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Recent experiments performed at "Carlo Novero" lab at INRIM on Quantum Information and Foundations of Quantum Mechanics.

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In this paper we present some recent work performed at "Carlo Novero" lab on Quantum Information and Foundations of Quantum Mechanics.

Keywords: entangled states; local realism; quantum communication.

1. Introduction

"Carlo Novero" laboratory (named after our bewailed colleague and friend who founded this activity in our institute) is a facility at the Italian National Institute of Metrological Research (INRIM) devoted to the experimental study of the foundations of quantum mechanics and quantum information by using quantum optical states.

In particular most of the activity was addressed to produce and use Parametric Down Conversion (PDC) biphoton pairs [1].

A first application of these states concerned quantum metrology, i.e. the calibration of single photon detectors [2], but the same states also find wide application to the related fields of Quantum Information and Foundations of Quantum Mechanics: in this paper we present our most recent and interesting studies on these two subjects.

2. Two type I crystals source and application to tests of realistic theories

In our laboratory we used various different sources of polarization entangled photons, some based on a type II PDC crystal other on the superposition of the emission of two type I PDC crystals.

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A large part of our experimental work concerning tests of local realism was realized with the last one.

This source (Fig. 1) was built by superimposing the emission of two separated type I crystals [3] ($LiIO_3$, 1.5 cm length), whose optical axes were at 90°, by using an optical condenser. The pump polarization was rotated of 90° between them. This setup realized a very bright source [1] of polarization entangled states (10 kHz for the coincidence rate at 200 mW pump power) and a very good superposition was possible (in principle much better than what realizable with two adjacent thin crystals [6]), therefore representing an interesting resource for quantum information protocols.

A first application was to test Bell inequalities [4] with non-maximally entangled states [5], a step toward a solution of detection loophole, since the quantum efficiency limit for a loophole free experiment is lowered for non maximally entangled states [7]. A clear violation of Clauser-Horne inequality (less than zero for local realistic theories) was observed, 513 ± 25.
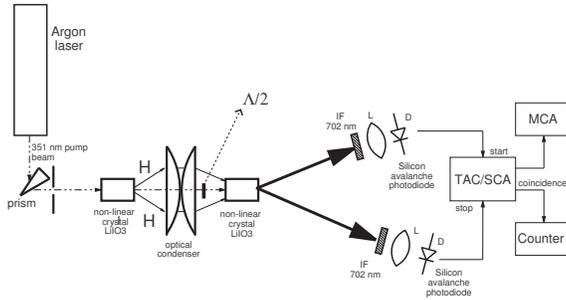

Fig. 1. Sketch of the bright source of polarization entangled photons realized by superimposing two type I PDC emissions. The detection apparatus is shown as well.

Furthermore, this experiment allowed a clear negative test of stochastic electrodynamics [8], a theory built for reproducing quantum electrodynamics results in a classical field theory framework where 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 under a certain level of detection rate [9]. Indeed a clear violation of Clauser-Horne inequality was observed in our experiment even being well (many order of magnitude) under this threshold.

Incidentally, as a further test of stochastic optics we also searched for a spontaneous up conversion (SPUC) emission predicted in this theory [10]. More in details we pumped with both a diode laser at 789 nm (50 mW power) and a Neodimium-Yag laser beam (1064 nm, 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) 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
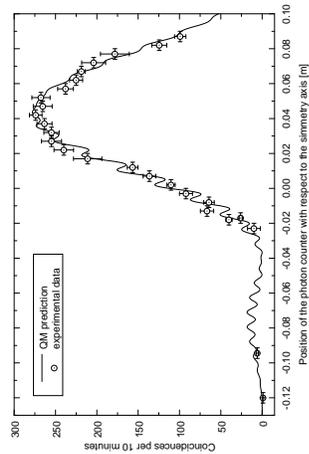
Fig. 2.   Coincidences data compared with quantum mechanics predictions (solid curve). On the x-axis we report the position of the first detector with respect to the median symmetry axis of the double slit. The second detector is positioned at -0.01 m (out of scale). The leftmost region of the data is inaccessible since the two detectors overlap, while on the right, a rather flat behavior for coincidences is predicted. A clear coincidence signal in the forbidden region for dBB is observed (negative part of x axis).
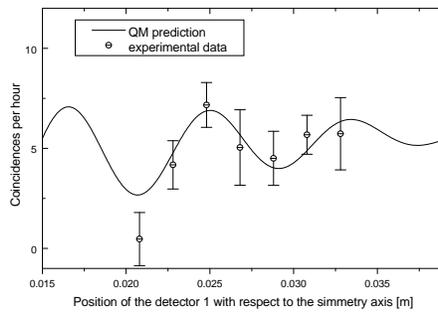

Fig. 3.   Coincidences data (with a 2 mm iris) compared with quantum mechanics predictions (solid curve) for the 4th order interference. On the x-axis we report the position of the first detector with respect to the median symmetry axis of the double slit. The second detector is positioned at -0.01 m (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.

emission after the crystal with a ccd camera [11] (i.e. SPUC signal was at least 160 times smaller than the PDC one). Again, no emission was observed (by scanning substantially all the possible angles for the emission) when the same experiment was reproposed by using a 5 mm BBO crystal pumped by a 789 nm wave length,
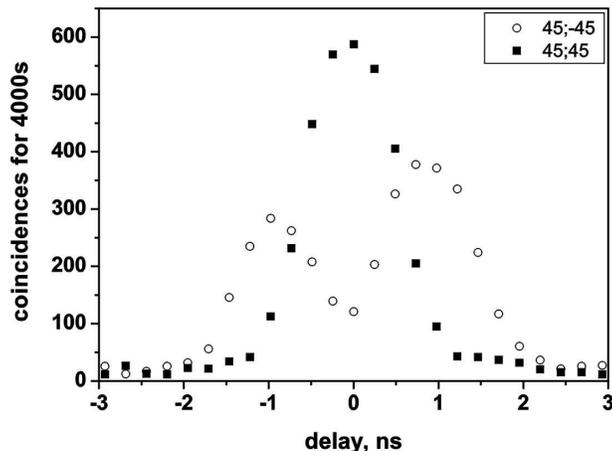
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Fig. 4.   Coincidences observed when the polarizers are parallel or orthogonal in 45° basis. The configuration is the double fiber cross with a Faraday mirror reflecting back the biphotons and a 250 m fiber.

90 mW power, diode laser beam.

Thus, altogether all these negative results clearly falsify this theory [a].

Finally, we would like to mention that, by substituting the second crystal with a double slit, it was possible to realize the experiment proposed by ref. [13] for testing standard quantum mechanics (SQM) against de Broglie-Bohm theory. In extreme synthesis, ref. [13] proposed that when two identical bosonic particles cross each a slit of a double slit at the same time they never cross the symmetry axis of the slits at variance with SQM predictions. Opposite to this prediction we clearly observed coincidences of identical photons (702 nm PDC conjugated photons) in the same semiplane [14] after crossing each a 10 micrometers slit (being the two slits separated of 100 micrometers), see Fig. 2. As a further result obtained with this set-up in Fig. 3 a detail of the coincidence curve is shown: 4th order interference is clearly observed (rejecting the absence of interference at 95% confidence level both for a χ^2 and a run test). On the other hand, 2nd order interference is not observed since in this case the distinguishability of the path of the two photon is kept.

3. Type II PDC sources and applications

Various other experiments were realized with type II PDC sources.

Here we would like only to mention the two most recent of them.

In the first one we generated collinear degenerate biphotons [16] that travelled through a dispersive medium (a fiber) before being split by a beam splitter and detected (see Fig. ??). The temporal growing of the wave packet into the fiber was

[a]Incidentally, also experiments at single photon level where zero-point field does not look to play a relevant role [12] appear not to be describable in such a theory.

demonstrated to allow on the one hand to measure interference effects [15] otherwise under temporal resolution of detector apparatuses and on the other hand to restore indistinguishability (by erasing longitudinal walk-off) and therefore entanglement for pairs in the center of the coincidence peak (allowing the observation of a violation of Bell inequalities). The effect was studied for various configurations: 250 m and 1 km fiber and two passes through a 250 m fiber with a Faraday mirror reflecting back the light (since the Faraday mirror acts as a time reverse operation [17] this configuration allowed for an erasure of fiber polarization effects allowing a very high stability of the setup). The Full Width at Half Maximum of the coincidence peak grew from 0.8 ns in absence of the fiber up to 4.5 ns with the 1 km one. The high visibility in the center of the peak (see Fig. 4) between the configuration with polarizers orthogonal and parallel in 45° basis (where the pump beam is vertical) certifies the restoration of the entanglement. Indeed, for example, with the 1 km fiber a clear violation of the Bell inequality

$$R = \frac{|N(\pi/8) - N(3\pi/8)|}{N(\infty, \infty)} \leq 0.25 \tag{1}$$

($N(\theta_1, \theta_2)$ being the number of coincidences for polarizers settings θ_1, θ_2 and ∞ denoting no selection) was observed when selecting the central 0.43 ns, $R = 0.322 \pm 0.061$.

This setup also allowed the study of transmission in fiber of polarization entangled states, permitting researches on decoherence effects. The rapid variation of the polarization effects suggested a scheme for realizing a controlled decoherence on a quantum channel based on plunging the fiber into an ultrasound bath. This setup is now under realization and will find applications ranging from characterization of the channel as a Completely Positive map to studies on decoherence in realistic Quantum Key Distribution protocols.

The second experiment was addressed to reconstruct the photon statistics by using on/off detectors only [18]. Since the knowledge of the statistics of quantum optical states is a prerequisite for various experiments ranging from quantum optics to quantum information, and no available detector can well determine the number of incident photons, this research has large relevance for a wide spread application. In little more detail, we reconstructed the photon statistics of various optical states by a maximum likelihood algorithm applied to data obtained by varying the optical transmittivity through the introduction of calibrated neutral filters, both for mono-partite [19] and bi-partite [20] cases, showing the large potentialities of the method. In particular, for example, very interesting results were obtained with single heralded photons produced by type II PDC (see Fig. 5).
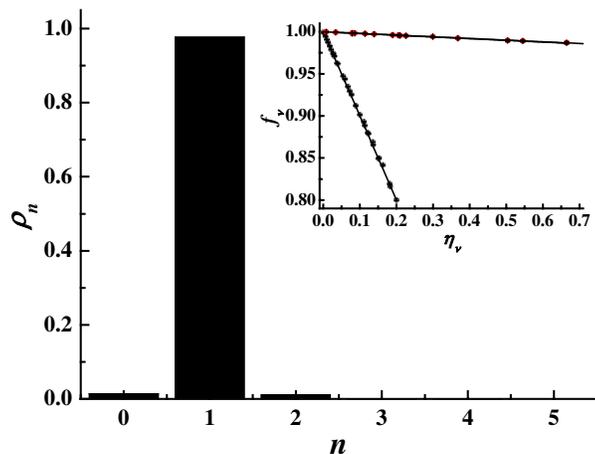
4. Acknowledgements

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Fig. 5.   Reconstruction of the photon distribution for the heralded single-photon state produced in type II PDC. Inset: The steepest curve corresponds to experimental frequencies f_ν of no-click events as a function of the quantum efficiency η_ν for a PDC heralded photon state compared with the theoretical curve $p_\nu = 1 - \eta_\nu$. The small vacuum and two photon components are in agreement with what estimated. For the sake of completeness the curve for data on a weak coherent state is shown as well (highest one).

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