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Non-standard realistic models of quantum phenomena and new forms of complementarity

Niccolò Covoni, Giovanni Macchia, Davide Pietrini, and Gino Tarozzi

Dipartimento di Scienze Pure e Applicate, Università Urbino Carlo Bo, Via Valerio 9, 61029 Urbino, Italy

Abstract. This paper addresses the problem of different complementary interpretations of atomic phenomena. We take complementarity seriously as a meaningful philosophical principle, in the same way that the same principles to which complementarity limits simultaneous recourse, such as realism and causality, are endowed with meaning.

We will then discuss the attempts to overcome the complementary relation between waves and particles in a realistic sense by attributing an independent physical reality to both wave-like and particle-like entities, showing the negative results of such attempts, which instead reveal the validity of another formulation of the principle of complementarity: the so-called *smooth complementarity*, according to which wave and corpuscular representations can mix without a rigid distinction, although one continues to manifest itself at the expense of the other.

We will emphasize how a particularly weak realist interpretation of the quantum mechanical wave function conflicts with a (strong) formulation of the causal principle, and show the emergence of another form of classical complementarity between the realist and causal interpretations, which may assume a new smooth form even in this case. Complementarity confirms, in this way, its central role in the foundations of quantum mechanics and indicates at the same time how the philosophical interpretation of this theory, from the point of view of both realism and causality, remains a meaningful open question.

1 Bohr's (non-)famous proposal at the Lake Como congress

Niels Bohr's principle of complementarity, which posits that specific pairs of complementary properties cannot be observed or measured simultaneously, is one of the most debated principles in quantum mechanics. This principle has been criticized both by proponents of non-standard interpretations and by advocates of the orthodox interpretation of quantum mechanics, who have often attempted to reduce it to a synonym for Heisenberg's uncertainty principle. The latter, as is well known, asserts a fundamental limit to the precision with which certain pairs of classical physical properties—such as position and momentum, or time and energy—can be simultaneously known.

In 1927, a pivotal year for quantum physics, Heisenberg introduced the uncertainty principle, and two fundamental physics congresses were organised: the *International Congress of Physicists* in Como and the *Fifth*

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Congress Solvay in Brussels. During the Como congress, Bohr exposed the famous complementarity principle that, together with Heisenberg's uncertainty principle, would give rise to modern quantum mechanics.

The Como Congress was organised by the *Italian Physical Society* (SIF) and the *Italian Electrotechnical Association* (AEI) in honour of the first centenary of Alessandro Volta's death.

For the first time, the discussions were broadcast via radio, allowing the public to follow the proceedings and hear the voices of the distinguished scientists in attendance. This technical achievement was made possible by the *International Standard Electric Corporation* carried out this task so that anybody could follow the proceedings and hear the voices of the eminent personalities convened in Como (Auctores varii 1928, p. xii).

The Congress was attended by the most influential physicists of the time. Remarkable was the absence of Albert Einstein, who rejected the invitation due to opposition to the Mussolini fascist government.

The Congress opened on September 11, 1927, in Como and closed on September 20, 1927, in Rome on the Campidoglio. On September 17, Bohr, at the same Pavia University where Alessandro Volta taught, presented his lecture on the principle of complementarity titled "The quantum postulate and the recent development of atomic theory". His lecture was shorter than he had prepared for the Congress. A few weeks before the Congress, the congress committee had informed the Danish physicist that the lecture should have lasted only twenty minutes. Comparing his lecture with the article for the proceedings published in 1928, we can observe that Bohr cut his lecture. The published article contains a more complete presentation than the one held at the Congress and includes some observations made during the next Solvay congress in October 1927. It should also be noted that Bohr used the neologism "complementarity" for the first time in the proceedings. The reviewer also underlined the originality of this term.

Bohr's talk at the Como congress was not warmly received. The lecture during the Congress probably did not clarify the core of his thought on complementarity.

In the days following the conference, the reception of the principle of complementarity was not jointly accepted, above all in the Italian academic community. The spirit of the time can be summarised by one of the most influential physicists in Italy, the President of the Pontifical Academy of Science, Giuseppe Gianfranceschi, who was well known for translating Minkowski's paper on space-time into Italian. Over the years, Gianfranceschi tried to reinterpret modern physics according to Aristotelian physics (Maiocchi 1991, pp. 194–198; Fano 1991; Pietrini 2019). Gianfranceschi also participated in the Como Congress by giving a lecture, just before Bohr's, entitled "The Physical Significance of Quantum Theory". This was followed by a discussion with Maurice de Broglie on the measurement of individual electronic quantities.

Gianfranceschi's lecture summarized the main doubts and criticisms of quantum mechanics. According to him, quantum mechanics could not be interpreted as a physical theory because a physical theory should be "a model capable of accounting for what we find in phenomena and bodies, and must precisely serve as a guide in the search for the true nature of things" (Gianfranceschi 1928, pp. 559–564). Finally, Gianfranceschi, after recalling the importance of quantum formulas in the solution of many problems, said that "the criteria of statistical distribution [...] are those that are best suited to transport problems from a discontinuous process to a process of continuity". He asserted that it was not necessary to exclude other ways of investigation. Gianfranceschi's reservations were partly shared by many Italian physicists of the "older generation" who, because of their certainties and scientific background, were not inclined to fully accept the characteristics of young modern physics. Behind their criticism lay the problem of causality. Physicists are worried about rejecting the principle of causality, one of the main pillars of science.

Born's comment after Bohr's lecture answered this problem:

> Quantum theory abandons the determinism that has dominated all-natural research. However, in the strict sense, the abandonment of causality is only an apparent distortion. The mechanistic view of nature, as it was in force before, in order to predict future events, had to assume that the state of the world was completely known in every detail at all times. However, this assumption is an illusion. The real insight of quantum theory is that the very laws of nature forbid completely fixing the state of a closed system. The more precisely one measures a coordinate, the less precisely one determines the associated momentum (Bohr 1928, pp. 589–591).

Concerning the problem of causality, Bohr will explain his position in his memory: "This recognition, however, in no way points to any limitation of the scope of the quantum-mechanical description, and the trend of the whole argumentation presented in the Como lecture was to show that the viewpoint of complementarity may be regarded as a rational generalisation of the very idea of causality" (Schilpp 1970, p. 211).

2 The irrelevance of complementarity in the treatises of quantum mechanics

Complementarity has played only a minor role in the orthodox interpretation of quantum mechanics, as evidenced by its limited presence in the two foundational texts of the field: Dirac's *Principles of Quantum Mechanics* and von Neumann's *Mathematical Foundations of Quantum Mechanics*. In both books Bohr's principle is rarely mentioned, while a great space is given to the exposition and discussion of Heisenberg's uncertainty principle. In particular, Dirac underlined how the two founding principles of the new theory were the uncertainty principle and the superposition principle. He characterized the former as a negative principle because it imposes restrictions on classical notions, such as the simultaneous attribution of position and momentum to a physical system. Conversely, he described the superposition principle as a positive principle because it allows phenomena impossible in classical physics, such as describing a system's state as a combination of multiple possible values before measurement.

Non-orthodox quantum theorists have also criticized the role and relevance of complementarity. They viewed it as a term rooted in dubious philosophical premises, introduced to compensate for the inability to develop new concepts that could adequately explain quantum phenomena. For instance, Louis de Broglie referred to Bohr as a "master of chiaroscuro," while Einstein remarked on the incomprehensibility of complementarity, finding it resistant to any attempt at understanding.

In the case of Göttingen theorists, two interpretations of complementarity were identified, the first related to the limitation of two classically compatible concepts or descriptions such as position or momentum, or causal and spacetime coordination. The importance of the latter was underlined above all by Pauli. The second interpretation, peculiar of Bohr's view, extended complementary relation to incompatible classical concepts like waves and particles. Such a dual nature of atomic objects represented for Bohr the fruitful experimental evidence on which the quantum theory was born and developed, whereas for Göttingen theorists saw it as a metaphysical assumption linked to the old ontology of classical physics.

On the ground of Dirac's distinction between the negative and positive nature of the principles of quantum mechanics, Bohr's complementarity, according to its original formulation, should have had the double status of a negative and, at the same time, positive principle: negative for restricting the use of compatible classical concepts, and positive for enabling the simultaneous consideration of incompatible classical representations. However, the restrictive interpretation of the Göttingen school reduced complementarity to a purely negative principle, synonymous with indeterminacy relations, adding no substantial insights. This is probably the reason why Dirac did not include complementarity among the basic principles of quantum mechanics. Complementarity was accepted, therefore, only as a negative principle by the Göttingen school, but was rejected as a positive principle, allowing the recourse to classically incompatible concepts such as particles and waves, thus denying one of the peculiarities and conceptual novelty of quantum theory.

A further restrictive version of complementarity was proposed more than thirty years later by the Soviet physicist Vladimir Fock (Fock 1957) in the form of the principle of relativity to our means or instruments of observation. Based on this principle, which Fock considered an extension of the principle of relativity to our reference frame, the wave or corpuscular properties of atomic objects would have manifested themselves depending on the instruments used to investigate them. According to this point of view, some instruments or classes of instruments would have only detected waves. In contrast, other ones would have detected only particles but never the properties of these objects simultaneously. As Karl Popper would have rightly pointed out in his criticism of the restricted interpretations of complementarity, the classic and well-known double-slit experiment already contradicts this kind of merely "negative" interpretations since, on the detector screen, we reveal both localised impacts of particles and the classic wave-like interference pattern of their distribution.

3 Arguments against and for the wave-particle duality

Three main arguments have been proposed to reject the wave-particle duality as conceptualized by Bohr.

The first stems from the interpretation of "beables"[1] in ontological analyses. In the complementarity framework, both waves and particles are considered to exist. However, some argue that neither truly exists, suggesting instead that their apparent dual behavior is a pseudo-problem tied to the outdated ontology of classical physics. This view is supported by figures like Heisenberg and Jordan, who advocated a radical anti-realist stance that emphasized the necessity of "withdrawing" into mathematical formalism.

The second and third arguments involve asserting the exclusive existence of either particles or waves. One possibility is that only particles exist

The first possibility is that particles exist without waves. This is the case of Born's famous interpretation of the Schrödinger equation, in which the wave function is regarded as a mere mathematical tool that allows one to calculate, through its square modulus, the probability density of finding a given particle in a given region of space.

The alternative argument posits that only waves exist. Schrödinger's view supports this proposal. He advocated a purely wave-like ontology, interpreting his wave function as a real physical wave and denying any corpuscular aspect to atomic phenomena.

There are also three reasons to endorse a form of wave-particle duality. According to Bohr's principle of complementarity, either waves or particles (in a mutually exclusive sense) exist. In his view, the necessity of resorting to

[1]The term "beable" refers to items that exist according to the theory, things that are "just there." The beables of a theory just are the ontology of the theory (Maudlin 2019).

both representations (wave and corpuscular) is assumed with the impossibility of fully reconciling them in one unitary image of physical reality. In addition, without accepting the complementarity principle, it is possible to advocate for a duality of both waves and particles. De Broglie—who firmly believed, having extended the duality from radiation to matter in the dual nature of atomic objects—rejected the limitation of complementarity, asserting the possibility of coexistence between an extended wave phenomenon and a localised particle.

Another possibility is represented by particles driven by ghost waves, as sustained by Einstein, who, despite having reintroduced through his famous hypothesis of light quanta a corpuscular theory of radiation, believed that the phenomena of interference and diffraction were not explainable on the grounds of a purely corpuscular conception, but also required the presence of a wave, accompanying and guiding the quanta in their movement. However, the fact that all the energy was concentrated in the quantum and that the wave associated with it was consequently devoid of this fundamental property led Einstein to introduce the term *Gespensterfelder*[2] for such "waves".

4 Alternatives to complementarity with an ontological commitment to the reality of the wave function

To bypass the notion of complementarity, one possibility is to make some ontological commitments about the reality of the wave function. In this section, we will briefly introduce three non-standard realistic interpretations of the wave function, on which one of us (G. T.) has focused our research on the foundations of quantum mechanics for some time.

These realistic interpretations of quantum mechanics are the following:

1. de Broglie pilot waves (de Broglie, 1957), according to which the fundamental ontology of the quantum world consists of particles guided by pilot waves, which are understood as real physical entities;

2. Selleri empty (or quantum) wave (Selleri, 1971) defined by Renninger and Selleri as *zero energy wave-like (undulatory) phenomenon*;

3. the approach of the reality of the "no-photon" state (Albert 1996, 2023, Ney 2023), replacing traditional superposition with an *entanglement* between a particle and a *no-particle* in the case of a single particle.

These three realist interpretations seem apparently different but are actually conceptually very close. They reject the antirealist perspective of the Göttingen School and attempt to eliminate the complementary and exclusive nature of the wave-particle duality. As we shall show, however, they each lead to new forms of complementarity.

[2]The term introduced by Einstein can be translated as ghost waves.

On the one hand, the reality of de Broglie's pilot waves and Selleri's empty waves imply smooth complementarity, which we will explain in the following paragraphs, between wave-like and particle-like behaviour. On the other hand, the reality of the no-thing, in the sense of the attribution of a physical state to the no-photon, conflicts, as we will see, with a non-metaphysical formulation of Cartesian causality, highlighting how even the complementarity between two philosophical principles, such as realism and causality, highlighted by Bohr since the Como congress in the case of space-time coordination and Kantian causality, can have a smooth nature.

Let us briefly introduce each of these interpretations in the following paragraphs.

4.1 Pilot wave interpretation

The first realistic interpretation of the wave function that tries to avoid complementarity is the theory of the pilot wave proposed by de Broglie.[3] This interpretation posits that the quantum world comprises two distinct entities, both endowed with physical reality: the wave and the particle.

In this interpretation, the wave ψ is understood as a classical field that moves wave-likely in 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. From this perspective, there is no complementarity between wave and particle and no 'indeterminacy'.

Einstein's point of view constituted a sort of weakening of de Broglie's pilot wave interpretation and, at the same time, rejected the incomprehensibility of Bohr's complementary interpretation.

Nonetheless, this approach raises an essential question: how can we accept the existence of an entity, such as the guiding wave, that lacks directly observable physical properties?

De Broglie's interpretation was unsatisfactory because the physical quantities were mainly associated with particles. However, an infinitesimally small fraction of them, so small that it escaped all possible observations, was associated with the wave in contrast with Planck's fundamental postulate of unity and indivisibility of the quantum of action.

[3] He proposed this interpretation in several articles and presented his theory at the Fifth Physical Conference of the Solvay Institute in Brussels (October 1927). However, the various essential criticisms of his proposal led de Broglie to abandon the theory. He did so in a public lecture at the University of Hamburg in early 1928, but later (1955–1956), he returned to his old proposal.

4.2 Selleri empty wave

De Broglie's interpretation was revived in the 1960s by Renninger in his paradox of negative measurement and by Selleri, who developed an original alternative interpretation of the wave function. This interpretation, like that of de Broglie, assumed the reality of waves and corpuscular particles, but with an ontological priority of the latter over the former, insofar as quantum waves were identified as a "zero energy undulatory phenomenon".

Selleri proposed a new hypothesis according to which the wave function, even without any physical quantity associated with it, could give rise to physically observable phenomena. Indeed, in quantum mechanics, "we do not only measure energies, momenta, and so on. We also measure probabilities, e.g. the lifetime of an unstable system" (Selleri 1969, p. 910). The wave function could, therefore, have acquired physical reality, independently of the associated particles, if it can give rise to changes in the transition probabilities of the system with which it interacts.

Starting from this original intuition, Selleri presented the first version of his experiment to reveal the properties of quantum (empty) waves, considering a piece of matter composed of unstable entities, such as nuclei, atoms or excited molecules crossed by a continuous flow of neutrinos. He, therefore, proposed to measure the average life of these nuclei and then compare it with the average life of the same entities in the absence of any flow: if a difference is observed, the only logical explanation is that "it is due to the action of the wave function since the neutrinos are extremely weakly interacting particles and only a few of them, at most, can have interacted in the piece of matter with presently available neutrino intensities" (Selleri 1969, p. 910).[4]

4.2.1 De Broglie's endorsement and the revival of the pilot wave

Selleri's hypothesis was greatly appreciated by de Broglie, who identified that idea as "an important attempt aimed at obtaining an interpretation of wave mechanics more satisfactory than the one currently adopted and a confirmation of the ideas that had guided me when I proposed the basic conceptions of wave mechanics in 1923–24" (L. de Broglie, letter to F. Selleri, 11–IV 1969).

This endorsement also led to a revival of de Broglie's pilot wave by the main exponent of the de Broglie school, Jean-Pierre Vigier, who was strongly motivated in the search for a realistic and causal interpretation of quantum mechanics, on which he had already worked with David Bohm, proposing their nonlocal theories of hidden variables.

The experiments proposed by Vigier and others were aimed at revealing the wave-like interference properties by finding the persistence of the inter-

[4] Selleri's original idea was perfected in the proposal of an experiment: see Selleri (1971).

ference pattern, even in physical situations where, in a Mach-Zender device (such as the double slit), one can distinguish the path followed by the wave without the particle and the path followed by the wave with the particle.

In these cases, however, we are not simply dealing with an alternative philosophical interpretation of the wave function, but with experiments that also test the validity of the reduction postulate, according to which the interference disappears every time one is able to know which path the particle has followed.

The most advanced of these experiments, designed by Vigier, Garuccio, Rapisarda, and in a later version by these three authors together with Karl Popper, was based on the possibility of being realised only if the hypothesis of the detection of the Selleri wave's property of producing stimulated emission in a laser gain tube was verified.

However, G. T. has shown that the possibility of detecting the interference while determining the path followed by the particle without producing the reduction of the wave function did not necessarily require the denial of Selleri's hypothesis, and therefore, it was possible to do a single experiment to detect either de Broglie–Vigier waves or Selleri waves.

4.3 The failure to reveal empty waves and the emergence of *smooth* complementarity

Two types of experiments were done to detect quantum waves.

The first type was to find the empty wave, that is, to see if it produced stimulated emission or had properties separate from the particle; in this case, it did not contradict the formalism of quantum mechanics but only Born's interpretation of the wave function. The results were negative both in the Mandel and co-worker experiment and of Hardy[5], which could arrive at no conclusive results because the effect could also be explained by ordinary quantum mechanics without empty waves.

Therefore, Selleri's hypothesis was not confirmed by experiments.

The second type of experiment—which we have already mentioned in the previous paragraph—consisted, instead, of searching for the path of a photon or electron inside an interferometer without destroying the interference pattern in order, therefore, to have both the path and the interference, thus violating complementarity. This proposal by Vigier and co-authors would have undermined a postulate of the wave function collapse. Therefore, it would have been a much more crucial experiment concerning the validity of the formalism of quantum mechanics.

These experiments seemed at first to favour Vigier's interpretation, in the sense of the possibility of both determining the path and finding the interference; in reality, it was later discovered, thanks to Mittelstaedt, Prieur,

[5] For both experiments, see Auletta and Tarozzi (2004b).

and Schieder (1987), that these two aspects were not fully determined. They were only partially determined (neither was precise). Therefore, an experiment that initially had to contradict complementarity by letting waves and particles coexist was transformed into an experiment that contradicted complementarity only in the restrictive form of Heisenberg and, more generally, of Göttingen (i.e., the one that stated that there are classical properties that are mutually exclusive)[6]. Mittelstaedt, Prieur, and Schieder reinterpreted these experiments as a confirmation of a new version of complementarity, called *smooth*, according to which one can have partly the path, partly the interference, that is, a form of complementarity no longer sharp between waves and particles, but between a partly wave image and a partly corpuscular image, which can coexist but only partially. They showed that complementarity is a smooth variation between wave-like and particle-like behaviours. Therefore, there are infinite intermediate possibilities between the two extreme alternatives. What emerged, therefore, was a confirmation of Bohr's complementarity, indeed, in some ways even beyond Bohr, towards a somewhat more realistic perspective.

The previous examinations seem to lead to no conclusive result: any attempt to prove the reality of quantum waves seems to fail. However, we underline the positive result of the smooth complementarity, which runs against the idea that complementarity is a sharp relation in which we have either the wave or the particle: the smooth version shows that there is no reason to assign reality only to the particle since there is a continuous link between something like the particle—that we do not hesitate to judge physical and real because it is provided with energy and momentum—and a wave which seems devoid of these detectable properties.

In the spirit of Heisenberg's interpretation, one could also reject the reality of the particle and limit oneself to admitting the reality of detection events only. However, there are reasons to think that a measurement can never completely purify a system from the interference effects that are present. In fact, interference effects have been shown to exist also at the mesoscopic level and probably still exist in the macroscopic world.

4.4 The reality of the state of the no-photon

This section explores a weaker realist interpretation of the wave function, grounded in the recognition of physical reality as "nothingness"—specifically, the absence of a particle (such as a photon or electron). This approach reframes the wave function collapse as a consequence not of an interaction between an empty wave and the measuring device, but of detecting the particle's absence.

[6]Note that Mittelstaedt et al.'s results were anticipated by Wootters and Zurek, and confirmed by Greenberger and Yasin, and by Englert (see the references in Auletta and Tarozzi 2004b).

Our argument is based on the idea of describing a single photon that can be found at one or another of two distant places, here and there. Let us suppose, for instance, Bologna and Münster, through an entanglement replacing the standard superposition state.

The photon is indivisible and cannot appear partly here and partly there. It will not be there if it is found here, and vice versa. We will use $|1\rangle$ to denote the presence of the photon, $|0\rangle$ to denote its absence; the product $|0\rangle \otimes |1\rangle$, which we can write $|01\rangle$, will accordingly indicate that there is a photon there and nothing (no photon) here. Similarly, $|10\rangle$ indicates a photon here and no photon there. If we consider the physical situation similar to de Broglie's paradox, here and there would correspond to Bologna and Münster.

The two possibilities $|01\rangle$ and $|10\rangle$ can be combined in the superposition:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle),$$

whose fundamental aspect stays in its coherence, expressed by the minus sign between the two terms, which means the two products are physically related and communicate. This coherence means that both possibilities, $|01\rangle$ and $|10\rangle$, are present before an observation or a measurement operation produces the collapse to either one or the other.

Note that the state of entanglement that we will use is a formal complication intentionally adopted to do the detection. This state is a sort of formal stratagem precisely chosen, as we will see shortly, to give a physical state to the non-being of the photon (no-photon) and, therefore, make an overlap between being (here or there) and non-being (there or here, respectively) of the photon. So without entanglement, one does not have the detection of the no-photon that causes the collapse, as the one of the empty wave in Selleri's interpretation.

Let us make an observation or a measuring operation on the photon *here* in Bologna and not find the photon. Its absence will produce a collapse of the superposition to its second term $|01\rangle$, while the expectation of the photon *there* in Münster jumps from 0 to 1.

The jump takes place once we have found out that the photon is not here in Bologna, where we have detected or registered nothing. However, what does the discovery of the absence of the photon involve?

Our no-thing does not correspond to an absolute no-being or nothingness, but simply to a relative no-photon. In this way, one attributes the collapse of the wave function, and the corresponding modification of the physical situation, to the registration process of the absence of the photon, namely, in our formalism, $|01\rangle$, *no-photon* here and photon there, or in other terms to the photon registration failure here and consequent registration there.

So that, if there is no photon, one can explain the collapse of the wave function and the corresponding modification of the physical situation by appealing to the physical properties of nothing, here understood as the absence of the photon (*no-photon*).

Does this attempt allow us to get rid of complementarity and also of Born's interpretation, according to which the wave function is only a mathematical tool for calculating the probability of particle detection, through a new form of wave function realism, assuming the reality of the particle and of the no-particle (wave function without the particle)?

We will try to show that if this may be true for the complementary interpretation of the wave-particle duality, this conclusion cannot be maintained for the complementary principle in general. To do this, we must briefly introduce Descartes' concept of causality.

5 Cartesian causality and the consequences of its violation

Descartes' causality is based on his so-called principle of "non-inferiority of causes" as outlined in his *Third Meditation*:

> But Now, it is evident by the *Light of Nature* that there must be *as much* at least in the *Total efficient Cause*, as there is in the *Effect* of *that Cause*; For from Whence can the *effect* have its *Reality*, but from the *Cause*? and how can the *Cause* give it that *Reality*, unless *it self have* it?
>
> And from hence it follows, that neither a *Thing* can be made out of *Nothing*, Neither a *Thing* which is *more Perfect* (that is, Which has in it self *more Reallity*) *proceed* from *That* Which is *Less Perfect*. (in Gaukroger, 2006, pp. 216–217).

According to this fundamental conception, the Cause can never be "inferior" to its effect: a "more real" thing cannot come from a "less real" thing. Hence, it follows that a thing whatsoever cannot be made out of nothing since nothing is the "least real" of all things. This view is similar to the principles already expressed by Parmenides and Lucretius.

It is important to note that Cartesian causality's concept of "nothing" is a form of metaphysically absolute nothingness, namely the complete absence of any property or determination of being. This is even more explicit in the fourth meditation in which Descartes stresses that nothing is a *negative idea* and an absolute *no-being* (an antipode to the perfect and absolute being, which is God):

> ... when I return to the *Contemplation* of *my self*, I find my self liable to *Innumerable Errors*. Enquiring into the *cause* of which, I find in my self an *Idea*, not only a *real* and *positive one* of a *God*, that is, of a

> *Being infinitely perfect*, but also (as I may so speak) a *Negative Idea* of *Nothing*; that is to say, I am so constituted between God and Nothing or between a perfect *Being* and *No-being*, that as I am *Created* by the *Highest Being*, I have nothing in Me by which I may be *deceived* or drawn into *Error*; but as I pertake in a manner of *Nothing*, or of a *No-Being*, that is, as I my self am *not* the *Highest Being*, and as I *want* many *perfections*, 'tis no Wonder that I should be *Deceived.* (*ibid.*, p. 223)

Cartesian causality is violated in the realistic interpretations of QM seen before, both in attributing a weak level of physical reality to the wave function and in recognising some kind of reality as nothing. The reason for the former interpretations is evident: the lower causes embodied in empty waves would give rise to more "real", in a sense more manifest, effects embodied in interferences and stimulated emissions of particles so that a weaker level of reality would produce a detectable stronger one, contrary to Cartesian' principle of the inferiority of causes over effects.

Regarding the latter interpretation, in order to comprehend the kind of nothing implied by our previous argument—a nothing as negation—is useful to recall Henri Bergson's concept of void as introduced in his *Creative Evolution*: "The void of which I speak [...] is, at bottom, only *the absence of some definite object, which was here at first, is now elsewhere* and, in so far it is no longer in its former place, leaves behind it, so to speak, the void of itself" (1922, pp. 296–7). Therefore, Bergson's relative void adheres perfectly to our partial/relative nothing regarded as the no-photon: it is a nothing understood not as the absence of a metaphysical being but of a physical object that could be identified by the measurement process, before which QM attributes a sort of potential reality through the wave function.

In this way, the attribution of some sort of reality—we could paradoxically say of presence—to the absence of the photon, which implies the reality of a relative nothing, entails a significant violation of Cartesian causality, in its more general form corresponding to the principle of the non-inferiority of causes: the no-photon state, being fundamentally a relative nothing devoid of all the physical characteristics of normal things, has a weaker degree of reality than the consequences it originates.

Therefore, the increasingly weaker realistic interpretations seen so far conflict with Cartesian causality. This implies that overcoming the complementarity between waves and particles effectively means reintroducing the classical complementarity between realism and causality, which was the original one of the Como Congress. However, unlike the one that emerged in that Congress, the complementarity between realism and causality is *smooth*, just as Mittelstaedt, Prieur, and Schieder had shown for waves and particles. Thus, in QM, there are other forms of incompatibility between causality and realism (in addition to that of Bohr, where realism is identified with space-time coordination and causality with conformity to law, according to Kant). It turns out that Mittelstaedt's smooth complementarity is not limited only to ontology, namely to the wave-particle pair, but can also be extended to philosophical conceptions (or categories): in our case, to the "pair" realism-causality.

6 Conclusions

Based on the preceding analysis, we conclude that adopting a minimal ontological commitment to the foundational concepts of quantum mechanics ultimately reaffirms the principle of complementarity, albeit in the weaker and smoother forms discussed. Simultaneously, this analysis rejects restrictive interpretations of complementarity that oversimplify its scope.

All the tentative attempts to eliminate complementarity made by the wave function realists (like Albert, de Broglie, Selleri) have led to the reintroduction of complementarity between two philosophical concepts: weak realism and strong Cartesian causality.

On the other hand, it must be stressed that Bohr's position was never closed with regard to the recognition of the reality of the wave-like phenomena.

First of all, it must be remembered that in 1924 Bohr tried to develop his theory of the virtual wave (which was soon abandoned because it was contradicted by experimental evidence).

Finally, it should not be forgotten that less than a year after Born interpreted the Schrödinger wave function as a mathematical tool to calculate the probability density of finding a particle, Bohr formulated his complementarity principle, which implied the wave-particle dualism instead.

The complementarity principle survives independently of the various interpretations of quantum mechanics and the beables that they assert.

We are persuaded that the dualism claimed by complementarity, despite repeated criticism and attempts to eliminate it by both orthodox and non-standard interpretations, is destined to persist, taking on different forms and modalities from time to time, as a fundamental character of quantum phenomena, at least until a more satisfactory theory is found.

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