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On the Physical Reality of Quantum Waves

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The main interpretations of the quantum-mechanical wave function are presented emphasizing how they can be divided into two ensembles: The ones that deny and the other ones that attribute a form of reality to quantum waves. It is also shown why these waves cannot be classical and must be submitted to the restriction of the complementarity principle. Applying the concept of smooth complementarity, it is shown that there can be no reason to attribute reality only to the events and not to the wave or to the initial state of a given system. Thereafter, an experiment proposed by the authors is presented, where it is shown that the wave-like behaviour allows predictions that are not allowed on the grounds of a particle-like behaviour. In conclusion, we upheld that quantum waves must be real even if they do not belong to the same ontological level of events, which connected with particle detections.

KEY WORDS: complementarity; ghostfield; virtual field; potentiality; empty wave.

1. INTRODUCTION

The nature of the wave–particle duality, the fundamental empirical evidence on which has been created quantum mechanics, is a highly controversial question, and from the very beginnings of such a theory all possible alternatives have been explored. The interpretations of the Schrödinger wave function, and of its relationship with particles or particle-like behaviour, may be broadly cast into two main groups: In the first one, there are those interpretations that have refused to attribute any form of reality to the quantum wave. In the second group, on the contrary, fall all other interpretations that have tried to assign a reality to the quantum waves. Let us first briefly consider these two historical positions. Then, we will try to find a third position.

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2. THE QUANTUM WAVES ARE NOT REAL

The most radical position connected with to the first group may be resumed saying that there are *neither waves, nor particles*. In this case, a radical refute of the classical categories is expressed, assuming that only the mathematical formalism is meaningful and any attempt at giving an ontological interpretation is considered as nonsense and as a metaphysical way to handle the problem. This first interpretation may be found in early works of Heisenberg, who thought that the concepts of position and velocity and that therefore also a space–time description are applicable to quantum systems(1) (pp. 344–345). He assumed that the meaning of quantum observables coincides with the place they have in an experimentally tested formalism and consists in their mutual relationships at a formal level, for instance in the uncertainty between conjugate pairs(2) (p. 478).

A second position rejecting quantum waves is represented by Born's statistical interpretation. Born dropped both Heisenberg's and (as we shall see) Schrödinger's interpretations, proposing a further solution (for which he was awarded of the Nobel Prize in 1952) according to which the quantum wave may be understood as a ghostfield (*Gespensterfeld*, a word introduced by Einstein), in the sense that the waves could guide the particles on their path.(3) However, this field represented a mere mathematical tool being devoid of energy and momentum. These physical properties, on the contrary, may only be attributed to the particles, which, in this way, become the exclusive ontological referents of the quantum theory. Max Born was one of the first physicists to acknowledge the importance of the Schrödinger equation and to stress that the dynamical evolution of quantum systems must obey to it. Exactly as a consequence of this assumption, together with the previous understanding of quantum waves, Born coherently expressed the thesis that the quantum evolution must be indeterministic and that the Schrödinger equation must consequently rule only transition probabilities and not individually determined systems or events in the classical sense. These probabilities cannot therefore be dependent on subjective ignorance of the state of the system and are rather objective (again the expression 'ghostfield' may be helpful). The successive step was to interpret the square modulus of the coefficients of the wave function expansion as the probabilities to find the particle in the relative states.(4,5)

Born's point of view was combined with Heisenberg's original position and perhaps most coherently developed by Wigner(6) and is meanwhile almost become the official doctrine in quantum mechanics.(7) Wigner pointed out that only detection events are real (what you get is what you measure) and that the wave function is only a mathematical tool in order to calculate probabilities between a detection event and another.

The third position is represented by the complementarity between wave and particle-like description. It is difficult to completely understand and synthesize the original position of Bohr when he expressed, in 1927–1928, his complementarity principle.(8) What is sure is that Bohr refuted to attribute any reality to the particle or to the wave independently from the context of macroscopic experience and of a given experimental set-up. In other words, these two classical concepts were considered applicable to quantum-mechanical systems only to the extent to which the latter are inserted in a given experimental context, and the contexts in which the wave-like behaviour or the particle-like behaviour appears are mutually exclusive. Does this mean a form of idealism or at least of subjectivism as suggested by many authors? It is difficult to answer to this question; it seems to us that Bohr preferred to leave it to a certain extent unanswered. We wish, moreover, to point out the existence of two possible variants of the complementarity principle.

- In the first, no ontological level can be assigned, neither to the wave nor to the particle. Here, a kind of subjectivism seems unavoidable.
- However, there is also a second possibility, which we will discuss in the following: a form of interactionism that does not exclude the possibility to ascribe a form of ontological reality both to the waves and to the particles. As we shall see, probably Bohr has shifted from one position to the other.

3. THE QUANTUM WAVES ARE REAL

The first attempt at assigning a form of physical reality to the waves of quantum-mechanical systems was the historical article of Bohr, Slater, and Kramers (BSK)(9) and Jammer(1), in which they supposed the existence of a virtual radiative field (the analogy with Einstens ghostfield is evident, but, as we shall see, there are very important differences), such that the transitions between atomic stationary (stable) states are induced by the field of the atom itself and of the surrounding atoms, but are insensitive to the fields of atoms that are located far away. The interferences produced by the field originated by a given atom and those generated by the surrounding atoms explains the probabilistic, and not deterministic, nature of the transitions. However, for this reason, the authors supposed that also the vectorial momentum of the electrons had a non-zero probability to be directed everywhere, and, as a consequence, the conservation laws of momentum (and of energy) could only have a statistical value and not an exact validity for the individual systems. As it is well-known, this hypothesis was explicitly disproved very soon by an experiment performed by Bothe and Geiger(10–12) and by Compton and Simon.(13) In the article of BSK there were also two points which, from our present perspective, appear as two weaknesses:

(1) We cannot have a field in any classical sense where there are non–local relations between the components — as it happens actually for quantum systems, — that is we cannot have relations that violate the separability principle. In fact, the authors supposed that the field was a space–time mechanism or at least equivalent with a space–time mechanism.

(2) The transitions between stationary states were supposed to be induced by the field. It is true that the BSK also assumed (due to the interference between different fields) that these transitions are probabilistic. However, interferences and probabilities, here, have both a classical nature, so that it could be in principle possible to account for the final transition wholly in a deterministic manner. On the contrary, quantum systems show an irreducible probabilistic behaviour, such that there is no way to reduce the indeterministic character of quantum events, which for this reason remain unpredictable.

Two years or so later, Schrödinger tried to attribute a classically ontological reality to the waves, maintaining, moreover, that they constituted the only reality and that what we call particles are actually simple wave-packets confined in small portions of space.(14,15) Against such a perspective, several objections were advanced promptly, in particular that quantum waves do not propagate in ordinary space(8) and that wave packets will be dispersed in a too tiny time in order to be in accordance with the experienced stability of matter(16)(pp. 31–33).

A more sophisticated realistic approach to the problem was proposed by de Broglie. In order to understand de Broglie's position, one must have clear the distinction between two different approaches:

- the theory of the pilot wave,
- and that of the double solution.

The theory of the *pilot wave* is a de Broglie's proposal in order to understand the basic ontology of the microworld as composed of two different entities both endowed of physical reality: a wave and a particle. The wave ψ is a classical field that moves wave-like in the space and that 'pilots' a classical particle embedded in the field, The particle is therefore sensible to any wave-like superposition of the field. In the example of a two-slit experiment, the particle, factually, though both slits are open, always passes only through one slit, and the diffraction pattern is entirely due to the strange and wave-like trajectory impressed by the field. In this perspective there is no complementarity between wave and particle and no 'indeterminacy' at all.

The *double solution theory* is a mathematical treatment of the same idea: The correlation between particle and wave is a phase correlation, such that the particle is a singularity of the field, which differs from ψ only in amplitude, and which represents another, non-linear solution of the wave equation.

De Broglie published his results in a series of articles(17–19), but, in his lecture to the great scientific auditorium at the Fifth Physical Conference of the Solvay Institute in Brussels (October 1927), he presented only the simplified version of the whole: the pilot wave theory.(20) The several important criticisms to his proposal, brought de Broglie to abandon the theory. Hence, in a public lecture at the university of Hamburg in early 1928 he embraced the complementarity principle(16)(pp. 110–114), but he returned later (1955–1956) to his old proposal in a more systematic way, i.e. in the form of a double solution theory.(21)

As we have stressed, a logic consequence of de Broglie's interpretation would be the non-linear effects produced by the field. On the grounds of these ideas Bialynicki-Birula and Mycielski tried to develop an explicit non-linear formalism.(22) Successive experimental attempts at determining the value of these non-linear factors have however failed,(23,24) so that, even if the hypothesis could not be completely ruled out, also its proponents admitted its extreme improbability(25)(p. 50).

Another important consequence of the previous perspective is that a classical field together with a classical wave should produce deterministic results. This line of thought was in particular developed by Bohm initiating a new field of investigation: the one of hidden-variable theories.(26) However, also in this case experimental evidence does not support such an interpretation(27)(part IX).

4. THE QUANTUM WAVES ARE REAL BUT NOT IN THE CLASSICAL SENSE ...

Towards the end of the fifties Bohr, Born, and Heisenberg, the three main exponents of the non-realistic interpretation of quantum waves have partially modified their position. As Selleri has pointed out,(28) after Fock's criticism to the subjectivistic interpretation of quantum mechanics, according to which there are no valuable reasons to deny the reality of the wave function and that the interaction between observed system and apparatus is not as much incontrollable as Bohr originally thought, the latter began to shift his position giving to it a more objective turn. It is very interesting when we confront two quotations of Bohr. In 1955 he said:(29)

> One has sometimes seen in the notion of complementarity a reference to the subjective observer, incompatible with the objectivity of scientific description. Of course, in every field of experience we must retain a sharp distinction between the observer and the content of the observations, but we must realize that the discovery of the quantum of action has thrown new light on the very foundation of the description of nature and revealed hitherto unnoticed presuppositions to the rational use of the concepts on which the communication of experience rests.

Though Bohr refuted to dissolve physics in a form of subjective idealism, it is also almost clear that he thinks here that the subjective side cannot be eliminated since it enters in the rational use of the concepts. However, three years later he says:(31)

> The decisive point is that in neither case [relativity and complementarity] does the appropriate widening of our conceptual framework imply any appeal to the observing subject, which would hinder unambiguous appeal to the observing experience. [...] In complementary description all subjectivity is avoided by proper attention to the circumstances required for the well-defined use of elementary physical concepts.

Here the position seems quite opposite and, anyway, any ambiguity that was present in previous formulation of complementarity is disappeared.

Born, on the other hand, showed later a more positive attitude toward waves because, in 1964, he affirmed that it is impossible to perform probability predictions without referring to something objective(32)(p. 105). In this case, the ghostfield that he introduced in 1926 may be something more than a pure *façon de parler*.

Even Heisenberg, though never abandoning his strong faith in the superiority of the formalism as such, seemed to shift his initial positions.(33) In the fifties, Heisenberg asked what happens ‘in reality’ in quantum processes. He acknowledges that the concept ‘event’ must be limited to observations and that any attempt at attributing reality to quantum phenomena independently from observation leads to contradictions. Notwithstanding, the wave function joints subjective and objective elements, because it contains assertions on the tendencies of a given system, and these are completely objective and independent from the observer. Now, Heisenberg’s point of view is that, when measuring the interaction of the system with the whole universe also enters in the dynamical process and this may be called the subjective component only to the extent to which we cannot control these effects. For this reason, Heisenberg could use the Aristotelian concept of *potentia* when speaking of the initial state of the system and affirm that it is the dynamical process during the measurement

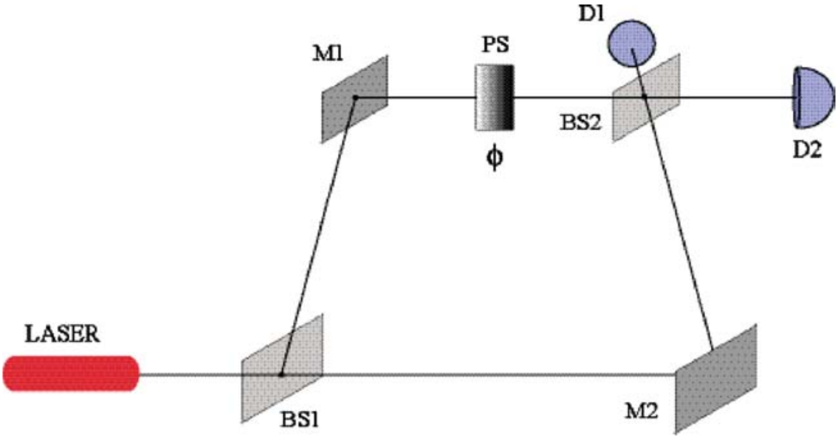

Fig. 1. Mach–Zender interferometer. The photons are pumped one at a time from the laser on the left and be split at the beam splitter BS1 into two components, going the upper and the lower arm, respectively. After being reflected by mirrors M1 and M2, a phase shifter PS is tuned for producing interferences between the two components that are merged and resplit at BS2. Finally, the two outgoing beams fall into detectors D1 and D2.

to allow the passage from the *potentia* to the actuality, i.e. to a given component of the initial superposition.

A realistic interpretation was further developed by Franco Selleri.(34) In fact, Selleri pointed out that, while no momentum and energy could be attributed to the wave (but only to the particle), its interference effects (the guide function of the field) would be notwithstanding real and detectable because it would have to produce sensible effects on the probability distributions. Moreover, as already said, Selleri was conscious to work in a line partially going back to the later efforts of Bohr and Born,(28) but he combined this line of thought with the ideas of de Broglie. In order to understand this point, we must consider a further consequence of de Broglie's positions, which was seen and understood for the first time by Selleri himself.(34) Let us consider the apparatus shown in Fig. 1. As it is well known, if the phase difference between the two paths is put to zero, the detector D1 will detect the dark output (no photon): This is due to the geometry of the apparatus and in particular to the destructive interference that is produced in BS2.

Suppose now a variation of the set-up, as shown in Fig. 2. In this case, if a photon is not absorbed by the object O, it will no longer show interference at BS2 and will have therefore a non-zero probability to fall into D1. In this case, we have detected the presence of an obstacle without interacting with the object O. How could we explain this situation?

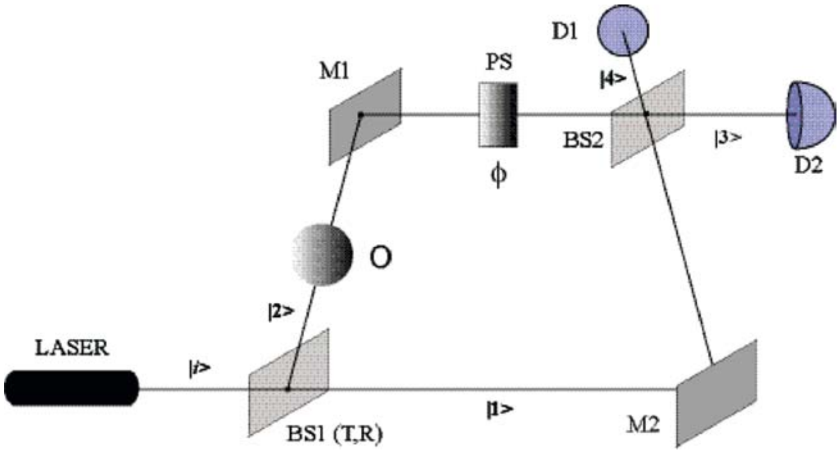

Fig. 2. An interaction–free measurement set-up proposed by Elitzur and Vaidman.(30) If $\phi = 0$, detector D_1 clicks only if one of the arms is blocked by the object O.

A possibility could be de Broglie's model. Let us first return to the initial situation of Fig. 1. In this case, the photon (that, according to de Broglie, is always localized in one of the two arms) takes one of the two paths, but interference is notwithstanding produced at BS2 because the field also act on the other path. Since there is no photon in this component, it may be called an empty wave. In the case of interaction-free measurements, the interference is avoided because the empty wave is blocked by O. This is a very clear model of the situation.

It is very important to stress that this line of thought is quite different from Bohr's complementarity, even if the latter is interpreted with an objective turn. In fact, de Broglie's hypothesis is the contemporary existence of wave and particle and is therefore completely foreigner to any idea of exclusion or complementarity. De Broglie's ideas were strongly supported by Vigier and co-workers.(35,36) It is important to stress that Vigier and co-workers' attempts, differently from Selleri's ones, were sharply characterized by an aim to directly contradict the complementarity principle. Their idea was to show that, even if a particle is detected, a real classical, Maxwell, wave is always present.

Another experimental proposal is due to one of us, and is more faithful to the original Selleri's idea.(37) Instead of two detectors and two beam splitters, we have four detectors and four beam splitters (see Fig.3). The idea is this: Suppose that a photon is detected by D1 or D2. Will there be still an interference at D3–D4? If this is the case, this can only be because an empty wave has travelled through the other path. A further

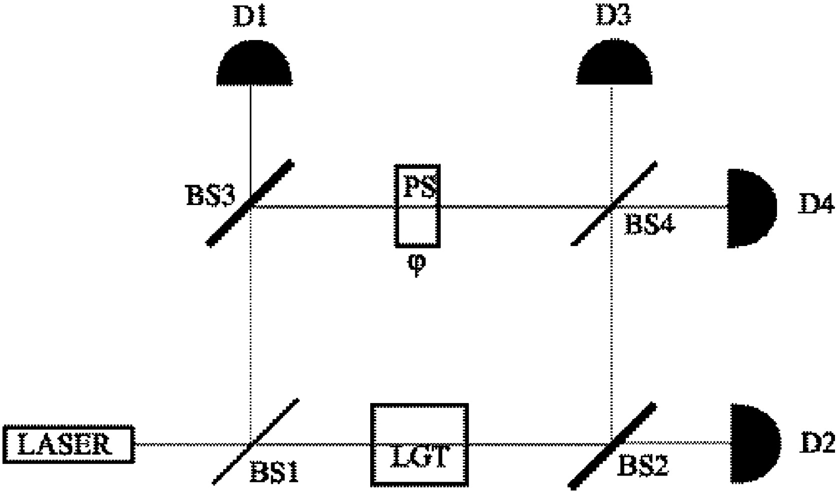

Fig. 3. The experiment proposed by Tarozzi. LGT represents here a laser gain tube.

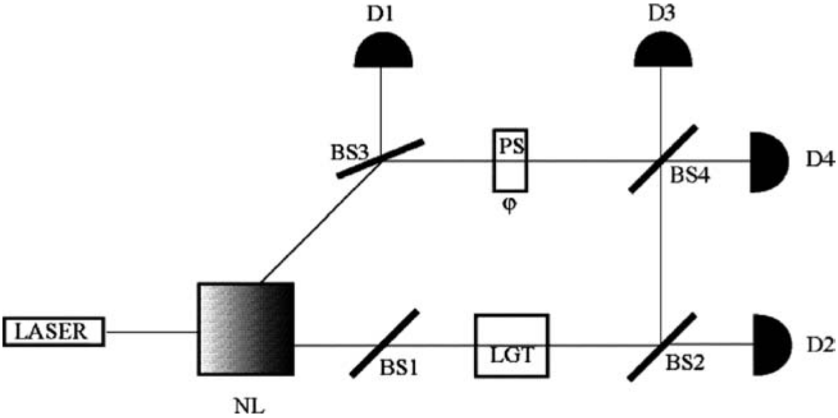

Fig. 4. The figure shows as lightly different version from the original proposal of Tarozzi. The geometry is not exactly reproduced.

improvement of Tarozzi's original idea could be the apparatus shown in Fig. 4. In this case, we have a non-linear crystal NL that produces two outgoing photons in the same state. The ideas of Tarozzi have influenced further contributions.(38)

For a certain time, it seemed that the idea of Vigier and co-workers could be confirmed. In particular, an experiment of Rauch and co-workers seemed to show that they may be interference effects also when

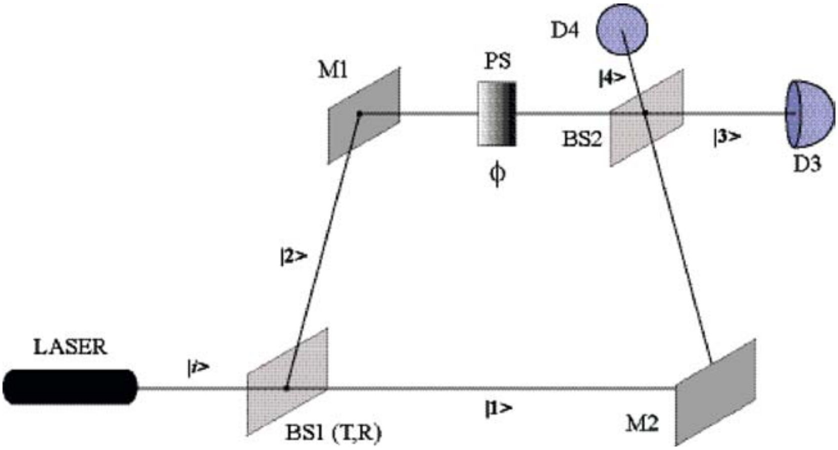

Fig. 5. Smooth complementarity between wave and particle.

a particle is detected,(39) and in this way Vigier and co-workers interpreted the result.(40) However, the experiment could also receive a completely different interpretation. It could be the case, that instead to be a refutation of complementarity, it were a confirmation of this principle, but introducing a significative modification of Bohr's original ideas. In fact, in the same year, Mittelstaedt, Prieur, and Schieder published a paper in which they showed that complementarity is a smooth variation between wave-like and particle-like behaviours and that therefore there are infinite intermediate possibilities between the two extreme alternatives.(41) Obviously, this run against Bohr's idea that complementarity is a sharp relation in which we have *either* the wave *or* the particle. The set-up of Mittelstaedt and co-workers is very simple (see Fig. 5): By letting varying the reflection and transmission parameters of BS1 we may obtain all intermediate situation between a wave and a particle. This threw light on the results of Badurek and co-workers: They obtained in fact an intermediate situation and for this reason they could detect something by obtaining at the same time interference. The results of Mittelstaedt and co-workers were anticipated by Wootters and Zurek,(42) and confirmed by Greenberger and Yasin(43) and by Englert.(44)

On the other hand, the idea of an empty wave or at least the idea of a classical (de Broglie) empty wave was disproved by some experiments performed by Mandel and co-workers(45) (see Fig. 6). In this experimental set-up is supposed that a non-null empty wave may go through the second non-linear crystal. In another, more complicated, experimental set up(46) there is no necessity of this assumption.

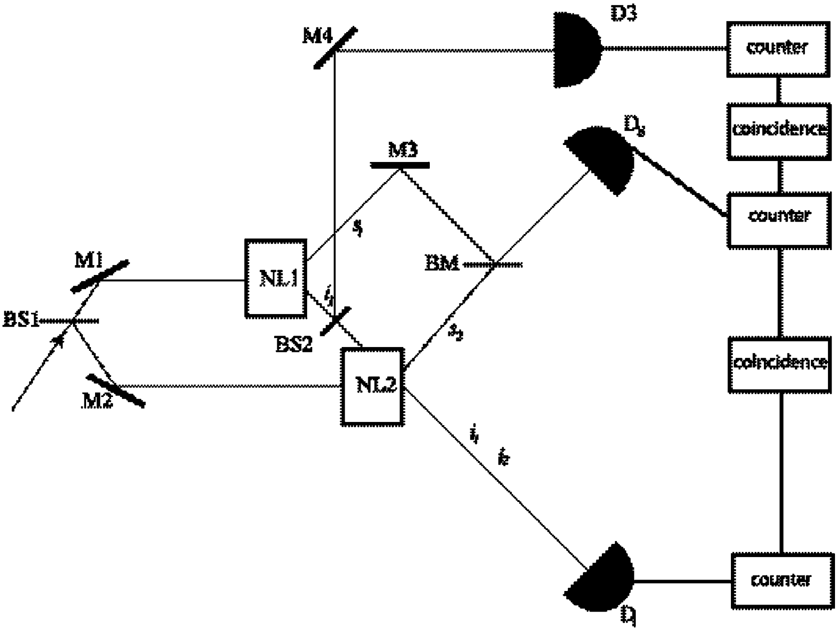

Fig. 6. Schematic representation of Mandel's experiment on empty waves. An initial beam is split by a beam splitter (BS1) and the resulting beams travel toward two non-linear crystals of $LiIO_3$ (NL1 and NL2). From NL1 a signal photon (s_1) and an idler photon (i_1) emerge: The i-photon passes through NL2 and will be aligned with the second idler (i_2), emitted by NL2 together with the second signal photon (s_2). The two s-photons are combined by the beam merger (BM) and the outgoing beam falls on detector D_s, whereas the two idler photons fall on detector D_i, The action of BS2 is such that the output beams travel toward the second non-linear crystal (NL2) and toward the third detector (D3). Now, if detector D3 clicks, from the point of view of the empty wave theory an empty wave (i_1) should fall on D1 and still induce coherence between s_1 and s_2. Experimental results showed no coherence in this case, which supports the interpretation of quantum waves as probability amplitudes.

Also an experiment of Hardy, in order to prove the existence of empty waves(47) (see Fig. 7) could arrive to no conclusive results because the effect could be explained by means of the ordinary quantum mechanics without empty waves(27)(pp. 484–487).

5. TO WHAT EXTENT BE REAL?

The previous examination seems to lead to no result: Any attempt at proving a reality of quantum waves seems to fail. However, there is also a positive result. The smooth complementarity shows that there is no reason

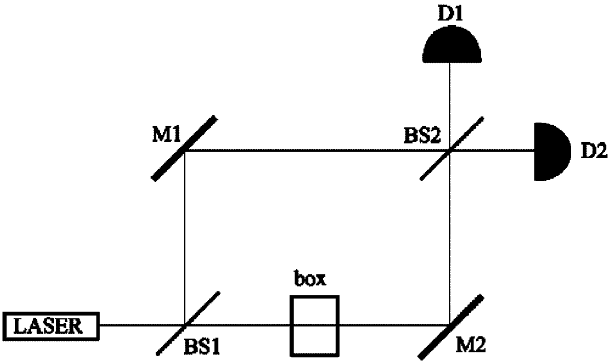

Fig. 7. Hardy's experiment. In the box in the lower path there is an atom. The main idea is that, if the phase difference between the two paths is tuned to 0, the detector D1 will click only in the case the photon takes the upper path, since, otherwise it would be absorbed by the atom. In this case, then, if the state of the atom will be changed, this can only be a consequence of an empty wave that took the lower path.

to assign reality only to the particle, since there is a continuous chain between something that we do not hesitate to call physical and real — because it is provided with energy and momentum — and a wave. Obviously, one could reject also the reality of the particle and limit oneself to admit the reality of detection events only, in the spirit of the first Heisenberg's interpretation. However, there are reasons to think that a measurement can never completely purify a system from the interference effects that are present, and as a matter of fact interference effects have been shown to exist also at mesoscopic level,(48,49) and probably still exist in the macroscopic world. Then, in the general case we can also conceive a continuous transition between a detection event and an initial, say, superposed state(27)(parts IV–VI). This will not mean that the measurement result is predictable. In fact, during a measurement we may suppose that the off-diagonal elements of the density matrix describing the object system tend to zero, but actually never reach zero.(50,51) Now, it is very easy to conceive a continuum between the density matrix describing the initial state of the system and that describing the state after the measurement. On the other hand, the final density matrix approaches to a mixture and this is a consequence of the fact that a large part of the initial information has been downloaded in the environment. As already Heisenberg suggested, it is an incontrollable process(52) and this explains why we cannot predict the measurement result. If we are right, then there is no reason to attribute ontological reality to the detection events and not to the initial state or to the quantum wave.

However, if a quantum wave has somehow an ontological reality, then, as already Selleri suggested, there must be a means to obtain predictions that are different from those that we would perform on the basis of a corpuscular behaviour. Obviously, this must happen, as explained in the previous section, by satisfying the smooth complementarity principle. This idea led the authors to propose an experiment that can show how to obtain different predictions in a complementary experiment.(53) Suppose the apparatus shown in Fig. 8. If we discard the cases where a single detector detects two photons, we obtain an entangled state of the form

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|1\rangle\,|4\rangle + |2\rangle\,|3\rangle) \ . \tag{1}$$

In other words, if detector D1 clicks, we can predict with certainty that D4 will click, and, if D2 clicks, we can predict that D3 will click. In this case we have both entanglement and wave-like behavior. It is interesting, now, to see what happens if we displace detectors D3 and D4 to a position before BS4 once a photon has already been detected by D1 or D2 — this is a delayed-choice experiment,(54) but with an important difference: Here, already an event occurred (D1 or D2 has already clicked). In this case, we can obtain information about which photon has been detected by D1 or D2

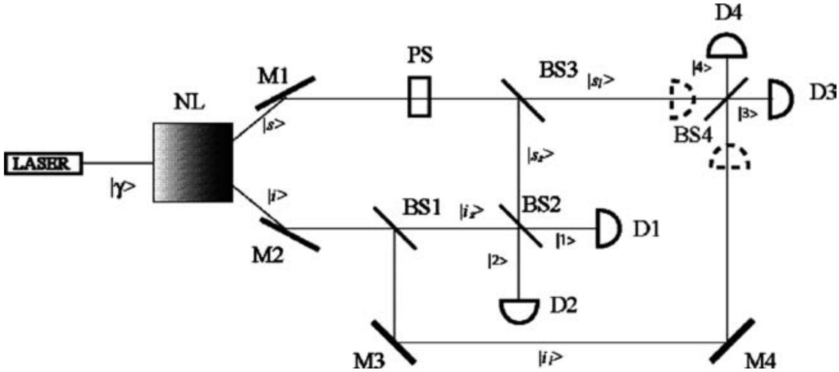

Fig. 8. A source laser pomps a photon in the state $|\gamma\rangle$. Successively, a parametric-down-conversion allows the emission of two photons, the *idler photon* (in the state $|i\rangle$) and *signal photon* (in the state $|s\rangle$). if γ has frequency ν and energy $h\nu$, the two outgoing photons have smaller frequencies ν_i and ν_s (and energies $h\nu_i$ and $h\nu_s$), respectively, with $\nu = \nu_i + \nu_s$. The two beam splitters BS1 and BS3 split each photon in two components, the ‘shorter’ and ‘longer’ components ($|i_s\rangle$, $|i_l\rangle$ and $|s_s\rangle$, $|s_l\rangle$, respectively). The two shorter (longer) components, $|i_s\rangle$ and $|s_s\rangle$ ($|i_l\rangle$ and $|s_l\rangle$) are recombined at BS2 (BS4), giving rise to photons in states $|1\rangle$ and $|2\rangle$ ($|3\rangle$ and $|4\rangle$), falling to detectors D1 and D2 (D3 and D4). Eventually, detectors D3 and D4 are placed before BS4 when D1 or D2 has already clicked.

and which photon has been detected by D3 or D4. Now, although we can know which photon has been detected by which detector and therefore the paths they follow, we cannot predict whether detector D3 or detector D4 will reveal the photon after either detector D1 or detector D2 has clicked. We also observe that, on account of the first interference (by BS2) and of the superposition of the two components of the i-photon and of the superposition of the two components of the s-photons, the latter situation (when detectors D3 and D4 are placed before BS4) is not the classical situation that would arise if both BS2 and BS4 were removed. In this case, if D1 clicks, we know with certainty that the i-photon has been detected and that the s-photon (if not detected by D2) will reach D3. On the other hand, if D2 clicks, we know with certainty that the s-photon has been detected and that the i-photon (if not detected by D1) will reach D4. We see that the conditional probabilities of the 'classical' case are neither similar to the conditional probabilities of the path detection after the interference at BS2, nor to the 'entangled' situation. In fact, in the latter case, if D1 clicks only once, D3 will click too, whereas in the 'classical' set up, if D1 clicks (and not D2), D3 will click as well; and similarly if D2 clicks.

We wish to stress that our proposed experiment differs from other performances testing the complementarity principle, because, in general, many runs are needed in order to obtain an interference (undulatory) pattern at the detectors. In our experiment, on the contrary, the effect of the undulatory pattern is shown in single runs and therefore for individual systems.

Now, if we are able to predict something different and new (i.e. whether D3 or D4 will click) when we have wave-like behaviour relative to the predictions allowed by the corpuscular behaviour, we see no reason for not attributing an ontological reality to the wave. Obviously, the difficulty is to understand what type of reality this can be. However, before examining the problem, we wish to stress that here two different questions are merged together.

- It is an uncontroversial fact that measurement results are unpredictable and that therefore there cannot be a classically causal relationship between the initial state and the detection event.
- However, should this mean that this measurement outcome comes from nothingness? Let us consider, for the sake of simplicity, the delayed choice experiment in Wheeler's original formulation.(54) We have a photon as input and a photon as output. In between we have no event. Will this perhaps mean that the photon has disappeared and is then (from nothingness) reappeared at the detectors? We think this is a vital question, because if the answer were positive, the whole scientific enterprise would become a non-sense. Then, the only possible answer can be negative.

If so, we are forced to admit that there must be a form of reality that is not of the type of events and that is not connected through classically causal chains with other realities. In other words, we must distinguish between (1) causal conditions and events, on the one hand and (2) a more general class of conditions that are not events and do not determine the individual output through a univocal causal chain, on the other. This means that the initial state is a complex of conditions that is somehow real but not sufficient to determine individual events.

As a consequence, this reality (the wave or the initial state of a given system) cannot be directly measured. It has been shown, that a measurement of the state of a single system would contradict the unitarity of quantum transformations.(55) This may be also seen in this way: Any measurement is local in nature, whereas the wave is non-local as such due to the correlation between different components. (Obviously these correlations do not violate the relativity but only the separability principle.) As we have said, to do not having taken into account this fact is one of the weakness of the 1924 article of Bohr and co-workers.

For these reasons, the reality of the wave can only be inferred and it is not possible to do direct experience of it. This is due to the fact that any experience of a quantum system presupposes a specific selection of an initial (possible and continuous) amount of information.(52,56). In other words, the initial state or the wave contains, at the level of potentiality, all the information that is possible to extract from it. But this information cannot be accessed to because it is the entangled ensemble of all possible answers to our questions to the system. In this way, we return to Heisenberg's idea that the initial state is a form of Aristotelian potentiality.

If we are right, the reality of the waves cannot be at same level as the reality of the particles or of the detection events — to this extent we also agree with the initial Born's tenet. Of the latter is possible to do experience, of the former not.

6. CONCLUSIONS

One could reply: What is this fuzzy idea that there can be a reality we cannot have direct experience of, and this not because of our physical limitations but in principle? Obviously, this is a difficulty. However, our conclusion for us seems to be the only legitimate one from the data at our disposal. Then, the problem is that science is not prepared, has not the instruments to handle a problem of this import because the main axiom on which modern science is built is that the only things which are real are the ones of which we can do direct experience. Therefore, at the actual state of facts, we cannot proceed very much on the path of determining what is this quantum-mechanical entity that we call ‘wave’. However, as we have already said, our ignorance cannot be a reason to deny that the things are so.

APPENDIX: DIALOGUE BETWEEN AN ORTHODOX AND A REALIST

R: My problem is the following. In an interferometry experiment, could we speak of the existence of something, of a form of reality before we detect the photon?

O: How should I know this if not through a detection? This makes the expression ‘the existence of something before detecting it’ a pure non–sense. In order to know that something exists, you must do experience of it and therefore, in a physical context, detect it.

R: However, there are plenty of things which we never experience directly: Quarks, black holes, and so on.

O: This is right. However, we speak here not of a problem of scale, rather of an impossibility in principle, i.e. to detect something before we detect it.

R: In many cases, we are obliged to have recourse to inferences when direct experience is impossible. Then, I would say: ‘To infer the existence of something before we detect it’.

O: I do not see how you could perform this inference, given that it is only the experimental context as such to guarantee the necessary conditions in order to extract any conclusion. Your inference seems to be rather a form of pure imagination.

R: I can restate the problem as follows: You have a photon as input in the interferometer and a photon as output (at the detectors). Is there nothing in between?

O: How can I speak of something without having the possibility to experience it? Now, you should agree that before the detection event we have no event at all, and without an event it is impossible to speak of ‘experience’. It did not happened anything at all! Moreover, what assures to me that I have a photon as input?

R: This is a very easy problem to solve. You can tune the laser in order to emit photons so that two next emissions are separated by a given time interval. We can verify this by let the photons be detected before they enter in the interferometer. Once we have perfectly tuned the laser, we may be assured that, after a certain time, the photon has passed the first beam splitter.

O: This is right. However, my main question remains unanswered: How can I speak of something without having the possibility to experience it?

R: Please, let aside a moment the epistemological question (how it is possible to know something before a detection) and, please, answer simply to this question: Is the input photon disappeared in the nothingness and is the output photon reappeared from the nothingness?

O: This cannot be the case, since we would fall in a pure idealism, which is absolutely contrary to the enterprise of natural science. However, it is devoid of meaning to attribute any character to this 'in between', given that any attribution presupposes at least the possibility to do experience of the object to which I attribute the character.

R: This is right. However, can a physical reality come out from something that is not a physical reality?

O: This is again impossible.

R: Then, you must coherently admit that, before the detection event, you have a physical reality.

O: This can be. However, it is a very strange physical reality such a one whose I cannot do experience.

R: This is right. Perhaps, the time is ripe to change our understanding of physical reality. Perhaps the world does not consist only in objects that can be directly experienced.

O: This is again a strange conclusion.

R: It can be. But it is the only rational conclusion. If it is so, then this reality can and must be thought appropriately. Physics would abdicate if it would show itself unable to do this.

O: Perhaps I begin to see your point of view.

R: Once we agree on this result, I leave to your intelligence and personal reflection to think about how this reality can be interpreted.

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