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An "experiment to throw more light on light": implications

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Mizobuchi and Ohtaké [Phys. Lett. A 168 (1992) 1] have performed the double-prism experiment with single photon states proposed by us [Phys. Lett. A 153 (1991) 403] and verified the quantum optical prediction outlined in that paper. Here we give a detailed justification of our claim that this experimental result contradicts the tenet of mutual exclusiveness of classical wave and particle pictures assumed in Bohr's complementarity principle.

In an earlier paper [1] we proposed an experiment using single photon states incident on a combination of two prisms placed opposite each other with a variable gap between them. Recently, Mizobuchi and Ohtaké [2] have reported results of this experiment corroborating the prediction of quantum optics we had discussed in our paper. The conceptual significance of this experiment as regards wave–particle duality and Bohr's complementarity principle has meanwhile evoked discussions [3]. The interpretation of such an experiment is, of course, a delicate issue; perhaps inevitably, there would be different points of view on what it all means. In this context the purpose of the present paper is to provide a detailed clarification of what in our opinion is the precise significance of this experiment. In particular, we seek to make it clear in what sense the experimental result "confronts the complementarity principle" as asserted in ref. [1].

We recall that in order to observe truly single particle-like behaviour of light one needs a special source emitting what is known as a "single photon state". This is a Fock space state which is an eigenstate of the photon number operator corresponding to the eigenvalue unity. The probability of a joint detection of more than one photon is exactly zero for an "ideal" single photon state. It is in this sense that a single photon state entails a single particle-like propagation. This feature is not exhibited by other states of light (classical or non-classical states such as multiphoton Fock states, squeezed states or states having sub-Poissonian character) for which the probability of a joint detection of more than one photon is different from zero even when the average number of photons (computed by expanding the state concerned as a superposition of photon number eigenstates) is less than unity. It is therefore worth emphasizing that though non-classical effects of light are extensively studied, the notion of mutual exclusiveness between classical wave and particle pictures of light as embodied in the complementarity principle can be critically tested only by using single photon states.

Let us recapitulate the basic idea of our proposed

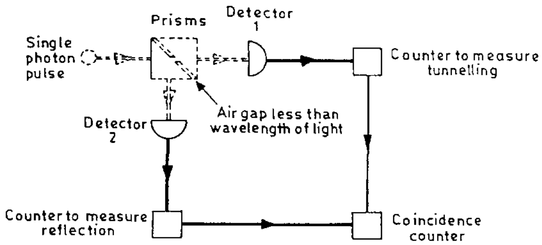

Fig. 1.

experiment (fig. 1). When the gap between the prisms is sufficiently large compared with the wavelength, the incident light would suffer total internal reflection inside the first prism (registered by the detector 2). When the gap is less than the wavelength, there is a possibility that it will tunnel across the gap and emerge from the second prism (registered by the detector 1). We showed that the formalism of quantum optics predicts that the detectors 1 and 2 should click in perfect anticoincidence for "ideal" single photon states. The interesting aspect of this experiment is that although tunnelling is exclusively a wave phenomenon, single photon states can also tunnel. At the same time, perfect anticoincidence between the two detectors implies particle-like propagation. In what follows we shall concentrate on this feature and its implications in the context of Bohr's complementarity principle (henceforth referred to as BCP). For this purpose it is important keep the discussion strictly confined within the framework of BCP and we shall not consider the other points of view such as those based on the causal interpretation or stochastic optics.

At the outset we should like to stress that, contrary to what is popularly believed, discrete localized detection events per se (for example, measuring the photoelectron counts) do not necessarily imply particle-like propagation of the detected entities. Instead, they can be regarded as originating entirely from the quantized energy levels of the atomic constituents of the detector. The crucial point about the experiments of fig. 1 is that, in contrast to tunnelling or interference, the predicted anticoincidence for a single photon state cannot be accounted for in terms of a classical wave-like propagation of the detected entity. Instead, it is compatible only with indivisible particle-like propagation (if one wants to comprehend it by using a classical picture).

In order to set a proper perspective, we shall now briefly discuss the essence of BCP. We note that there are three types of complementarity that Bohr talked about: (a) complementarity between "space–time coordination" and "causal description"; (b) complementarity between position and momentum; (c) complementarity between wave and particle pictures. The relationship between these three types has been the subject of considerable debate (see, e.g. refs. [4–6]). In this paper we are primarily concerned with the complementarity of type (c). Nevertheless, the basic argument common to all variants of complementarity can be summarized as follows.

A crucial ingredient is Bohr's insistence on *classical pictures* as the necessary means of conceptual comprehension of microphysical phenomena (as a supplement to the "symbolic" description provided by the mathematical formalism of quantum mechanics). Bohr's belief that a proper comprehension of quantum mechanical phenomena would come *only* with an understanding of how the classical pictures can be used in a new framework motivated the formulation of BCP. According to BCP, the quantum mechanical formalism *limited* but did not discard the use of classical pictures or concepts.

Here it is important to point out that within the framework of BCP classical concepts are used essentially in the *epistemological* sense, devoid of any ontological significance. In other words, the classical pictures invoked are to be regarded as purely "idealized" representations of our knowledge and they do not correspond to objectively real properties of microphysical entities in the absence of any measurement interaction (see ref. [4], p. 117, ref. [6], pp. 100, 101). This distinction between BCP and the classical framework of describing nature was clearly pointed out in Bohr's famous Como paper (see ref. [7], pp. 56, 57) while referring to entities such as "radiation in free space" and "isolated material particles". At the same time Bohr stressed the necessity of having a suitable *pictorial* representation of their behaviour (in the epistemological sense) by using classical concepts such as wave or particle. Bohr called such pictures "abstractions" which are "indispensable for a description of experience in connection with our ordinary space–time view" (ref. [7], pp. 56, 57). In an interview in 1963 Heisenberg had recalled: "... just by these discussions with Bohr I learned ... that is one cannot go entirely away from the old words because one has to talk about something ... so I saw that in order to describe phenomena one needs a language" [8].

In the Introductory section of his Como paper Bohr wrote: "The quantum theory is characterized by the acknowledgement of a fundamental limitation in the classical physical ideas when applied to atomic phenomena. The situation thus created is of a peculiar nature, since our interpretation of the experimental material rests essentially on the classical concepts" (ref. [7], p. 53; see also ref. [9]). It is the tension between these two aspects (on the one hand, classical concepts are taken to be indispensable for describing quantum mechanical phenomena, and on the other hand, they are subject to certain fundamental limitations) that led Bohr to introduce the notion of *mutual exclusiveness* (abbreviated ME) in the conceptual scheme of BCP.

A precise statement of ME was provided by Bohr in his Introduction to ref. [7]: "... any given application of classical concepts precludes the simultaneous use of other classical concepts which in a different connection are equally necessary for the elucidation of the phenomena" (ref. [7], p. 10). It is abundantly clear from Bohr's writings that he regarded ME as a "necessary" element in BCP to ensure its inner consistency. He also stated categorically that the term "complementarity" was used by him "to denote the relation of mutual exclusion characteristic of the quantum theory with regard to the application of the various classical concepts and ideas" (ref. [7], p. 19; see also for related comments ref. [10]).

With this background (as a supplement to our analysis of BCP see ref. [11]) let us now focus on wave–particle complementarity with particular reference to the beam splitter experiment with single photon states performed by Aspect and his collaborators [12]. Using single photon states (to a very close approximation) produced from the atomic cascade process, they first performed the experiment of fig. 2, showing that the measured probability of coincidence (P_c) for detection on the two sides of the beam splitter is *less* than the *minimum* bound $P_r \times P_t$ derived from the *classical wave* picture, where P_r is the probability of reflection and P_t the probability of

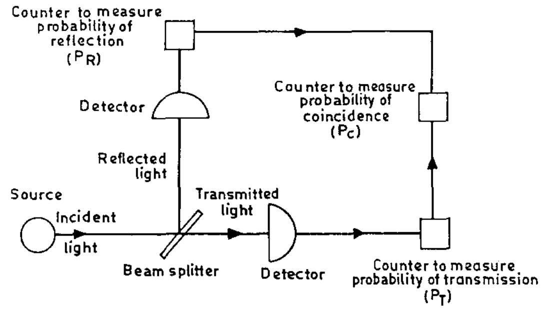

Fig. 2.

transmission [#1] (for strongly attenuated sources of classical or semi-classical light, P_c is found to be greater than or equal to ($\geqslant$) $P_r \times P_t$ even when the average number of photons is less than unity). It is therefore clear that if one wants to comprehend this particular experimental fact (that $P_c < P_r \times P_t$ when single photon states are used) according to the logic of BCP, the classical picture must correspond to that of a particle.

Next, Aspect et al. performed a different experiment using the same source and the same beam splitter, but the detectors on either side of the beam splitter were removed and the light pulses on both sides were recombined using mirrors and a second beam splitter (fig. 3). This is essentially a two-slit experiment with genuine single photon states. It was found that the detection rates measured on either side of the second beam splitter showed interference effects implying wave-like behaviour.

[#1] In deriving this lower bound on P_c [12] it is assumed that the incident *wave* is split on a beam splitter and the probability of detection in a particular detector is proportional to the localised intensity of the light pulse inpinging on that detector.

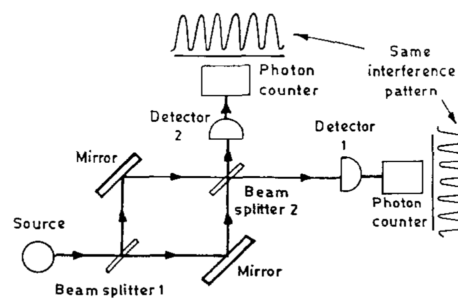

Fig. 3.

Now, the crucial point is that though the above two experiments correspond to mutually incompatible classical pictures, their mutual exclusiveness (in the sense that they cannot be performed simultaneously) protects BCP from any logical inconsistency. It is precisely on this point that the experiment of ref. [1] seeks to confront BCP.

The central tenet of BCP that mutually incompatible classical pictures are called for *only* in mutually exclusive physical conditions cannot be justified by a rigorous general argument based on the mathematical formalism of quantum mechanics. Instead, Bohr's strategy was to argue for the ME hypothesis by illustrative analyses of positive instances. As recently discussed in detail by Scully, Englert and Walther [13], as far as interference type experiments are concerned, the quantum mechanical formalism guarantees the validity of ME because it contains a built-in mechanism (through correlations between states of the observed system and the measuring apparatus) that ensures disappearance of the interference pattern whenever one has "which path" information. Like interference, tunnelling is also a hallmark of wave-like behaviour. However, the quantum mechanical formalism does not imply any ME between tunnelling and anticoincidence which is interpretable as a signature of particle-like propagation providing "which path" information. It is this feature which is exploited in the experiment of fig. 1.

Referring to fig. 1, we note that the registrations by the counter 2 to measure the tunnelling rate pertain to a propagation of light pulses which is consistent with a classical wave picture. However, at the same time let us consider the rates measured by the coincidence counter (connected to detectors 1 and 2) when the incident light pulses are in states that are close approximations to single photon states [#2]. If the coincidence rates are found to be lower than the minimum bound derived from the classical wave picture (perfect anticoincidence for "ideal" single photon states), as reported by Mizobuchi and Ohtaké [2], the propagation cannot be comprehended using a classical wave picture, but is amenable to a description in terms of the particle picture. We, therefore, contend that an understanding of this experiment in terms of classical pictures (which BCP necessarily requires) can only be obtained by using *both* particle and wave pictures; in other words, the experimental data recorded in the three counters of fig. 1 contain both wave-like and particle-like information about the propagation of light pulses. It is in this sense that the experiment of fig. 1 "confronts" BCP by showing that there is a situation allowed by the formalism of quantum mechanics where the notion of "mutual exclusiveness of classical pictures" is not applicable.

The two-prism arrangement of fig. 1 is like a special tunable beam splitter where one has a control over the transmission mechanism by varying the gap (d) between the prisms relative to the wavelength (λ) associated with the incident single photon states. The fact that the transmission rate varies with the gap (specifically as $\exp(-d/\lambda)$) for a given orientation and surface of the first prism implies that the phenomenon cannot be understood in terms of a particle-like description. The significance of using this special arrangement lies in the fact that for every beam splitter such as the one used in the experiment of ref. [12], transmission may not necessarily imply wave-like behaviour – there remains the possibility of modelling it in such a way that certain specified fractions of incident *particles* are reflected and transmitted [#3].

As in the case of an ordinary beam splitter, the state vector of the emergent single photon state from the two-prism arrangement, entangled with the vacuum states can be written in the form

[#2] It should be noted here that both the coincidence rates and singles rates pertain to the *same* ensemble of light pulses incident on the two-prism arrangement, *unlike* in the so-called "intermediate type" interference experiments [14]. In the latter an imperfect (less than 100% efficient) "which path" determination splits the input ensemble into two, one subensemble giving rise to an interference pattern and the other providing "which path" information that does not contribute to the interference pattern.

[#3] There could be a variant of the conventional beam splitter experiment analogous to our two-prism experiment. By varying the orientation of the beam splitter (i.e., changing the angle of incidence of the incident light pulse) transmission and reflection probabilities can be varied, which is considered to be a wave-like property (see, for a comprehensive treatment, ref. [15]). However, this effect is not expected to be as pronounced as the one due to the variation of the gap between the two prisms in fig. 1.

$$|\Psi\rangle = \alpha|1,0\rangle + \beta|0,1\rangle\ , \qquad (1)$$

where $|\alpha|^2$ gives the transmission probability and $|\beta|^2$ the reflection probability. Perfect anticoincidence between the detectors 1 and 2 (fig. 1) follows from this form of $|\Psi\rangle$.

As regards tunnelling in the quantum optical treatment, as long as there are no losses or no thermal photons added by the prism material, the Maxwell equations can be looked upon as Heisenberg equations with the classical fields replaced by quantum mechanical operators. Classical boundary conditions now become the boundary conditions for the electric and magnetic field operators. Tunnelling identical to that obtained from classical electromagnetic theory is then predicted, just as classical wave-like interference is obtained from a single photon state. In the two-prism experiment, it is to be noted that while anticoincidence is a *kinematic* feature (derived from the structure of the state vector (1)), tunnelling follows from the *dynamics* of field propagation. Most importantly, the kinematic and the dynamic aspects are concomitant (instead of being mutually exclusive) in this particular experiment.

Finally, as regards *other* interpretations of our experiment than BCP, we should like to mention that there remains the possibility of a consistent ontological description by either applying the causal interpretation to electromagnetic fields (see, e.g., ref. [16]), or by invoking de Broglie's original picture of photons propagating as localized particles associated with objectively real waves (see, e.g., refs. [17,4]).

We have benefitted from helpful criticisms and comments received from many after talks based on this work were given at various places and after the publication of ref. [1]. We hope this paper addresses all the points that were raised. DH and GA are grateful to the Department of Science and Technology, Government of India for supporting their research work.

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