Niels Bohr's Interpretation and the Copenhagen Interpretation

Are the two incompatible?

by

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Abstract:

The Copenhagen interpretation, which informs the textbook presentation of quantum mechanics, depends fundamentally on the notion of ontological wave-particle duality and a viewpoint called “complementarity”. In this paper, Bohr’s own interpretation is traced in detail and is shown to be fundamentally different from and even opposed to the Copenhagen interpretation in virtually all its particulars. In particular, Bohr’s interpretation avoids the ad hoc postulate of wave function ‘collapse’ that is central to the Copenhagen interpretation. The strengths and weakness of both interpretations are summarized.

"I have been unable to achieve a sharp formulation of Bohr's principle of complementarity despite much effort I have expended on it"

Einstein (1949, 674)

"While imagining that I understand the position of Einstein, as regards the EPR correlations, I have very little understanding of his principal opponent, Bohr."

Bell (1987, 155)

"Niels Bohr brain-washed a generation of physicists into believing that the problem had been solved fifty years ago."

Gell-Mann (1979, 29)

"Every sentence I say must be understood not as an affirmation, but as a question."

Bohr (Jammer 1966, 175)

"Bohr's interpretation has never been fully clarified. It needs an interpretation itself, and only that will be its defense."

Von Weizsäcker (1971, 25)

1. Introduction. It may be said that the 'Copenhagen interpretation' has as many versions as it has adherents. Nevertheless, there is a common core to the plurality of Copenhagen interpretations, which I shall refer to as *the* "Copenhagen interpretation" in this paper.

In brief, this Copenhagen interpretation, also referred to as the 'standard interpretation', treats the quantum mechanical wave function as providing not only a description of the real state of a single quantum system, but its most complete possible description. This state, which in the most general case is a physically real superposition state, evolves as per the Schrödinger equation in between observations. The wave function is, however, assumed to change into an eigenstate at the point of an actual individual measurement in a manner that is *not* governed by the Schrödinger equation. This dual status (superposition/eigenstate) of the Ψ function can be taken as the basis of ontological wave-particle duality. To account for the physical change from one status to another at the point of measurement in a meaningful manner, a panoply of interpretive ideas is invoked whose precise details can vary from one version to another. But there is one idea common to all versions of the Copenhagen interpretation: wave-particle *complementarity*. It is assumed that this notion originated with Niels Bohr. I shall show that Bohr's own version of complementarity has some basic features that are simply incompatible with the Copenhagen interpretation, and that the two bear only a superficial resemblance.

Indeed, I will argue that what Bohr presented as his own interpretation is radically different from the Copenhagen interpretation. I shall outline the principle elements of Bohr's interpretation and compare them with the corresponding ideas of the Copenhagen interpretation. I briefly summarize the virtues and difficulties of the two interpretations.

2. The Principal Elements of Bohr's Interpretation. Consider what Feynman has called "the only mystery in quantum mechanics," namely the self-interference of a single photon in the standard two-slit experiment. *Where* on the distant photographic plate a photon will land depends on whether one or both slits are open (wave behavior). If we place detectors close to the two-slit screen, however, only one of them fires (particle behavior).

To account for this behavior, the Copenhagen interpretation begins by accepting superposition to be the real state of the individual quantum system at the two-slit screen. Then, via the so-called collapse postulate, it is held that the observed behavior at the detection site is correlated with the eigenstate the photon enters *after* interaction with a specific experimental arrangement. The EPR argument showed that such a change of state at the point of and *due to* (some as yet unknown aspect of) the measurement interaction, however, entails a violation of the locality condition in the case of particle pairs with a space-like separation. In response the Copenhagen interpretation, which is thought to be based on Bohr's ideas, has embraced nonlocality as an essential consequence of quantum theory.

The collapse postulate (which Bohr never mentions; see Teller 1980) relates the Ψ function to the state of the individual system. As will be shown, Bohr rejects this interpretation of the Ψ function, and thus avoids the consequent non-local collapse.

Similarly, Bohr developed his interpretation to *avoid* ontological wave-particle duality, not to explain it. In Bohr's writings, "the duality is always presented as a puzzle, a dilemma, a paradox or even a contradiction: *always as something to be overcome and done away with*" (Scheibe 1973, 17-8, emphasis added).

Bohr avoids ontological wave-particle duality by relating the Ψ function, not to the state of the individual electron (as in the Copenhagen interpretation), but to the *joint* state of the electron and the experimental arrangement.

> "The main point here is the distinction between the *objects* under investigation and the *measurement instruments* which serve to define, in classical terms, the conditions under which the phenomena appear . . . these bodies together with the particles would in such a case constitute the system to which the quantum mechanical formalism is to be applied." (Bohr [1949], 1970, 221-2, italics Bohr's; underlines added)

I shall call this point Bohr's "inseparability" hypothesis. The 'quantum system' is now the totality of the experimental arrangement (i.e. the observed system *plus* the observing apparatuses), and is simply *different* in the two experiments. We no longer have the '*same'* object behaving differently in two different experiments. This difference in the two observed experimental systems straight-forwardly accounts for the difference in the two experimental outcomes. How, then, does Bohr reconcile his approach with the quantum mechanical praxis wherein physicists interpret the experimental outcomes as giving quantitative information about the physical properties of an individual electron? I shall return to this point later.

To better understand the epistemological status of Bohr's inseparability hypothesis, we also note that Bohr assumes that individual particles have an objective reality which is independent of the formalism: "Owing to the great energy of the fragments expelled by the atomic nuclei, the paths of these particles may be *directly observed*" (Bohr 1934, 112, emphasis added) (See also: Bohr 1963, 16, 24).

The macroscopic objects forming the experimental arrangement are also real. Given that there are two independent, real, physical systems in an experiment, their 'inseparability' can only be *epistemic*. This 'inseparability' constitutes the essential "epistemological lesson" imparted by the finite quantum of action. Due to this epistemic inseparability, *within the formalism*, the observations cannot be interpreted as measuring properties of the individual atomic system or *even of the macroscopic measuring devices*, as is commonly done by quantum physicists.

> "The quantum postulate implies that any observation of atomic phenomena will involve an interaction with the agency of observation not to be neglected. Accordingly, an independent reality in the ordinary physical sense can neither be ascribed to the phenomena *nor to the agencies of observation.*" (Bohr 1934, 54, emphasis added)

> “No result of an experiment . . . can be interpreted as giving information about *independent properties* of the objects, but is inherently connected with a definite situation in the description of which the measuring instruments interacting with the objects also enter essentially.” (Bohr 1957, 25-26, emphasis added)

These two quotations clearly show that the “inseparability hypothesis” is fundamentally different from the idea of ‘quantum contextuality’ characterizing the Copenhagen interpretation. As seen above, Bohr does not relate the quantum mechanical formalism to the description of the individual system alone. Quantum contextuality is the idea that the Ψ function *does* describe the individual system, although definite values for its properties can only be predicated in the context of an actual (or possible) observation; eigenstates and eigenvalues are created *at and by* measurement. Bohr cautions:

> “We are here dealing with a purely symbolic procedure, the unambiguous physical interpretation of which in the last resort requires a reference to a *complete experimental arrangement*. Disregard of this point has sometimes led to confusion, and in particular the use of phrases like ‘disturbance of phenomena by observation’ or ‘creation of physical attributes of objects by measurements’ which is hardly compatible with common language and practical definition.” (Bohr 1963, 5, italics added)

Contextuality also raises the question: why does one particular value amongst the many possible eigenvalues turn up in an individual observation? We have to either embrace quantum randomness or accord a causal role to measurement, neither of which is acceptable to Bohr. Bohr's inseparability is therefore incompatible with contextuality.

Inseparability operates only at the level of the formalism. Thus, within the formalism laboratory events have to be treated as our simple sense experiences. Thus, after 1935 Bohr came to limit his use of the term 'quantum phenomenon' to apply only to individual observational experiences. Such phenomena are complementary only in the special sense that the 'formal systems' giving rise to these observations are themselves different.

The most mysterious aspect of the two-slit experiment — the correlation between the experimental configurations *we* choose and the behavior of the individual electron — now stands dissolved. In choosing different experimental arrangements, we are *not* bringing about different behaviors of the 'same' system (i.e., the individual electron), but we are simply choosing to observe different 'quantum systems' (the experimental wholes) and the complementary phenomena they give rise to: "In any well-defined application of quantum mechanics, it is necessary to specify the whole experimental arrangement . . . which in turn means the freedom to choose between the different complementary types of phenomena we wish to study" (Bohr 1950, 53).

This freedom of choice for the experimenter is the same as in classical physics. In this sense, Bohr's is an objective interpretation.

> "The question was whether, as to the occurrence of the individual effects, we should adopt a terminology proposed by Dirac, that we were concerned with a choice on the

> part of “nature” or, as suggested by Heisenberg, we should say that we have to do with a choice on the part of the ‘observer’ constructing the measuring instruments and reading their recording. *Any such terminology would however, appear dubious* . . . our possibilities of handling the measuring instruments allow us to only make a choice between different complementary types of phenomena we want to study.” (Bohr [1949], 1970, 223, emphasis added)

As a result of inseparability, there is no notion of ‘path’ within the *formalism*. It just does not describe the individual electrons at all, much less their motion: “In contrast to ordinary mechanics, the new quantum mechanics does not deal with a space-time description of the motion of atomic particles” (Bohr, 1934, 48).

The quantum formalism simply accounts for the observations via a mode of description in which the electron and the experimental arrangement form a single whole, and the observations can only be interpreted as our sense experiences: “The physical content of quantum mechanics is exhausted by its power to formulate statistical laws governing observations obtained under conditions specified in plain language” (Bohr 1957, 12).

The flip side of this interpretation is that nothing in the theory inherently disallows definite trajectories for electrons, in contrast with the textbook or so-called Copenhagen interpretation. Bohr believes that particles do have definite trajectories, when experimental outcomes are directly and realistically interpreted independent of the quantum formalism.

> “. . . we have here *a direct connection with the customary ideas of motion*, since, owing to the great energy of the fragments expelled by the atomic nuclei, the paths of these particles may be directly observed.” (Bohr 1934, 102, 112, emphasis added)

If electrons do have definite trajectories as per direct experimental evidence, then why do the electrons ‘going through’ the top slit (in the two slit experiment) arrive at two different locations depending on whether the ‘other’ slit is open or not? Within the quantum formalism, the idea of an electron “going through” a slit is inadmissible. Similarly, if we interpret the bubble chamber experiment as revealing the trajectory of an electron, then according to Bohr this is *not* an experimental result that quantum theory can account for. Rather, the quantum formalism predicts only the relative probability that a given succession of individual condensed water drops will occur. That we integrate these events into a trajectory in commonsense thinking is *independent* of the quantum formalism, and Bohr offers ‘inseparability’ as a way to avoid conflict between this habit and the formalism.

According to this view, *at the formal level* the two-slit experiment is not designed to observe “through which” slit the particle is going through, since one cannot interpret this experiment in terms of visualizing an individual electron’s or photon’s behavior at the two-slit screen.

Hence, “as regards light, its propagation in space and time is adequately expressed by the electromagnetic theory” (1934, 55). Nothing in the quantum formalism need contradict this.

> “In the general problem of quantum theory, one is faced not with a modification of the mechanical and electrodynamical theories describable in terms of the usual physical concepts, but with an essential failure of the pictures in space and time on which the description of the natural phenomena has hitherto been based.” (Bohr 1934, 34-5)

Aage Peterson’s (1968) attribution to Bohr, that “there is no quantum world” (since the Ψ function does not describe the individual real particles) “but only quantum description” (successful predictions), now makes sense. The net result is that for Bohr, the quantum formalism is *not about the real states of individual quantum particles (electrons or photons) as is commonly held in the Copenhagen interpretation*. The quantum formalism is not directly about light or material particles *per se*, due to inseparability.

3. On the Role of Classical concepts within Quantum Theory. Quantum physicists see quantum theory as a theory of ‘motion’, and they use classical kinematical concepts such as position and momentum to interpret the observations. Bohr, as has been shown, does not see quantum theory as a theory of individual particles, much less their motions. If anything, Bohr does not even allow classical concepts to enter the formalism. Bohr’s interpretation still needs to account for the experimental praxis, however, which does use classical kinematical concepts.

Here Bohr’s interpretation pre-supposes a theory of knowledge which he does not readily elaborate upon and requires a separate gloss. Briefly, scientific realism involves at least two steps. Laboratory events are first interpreted as simple ‘observations’ using ordinary language, while ‘measurements’ are subsequent interpretations of the observations using theoretical terms. In classical physics, a measurement is taken to reveal the state of the observed system that existed prior to and independent of measurement. This interpretation is based on the assumption that perturbations to the observed system can be made arbitrarily small in principle. The Copenhagen interpretation claims that this assumption fails in the quantum realm, where the act of measurement causes an unavoidable disturbance in the state of the observed system such that the observed state can only be applied *at* the point of observation. To talk of measurements, however, the formalism must be taken to describe the individual observed system. With Bohr’s inseparability, this viewpoint is not available. Due to inseparability, the observation is “epistemologically irreversible”. Thus, Bohr locates the failure of the classical theory of measurement at the step of observation itself. For Bohr, at the level of the quantum formalism, there are only observations; there are *no* measurements, and hence *no measurement problem* at the level of the formalism.

We can now offer a justification of the textbook use of classical concepts to interpret observations. Bohr’s “inseparability” presumes the reality of atomic particles. Yet inseparability also obliges him to interpret the formalism itself from an instrumental viewpoint. It follows that to realistically interpret the observations as measurement results, the concepts of ‘classical’ physics are the only ones available. We can thus understand Bohr’s insistence on classical concepts.

In other words (not Bohr’s), Bohr is an anti-realist at the formal level, but a direct *realist* at the experimental level. Inseparability limits the formalism to an anti-realist reading, but also opens up the possibility of interpreting mutually exclusive experiments in terms of the behavior of the single system using ‘classical’ kinematical concepts. In contrast, the Copenhagen interpretation links classical concepts directly to the quantum mechanical observables, resulting in enormous conceptual difficulties such as ontological wave-particle duality, the measurement problem, and nonlocality, all of which Bohr avoids.

The traditional realistic 'physical explanations' offered using QT, starting with atomic stability, remain valid in Bohr’s interpretation via his insistence on realism at the experimental level. Bohr only wants us to remember that these explanations are independent of the formalism, and are arrived at in a manner not explicitly contradicting it.

If the underlying ontology is only ‘classical’, what are we to make of the use of non-classical notions such as “spin” in quantum theory? At the level of our experiences, any notion of property is permissible as long as we deploy it in conformity with the formalism. In this sense, a ‘classical’ concept need not be necessarily a concept taken from classical physics. A property can be generally termed ‘classical’ if we can *think* of it as a property whose value is independent of the measurement context. This is also true of classical physics. As Bohr points out, “within the scope of classical physics, all characteristic properties of a given object can in principle be ascertained by a single experimental arrangement, although in practice various arrangements are often convenient for the study of different aspects of the phenomena” (1963, 4).

Within the quantum *formalism,* we can’t even think of a quantum system in terms of its properties, either by itself or at the point of observation. Due to the inseparability hypothesis, “the numbers expressing the values of the quantum or spin in ordinary physical units do not concern direct measurements of classically defined actions or angular momenta, but are logically interpretable only by consistent use of the mathematical formalism of quantum theory” (Bohr, 1963, 61). The “consistent use” of the formalism is on the one hand a strictly instrumental interpretation, and on the other hand an interpretation/analysis of the experiments using ‘classical’ concepts in the above sense.

4. Complementarity — What It Is, and Is *Not*. Pauli (1994, 7) remarked, "we might call modern quantum theory, the theory of complementarity." I now identify certain complementarities in Bohr's interpretation, which are a *consequence* of his inseparability hypothesis. The list below is not exhaustive, nor taken directly from Bohr.

1. Complementarity of 'quantum systems' to which the formalism can be applied, when we consider two measurements, say corresponding to the x and p observables.
2. Complementarity between the formalism and the experimental praxis of quantum theory. The formalism is solely instrumental; the experimental praxis is realistic.
3. Complementarity of experimental arrangements corresponding to non-commuting observables.
4. Complementarity of the respective classical concepts that must be applied to these experimental arrangements to interpret the observations realistically.
5. Complementarity of the observations themselves qua sense phenomena.

Bohr asserted (5) but did not offer any justification. Two sense phenomena, to be mutually exclusive, must be *different*. But in all experiments, observation outcomes are *identical* (i.e., localized) detection events. Perhaps quantum observations are different from classical observations, in the sense that we have to report them differently in our ordinary language. But Bohr explicitly denies this. "We must remember, above all, that, as a matter of course, all new experience makes its appearance within the frame of our customary points of view and forms of perception" (1934, 1).

If the import of (5) is merely that such observations are the result of complementary experimental arrangements, interpreted in mutually exclusive classical ways, then (2) - (4) are adequate to convey it.

As for the Copenhagen interpretation, it embraces points (2) - (4), which merely state the experimental praxis. (1) provides an interpretive justification, but is incompatible with the Copenhagen interpretation.

Complementarity (1) helps us to see why the 'cat paradox' is not a problem at all for Bohr. Given a electron + detector + poison + cat system, we have two choices. Either the observation is interpreted as revealing the state of the cat *independent of the formalism* (in which case, quantum theory itself only makes statistical predictions pertaining to an ensemble of cats and says nothing about the individual cat), or the observation is linked to an inseparable quantum state of the experimental whole *within the formalism* (in which case, the independent state of neither the individual electron nor the cat can be referred to). The two views are complementary. Bohr's interpretation allows for both. Neither view involves a cat that is itself in a superposition of dead and alive states.

There is one more complementarity that Bohr does not make explicit, but seems to be implied by his writings:

6. *Complementarity between the classical and quantum theories of light and matter.*

Quantum theory is taken to supplant classical theory, but Bohr treats both theories as necessary. Classical theories give an ontological account of matter and radiation, and thereby predict certain observations. Does Bohr view quantum theory as only filling the predictive gap, accounting for certain observations related to the behavior of matter and radiation that cannot be accounted for by classical theory, via a non-classical descriptive viewpoint?

Surely, quantum theory must be a ‘deeper’ theory than classical physics. Perhaps (6) hints at a deeper truth about the proper relationship between classical and quantum theoretical description that we are yet to discover? (Gomatam 2004a)

5. On the Uncertainty Relations. Since Bohr relates the Ψ function to a “quantum system” consisting of the experimental whole, measurement results corresponding to the *x* and *p* observables (which involve two mutually exclusive experimental arrangements) can never apply to the same “quantum system” within the formalism. Nor can these observables within the formalism correspond to the classical concepts of ‘position’ and ‘momentum’. Thus, the formalism implies no inherent conflict with our intuition of a single particle in motion along a definite trajectory, having a definite momentum but an indefinite position.

The position and momentum concepts can be applied at the point of observation to a single particle, but this is independent of the formalism. At the point of observation, the two are constrained by the uncertainty relations and in that sense mutually exclusive. However, at the *formal* level, the uncertainty relations indicate the impossibility of simultaneously invoking both classical kinematic concepts to describe the same system (i.e. the same totality of the experimental arrangement) in a single observation. Bohr is cited as saying as much by Philip Frank (1949, 163-4).

> “Quantum mechanics speaks neither of particles the positions and velocities of which exist but cannot be accurately observed, nor of particles with indefinite positions and velocities. Rather, it speaks of experimental arrangements in the description of which the expressions 'position of a particle' and 'velocity of a particle' can never be employed simultaneously.”

The textbook interpretation of quantum theory does not ask whether or not the *x* and *p* observables correspond to new (non-classical) properties of the system. Instead, it imposes classical kinematical notions on the formalism. These properties cannot simultaneously have definite values due to the non-zero value of *h*-bar. Why, then, does *h*-bar come into the theory? The Copenhagen interpretation holds that *h*-bar has an ontological significance within the formalism, since the underlying electron cannot simultaneously have properties corresponding to definite *x* and *p*. At the level of the formalism, Bohr claims instead that *h*-bar stands for inseparability; the *x* and *p* observables pertain to two *different* quantum systems. In other words, *h*-bar represents the *epistemic* inseparability of the observed and observing systems, unlike in the Copenhagen interpretation.

> *"The finite magnitude of the quantum of action prevents altogether a sharp distinction being made between a phenomenon and the agency by which it is observed*, a distinction which underlies the customary concept of observation and, therefore, forms the basis of the classical ideas of motion." (Bohr 1934, 11-12, emphasis in the original)

The Copenhagen interpretation directly interprets the *x* and *p* observables as position and momentum in the classical kinematical sense, and also accepts them to be mutually exclusive. In Bohr's interpretation, such an explicit contradiction between classical concepts and the formalism is avoided, but it is equally unclear why the labels "position" and "momentum" should be used at all to describe the joint experimental wholes.

6. Bohr's Response to the EPR Argument. Bohr rejects the EPR notion of "elements of reality" for individual particles via his inseparability hypothesis, claiming instead that "the physical content of QT is exhausted by statements about observable outcomes" (1957, 12). For the nonlocality argument to hold weight with Bohr, EPR would thus have to demonstrate a physical impossibility: that a measurement made on one particle produces an observable outcome upon the other. Thus, Bohr easily dispenses with the EPR charge of superluminal causal influences.

The Copenhagen interpretation, on the other hand, has no such recourse. It directly links the Ψ function to a realistic interpretation of individual observations. Textbook wisdom therefore accepts the validity of the EPR argument and embraces a 'mysterious', non-local causality. It is thus wrong to think that Bohr's reply to the EPR paper is on behalf of the textbook 'Copenhagen interpretation'.

Bohr's rejection of EPR's "elements of reality" does not of course imply rejection of the reality of individual electrons. As cited above, Bohr accepts the reality of individual particles (*and* their motions) based on direct experimental evidence, the "adequacy of which can be judged only from a comparison of the predicted results with actual observations" (Bohr 1950, 53). The descriptive schema of quantum theory (via inseparability) succeeds in predicting the resulting observations. That is all we can demand of a physical theory, not conformity with some *a priori* requirement about description. "The purpose is not to disclose the real essence of the phenomena but only to track down, so far as it is possible, relations between the manifold aspects of our experience" (1934, 18).

Of course, in such a formally anti-realistic, but ontologically realistic interpretation embracing inseparability, there can be no causal account of the individual event in terms of the behavior of individual particles. But at least contradictions are avoided: "We cannot seek a physical explanation in the customary sense, but all we can demand in a new field of experience is the removal of any apparent contradiction" (Bohr 1957, 90).

7. Conclusion. The focus of this paper has been to show how Bohr's interpretation fundamentally differs from, and hence is incompatible with, the textbook Copenhagen interpretation. Due to space limitations, I have not surveyed the works of other Bohr scholars. It will have to be attempted elsewhere.

Bohr developed his interpretation on his own, and as Howard (2004) has pointed out, the Copenhagen interpretation developed via the work of von Neumann (who axiomatized the projection postulate), latter-day Heisenberg (who developed his own 'potentia' interpretation; see Gomatam, 2007), Bohm and others.

There are many interpretations which attempt to avoid the "collapse" of the wave function (many worlds, hidden variables, etc.). The motivation is clear: once we introduce the collapse postulate, we cannot avoid assigning a causal role to measurement. But then the claim that superposition describes a physically real state of an individual system must remain pure metaphysics. Bohr's interpretation (which views the formalism anti-realistically) avoids the collapse postulate because Bohr never relates the wave function to the state of an individual particle (via his inseparability hypothesis).

In the process, Bohr’s interpretation remains “wholly epistemological”. The textbook interpretation with its collapse postulate will remain the preferred approach, unless Bohr’s ideas can be built upon to offer a realistic interpretation of the formalism.

In this regard, Feyerabend (1961, 372) and Jammer (1974, 197-8) have noted that the idea of relations is implicit in Bohr’s writings. Elsewhere I have explored, as part of my ongoing work, the notion of *relational properties* that feature epistemic inseparability at the point of observation, and yet allow the Ψ function to be treated as a description of the ontological state of the individual quantum system (Gomatam, 1999, 2004b).

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