We review some recent experimental progresses concerning Foundations of Quantum Mechanics and Quantum Information obtained in Quantum Optics Laboratory "Carlo Novero" at IENGF.

More in details, after a short presentation of our polarization entangled photons source (based on precise superposition of two Type I PDC emission) and of the results obtained with it, we describe an innovative double slit experiment where two degenerate photons produced by PDC are sent each to a specific slit. Beyond representing an interesting example of relation between visibility of interference and "welcher weg" knowledge, this configuration has been suggested for testing de Broglie-Bohm theory against Standard Quantum Mechanics. Our results perfectly fit SQM results, but disagree with dBB predictions.

Then, we discuss a recent experiment addressed to clarify the issue of which wave-particle observables are really to be considered when discussing wave particle duality. This experiments realises the Agarwal et al. theoretical proposal, overcoming limitations of a former experiment.

Finally, we hint to the realization of a high-intensity high-spectral-selected PDC source to be used for quantum information studies.

I. INTRODUCTION

Quantum Mechanics (QM) is one of the pillars of modern physics, verified by a huge amount of extremely precise experimental data. Nevertheless, one century after its birth, it still presents many unclarified issues at its very foundations as the transition from a probabilistic microscopic world to a deterministic macroscopic one, quantum non-locality, the correct interpretation of duality principle, etc. Of course a clear understanding of all these points is of the greatest relevance.

Most of foundational problems of QM and its unintuitive properties are related to entanglement, which, according to E. Scrödinger, is "the characteristic trait of quantum mechanics". For example one can recall the EPR paradox and all the discussion about Bell inequalities.

Beyond its huge conceptual interest, in the last years entanglement has been recognized as a main resource for quantum communication and quantum computation. In quantum communication the use of entangled photons is, without any doubts, the main resource for future developments, being the basis of various protocols as quantum teleportation, quantum dense coding and entanglement swapping or quantum key distribution. Furthermore, it has some interest for quantum metrology as well.

Thus the realization of efficient sources of entangled states is of the utmost relevance.

In the following we describe our high intensity source of polarisation entangled states of photons. Then we describe a first test of dBB theory against Standard Quantum Mechanics obtained in a double slit experiment and discuss an experiment addressed to reach a conclusive answer to the interpretation of complementarity principle. Finally, we hint to the realization of a PDC source of correlated photons with high spectral selection addressed to an experiment of photon-photon interaction in Kerr cell.

II. OUR POLARISATION ENTANGLED BIPHOTON SOURCE

Various schemes have been proposed for generating entangled states of photons.

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After the very low efficiency first schemes based on the use of polarisation entangled states of photons generated by cascade decay of atoms \(^8\), in the 90’s a big progress has been obtained by using parametric down conversion (PDC) processes \(^4\). The first experiments \(^11, 12\) used beam splitters for generating entanglement, reducing in this way the total efficiency. More recently, high intensity sources of polarisation entangled states of two photons have been obtained by using Type II PDC \(^12\) or by superimposing two type I PDC emissions, in this case either of two thin adjacent crystals \(^14\) or by inserting them in an interferometer \(^13\).

In our set-up two \(^12\) type I emissions are also superimposed, but by using an optical element between the two crystals. The advantages of this scheme are that, in principle, a perfect superposition can be obtained and that non-maximally entangled states of different degrees of entanglement can be easily realized. More in details (see Fig.1), two crystals of \(\text{LiIO}_3\) (10x10x10 mm) \(^56\) (see Fig. ??) are placed along the pump laser propagation (an argon laser emitting at 351 nm), 250 mm apart, a distance smaller than the coherence length of the pumping laser. This guarantees indistinguishability in the creation of a couple of photons in the first or in the second crystal. An optical condenser, drilled for leaving pass the pump beam, focalizes PDC emission from the first crystal into the second one, whose optical axis is rotated of 90° respect to the first. A quartz plate and a half-wavelength plate inserted on the path of pump beam between the two crystals compensate the birefringence on the first crystal and rotate the polarisation of the beam.

Due to the coherent superposition of the two PDC emissions of different polarisation the output of this set-up is the state:

\[
|\Psi\rangle = \frac{|H\rangle|H\rangle + f|V\rangle|V\rangle}{\sqrt{1 + |f|^2}}
\]  

(1)

where \(H\) and \(V\) are horizontal and vertical polarisation respectively.

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 tune (keeping the maximum available power for the first PDC) the value of \(f\), which determines how far from a maximally entangled state (\(f = 1\)) the produced state is. This is a fundamental property, which allows to select the most appropriate state for the experiment.

This source is very bright since we observe about 10 kHz coincidence rate at 200 mW pump power (result next to the best obtained with two adjacent thin type I crystals and by far larger than the ones realised with type II sources \(^17\)).

Finally, let us notice that by modifying the polarisation of one branch or the phase of the parameter \(f\) all the four Bell states can be easily generated.

A test of the state produced by this source can be obtained by measuring Bell inequalities, as discussed in the following paragraph.

### III. APPLICATIONS TO TEST LOCAL REALISM

In 1964 Bell demonstrated \(^18\) that one can test, with complete generality, standard quantum mechanics (SQM) against every local hidden variable theory (LHVT) by considering specific inequalities involving correlation measurement on entangled states. More recently these inequalities assumed a relevant role in quantum communication as well, since it was shown that they can be used for checking the presence of an eavesdropper in quantum key distribution protocols using entangled states \(^1\).

Many experiments have already been devoted to test Bell inequalities \(^8, 10, 11, 12, 13, 14\), leading to a substantial agreement with quantum mechanics and disfavouring realistic local hidden variable theories. However, due to the low total detection efficiency (the so-called ”detection loophole”) no experiment has yet been able to exclude definitively realistic local hidden variable theories, for it is necessary a further additional hypothesis \(^16\), stating that the observed sample of particles pairs is a faithful subsample of the whole. This problem is known as detection or efficiency loophole. Incidentally, it must be noticed that a recent experiment \(^21\) based on the use of Be ions has reached very high efficiencies (around 98 %), but in this case the two subsystems (the two ions) are not really separated systems during the measurement and the test cannot be considered a real implementation of a detection loophole free test of Bell inequalities, even if it represents a relevant progress in this sense. Analogously, the suggestion that a loophole free experiment could be obtained by using K or B mesons \(^20\) has been shown to be wrong \(^22\), since the detection loophole reappears due to the necessity of selecting specific decay channels in order to tag the mesons.

Considering the extreme relevance of a conclusive elimination of local hidden variable theories, the research for new experimental configurations able to overcome the detection loophole is of the greatest interest.

A very important theoretical step in this direction has been achieved recognising that for non maximally entangled pairs a total efficiency larger than 0.67 \(^24\) (in the limit of no background) is required to obtain an efficiency-loophole free experiment, whilst for maximally entangled pairs this limit rises to 0.81 (see Fig. ??).
Our set-up, allowing the generation of a chosen non-maximally entangled state, allows a step in this direction. In particular we have produced a state with $f \simeq 0.4$.

As a first check of our apparatus, we have measured the interference fringes, varying the setting of one of the polarisers, leaving the other fixed. We have found a high visibility, $V = 0.98 \pm 0.01$, confirming that a good alignment was reached.

As Bell inequality test we have considered the Clauser-Horne sum,

$$CH = N(\theta_1, \theta_2) - N(\theta_1, \theta'_2) + N(\theta'_1, \theta_2) + N(\theta'_1, \theta'_2) - N(\theta'_1, \infty) - N(\infty, \theta_2)$$  \hspace{1cm} (2)

which is strictly negative for local realistic theory. In $\mathbb{R}^2$, $N(\theta_1, \theta_2)$ is the number of coincidences between channels 1 and 2 when the two polarisers are rotated to an angle $\theta_1$ and $\theta_2$ respectively. Because of low detection efficiency we have substituted in Eq. (2) as in any experiment performed up to now, single counts $N(\theta'_1)$ and $N(\theta_2)$ with coincidence counts $N(\theta'_1, \infty)$ and $N(\infty, \theta_2)$, where $\infty$ denotes the absence of selection of polarisation for that channel. This is one of the form in which detection loophole manifests itself.

On the other hand, quantum mechanics predictions for $CH$ can be larger than zero: for a maximally entangled state the largest value is obtained for $\theta_1 = 67^\circ.5$, $\theta_2 = 45^\circ$, $\theta'_1 = 22^\circ.5$, $\theta'_2 = 0^\circ$ and corresponds to a ratio

$$R = [N(\theta_1, \theta_2) - N(\theta_1, \theta'_2) + N(\theta'_1, \theta_2) + N(\theta'_1, \theta'_2)]/[N(\theta'_1, \infty) + N(\infty, \theta_2)]$$  \hspace{1cm} (3)

equal to 1.207.

For non-maximally entangled states the angles for which $CH$ is maximal are somehow different and the maximum is reduced to a smaller value. The angles corresponding to the maximum can be evaluated maximising Eq. (2) with

\begin{align*}
N[\theta_1, \theta_2] &= \epsilon_1^\bot \epsilon_2^\bot (\sin[\theta_1]^2 \cdot \sin[\theta_2]^2) + \\
&\quad \epsilon_1^\bot \epsilon_2^\Bot (\cos[\theta_1]^2 \cdot \cos[\theta_2]^2) \\
&\quad \epsilon_1^\bot \epsilon_2^\bot (\sin[\theta_1]^2 \cdot \cos[\theta_2]^2 + \epsilon_1^\bot \epsilon_2^\bot (\cos[\theta_1]^2 \cdot \sin[\theta_2]^2) \\
&\quad + |f|^2 \cdot (\epsilon_1^\bot \epsilon_2^\bot (\sin[\theta_1]^2 \cdot \sin[\theta_2]^2) + \epsilon_1^\bot \epsilon_2^\bot (\cos[\theta_1]^2 \cdot \cos[\theta_2]^2)) \\
&\quad + |f|^2 \cdot (|\epsilon_1^\bot \epsilon_2^\Bot |^2 \cdot \sin[\theta_2]^2 + |\epsilon_1^\bot \epsilon_2^\bot |^2) \\
&\quad + (f + f^*) \cdot (\epsilon_1^\Bot \epsilon_2^\bot (\cos[\theta_1]^2 \cdot \sin[\theta_2]^2)) / (1 + |f|^2) \\
&= \epsilon_1^\bot \epsilon_2^\bot (\sin[\theta_1]^2 \cdot \sin[\theta_2]^2) + \epsilon_1^\bot \epsilon_2^\bot (\cos[\theta_1]^2 \cdot \cos[\theta_2]^2) + |f|^2 \cdot (\epsilon_1^\bot \epsilon_2^\bot (\sin[\theta_1]^2 \cdot \sin[\theta_2]^2) + \epsilon_1^\bot \epsilon_2^\bot (\cos[\theta_1]^2 \cdot \cos[\theta_2]^2)) + |f|^2 \cdot (|\epsilon_1^\Bot \epsilon_2^\bot |^2 \cdot \sin[\theta_2]^2 + |\epsilon_1^\bot \epsilon_2^\bot |^2) + (f + f^*) \cdot (\epsilon_1^\Bot \epsilon_2^\bot (\cos[\theta_1]^2 \cdot \sin[\theta_2]^2)) / (1 + |f|^2)
\end{align*}

where (for the case of non-ideal polariser) $\epsilon_1^\bot$ and $\epsilon_2^\bot$ correspond to the transmission when the polariser (on the branch $i$) axis is aligned or normal to the polarisation axis respectively.

The phase of $f$ must be kept next to zero. Any relative phase between the two components of the entangled state reflects into a reduction of Clauser-Horne inequality violation, up to reaching no violation at all for a phase difference of $\pi/2$.

In order to measure $CH$ we selected two conjugated directions at 789 and 633 nm geometrically and by using two interference filters of 4 nm FWHM preceding the avalanche photodiode photo-detectors.

For our produced state, corresponding to $f \simeq 0.4$, the largest violation of the inequality is reached for $\theta_1 = 72^\circ.24$, $\theta_2 = 45^\circ$, $\theta'_1 = 17^\circ.76$ and $\theta'_2 = 0^\circ$, to $R = 1.16$.

Our experimental result $CH = 513 \pm 25$ coincidences per second, is more than 20 standard deviations from zero and compatible with the theoretical value predicted by quantum mechanics. In terms of the ratio $R$, our result is $1.081 \pm 0.006$. The smaller value respect to the theoretical prediction is easily explained in terms of a residual non-perfect alignment.

For the sake of comparison, one can consider the value obtained with the angles which optimize Bell inequalities violation for a maximally entangled state. The result is $CH = 92 \pm 89$, which, as expected, shows a smaller violation than the value obtained with the correct angles setting.

Thus, our result represents a further indication favouring SQM against LHVT. Its main interest is due to the fact that using tunable non-maximally entangled states is a relevant step toward a conclusive experiment eliminating the detection loophole.

Furthermore, it allows also to exclude some specific local realistic models. In particular, we have considered the model of Casado et al. $^{27}$. These authors have presented a local realistic model addressed to be compatible with all the available experiments performed for testing local realism. This model represents the completion of series of papers where this scheme has been developed $^{27}$. The main idea is that the probability distribution for the hidden variable is given by the Wigner function, which is positive for photons experiments. Furthermore a model of photodetection, which departs from quantum theory, is built in order to reproduce available experimental results.
This model has the great merit of giving a number of constraints, which do not follow from the quantum theory and are experimentally testable.

In particular, there is a minimal light signal level which may be reliably detected: a difference from quantum theory is predicted at low detection rates, namely when the single detection rate \( R_S \) is lower than

\[
R_S < \frac{\eta F^2 R_c^2}{2Ld^2\lambda\sqrt{\tau T}} \tag{5}
\]

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, \( \lambda \) the average wavelength of detected photons. \( L \) and \( T \) are two free parameters which are less well determined by the theory \cite{27}: \( L \) can be interpreted as the active depth of the detector, while \( T \) is the time needed for the photon to be absorbed and should be approximately less than 10 ns \cite{27}, being, in a first approximation, the length of the wave packet divided for the velocity of light.

Referring to the parameters of Eq. \( 5 \) we have \( \eta = 0.51 \pm 0.02 \) (a value which we have directly measured by using PDC detector calibration \cite{28}), \( F = 0.9 \) cm, \( R_c = 1 \) mm, \( d = 0.75 \) m and \( \tau = 4.2 \cdot 10^{-13} \) s (due to spectral selection by an interferential filter). \( L \) can be estimated of \( 3 \cdot 10^{-5} \) m. This leads to \( T > 1 \) s, extremely higher than the limit of 10 ns suggested in the model \cite{26}. Thus, we are strictly in the condition where quantum mechanics predictions are expected to be violated and, in particular, a strong reduction of visibility is expected. Nevertheless, our results show a strong violation of Clauser-Horne inequality and a high visibility, in agreement with standard quantum mechanics, and therefore substantially exclude \cite{29} the model of Ref. \cite{26} \cite{57}.

For the sake of completeness, it can be noticed that one of the authors of the previous model presented a new LHVT model \cite{32}, which does not have the same degree of development of the former one, but in its simplicity allows to reproduce all Bell inequalities tests performed with polarisation entangled photons.

In Ref. \cite{32} it is suggested that a test of the model can be performed by comparing the visibility:

\[
V_a = \frac{N(0) - N(\pi/2)}{N(0) + N(\pi/2)} \tag{6}
\]

with

\[
V_b = \sqrt{2} \frac{N(\pi/8) - N(3\pi/8)}{N(\pi/8) + N(3\pi/8)} \tag{7}
\]

where \( N(\theta) \) are the coincidence counts when the two polarizers are set to two angles differing of \( \theta \).

In fact, in the model of Ref. \cite{32}

\[
V_b/V_a > 1 + \cos^2(\pi\eta/2) \left[ V_b - \frac{\sin^2(\pi\eta/2)}{(\pi\eta/2)^2} \right] \tag{8}
\]

is expected, result that can be violated in SQM.

For the moment, the use of our data does not allow to exclude this model since we obtain for the inequality \( 8 \) the value 1.177 > 1.04 (a value above unity probably denotes that our data, not explicitly taken for this purpose, do not yet allow a sufficient accuracy for this test). A further dedicated experiment will be realized in a near future.

Finally, we would like to point out that this high intensity source can find a natural application in quantum communication. In particular, at the moment we are implementing a scheme \cite{31} for codifying in four dimensional Hilbert spaces (since codification in higher dimensional Hilbert Spaces may present a larger security \cite{33}) and another addressed to use Kerr interaction in rubidium atoms cell for realizing a controlled unitary gate at single photon level \cite{34}.

**IV. AN INNOVATIVE DOUBLE SLIT EXPERIMENT**

Even if Bell inequalities experiments will lead to a conclusive test of local hidden variable theories, non-local hidden variable models (NLHVT) will still be possible.
The most interesting example of NLHVT is the de Broglie Bohm theory (dBB). dBB 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 it is non-local. 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 by Ref.s [35, 36, 37].

In particular Ref.s [35, 36, 37] suggest that differences can appear in a double slit experiment where two identical particles cross each a specific slit at the same time.

Such a configuration can be easily realized with our set-up substituting the second crystal with a double slit. In particular we have used two slits separated by 100 µm of a width of 10 µm. They lay in a plane orthogonal to the incident laser beam and are orthogonal to the table plane.

Different PDC photon pairs crossing the double slit are statistically distributed with a dispersion of the order of 10µm determined by geometrical acceptance, but photons in a single pair have strong spatial correlation. By using the formalism presented in Ref. [42], we can calculate that the dispersion of the positions of photons of a single pair at the double slit is geometrically around 0.25µm (see the Fig. ??). Furthermore, in any case the two photons arrive at the double slit at the same time, in the sense that both cross the slit at the same instant largely within their coherence time (? ? 400/fs). In this sense the theoretical proposal is well realized and a partial penetration of at most few tens of micrometers of trajectories in the same semiplane is expected.

Two single photon detectors are placed at 1.21 m and at 1.5 m from the slits after an interference 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.

In Fig. ?? we report the measured coincidence pattern. The data are obtained by averaging 7 points of 30’ acquisition each. One detector is placed at −5.5 cm from the symmetry axis, whilst the second is moved sweeping the whole diffraction peak. The data are in agreement with the pattern predicted by SQM,

\[ C(\theta_1, \theta_2) = g(\theta_1, \theta_B^A)^2 + g(\theta_2, \theta_B^A)^2 + 2g(\theta_1, \theta_B^A)g(\theta_2, \theta_B^B)g(\theta_1, \theta_B^B)\cos(k_s(\sin\theta_1 - \sin\theta_2)) \]

where

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

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

A clear coincidence signal is observed also when the two detectors are placed in the same semiplane respect to the double slit symmetry axis. In particular, when the centre of the lens of the first detector is placed -1.7 cm after the median symmetry axis of the two slits (the minus means to the left of the symmetry axis 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 minutes after background subtraction, ruling out a null result at nearly eight standard deviations. Thus, if the former theoretical prediction will be confirmed, this experiment poses a strong constraint on the validity of de Broglie-Bohm theory, which is the most successful example of a non-local hidden variable theory, representing a very relevant progress on the line of a final clarification of foundations of quantum mechanics [41].

Even if the former theoretical prediction is still somehow subject to discussion [39], we think that our results [40], in agreement with SQM predictions but at variance with dBB ones, represent a relevant contribution to the debate about the foundations of quantum mechanics urging a final clarification about validity of this theoretical proposal.

A further interesting property of this scheme is that it allows a new clear test of the connection between which path knowledge and absence of interference. Since idler and signal photons have no precise phase relation and each photon crosses a well defined slit, no interference appears at single photon detection level. When the coincidence pattern is considered, path undistinguishability is established since the photodetector 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.

In Fig. ?? we report the observed coincidence pattern (with 10 acquisitions of one hour 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 \( \chi^2 \) of 0.9. By comparison, a linear fit (absence of interference) gives \( \chi^2 = 12.6 \) (with 5 degrees of freedom) and is therefore rejected with a 5% confidence level. 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.

V. WAVE PARTICLE DUALITY EXPERIMENT

Wave particle duality is one of the fundamental aspects of Quantum Mechanics. Nevertheless, the original Bohr statement about the term complementarity (in particular complementarity between wave and particle behaviours) “to denote the relation of mutual exclusion characteristic of the quantum theory with regard to an application of the various classical concepts and ideas” has been recently subject of a wide debate and a paradigm where this “mutual exclusion” must be interpreted in a weaker sense is emerging.

Several experiments with single photons and atoms in interferometers have shown how a gradual transition takes place between the two aspects, wave (interference) and particle (which path knowledge). The knowledge of “welcher weg” (which path) is therefore alternative to coherence (and thus to the possibility of having interference) with a smooth transition between a perfect “welcher weg” knowledge and a 100% interference visibility. However, the extension of complementarity to classical concepts of waves and particle in every situation (including, also, for example tunnel effect or birefringence) is not contained in the mathematical formalism of Quantum Mechanics (and not tested by interference experiments) and can be questioned. Furthermore, in interference experiments the use of beam splitters (or similar devices) can be somehow modelled with classical particles transmission and reflection.

In this sense a large interest arouses an experiment based on the theoretical proposal of Ref. where the coincidences between photodetectors after a tunnel effect in a double prism of single photons produced in Parametric Down Conversion are studied.

In more detail, a single photon arriving on two prisms separated by a small distance (less than the photon wave length) can either be totally reflected or tunnels through the gap. In the first case it will be sent to a first detector, in the second case to another one; coincidences (anticoincidences) between these two detectors are then measured. The “sharp” particle, anticoincidence, and wave, tunnel (rather than interference), properties are simultaneously realized. The observation of coincidences is incompatible with quantum optics, but could be explained in terms of stochastic optics.

The result of this experiment was the observation of anticoincidences between detectors showing that single photons both had performed a tunnel (wave behaviour) and had been detected in only one of the detectors (“welcher weg” knowledge), leading, therefore, to an agreement with quantum optics, namely, light showed both classical wave-like and particle-like pictures simultaneously “in contrast with conventional interpretation of the duality principle.”

In Ref. this result was interpreted as an indication in favour of de Broglie-Bohm theory.

Nevertheless, the results of this experiment were questioned as a case of “an insufficient statistical precision”. More in detail, in Ref. it was introduced the parameter \( \alpha = \frac{N_1 \times N_2}{N_{c} \times N_{c}} \) (where \( N_{c} \) denotes coincidence counts, \( N \) the number of gates where photons are counted and \( N_1 \) and \( N_2 \) single detector counts), which should be \( \geq 1 \) for a classical source and \( < 1 \) for PDC quantum states (strictly zero in absence of background) applying it to a test of interference - “welcher weg” knowledge experiment. In Ref. this parameter was estimated to be \( \alpha \simeq 1.5 \pm 0.6 \) for the data of Ref. Given that, according to Ref., this parameter \( \alpha \) is the best discriminator between classical and quantum states, the experimental precision of Ref. was therefore largely insufficient to discriminate between classical and quantum light.

Considered the large relevance of these studies for the very foundations of Quantum Mechanics, we have realized a new version of this experiment, where the wave behaviour is related to birefringence as suggested in Ref., overcoming the previous limitations.

Our scheme consists (see Fig.) of a heralded single photon source based on type I parametric fluorescence generated by an UV pump laser (at 351 nm) into a non-linear crystal. From PDC properties, the observation of a photon (at a 633 nm), after spatial and spectral selection, in a first detector (D3) implies the presence of a second photon on the conjugated direction (at 789 nm) and can therefore be used to open a coincidence window (by starting a ramp of two TACs) where the second photon is expected to be detected. Before detection this second photon crosses a birefringent crystal where its path is split according to its polarisation: birefringence (and in particular the fact that refractive indices are both larger than unity) is a typical phenomenon explained only in terms of wave like propagation. Finally, two single photon detectors (D1 and D2) are placed on the two possible paths (for ordinary and extraordinary polarisation) and their outputs are respectively routed (as stop) to the previous TACs. The measurement of coincidences between these two last detectors (by an AND circuit) in the window opened after a count in the first detector (D1) allows in complete analogy to Mizobuchi and Oltaké experiment, observation of corpuscular properties of the photon (specific path) together with wave ones (birefringence). On the other hand, the use of a high intensity source and of a simple scheme allow to overcome the low statistic limitations of the previous experiment.
In this configuration the logical AND between the valid starts of the two TACs (where the start is the number of counts measured by D3) represents therefore the number of gates (N). \( N_c \) and \( N \), together with the number of counts in the 7ns temporal window measured by D1 (\( N_1 \)) and D2 (\( N_2 \)), allow the evaluation of \( \alpha = \frac{N_c N}{N_1 N_2} \).

The results of our experiment for this parameter in function of the average single counts on trigger channel D3 (corresponding to different attenuations of the pump laser beam), are shown in Fig. ???. The data are obtained with 500 acquisitions of 1 s per point, except the one at 20000 counts/s obtained with 5000 acquisitions of 1 s. As expected, due to small background, data are compatible with zero at low single counts values. At larger values accidental random coincidences are not anymore negligible and the measured \( \alpha \) increases, remaining however largely under unity in the whole investigated region. The weighted average of the first three points \( \alpha = 0.022 \pm 0.019 \) is (within almost one standard deviation) compatible with zero, as expected from QM, differing from unity of more than 51 standard deviations.

In order to compare PDC single photon results with a classical source, we have repeated the measurement by using an attenuated He-Ne laser, emitting at 633 nm, and a thermal source (tungsten lamp). In this case the gate (the start of TACs) is given by a pulse generator with a trigger frequency rate of 65 kHz (see Fig. ??); the rest of the apparatus is the same as before. In Fig. ?? (similarly to Fig. ???) we report the results (with 500 acquisitions of 1 s per point) for the laser as function of the average single counts of one of the detectors (i.e. of laser power, attenuated by inserting neutral filters). Our experimental average datum \( \alpha = 0.9980 \pm 0.0022 \) is in perfect agreement (within one standard deviation) with the result expected for laser coherent light, i.e. \( \alpha = 1 \). Similarly, for the thermal source we obtain (see Fig. ??) the average value \( \alpha = 1.0010 \pm 0.0028 \) in perfect agreement with the expected value \( \alpha = 1 \).

Thus, in conclusion, we have realized a new version of the experiment suggested in Ref. [47, 49], which overcomes limitations [51] of a previous similar experiment [50] leading to a conclusive answer to the questions raised in the original theoretical paper.

VI. SOURCE OF PDC PHOTONS WITH A HIGH SPECTRAL SELECTION

In the last years the need of high intensity PDC sources has assumed a large relevance for several applications. Among them, interaction of entangled photons with atomic levels, which requires very strong spectral selection (a band width around \( 10^{-5} \text{nm} \)) and therefore a large initial power for having a final sufficient intense signal, is very important for many applications as quantum memories [54], remote quantum clocks synchronisation [55], realisation of quantum logical gates, etc. In our laboratory a work is in progress (in collaboration with Camerino University, LENS and INOA) for realising a controlled-not gate by interaction of two photons by mean of Kerr effect in Bose-Einstein condensate [56].

For this purpose we have realized a PDC pulsed source with a spectral selection up to 0.01 nm obtained with two monochromators.

The source is based on a 5 ns (10 Hz repetition rate) triplicate Neodimium-YAG laser (355 nm) emitting pulses with a power up to 200 mJ that are used for pumping a 5x5x5 mm BBO crystal where PDC light is generated (see Fig. ??). After the crystal and a first spatial selection two conjugated directions, corresponding to a wavelength of 780 nm and 651 nm, are addressed to the monochromators.

In order to clearly identify the direction corresponding to the wavelength 780.251 nm of the rubidium 87 transition \( 5 \ 2 F = 2 \rightarrow 5 \ 2 F' = 3 \) we have locked a diode laser to the transition line and then used it for tracing the optical paths of this wavelength and of the conjugated stimulated emission in the PDC. The locking is achieved by injecting the laser diode beam into a Rb gas sample and varying its frequency until a dip in the transmission profile of the Rb sample is seen on a photodiode output; the frequency modulation is achieved by means of a modulation in the length of the extended cavity of the laser diode. The alimentation current of the laser diode is then finely varied by a feedback electronic module in order to lock the frequency to the transmission dip corresponding to the chosen Rb.

The output of monochromators is then addressed to two avalanche photo-diodes, whose output is 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 analyse for selecting and counting coincidence events.

Even if the low repetition rate of the laser (and the dead time of detectors) limits the number of coincidences to 10 per second, due to the high intensity of the laser the number of pairs produced per pulse is high and one has a large number of pairs even after a strong spectral selection. The set-up is therefore suited for looking for Electromagnetic-Induced-Transparency and Kerr effect at single photon level with the purpose of realizing, in perspective, a controlled-not gate at single photon level (the fundamental missing gate for realizing optical quantum computation [1]).
VII. CONCLUSIONS

In this proceeding we have presented some recent experiment realized at the "Carlo Novero" laboratory at IENGF (some other results is presented in the contribution of M. Chekhova et al. in this proceedings).

In particular, we have described one of our sources of polarisation entangled photons, constituted of two \( \text{LiIO}_3 \) crystals whose type I PDC emission (of opposite polarisation, having rotated the polarisation of the pump laser which pumps both of them) are superimposed by means of an optical condenser. Since the distance between the two crystals is smaller of the coherence length of the pump laser, the emitted state is an entangled one of the form:

\[
|\Psi\rangle = \frac{|H\rangle|H\rangle + f|V\rangle|V\rangle}{\sqrt{1 + |f|^2}}
\]

where the degree of entanglement \( f \) can be tuned by varying the pump intensity and phase between the two crystals.

This source is rather brilliant: we measured a 10 kHz coincidence rate at 200mW pump power.

Because of these properties this source represents an interesting device for quantum communication and foundations of quantum mechanics experiments.

Then, we have reviewed an experiment realized with it, where non-maximally entangled states were used for testing Bell inequalities for the first time. Furthermore, we have described a double slit experiment that we have realised with a modification of this set-up, which was addressed to a first comparison between Standard Quantum Mechanics and de Broglie-Bohm theory, with an unfavourable result for this last.

We have then reported on a recent experiment about wave-particle duality that was devoted to overcome limitations of a previous one [49], giving a final answer to the theoretical discussion started by ref. [49].

Finally, we have hinted to the realization of a pulsed high intensity PDC source which will be used in an experiment about photon-photon interaction in atomic medium.

Altogether we hope to have given an idea of the experimental activity about Foundations of Quantum Mechanics and Quantum Information performed in "Carlo Novero" laboratory in our institute.

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Figures Captions

Fig. 1 Sketch of the source of polarisation entangled photons. NLC1 and NLC2 are two LiIO$_3$ crystals cut at the phase-matching angle of 51°. L1 and L2 are two identical plano-convex lenses with a hole of 4 mm in the centre. C is a 5 x 5 x 5 mm quartz plate for birefringence compensation and $\lambda/2$ is a first order half wave-length plate at 351 nm. U.V. identifies the pumping radiation at 351 nm.

Fig. 2 Contour plot of the quantity $CH/N$ (see Eq. 2. N is the total number of detections) in the plane with $f$ (non maximally entanglement parameter, see the text for the definition) as y-axis and $\eta$ (total detection efficiency) as x-axis. The polarisers are supposed to have $\epsilon_{||} = 0.99$. The leftmost region corresponds to the region where no detection loophole free test of Bell inequalities can be performed. The contour lines are at 0, 0.05, 0.1, 0.15, 0.2.

Fig. 3 Scheme of our experiment where two different pairs produced in two different point of the crystal are shown. The first pair is produced exactly on the double slit symmetry axis. The second is produced 10 $\mu$m above this, and is at the limit of geometrical acceptance. The cones represent the spatial dispersion of photons of the single pair due to finite crystal dimension and pump width. Figure is not in scale.

Fig. 4 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 region without data around this point is due to the superposition of the two detectors). The x errors bars represent the width of the lens before the detector. A correction for laser power fluctuations is included.

Fig. 5 Plot of coincidences pattern (in arbitrary units) as a function of the positions of the first photo-detector when the second one is kept fixed at -1 cm from the symmetry axis.

Fig. 6 The experimental set-up. A vertically polarized Argon laser beam at 351 nm pumps a lithium iodate crystal (5x5x5 mm) where type I PDC (i.e. horizontally polarized) is produced. One photon of the PDC correlated pairs (at 633 nm) is detected, after an iris, a lens (L) and an interference filter (IF) by an avalanche single photon-detector (D3) and used as start of two Time to Amplitude Converters. To these TACs are then routed (as stop) the signals obtained by two single photon detectors (D1 and D2) placed on the ordinary (45°) and extraordinary (135°) paths selected by a calcite crystal placed on the conjugated direction (789 nm) to the former one (both detectors preceded by an iris, lens and an interference filter). The outputs of the two TACs are then routed to an AND circuit giving coincidences ($N_c$).

Fig. 7 Values of the parameter $\alpha$ (see text) for heralded single photons produced by PDC in function of the single counts of trigger detector (intensity of the pump laser).

Fig. 8 Experimental set-up for a classical source. The attenuated classical source light is focalized into the calcite crystal splitting ordinary and extraordinary rays. The two branches are than measured by single photon detectors which are routed as stop to two TACs. The start signal to TACs is given by a pulse generator. The outputs of TACs feed an AND logical gate giving the coincidence counts.

Fig. 9 Values of the parameter $\alpha$ in function of the single counts of one of the detectors for an He-Ne laser beam.

Fig. 10 Values of the parameter $\alpha$ in function of the single counts of one of the detectors for thermal light (tungsten lamp emission)

Fig. 11 Sketch of the optical bench with the pulsed high intensity PDC source. A 355 nm pump beam is injected in a BBO crystal and produces PDC emission. Two conjugated directions are spatially selected and focused by lenses in the input slits of monochromators. The one corresponding to the wavelength 780 nm is sent into a Rb gas sample. The two conjugated directions are then picked up by single photon detection modules and the signals are routed to a coincidence circuit. The tracing of the chosen wavelengths in the PDC emission is obtained using a laser diode beam locked to the Rb absorption line. The locking is achieved sending the laser beam in a Rb sample, monitoring the absorption on a photodiode and modifying consequently the length of the extended cavity of the laser. The polarizing beam splitter in figure, jointly with a rotatable lambda-quarter waveplate, allows for directing the beam towards the photodiode or towards the BBO crystal.

Fig. 12 Picture of the optical bench with the pulsed high intensity PDC source. On the bench one can recognize the Neodium-Yag laser (foreground right), the BBO crystal, the monochromators followed by detectors (background) and the rubidium-line locking system (foreground left).
QM prediction

Experimental data

Position of the detector 1 with respect to the symmetry