Experimental tests of hidden variable theories from dBB to Stochastic Electrodynamics

Marco Genovese 1, Giorgio Brida 1, Marco Gramegna1, Fabrizio Piacentini1, Enrico Predazzi2, Ivano Ruo-Berchera1
1I.N.R.I.M., Str. delle Cacce 91, I-10135 Torino, Italy
2Dip. Fisica Teorica Univ. Torino and INFN, via P. Giuria 1, 10125 Torino, Italy
E-mail: genovese@inrim.it

Abstract. The studies concerning the possible existence of a deterministic theory, of which quantum mechanics would be an approximation, date to the celebrated 1935 Einstein-Podolsky-Rosen paper. Since Bells proposal of 1964 various experiments were addressed to a general experimental test of local hidden variable theories, leading to strong indications favourable to Standard Quantum Mechanics. Nevertheless, detection loophole still persists. In this, after a short presentation of recent PDC photon experiments, we will present our recent works in this field and in particular a conclusive negative test of stochastic electrodynamics. Finally, we will also mention possible tests of non-local deterministic models and give some detail on our test of the dBB model.

1. Introduction

The quest for a realistic theory of which quantum mechanics would be an approximation dates to more than 70 years and in the last years has accelerated due to both experimental and theoretical progresses [1].

Already in 1935 Einstein-Podolsky-Rosen [2], analysing the measurement on an entangled state, proposed that Quantum Mechanics (QM) could be an incomplete theory, representing a statistical approximation of a complete deterministic theory: this was the birth of Local Hidden Variable Theories (LHVT), where the values of the observables are fixed by some hidden variable and probabilistic predictions become epistemic, being due to our ignorance of the hidden variables.

A subsequent fundamental progress in discussing Local Hidden Variable was Bell’s discovery that any theory of this kind must satisfy certain inequalities that can be violated in QM leading in principle to a possible experimental test of the validity of the standard interpretation of QM (SQM) compared to LHVT.

Since then, many interesting experiments have been devoted to test Bell inequalities, the most interesting of them using photon pairs [4, 5, 6, 7, 8], leading to a substantial agreement with quantum mechanics and disfavouring LHVT. Up to now, however, no experiment has yet been able to exclude definitively such theories. In fact, due to the low total detection efficiency, so far one has always been forced to introduce at least one further additional hypothesis [10], i.e. the observed sample of particle pairs is a faithful subsample of the initial set of pairs. This problem is known as detection or efficiency loophole. The research for new experimental configurations able to overcome the detection loophole is, of course, of the utmost interest.
In the 90’s a relevant progress in the direction of eliminating this loophole has been obtained by using Parametric Down Conversion (PDC) process.

This technique [4] has been largely employed to produce "entangled" photon pairs, i.e. pairs of photons described by a common wave function that cannot be factorized into the product of the wave functions of individual photons.

The generation of entangled states by parametric down conversion (PDC) has replaced other techniques, such as the radiative decay of excited atomic states, as it was in the celebrated experiment of A. Aspect et al. [5], for it overcomes some previous limitation. In particular, it overcomes the poor angular correlation of atomic cascade photons, that is at the origin of the small total efficiency of this type of experiments where one is forced to select a small subsample of the produced photons, leading inevitably to the detection loophole, since PDC presents angular correlations better than 1 mrad.

The first experiments using this technique were performed with type I PDC, which gives phase and momentum entanglement and can be used for a test of Bell inequalities using two spatially separated interferometers [6], as realized by Ref. [7]. The use of beam splitters, however, strongly reduces the total quantum efficiency.

In alternative, a polarization entangled state can be generated [9]. However, in the earlier attempts, in generating this state, half of the initial photon flux was lost and the efficiency loophole could not be eliminated even in principle [10].

More recently experiments where a polarization entangled state is directly generated, have been realized using Type II PDC [8, 1]. This scheme has allowed a much higher total efficiency than the previous ones at the price of delicate compensations for having identical arrival time of the ordinary and extraordinary photons. Such an efficiency, however, is at most $\approx 30\%$, still far from the value of 0.81 required for eliminating the detection loophole for a maximally entangled state. In addition, experiments studying equalities among correlations functions rather than Bell inequalities [11, 12] are very far from giving a loophole free test of local realism [13]. A large interest remains therefore for new experiments increasing total quantum efficiency in order to reduce and finally overcome the efficiency loophole [1].

On the other hand, even if conclusive loophole free experiments will allow to exclude LHVT beyond any possible doubt, room will remain for non local Hidden Variable Theories [1, 16] or models were "true" degrees of freedom, on which Bell inequalities tests should be performed, are at large (Plank) scales [17].

In this paper we will present some experimental investigation in this field based on the production of various polarization entangled states in both cases: type I and type II sources. In particular, we will describe a bright source of (non-maximally) polarization entangled states of photons and its use to test Bell inequalities. Then, we will describe its application to exclude a specific local realistic theory (stochastic electrodynamics), that survived previous experiments due to detection loophole. Finally, we will mention that a modification of this apparatus has been used for a first test of de Broglie-Bohm theory.

1 It must be acknowledged that a recent experiment [14] based on the use of Be ions has reached very high detection efficiencies (around 98 %), largely sufficient for closing the detection loophole. However, in this case not only space like separation required for closing locality loophole was not satisfied, but the two subsystems (the two ions) were even not really separated during the measurement. Therefore, this experiment cannot be considered a real implementation of a loophole free test of Bell inequalities, even if it represents a relevant progress in this sense. Also tests with pseudoscalar mesons, albeit interesting, look far from a suitable way for eliminating detection loophole [15].

2 Incidentally, it must be noticed that the perfect fitting of SQM predictions to data obtained by varying one polarizer angle for various different settings of the other one both obtained in our experiments as in many other ones [1] [18] conclusively falsifies LHVT based on the violation of rotational invariance, e.g. [19].
2. Bright source of non-maximally polarization entangled photons

With the purpose of building a bright source of (non-maximally) entangled states, we have considered \[20\] the possibility of generating a polarization entangled state via the superposition of the spontaneous fluorescence emitted by two non-linear crystals (rotated in order to have orthogonal polarization) driven by the same pumping laser \[21\]. The crystals are in cascade along the propagation direction of the pumping laser and the superposition is obtained by using an appropriate optics. If the path between the two crystals is smaller than the coherence length of the laser, the two photon paths are indistinguishable and a polarization entangled state is created. In fact, applying the evolution operator given by the PDC Hamiltonian one has, in first order of the perturbation expansion (a good approximation in low gain regime):

\[
|\Psi\rangle = |\text{vacuum}\rangle + f_1 V_1 |H\rangle|H\rangle + f_2 V_2 |V\rangle|V\rangle
\]  

(1)

where \(f_i\) takes into account the properties of crystal \(i\) (\(|f_i|^2\) is the fraction of incident light down converted by the non-linear crystal) and \(V_i\) the pump intensity at the crystal \(i\).

The possibility of obtaining easily a non maximally entangled state (where \(V_1 f_1\) and \(V_2 f_2\) are different) is very interesting, since it has been shown that for non maximally entangled pairs the lower limit on the total detection efficiency for eliminating the detection loophole is reduced to 0.67 \[22\] (compared with 0.81 for maximally entangled states). However, it must be noticed that, for non-maximally entangled states, the largest discrepancy between quantum mechanics and local hidden variable theories is also reduced: thus a compromise between a lower total efficiency and a still sufficiently large value of this difference is necessary when realizing an experiment addressed to overcome the detection loophole.

In our experimental set up two \(LiIO_3\) crystals (10x10x10 mm, \(d_{31} = 3.5 \pm 0.4\) pm/V \[23\]) were placed along the pump laser propagation, 250 mm apart, a distance smaller than the coherence length of the pumping laser. This guaranteed indistinguishability in the creation of a couple of photons in the first or in the second crystal. A couple of plano-convex lenses of 120 mm focal length centered in between, focalized the spontaneous emission from the first crystal into the second one maintaining the angular spread. A hole of 4 mm diameter was drilled into the center of the lenses to allow transmission of the pump radiation without absorption and, even more important, without adding stray-light, because of fluorescence and diffusion of the UV radiation. A small quartz plate (5 x5 x5 mm) in front of the first lens of the condensers compensated pump birefringence. Finally, a half-wavelength plate immediately after the condenser rotated the polarization of the laser beam and excited in the second crystal a spontaneous emission cross-polarized with respect to the first one. Two correlated emissions at 633 and 789 nm were selected and, after the polarizers, detected by two avalanche photodiodes with active quenching. The output signals from the detectors were routed to a two channel counter, in order to have the number of events on single channel, and to a Time to Amplitude Converter circuit, followed by a single channel analyzer, for selecting and counting coincidence events.

A very interesting degree of freedom of this configuration is given by the fact that by tuning the pump intensity between the two crystals, one can easily select the value of \(f = (f_2 V_2)/(f_1 V_1)\), that determines how far from a maximally entangled state \((f = 1)\) the produced state is. This is a fundamental property, which permits to select the most appropriate state for the experiment.

Our main result was the observed violation of the Clauser-Horne (CH) inequality

\[
CH = N(\theta_1, \theta_2) - N(\theta_1, \theta_2') + N(\theta_1', \theta_2) + N(\theta_1', \theta_2') - N(\theta_1', \infty) - N(\infty, \theta_2) < 0
\]  

(2)

valid for every local realistic theory. In \[2\], \(N(\theta_1, \theta_2)\) is the number of coincidences between channels 1 and 2 when the two polarizers are rotated to an angle \(\theta_1\) and \(\theta_2\) respectively (\(\infty\) denotes the absence of selection of polarization for that channel).
In our case we have generated a state with $f \simeq 0.4$: in this case the largest violation of the inequality is reached for $\theta_1 = 72^\circ.24$, $\theta_2 = 45^\circ$, $\theta'_1 = 17^\circ.76$ and $\theta'_2 = 0^\circ$. Our experimental result is $CH = 513 \pm 25$ [24, 25].

This clear violation of the CH inequality with non maximally entangled states represented an interesting progress toward a loophole free test of local realism [3]. Furthermore, this experiment [25] allowed a clear negative test of stochastic electrodynamics [28], a theory built for reproducing quantum electrodynamics results in a classical field theory framework when a zero-point field is introduced. In its subpart concerning the quantum properties of radiation, named stochastic optics, it was forecasted that Bell inequalities should not be violated below a certain level of detection rate [29]. Indeed a clear violation of CH inequality was observed in our experiment even well below this threshold (by many orders of magnitude).

A little more in detail, no violation of Bell inequalities should be measured when the single detection rate $R_S$ is lower than

$$R_S < \frac{\eta F^2 R_c^2}{2 L d^2 \lambda \sqrt{T}}$$

where $\eta$ is the detection quantum efficiency, $F$ is the focal distance of the lens in front of detectors, $R_c$ is the radius of the active area of the non-linear medium where entangled photons are generated, $\tau$ is the coherence time of incident photons, $d$ is the distance between the non-linear medium and the photo-detectors, $\lambda$ is the average wavelength of the detected photons. $L$ and $T$ are two free parameters which are less well determined by the theory: $L$ can be interpreted as the active depth of the detector, while $T$ is the time needed for the photon to be absorbed, which should be approximately less than 10 ns, i.e. in a first approximation, the length of the wave packet divided for the velocity of light.

By introducing the parameters of our experiments in Eq. 3 one obtains $T > 1s$, which is largely above any realistic estimate.

Besides, as a further test of stochastic optics we also searched for a SPontaneous Up Conversion (SPUC) emission predicted in this theory [30] with an intensity comparable with SPDC. More in details, following the indications of [31], we pumped with both a diode laser at 789 nm (50 mW power) and a Neodimium-Yag laser beam (1064 nm wave length, 0.51 W power) a 1.5 cm Lithium Iodate crystal in the configuration were a stimulated emission was emitted when a UV pump (351 nm Argon laser beam, 0.3 W) was present. In the same configuration SPUC was expected when the UV beam was turned off. We did not observe any emission by monitoring the emission after the crystal with a ccd camera [32], being the SPUC signal at least 160 times smaller than the PDC one.

Even a more severe test was later performed by scanning substantially all the possible angles for the emission when a 5 mm BBO crystal was pumped by a 789 nm wave length, 90 mW power, diode laser beam. For the sake of completeness the angle between pump laser and crystal optical axis was also systematically varied of small steps. Again no SPUC emission was observed up to two orders of magnitude less than SPDC emission (after having normalized for the different pump power).

Thus, taken together, all these negative results clearly falsify this theory [4].

Finally, we would like to mention that, by substituting in the two crystals set-up for generating polarization entangled states the second crystal with a double slit, it was possible to realize the experiment proposed by Ref. [35] for testing standard quantum mechanics against de Broglie-Bohm theory. In extreme synthesis, two theoretical groups [34] proposed that when each of

3 In Ref. [26] a test of local realism was also performed with non-maximally entangled states by using equalities [27].
4 Incidentally, also experiments at single photon level where the parameter $\alpha$ (see [33] for a definition) is substantially zero [34] appear not to be describable in such a theory.
two identical bosonic particles cross one of a double slit at the same time, they never cross the symmetry axis of the slits at variance with SQM predictions. Contrary to this prediction we clearly observed coincidences of identical photons (702 nm PDC conjugated photons) in the same semiplane after crossing each a 10 micrometers slit (being the two slits separated by 100 micrometers), e.g. with 35 acquisitions of 30' each we obtained an average of 78 ± 10 coincidences per 30' when both the detectors were clearly in the same semiplane.

Even if the validity of this theoretical proposal is still under discussion, our result represents, as far as we know, the first experimental attempt to test dBB theory. If this theoretical prediction will be accepted as correct, then our experiment could be interpreted as a conclusive test of dBB theory (at least) in the version where photons have trajectories.

3. Conclusions
In this paper we have reviewed, after a general introduction to this researches, part of our work on testing realistic alternative to standard quantum mechanics. In particular, a bright source of non-maximally polarization entangled states and its applications to moving toward a loophole free Bell inequalities experiment were described. We also discussed how the analysis of the results obtained allows a falsification of stochastic electrodynamics. Finally, we have hinted at the results obtained with a modification of this set-up conceived to test SQM against dBB according to the predictions of Ref.[35].

3.1. Acknowledgments
We acknowledge the support of MIUR (FIRB RBAU01L5AZ-002), Fondazione San Paolo and Regione Piemonte (E14).

4. References
4.1. Reference lists
[1] M. Genovese, Phys. Rep. 413 (05) 319.
[2] A. Einstein, B. Podolsky and N. Rosen, Phys. Rev. 47 (1935) 77.
[3] J.S. Bell, Physics 1 (1965) 195.
[4] see L. Mandel, and E. Wolf, Optical Coherence and Quantum Optics, Cambridge University Press, 1995 and references therein.
[5] A. Aspect et al., Phys. Rev. Lett. 49, 1804, (1982).
[6] J. P. Franson, Phys. Rev. Lett. 62, 2205 (1989).
[7] J. G. Rarity, and P. R. Tapster, Phys. Rev. Lett. 64, 2495 (1990); J. Brendel et al. Eur.Phys.Lett. 20, 275 (1992); P. G. Kwiat et al, Phys. Rev. A 41, 2910 (1990); W. Tittel et al, quant-ph 9806043.
[8] A. Garuccio, in "Fundamental Problems in Quantum Theory", Ed. D. Greenberger, (New York Academy of Sciences, 1995); T.E. Kiess et al., Phys. Rev. Lett. 71 (1993) 3893; P.G. Kwiat et al., Phys. Rev. Lett. 75 (1995) 4337.
[9] Z.J. Ou and L. Mandel, Phys. Rev. Lett. 61, 50, (1988); Y.H.Shih et al., Phys. Rev. A 47, 1288, (1993).
[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] J.W. Pan et al., Nature 403 (2000) 515.
[12] J.R.Torgerson et al., Phys. Lett. A 204, 323 (1995); G.Di Giuseppe, F.De Martini and D.Boschi, Physical Review A 56, 176 (1997); D.Boschi, S.Branca, F.De Martini and L.Hardy, Phys. Rev. Lett. 79, 2755 (1998).
[13] A. Garuccio, Phys. Rev. A 52, 2535 (1995).
[14] M. A. Rowe et al., Nature 409, 791, 2001.
[15] M. Genovese et al., Phys. Lett. B 513 (01) 401; Found. Of Phys. 32 (2002) 589. M. Genovese, Phys. Rev A 69, (2004) 022103; Eur. Journ. Of Phys. C 42 (2005) 25.
[16] S. Adler, “Quantum Theory as an Emergent Phenomenon”, Cambridge University Press, 2004
[17] G. ‘t Hooft, quant-ph 0212095, Conf. Proceedings, “Quo Vadis Quantum Mechanics”, (Philadelphia, 2002).

5 For other proposals of possible experimental tests of dBB against SQM see 37.
M. Blasone et al., J. Phys. Soc. Jap. Suppl. 72 (2003) 50. T.S. Biró and B. Müller, hep-lat/0307028. H.-T. Elze, Phys. Lett. A 310 (2003) 110.

[18] T. Kim et al., quant-ph/0509219.

[19] M. Minozzo, “Bell inequalities and correlation experiments: a purely particle statistical investigation”, in “The Foundations of Quantum Mechanics: Historical Analysis and Open Questions” (eds. C. Garola, A. Rossi), World Scientific, Singapore, (2000) 307-318.

[20] M. Genovese, G. Brida, C. Novero and E. Predazzi, proceeding of ICSSUR, Napoli may 1999.

[21] L. Hardy, Phys. Lett. A 161, 326 (1992).

[22] P. H. Eberhard, Phys. Rev. A 47, R747 (1993).

[23] G. Brida, M. Genovese and C. Novero., European Journal of Physics D. 8 273 (2000).

[24] G. Brida et al., Phys. Lett. A 268 (2000) 12.

[25] G. Brida et al., Phys. Lett. A 299 (2002) 121.

[26] A.G. White et al., Phys. Rev. Lett. 83 (1999) 3103.

[27] L. Hardy, Phys. Rev. Lett. 71 (1993) 1665.

[28] T.W. Marshall, Proc. Cambridge Philos. Soc. 61, 537 (1965); T. H. Boyer, Phys. Rev. 182, 1374 (1969); E. Santos, Lett. Nuovo Cimento 4, 497 (1972); M. Surdin, Ann. Inst. Henri Poincar 15, 203 (1971); L. de la Pena and A.M. Cetto, “The quantum dice : and introduction to stochastic electrodynamics”, Kluwer, 2000.

[29] A. Casado et al., J. Opt. Soc. Of Am. B 14 (1997) 494; A. Casado et al., Phys. Rev. A 55 (1997) 3879. A. Casado et al., Phys. Rev. A 56 (1997) 2477. A. Casado et al., J. Opt. Soc. Of Am. B 15 (1998) 1572; A. Casado et al., Eur. Phys. Journ. D 11 (2000) 465; D 13 (2001) 109; A. Casado et al., quant-ph 0202097.

[30] Dechoum, K., Marshall, T.W., and Santos, E., Journ. Of Mod. Opt., 2000, 47, 1273; T.W. Marshall, quant-ph 0203042.

[31] T.W. Marshall, quant-ph 9803054.

[32] G. Brida et al., Journ. Mod. Opt. 11 (2003) 1757.

[33] P. Grangier, G. Roger and A. Aspect, Eur. Phys. Lett. 1 (1986) 173;

[34] G. Brida et al., Phys. Lett. A 328 (04) 313.

[35] P. Ghose, Proc. of Foundations of Quantum Theory and Quantum Optics, Calcutta, ed. S.M. Roy, published in Pramana 56 (2001) 211; P. Ghose, A. S. Majumdar, S. Guha and J. Sau, Phys. Lett. A 290 (2001) 205; M. Golshani and O. Akhavan, J. Phys. A. Math. Gen. 34 (2001) 5259.

[36] G. Brida et al., J. Phys. B: At. Mol. Opt. Phys. 35 (2002) 4751; Journ. Mod. Opt. 51 (2004) 1079; Phys. Rev. A 68 (2003) 033803.

[37] H. Nikolic, Found. of Phys. Lett. 18 (05) 549, quant-ph 0512065; L. Feligioni et al., quant-ph 0202045. N. Redington et al., Nuovo Cim. 109B (1994) 116; P. Ghose and M. K. Samal, Phys. Rev. E 64 (2001) 030620;

[38] L. Marchildon, quant-ph/0101132 (2001); L. Marchildon, J. Modern Optics 50 (2003) 873. E. Guay and L. Marchildon, quant-ph/0302085. W. Struyve et al., Journ. Phys. A 34 (2003) 5299. O. Akhavan and M. Golshani, quant-ph 0305020. G. Introzzi, proc. of “Meeting of Italian Society of Phylosophy of Science and Logic 2004” in press. P. Ghose, quant-ph 0609045; quant-ph/0208192; quant-ph/0102131. X. Oriols, Phys. Rev. A 71, 017801 (2005).