifting the delay between start and stop of TAC of 16 ns and
acquiring data for the same time of the undelayed acquisition. When the edge of the lens of
the first detector is placed -1.4 cm (the center -1.7 cm) after the median symmetry axis of the
two slits (the minus means on the left of symmetry axis looking toward to the crystal), whilst
the second detector is kept at -5.5 cm, with 35 acquisitions of 30‘ each we obtained 78 ± 10
coincidences per 30 minutes after background subtraction, whilst in this situation the dBB
prediction for coincidences is strictly zero. Furthermore, even when the two detectors
were placed in the same semiplane the first at -4.44 and the second at -11.7 cm from the
symmetry axis, in correspondence of the second diffraction peak, a clear coincidence signal
was still observed (albeit less evident than in the former case): We obtained in fact, after
background subtraction, an average of 41 ± 14 coincidences per hour with 17 acquisitions
of one hour (and a clear peak appeared on the multichannel analyser).

Therefore we can conclude that our results are in perfect agreement with SQM predictions,
but contradict of almost 8 standard deviations the predictions of dBB theory presented in
ref. [4, 5, 6].

III. CONCLUSIONS

In conclusion we have realised the first experimental test of de Broglie-Bohm theory
against standard Quantum Mechanics following the proposal of ref. [4, 5, 6]. DBB predicts
that in a double slit experiment, in which two identical particles simultaneously cross each
a precise slit, their trajectories remain in the semiplane of the crossed slit and thus no
coincidence can be measured when two detectors are placed on the same side respect to the
median symmetry axis. This result is at variance with SQM prediction. In our experiment
we have clearly observed a coincidence peak when the detectors are placed in the same
semiplane, confirming SQM prediction against dBB one.

Acknowledgments

We acknowledge support of Italian minister of research. We thank P. Ghose,
A.S.Majumdar and G. Introzzi for useful discussions. We thank R. Steni for the realisa-
tion of the double slit.

[1] G. Auletta, *Foundations and interpretation of quantum mechanics* (World Scientific, Singapore 2000) and ref.s therein.
[2] A. Einstein, B. Podolsky and N. Rosen, Phys. Rev. 47, 777 (1935).
[3] G. Brida, M. Genovese, C. Novero, and E. Predazzi, Phys. Lett. A 268, 12 (2000).
[4] P. Ghose, in *Foundations of quantum theory and quantum optics 1999/2000* (ed. Roy, S.M.) (Indian Academy of Sciences) 211 and quant-ph/0003037.
[5] P. Ghose, A.S. Majumdar, S. Guha, and J. Sau, Phys. Lett. A 290, 205 (2001).
[6] M. Golshani, and O. Akhavan, J. Phys. A34, 5259 (2001).
[7] P. Ghose, *Testing quantum mechanics on a new ground* (Cambridge Univ. Press, 1999).
[8] P. Holland, *The quantum theory of motion* (Cambridge Univ. Press).
[9] J.S. Bell, Physics 1, 195 (1964).
[10] E. Santos, Phys. Lett. A 212, 10 (1996); L. De Caro and A. Garuccio Phys. Rev. A 54, 174 (1996) and references therein.
[11] P. Ghose, Found. of Phys. 26, 441 (1996).
[12] C.K. Hong and T.G. Noh, J. Opt. Soc. Am. B15, 1192 (1998).
[13] E.J.S. Fonseca, C.H. Monken, and S. Padua, Phys. Rev. Lett. 82, 2868 (1999).
[14] A.F. Abouraddy, B.E.A. Saleh, A.V. Sergienko and M.C. Taich, J. Opt. B 3, S50 (2001).
[15] P. Ghose, quan-ph/0103126.
IV. FIGURES CAPTIONS

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 piano-convex lenses in a way that each photon of the pair crosses a well defined slit. A first photodetector is placed at 1.21 m a second one at 1.5 m from the slit. Both the single photon detectors (D) are preceded by an interferential filter at 702 nm (IF) and a lens (L) of 6 mm diameter and 25.4 mm focal length. Signals from detectors are sent to a Time Amplitude Converter and then to the acquisition system (multi- channel analyser and counters).

Fig.2 Coincidences data in the region of interest compared with quantum mechanics predictions. On the x-axis we report the position of the first detector respect to the median symmetry axis of the double slit. The second detector is kept fixed at -0.055 m. The x errors bars represent the width of the lens before the detector. A correction for laser power fluctuations is included.

Fig.3 Observed coincidence peak (output of the multi-channel analyser) when the centre of the lens is placed 1.7 cm after the median symmetry axis of the double slit in the same semiplane of the other photodetector, which is kept at 5.5 cm after the median symmetry axis. Acquisition time lasts 17 hours. No background subtraction is done. A coincidence peak is clearly visible for a delay between start (first photodector) and stop (second photodector) of 9ns (the delay inserted on the second line signal). This result is at variance with the prediction of de Broglie - Bohm theory [4, 5, 6].
This figure "fig2.jpg" is available in "jpg" format from:

http://arxiv.org/ps/quant-ph/0206196v1
This figure "figure3.jpg" is available in "jpg" format from:

http://arxiv.org/ps/quant-ph/0206196v1