A non-quantum mechanical explanation of the single photon double slit experiment.

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ABSTRACT

Double slit experiments with true single photons are presently becoming reality. Thus one may speculate that the wave particle duality of light and photons can now be proven unequivocally. This was not the case with earlier experiments using attenuated multi-atom light sources. Here it is suggested that the few available experiments which indeed are using single photons can be explained in a comprehensible manner without invoking quantum mechanics and wave particle dualism. However, one has to give up the notion of an indivisible photon.

KEYWORDS:
double slit experiment, wave particle dualism, indivisible photon

INTRODUCTION

The double slit experiment with true single photons is at the heart of quantum mechanics. It is essentially its only mystery[1]. Until the advent of true single photon sources such experiments had to be performed in the "single photon limit" of attenuated multi-atom light sources. Such single photon sources may be single ions, atoms, molecules and the particularly stable vacancy defect centers in crystals[2,3]. In an earlier paper of this conference series[3] a whole number of arguments were given, why the light of multi atom light sources cannot be attenuated to safely generate single photon quantum states (see also[4]). Thus, all "single photon" double slit experiments reported until the late 1990ies, cannot safely be invoked to discuss one of the most fundamental aspects of physics, namely the wave particle dualism of light.

Recently this problem has been overcome. In a beautiful experiment the group of Alan Aspect has presented the single photon double slit experiment in the Mach-Zehnder version[4]. As light source an individual nitrogen vacancy in a diamond microcrystal was used[1,2]. This experiment does not only show all long sought elements of the single photon double slit experiment, but also the delayed choice experiment proposed by J.A. Wheeler could be verified[4]. It appears that now, at last, Feynmans's only mystery of quantum mechanics has been demystified.

However, the quantum-mechanical interpretation of ref.[4] and of a second experiment [7] in terms of "which path information" is not the only one possible. A more classical interpretation considering functional details of optical elements in the apparatus explains the results equally well. Suggesting such an alternative explanation is aim of the following discussion.

GIVING UP THE NOTION OF AN INDIVISIBLE PHOTON

For the following discussion it will be necessary to abandon the notion of an indivisible photon. This may come as an insult for those thinking completely in terms of quantum mechanics and wave particle dualism. However, a thorough inspection of the literature since the early days of the photon shows that so far not a single experiment was reported which definitely requires an indivisible, particle like, photon[5,6]. This is immediately evident for the photo-effect or the Compton-effect which both have served in the early days to define what a photon is. Both are based on the energetics of photon-matter interaction but cannot really give details on shape. Also, modern experiments in cavities cannot really give such information. The only approach to get some idea on this shape is the accumulation -time argument which in principle could distinguish between a photon shape which is larger than the detecting object and one which is smaller. Recently it was discussed that the accumulation time argument has, so far, not yet been satisfied[5,6] and consequently there is no justification to give a particle like photon priority over a photon which resembles more a light flash which may be described as a physical wave packet or a transient, divisible electromagnetic field. In lack of a sharp experimental distinction, discussions on double slit experiments using divisible and indivisible photons are equivalent.

ON THE MECHANISM OF FUNCTION OF WOLLASTON PRISM

For an experimentalist it is clear that building blocks of an optical experiment are complex and this complexity is not always completely reflected in the quantum mechanical description as simple operators. One critical optical element in many double slit or equivalent experiments are Wollaston prisms. They are supposed to direct perpendicularly polarized light pulses into different directions. This is certainly correct when the pulses are temporally separated by a sufficiently long time. Still not yet understood in detail is what happens when the two photon pulses arrive only a few up to a few tens of femtoseconds after each other.

Assume a light source which generates pairs of pulses identical in polarization and phase, only separated by a tunable temporal distance of a few up to 15 femtoseconds (a few up to 10 wavelengths). These pulse pairs impinge on a Wollaston prism with two output directions and are counted by an avalanche photodiode each (fig 1)

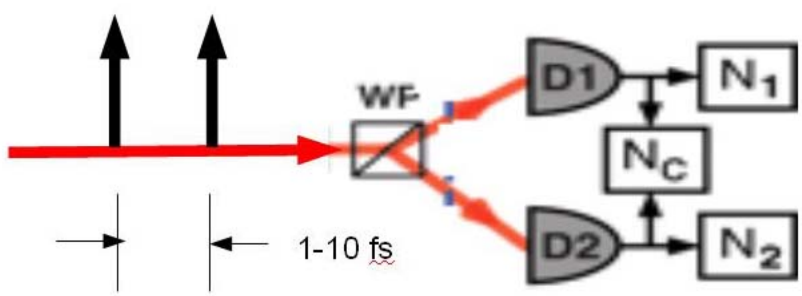

Fig. 1: An experiment revealing the action of a Wollaston prism when a pair of photon pulses impinges at a short temporal (a few femtoseconds) and spatial (a few wavelengths) distance. The two pulses of a pair may have identical (as shown here) or perpendicular (not shown) polarization. (modified from ref.[4].)

When the electro-optic modulator is on and thus the two pulses of the pair have identical orientation, the result is as shown in fig. 2 A: a periodic variation of the count rate in each of the two detectors. When two pulses of a pair are separated by 0, 2, 4, … wavelengths, the count rate is maximal in detector 1 and zero in detector 2. Correspondingly, at a separation of 1,3,5 …. wavelengths the count rate is maximal in detector 2 and zero in detector 1. At other distances, the count rate periodically varies between these extremes, where the sum of the count rates of both detectors is constant. A straightforward explanation of this result is, that the Wollaston prism mixes the action of these pulses and directs them toward detector 1 when the two pulses arrive in phase and towards detector 2 when they arrive in anti – phase. There is no direct interaction of the two pulses in the sense of interference but cooperation of their action on the atoms of the material from which the Wollaston prism is made.

When the electro-optic modulator is off, the two pulses of a pair act as separate objects. Each pulse pair is directed into its own path as one expects this for a Wollaston prism, one towards detector 1 and one towards detector 2. The result is shown in fig. 2 B: The count rate in each of the detectors is independent on spatial and temporal separation, constant and both count rates are half of the maximum rate of the case above where the polarizations were equal.

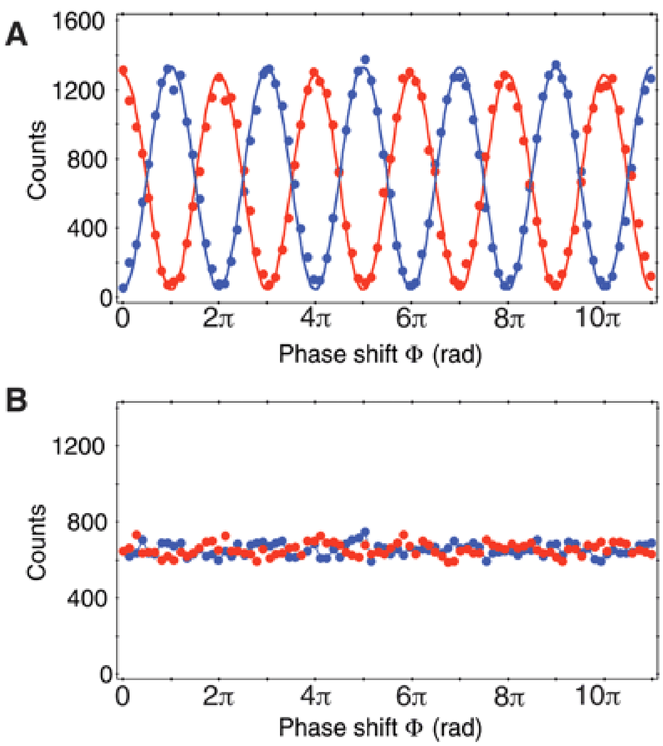

Fig. 2: When the pulses have identical polarization, interference is seen. The temporal delay has the same effect as if the polarization were rotated, with an apparently perpendicular orientation at a delay of half a wavelength. Then, all pulses go to detector 2. The count rate in detector 1 vanishes. The sum of both rates is constant, i.e. no energy is lost. There is nothing like a destructive interference. Looking only at one channel would generate the impression of constrictive and destructive interference, depending on the delay between both pulses of the photon pair (reproduced from ref.[4]).

A SOURCE OF IDENTICAL PAIRS OF PHOTON PULSES

Constructing a suitable source for such pulses is not straightforward. The highest trigger rate of commercially available pump sources is of the order of 100 MHz in Ti Sapphire lasers, i.e. one trigger pulse every 10 nanoseconds, a factor of a million too slow. There is, however, a way out of this dilemma: using a 50:50 beam-

splitter, which allows travelling each of the two pulses along different paths with slightly different lengths and the recombining them by a second beam splitter.
This is depicted in fig. 3.

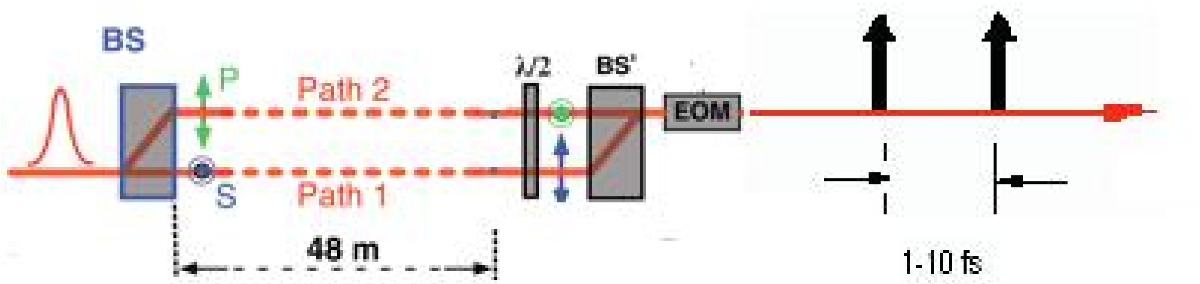

Fig. 3: A source of photon pairs following each other at a short distance. The photon pulse is split in the polarizing beam splitter BS, which also polarizes the outgoing light perpendicularly. At beam splitter BS` the two lines are recombined. By tilting BS', a difference in path length can be generated, so that the part having travelled path 1 comes a few femtoseconds earlier that the one of path 2. The electro optic modulator (EOM) acts as a switchable half wave plate. When it is switched off, the two photons keep their perpendicular polarization. When it is switched on, the both polarizations are turned towards each other so that they finally have identical polarization. (modified from ref.[4].)

THE STEP TOWARDS QUANTUM MECHANICS

The setup of the whole experiment can be seen when light source (fig.2) and the detection part (fig.1) are put together, as shown in fig. 4. It turns out that this is exactly the configuration of the single photon double slit experiment mentioned above[4], except a random switch generator which is used to perform Wheeler's delayed choice. Since by simply combining light source and detection part the physics should not change, i.e. the whole experiment should be explainable in the same non quantum mechanical way as described above.

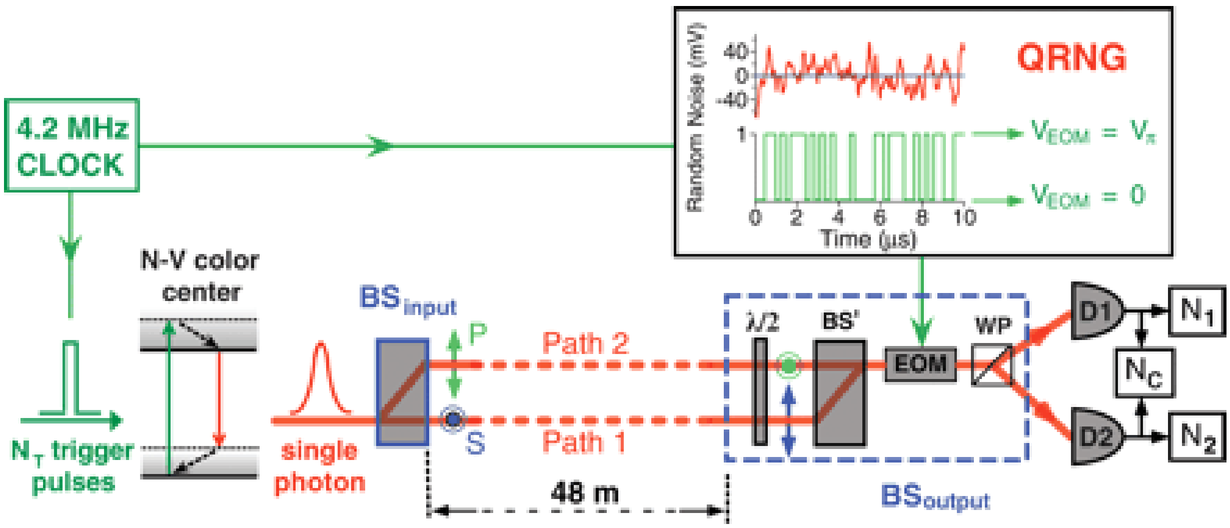

Fig. 4 is a simple combination of fig. 1 and 2, both which have both been described in classical terms of experimental physics. It exactly reproduces the experiment of ref.[4]. There however, the same data, as shown in fig. 3 A and B have been interpreted differently, namely that, when the EOM is switched on and acts as half wave plate, the two photons do interfere and thus reflect the wave properties of light, while, at switched off EOM, the photons cannot interact and thus reveal its particle aspect.

THE MICHELSON VERSION

When individual photons are fed into a Michelson interferometer, interference is detected (see ref.[7]). With an indivisible photon this result is explained as follows: the beam splitter does not split the photon but distributes 50 % of the non divided photons into the path of VD and 50 % into the direct path. The interference does then occur by interference of the wave trains associated with the individual photon.

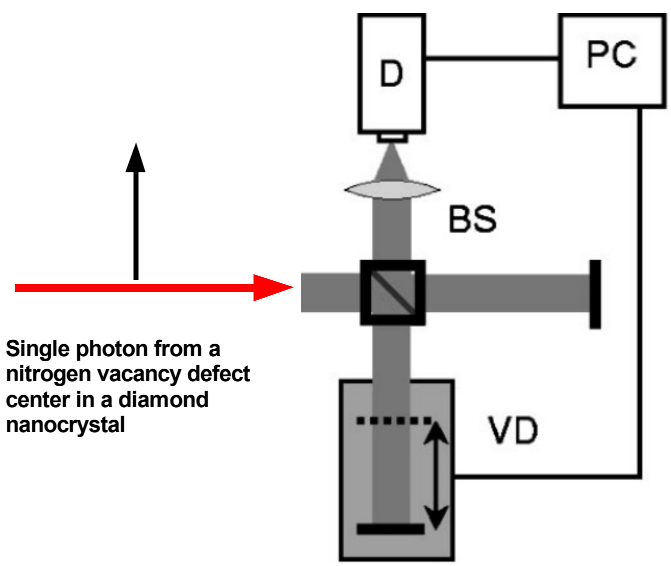

Fig. 5 A double slit experiment in the Michelson version. The beam splitter BS distributes the pulses into two paths, one of which can be varied in length by a motor stage VD. Finally the detector D registers the photons. The compute PC organizes the settings of VD (modified from ref.[7])

This is the well known argumentation of quantum mechanics. How the wave train is associated with the photon becomes comprehensible only in a very vague manner. This complex argumentation is necessary solely to save the indivisible photon, which has, as mentioned above, little experimental justification. When one is willing to give up the indivisibility things become much simpler: The two parts of the photon travel physically along he two paths of different length and are finally recombined in the detector. When they arrive in phase, the detector registers a photon, when they arrive in anti – phase, their action on the material of the detectors is cancelled and the detector registers no signal, simulating extinction. As in the discussion above, this is not really destructive interference but only cancelling of the action on materials. This avoids the often discussed and rarely explained problem where the energy of the photons is going upon destructive interference.

A NON-QUANTUM-MECHANICAL INTERPRETATION IS EQUALLY SUITED

Note that in the present discussion it is not claimed that the quantum –mechanical interpretation may be incorrect. What is claimed is that there is an equivalent non-quantum-mechanical interpretation possible when one abandons the notion of an indivisible photon. Then, interpretations of Mach – Zehnder and Michelson versions of the single photon double slit experiment become much more comprehensible. To finally distinguish between both interpretations, an experiment is needed which shows how a Wollaston prism reacts toward identical single photons impinging within a few femtoseconds, whereby the latter are not prepared, as shown here, by a two-path technique. When such an experiments has a result as described in fig, 2 A, the non-quantum-mechanical interpretation is correct. A result of type shown in fig 2 B would favor the interpretation given in ref.[4].. For the time being, one has to state that the long sought single photon double slit experiment is still not yet safely verified.

APPENDIX

There is a further experiment using the described single photon source[8]. There, the photons are distributed into two paths by a Fresnel bi-prism. One counting arrangement is essentially that of fig. 2. In that case, particle like properties are observed by comparing the count rates in each of detectors D1 and D2 (which is of the order of 50 000 per 5 seconds) with the coincidence rate in detector N_c, (which is in the order of 28 per 5 seconds). Since according to theory, the term

$$\alpha = N_C * N_T \; / \; N_1 * N_2$$

where N_T is the trigger rate of the single photon source (the nitrogen vacancy in the diamond) turns out to be 0.13, this indicates particle like behavior (ideally α should be zero). Would it have been 1, this would have reflected wave properties. The result is interpreted as indicating particle like properties. The non-ideal value of 0.13 is discussed as the result of experimental imperfections.

Then, a CCD camera is placed close to the bi-prism, and a fringe like pattern builds up, confirming wave properties. The latter result is interpreted as confirmation of the wave particle properties of light. Both results together are thought to confirm the wave particle dualism of light. However, the interpretation bears a significant problem. The count rare of the CCD camera is 40 photons per 5 seconds, pretty close to the N_c of the experiment where this count rate of 28 has been discarded because of experimental inaccuracies. Where the 50 000 other counts have gone is not explained in ref.[8]. Since this experiment has also other inconsistencies, it is presently not safe to include it in the discussion on the nature of light.

REFERENCES

[1] Feynman, R.P., Leighton, R.B. and Sands, M.L., [Lectures on Physics], Addison-Wesley, Reading MA (1965)

[2] Beveratos, A., Brouri, R., Gacoin, T., Poizat, J.-P., Grangier, P., "Nonclassical radiation from diamond nanocrystals," Phys. Rev. A 64, 0611802 (2001)

[3] Gruber, A., Dräbenstedt, A., Tietz, C., Fleury, L., Wrachtrup, J. and von Borczyskowski, C., "Scanning Confocal Optical Microscopy and Magnetic Resonance on Single Defect Center," Science 276, 2012 - 2013 (1997)

[4] Jacques, V., Wu, E., Treussart,, F., Grangier, P., Aspect, A. and Roch, J.-F., "Experimental realization of Wheeler's delayed choice Gedanken experiment," Science 315, 966 -968 (2007)

[5] Greulich, K.O., "Single photons cannot be extracted from the light of multi - atom light sources,"Proc. SPIE 6664,66640B (2007) doi: 10.1117/12.735798

[6] Greulich, K.O., "Single molecule experiments challenge the strict particle aspect of the photon,"Proc German Physical Society Hamburg, Q 10 (2009)

[7] Jelezko, F., Volkmer, A., Popa, I.,. Rebane, K.K., and Wrachtrup, J., "Coherence length of photons from a single quantum system," Physical Review A 67, 041802R (2003)

[8] Jacques, V., Wu, E., Toury, T., Treussart,, F., Aspect, A., Grangier, P., and Roch, J.-F., "Single-photon wavefront splitting interference," Eur. Phys. J. D 35, 561-565 (2005)