Studies in History and Philosophy of Modern Physics 59 (2017) 136–142

Contents lists available at ScienceDirect

Studies in History and Philosophy of Modern Physics

journal homepage: www.elsevier.com/locate/shpsb

# Complementarity, wave-particle duality, and domains of applicability

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ARTICLE INFO

*Article history:*
Received 28 July 2016
Received in revised form
28 November 2016
Accepted 9 June 2017
Available online 14 August 2017

*Keywords:*
Complementarity
Dualities
Wave
Particle
Bohr
Quantum

ABSTRACT

Complementarity has frequently, but mistakenly, been conflated with wave-particle duality, and this conflation has led to pervasive misunderstandings of Bohr's views and several misguided claims of an experimental "disproof" of complementarity. In this paper, I explain what Bohr meant by complementarity, and how this is related to, but distinct from, wave-particle duality. I list a variety of possible meanings of wave-particle duality, and canvass the ways in which they are (or are not) supported by quantum physics and Bohr's interpretation. I also examine the extent to which wave-particle duality should be viewed as an example of the sort of dualities one finds in, e.g., string theory. I argue that the most fruitful way of reading of Bohr's account complementarity is by comparing it to current accounts of effective theories with limited domains of applicability.



When citing this paper, please use the full journal title *Studies in History and Philosophy of Modern Physics*

## 1. Bohr's account of complementarity

Any attempt to understand Bohr's account of complementarity faces several hurdles. The first is that Bohr's writings on the subject are notoriously opaque. Bohr struggled mightily to articulate his points with clarity and precision, going though several drafts and choosing his words with great care, but it is easy to get the impression that his efforts only resulted in making his arguments more obscure. Second, many readers come to Bohr's writings looking for something other that what Bohr though he was offering. Physicists look for a "principle" of complementarity that they can apply to physical theory and experiment. Philosophers search for an "interpretation" of quantum mechanics that can be subjected to metaphysical analysis. However, Bohr never speaks of complementarity being a principle or theory; instead he typically refers to it as a "framework" or a "viewpoint", and he tells us that its lessons are *epistemological* (which might be contrasted with a *physical* principle or an *ontological* interpretation). Third, many physicists believe that they were taught all about complementarity in their introductory quantum mechanics courses, and they assume that their professor's account is a faithful rendering of Bohr's position. If they do look in Bohr's writings, they are often looking for phrases that match their prior understanding, and we shouldn't be surprised that they manage to find them.

Bohr believed that he had uncovered a fundamental epistemological truth, one so simple and general that (he fancied) it might become part of the curriculum for school children.[1] However, the primary application of complementarity, and the arena in which Bohr formulated it, was in the new field of quantum mechanics. It will be useful to distinguish between the relatively narrow case of how Bohr thought complementarity explained the situation in quantum physics, and the more sweeping claims suggested by Bohr. Let's use the label *quantum complementarity* to capture Bohr's views of the relationship between various quantum properties or concepts, and *broad complementarity* to capture his general epistemological claims.

To say that two concepts are complementary is to say that both concepts would be necessary for an idealized complete description of some scenario, but that the two concepts are mutually incompatible, at least to some degree; that is, one conception might be applicable with more precision, but only at the cost of making the other conception less applicable. Complementarity means two concepts are jointly necessary but mutually incompatible. The reason that some concepts can be, and are, incompatible is that some concepts require a

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[1] See Beller, (1999), p. 244.

http://dx.doi.org/10.1016/j.shpsb.2017.06.004
1355-2198/

certain *context* for their application. If the necessary context does not obtain, then the concept cannot apply. Further, some of these necessary contexts are *incompatible* with each other. We can only apply the concept in a certain context, but since some contexts cannot obtain at the same time, some concepts cannot simultaneously be applied.

Bohr would often discuss cases of broad complementarity with his friends and students. Pauli recalls that Bohr "attempted to apply this to ethics (good - evil, justice - love)" (quoted in Laurikainen, 1988, p. 207). The idea seems to have been that some contexts call for, or are required for, a relationship of love to obtain. A parent's love for his child, for example. On the other hand, there are contexts that demand an accounting in terms of justice: e.g., when a magistrate is passing judgement. To ignore either of these relationships would be to miss out on some real information about the world. But (the suggestion goes) the two contexts are not jointly compatible: one cannot fill both the role of the loving forgiving parent and the role of the impartial magistrate. The two ways of thinking about the situation are incompatible with each other.

It is not entirely clear whether Bohr thought that comparing these sorts of cases to quantum mechanics was thought-provoking but ultimately loose and light-hearted, or whether he thought the connections would hold up to close scrutiny. It seems, not surprisingly, that his opinions here weren't entirely fixed. However, it is clear that he remained convinced that complementarity was crucial for understanding the theory of quantum mechanics.

One of the challenges of our understanding quantum complementarity is figuring out precisely what the relata are. Bohr's first articulation of complementarity, in the Como lecture of 1927, focuses on what he calls "claims of causality" and "spacetime descriptions." He also speaks of a complementarity between the wave picture and the particle picture of matter, but this is clearly secondary. The precise meanings of Bohr's "spacetime descriptions" and "claims of causality" are not entirely transparent (we'll come back to this below when we dig into particle descriptions and wave descriptions), but the central meaning is clear enough: a spacetime description attributes a position to a particle at a time, while talking about "causality" involves attributing a value of momentum to a particle. The connection between momentum and causation is not completely and immediately obvious, but Bohr's line of thought here seems to be that conservation laws lie at the heart of physical dynamics and physical predictions, and so if we are going to say anything about what is physically required, we will need to assign a well-defined momentum to the object in question. If we cannot say what a particle's momentum is, then we will be unable to predict the result of that particle's impact with another particle: their future dynamical state will be uncertain.

Thus from the beginning the primary relata of quantum complementarity have been the concepts of position and momentum, and of other dynamical properties that can be ascribed to quantum systems. According to Bohr, the limitations of classical mechanics result in limitations in the applicability of classical concepts like position and momentum. However, we are still required to use these concepts to make sense of quantum theory and experiments:

> [H]owever far the phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms. The argument is simply that by the word "experiment" we refer to a situation where we can tell others what we have done and what we have learned and that, therefore, the account of the experimental arrangement and of the results of the observations must be expressed in unambiguous language with suitable application of the terminology of classical physics (Bohr, 1949, p. 209, p. 209).

Although the concepts are not universally applicable (the way classical mechanics asserted), there are certain contexts in which we *can* legitimately use concepts like position and momentum. Because we can only understand measurement results if they employ classical concepts, to perform a measurement we need to make sure that we have the proper context in place. However, Bohr's point isn't merely that we cannot *measure* some value without a given experimental arrangement; his claim is that the very *concept* cannot legitimately (or "unambiguously" as Bohr liked to say) be applied to a quantum process outside of the context required for that concept.

His well-known thought experiments that emerged from his dialogues with Einstein established that there were no contexts that could ensure the applicability of two complementary concepts to the same quantum system at the same time. This incompatibility was often taken as an incompatibility of possible *measurements*, by many of Bohr's contemporaries and by later physicists, philosophers, and historians. Indeed, Bohr himself sometimes did emphasize the question of possibilities of measurement.[2] This has led many to accuse Bohr of some combination of positivism, operationalism, and verificationism, but it is clear that he believes that the limitations on applicability of concepts is *primary*, and that the limitations on the possibility of measurement follow from this complementary relationship. There are limitations to the possibility of measurement *because* there are limits to the applicability of quantum concepts. It is not the case that concepts are limited *because* there are limits to measurability.

In Bohr's words, "we have in each experimental arrangement suited for the study of proper quantum phenomena not merely to do with an ignorance of the value of certain physical quantities, but with the impossibility of defining these quantities in an unambiguous way" (1935, p. 699). Nonetheless, it is true that when we can perform an experiment to legitimately assign a value of a property to a system, this implies that the concept of the property can be applied in that circumstance. Thus if there were experimental contexts that allowed for the joint measurement of incompatible properties (properties represented by noncommuting canonically conjugate operators in the quantum formalism), then Bohr's account of the complementarity of the associated concepts would fail.[3]

Quantum complementarity is therefore a special case of broad complementarity: Concepts like position and momentum can only be applied in certain circumstances, but the necessary conditions are incompatible when we get down to the quantum scale. Bohr tells us that this incompatibility is due to the existence of Planck's constant, which he sees as an indivisible "atom" of interaction that is foreign to classical mechanics. The difference between quantum mechanics and classical mechanics does not lie in the *dynamics* – the quantum Hamiltonians are identical to the classical Hamiltonians –, instead the nonclassical "irrationality" that is distinctive of quantum mechanics "comes in *only* in the failure of commutativity" between operators representing incompatible properties (Bohr, 1932). Thus the Heisenberg uncertainty relations are a theoretical expression of the limitations of the applicability of concepts of position, momentum, etc., and detailed analyses of measurement arrangements reveal that the finite value of Planck's constant

[2] For example, in his 1935 response to Einstein, Podolsky and Rosen, Bohr writes, "But even at this stage there is essentially the question of *an influence on the very conditions which define the possible types of predictions regarding the future behavior of the system*. . . . [T]hese conditions constitute an inherent element of the description of any phenomenon to which the term "physical reality" can be properly attached" (p. 700, Bohr's emphasis).

[3] For more elaboration on this point, see Bokulich & Bokulich, 2004.