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The Two-Prism Experiment and Wave-Particle Duality of Light

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A number of papers on wave-particle duality has appeared since the two-prism experiment was performed by Mizobuchi and Ohtake, based on a suggestion by Ghose, Home, and Agarwal. Against this backdrop, the present paper provides further clarification of the key issues involved in the analysis of the two-prism experiment. In the process, we present an overview of wave-particle duality vis-a-vis Bohr's complementarity principle.

1. INTRODUCTION

Following a proposal by Ghose, Home, and Agarwal (henceforth referred to as GHA),[1] Mizobuchi and Ohtake[2] performed an experiment with a two-prism device (Fig. 1) which demonstrated wave-particle duality of single-photon states in a novel form. Apart from exhibiting the wavelike tunneling of single-photon states similar to that of classical electromagnetic pulses, a characteristic signature of classical particlelike propagation, namely the "which path" information (provided by either reflection by the two-prism device or transmission through it), was also obtained in the same experiment because of the near perfect anticoincidences recorded by the two detectors 1 and 2 (only one of them clicked at a time). Conceptual implications of this experiment in the context of Bohr's wave-particle complementarity were analyzed in Ref. 3. However, in view of a number of papers[4–9] relevant to this issue that have appeared subsequently, further elaboration has become necessary on some related aspects of the wave-particle duality of light.

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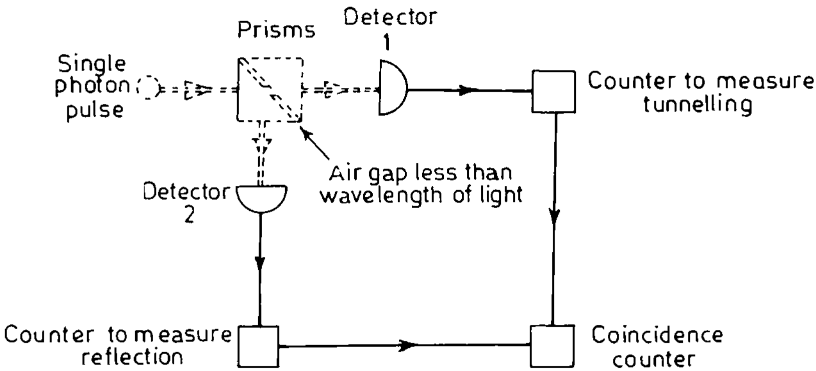

Fig. 1. The experimental arrangement using a double-prism device which demonstrates a violation of Bohr's wave-particle complementarity.

2. THE TWO-PRISM EXPERIMENT: SALIENT CONCEPTUAL FEATURES

The entire issue of wave-particle duality hinges on the sense in which one uses the ideas of "wave" and "particle." In this note we consider these notions from the perspective of Bohr's wave-particle complementarity. In what follows, the key points of the double prism experiment are outlined:

(i) Following Bohr, if one invokes the classical wave-particle models, then in order to have a visualizable description of the propagation of a microentity from a source to a detector it is imperative that one must use the complementarity principle in order to ensure the inner consistency of such a description. It is important to bear in mind that this mode of interpretation is restricted to only those experiments which can be understood in terms of classical pictures of propagation between emission and detection. Experiments whose results are irreducibly nonclassical are left out, like the ones involving squeezed states of light or states having sub-Poissonian photon statistics (in which the variance of photon counts is less than the mean number of photon counts within some appropriate time interval); there are also a number of nonclassical higher-order quantum interference effects using single-photon states which are incomprehensible in terms of the classical wave-particle models.

(ii) The central tenet of Bohr's wave-particle complementarity, namely that mutually incompatible classical pictures are applicable *only* in *mutually exclusive* physical situations [10],[3] is not a consequence of any rigorous general argument based on the mathematical formalism of quantum mechanics. Instead, Bohr's strategy was to defend this hypothesis by illustrative analyses of positive instances. In such analyses, an interference pattern that can be reproduced by a classical wave model is viewed as a signature of wavelike propagation. If, on the other hand, the experimental arrangement provides results that can be reproduced by imagining which of the possible paths a single photon follows all the way from a source to a detector, this is taken to signify particlelike propagation. What is meant by classical wave and particle pictures in Bohr's wave-particle complementarity is therefore operationally well specified,[(3)] contrary to the criticism by Canals-Frau.[(7)]

(iii) As pointed out by Scully *et al.*[(11)] and also discussed by others, it is in an interference type experiment that the quantum mechanical formalism guarantees the validity of the hypothesis of mutual exclusiveness (hereafter referred to as ME). Disappearance of an interference pattern is ensured whenever particlelike "which path" information is available, at least in principle.[4] This is because any measurement scheme capable of yielding "which path" information in position space would couple interfering wave functions of an observed entity with the mutually orthogonal (macroscopically distinguishable) states of the measuring apparatus. Storey *et al.*[(14)] have given a general proof that such an entanglement entails momentum transfer to the observed system whose magnitude cannot be less than that required by the uncertainty relation. It is this entanglement that guarantees washing out of the interference effects. However, exceptions can occur, consistent with the quantum formalism, if the observed interference effects originate from coherence between wave functions in a space other than position space, as in the nuclear heavy ion experiment pointed out by Ray and Home.[(6)] In this example, the observed interference in the angular correlations between the emitted gamma pulses stems from quantum coherence between the nuclear angular momentum eigenfunctions of the emitting nuclei—hence "which path" information of the emitted gama pulses in position space can be obtained without affecting the interference.

[3] Note, for example, a typical Bohrian statement that quantum theory "forces us to adopt a new mode of description designated as complementarity in the sense that 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."[(10)]

[4] A precise connection between the fringe visibility in an interference experiment and the degree of intrinsic indistinguishability of the photon paths is given in the treatment by Mandel.[(12)] A further quantitative elaboration has recently been provided by Jaeger *et al.*[(13)] who also analyze some interesting aspects of the relation between the visibility of one-particle interference fringes and the visibility of two-particle fringes.

The form of interference in such examples, coexisting with "which path" information, cannot be understood in terms of any classical wave model. Though this type of experiment does not contradict Bohr's wave-particle complementarity, it indicates that although in the examples where quantum mechanics predicts classical wavelike interference in ordinary position space, interference and "which path" information are mutually exclusive (ME), this is not so for every type of quantum interference effect.

(iv) Bohr had elevated his complementarity interpretation embodying the ME hypothesis to the status of a general epistemological principle of fundamental significance. As discussed in detail by Folse,[15] a comprehensive examination of Bohr's writings makes it clear that Bohr had envisioned the core idea of wave-particle complementarity (viz. a framework comprising apparently incompatible but mutually exclusive descriptions that jointly complete each other) extending into various fields of human knowledge. In the words of Bell[16]: "Bohr thought that 'complementarity' was important not only for physics, but for the whole of human knowledge." Notwithstanding Bohr's considerable conviction in the strength and generality of the complementarity principle, it remains a curious fact that his discussion of wave-particle complementarity was strictly restricted to interference experiments. He never alluded to the other type of experiments involving classical wavelike behavior. Was there any physical reason why Bohr thought that in the context of the complementarity principle interference was in some sense more "fundamental" than other manifestations of classical wavelike behavior?

There is no clue in Bohr's writings, at least after he had propounded wave-particle complementarity. Before arriving at the idea of complementarity, Bohr was, however, strongly opposed to the photon concept. For an in-depth discussion of this phase of Bohr's thinking and how he gradually reconciled himself to the photon concept by accommodating it within the framework of complementarity, see Murdoch.[17] During that period, in order to emphasize the inadequacy of the photon concept in accounting for all types of optical phenomena, Bohr used to invoke interference as an archetypal counterexample to the applicability of the photon model. He had then remarked "... interference phenomena constitute our only means of investigating the properties of radiation and therefore of assigning any closer meaning to the frequency which in Einstein's theory fixes the magnitude of the light-quantum" (Nobel Prize Address of 1922).[18] The authors of Ref. 19 quote such a remark by Bohr[20] to support their contention that Bohr never implied "any arbitrary wave property is complementary to any so-called particle property" (quotation marks ours). That remark[20] was, however, made by Bohr in the introductory section of his

1949 article while reviewing his position toward Einstein's photon hypothesis during the period preceding his formulation of complementarity. In other words, the context in which this remark was made was not while explaining or elaborating on the complementarity principle. Moreover, in the absence of any justification as to why interference should be regarded as the "only means" (quotation marks ours) of defining the concepts of frequency and wavelength (if, for example, one measures wavelength by using any classical wave phenomenon like refraction or optical tunneling, there is no fundamental reason why it should not be regarded as a valid specification of the property of a wave), there is no *a priori* logical basis for restricting the domain of applicability of wave-particle complementarity.

In view of the overwhelming evidence in support of Bohr's belief in the generality of his complementarity principle, a close examination of its wider validity (at least in the domain of wave-particle duality of light) is called for. This is what motivated the GHA proposal[1] leading to the experiment by Mizobuchi and Ohtake.[2] The central feature of this experiment (Fig. 1) is that while a single photon state can be observed to tunnel like a classical electromagnetic wave pulse, anticoincidence between the two detectors 1 and 2 (meaning that each detection event can be associated with either the reflected or the transmitted pulse) can be interpreted as implying the classical particlelike propagation of the pulse all the way from the source to one of the detectors 1 and 2. It therefore follows that if one tries to comprehend the results of this experiment in terms of classical pictures, this is only possible by using both wave and particle models. Bohr's ME hypothesis is thus contradicted in this particular experiment.

(v) As to the special significance of the two-prism arrangement of Fig. 1, compared to any beam splitter, it should be noted that the transmission probability recorded at the detector 1 decreases (exponentially) with the increase of gap (between the prisms) compared to the wavelength. The two-prism device therefore serves to bring out clearly the essentially wavelike character of tunneling or frustrated internal reflection occuring at the first prism on which the light pulse is incident (of course, to some it may appear less obvious that tunneling requires a "wave" picture than that required by interference). For an arbitrarily chosen beam splitter, transmission may not necessarily imply wavelike behavior—there remains the possibility of modelling in terms of particles such that specified fractions of incident particles are reflected and transmitted.

(vi) In interpreting the near perfect anticoincidences between the detectors 1 and 2 as a signature of particlelike propagation, a formal justification lies in the fact that any classical wave model predicts a lower bound on the probability of coincidences between the detectors 1 and 2.[21]

An important assumption implicit in deriving this bound is that the probability of detection at a detector depends only on the local intensity of the light pulse registered in that detector. Clearly this assumption is not valid in a nonlocal quantum wave model in which detection at a point depends on the quantum state of the globally extended wavefield (for example, in Bohm's causal interpretation of quantized electromagnetic fields[22]). It is therefore not surprising that, following Bohm's approach, it should be possible to interpret the double-prism experiment entirely in terms of the notion of waves, as pointed out by Dewdney *et al.*[4] However, this has no direct bearing on any analysis within the framework of Bohr's wave-particle complementarity because the Bohmian notion of waves is essentially nonclassical (due to an inherent nonlocality). Furthermore, the basic principle of the double-prism experiment holds for material particles such as electrons and neutrons (see Ghose and Home[23]). For such systems, the Bohm model entails the notion of particle trajectories determined by the Schrödinger wave function—the notion of a quantum wave is thus present concomitant with a particle. What the discussion by Dewdney *et al.* indicates is that there is no difficulty in understanding the results of the double-prism experiment in terms of spacetime pictures if one adopts the Bohmian scheme. From this point of view, one may regard the double-prism experiment as suggesting a certain conceptual superiority of the Bohm model over Bohr's complementarity approach.

(vii) It is instructive to compare the two-prism experiment with a "single particle at a time" interference experiment in which an interference pattern is built up by a gradual accumulation of discrete detection events registered as "spots" on a visual screen. If one imagines an array of detectors on a screen with all the detectors connected to an anticoincidence circuit, one would surely observe anticoincidence between the counts at the detectors. However, "which slit" or "which path" information for an individual particle all the way from its source to a detector would not be available. Hence this form of coexistence of anticoincidence (without "which path" information) and interference cannot be interpreted as showing classical wave and particlelike behavior in the same arrangement.

As a further illustration of the above point, consider the arrangement shown in Fig. 2. If a source of single-photon states is used and detectors 1 and 2 are connected to an anticoincidence circuit, one would observe both anticoincidence between the detectors 1 and 2 and an interference pattern in each. These interference patterns would arise because of the wavelike propagation of the photons between the source and the beam splitter 2 (it is not possible to know "which path" a light pulses follows between the beam splitters 1 and 2), while the anticoincidence provides "which path"

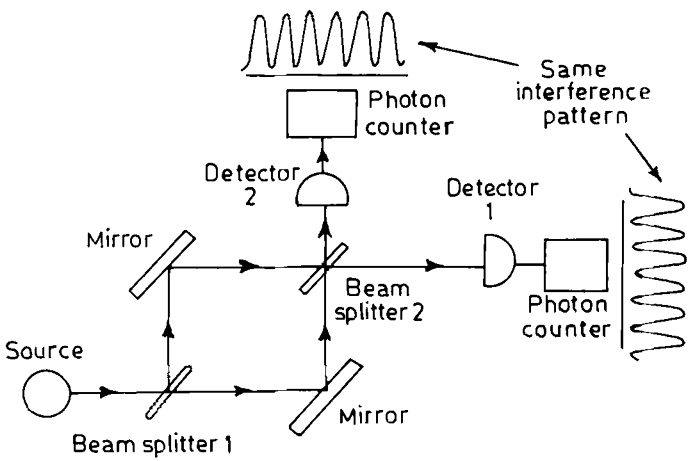

Fig. 2. Anticoincidence between the detectors 1 and 2 for single-photon states does not provide "which path" information from the source to the detectors *all the way* via the two beam splitters.

information only between the beam splitter 2 and the detectors (implying particlelike propagation from the beam splitter 2 to any one of the two detectors 1 and 2).

(viii) The experiments discussed by Rangwala and Roy[9] are variations of the above type. Consider, for example, the proposed arrangement in which the reflected pulse from a beam splitter is detected by a photomultiplier P_1, whereas the transmitted pulse passes a single slit of width d before being recorded on a screen filled with a set of detectors P_2. For single-photon states, there will be anticoincidence between the counts at P_1 and P_2. On the other hand, the distribution of counts at the various detectors P_2 will show the single-slit interference pattern for a suitable choice of d (small compared to the wavelength). Here again, due to diffraction effects at the slit concerned, no information can be obtained about which of the mutually interfering paths a given photon pulse follows after crossing the slit and before being registered at one of the detectors P_2. In other words, anticoincidence in this example does not furnish "which path" information all the way from the source to P_2 because of the presence of an intervening slit which destroys "which path" information (mutually interfering paths emerge from the slit). It therefore follows that while anticoincidence between P_1 and P_2 may be interpreted as indicating classical particlelike behavior of the photon pulses in their encounter with the beam splitter (reflected or transmitted), interference pattern recorded at the detectors P signifies their classical wavelike behavior in a different and independent sector of the experimental arrangement, viz. while passing the slit which can be placed at an arbitrary distance from the beam splitter. This kind of wave-particle duality is consistent with Bohr's complementarity interpretation. In contrast, in the experiment of Fig. 1, the double-prism device acts as a beam splitter by incorporating within it classical wavelike tunnelling as the transmission mechanism (the second prism merely helps to amplify the exponentially falling evanescent wave amplitude). Anticoincidence between the reflected and transmitted channels is interpretable as evidence of a classical particlelike propagation all the way from the source to the detectors, concomitant with a classical wavelike behavior.

(ix) An important point concerning the experiment of Fig. 1 is that the coincidence rates as well as the singles rates pertain to the entire ensemble of light pulses incident on the two-prism arrangement. This is unlike the "intermediate experiments"[24] in which by using partial "which path" determination, the initial ensemble is split into two—out of them, one subensemble gives rise to an interference pattern and the other (for the members of which one has "which path" information) does not contribute to the interference pattern. There is therefore no inconsistency with Bohr's wave-particle complementarity in such experiments.

(x) Tunnelling is not the only wavelike phenomenon for which Bohr's ME hypothesis fails. Double refringence is another, which serves as evidence of wavelike propagation. A doubly refracting crystal would also behave like a beam splitter for single-photon states—an individual pulse would take either of the two possible paths (the ordinary and the extraordinary ray). Therefore the detectors placed along these two paths (with angles of refraction less than the incidence angle) would record anticoincidence counts. One will thus have "which path" information along with wavelike behavior.

3. CONCLUDING REMARKS

Finally, in order to have a wider perspective on this issue, it should be useful to make some broad remarks comparing the following different approaches:

A. If one remains confined within the formalism of quantum theory without requiring an ontological understanding or a pictorial interpretation, the problem of wave-particle duality ceases to have any conceptual relevance. In particular, if we consider the optical experiments, the rules of quantum optics are well defined and sufficient to predict correctly all observable results. The electric and magnetic field operators are the basic dynamical variables in this formalism. The notion of photons enters the theory only as a secondary entity, defined as excitations associated with the normal modes in terms of which any electromagnetic field can be expanded. From this point of view, the "particle" aspect of radiation can take on a concrete meaning only when a detection process is considered —the quantized decrease in field energy resulting from a detection process may be described in terms of the removal of photons from the field. Dirac's overworked metaphor "each photon interferes only with itself" has added to the confusion—strictly speaking, photons do not interfere, neither with themselves nor with each other, but rather the interference pattern is in the linear superposition of field amplitudes. Within the standard formalism, it is therefore superfluous to use the notion of "photons" in the context of quantum interference effects. This point, often not appreciated, has recently been discussed by Jones[8] while reviewing the experiments on wave-particle duality. The double-prism experiment poses no problem for the standard formalism since its observed results are a clearcut consequence of the rules of quantum optics.[1]

B. The Bohrian interpretation of wave-particle dualism stems from the consideration that, apart from formal predictions of the observed results, some intuitive understanding is also required in terms of classical pictures. However, the peculiarity of this approach is that no causal and realistic description of individual events is permitted before the final detection of light pulses takes place. To invoke Wheeler's mystical metaphor, a light pulse is like a "smoky dragon" before it bites a detector. As Wheeler puts it, "It is wrong to attribute a tangibility to the photon in all its travel from the point of entry to its last instant of flight.... What answer we get depends on the question we put, the experiment we arrange, the registering device we choose. By this choice of question, the observer decides about what feature of the object he shall have the right to make a clear statement."[25] Once the detection processes are completed, then only according to the nature of the observed results one may infer which of the two classical models, wave or particle, is relevant to the experiment concerned. The mutual incompatibility between these classical pictures is shought to be avoided by precluding the possibility of any single experiment whose observed results would contain one subset of data comprehensible in terms of a classical wavelike propagation, coexisting with another subset interpretable using a classical particlelike propagation embodying "which path" information all the way from the source to a detector. The double-prism experiment is a counterexample to this dictum and therefore highlights an inadequacy of the Bohrian framework.

C. The remaining alternative is to attempt a realistic and causal but nonclassical description of the behavior of an individual light pulse while propagating from the source to a detector. One such scheme adopts the Bohm model[22] in which the deterministic evolution of field coordinates in spacetime is determined by the quantum potential calculated from the wave functional. The other possible scheme is along the lines of de Broglie's model of photons propagating as localized entities (embodying concentrated energy-momentum) along definite trajectories, guided by physically real waves in ordinary three-dimensional space.[26] Observed results of the two-prism experiment are consistent with both these approaches.

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It is our pleasure to contribute this paper in honor of Max Jammer and to wish him many more happy years of creative activity. One of the authors (D.H.) takes this opportunity to recall that Max Jammer's stimulating work *The Philosophy of Quantum Mechanics* (Wiley, New York, 1974) provided to him an invaluable initial introduction to the foundational issues of quantum mechanics.

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