Classical Concepts and the Bohrian Epistemological Thesis

Abstract

In this paper we establish an Epistemological Thesis based on Bohrian thought constituted of three different claims: the continuity claim, the classicality claim, and the limiting claim. The thesis is founded on a notion of physicality as spatio-temporality which is used to show the necessity of application of classical concepts in physical descriptions within physical theories. Further, various views on the metaphysics of the wavefunction are analysed in view of the notion of physicality as mentioned above, along with the implied necessity of the classical conceptual framework. These approaches to the metaphysics of the wavefunction necessitated by non-locality is seen as the basis of limit of classical physical description, therefore, of description of quantum phenomena. In view of the established thesis, two more complete alternatives to Bohrian thought, Bohmian Mechanics and GRW theory are analysed and the persistence of elements of Bohrian thought along with a vindication of the doctrine of classical concepts within both of these alternative theories is shown.

Keywords: Interpretations of Quantum Mechanics, Bohr, Classical Concepts, Physicalism, Metaphysics of Wavefunction, Principle of Complementarity

1 Introduction

Ever since the first experiments, which would later be identified as quantum mechanical experiments, it was clear that the classical physical theories which had been the canon of physical science since a very long time would be inadequate to give a proper account of the physical phenomena that was observed in those experiments. For physics of the time, a revolutionary physical theory was not something new as Einstein, through his monumental papers in 1905, had already established that the classical physical theories were not sacrosanct. Within two decades of the revolution in the study of spacetime, a new revolution occurred in the study of matter, motivated by various, apparently disconnected experiments. The Quantum Mechanical framework was thus developed as a physical theory based on these experimental evidences, while having almost no standard metaphysical background that was agreed upon by the pioneers of the field. The theory that came about was a mathematical formalism developed without any metaphysical structure to inform its mathematics, and hence the task of understanding of the theory in physical or metaphysical terms became an a posteriori objective which the early developers of the mathematical formalism of the theory and the philosophers of science of the age had to take up.

The mathematical formalism of the theory was such that, having evolved in view of phenomena alone, it did not immediately lead to any unambiguous metaphysical interpretation. One could not simply read off the ontology and the dynamics, the metaphysical structure, and the causal relations directly from the mathematical framework that. Rather, it proved to be very difficult to do so in view of certain novel principles which appeared to be running under the experimental observations and the resulting mathematical structure of the theory. Amongst many problems of the theory were the problems of non-locality and instantaneous action motivated by correlations that were impossible, as Bell later proved, to explain through a local causal mechanism, the problem of the ontological status and reality of the wavefunction, the problem of superposition which disallowed the existence of definite values of various properties of the quantum entities unless observed under specific experimental conditions, and not to mention the uncertainty principle that disallowed certain pairs of properties to have exact values simultaneously.

In this regard, the question of a complete change in the conceptual framework that was used to understand physical theories as such became a relevant proposal. Schrödinger in one of his correspondences with Bohr talks about the "the introduction of new concepts" (cited in (Bitbol & Osnaghi, 2016)) that would change the very way in which we think about matter, space, time and so on. Before the development of the quantum mechanical framework, the physical science enterprise had relied on the classical conceptual framework to construct theories which were required to explain new physical phenomena that could not be incorporated in the previous physical theories. This was also so because in most of the cases before the development of the physical theory the metaphysical structure of the world was considered before, and the theory generally precipitated as the mathematical formalism informed by the metaphysical structure that was assumed. As a result the conceptual framework as such was never questioned within the as it was presupposed in theory building, and no previous observations had challenged it to the extent that quantum mechanical experiments suggested. On the other hand, quantum mechanics, having been developed with experimental evidence in view alone and without having a prior mathematical picture, required a posterior application of the classical conceptual framework in the explanation of the metaphysical structure of the theory. Hence it became imperative to either find a consistent metaphysical visualisation of the complete quantum picture, or change the very concepts that are used in that metaphysical picture and find new quantum concepts, as suggested by Schrödinger in his letter above, to explain the world in a completely different way.

In this regard, Bohr, as a philosopher-physicist, was persistent on the indispensability of the classical conceptual framework. Throughout his academic life, Bohr remained adamant that the classical concepts and classical concepts alone constitute the framework that can be used to explain any physical phenomena. The physical description then must be given in terms of those very classical concepts. But, at the same time, for Bohr there was something inherent in quantum mechanics that did not allow for an unambiguous application of the classical conceptual framework in its entirety. Therefore, for him, quantum mechanics came along with a recognition that the classical conceptual framework, although necessary and being the only conceptual framework that can be used to provide a physical description, was limited and could not give a complete physical description of the quantum phenomena in the way that was possible in classical physics. This then led him to propose a new way in which these classical concepts are applied, a new way in which the classical conceptual framework is used to interpret and explain phenomena, the principle of complementarity, according to which different conceptual explanations took place mutually exclusively such that the different parts of explanation taken together form a complete description of the quantum process.

Recent attempts at the interpretation of quantum mechanics have seen a shift away from Bohr. The rejection of thought that a Bohrian doctrine is often faced with can be rightly pointed out to the questions that an interpretation of quantum mechanics is supposed to answer. In the recent past, evaluation of every philosophical doctrine on quantum theory has presupposed a set end, an interpretation of quantum mechanics culminating in a metaphysics of quantum theory. To this end, the Bohrian doctrines have not fared well against the other interpretations of quantum mechanics. But this is not to be seen as a defeat of Bohrian thought. Rather, it is a mark of philosophical close mindedness that disallows raising questions which are unconventional and unorthodox.

In this regard, as Folse(Folse, 1985) has pointed out, the outright rejection of Bohrian philosophy can be attributed to asking the wrong questions to the Bohrian Doctrines which are made inevitable by our own philosophical perspectives. Camilleri has put it precisely: "... Bohr's philosophical viewpoint has remained elusive in large part because we have persistently asked the wrong questions in interrogating his texts." (Camilleri, 2017) For Bohr, the questions that are considered to be the central problem of modern philosophy of quantum mechanics, the metaphysical questions of ontology and dynamics do not have the same centrality. Rather, questions that Bohr is concerned with are epistemological in nature. Instead of talking about the ontology, the question that Bohr would be inclined to ask would be: Whether or not the conceptual framework of the classical physical theories apply to quantum mechanics? Does it make sense to classify the ontological entities of quantum mechanics into waves and particles? How would we use the quantum mechanical framework to give a physical description of experimental phenomena? and so on. But Bohr does not answer the questions central to interpretation of quantum mechanics! Yes, and he is not bound to do so if other he finds other philosophical questions to be more foundational and pressing.

Our aim in this paper is to go back to Bohr to develop an understanding of the enigma of the modern philosophy of quantum mechanics and a nuanced understanding of what these problems might be based on. We will begin with Bohr's doctrine of classical concepts. Like Howard had claimed in (Howard, 1994) this is an unorthodox point to begin with. Also, similar to Howard, our aim is to give new perspectives on Bohr's doctrine, but at the same time, we claim that the doctrine of classical concepts can be seen as the fundamental problem of quantum mechanics, an aim which can be considered in addition to what Bohr has to say.

We establish a Bohrian Epistemological Thesis by viewing it in isolation, removed from the rather derivative ideas of the principle of complementarity and the principle of correspondence and other characteristics of the 'Copenhagen Interpretation'. We claim that the idea of the necessary application of the classical conceptual framework can be based on an elaborated idea of physicality, that the conceptual categories that are present in the classical conceptual framework are necessary resultants of the very notion of physicality itself where the necessary and sufficient condition of physicality is taken to be spatio-temporality. Along with this we claim that the idea of the inadequacy of the classical conceptual framework in giving an explanation of the quantum mechanical picture or a physical description of the quantum phenomena, is based on the metaphysics of the wavefunction and the existence of instantaneous actions, and through them the resulting non-local structure. At the same time, we try to show that other prominent interpretations of quantum mechanics, especially of the primitive ontological kind, are still bound within Bohrian principles which they claim to reject.

Now, any writing on Bohrian thought is faced with the challenge of interpretation and reconstruction of Bohrian arguments, picking bits and pieces from several writings, speeches, and correspondence, spanning over decades and trying to construct a coherent picture of what Bohr might have in mind. We, on the other hand, view Bohrian thought as a Lakatosian Research Programme, with certain core elements, like the principle of complementarity, and the doctrine of classical concepts, along with various auxiliary axioms. In this regard, the approach taken in this paper is not simply to understand what Bohr might have said, but at the same time contribute to Bohrian thought. The basic principles of complementarity and the doctrine of classical concepts are upheld, along with the idea that classical conceptual framework is inadequate to provide a complete physical description in the classical sense. On the other hand, new arguments for justification for these principles are presented, inspired partly by Bohrian writings, and enabled by the modern philosophical tools. In hope of enabling Bohrian thought further and re-establishing Bohr as a prominent philosopher of science against the harsh reactions against him in modern philosophy of science, let us begin begin with an exposition of the Bohrian idea of the classical concepts.

2 Bohr's Classical Concepts: Fixed or Moving?

Having looked at the problem that Bohr was facing and an outline of the epistemological thesis that we will develop in a later section, let us go over to Bohr's own writings and try to understand what is it that he had in mind when he talked about conceptual frameworks and the persistence of the classical concepts. Although expositions of Bohrian Philosophy in general are available in abundance which try to look at the various strands of arguments arising from Bohr(Folse (1985), Honner (1982), Bitbol and Osnaghi (2016), Bitbol (2017), Cuffaro (2010), (Camilleri, 2007) to mention a few), an independent exposition will help us understand the existing problem with all the required clarity.

Bohr's doctrines are not concerned with the questions of ontology, or of dynamics, as much as they are concerned with the new epistemological problems that arise from the Quantum Mechanical framework. Hence, for Bohr, the primary question was not one of a consistent metaphysical structure of the quantum theory, instead Bohr was concerned with questions like: Whether physical description of phenomena in quantum mechanics resemble the physical description of phenomena in classical physical theories? In this regard, we may even consider Bohr to be some sort of a meta-metaphysicist, in that his doctrines appear to constraint any future metaphysics of Quantum Mechanics. It is precisely this constraint that we will consider here, a constraint which we will call the doctrine of classical concepts.

Even though Bohr does not explicitly list what he considers to be the classical conceptual framework, or the conceptual schema on which the metaphysics of classical physical theories is based, we can easily take it from his writings that for him the classical conceptual framework stands for the concepts that we use in classical physics, constituting of concepts like position, momentum, particles, waves, energy, and so on. For Bohr, the primary problem with quantum mechanics is that we cannot unambiguously apply the classical conceptual framework to develop a metaphysics of quantum mechanics, in fact, it is difficult to explain simplest experiments without running into troubles, for example, the simultaneous application of the concept of position and momentum to the quantum entity.

At the same time, the constraint that Bohr applies to the metaphysics of quantum mechanics is an indispensability doctrine. To begin understanding the doctrine, let us begin with a fundamental idea of Bohrian thought:

> "all knowledge presents itself within a conceptual framework." (Bohr, 1958)

Therefore, we see that for Bohr, there is nothing as 'raw' information that we receive when we observe a phenomena, therefore, whenever we try to theorise or conceptualise the workings that may be behind the phenomena, the phenomena itself is concept-laden. In its very being as knowledge, it is required that the phenomena and the information we receive from it is necessarily within a conceptual framework. In so far we consider this statement, Bohr's thought appear to resoundingly correspond with Kantian or Pragmatic thought. Studies in this direction can be found in abundance. Since a parallel with either school is not our concern in this paper, we would skip this and move forth.

But Bohr was not satisfied with the mere association of a conceptual framework with knowledge, for him, the conceptual framework that persists and pervades all physical descriptions was the classical conceptual framework, the same classical conceptual framework that is used to provide a physical description in classical theories.

> "...our interpretation of the experimental material rests essentially upon the classical concepts." (BOHR, 1928)

There were multiple arguments which Bohr mobilises to this end. One of these arguments is the argument of communicability.

> "... the requirement of communicability of the circumstances and results of experiments implies that we can speak of well defined experiences only within the framework of ordinary concepts" (Bohr, 1937)

In so far as we have to communicate the description of the experimental apparatus, and the results of the experiments, we must do so within the classical conceptual framework, the framework of ordinary concepts or the framework that we utilise in the explanation of ordinary things. We will take a look at this argument in greater detail later.

We also see that Bohr, in his correspondence with Schrödinger, upon the urge by the latter to shift to a new conceptual framework, tries to argue saying "The 'old' experimental concepts seem to me to be inseparably connected with the foundation of man's powers of visualising." (quoted in (Bitbol & Osnaghi, 2016)) This points to another way in which the argument is made for the classical concepts, that is the classical concepts become as essential part of our physical description because they are inherently linked with our powers of visualisation and pictorialisation. This points to the fact that the very idea of classical concepts must somehow be related to something inherent in pictorialisation, which we will later see to be the aspect of spatiality.

Given this, we also see Bohr insisting upon the widening of the scope of the framework in several instances.

> "As our knowledge becomes wider, we must always be prepared, therefore, to expect alterations in the points of view best suited for the ordering of our experience. " (Bohr, 1934)

Since its inception, quantum mechanics challenged many metaphysical presumptions of the classical physical theories. How could we then apply the classical conceptual framework to provide a physical description of the quantum theory? This is where we see the introduction of the principles of complementarity, which allows the application of the classical conceptual categories in complement to each other, such that complementary categories cannot be simultaneously applied but the application of the categories to describe different parts of the quantum phenomena provides a complete physical description of the phenomena. This constitutes a new way of physical description of phenomena:

> "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 connection are equally necessary for the elucidation of the phenomena." (Bohr, 1934)

Therefore, we see two different lights in which Bohr's idea of classical concepts is perceived. In one case, upon his insistence on the use of classical conceptual framework to order, communicate and visualise classical phenomena, it appears that Bohr posits unchanging indispensable categories. On the other hand, by including the widening of the scope of the framework or by talking about alteration in view points, it appears that these categories appear to be changing according to Bohr. We argue that the problem is only an apparent one which vanishes upon a closer analysis.

Bohr in his insistence upon the alteration of the point of view is not talking about a change in the classical conceptual framework or the categories that constitute it. Rather, Bohr is talking about an alteration in the way in which these categories (hence, the classical conceptual framework) are applied to provide a physical description of the phenomena. The change is thus in the application of the conceptual framework not the framework itself. The same is reflected in the following statement by Bohr in (Bohr, 1958):

> The extension of physical experience in our days has, however, necessitated a radical revision of the foundation for the unambiguous use of our most elementary concepts...

The revision does not take place in the elementary physical concepts themselves, rather it takes place in the way in which we have learned to use them.

Given this understanding of Bohr, we see that the idea of a fixed classical conceptual framework, in that it is constituted by classical concepts that are present in the classical physical theories, is one that is necessary. But there appears to be no coherent justification of the same apart from fragmented references to language, visualisation, etc. We would base this necessity on the idea of physicality seen as spatio-temporality.

3 The Problem of Physicality

Let us now move our attention towards the notion of physicality. The question that we would look at is the following one: Which entities are the ones that we consider to be physical? or to be more precise: What is the necessary and sufficient condition for an object to be a physical object? The answer to this is generally given in two senses: the theory conception of physicality which says that the physical objects are those that are considered to be a part of the ontology of a physical theory, and the object conception of physicality which considers physical objects to be those which have characteristics similar to the objects which are generally considered physical. For our purposes, we do not simply want a definition of physicality, rather we need a useful decision making mechanism that helps us distinguish physical objects from the non-physical ones. Hence, the sufficiency condition should either itself constitute that mechanism, or else it must point out to a way that enables us to do so.

What we want in our case is the ability to discern the difference between physical and non-physical objects or entities within a theory, in our case the theory of quantum mechanics. Now, this is where the theory account of physicality faces problem. The distinction we want to make here is a distinction between the physical and non-physical objects within the theory, and if we go by the theory account, then the status of physicality is given to the entity by the virtue of it being a part of the ontology of the theory. In this regard, it makes the task simple: every ontological entity that is a part of quantum mechanics would be a physical object. But if the problem is such that we are not sure whether the objects which are a part of the ontology of a physical theory are physical or not, then the problem cannot be solved by the physical theory account. Hence, if a theory's status of physicality is under dispute, or if the physicality status of the ontological categories within the theory are disputed, then we do not have a way to discern the physical entities from the non-physical ones. On the other hand, if we go by the physical object account and look at the objects that are generally considered physical, we may be able to discern the difference between a physical and a non-physical object by considering a metaphysical condition on the object itself. If the condition is placed on the metaphysical constitution of the object then the status of that object can be discerned without making reference to any other object or theory outside the object in consideration. Therefore, the object account of physicality makes it so that physicality becomes a property of the object itself and does not require any reference to anything external.

Then, with the object based account of physical theory as our chosen methodology, let us move forward and ask ourselves what is it that makes physical objects physical? Consider a particle, and compare the idea of a particle with a universal law, or a number. What is it that is common to all objects which are material, similar to the particle, which is not there in the idea of nomological entities, mental entities or other abstract entities? To answer this, we go with Ned Markosian's account of a physical object. In his paper (Markosian, 2000), Markosian presents the Spatial Locality Account of a physical object. The spatial locality account ascribes physicality to all those objects which have a spatial location. This account, at the same time, is different from the Spatial Extension Account which allows the ascription of physicality to only those objects which are extended in space. The latter appears to reject point particles as being physical whereas the Spatial Locality Account allows for point particles to be physical as well. Considering the overwhelming presence of point particles in almost every metaphysical account of almost all the physical theories, we support Markosian in favour of the Spatial Locality Account.

With this we have that objects like a stone, a particle, a wave, and so on, all have been ascribed a physicality whereas objects like mental representations, countries, laws, and political entities are not ascribed complete physicality. Markosian goes on to talk about how there may be complex objects, taking the example of human beings, which may be considered to be partly physical, in that they have a physical body which is spatially located, and partly non-physical, consisting in their mental aspects which do not have a location. With this, let us look at classical mechanics and try to discern what might be considered physical and what might not be considered physical in the theory. The theory consists of point particles which change their positions (locations) according to the Netwon's equation of motion $\vec{F} = m\vec{a}$. Now, the point particle in this scenario always have a spatial location therefore they are considered to be physical objects. On the other hand, the law itself is not a physical object in that it has no spatial location.

Dynamical quantities like the mass of the object, the acceleration, velocity and so on may be considered as physical properties and do not appear to be objects in the sense that the particles do in that these properties are what the physical object 'has' and not something that itself is a physical object. Forces may be considered relational properties between two physical particles, there are no forces which do not exist between two physical objects. Therefore, the idea of physicality appears to be adequate in giving a proper physical account of the entities considered in mechanics. Now, the idea of physicality as spatial location leads to a notion of physicality as saptio-temporality. This is because temporality is generally ascribed to all entities physical or mental, therefore, temporality does not appear to be a sufficient condition for physicality. On the other hand, spatiality is something unique to the physical objects alone, but they are temporal too. Therefore, the condition of spatial location implies spatio-temporality of the physical objects.

Given the Spatial Location Account we see an interesting and important result emerging. According to most of the interpretations of the wavefunctions, indeed the ones which consider the wavefunction or some part of the quantum dynamical mechanism as a part of the ontology which is not 'located' in the spatio-temporality, the wavefunction suddenly gains a non-physical status. We will explore this idea further in the next section and see what can be implications of this result.

4 Bohr's Epistemological Thesis

With this, we would now want to formulate the Bohriam Epistemological Thesis. To situate the Epistemological Thesis in the broader Bohrian writins, we go back to the first few lines of the Como Paper:

> The quantum theory is characterised by the acknowledgement of a fundamental limitation 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 upon the classical concepts. (BOHR, 1928)

Bohr indicates in a succinct manner, three different claims within these lines. Here, we break Bohr's statement into these three distinct claims which together form Bohr's picture of a physical description in terms of classical concepts, these are the Continuity Claim, the Classicality Claim and the Limiting Claim. Together, these claims form the Epistemological Thesis.

4.1 The Continuity Claim

As Friebe has rightly pointed out: "The question..." for Bohr is "whether and how quantum physics can permit a unified theoretical structure of physics as a whole." (Friebe et al., 2018). In so far as the unified theoretical structure of physics is regarded, the this says that the conceptual framework that is utilised within one field of theoretical physics, must necessarily be the same as the conceptual framework as that applied in a different field of theoretical physics to maintain an overall conceptual consistency.

The Continuity Claim says that the conceptual framework that is to be used to explain quantum phenomena must be the same as the conceptual framework that is to be used to explain the classical phenomena. The claim here is that the concepts like position, momentum, energy as used in the classical and quantum description must necessarily be the same. At the same time, the application of the concepts in various theories may be different. This would mean that the dynamical laws that relate various concepts with each other may be different in different theories, but there must be a continuity in the understanding what the concepts mean, and at the same time, there must be consistency in the way that they are applied in one theory with the way they are applied in another theory. We also have that once the same conceptual framework is used to explain the classical and quantum phenomena, there must be some way to explain the applicability and show how the way in which the conceptual framework is utilised at the quantum phenomena is a generalisation, or gives in to the way in which the conceptual framework is utilised in the classical picture.

The continuity claim simply says that the idea of position and momentum, for example, in the quantum theory is the same as the idea of position and momentum in classical theory. The argument behind this is fairly simple. Consider a macroscopic object whose position is described using a classical setup where a three-dimensional grid is placed around the object and its spatial location and extension is discerned. The description of position and extension that we would so receive in this case is would be the value for, let's call it $\text{position}_{\text{classical}}$. Now, consider the quantum mechanical account of the same object, an apple let's say, which in the quantum mechanical picture is composed of billions and trillions of quantum entities which are spatially located and which have their own position described as the value of $\text{position}_{\text{quantum}}$. If we then have to explain the position of the apple in terms of the position of the quantum entities that constitute it, then we must have that the concept of $\text{position}_{\text{classical}}$ is the same as the concept of $\text{position}_{\text{quantum}}$ or else there has to be a way in which the two concepts are related, both quantitatively and qualitatively, that would tell us how one can be linked to the other or how one can be deduced from the other making them commensurable. The lack of such a continuity or link would result in a dissociation or the complete incommensurability of one concept from the other disallowing the explanation of one in terms of the other. [1]

Whenever we are dealing with quantum and classical physics, especially when we have to devise an apparatus, or when we have to deal with the description of the quantum entity in terms of the description of the apparatus, we always use the classical and quantum notions of position *interchangeably*. This interchangeability is assumed from the side of the physicist and the philosopher of science as the entire physical scientific enterprise is seen as a unified approach to probe into the nature of reality. If there is an incommensurability of one from another, we cannot have an experimental apparatus, a classical object, which can be used to probe into the quantum world. Consider the case of the double slit experiment, once the quantum entity has reached the screen, the point spot it makes on the screen acts as the result of a position measurement done on the quantum entity through the screen as the apparatus of measurement. If we then ask what is the position of the quantum entity upon reaching the screen, we

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[1] An objection may be raised by the Kuhnian here, one of the shift in scientific paradigms bringing in an incommensurability within concepts from one physical theory to another (Kuhn, 1962), disallowing the use of same conceptual structure in so far as a new paradigm is considered. But in so far as we believe in the possibility of communication between different physical theories, we can disregard this objection.

ascribe it the position based on a grid marked on the screen which helps us discern the position of the spot, and the position of the spot is taken to be the position of the quantum entity. This position is thus measured in terms of a classical concept of position, it is the same as the concept of classical position. Therefore, we have that the classical and quantum concepts of position are one and the same.

At the same time, all that we have established in the Continuity Claim is that the conceptual framework that is used in the physical description of classical phenomena is that same as the conceptual framework that is used in the physical description of quantum phenomena. This claim is far from the Bohrian claim of the necessary application of the classical conceptual framework in the explanation of phenomena. In fact, the Continuity Claim is also consistent with what Schrödinger has been seen to propose above, a new conceptual framework that is based on the quantum phenomena, as long as the classical physical phenomena are also explained using the same conceptual framework. Therefore, what we may have as a possibility is a new conceptual framework, constituted by new conceptual categories that can then be used to explain all physical phenomena, but at the same time, all the physical phenomena, classical and quantum alike, must be explained using the same conceptual framework. These quantum concepts won't be that of position or momentum and so on, rather they can be something completely different which will then replace the present conceptual schema completely. The entirety of the physical world would then be described in terms of these concepts.

4.2 The Classicality Claim

While the continuity claim only establishes the continuity of the conceptual framework in the description of quantum and classical phenomena, Bohr claims that it is the classical conceptual framework, comprised of conceptual categories like the position of an entity, its momentum, its energy, time and so on, that are indispensable in all physical descriptions. We claim that this idea is based on the idea of *physical* description itself. Consider the notion of physicality as spatio-temporality as we have seen before. Then for any description to qualify as a physical description, we have to have that the description is at least partly spatio-temporal in nature. The physical description would then at the very least involve the idea of an object in space and in time. The spatio-temporality of these objects means that these objects must be located in the space and in time. This location in space and time is exactly that which ascribes these objects with physicality and at the same time makes it so that the objects of the physical study have to be necessarily viewed through the conceptual framework that results from the ascription of spatiality and temporality to the object.

The notion of a spatiality is intrinsically linked with the notion of position of an object. Consider an object which is spatially located. This would mean that the object has some spatial location in space. In a mathematical sense, the spatiality as we have explained above can be seen as being present in some sort of a three or four dimensional manifold. Given the presence of the object in such a manifold, the idea that the object of the theory is located in such a manifold implies that it has a location in that manifold. There is a particular *position* at which that object exists. And it is only under this condition that we can ascribe the object with a location, therefore saying that the object is located in space, and hence thee object is spatial. Therefore, for an object to be spatial, it must necessarily be located in space, hence have a position in that space. In mathematics, this position is either identified with the point in the manifold in which the object is located or else with a position vector which is an element of the position vector field drawn from a reference point which is taken to be the origin. In that sense, the very spatiality of the object results in it having a position. Therefore, as far as position as a conceptual category is considered, we have that the object must necessarily have that in order to have a physical description of the object.

In classical mechanics, this idea of position immediately leads to an idea of velocity, and subsequently acceleration which is something that is derived by taking the derivative of the spatial location vector of the physical object with time, which is generally considered a parameter, once and twice respectively. On the other hand, in case of quantum physics, since the position measurement itself is such that it appears to disturb the state of the system sufficiently such that no prior position can be determined by taking the position measurement, the idea of velocity and acceleration as they are stated above cannot be applied. In their stead there is no new concept that appears to explain the change in position of the object with respect to time, rather the nature of measurement itself makes it so that the meaning of velocity and acceleration is lost. At the same time this does not hurt the claim that the classical conceptual framework is the only one that is applicable in case of physical theories as all that we have said is that some concepts lose their applicability (at least in the way they are applicable in classical mechanics, for example) when it comes to quantum phenomena, but this does not imply that another conceptual framework takes their place, or that another conceptual framework can take their place.

At the same time, when we talk of spatio-temporality of these physical objects, one might ask what spatiality is it that is the determining factor between physical and non-physical objects? In mathematics, a space is any object that is constituted of a set with some extra structure on it. Therefore, can we say that the location of an object in this set of varied elements with some structure on it can be considered as spatiality and hence making the object a physical object? The answer to this is no because the spatial objects that we generally think of are not located in a space in the general mathematical sense of the word, rather what we are talking about is a space as in a manifold, a continuous space which has certain characteristics that help us position objects in it and allow us to explain the dynamics of the objects, the movement of the objects in it. The manifold structure is often seen as the one that can easily mimic the manifest image of space as we see it around us, and at the same time has enough structure in it to allow for the movement and dynamics of various bodies.

Now, the question would then be, what sort of a manifold can be consider the object to be in for the object to be a physical object? The manifold that we would like to have is of the Riemannian kind with a particular dimensionality, in that there must be three-dimensions of space and an added extra dimension of time, and only those objects that exist in this space would be the objects that will be ascribed physicality. But this is something that we ought to think about more properly, in that when we talk about spatiality, what we have in mind is the general notion of spatiality, of things existing as they do in everyday life, of objects having a certain height, width, and depth, of there being only three perpendicular lines that can be drawn in the normal space. This is the notion of space we are dealing with.

The very idea of spatiality is one that is borrowed from all that we observe in the manifest image of the world. The physical apparatus that exists in our laboratories exist in the manifest image of the world (W. deVries, 2021). They are along with all object macroscopic objects that are considered to be physical objects, based on which we arrive at a notion of physicality, are all placed in such a space. With the General Theory of Relativity, what changes is the structure of space and time, but at the same time, the space time explained in the general theory of relativity is dynamic enough to allow for the existence of the general notions of three-dimensional space and a one-dimensional time along with it at velocities which are much lower that light and not under very intense gravitational forces. This is exactly what allows us to have a continuity between the scientific image of the world and the manifest image of the world as we see it. In case of quantum mechanics and especially with the dimensionality of the wavefunction, the non-locality of entanglement and so on, this continuity appears to be lost. We will look into that in the next subsection.

In the Newtonian picture of classical mechanics, what we see is a mathematisation of the manifest image of the world. The mathematical structure that best suits Newton to define the space in order to have a description of the dynamics of the objects which exist in it, in accordance with what is generally visible is the Euclidean Space. In that space, the Newtonian theory then goes on to define the position of an object, and through the rate of change of that position with respect to time, which is also assumed to be absolute, we get a velocity. Through that and the idea of mass follows the idea of momentum. In later, more complex, and robust expansions of classical mechanics, the Lagrangian and Hamiltonian formulation, momentum becomes a variable defined through certain relations it has with generalised coordinates, for example the poisson bracket relations.

Similarly in quantum mechanics, since we have that position is a necessary conceptual category for as long as we have that the objects in quantum mechanics are spatial. And as also have that the momentum is an essential part of the manifest image of the world, of the classical world of which the measuring apparatus which enables us to probe into the quantum world is a necessary part, we have that in a manner similar to classical mechanics, momentum is defined through taking the commutator to be equal to iota times the reduced planck's constant, something taken mostly directly from classical mechanics upon first quantisation gives us a definition of momentum. Hence, the spatiality of the physical objects necessitates the application of the concept of position, then the mathematical framework of quantum mechanics is designed such that it allows for a definition of momentum in the quantum picture which is continuous to the picture of momentum in the classical picture and allows for a continuity of concepts such that the measuring apparatus and the quantum entity can then be seen under the same concepts. Similarly, other classical concepts are defined in the quantum picture necessitating their existence in the conceptual framework as Bohr tries to point our frequently. This is also apparent in the paragraph quoted above:

> Nevertheless, these abstractions are, as we shall see, indispensable for a description of experience in connexion with our ordinary space-time view. (BOHR, 1928)

For Bohr, the indispensability of these abstractions was because he wanted a "description of experience in connexion with" or a description of experience in terms of our ordinary space-time view.

At the same time, this also appears to place quantum mechanics in the historical series of sciences which have been then or in retrospect identified as physics, the systems of knowledge which aim at explaining the motion of bodies as we see them, which aims at explaining how the position of bodies change over time and so on. As we have seen this historical notion of physics also fits well with the definition of physicality as we have taken above, as the condition of being located in space and time. To do so, we have often posited many entities which we cannot directly observe, this is when the scientific image of the world separates from the manifest image of the world (Sellars et al. (1956),W.A. deVries (2016)), and this is done in almost all modern physical theories, consider for example classical mechanics and the notion of force, even thought we can feel force in some sense, the force itself is only perceived through its affect on bodies and not as something directly observable, and throughout, what has been the anchor point has been the notion of position in physical space, and all the physics can be said to revolve around explaining the changes in the position of physical objects.

At the same time, there is a mathematical necessity in having the concept of momentum in the mathematical formalism of the quantum theory. This is in the idea of the generation of translations in the position of the quantum entities. In the quantum framework, we have, for every position vector$\vec{x}$, a translation operator that translates the position of the quantum entity on which it is applied, by the vector $\vec{x}$. Therefore, the task of the translation operator for a given position vector, is to displace the quantum entity by that amount in that direction that combined gives us the displacement vector. Now, considering this, we have that the generator of these translations is the momentum operator, the very definition of the momentum operator is based on it being the generator of the translations.

The exact mathematical derivation is something that is not important in the given context. A brief outline would be that the requirements for the translation operator are such that, taking an analogy from the classical definition of the momentum as the generator of translations. This then leads to a definition of momentum which follows all the properties that it has to, and that it does due to the way translation works in the quantum framework. As a result, as soon as we have the idea of position in the quantum mechanical framework which is a necessity in that the idea of position is intrinsic to all the objects which are spatially located which becomes a necessity due to their physicality based on the spatial location account, we see that the idea of translation naturally appears as that which marks the translation of quantum entities, the translation here simply means a change in the position of the entities, and for the translation to be defined, we need to have the momentum operator, defined as the generator of those translations. Of course, what we have here is a mathematical framework which is anchored on the idea of physicality through the concept of position and spatio-temporality after which we go on defining new concepts in view and in analogy to the classical picture based on the manifest image of the world, but the definition of new concepts as well is not out of any arbitrariness, rather, the definition of the new concepts is based on necessity required from the proper application of the previous concepts.

Let us also look at how the Hamiltonian operator enters the mathematical formalism of quantum mechanics. For this we take into consideration the fact that the physical object is not only spatial but also temporal. With the idea of temporality and the idea of change and evolution in time, we have in quantum mechanics the time evolution operator. For any given amount of time, the time evolution operator changes the time parameter of the quantum state of an entity by that amount of time. With this, we have that the time evolution operator, similar to the spatial translation operator, is used to define the movement of an object in time. Due to the similarity of requirements that it has to the spatial translation operator, we see that this too naturally leads to the idea of a generator, and the generator of temporal evolution is the Hamiltonian operator. Again, in analogy to classical mechanics, the temporal evolution of an entity is generated by the Hamiltonian. This idea is so central to the quantum mechanical framework that this line of deductions are exactly what lead to the Schrödinger equation when applied to the quantum state of an entity.

Therefore, we see that the definition of the momentum and the hamiltonian operators arise from them being seen as the generator of spatial translation and temporal evolution, which in turn are naturally defined on the idea of change of position and time of a physical entity, concepts directly applicable by the very idea of physicality as spatio-temporality, and the physical objects as those that are spatially and temporally located. Hence we see that the Classicality Claim that the classical conceptual framework is the one that is necessarily applicable to the quantum framework is established. But this still does not explain how the classical conceptual framework is 'limited' when it comes to the explanation of quantum phenomena. Where and what is this limit that Bohr talks about?

4.3 The Limiting Claim

The explanation of the Bohrian Limit is where the idea of wavefunction becomes important and the mathematical structure of the wavefunction takes the front position in the discussion. In quantum mechanics, there are a lot of difficulties in presenting a pictorial representation of entirety of quantum processes without having faced with extremely weird notions like the conversion of an extended wave which is extended in all of space to a point as soon as the associated quantum entity is observed for its location, or the immediate action of a particle on another, or the impossiblity of the isolation of a system due to an essential presence of action at a distance which violates local causal account present in all other physical theories. All these problems in explanation can, in one way or another, be traced back to the characteristics of the wavefunction as the primary dynamical variable in quantum mechanics which guides the motion and general behaviour of all the physical objects in the quantum picture. This was something that was known to Bohr very well. For him this was the primary reason for the symbolic nature of the quantum mechanical framework. Further down in the Como Paper, Bohr writes:

> The symbolical character of Schrodinger's method appears not only from the circumstance that its simplicity, similarly to that of the matrix theory, depends essentially upon the use of imaginary arithmetic quantities. But above all there can be no question of an immediate connexion with our ordinary conceptions because the 'geometrical' problem represented by the wave equation is associated with the so-called co-ordinate space, the number of dimensions of which is equal to the number of degrees of freedom of the system, and hence in general greater than the number of dimensions of ordinary space. Further, Schrödinger's formulation of the interaction problem, just as the formulation offered by matrix theory, involves a neglect of the finite velocity of propagation of the forces claimed by relativity theory. (BOHR, 1928)

Thus Bohr gives three reasons for his anti-realist stance towards the quantum mechanical framework:

1. The quantum mechanical wavefunction has imaginary values
2. The quantum mechanical wavefunction is defined on the configuration space which has much higher dimensions that the ordinary space
3. The quantum mechanical formulation allows for interactions that take place immediately, that is infinitely fast, hence appearing to be in contradicition with the postulates of the theory of relativity

Let us look at these problems one by one. The configuration space problem is that the wavefunction of a system of quantum entities is defined on the configuration space of these entities, that is, the wavefunction cannot be asked to give values at this point or that point in ordinary three-dimensional space. Rather the wavefunction generates values for configurations of entities. Hence, instead of taking as input three variables of space and one variable of time, the wavefunction takes as input the configuration of particles, that is the spatial location of all particles, hence a total of $3N$ values of spatial coordinates and a value of time coordinate which is generally treated as a parameter. Hence, the wavefunction exists in a hyperspace which is different from our own. The reason for this is that the wavefunction of system of entities cannot be uniquely broken into three-dimensional wavefunctions of these various entities which can be done in classical mechanics where the configuration space points can be uniquely traced to multiple points in the ordinary three-dimension space as the configuration space in classical mechanics is nothing more than a convenient mathematical tool. We arrive at the configuration space in classical mechanics by first taking the particles in three-dimensional space and forming points in higher dimensional spaces which represent the configuration of these points in the three-dimensional space. Thus, there is no structure which is explicitly present or defined over that space which cannot be broken into structure defined on the three-dimensional space.

Unfortunately, the name of the configuration space was carried for some reason in the quantum conversations as well which can be read, similar to its classical counterpart, as merely a mathematical convenience instead of being an essential feature of the quantum mechanical framework. But this is not the case due to the non-uniqueness in the way of transition from the configuration space to the ordinary space, therefore, the wavefunction is essentially a higher dimensional entity. [2]

Secondly, we have that given a configuration of the entities, what we get in return are imaginary values, therefore, the wavefunction takes in configuration of entities in terms of their spatial positions and time, and gives as output imaginary values. Now, there are several entities in physics that have been ascribed imaginary values, but this ascription of imaginary values have generally been done for the sake of mathematical convenience, and as such there is no observable entity, no fundamental observable quantity in classical physics which has been given an imaginary value. For example, in electromagnetic theory, we often use imaginary numbers to describe the behaviour of electromagnetic waves, and in wave phenomena generally, but this is nothing more than a mathematical convenience, the imaginary numbers generally allow for ease of mathematical operations, but in the case of quantum mechanics it becomes essential for us to use mathematical quantities which are essentially imaginary. There has been conversations about how this is not a fundamental problem as we can view every imaginary number as a pair of two real valued numbers, but recently there has been work which shows that no such real valued formulations of quantum mechanics can reproduce the result of the theory where imaginary numbers have been used (Renou et al. (2021), M.-C. Chen et al. (2022)). With this we have that the most fundamental quantity in quantum mechanics has complex values.

Moving onto the third problem as pointed out by Bohr is the disregard of the quantum mechanical framework for the postulates of the special theory of relativity. This is relatively clear in that Bohr is trying to put forth the contradictory results between two of the modern physics's greatest achievements. The theory of relativity postulates that the speed of light is the same for all observables and that the laws of physics do not change upon moving from one inertial reference frame to another. With this, we reach the conclusion that the speed of light becomes the upper limit of the speed for anything that moves in space-time. The idea of relativity also suggests that there is no unique way of foliation of space time, arising from no unique notion of simultaneity as the axis of space and time intermingle in the transformations from one frame to another all based on the two postulates given above. The notion of instantaneous action not only goes against one of the basic results, that of no interaction happening at a speed higher than the speed of light, but also that the instantaneous action allows for a preferred notion of simultaneity, in that there is a distinct notion of simultaneity because something happening at some place can instantaneously reach another place, allowing for a preferred way of foliation of space-time restoring time as a unique axis, another notion which special relativity discards. Therefore, the quantum mechanical framework is inherently in contradiction with the very structure of space-time that the

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[2] This higher-dimensionality is often beyond comprehension in that the wavefunction of the universe would have the dimensions of the same order as the number of particles in the universe, a number which is too large to be appreciated for its largeness.

theory of relativity puts forth, and through that, with the behaviour of the objects that exist in that space-time of the theory of relativity. This non-local feature in quantum mechanics can, again, be explained due to the metaphysics of the wavefunction.

Let us now try to see what is the problem with the wavefunction by looking at the various ways in which the metaphysics of wavefunction is done to see the problems it posits in terms of interpretation, especially physical interpretation which is, through our notion of physicality, of the spatio-temporal kind, or which could, in some sense, be visualised or pictorially represented through its spatio-temporality. Let us thus look at the metaphysics of the wavefunction, our guides for this tour would mostly be (D.Z. Ney Alyssa; Albert, 2013) and (E.K. Chen, 2019b)

4.3.1 Wavefunction as a Complex Field on a Hyperspace or the Problem of Higher Dimensionality

Under this approach to the metaphysics of quantum mechanics, we have that the wavefunction's metaphysics is, in some sense, being read off directly from the structure of the mathematical framework of quantum mechanics. Since in the quantum mechanical framework, the wavefunction is defined as a mathematical object which is a field, a complex field over the configuration space of the quantum entities, this is what it is. With this comes, as has been pointed out several times above, the problem of interpreting physically an object which does not exist in the same physical space as we do, a higher dimensional entity which exists on a completely different hyperspace. This is often seen as the problem of 3D vs 3N dimensionality, the first pointing to the manifest image of the world which is constituted of three dimensions and the other where we see that the dimensionality of the wavefunction is seen as the primary dimensionality.

There are various ways to accommodate the hyperspace and the general physical space in the picture we so have, philosophers and physicists have tried to reduce everything to the three-dimensional space, some others have tried to reduce everything to the 3N dimensional space, yet others have tried to talk about a combined 3N+3 dimensional space, but in all approaches problems have been faced. In the case of the 3D interpretation, there is a problem of the non-reducibility of the wavefunction to the 3D, there is no unique way of breaking a field in the 3N dimension configuration space to multiple fields in the 3D space, there is more information than can be represented in the multiple 3D fields. On the other hand, the other commonly taken path is to have a 3N dimensional reduction in which case, following (A. Ney, 2013) and (Albert, 2013) we have wavefunction realism, an approach under which we take the wavefunction to be a part of the ontology, as *the* physical entity. In this approach, the wavefunction exists in the 3N dimensional space, which is the real physical space and the value of the wavefunction at each point is somehow seen as a property of the point of that higher dimensional space itself.

The primary issue is that in the wavefunction realist approach, the issue of the explanation of the manifest image of the world remains present. When asked how does the manifest image or the world appear to be 3D if the world itself is 3N dimensional, the general answer to this is that the manifest image of the world is merely an emergent property from the wavefunction and that's it. There have been mathematical attempts to show how this can be done using the Hamiltonian which orders the coordinates such that the coordinates get paired into groups of three due to the way the potential within the Hamiltonian is defined but there are several criticisms of this, some strong criticisms come from (Monton, 2006), (Monton, 2002), (Monton, 2013) along the lines of this problem of uniqueness of describing an emergent 3D world from the 3N dimensional world, and by the another group, the primitive ontologists, (Allori, 2013) according to whom the wavefunction has a more nomological character than that of a physical entity, hence the non-necessity of a hyperspace to place it in.

At any cost, the mathematical issue of emergence of the manifest image of the world from wave function realism still remains a real problem for the wave function realist. Another way in which we may think of the problem is one where we say that both the spaces are physical spaces, the wavefunction as well as the quantum entities whose motion it guides are both real physical entities and part of the material aspect of the ontology. This appears to be the most direct way to read off the ontology from the mathematical framework of quantum mechanics. This suggests that there are two physical spaces of vastly different dimensionality. The issue with this approach is that a link between the two spaces must be established such that the causal structure that exists between the two physical spaces and the entities that inhabit them can be clearly explained. Without this metaphysical bridge between the two spaces, the two spaces remain out of touch, and one cannot affect the functioning of the other. There doesn't appear to be much work under this approach. Therefore, we see that every different way in which we try to deal with the dimensionality problem has issues which manifest as quickly as we begin positing our first idea about the dimensionality.

4.3.2 Wavefunction as a Vector in the Hilbert Space

As is pointed really well in the article, the idea of seeing the wavefunction as nothing more than a vector in the Hilbert Space is just another Everettian Approach, a radical one in that the issue of reality of the physical space faced by the configuration space still remains present in the idea of and question of the reality of the Hilbert space, and at the same time we also have that there is not enough structure in the Hilbert space to account for the complex structure of the world we see around us. For one, the Hilbert space has no manifold structure which comes even close to a definition of space-time in common sense view or in the recent physical view as expounded by the special and the general theory of relativity. In fact, there is no manifold structure at all, all that we have in this approach is the Hilbert space, a set of vectors with some added structure upon it and that's it. It is unclear how the proponents of this approach seek to show the emergence of the manifest world from the mathematically limited structure that a Hilbert space provides.

4.3.3 Wavefunction as a Multi-field on the 3D Space

Under this approach, which is pretty straightforward about its ontological commitment to the 3D space alone, we have that the wavefunction is a non-local structure upon the 3D space alone, there is nothing more to the wavefunction. It's non-locality comes from the fact that the wavefunction cannot be said to exist at this point or that, or we cannot ask what is the value of the wavefunction as this point or that apart from when the wavefunction is that of a single quantum entity, which we now know is more or less an approximation since with entanglement and immediate action, we cannot form isolated quantum entities, and hence the wavefunction of the world is then seen as a function that takes in the configurations of all the particles in the universe and gives a complex number in return for it. The wavefunction is thus non-local in character because it is something whose value is not determined by a definite locality of existence, rather it is something that takes things from multiple points in space simultaneously and from that gives us a value that helps us do quantum dynamics. This approach has been recently explained and elaborated upon in (E.K. Chen, 2017, E.K. Chen, 2019a, and Hubert & Romano, 2018) in which mathematical accounts and physical accounts of the multi-field approach are presented.

The primary problem that these face is the assertion that they are trying to make. The idea of something being *in* the physical space and yet not being located in the physical space is something that appears problematic in its very formulation. If the wavefunction is a multifield in that the wavefunction requires specification of multiple points to be, then the wavefunction appears to be an object of the configuration space and not that of the manifest physical space. At the same time, it also appears that this approach comes closest to the epistemological constraint which has already been considered above, the one concerning the serious opposition between quantum mechanical explanation and the general account of causality which is inherently local in character, and also marks how the idea of non-locality is yet to be explained in that the assertion that something is a non-local structure merely tells us that it is not local but gives us no further account of how that structure is, there is no positive account of how that structure is, instead the structure is defined by explaining what it is not. A similar problem appears here where the proponents of the multi-field appraoch have come to say that the wavefunction exists as a non-local structure on the 3D space but do not specify anything more before delving into complex mathematical justifications of the choice thus made. At the same time, all the problems that are present in the non-local account remain present in this multifield account for the metaphysics of the wavefunction.

There are several other approaches that deal with the wavefunction as a property of systems and other approaches that think of the wavefunction as a nomological entity, but in either case there is a point of ontology that remains. The problem of the ontological statue of the nomological entities is still an open problem. On the other hand, what explains the behaviour of the combined system composed of two particles such that the first and the second particle are too far apart, and when the interaction with one is done, the state of the other is immediately determined? What is it that carries this interaction immediately to the other entity? The answer cannot simply be a nomological entity, there must be some metaphysical connection of the ontological kind between the two entities which is responsible for the transmission of this interaction from one place to another. The same problem holds with asserting the wavefunction as a property. The question one can ask immediately is how then do we account for the transmissions of interaction? At the same time, this question does appear to presume some sort of explanation in terms of a local causal structure, in that the interaction must be taken from one place to another through a physical and ontological something, but the assertion of non-locality is not enough to explain this.

In all these approach something figures in and that is the assertion of an intrinsic and essential non-locality. This non-locality of the wavefunction, or the action at a distance, or the immediate action, is something that is, as if, written in the structure of the wavefunction itself and asserted and supported by all experimental evidences, various theorems of the bell kind and further in all philosophical explanations of the pictorial kind that have tried to answer the question of interpretation of the wavefunction. But as soon as we assert the immediacy of some action, we assert a black-box that represents a lack of knowledge. Historically too, upon the assertion of action at a distance through the Newtonian theory of gravity, there was discomfort amongst the scientists and the philosophers, until much later when Einstein restored locality with his theory of relativity, which ended up showing that our idea of the immediate action of gravitational force was ill-informed. With this we have that the idea of immediate action has generally represented a lack of knowledge, as something that is as yet unknown, and so is the case with non-locality.

There is no physical account of this non-locality in that for there to be a physical account, there has to be some spatio-temporality to the entity that we are talking about. But this is not the case with the wavefunction. The wavefunciton as an entity exists either in the configuration space, or it exists in a Hilbert space, or it is said to be a non-local structure, in that it is in the 3D space but at the same time it is not located in it, it is some how in it without having a location in it. On the other hand, its status as a property or a nomological entity only increases the already convoluted situation of the wavefunction in regards of it being a part of the ontology. Therefore, we have that in all the various approaches to the metaphysics of a wavefunction, there is an essential non-locality, or non-spatio-temporality. Since the wavefunction, seen as an entity is not spatio-temporal or at least not spatio-temporally located, we have that wavefunction appears to be a non-physical object. It appears that, like the other instances of positing some immediate action, immediate itself saying that the action or the interaction takes place without mediation, in that it takes place without temporal or spatial mediation, only signifies something that cannot be described physically due to the limitations of the physical description to spatio-temporal objects alone.

Therefore, the categories that come with the idea of physicality, that which comes then from the spatio-temporality of the physical object, the categories of position, time, translation, evolution, momentum, energy, and so on, are not categories that are applicable to the description of this interaction. This interaction is therefore either mediated through something that we cannot physically describe because it does not live in the same physical space as our physical description allows, or because, even though it is in the same space, it is not located in the space. Therefore, we have the limiting claim: the classical physical concepts are inherently incapable of describing the wavefunction and through that a complete physical spatio-temporal and in some sense pictorial description of the wavefunction is not possible.

Thus we finally have established the three claims which together form the *Bohrian Epistemological Thesis*: *The conceptual framework in quantum mechanics must be the same as the conceptual framework in classical physics. This conceptual framework is the classical physical conceptual framework, necessitated by the idea of physicality as spatio-temporality. And the metaphysics of wavefunction, instantaneous action, and non-locality makes it such that the explanation of quantum mechanics becomes impossible within that classical conceptual framework*

5 Bohrian Philosophy in View of Modern Interpretations

Ever since the development of the quantum formalism, various interpretations of the formalism, which in themselves are complete physical theories as compared to the doctrines in Bohrian thought have been developed. In general, these complete physical theories have been seen as counter-examples of the epistemological claim of Bohr, in that the theories provide a rather more complete attempt at the explanation of quantum mechanics than the original complementarity and correspondence principle based understanding put forth by Bohr. We argue that this is not the case in so far as the Epistemological Thesis in Bohrian Philosophy is read in the way given above. Let us then look at two of the primary interpretations that are considered as complete physical theories in view of the Bohrian Epistemological Thesis.

5.1 Bohmian Mechanics, or the Pilot Wave Theory

The Bohmian Mechanics framework is relatively simple: the ontology is constituted of point particles along with the universal wavefunction (in some interpretations it is taken to be a single world particle along with the universal wavefunction), and the dynamical equations are the Schrödigner Equation:

$$i\hbar \frac{\partial \Psi(\vec{r},t)}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2 \Psi(\vec{r},t) + V(\vec{r},t)\Psi(\vec{r},t) \tag{1}$$

and the Guidance Equation:

$$\frac{dX(t)}{dt} = \frac{\hbar}{m}\mathrm{Im}\left[\frac{\Psi^* \frac{\partial \Psi}{\partial x}}{\Psi^* \Psi}\right] \tag{2}$$

which defines how the location of the particles change over time. Now, in the Bohmian Mechanical framework, we have that the particles' positions are defined at all times which is what we generally call the hidden variable. We also have that the guidance equation acts as the velocity formula for each and every particle. At the same time the momenta of the particles are also well defined.

Given a very basic outline of Bohmian Mechanics, we can now consider the same in light of the Epistemological Thesis given above. Bohmian Mechanics clearly uses the classical conceptual framework to understand the quantum formalism, move beyond it, and in some sense give a relatively more complete framework which would solve many problems present in the orthodox interpretation. But at the same time, we see that it *does* use the classical conceptual framework, the concepts of position, momentum, energy, velocity, time, and so on, are the things that the Bohmian theory talks about to understand the quantum world. At the same time, the theory makes use of non-locality and the idea of instantaneous action in the guidance equation itself. The guidance equation gives us the rate of change of position with respect to time given the universal wavefunction which depends on the positions of all that particles in the universe, *at that time*. This implies that the position of all the particles in the universe immediate determine the rate of change of position of each particle, which is a clear violation of locality, and explicitly makes use of non-locality. But, like we have seen the notion of non-locality is not a positive notion, instead it appears to be an ad hoc notion, as a stand in for an explanation that is not present yet. While at the same time making it impossible for the application of the classical conceptual framework to explain this determination of velocity of a particle based on the position of all others due its non-physical status, or as an interaction that appears to supersede spatio-temporality.

5.2 GRW Theory

The case with GRW theory is relatively difficult to spell out in its completeness due to the various ontological pictures that are consistent with the dynamics given by the GRW theory, but let us consider at least the basic GRWm and GRWf theories in brief. The basic dynamics are very simple in that the collapse processes do not occur due to any different measurement process, rather they are spontaneous and occur at a rate given by a new universal constant. This leads to the collapse of the wavefunction to a relatively localised size.

Now, in the GRWm theory the ontology is said to be the mass-density field along with the wavefunction. This mass density field mimics the distribution of the wavefunction. On the other hand, the GRWf theory posits space-time flashes as its ontology along with the wavefunction. In both cases, the quantum formalism as such goes through some heavy changes, yet the conceptual framework that is used to interpret the theory remains the same, it is still talking about the positions of various things, and how they change with time in the GRWm theory and the occurrences of space-time flashes in the GRWf at space-time events, or positions in space-time. The point being the conceptual framework remains the same although its application sees alterations. At the same time we have that the wavefunction itself is a part of the ontology, and the theory relies on non-local interactions, or, at the very least, correlations that cannot be explained locally to give an account of the physical phenomena. In this regard, the black box of immediate interaction and non-locality still remains present in the theory. Hence the GRW theory too faces the same problems as Bohmian Mechanics, and can be seen as another theory within the purview of the Bohrian Epistemological Thesis.

6 Conclusion

Bohr has been often seen as a figure of Quantum Mechanical orthodoxy and dogmatism. But as we have seen above, the Bohrian Philosophical 'System' is based on the Epistemological Thesis which runs as an undercurrent in Bohrian thought. With the Epistemological Thesis saying that the application of classical conceptual framework, which is a necessity, cannot explain the quantum mechanical theory, we have that the only way in which we can think of interpreting and describing quantum physical phenomena is by the application of the classical conceptual categories in different ways. Bohmian Mechanics and GRW are such different ways of explaining the quantum phenomena, and for Bohr such a way was the Complementary explanation.

We also see that the problems of communicability, and that of the usage of simple language in describing the classical measurement apparatuses can be seen as a result of the manifest image of the world, as how the world appears to be to us. In view of the manifest image of the world, when we see an object located in front of us, its physical description necessarily grabs hold of the position of the object as such. The object in our direct view is located, and hence has a position. We can extend this idea to other concepts as well but we see that the idea of communicability too is related to the general notion of physicality shown above. At the same time, the very idea of visualisation is that of pictorial representations. But what is pictorialisation apart from representation in space? We see that various argument that Bohr forwarded in support of the necessity of classical conceptual framework can be based on the idea of physicality.

At the same time, a valid objection still stands. What if we change the very notion of physicality itself? Is it simply that changing the definition of physicality is what is stopping us from changing the way we have physical descriptions? We answer the latter question by saying no. This is because the way in which we perceive physicality is not simply as a definition, rather this account of physicality emerges from the common-sense pre-theoretic notion of physicality, constituted by our everyday usage of language, and the way we think and process the world itself.

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