Bohr's Philosophy of Wave–Particle Complementarity

Dipankar Home

In this article, after briefly providing the pertinent historical background, the underlying motivation and essence of Bohr's idea of wave–particle complementarity are explained. To what extent the Bohrian notion of complementarity is relevant in the modern context is discussed. Bohr's belief in the generality of the complementarity framework is also touched upon.

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1. Historical Prelude

We begin by noting that as early as 1914, only a year after his celebrated work on the atomic model, Bohr wrote to his friend C W Oseen, ".... the possibility for an embracing picture should not be sought in the generality of viewpoints but perhaps rather in the strictest possible limitation of viewpoints" [1]. It is indeed striking that even this early, Bohr had believed that the way in which different possible conceptual frameworks for comprehending quantum phenomena could be reconciled was by finding a limit to the applicability of each such framework. Nevertheless, a curious fact is that in the years leading up to the eventual founding of the formalism of quantum mechanics and the uncertainty principle, Bohr had struggled hard to come to terms, in particular, with the duality between wave and particle aspects in the microphysical phenomena whose various aspects were gradually being revealed.

Although by the beginning of 1920s, it became increasingly clear that electromagnetic radiation could be conceived of either in terms of the wave model or by using the particle model, Bohr was unable to reconcile himself to the idea of photons or any particle-like model of radiation. This was because, as Bohr had stressed in his 1923 article in *Nature* that diffraction and interference effects

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of radiation could not be explained without invoking the wave model and that "interference phenomena constitute our only means of assigning any closer meaning to the frequency which in Einstein's theory fixes the magnitude of the light-quantum" [2]. At that time, in view of his reluctance to accept the light-quantum or photon hypothesis, Bohr had even contemplated a formulation of quantum theory that would be able to describe the interaction between radiation and atomic systems without requiring the notion of light-quanta. For this purpose, he was also not reluctant to consider that such a theory might require the abandoning of strict conservation of energy and momentum in individual emission and absorption processes.

However, when in the early part of 1927, the experiment by Davisson and Germer was reported that showed diffraction of electrons, Bohr immediately realised that further resistance against wave–particle duality would be futile because if particles like electrons can gave rise to diffraction effects then in the relevant experimental contexts, phenomena involving even matter must inevitably be conceived in terms of the wave model. Once he recognized that the feature of wave–particle dualism was inescapable, then instead of overthrowing the ideas of wave and particle, Bohr's approach was to concentrate on formulating an appropriate conceptual framework for reconciling the idea of wave with that of particle in a way consistent with the mathematical formalism of quantum theory. This led to the birth of the idea of wave–particle complementarity.

2. Bohr's Interpretation of Quantum Mechanics and Wave–Particle Complementarity

In his famous address to the International Congress of Physics at Como, Italy on 16 September 1927, where Bohr had presented for the first time the concept of complementarity, he declineated the core of his conceptual tenets on the basis of which he sought to interpret the various features of quantum phenomena. Later, over the years, Bohr elaborated his views in a number of writings, of which particlularly significant was his book titled *Atomic Theory* *and the Description of Nature* published in 1934, where the central aspect of Bohr's entire philosophy as regards quantum theory was spelled out as follows: "The quantum theory is characterized by the acknowledgement of certain fundamental limitations in the classical physical ideas when applied to atomic phenomena. The situation thus created is of a peculiar nature, since our interpretation of the experimental material rests essentially on the classical concepts" [3].

The above point was a recurrent theme in Bohr's writings; for example, in his much cited contribution in 1949 to the collection of articles in honour of Einstein, he wrote: "... however far the phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms" [4]. This contention rested on a view that in order to justify itself, any novel theory like quantum mechanics has to establish a contact between its mathematical formalism and the experimental results, and the most convenient language that can be used to describe the latter is in terms of the classical notions. As Heisenberg had recalled "... just by discussions with Bohr I learned that one cannot go entirely away from the old words because one has to talk about something .... so I saw that in order to describe phenomena one needs a language" [5]. Here we may also mention that Schrödinger once wrote to Bohr urging him to explain more clearly his often-expressed conviction about "the indispensable use of classical concepts" for understanding quantum phenomena. Bohr answered concisely: "My emphasis on the unavoidability of the classical description of the experiment refers in the end to nothing more than the obvious fact that the description of every measuring apparatus basically must contain the arrangement of the apparatus in space and its function in time, if we are to be able to say anything at all about the phenomena" [6].

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However, Bohr recognised and accepted that his viewpoint inevitably gave rise to a tension between two aspects, viz., that although classical concepts/models were invoked for the comprehension of quanum phenomena, their use needed to be constrained by suitable provisos. It is precisely to resolve this tension Bohr

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went about to formulate the framework of what he called the philosophy of complementarity. As Bell had put it, "Rather than being disturbed by the ambiguity in principle, Bohr seemed to take satisfaction in it. He seemed to revel in contradictions, for example between 'wave' and 'particle', that seem to appear in any attempt to go beyond the pragmatic level. Not to resolve these contradictions and ambiguitites, but rather to reconcile us to them, he put forward a philosophy which he called 'complementarity'" [7].

There are two crucial ingredients of Bohr's conception of complementarity – joint completion and mutual exclusiveness. Explaining the idea of 'joint completion', Bohr had said: ".... evidence obtained under different 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" [4]. The notion of 'mutual exclusiveness' was introduced by asserting that quantum theory "forces us to adopt a new mode of description designated as complementary in the sense that any given application of classical concepts precludes the simultaneous use of other classical concepts which in a different context are equally necessary for the elucidation of the phenomena" [8]. By incorporating both these aspects of 'joint completion' and 'mutual exclusiveness', a concise statement of how his notion of wave–particle complementarity accommodates wave–particle duality was given by Bohr as follows: "We are not dealing with contradictory but with complementary pictures of the phenomena, which only together offer a natural generalization of the classical mode of description so that the two views of the nature of light are rather to be considered as different attempts at an interpretation of experimental evidence in which the limitation of the classical concepts is expressed in complementary ways" [9].

The literal meaning of complementarity is 'mutually or jointly completing'. It is in this sense that two angles are said to be complementary if they make up a right angle. As Bell [10] had pointed out, Bohr's use of the term 'complementarity' implied going beyond its usual meaning. Consider, for example, as Bell had suggested, the different descriptions of an elephant from the front, from the back, from the side, from the top and from the bottom. These various descriptions are complementary in the usual sense. A key point is that they are consistent with one another and are not mutually exclusive; together they provide a single whole image of an elephant. In contrast, Bohr's wave–particle complementarity is based on elements, viz., the notions of wave and particle which are, on the one hand, inherently incompatible with one another but, on the other hand, even though mutually exclusive, are both necessary for a complete understanding of this situation.

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It is interesting that Bohr did not try to justify his notion of mutual exclusivity of wave and particle pictures as any consequence of a rigorous general argument based on the mathematical formalism of quantum mechanics. His strategy was to defend his hypothesis with illustrative analyses of specific examples confined basically to interference effects, since Bohr recognised that two-slit interference type phenomena contain the essential mystery of quantum theory. In such analyses, an interference pattern is viewed as a signature of wave-like propagation. If, on the other hand, the experimental arrangement can provide information about which of the possible paths a single particle follows from source to detector, this is taken to signify particle-like propagation.

Here it is important to stress that within the framework of Bohr's wave–particle complementarity, the wave- or particle-like picture acts essentially as a prop for visualizing the behaviour of micro-objects in a specific context. In other words, within the Bohrian framework, one may say that the mental images of wave and particle are like 'shadows' of 'real' objects. (This is something like the chained prisoners in the cave imagined by Plato in *The Republic*, *Book VII*, where the prisoners facing the wall of their prison are doomed to see only the shadows of objects outside the cave). However, though not 'real', Bohr considered such mental images to be expedients which could be conveniently used for describing, what he called, the "relationship between empirical evidences obtained under different experimental conditions."

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While providing his interpretation of Bohr's idea of wave–particle complementarity, Wheeler had invoked the following metaphor: A light pulse is imagined to be like a smoky dragon before it bites a detector. Expanding on this, Wheeler had stated: "It is wrong to atribute a tangibility to a photon in all its travel from the point of entry to its last instant of flight... . What answer we get depends on the question we put, the experiment we arrange, the registering device we choose. By his choice of question, the observer decides about what feature of the object he shall have the right to make a clear statement" [11]. What Wheeler essentially meant was that the notion of wave–particle complementarity needed to be applied only after the detection process was completed so that one could then infer which of the two models, wave or particle, was relevant to the experiment in question. Moreover, in applying the idea of complementarity, in order to avoid any logical inconsistency due to mutual incompatibility between the wave and particle pictures, the possibility is precluded that a single experiment using interference effect may exist whose observed results would contain one subset of data comprehensible in terms of wave-like propagation, with another subset of coexisting data interpretable by using particle-like propagation.

3. Some Remarks from Modern Perspectives

If one considers, say, the optical experiments, the rules of quantum optics are well-defined and sufficient to predict correctly all observable results. Electric and magnetic field operators are the basic dynamical variables in this formalism. The notion of photons enters the theory as excitations associated with normal modes in terms of which an electromagnetic field can be expanded. From this point of view, the particle aspect of radiation can be regarded as manifested when an emission or a detection process is considered; for example, the quantized decrease in field energy resulting from a detection process can be described in terms of removing photons from the field.

It is, therefore, clear that if one remains confined within the formalism of quantum thoery, the entire issue of wave–particle duality hinges on how one wants to use the ideas of wave and particle. The Bohrian interpretation of wave–particle dualism, as we have already emphasized, stems from the consideration that, apart from the formal predictions of observed results, some form of conceptual or intuitive understanding is also required in terms of the visualizable model of particles/waves. Nevertheless, it turns out that the notion of 'mutual exclusivity' entailed by the idea of wave–particle complementarity is consistent with the quantum formalism which ensures complete disappearance of wave-like interference pattern whenever fully efficient which-path information is available in position space, at least in principle. This is because any measurement scheme capable of yielding which-path information couples (entangles) interfering wave functions of the observed entity with mutually orthogonal distinguishable states of the measuring apparatus. Such an entanglement between states of the observed entity and those of the observing device serves to eliminate the interference effects pertaining to the observed entity.

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Within the framework of quantum formalism, there have also been analyses of the so-called intermediate experiments [12, 13] where by using inefficient or partial which-path determination, the initial ensemble is split into two – one giving rise to an interference pattern, while the other (yielding definite which-path information) does not contribute to interference. In terms of the language used in the context of wave–particle complementarity, such an intermediate experiment furnishes 'partial wave' knowledge and 'partial particle' knowledge using the same arrangment (for example, it may be possible to obtain with 99 % certainty which-path information while still retaining a significant interference pattern). Wootters and Zurek [12] have applied wave–particle complementarity in such cases by arguing: "The sharpness of the interference pattern can be regarded as a measure of how wavelike the light is, and the amount of information we have obtained about the photon trajectories can be regarded as a measure of how particlelike it is".

Here it is instructive to examine the subtle relationship between wave–particle complementarity and double-slit interference experiment of the type in which an intereference pattern develops by a gradual accumulation of discrete detection events registered as spots on a visual screen corresponding to individual particles reaching the screen one by one. For instance, one can see photographs of results obtained from the electron interference experiement by Tonomura *et al*. [14]. In such an experiment, one considers an array of detectors on a screen, with all detectors connected to an anticoincidence circuit. Then one observes anticoincidence between counts at detectors in the extreme low-intensity limit of single particles being emitted by the source one at a time. Such observed anticoincidence may appear to provide signature of particle-like behaviour, subsequent to wave-like propagation. However, note that in such an experiment, which-slit or which-path information for an individual particle is not available on its way from source to the detector. Hence, it is arguable that the coexistence of interference with anticoincidence in such an experiment cannot be interpreted to show wave-like and particle-like behaviour in the same experiment in the sense prohibited by Bohr's complementarity principle.

The usually used which-path detection methods in actual two-slit interference experiments (also known as 'Welcher Weg' experiments – the German word for 'which path') involve loss of interference by the exchange of momentum with the particle whose path is being determined. This has prompted the question of studying quantitatively the amount of momentum transfer that is necessary for enforcing mutual exclusivity between interference and which-path information. In this context, Storey *et al*. [15] gave a general proof that if in a double-slit interference experiment, the magnitude of momentum exchange of the particle with a detector is less than that permitted by a relation that they had derived, interference is not completely eliminated and path detection is not perfectly efficient. Such a demonstration has, in turn, stimulated instructive discussions in the literature [16, 17].

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Further, we note that in order to observe truly single particle-like behaviour with appropriate states of light, one needs sources which emit, which is called, the single photon state of light that is an eigenstate of the photon number operator corresponding to the eigenvalue unity. The probability of joint detection of more than one photon vanishes for an ideal single photon state – in this sense the single photon states entail particle-like behaviour. It is such consideration that motivated the testing of wave–particle complementarity by using single photon states, and experiments for this purpose were performed by Grangier *et al*. [18, 19].

The above-mentioned studies, therefore, serve to highlight that the idea of wave–particle complementarity, although conceived entirely on interpretational ground, has stimulated from modern perspectives, a number of theoretical and experimental investigations revealing interesting subtleties in the issue of wave–particle duality as well as revealing an interplay between interference-type effect and which-psath information that have relevant significance within the formalism of quantum mechanics.

4. Concluding Remarks

Although the scope of this article is confined to discussing wave–particle complementarity, we would like to briefly mention about Bohr's belief in the generality of the basic idea of complementarity. Over the years, Bohr's conviction grew stronger that a framework comprising apparently incompatible and mutually exclusive descriptions which jointly complete each other in interpreting the relevant experimental results should be applicable in wider contexts other than that involving wave–particle duality. For instance, as a statement of his generalized notion of complementarity, Bohr had asserted in his later years that, in general, "phenomena defined by different concepts, corresponding to mutually exclusive experimental arrangements, can be unambiguously regarded as complementary aspects of the whole obtainable evidence concerning the objects under investigation" [20]. In particular, in an application of his extension of the idea of complementarity during his celebrated exchange with Einstein

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Box 1. On Bohr's Idea of Generality of Complementarity

In his later years, Bohr continually struggled to generalize his notion of complementarity in a way that can be applied to different disciplines, like psychology and biology. Here we may just briefly summarize Bohr's final viewpoint on the possible role of complementarity in the context of, say, biological phenomena.

In one of his last lectures [N Bohr, *Essays 1958–1962 on Atomic Physics and Human Knowledge*, John Wiley, New York, p.26, 1963], delivered in honour of his one-time student and pioneer molecular biologist Max Delbruck, Bohr elaborated on his notion that "the very existence of life must be taken as a basic fact in biology in the same sense as the quantum of action has to be regarded in atomic physics as a fundamental element irreducible to classical physical concept." Bohr argued that in biology, "structure" as described mechanistically and "function" as described teleologically represent "complementary manifestations of biological phenomena". The descriptions are "complementary" because, according to Bohr, "a teleological description of the functioning of the organs in an organism provides the starting point for a mechanical analysis of that physical structure which makes possible such functioning."

As Bohr put it more elaborately, "Indeed, many terms used in practical physiology reflect a procedure of research in which, starting from the recognition of the functional role of parts of the organism, one aims at a physical and chemical account of their finer structures and of the processes in which they are involved. Surely as long as for practical or epistemological reasons one speaks of life, such teleological terms will be used in complementing the terminology of molecular biology."

One can, thus, see once again in this last extension of complementarity attempted by Bohr, the reflection of his strong commitment to the central philosophy of complementarity that for the advancement of our understanding of natural phenomena in any area, it is imperative that we should gain fuller recognition of *how* our concepts function and their inter-relationship in describing the diverse array of facts of experience relevant to the area in question.

concerning the Einstein–Podolsky–Rosen paper [21, 22], Bohr had argued the following.

Since an experimental setup needed for measuring a given physical quantity is incompatible with that needed to measure another one if the operators corresponding to these quantities do not commute, the very concept of the value of a dynamical variable in quantum mechanics acquires meaning only if one specifies the overall experimental context in which the relevant variable is meaured. In other words, within the framework of complementarity, it is not meaningful to discuss about the value a dynamical variable may have had in the absence of any measurement. For instance, if one wishes to consider the value of position of a particle, one can discuss about it only in the context of a well-defined experiment used to measure it. Similarly, for the value of momentum of a particle. However, these two experimental arrangements are mutually exclusive. This is what Bohr referred to as position–momentum complementarity, alongside its variant which he called "kinematic–dynamic" complementarity. For detailed discussions of the implications of such extensions of Bohr's notion of complementarity, see, for example, [1] and [23].

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Here it should be worth noting that Bohr's emphasis on context-dependence of the value to be ascribed to a dynamical variable has, of late, acquired more concrete meaning in terms of the modern studies, both theoretical and experimental, concerning the issue of Quantum Contextuality which is now an active area of research [24]. Futher, it needs to be stated that while Bohr's philosophy of complementarity continues to stimulate intense debates about foundations of quantum physics, alternative conceptual frameworks have been developed over the years for interepreting/understanding quantum phenomena, including wave–particle duality; for example, one may mention what is known as the Bohmian interpretation of quantum mechanics [25]. For an overall appraisal of Bohr's approach to quantum theory in the light of different strands of modern studies concerning quantum foundations, see, for instance, [26].

To sum up, we may say that what is usually referred to as a question about the nature of reality (e.g., are quantum entities really waves or particles?) is interpreted within the framework of comple-mentarity as a problem in redefining the use of available concepts. From a general perspective, Bohr's complementarity viewpoint advocated that as newer experimental results are revealed, the necessary improvement in our understanding of the relevant physical phenomena can be made by appropriately reformulating the conditions in a way that would enable consistent application of the descriptive modes already available, instead of requiring to invoke newer concepts. Finally, it should be remembered that in the initial years as quantum mechanics was emerg-

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ing, while the founding fathers were struggling to come to terms with myriad puzzles thrown up by the new discoveries, Bohr's approach towards interpreting quantum phenomena in a pragmatic way played a powerful pivotal role (for relevant historical details, see, for example, Jammer [27]) in shaping what is now known as the 'standard interpretation' of quantum mechanics.

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