SIMULTANEOUSLY SHARP WAVE AND PARTICLE-LIKE PROPERTY OF SINGLE PHOTON STATES IN A TWO-PRISM EXPERIMENT

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ABSTRACT

We discuss a two-prism experiment proposed by Ghose, Home and Agarwal [1] for which the formalism of quantum optics predicts anticoincidences for 'Single Photon States'. This implies simultaneous particle <u>and</u> wave-like propagation in contradiction with the complementarity principle.

If one wants to use classical pictures to describe quantum phenomena, it is well known that incompatible descriptions arise on using concepts such as particles or waves. Niels Bohr tried to resolve this problem through his complementarity principle which expresses the impossibility of simultaneously performing experiments corresponding to incompatible classical descriptions. This mutual exclusiveness between complete 'particle-knowledge' and complete 'wave-knowledge' ensures the inner consistency of using classical pictures to interpret quantum phenomena. Recently, however, certain experiments [2] have revealed variable degrees of sharpness of wave and particle-like behaviour, showing that it is possible to obtain partial wave-knowledge and partial particle-knowledge from the same experimental arrangement (<u>unsharp</u> particle <u>and</u> wave-like properties) in terms of the "which path" ("Welcher Weg") information and the corresponding contrast of the interference pattern. In this paper we shall discuss a new experiment with a single-photon source which is different from such "Welcher Weg" experiments and in which <u>simultaneously sharp</u> particle <u>and</u> wave-like properties should be seen in contradiction with the complementarity principle, although there is no ambiguity in the quantum mechanical mathematical description of the experiment.

The classical analogue of the proposed experiment [1] was performed by J.C. Bose [3] in 1897 as reported in Sommerfeld's "Optics" [4]. Bose took two asphalt prisms

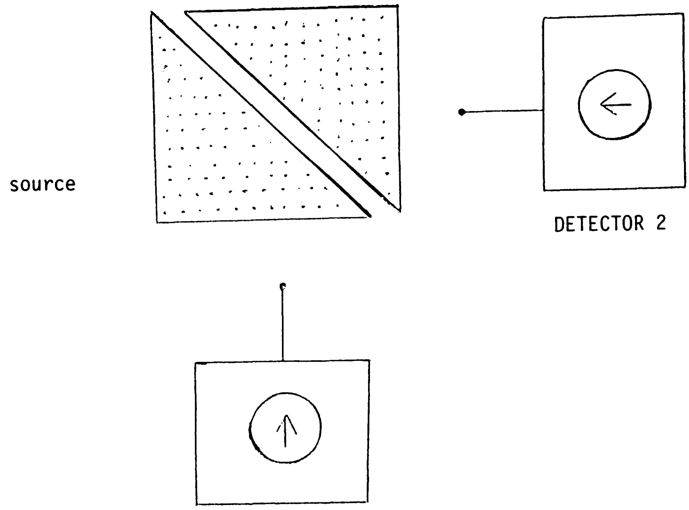

Figure 1

and placed them opposite each other with a large air gap between them (Fig. 1). When microwaves with $\lambda = 20$ cm were incident on the first prism, they were found to be totally internally reflected by it. As he decreased the air gap and made it of the order of several centimeters, Bose found that the waves could tunnel through the gap. This was a striking confirmation of the wave nature of microwaves. Similar experiments can also be done with visible light. Feynman [5] has given a detailed explanation of this effect based on the theory of classical electrodynamics.

The question that arises is: what would happen if this experiment is performed with "single photon states?" Let the single photon state be described by the state vector

$$\Psi = a_t \Psi_t + a_r \Psi_r \tag{1}$$

where Ψ_t is the state that optically tunnels through the gap between the prisms and Ψ_r the state that is internally reflected by the first prism. Let the final states of the two identical detectors (Fig. 1) be D_1 and D_2. The total state vector of the combined system after registrations by the detectors is given by (assuming ideal 100% efficient detectors)

$$\Psi' = a_t \Psi_t D_2 + a_r \Psi_r D_1 \tag{2}$$

For multi-photon states and classical light pulses $< D_1 | D_2 > \neq 0$ and coincidence counts are predicted. However, for single photon states $< D_1 | D_2 >= 0$ (anticoincidence) is the only possibility, and Ψ collapses to a mixed state comprising Ψ_t and Ψ_r with weight factors $|a_t|^2$ and $|a_r|^2$ respectively. One can therefore label each registered photon as coming either after tunneling through the gap or after internal reflection from the first prism. Tunneling through the gap is a clear-cut evidence of the wave-like propagation (to use a classical picture) of a single photon (it should disappear on making the gap larger than the wavelength), whereas perfect anticoincidence of the counts is clear-cut evidence of its particle-like propagation (again to use a classical picture).

To elucidate the difference from a double-slit interference experiment, let us recall that the state vector Ψ of a single photon in such an experiment can be written as

$$\Psi = a_1\Psi_1 + a_2\Psi_2 \tag{3}$$

where Ψ_1 and Ψ_2 are the states emerging from the two slits. The interference between Ψ_1 and Ψ_2 is usually interpreted classically as evidence of its wave-like property. If one places detectors near the two slits, the total wave function of the combined system after detection will be (assuming ideal 100% efficient detectors)

$$\Psi' = a_1\Psi_1 D_1 + a_2\Psi_2 D_2 \tag{4}$$

Since $< D_1|D_2 >= 0$ for single particle states, Ψ collapses to an incoherent mixture of Ψ_1 and Ψ_2 and the interference disappears. Here the anticoincidence between the two detector counts (particle-like propagation) invariably destroys the interference pattern. This is the genesis of Bohr's complementarity principle. In the 'two-prism' experiment, however, anticoincidence is concurrent with optical tunneling. Using classical language, one is therefore forced to use wave and particle pictures to describe the outcome of a single experimental arrangement. Nevertheless, the experiment is consistent with both the Einstein-de Broglie version of wave-particle dualism [6] and the viewpoint advocated by Heisenberg [7] who wrote in 1959: ". . . the concept of complementarity introduced by Bohr into the interpretation of quantum theory has encouraged the physicists to use an ambiguous rather than an unambiguous language, to use the classical concepts in a somewhat vague manner in conformity with the principle of uncertainty . . . When this vague and unsystematic use of the language leads into difficulties, the physicist has to withdraw into the mathematical scheme and its unambiguous correlation with the experimental facts."

A crucial feature of the proposed experiment is the use of genuine "single photon states" and not attenuated classical light pulses even though the average energy per pulse may be smaller than that of a photon of the same frequency. The latter type of source is known not to show any non-classical effect [8]. A very interesting experiment with such weak pulses and "single photon states" incident on a beam-splitter has already been done by Aspect et al. [9] which corroborates the complementarity principle. It shows coincidences with weak pulses but anticoincidences with single photon states exhibiting their particle-like propagation. Nevertheless, if the two channels of the beam splitter are re-combined, interference is observed ("a photon interferes with itself"). The 'two-prism' experiment proposed by us uses tunneling rather than interference and can confront the complementarity principle. It is already under way at the Central Research Laboratory, Hamamatsu Photonics K.K. Japan (Y. Mizobuchi et al.) [10].

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