A conclusive experiment to throw more light on ”light”

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Abstract

We describe a new realization of Ghose, Home, Agarwal experiment on wave particle duality of light where some limitations of the former experiment, realized by Mizobuchi and Ohtaké, are overcome. Our results clearly indicate that wave-particle complementarity must be understood between interference and ”whelcher weg” knowledge and not in a more general sense.

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Wave particle duality is one of the fundamental aspects of Quantum Mechanics, central element of the knowledge of every physics student.

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” [1] has been recently subject of a wide debate and a paradigm where this ”mutual exclusion” must be interpreted in a weaker sense is emerging. Incidentally, it must be noticed that the mutual exclusion was thought by Bohr as a necessary condition for internal consistency of his interpretation attributing a classical behaviour to detection apparatuses [123] (we do not enter in this letter in the extensively debated and still unclarified issue of measurement in quantum Mechanics, see Ref.s [34] and Ref.s therein).

In particular a series of experiments with single photons and atoms in interferometers have shown how a gradual transition takes place between the

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two aspects (wave and particle) [3], described by the Greenberger-Gisen inequality $P^2 + V^2 \leq 1$, where $P$ denotes the predictability of path (particle behaviour) and $V$ the visibility of interference (wave behaviour). 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. The extension of complementarity to classical concepts of waves and particle in every situation (including, also, for example tunnel effect or birefringence) is nevertheless not contained in the mathematical formalism of Quantum Mechanics and can be questioned [4].

Furthermore, in interference experiments [5,3] the use of beam splitters (or similar devices) can be somehow modelled with classical particles transmission and reflection [2]. In this sense a large interest arouses an experiment [7] based on the theoretical proposal of Ref. [6] where the coincidences between photodetectors after a tunnel effect in a double prism of single photons produced in Parametric Down Conversion are studied (quantum version of the 1897 J.C. Bose’s experiment [4]). More in 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 result of this experiment was the observation of antico incidences 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). Should the photon behave like a classical wave, part of it would be reflected and a part would tunnel, originating coincidences. If it would behave like a particle it would not be able to tunnel. On the other hand, in Quantum Optics, the single photon either tunnels or is reflected, thus it reveals itself as a wave when it tunnels through the gap, but keeping its particle behaviour indivisible and following a specific path. Experimental results, according to the authors, lead, 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. [2] this result was interpreted as an indication in favour of de Broglie-Bohm theory [2], however this interpretation is debated [3].

Nevertheless, the results of this experiment were questioned [8,4] as a case of "an insufficient statistical precision”. In particular in Ref. [8] it was noticed that the parameter $\alpha = \frac{N_c}{N_1 N_2}$ (where $N_c$ denotes coincidence counts, $N$ the number of gates where photons are counted and $N_1$ and $N_2$ single detector counts)
counts), which should be $\geq 1$ for a classical source and $<< 1$ for PDC quantum states [5] (strictly zero in absence of background), was $\alpha \simeq 1.5 \pm 0.6$ for the data of Ref. [7]. According to Ref. [5,8,4] this parameter $\alpha$ is the best discriminator between classical and quantum states. The experimental precision of Ref.[7] 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 decided to realize a new version of this experiment where the previous limitations are overcome. In particular, we have realized an experiment where the wave behaviour is related to birefringence, as suggested in Ref. [4] by one of the authors of the original proposal [6].

Our scheme consists of a heralded single photon source based on type I parametric fluorescence generated by an UV pump laser into a non-linear crystal. This source is obtained by using the PDC property that photons are produced in pairs emitted within few femtoseconds conserving energy and momentum, i.e. $\nu_0 = \nu_1 + \nu_2$ and $\vec{k}_0 = \vec{k}_1 + \vec{k}_2$ where indexes 0, 1, 2 denote the pump and the two PDC photons respectively. Thus, the observation of a photon, after spatial and spectral selection, in a first detector (D3) implies the presence of a second photon on the conjugated direction with a fixed frequency. The detection of the first photon is therefore used to open a coincidence window 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 polarization: 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 polarization). The measurement of coincidences between these two last detectors in the window opened after a count in the first detector (D1) allows [4], in complete analogy to Mizobuchi and Ohtake experiment [7], 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.

More in details, our set-up, see Fig.1, consists of a vertically polarized Argon laser beam at 351 nm pumping 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 and an interferential filter (4 nm FWHM) by an avalanche single photon-detector (D3). The output of this detector is used as trigger (start) of two Time to Amplitude Converters (TAC). The observation of this photon guarantees, thanks to the entanglement properties of PDC light [10], the presence of a single photon on the conjugated arm, namely realizes a heralded single photon source. To the previous TACs are then routed respectively (as stop) the signals obtained by the 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 (at 789 nm) to the former one. Both detectors are preceded by an iris and an interferential filter, 4 nm FWHM. As expected, clear coincidence peaks (between photodections in detectors D3 and the ones in D1, D2 respectively) were in fact observed sending TACs outputs to a multichannel analyzer, testifying its operativity as heralded single photon source.

Finally, the Single Channel Analyzer (SCA) outputs, giving the number of photo-detection in detectors D1 and D2 respectively arriving in a temporal window of 7 ns after a signal in detector D3, are routed to an AND circuit giving the coincidence counts (N_c). No background subtraction is performed (background contributes as a classical source). In this configuration a 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.2. 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 and differs from unity of more than 51 standard deviations.

This result is what is expected from quantum mechanics formalism, since type I PDC correlated pairs produced by a vertically polarized pump are well described by a state $|H\rangle|H\rangle$ ($H$ denoting horizontal polarization). The state of the second photon (idler) in the 45° − 135° polarization basis is therefore given by the superposition $|\Psi_i\rangle = \frac{|45\rangle + |135\rangle}{\sqrt{2}}$. The two components are split on different paths by the birefringent calcite crystal $|\Psi_i\rangle = \frac{\sqrt{2}}{|45, path_1\rangle + |135, path_2\rangle}$. Thus, coincidences of detections on path 1 and 2, are strictly zero (a part of background).

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. 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.3); the rest of the apparatus is the same as before. In Fig.4 (similarly to Fig.2) we report the results (with 500 acquisitions of 1 s per point) for this case 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. $\alpha = 1$.

For the sake of completeness we have also repeated the same experiment with thermal light emitted by a tungsten lamp focalized in the calcite crystal.

Following the formalism presented in Ref. [10], for orthogonal polarizations $(P_1, P_2)$, the correlation function $\Gamma^{(2,2)}(r_1, r_2) = \langle I(r_1)I(r_2) \rangle$ (where $r_1, r_2$ are the position of the detector 1 and 2 respectively and $I$ is the intensity of the field) factorizes $\Gamma^{(2,2)}(r_1, r_2) = \langle I(r_1, P_1) \rangle \langle I(r_2, P_2) \rangle$; therefore also in this case the expected result is $\alpha = 1$. Our experimental results (always with 500 acquisitions of 1 s per point), presented in Fig.5 in function of average single counts of one of the detectors (i.e. of the lamp intensity), give an average value $\alpha = 1.0010 \pm 0.0028$ in perfect agreement with the former prediction.

Thus, in conclusion, the PDC single photon result reported: $\alpha = 0.022 \pm 0.019$ agrees with Quantum Optics expectations, being largely below unity (more than 51 standard deviations) that would be the result expected (and obtained) by using classical sources.

In summary, we have realized a new version of the experiment suggested in Ref. [6,4], which overcomes limitations [8] of a previous similar experiment [7] leading to a conclusive answer to the questions raised in the original theoretical paper.

Our results, in perfect agreement with the mathematical formalism of quantum mechanics predictions, give a clear and conclusive indication that wave particle duality must be considered in a weak sense as a gradual disappearing of interference when "welcher weg" indications are obtained and not in the original Bohr’s form asserting a complete exclusion of every wave and particle aspects.

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Fig. 1. 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 interferential 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 interferential filter). The outputs of the two TAC are then routed to an AND circuit giving coincidences ($N_c$).
Fig. 2. 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. 3. 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. 4. Values of the parameter $\alpha$ in function of the single counts of one of the detectors for an He-Ne laser beam.
Fig. 5. Values of the parameter $\alpha$ in function of the single counts of one of the detectors for thermal light (tungsten lamp emission)