Critique of Quantum Optical Experimental Refutations of Bohr’s Principle of Complementarity, of the Wootters-Zurek Principle of Complementarity, and of the Particle-Wave Duality Relation

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September 4, 2014

Abstract

I argue that quantum optical experiments that purport to refute Bohr’s principle of complementarity (BPC) fail in their aim. Some of these experiments try to refute complementarity by refuting the so called particle-wave duality relations, which evolved from the Wootters-Zurek reformulation of BPC (WZPC). I therefore consider it important for my forgoing arguments to first recall the essential tenets of BPC, and to clearly separate BPC from WZPC, which I will argue is a direct contradiction of BPC. This leads to a need to consider the meaning of particle-wave duality relations and to question their fundamental status. I further argue (albeit, in opposition to BPC) that particle and wave complementary concepts are on a different footing than other pairs of complementary concepts.

Pacs no: 03.65.Ta, 42.50.Xa

Keywords: quantum mechanics, Bohr, complementarity, optical tests, particle-wave duality

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1 Introduction

In recent years there has been a proliferation of experimental tests of Bohr’s principle of complementarity (henceforth BPC) [1, 2, 3, 4]. In reality, such tests nearly always concern particle and wave complementary concepts. Many of the tests are optical tests. Representative and important examples of such optical tests are in references [5, 6, 7, 8, 9]. Rauch et al’s use of a single silicon crystal, suitably cut, as a neutron interferometer [10] allowed many experimental tests of aspects of particle-wave duality using neutrons (see for example [11, 12, 13, 14, 15, 16]). More recently, experiments on the particle-wave aspects of atoms have been made possible with the development of the atom interferometer [17, 18, 19, 20, 21, 22]. Further references of tests of complementarity may be found in Ghose’s book [24].

Many of the tests of complementarity give results which authors claim confirm complementarity. These include the neutron interferometry tests, the atom interferometer tests and many of the optical tests. A notable optical test which claims to confirm complementarity is that of Grangier, Roger and Aspect (GRA) [9]. The GRA experiment is notable because it was perhaps the first such experiment to use a gating system to produce genuine single photon states (Fock states) using photons produced by atomic cascades. However, GRA fail in their objective to confirm complementarity because, although their results are consistent with complementarity, their results can just as well be explained by the causal interpretation or its extension to the electromagnetic field [25]. All of the experiments which claim to confirm complementarity can be described in terms of the causal interpretation [26, 27], or its extension to boson fields [25, 28, 29, 30, 31]. Any experiment consistent with two or more alternative interpretations or theories cannot be regarded as proof of one them.

Before proceeding to my main aims, I review other experimental tests of BPC, and also very interesting related experiments which push the boundaries of complementarity (and which present challenges to alternative interpretations of the quantum theory): The Wheeler delayed choice experiment, and quantum erasure experiments.

A novel test of complementarity uses electrons following two-paths in an Aharanov-Bohm ring interferometer [32, 33]. After the electrons traverse the two paths they are recombined to produce interference effects. A quantum dot embedded in one path and coupled to a quantum-point-contact charge detector is used for path detection. Their results are consistent with BPC.

The interference of atoms raises the further question of what happens to their internal structure in an interference experiment. The same question applies, of course, to fundamental particles with their proposed quark structures, but the question seems to be particularly poignant with atoms. Further, the internal structure can be used to mark the path. As expected, when the path is identified interference is lost in agreement with BPC [17, 18, 19, 20, 21]. Intermediate experiments, where the path is only partially determined resulting in reduced visibility interference, have also been performed with results again consistent with complementarity [22, 23]. A particular question authors focused on is how complementarity is enforced. In many tests, complementarity is enforced by the position-momentum uncertainty relations. But,
in atom interferometer experiments, authors such as Dürr et al.\textsuperscript{[18]} and Li\textsuperscript{[19]} have demonstrated very clearly that complementarity is enforced by entanglement, rather than by the uncertainty relations. Specifically, an entangled state between the internal degrees of freedom and the possible paths is formed such that interference terms disappear once the path is determined. If we adhere strictly to BPC, then the question raised above concerning what happens to the internal structure when atoms interfere cannot be asked. This is so for two reason: First, in BPC physical reality cannot be attributed to classical concepts. Secondly, in BPC, an experiment must viewed as an undivided whole, not further analyzable. However, very few workers, including the present author, adhere to this strict view and tend to think of an underlying physical reality. So, although such atom experiments with markers are consistent with BPC, they surely question the plausibility of BPC. This point is highlighted with the description of atom interferometry experiments according to the causal interpretation.

Wheeler added another dimension to the experimental tests with his delayed-choice experiment. The decision of whether to measure path or interference is left until the last instant. This leads to the paradoxical conclusion that history is changed at the time of measurement, or Wheeler’s preferred interpretation, that history is created at the instant of measurement. Thus Wheeler writes, “No phenomenon is a phenomenon until it is an observed phenomenon”\textsuperscript{[35]} page 14. He adds that “Registering equipment operating in the here and now has an undeniable part in bringing about that which appears to have happened”\textsuperscript{[36]} page 194. Wheeler concludes, “There is a strange sense in which this is a ‘participatory universe’.”\textsuperscript{[36]} page 194. That this experiment is consistent with BPC is guaranteed by a central tenet of BPC, namely, classical concepts in the quantum theory are abstractions to aid thought and to communicate the results of experiment, but cannot be attributed physical reality. Wheeler\textsuperscript{[35, 36]} appears not to adopt the latter tenet, but instead follows Heisenberg\textsuperscript{[37]}, and, in some sense, attributes reality to complementary concepts (and to the wave function), hence the paradoxical conclusion. We note that Bohr anticipated delayed choice experiments, he writes “...it obviously can make no difference as regards observable effects obtainable by a definite experimental arrangement, whether our plans of constructing or handling the instruments are fixed beforehand or whether we prefer to postpone the completion of our planning until a later moment when the particle is already on its way from one instrument to another.”\textsuperscript{[3]} page 230. Again, both the causal interpretation\textsuperscript{[38]} and its extension to Boson fields\textsuperscript{[31]} can explain the Wheeler delayed-choice experiment in a causal, non-paradoxical way.

A further push of conceptual boundaries occurred with the introduction of quantum erasure experiments\textsuperscript{[39, 40, 41, 42, 43, 44, 45]}. Perhaps the best example is the quantum eraser experiment of Kim et al\textsuperscript{[45]}. I base my few comments on this experiment. The two slits of a two-slit experiment are replaced by two sources producing entangled photon pairs. One photon of an entangled photon pair travels backwards
carrying the path information of its partner photon, and is directed to one of four detectors by a system of mirrors and beam splitters. For a photon detected in either of the two outer detectors, the source from which it was produced is revealed so the path of its entangled partner is determined with certainty, i.e., photons detected in either of the two outer detectors retain path information. On the other hand, a photon detected in either of the two inner detectors passes through an extra beam splitter, so it may have come from either source, i.e., its path information is erased by the mixing of paths at the beam splitter. Consequently, the path of its entangled photon partner remains completely undetermined. The other photon of the entangled pair travels forwards toward an interference detector, where interference fringes can be observed. The detection of the entangled photon pairs is correlated. It was found that for the photons which retain path information, their entangled partners did not form interference fringes, while those for which path information was erased, their entangled photon partners did form interference fringes (click by click). What makes the experiment so paradoxical is that the “forward” photons reach the interference detector, long before their “backward” entangled photon partner reaches a beam splitter. Therefore, interference occurs (or not) long before, the path information is erased (or not). This implies that a measurement in the present affects a measurement in the past.

In the authors opinion, this is impossible and is not implied by quantum theory. The reason is that nonlocality is “once-only”, in other words, the entanglement between the two photons is broken upon the first detection. If nonlocality was not like this, and persisted after the first detection it would be possible to set up causal paradoxes and faster than light signaling leading to the possibility of experimental contradiction with relativity. Thus, once a photon reaches the interference detector, its entangled connection with its backward traveling partner is broken. Whatever happens to this “backward” photon, thereafter, cannot affect the “forward” detected photon. To justify this view, the experimental results have to be calculated based on the quantum feature of broken entanglement (or once-only-nonlocality).

Many of the experimental tests of complementarity do not deal directly with BPC, but deal instead with particle-wave duality relations which have evolved from the Wootters-Zurek (WZ) principle of complementarity [46]. WZPC has given rise to the so called “intermediate experiments”, in which the path is only partially determined, resulting in reduced visibility of the interference fringes[47]. Despite this, all experiments ultimately test BPC. Though I will argue below that the duality relations are a direct contradiction of BPC, there is a no need to consider the experiments as separately testing BPC and the duality relations, since the same reasoning saves both BPC and the duality relations.

My main aim, as I have said, is to show that the experiments which purport to refute complementarity fail, irrespective of whether the results are considered directly in terms of BPC or indirectly in terms of the particle-wave duality relations. But from what I have said above, there are crucial preliminaries that need to be clarified.

First, there is a need to emphasize an aspect of BPC that has been universally
overlooked, and that Bohr would never agree with, namely, that particle and wave complementary concepts are fundamentally different from other pairs of complementary concepts.

Second, we must clearly separate BPC and WZPC. To do this we first remind ourselves of the main tenets of BPC, and justify these tenets with some quotes from the great man himself. Though I am here defending BPC from experimental refutation, I will make some critical remarks against BPC on general theoretical grounds. Following this, I consider WZPC and provide reasons why it must be viewed as a separate principle from BPC, indeed, why it is a direct contradiction of BPC. Note that the term complementarity has been extended beyond the classical concepts envisaged by Bohr. An example is the complementarity between single photon and two-photon interference [48, 49]. Therefore, I will use the abbreviation “BPC” to refer to Bohr’s original strict version, and use the term “complementarity” in contexts where a more general usage is appropriate.

Third, I consider the particle-wave duality relations [13, 49, 50, 51, 52, 53, 54]. For my main aim, I select the following experiments for consideration: The 1991 Ghose, Home and Agarwal experiment (GHA) [5], later performed by Mizobuchi and Ohtake [7]; the Brida, Genovese, Gramegna, and Predazzi experiment (BGGP) [6]; and the Afshar experiment [8]. The Afshar experiment, in particular, has received considerable attention, so I will consider this experiment in greater detail.

In these experimental refutations, one complementary concept is actually measured (i.e. defined by the experimental arrangement as required by BPC), while the other complementary property is artificially introduced through an unjustified assumption. In such experiments the experimenters include some intermediate process, which in classical theory must be described by the classical concept opposite to the classical concept consistent with final actual measurement. But since this concept is not actually measured, it is never defined in the way demanded by BPC. Thus, BPC (and even the duality relations) are not even nearly challenged by these experiments.

I begin by considering particle and wave complementary concepts followed by BPC, WZPC, particle-wave duality relations, and then, in separate sections, the experiments of AHG, BGGP, and the Afshar experiment.

2 Particle-Wave Complementary Concepts

Following many authors before me, I begin with Feynman’s famous quote concerning particle-wave duality, [55] vol. III, p. 1-1, “In reality, it contains the only mystery”. I have emphasized this quote because it relates to the first crucial point I wish to emphasize, namely, that particle and wave complementary concepts are fundamentally different from other complementary concepts, such as position and momentum, which classically, are canonically conjugate dynamical variables (CCDV). Complementary concepts which are CCDV are identified with definite elements of the mathematical formalism of quantum mechanics, namely, linear hermitian operators, and satisfy uncertainty relations rigorously derivable from the quantum theory. Crucially, CCDV
are NOT mutually exclusive classical concepts. Classically, such variables have simultaneously well defined values at all times which precisely define the state of a classical system. On the other hand, the concepts of wave (field) and particle are mutually exclusive classical concepts. It is simply a contradiction of definitions to describe a single object as a wave and a particle. Moreover, Bohr never identified particle and wave concepts with mathematical elements of the quantum formalism. Bohr, of course, never accepted such a differentiation of complementary concepts, but instead sought a unified view with all pairs of complementary concepts on an equal footing. This is very likely, why, Bohr never viewed complementarity as identical with Heisenberg’s uncertainty relations. Jammer emphasized this point in his book \cite{4} and writes, “That complementarity and Heisenberg-indeterminacy are certainly not synonymous follows from the simple fact that the latter... is an immediate mathematical consequence of the formalism of quantum mechanics or, more precisely, of the Dirac-Jordan transformation theory, whereas complementarity is an extraneous interpretative addition to it” page 61. The importance of this separation is that it clarifies subsequent discussion, and it also removes the perceived need for a “missing” particle-wave relation. It is difficult to see how a conceptually non-contradictory interpretation of such an uncertainty relation could be given. Note that the particle-wave duality relations differ from uncertainty relations, as has been emphasized by Englert \cite{53}.

This distinction has important conceptual consequences. CCDV complementary concepts, which classically are simultaneously measurable and conceivable, are simultaneously conceivable in the quantum theory. The uncertainty relations place a limit on their simultaneous measureability, but not on their simultaneous conceivability. Thus, it is easy to picture a measurement of, say, position disturbing a previously known value of momentum so that the new value of momentum is not known, but this does not prevent us in the quantum theory from simultaneously picturing a particle with a well defined position (with a value known by the measurement) and a well defined momentum (with an unknown value because of the disturbance by the position measurement). But, with the mutually exclusive concepts of particle and wave, picturing a single object as a wave and a particle is not possible. This is just as true in quantum theory as it is in classical physics. A single object is simply not simultaneously picturable as a wave and a particle. This impossibility is the root behind the particle-wave duality paradox, and no wonder coined by Feynman “the only mystery”. In my view, this paradox or “mystery” is only resolved by an ontological interpretation of the quantum theory, such as the Bohm-De Broglie causal interpretation.

3 Bohr’s Principle of Complementarity

Not withstanding the countless articles relating to complementarity, I believe that it is still worthwhile to recall the main tenets of Bohr’s (original) principle of complementarity. As is well known, Bohr’s first presentation of complementarity in a fairly complete form was in his 1927 Como lecture \cite{1}. Further presentations of BPC can be found in references \cite{2} \cite{3} \cite{4}. 
The four core tenets of Bohr’s Principle of Complementarity are as follows:

(T1) The concept of a precisely definable classical state must be given up (because of the quantum postulate), and a separation of subject (experimental apparatus) and object (quantum system) is impossible. An experiment must therefore be viewed as an unanalyzable whole.

(T2) A single picture is not sufficient to exhaust the description of a quantum system. Rather pairs of complementary concepts are needed. Such complementarity concepts (for example, wave and particle concepts) can only be used in mutually exclusive experimental arrangements. Indeed, it is the experimental arrangement which defines the concept to be used.

(T3) Classical concepts are abstractions to aid thought and to communicate the results of experiment, but cannot be attributed physical reality.

(T4) A description of physical processes that underlie experiment in terms of a single well defined model is impossible, i.e., a description of underlying physical reality in terms of a single-well defined model is impossible.

T1 stems from Bohr’s quantum postulate, which states that a quantum system interacts with its environment (e.g. measuring apparatus) through the exchange of a quantum of action that is indivisible, uncontrollable, and unanalyzable. As a consequence, the concept of a classical state defined by a complete set of well defined dynamical variables has to be given up. This leads to the conclusion that the apparatus and quantum system must be viewed as an unanalysable whole. Bohr emphasized that it is the experimental arrangement which defines the property being measured. It seems likely that T2 was motivated by the photoelectric and Compton effects, which were interpreted as indicating the particle behaviour of light, considered classically to have a purely wave nature, and by the Davisson-Germer experiments which showed the interference of electrons, previously considered to have a particle nature. It seems reasonable to conjecture that T3 was motivated by the mutually exclusive nature of wave and particle concepts. Perhaps, Bohr felt that the application of wave and particle concepts to the same physical object is a contradiction of definitions, even if, as he stated, they cannot both be applied in the same experiment. It appears, especially with regard to particle and wave complementary concepts, that Bohr’s aim was to provide a framework for the non-contradictory use of classical language/concepts. The latter point is indicated in the following quotes from Bohr, “...in dealing with the task of bringing order into an entirely new field of experience, we could hardly trust in any accustomed principles, however broad, apart from the demand of avoiding logical inconsistencies...” [3] page 228, and “...we cannot seek a physical explanation in the customary sense, but all we can demand in a new field of experience is the removal of any apparent contradiction.” [2] page 90.

I finish this brief summary with some more quotes from Bohr’s writings:
(i) In the following quote, relating to T1 and indicating T4, Bohr, referring to the quantum theory, writes, “its essence may be expressed in the so-called quantum postulate, which attributes to any atomic process an essential discontinuity, or rather individuality, completely foreign to the classical theories and symbolized by Planck’s quantum of action. This postulate implies a renunciation as regards the causal space-time co-ordination of atomic processes. Indeed, our usual description of physical phenomena is based entirely on the idea that the phenomena concerned may be observed without disturbing them appreciably. . . Accordingly, an independent reality in the ordinary physical sense can neither be ascribed to the phenomena nor the agencies of observation.” [1] page 580.

(ii) With regard to T2, we recall the following quote from Bohr: “. . . however far the phenomena transcend the scope of classical physical explanation the account of all evidence must be expressed in classical terms” . . “this crucial point . . implies the impossibility of any sharp separation between the behaviour of atomic objects and the interaction with the measuring instruments which serve to define the conditions under which the phenomena appear. . . Consequently, evidence obtained under different experimental conditions cannot be comprehended within a single picture but must be regarded as complementary in the sense that only the totality of the phenomena exhausts the possible information about the objects. Under these circumstances an essential element of ambiguity is involved in ascribing conventional physical attributes to atomic objects, as is at once evident in the dilemma regarding the corpuscular and wave properties of electrons and photons, where we have to make do with contrasting pictures, each referring to an essential aspect of empirical evidence.” [3] page 209. Regarding the measurement of complementary concepts Bohr writes, “As repeatedly stressed, the principal point here is that such measurements demand mutually exclusive experimental arrangements.” [2] page 60.

(iii) Concerning the reality of particle or wave concepts (referred to in T3) he writes, “radiation in free space as well as isolated material particles are abstractions, their properties on the quantum theory being definable and observable only through their interaction with other systems. Nevertheless, these abstractions are . . . indispensable for a description of experience in connexion with our ordinary space-time view.” [1] page 149.

4 Critique of Bohr’s Principle of Complementarity

As I have stated, our main aim is to strongly defend BPC against experimental refutation. I do this because I believe that if BPC is to be rejected it should be rejected for the right reasons. I think that there are strong theoretical or conceptual grounds for rejecting complementarity. An experimental refutation would require two actual measurements, each consistent with the opposite complementary concept. I strongly
suspect that if such an experiment is ever achieved, it would also refute the quantum
theory. One criticism of BPC concerns the fact, discussed in some detail in section 2,
that particle and wave complementary concepts are fundamentally different to other
complementary concepts. This renders the unified view sought by Bohr somewhat
strained.

A more serious objection concerns my argument, also discussed in section 2, that
BPC is not a direct interpretation of the mathematical formalism of the quantum
theory. As I mentioned, though CCDV are identified with linear hermitian operators
(a highly abstract identification) particle and wave concepts in BPC are never identified
with any element of the mathematical formalism. It might be thought that the recently
(relatively) introduced particle-wave duality relation answers the latter failing, but this
view is subject to criticism, as we argue in section 6.

A final serious criticism of BPC is the requirement that a description of underlying
physical reality is impossible (tenet T4). This requirement is essential for the consis-
tency of BPC. This is an extremely high price to pay for consistency. Fortunately,
the existence of the Bohm-de Broglie causal interpretation based on which computer
models of underlying physical reality can be produced [56, 57, 58] not only shows that
we are not forced to accept this extreme position, but also that it is wrong (though I
note that recently, the reality of the trajectories in the causal interpretation has been
questioned [59]).

5 The Wootters-Zurek Principle of Complementar-
ity

In their 1979 article [46] WZ analysed Einstein’s two-slit experiment from the per-
spective of partial particle and partial wave information using Shannon’s measure of
information, defined as

\[ H = -\sum_{i=1}^{N} p_i \ln(p_i), \]

where \( H \) is a positive number giving the “information we lack”, \( N \) is the number of
possible states of the system, and \( p_i \) is the probability of the system being in state
\( i \). Using this definition, WZ developed a reciprocity measure of how much wave and
particle information can be obtained from the same experiment. Their analysis led WZ
to the following reformulation of complementarity: The sharpness of the interference
pattern can be regarded as a measure of how wave-like the light is, and the amount
of information we have obtained about the photon’s trajectories can be regarded as a
measure of how particle-like it is. I shall call this reformulation WZPC.

Mathematically, the WZ results are very interesting, but as I argued in my 1992
article [60], WZPC embodies everything that Bohr warned against. We recall the
following emphasis from Bohr, “The argument is simply that by the word “experiment”
we refer to a situation where we can tell others what we have done and what we have
learned and that, therefore, the account of the experimental arrangement and of the
results of the observations must be expressed in unambiguous language with suitable application of the terminology of classical physics.\textsuperscript{[2]} p. 39. WZPC hardly fulfills this condition.

We expect of a physical concept (together with its mathematical representation) to have an explanatory (and predictive) function. In classical physics the concept of wave and its mathematical representation explains interference. The visibility of the fringes has nothing to do with the degree to which the wave concept applies, but rather, fringe visibility is a measure of the degree of coherence of the particular wave profile. Even the tiniest level of visibility of interference fringes requires a 100% wave model; not 50% or 20%. What possible meaning can be given to the partial application of the wave concept. I conclude, that so called intermediate experiments in which partial path information is obtained at the expense of visibility (which WZ related to the degree of wave knowledge) are NOT intermediate at all. Even where the tiniest fringe visibility is observed, BPC clearly demands a 100% wave model. Attributing a particle concept to such experiments is arbitrary and artificial and certainly in contradiction with BPC. For example, in a two slit experiment with one slit half the size of the other, the fringe visibility would certainly be reduced. Classically, we say that twice as much wave energy passed through the bigger slit. WZPC would attribute a probability of 0.33 to the path through the smaller slit and a probability 0.67 to the path through the larger slit, then substitute these values into their formula to determine the path information. But this allocation is purely arbitrary, since the experiment does not define the particle concept in the way specified by BPC.

For these reasons I conclude that WZPC is a contradiction of BPC. This conclusion does not mean that the WZ analysis based on information theory is not an interesting and valuable analysis; our objection is only in the interpretation of the analysis, and in the reformulation of BPC. Henceforth, BPC and WZPC will be considered to be two entirely separate principles.

Perhaps ironically, WZPC can be consistently interpreted using Bohm's nonrelativistic causal interpretation \textsuperscript{[26, 27]} (but not its extension to Boson fields\textsuperscript{[4]}). In other words, WZPC can be given a conceptually consistent interpretation with reference to an appropriate ontology. This is not a surprise, since classical probability and classical information theory refer to an underlying ontology. In BPC electrons, protons etc (but not photons, for the reasons given in footnote\textsuperscript{[2]} are particles with associated guiding fields (the $R$- and $S$-fields\textsuperscript{[5]}). This model contains a 100% particle concept and a 100% wave concept. In the two-slit experiment, an electron, say, passes through only one slit, and is then guided by the $R$- and $S$-fields to a bright fringe. In intermediate experiments it now becomes meaningful (and non-artificial) to attribute a probability to each possible path. Therefore, a particle is a 100% a particle, but its path in a

\textsuperscript{2}Photons are bosons and are governed by the second quantized Maxwell equation's. In the causal interpretation of boson fields, fundamental entities are purely fields; there are no boson particles. In this case WZPC cannot be given meaning based on this ontology.

\textsuperscript{3}The $R$ and $S$-fields, defined by $\psi = R \exp(iS/\hbar)$, are not independent of each other. Both play an equal part in determining a particle's motion, the $R$-field through the quantum potential $Q = -\hbar^2/(2m)\nabla^2 R/R$, and the $S$-field through the guidance formula $v = \nabla S/m$. 

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particular experiment may not be determined with 100% certainty. The visibility, as in classical physics, is defined with respect to a 100% wave concept, and measures the coherence of a particular wave profile, i.e., a particular profile of the $R$- and $S$-fields.

6 The Particle-Wave Duality Relation

An indication of the importance of the WZ analysis is indicated by the interest it has attracted from numerous authors, who, based on the WZ analysis developed particle-wave duality relations. The first such relation was introduced by Greenberger and Yasin (GY) \[13\], with further developments in references \[19, 50, 51, 52, 53, 54\]. Detailed derivations followed, the most notable by Jaeger, Shimony and Vaidman (JSV)\[19\], and then by Englert \[53\]. The JSV derivation is notable because of the detailed discussion on the interpretation given to the duality relations. The Englert derivation is notable because of its mathematical rigor.

Although the various authors beginning with Greenberger and Yasin arrive at a similar expression of the particle-wave duality relations,

$$D^2 + V^2 \leq 1,$$

and to a similar use of $D$ as a measure of the particle aspect, and of $V$ as a measure of the wave aspect, the precise interpretation given to $D$ varies considerably. Later authors define $D$ as the distinguishability, while $V$ is always defined as the visibility. The particle-wave duality relation, given that it originates from WZPC, suffers from the same criticisms as given above for WZPC. Like WZPC, the duality relation can be given meaning with reference to an ontology such as the Bohm-de Broglie causal interpretation, but in this case its conceptual significance is lost. Since in this interpretation fundamental entities are modeled as particles guided by fields, it becomes meaningful to ask for the probability that a particle passes through one slit or the other in a two-slit arrangement. It also becomes meaningful to ask for the visibility of the interference fringes, since the profile of the fields (the $R$ and $S$-fields) guiding the particles determine the visibility. Making one slit half the size of the other will decrease the visibility while increasing the probability of a particle passing through the larger slit.

But note, in the Bohm-de Broglie model, the duality relation is not interpreted as “how wave-like” or “how particle-like” a quantum system is. Particles are 100% particles and fields (waves) are a 100% fields (waves). Instead, definite probabilities can be attached to each path a particle might take (from which the path parameter $P$ can be defined). The visibility $V$ is determined by direct measurement of the maximum and the minima of the interference pattern, but there is no question of the level of visibility placing a limit on the wave concept; the full wave concept is needed to explain even the smallest level of fringe visibility.

\[4\]Actually, in computer models of the two-slit experiment \[56, 57, 58\] it is seen that trajectories never cross so that a particles path can be theoretically determined with certainty even when their is interference, and irrespective of whether the experiment is of an intermediate type or not.
But, a more correct model of photons is given by the causal interpretation of the electromagnetic field (CIEM) [25, 30, 31]. In this interpretation there are no photon particles; photons are fields (waves). With reference to this ontology, the duality relations must be interpreted entirely differently, perhaps as a measure of the coherence of a particular wave profile, without reference to particles.

Without reference to an ontology the interpretation of the duality relations requires care to avoid ambiguity or even contradiction. If the duality relations are interpreted along the lines of WZPC, i.e., as a measure of partial wave behaviour or partial particle behaviour, then again we are faced with a contradiction of definitions. Further, the use of the visibility as a measure of the wave aspect of a physical system seems questionable, since even the tiniest level of interference requires a full wave model for its explanation. If instead, the duality relations are interpreted in terms of particle and wave information only, contradiction might be avoided, but such an interpretation leaves the question of what the information is referring to unanswered. This is hardly satisfactory. We surely expect some kind of explanation of how an experimental result comes about. Since both of these interpretations apply the particle and wave concepts to the same experiment, they are not consistent with BPC. The best interpretation that does not refer to an ontology, in my opinion, is due to Jaeger, Shimony and Vaidman (JSV) [49]. They interpreted the duality relation in terms of predictability with the path parameter and the visibility parameter referring to two different mutually exclusive experiments. Thus, the duality relation predicts that if in a given experimental arrangement (e.g. the two-slit arrangement) the path is measured with result $P$ for the path parameter, then a separate mutually exclusive measurement of visibility $V$ would yield a result consistent with the duality relation (1). Thus, by interpreting the particle-wave duality relation as referring to two mutually exclusive experimental arrangements, consistency with BPC is achieved.

We see that the duality relation can be interpreted in different ways depending on the point of view of the interpreter. This fact, especially because of the existence of ontological interpretations, in my view, diminishes the fundamental significance normally attributed to it.

7 Optical Experimental Tests of Complementarity

Having - hopefully - clarified aspects of complementarity and particle-wave duality relations, I come to my main focus which is to argue that quantum optical experiments which claim to refute complementarity fail in their aim. As mentioned, I will consider the GHA experiment [5], the BGGP experiment [6], and especially the Afshar experiment [8], which has received a great deal of attention. Some of the experiments test the duality relations and not BPC directly. As I mentioned earlier, despite this, all experiments ultimately test BPC. Since the same reasoning saves both BPC and the duality relations, the experiments need not be considered as separately testing BPC and the duality relations.

A refutation of complementarity requires two actual measurements, with one mea-
measurement consistent with the wave concept, while the other measurement is consistent with the particle concept. Yet, to repeat what I have said in the introduction, in all of these claimed experimental refutations, one complementary concept is actually measured (i.e. defined by the experimental arrangement as required by BPC), while the other complementary concept is artificially introduced through an unjustified assumption. In such experiments, the experimenters include some intermediate process, which in classical theory must be described by the classical concept opposite to the complementary classical concept consistent with final actual measurement. But since this concept is not actually measured, it is not even defined in the way demanded by BPC. Thus, BPC (and even the duality relations) are not even nearly challenged by these experiments.

I strongly suspect that an experiment which enables the simultaneous measurement of complementary concepts (whether particle-wave concepts or canonically conjugate variables), will also contradict the quantum formalism itself.

8 The Experiment of Ghose, Home and Agarwal

Here I consider the 1991 experiment proposed by Ghose, Home and Agarwal \[5\] and later performed by Mizobuchi and Ohtake \[7\]. It is based on the experiments performed by Bose (\[61, 62\] and \[55\] vol. II, p. 33 -12) in 1887 in which Bose observed the tunneling of microwaves when two asphalt prisms were placed sufficiently close to each other. The novelty of the GHA proposed experiment is the use of a single photon states.

Genuine single photon states, or one photon Fock or number states, are not as easy to produce as might be thought. Early experiments used very low intensity chaotic light where on average only one photon is present in the apparatus, but such low intensity light is not a Fock state and possesses very different properties. As I mentioned earlier, Grangier, Roger and Aspect were, perhaps, the first to use genuine single photon states. Pairs of entangled photons produced either by atomic cascades or by parametric down conversion are used. One of the pair is used to trigger a gate which remains open for a time of suitable length to allow its photon partner to pass with very high probability. The photon partner is then in a single photon state (at least to a good approximation).

Consider the configuration shown in figure 1. The single photon source is arranged so that only one photon is present in the apparatus at any one time. Since the 45° angle of incidence is greater than the critical angle, total internal reflection occurs when only one prism is in place. In this case, we expect only photomultiplier PM1 to register a series of single photon counts. When the gap between the two prisms is reduced to about a wavelength, tunneling can occur, so that a photon may be either reflected or transmitted.

This two-prism configuration can obviously be treated mathematically in the same way as in the case of a single prism beam splitter \[63, 64, 65\]. Let \( R \) be the reflection coefficient and \( T \) the transmission coefficient. There values will depend on the gap
between the two prisms. Phase changes are included by allowing $R$ and $T$ to be complex numbers. It is assumed that the two prism configuration corresponds to a lossless symmetrical beam splitter.

Figure 1. GHA’s beam-splitter photon configuration using a single source. When the gap is of the order of a wavelength, tunneling can occur.

In figure 1, $\hat{a}_1$ and $\hat{a}_2$ are the input annihilation operators, and $\hat{a}_r$ and $\hat{a}_t$ are the output annihilation operators. These are related by

$$
\begin{pmatrix}
\hat{a}_r \\
\hat{a}_t
\end{pmatrix}
= 
\begin{pmatrix}
R & T \\
T & R
\end{pmatrix}
\begin{pmatrix}
\hat{a}_1 \\
\hat{a}_2
\end{pmatrix},
$$

or

$$
\begin{align*}
\hat{a}_r &= R\hat{a}_1 + T\hat{a}_2, \\
\hat{a}_t &= T\hat{a}_1 + R\hat{a}_2.
\end{align*}
$$

The creation and annihilation operators satisfy the usual commutation relations

$$
[\hat{a}_i, \hat{a}_j^\dagger] = \delta_{ij},
$$

where $i, j = 1, 2, 3, 4$. These commutation relations led to the following conditions on $R$ and $T$

$$
\begin{align*}
|R|^2 + |T|^2 &= 1, \\
RT^* + TR^* &= 0.
\end{align*}
$$

In the experiment, a single photon enters the beam-splitter from input 1, while input 2 is in the vacuum state. Hence, it is necessary to find $\hat{a}_1^\dagger$, which can be done using eq.’s (3) to (7):

$$
\hat{a}_1 = R^*\hat{a}_r + T^*\hat{a}_t,
$$
The complex conjugate of eq. (8) gives
\[ \hat{a}_1^\dagger = R\hat{a}_r^\dagger + T\hat{a}_t^\dagger. \] (9)

Let \( |0\rangle = |0\rangle_1|0\rangle_2 = |0\rangle_r|0\rangle_t \) be the vacuum state for all the beam-splitter inputs and outputs. The state before and after the beam splitter may now be written as:
\[ \hat{a}_1^\dagger|0\rangle = |1\rangle_1|0\rangle_2 = R\hat{a}_r^\dagger|0\rangle_r + T\hat{a}_t^\dagger|0\rangle_t \]
\[ |1\rangle_1|0\rangle_2 = R|1\rangle_r|0\rangle_t + T|0\rangle_r|1\rangle_t \]
(10) (11)

The state after the beam-splitter is seen to be an entangled state. The amplitude \( A_r \) for reflection, and the amplitude \( A_t \) for transmission are:
\[ A_r = r\langle 1|_t\langle 0|_1|1\rangle_2 \]
\[ = R_r\langle 1|_1\rangle_r\langle 0|_0\rangle_t + T_r\langle 1|_0\rangle_r\langle 0|_1\rangle_t \]
\[ = R \]
(12)
\[ A_t = r\langle 0|_t\langle 1|_1|0\rangle_2 \]
\[ = R_r\langle 0|_1\rangle_r\langle 1|_0\rangle_t + T_r\langle 0|_0\rangle_r\langle 1|_1\rangle_t \]
\[ = T \]
(13)

The corresponding probabilities are \( |A_r|^2 = |R|^2 \) and \( |A_t|^2 = |T|^2 \). The amplitude \( A_c \) for a coincidence count is
\[ A_c = r\langle 1|_t\langle 1|_1|0\rangle_2 \]
\[ = R_r\langle 1|_1\rangle_r\langle 1|_0\rangle_t + T_r\langle 1|_0\rangle_r\langle 1|_1\rangle_t \]
\[ = 0, \]
(14)

so that the probability \( |A_c|^2 \) for a coincidence count is also zero.

GHA took perfect anticoincidence to be consistent with particle behaviour. That is to say, the final experimental results are consistent with particle behaviour. For a photon detection in PM1 tunneling must have occurred. Classically tunneling at the gap can only be explained by wave theory. Therefore, GHA argued that the classical requirement that tunneling must be explained by the wave concept amounted to the observation of wave behaviour. GHA therefore concluded that wave and particle behaviour are observed in the same experiment in direct contradiction of BPC. In this way, GHA claimed that their experiment constitutes a refutation of BPC. The theoretically predicted results were confirmed by the experiment of Mizobuchi and Ohtaké. This was expected as different results to those predicted would contradict quantum theory.

The refutation however fails. The key point is that the wave behaviour is never actually measured, but rather, it is only inferred based on the circumstance that classically tunneling can only be explained in terms of the wave concept. However, Bohr insisted that a description of mechanisms underlying experiment are impossible and
that classical concepts are in any case abstractions to aid thought that cannot be attributed physical reality. The only requirement of BPC is that the classical concept be consistent with the experiment as a whole, i.e., the experimental arrangement and the final experimental result. Indeed, it is the experimental arrangement and measurement that defines the concept. Since the wave concept is inferred but not measured it is completely illegitimate under BPC to apply the wave concept to the GRA experiment. Thus, according to BPC, the GHA experiment is consistent with (defines) one and only one complementary concept, namely, the particle concept. I conclude that the GHA experiment is perfectly consistent with BPC.

Although BPC does not require a mechanism for tunneling of particles, we note that the Bohm-de Broglie nonrelativistic causal interpretation provides a model for the tunneling of particles (impossible classically) by use of the quantum potential. The model is therefore in terms of both wave and particle concepts simultaneously, and it may be thought that GHA experiment provides evidence for the causal interpretation. But again, this is not so, since the wave behaviour is never actually measured. A truer model of the GHA experiment is provided by the causal interpretation of boson fields, which includes the electromagnetic field. In this interpretation photons (bosons, in general) are fields; there are no photon(boson) particles. In this case, tunneling is explained according to a wave model as in classical physics, while perfect anticoincidence is explained nonclassically by the nonlocal absorption of photons. In the absence of a measurement of the field behaviour as well as the actually measured particle behaviour, the GRA experiment neither refutes BPC, nor distinguishes between BPC and the two latter models.

9 The Brida, Genovese, Gramegna, and Predazzi Experiment

Some authors questioned the statistical accuracy of the results of the Mizobuchi and Ohtaké experiment. This prompted Brida et al to carry out an improved experimental test addressing the criticisms of the Mizobuchi and Ohtaké experiment. In the BGGP experiment, birefringence replaces tunneling through a gap between two prisms as the phenomenon that in classical theory can only be described by the wave concept. The single photon source uses type I parametric fluorescent light generated by a UV pump laser which is then passed through a nonlinear crystal. It is arranged so that only one photon at a time passes through a birefringent calcite crystal. Through the crystal the photon path splits along the ordinary or extraordinary directions. After exiting the crystal the two possible paths are directed to two different photodetectors.

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5 Though the $R$-field gives rise to the quantum potential the $S$-field can also explain tunneling since the $R$ and $S$-fields co-determine one another. See ref. [56] for a computer model of quantum tunneling based on the causal interpretation.

6 In the causal interpretation of boson fields there are still $R$- and $S$-fields which codetermine one another, as in the nonrelativistic case, but these now depend on the normal mode coordinates of the field. These fields are also involved in tunneling so there is this difference with classical wave theory.
The perfect anticoincidence predicted by quantum mechanics was again observed. The perfect anticoincidence is consistent with a particle picture. Brida et al inferred wave behaviour from the fact that the photon underwent the birefringent phenomenon that classically can only be explained by wave behaviour. Brida et al, like GHA, claimed that both wave and particle behaviour is observed in the same experiment thus refuting complementarity.

But, the Brida et al variation of the GHA experiment suffers from the same criticism as the GHA experiment. The particle behaviour is consistent with the observed experimental results. The wave behaviour is not measured, but only inferred from the fact that in classical theory birefringence can only be explained by a wave theory. But, as for the GHA experiment, the description in terms of BPC is neither constrained by classical theory nor requires any other mechanism for birefringence, especially since classical concepts are not attributed physical reality. BPC only requires that the classical concept be consistent with the experimental arrangement and the final measured experimental result. There is no conceptual inconsistency in imagining a photon particle following either the ordinary or extraordinary direction. We see that the BGGP experiment is consistent with (defines) one and only one complementary concept; the particle concept. I again conclude that the BGGP experiment is perfectly consistent with BPC.

As for GHA, two alternative descriptions of the BGGP experiment can be given in terms of the causal interpretation. In the nonrelativistic interpretation the quantum potential (equivalently the \( S \)-field) produces the splitting of paths along the ordinary or extraordinary directions, with particles following one or other alternative path depending on their (hidden) initial position. The explanation of anticoincidence follows since the particle registers in one or other of the detectors. A truer model in terms of CIEM explains bifringence, as in classical physics, by a wave model (but involving the nonclassical \( R \)- and \( S \)-fields), and explains perfect anticoincidence by the nonlocal absorption of a photon.

10 The Afshar Experiment

The aim in the Afshar experiment is to obtain undiminished image quality of two pinholes of a standard interference experiment when a wire grid is placed at the previously measured positions of the dark fringes of an interference pattern. Afshar argued that with the wire grid in place, and if interference occurs, there should be little or no loss of radiant flux, so that the image quality should be comparable to the image quality without the wire grid in place. In this way, Afshar devised a nondemolition measurement of interference fringes. The experiment indeed confirmed that there was almost no loss of resolution or total radiant flux.

If interference did not occur, the wire grid would block some radiant flux with a corresponding reduction of image quality and resolution. Since there was almost no loss of resolution or total radiant flux, Afshar concluded that interference occurred prior to image formation. He attributed the interference to wave behaviour. Following
Afshar assumed that the image of a pinhole must be formed by photons coming from that pinhole, and considered this to constitute a determination of the photon path. With this he associated particle behaviour. Afshar concluded that his experiment demonstrates the measurement of wave and particle behaviour in one and the same experiment in direct contradiction of BPC (and the duality relation).

Afshar’s experiment is split into three separate experiments. Experiment 1, shown in figure 2, is a standard two-pinhole interference experiment. Coherent and highly stable laser light of wavelength $\lambda = 650$ nm is directed at a screen with two pinholes with diameters $b = 250 \mu m$, and separated by a distance $a = 2000 \mu m$. The interference pattern is observed at a photoplate placed in the plane $\sigma_1$ 4 m from the pinholes. The nonstandard feature of this experiment is the very accurate measurement of the positions of the dark fringes of the interference pattern.

![Figure 2. Afshar’s experiment 1: Detection of interference by the photoplate at position $\sigma_1$ and the accurate measurement of the position of the dark fringes.](image)

In experiment 2, shown in figure 3, the photoplate at $\sigma_1$ is removed and a lens of diameter 3 cm and focal length $f = 100$ m is placed 4.2 m from the pinholes. The lens forms images of the two pinholes in the plane $\sigma_2$ 1.38 m from the lens. Experiment 2 acts as the control experiment with which the images formed with the wire grid in place are compared.

In experiment 3, shown in figure 4, a wire grid consisting of six wires is placed in the plane $\sigma_1$. The grid is positioned so that the wires of the grid coincide with the previously measured positions of the dark fringes. Again, images of the two pinholes are formed at the image plane $\sigma_2$. As I mentioned earlier, Afshar observed almost no loss in resolution or of total radiant flux as compared to the pinhole images obtained in experiment 2. He took this to be a definite detection of an interference pattern. To further justify his reasoning he closed pinhole 1, and obtained an image of pinhole 2 but...
with reduced intensity (i.e. less radiant flux formed the image compared to the control experiment). This showed two things. First, the image gives perfect path information so that \( D = 1 \) and supports the interpretation, according to Afshar, that even with both pinholes open the images give perfect path information. Second, the reduction in radiant flux shows that there is no interference, so the wire grid scatters photons significantly. Since image quality (very few photons scattered) is restored when both pinholes are opened, Afshar considered this as further evidence that an interference pattern is detected with both pinholes open.

Figure 3. Afshar’s experiment 2: The photoplate at \( \sigma_1 \) is removed and a lens is used to form images of the two pinholes in the image plane \( \sigma_2 \).

Figure 4. Afshar’s experiment 3: A grid consisting of six wires is placed in plane \( \sigma_1 \) so that the wires coincide with the six central dark fringes of the interference pattern observed in experiment 1. Almost no reduction in resolution or total radiant flux of the images of the two pinholes formed in plane \( \sigma_2 \) was observed.
Placing detectors directly in the positions shown in figure 5 directs the pinhole images into two separate high resolution detectors producing more accurate measurements.

In this way, Afshar concluded that the presence of the wire grid constitutes a (nondemolition) measurement of interference, and therefore wave behaviour. On the other hand, by assuming (not measuring) that a photon forming a pinhole image must have come from that pinhole, Afshar claims to have determined the photons path, and therefore to have observed particle behaviour. Thus, Afshar claims to have observed wave and particle behaviour in the same experiment in direct contradiction of BPC.

Afshar equates the particle-wave duality relation to BPC, and measures $D$ (or his version of the particle parameter) and $V$. He claims that his experiment give values of both $D$ and $V$ nearly equal to 1, so that $D^2 + V^2$ has a value nearly equal to 2 in direct violation of the duality relation (1), and BPC.

Though I will argue below that the Afshar experiment fails to refute either BPC or the duality relation (1), it is nevertheless an interesting experiment from a technical perspective. The very interesting feature is the clear demonstration that interference takes place prior to the formation of the image and without any significant loss of image quality.

The experiment would by even more interesting if it could be repeated using a genuine single photon source of the type used in the GRA experiment [9] and in the BGGP experiment [6].
11 Critique of the Afshar Experiment

The Afshar experiment fails to refute either BPC or the duality relation for a similar reason that the GHA and BGGP experiments fail, namely, because one complementary concept (the particle concept) is measured while the other (the wave property) is inferred. In the case of the Afshar experiment, the unjustified assumption is that a photon forming a pinhole image must have come from that pinhole. Henceforth, I will refer to this as the Wheeler-Afshar Pinhole Assumption (WAPA). The WAPA is first of all not justified by the mathematical formalism of the quantum theory since the initial wave function is a superposition of wave functions emerging from each pinhole. We recall Dirac’s famous statement, “The new theory, which connects the wave function with probabilities for one photon, gets over the difficulty by making each photon go partly into each of the components. Each photon then interferes only with itself. Interference between two different photons never occurs” [66] page 9. A further argument against WAPA is the description of the experiment according to the causal interpretation of boson fields applied to the electromagnetic field (CIEM) [25, 30, 31]. According to this interpretation, which is a direct interpretation of the second quantized Maxwell equations, the photon, as I said earlier, is a field and so passes through both pinholes in a two pinhole arrangement. Further, the splitting of the photon at two pinholes, as deduced by Dirac and as required by CIEM, is indicated in the experiment of Tan, Walls and Collet in which homodyne detectors detect a single photon in both paths produced by a beam splitter [67]. A photon reaching the detector at $\sigma_2$ is spread over the images of the two pinholes, but registers as a ‘spot’ in the detector. In CIEM, this is explained by the nonlocal absorption of the photon by atoms/molecules in the detector. The probability of absorption is highest at positions of highest intensity. When enough photon ‘spots’ are detected, the images of the two pinholes emerge.

Perhaps WAPA is suggested by the rays of geometric optics. However, the identification of photon trajectories with rays of geometric optics is arbitrary and has no theoretical justification. Again, the existence of CIEM emphasizes that such an association is erroneous, since, in this model, a photon is a field and passes through both slits.

Image formation and interference are perfectly consistent with a pure wave theory, so that according to BPC the entire Afshar experiment is perfectly consistent with one and only one complementary concept; the wave concept. Thus, once we recognize that the claimed detection of path is based entirely on an arbitrary, unjustified assumption, we see that the Afshar experiment is perfectly consistent with BPC.

Numerous other authors have also criticized Afshar’s refutation. These authors, like Afshar, equate BPC with the duality relation [1], and defend BPC by defending the duality relation. Invariably, these defences of BPC, like Afshar, contain unjustified assumptions. I mention a few such authors: Kastner [68, 69], Steuernagel [70], Qureshi [71] and Drezet [72]. Flores and others have agreed with Afshar, and have worked on modified versions of Afshar’s experiment, either independently [73] or together with Afshar [74]. The modified experiments suffer from the same serious objections that
Afshar’s experiment suffers.

Kastner agrees with Afshar that a photon detection constitutes a which-path measurement, but disagrees with Afshar in that he considers the state before the photon detection as a superposition state containing no path information. Kastner considers the photon detection in one image or the other as changing the photon’s state from the superposition state containing no path information, to a “path” eigenstate. In this case, unlike Afshar, Kastner concludes that the “path” eigenstate state formed after the photon is detected does not reveal from which pinhole the photon came. Kastner thus concludes that $D$ in the Afshar experiment is zero. With $D = 0$ and accepting Afshar’s measurement of $V$ close to 1, Kastner concludes that the duality relation is preserved. Kastner’s conclusion is in line with mine, except that I disagree that the final photon state after detection is a “path” eigenstate. The photon is destructively absorbed and what is left is an atomic or molecular state.

Steuernagel criticizes Afshar’s result $D^2 + V^2 = 2$ based on a classical calculation (with results interpreted according to quantum theory). He saves the duality relation by calculating a value of $V$ to be close to zero and by calculating a value of $D$ close to one, values that are opposite to those of almost all other authors, including us. Aside from Steuernagel’s calculation of $V$ close to zero being a direct contradiction of the actual (albeit, indirect) measured value in Afshar’s experiment, a measurement considered genuine by almost every other author, his calculation has been severely criticized by Kastner [69] and Flores [75]. Further, implicit in Steuernagel’s analysis is the identification of photon trajectories with the rays of geometric optics. This is the same identification that seems to underpin Wheeler’s and Afshar’s WAPA, mentioned and criticized in some detail in section (11). Steuernagel’s (and Afshar’s) value for $D$ close to one, based on the latter arbitrary, unjustified assumption, cannot therefore be maintained. We conclude that Steuernagel reaches the correct conclusion but for the wrong reasons. Qureshi also concludes that Afshar’s analysis is flawed. He saves the duality relation by arguing that the occurrence of the interference destroys the path information. This argument can be criticized, both from our arguments above, but also from the fact that a superposition state is required for interference to occur. Such a state does not carry path information. In other words, there was no path information in the first place to destroy.

12 Conclusion

We have tried to make a clear distinction, first, between particle and wave complementary concepts, which classically are mutually exclusive concepts, and complementary concepts which classically are simultaneously definable (and measurable) canonically conjugate variables, and second, between Bohr’s principle of complementarity and the Wootters and Zurek reformulation of complementarity. We have argued that the duality relations, which evolved from WZPC, do not have the fundamental significance that they are normally attributed. But, because of its clear mathematical significance it is worthwhile to note that the duality relation has been given a conceptually consis-
tent interpretation by Jaeger, Shimony and Vaidman, an interpretation also consistent
with BPC. I have suggested that a better interpretation of the duality relations should
be based on an ontological interpretation of the quantum theory, such as the causal
interpretation.

Concerning my main task, I have argued that quantum optical experiments which
purport to refute BPC fail. I have tried to show that the reason such experiments fail
is because only one complementary concept is actually consistent (defined) with the
experimental arrangement and the measured result, while the other complementary
concept is inferred based on an arbitrary and unjustified assumption.

Although, I have argued against experimental refutations of BPC, I nevertheless
feel that such tests are important, because, ultimately, such tests also test the quantum
theory. Moreover, such tests seem to continually push technological limits. For both
of these reasons such experimental tests are to be encouraged.

Finally, we have suggested that although BPC has not been experimentally refuted,
it can be severely criticized on theoretical and conceptual grounds.

References

[1] N. Bohr The Quantum Postulate and the Recent Development of Atomic Theory
at Atti del Congresso Internazionale dei Fisici Como, 11-20 September 1927
(Zanichelli, Bologna, 1928), vol 2 p. 565; substance of the Como lecture is reprinted
in Nature 121 580 (1928); N. Bohr Atomic Theory and the Description of Nature
(Cambridge University Press, Cambridge, 1934) p. 52

[2] N. Bohr Atomic Physics and Human Knowledge (Science Editions, New York,
1961)

[3] N. Bohr Discussion with Einstein on Epistemological Problems in Quantum Me-
chanics in Albert Einstein, Philosopher-Scientist ed. P. A. Schilpp (Evansten, IL:
Library of Living Philosophers, 1949) p. 201; reprint: (Open Court, Lasalle, Illi-
nois, third edition, 1982) p. 201

[4] M. Jammer The Philosophy of Quantum Mechanics: The Interpretations of Quan-
tum Mechanics in Historical Perspective (USA, John Wiley & Sons, 1974)

[5] P. Ghose, D. Home & G. S. Agarwal An Experiment to Throw More Light on
Light Phys. Lett. A 153, 403 (1991)

[6] G. Brida, M. Genovese, M. Gramegna & E. Predazzi A Conclusive Experiment to
Throw More Light on “Light” Phys. Lett. A 328, 313 (2004)

[7] Y. Mizobuchi & Y. Ohtake An “Experiment to Throw More Light on Light” Phys.
Lett. A 168, 1 (1992)

[8] S. S. Afshar Violation of the Principle of Complementarity, and its Implications
in The Nature of Light: What is a Photon? ed. C. Roychoudhuri & K. Creath,
[9] P. Grangier, G. Roger & A. Aspect Experimental Evidence for a Photon Anticorrelation Effect on a Beam Splitter: A New Light on Single-Photon Interferences EuroPhys. Lett. 1, 173 (1986)

[10] H. Rauch, W. Treimer & U. Bonse Test of a Single Crystal Neutron Interferometer Phys. Lett. A 47, 369 (1974)

[11] H. Rauch & S. Werner Neutron Interferometry: Lessons in Experimental Quantum Mechanics (Clarendon Press, Oxford, 2000)

[12] H. Rauch & J. Summhammer Static Versus Time-Dependent Absorption in Neutron Interferometry Phys. Lett. A 104, 44 (1984)

[13] D. M. Greenberger & A. Yasin Simultaneous Wave and Particle Knowledge in a Neutron Interferometer Phys. Lett A 128, 391 (1988)

[14] P. N. Kaloyerou & H. R. Brown On Neutron Partial Absorption Experiments Physica B 176, 78 (1992)

[15] H. R. Brown, J. Summhammer, R. E. Callaghan & P. N. Kaloyerou Neutron Interferometry with Antiphase Modulation Phys. lett. A 163, 21 (1992)

[16] G. Badurek, H. Rauch & D. Tuppinger Neutron Interferometric Double-Resonance Experiment Phys. Rev. A 34, 2600 (1986)

[17] P. Bogár & J. Bergou Entanglement of Atomic Beams: Tests of Complementarity and Other Applications Phys. Rev. A 53, 49 (1996)

[18] S. Dürr, T. Nonn & G. Rempe Origin of Quantum-Mechanical Complementarity Probed by a Which-Way Experiment in an Atom Interferometer Nature 395, 33 (1998)

[19] Z.-Y. Li Atom Interferometers: Beyond Complementarity Principles arXiv:quant-ph/0109023v1, 4 Sep 2001

[20] P. Bertet, S. Osnaghi, A. Rauschenbeutel, G. Nogues, A. Auffeves, M. Brune, J. M. Raimond & S. Haroche A Complementarity Experiment with an Interferometer at the Quantum Classical Boundary Nature 411, 166 (2001)

[21] M. O. Scully & M. S. Zubairy Quantum Optics (Cambridge University Press, Cambridge, 1997) p. 494

[22] S. Dürr, T. Nonn & G. Rempe Fringe Visibility and Which-Way Information in an Atom Interferometer Phys. Rev. Lett. 81, 5705 (1998)
[23] K.-P. Marzlin, B. C. Sanders & P. L. Knight *Complementarity and Uncertainty Relations for Matter Wave Interferometry* Phys. Rev. A **78**, 062107 (2008)

[24] P. Ghose *Testing Quantum Mechanics on a New Ground* (Cambridge University Press, Cambridge, 1999)

[25] P. N. Kaloyerou *The GRA Beam-Splitter Experiments and Particle-Wave Duality of Light* J. Phys. A: Math. Gen. **39**, 11541 (2006)

[26] D. Bohm *A Suggested Interpretation of the Quantum Theory in Terms of “Hidden” Variables. I* Phys. Rev. **85**, 166; D. Bohm *A Suggested Interpretation of the Quantum Theory in Terms of “Hidden” Variables. II* Phys. Rev. **85**, 180 (1952)

[27] L. de Broglie *Une Interpretation Causale et Non Lininaire de la Mechanique Ondulatoire: la Theorie de la Double Solution* (Gauthier-Villars, Paris, 1956). [English translation: *Non-linear Wave Mechanics: A Causal Interpretation* (Elsevier, Amsterdam, 1960)]; L. de Broglie *The reinterpretation of wave mechanics* Found. Phys. **1**, 5 (1970)

[28] P. N. Kaloyerou, PhD Thesis *Investigation of the Quantum in the Relativistic Domain* University of London (1985)

[29] D. Bohm, B. J. Hiley & P. N. Kaloyerou *An Ontological Basis for the Quantum Theory: A Causal Interpretation of Quantum Fields* Phys. Rep. **144**, 349 (1987)

[30] P. N. Kaloyerou *The Causal Interpretation of the Electromagnetic Field* Phys. Rep. **244**, 287 (1994).

[31] P. N. Kaloyerou *A Field Theoretic Causal Model of the Mach-Zehnder Wheeler Delayed-Choice Experiment* Physica A **355**, 297 (2005)

[32] E. Buks, R. Schuster, M. Hieblum, D. Mahalu & V. Umansky *Dephasing in Electron Interference by a ‘Which-Path’ Detector* Nature **391**, 871 (1998)

[33] D.-I. Chang, G. L. Khym, K. Kang, Y. Chung, H.-J. Lee, M. Seo, M. Heiblum, D. Mahalu & V. Umansky *Quantum Mechanical Complementarity Probed in a Closed-Loop Aharanov-Bohm Interferometer* Nature Physics **4**, 205 (2008)

[34] C. S. Unnikrishnan & S. A. Murthy *Some comments on the two prism tunnelling experiment* Phys. Lett. A **221**, 1 (1996)

[35] J. A. Wheeler *The “Past” and the “Delayed-Choice” Double-Slit Experiment in Mathematical Foundations of Quantum Theory* ed. A. R. Marlow (Academic Press, New York, 1978)

[36] J. A. Wheeler *Law Without Law in Quantum Theory and Measurement* ed. J. A. Wheeler & W. H. Zurek (Princeton University Press, New Jersey, 1983) p. 182
[37] W. Heisenberg *The Physical Content of Quantum Kinematics and Mechanics* in *Quantum Theory and Measurement* ed. J. A. Wheeler & W. H. Zurek (Princeton University Press, 1983) p. 62

[38] D. Bohm, B. J. Hiley & C. Dewdney *A Quantum Potential Approach to the Wheeler Delayed-Choice Experiment* Nature **315**, 294 (1985)

[39] M. O. Scully & K. Drühl *Quantum Erasure: A Proposed Photon Correlation Experiment Observation and Delayed Choice in Quantum Mechanics* Phys. Rev. A **25**, 2208 (1982)

[40] A. G. Zajong, L. J. Wang, X. Y. Zou & L. Mandel *Quantum Erasure* Nature **353**, 507 (1991)

[41] M. O. Scully, B.-G. Englert & H. Walther *Quantum Optical Tests of Complementarity* Nature **351**, 111 (1991)

[42] P. G. Kwiat, A. M. Steinberg & R. A. Chiao *Observation of a “Quantum Eraser”: A Revival of Coherence in a Two-Photon Interference Experiment* Phys. Rev. A **45**, 7729 (1992)

[43] T. G. Herzog, P. G. Kwiat, H. Weinfurter & A. Zeilinger *Complementarity and the Quantum Eraser* Phys. Rev. Lett. **75**, 3034 (1995)

[44] B.-G. Englert, M. O. Scully & H. Walther *Quantum Erasure in Double-Slit Interferometer with Which-Way Detectors* Am. J. Phys. **67**, 325 (1999)

[45] Y.-H. Kim, R. Yu, P. Kulik, Y. Shih & M. O. Scully *Delayed “Choice” Quantum Erasure* Phys. Rev. Lett. **84**, 1 (2000)

[46] W. K. Wootters & W. H. Zurek *Complementarity in the Double-Slit Experiment: Quantum Nonseparability and a Quantitative Statement of Bohr’s Principle* Phys. Rev. D **19**, 473 (1979)

[47] L. S. Bartell *Complementarity in the Double-Slit Experiment: On Simple Realisable Systems for Observing Intermediate Particle-Wave Behaviour* Phys. Rev D **21**, 1698 (1980)

[48] G. Jaeger, M. A. Horne & A. Shimony *Complementarity of One-Particle and Two-Particle Interference* Phys. Rev. A **48**, 1023 (1993)

[49] G. Jaeger, A. Shimony & L. Vaidman *Two Interferometric Complementarities* Phys. Rev. A **51**, 54 (1995)

[50] B. C. Saunders & G. I. Milburn *Complementarity in a quantum nondemolition measurement* Phys. Rev. A **39**, 694 (1989)

[51] X. Y. Zou, L. J. Wang & L. Mandel *Induced Coherence and Indistinguishability in Optical Interference* Phys. Rev. Lett. **67**, 318 (1991)
[52] L. Mandel *Coherence and Indistinguishability* Opt. Lett. **16**, 1882 (1991)

[53] B.-G. Englert *Fringe Visibility and Which-Way Information: An Inequality* Phys. Rev. Lett. **77**, 2154 (1996)

[54] H.-Y. Liu, J.-H. Huang, J.-R. Gao, M. S. Zubairy & S.-Y. Zhu *Relation Between Wave-Particle Duality and Quantum Uncertainty* Phy. Rev. A **85**, 022106 (2012)

[55] R. P. Feynman, R. B. Leighton & M. Sands *The Feynman Lectures on Physics* vol I II & III (Addison-Wesley, Reading, 1964)

[56] C. Dewdney, Ph.D. Thesis, University of London, 1983

[57] C. Dewdney, C. Phillipides & B. J. Hiley *Quantum Interference and the Quantum Potential* Nuovo Cimento B **52**, 15 (1979); C. Dewdney *Particle Trajectories and Interference in a Time-Dependent Model of Neutron Single Crystal Interferometry* Phys. Lett. A **109**, 377 (1985); C. Dewdney, P. R. Holland & A. Kyprianidis *What Happens in a Spin Measurement* Phys. Lett. A, **119**, 259 (1986); C. Dewdney, P. R. Holland & A. Kyprianidis *A Quantum Potential Approach to Spin Superposition in Neutron Interferometry* Phys. Lett. A **121**, 105 (1987)

[58] D. Home & P. N. Kaloyerou *New twists to Einstein’s Two-Slit Experiment: Complementarity vis-a-vis the Causal Interpretation* Journal of Physics A **22**, 3253 (1989)

[59] B.-G. Englert, M. O. Scully, G. Süssman & H. Walther *Surrealistic Bohm Trajectories* Z. Naturforsch **47a**, 1175 (1992)

[60] P. N. Kaloyerou *The Wootters-Zurek Development of Einstein’s Two-Slit Experiment* Found. Phys. **22**, 1345 (1992)

[61] J. C. Bose *Collected Physical Papers* (Longmans and Green, London,1927) p. 44

[62] A. Sommerfeld *Optics* (Academic Press, New York, 1964) p. 32

[63] A. Zeilinger *General Properties of Lossless Beam Splitters in Interferometry* Am. J. Phys. **49**, 882 (1981)

[64] R. A. Campos, B. E. Saleh & M. C. Teich *Quantum-Mechanical Lossless Beam Splitter: SU(2) Symmetry and Photon Statistics* Phys. Rev. A **40**, 1371 (1989)

[65] R. Loudon *The Quantum Theory of Light* (Oxford University Press, Oxford, third edition, 2000) p. 212

[66] P. A. M. Dirac *The Principles of Quantum Mechanics* (Clarendon Press, Oxford, 1958)

[67] S. M. Tan, D. F. Walls & M. J. Collet *Nonlocality of a Single Photon* Phys. Rev. Lett. **66**, 252 (1991)
[68] R. E. Kastner Why the Afshar Experiment does not Refute Complementarity History and Philosophy of Modern Physics 36, 649 (2005)

[69] R. E. Kastner On Visibility in the Afshar Two-Slit Experiment Found. Phys. 39, 1139 (2009)

[70] O. Steuernagel Afshar’s Experiment does not Show a Violation of Complementarity Found. Phys. 37, 1370 (2007)

[71] T. Qureshi Complementarity and the Afshar Experiment arXiv:quant-ph/0701109v2, 19 Jan 2007.

[72] A. Drezet Complementarity and Afshars Experiment, arXiv:quant-ph/0508091v3, 22 Dec 2005; A. Drezet Wave Particle Duality and the Afshar Experiment Progress in Physics 1, 57 (2011)

[73] E. V. Flores Modified Afshar Experiment: Calculations in The Nature of Light: What are Photons? III Proc. SPIE vol 7421 ed. C. Roychoudhuri, A. F. Kracklauer & A. Y. Khrennikov (San Diego: SPIE, 2009) p. 74210W

[74] S. S. Afshar, E. V. Flores, K. F. McDonald & E. Knoesel Paradox in Wave-Particle Duality Found. Phys. 37, 295 (2007)

[75] E. V. Flores Reply to Comments of Steuernagel on the Afshars Experiment Found. Phys. 38, 778 (2008)