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Niels Bohr on the wave function and the classical/quantum divide

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ABSTRACT

It is well known that Niels Bohr insisted on the necessity of classical concepts in the account of quantum phenomena. But there is little consensus concerning his reasons, and what he exactly meant by this. In this paper, I re-examine Bohr's interpretation of quantum mechanics, and argue that the necessity of the classical can be seen as part of his response to the measurement problem. More generally, I attempt to clarify Bohr's view on the classical/quantum divide, arguing that the relation between the two theories is that of mutual dependence. An important element in this clarification consists in distinguishing Bohr's idea of the wave function as symbolic from both a purely epistemic and an ontological interpretation. Together with new evidence concerning Bohr's conception of the wave function collapse, this sets his interpretation apart from both standard versions of the Copenhagen interpretation, and from some of the reconstructions of his view found in the literature. I conclude with a few remarks on how Bohr's ideas make much sense also when modern developments in quantum gravity and early universe cosmology are taken into account.

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1. Introduction

Foundational discussions of quantum mechanics routinely include reference to the Copenhagen interpretation. Though this interpretation is supposed to originate with Niels Bohr, there is often some confusion concerning both what the Copenhagen interpretation precisely amounts to, and which parts of this interpretation are associated with whom of the founding figures of quantum mechanics. But there are signs that the mist is beginning to clear up. For instance, Howard (2004) convincingly argues that critics of the Copenhagen interpretation often conflate Heisenberg's views with Bohr's, and Faye (2008) gives a very helpful overview of the main tenets in Bohr's thinking.

Even among friends of Bohr, however, there are still disagreements about how best to understand him. It is well known that Niels Bohr insisted on the necessity of the concepts of classical physics in the description of quantum phenomena. But there is little consensus concerning the justification, and the philosophical implications of this idea. Relatedly, or so I will argue, there is little consensus concerning Bohr's view on the wave function, the quantum measurement problem, and, more generally, the relation between classical and quantum physics. This paper is part of a series which aim to clarify and defend Bohr's interpretation of quantum mechanics. At the same time, the proposed clarification should be helpful for situating Bohr in relation to contemporary philosophical debates of quantum mechanics in which the wave function, the measurement problem and the classical/quantum relationship are central topics.

The lack of consensus among Bohr commentators regarding the role and status of the classical concepts is perhaps not surprising, given Bohr's own enigmatic accounts of his view. In one of its most quoted forms, Bohr expressed the necessity of classical concepts thus (1949, p. 39):

> [I]t is decisive to recognize that, *however 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. [Emphasis in original]

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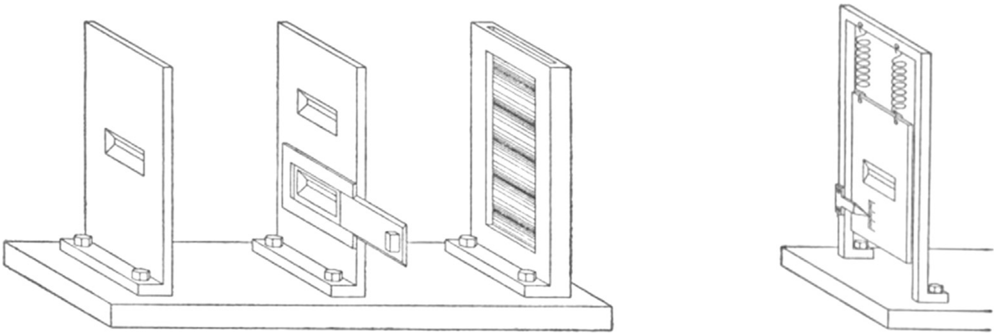

Fig. 1. Two variations of the double slit experiment. In the second variation, only the spring-suspended single slit diaphragm is depicted. Taken from Bohr (1949, p. 48).

Generations of physicists and philosophers have questioned the reasoning behind, and the simplicity of, this type of argument. For instance, after having read Bohr's response to the famous Einstein, Podolsky and Rosen paper, Schrödinger wrote in a letter to Bohr:

> There must be quite definite and clear grounds, why you repeatedly declare that one *must* interpret observations classically, which lie absolutely in their essence…. It must belong to your deepest conviction and I cannot understand on what you base it.
>
> (Schrödinger to Bohr (1935), quoted from Howard (1994, p. 201))

In what follows I will attempt to answer Schrödinger's question on behalf of Bohr by re-examining Bohr's writings.[1] This will include, in Section 2, briefly recalling Bohr's notion of complementarity, clarifying his view on the wave function, and providing new evidence regarding his conception of the wave function collapse. With these elements in place, Section 3 will frame the necessity of the classical in terms of Bohr's response to the measurement problem, and his demand for a reference frame. Section 4 will treat the more general question of the relation between the classical and the quantum in light of Bohr's view on the stability of matter (an issue which has so far been little discussed in the literature). Finally, in Section 5, I sum up and briefly indicate how Bohr's interpretation of quantum mechanics still makes much sense also in the current landscape of cosmology and fundamental physics.

2. Elements of Bohr's view

2.1. Complementarity

Bohr's idea of complementarity has been treated extensively in the literature. But it is worthwhile to give a brief summary of the idea since, as we shall see below, it provides a good starting point regarding Bohr's view on the wave function and wave function collapse. In general, complementarity means that the attribution of certain properties to quantum objects can take place only in experimental contexts which are mutually incompatible. Thus, for example, an experiment which can determine the position of an electron cannot be used to determine its momentum. Complementary properties, such as position and momentum, are both necessary for a full understanding of the object but, as manifested in Heisenberg's uncertainty relations, the object cannot possibly be attributed precise values of both properties at the same time.[2]

In a characteristic exposition from 1949, Bohr introduces the notion of complementarity by considering two variations of the famous double slit experiment. In the first, the diaphragms are kept fixed, and this allows for the appearance of an interference pattern on the photographic plate. In the second variation, the single-slit diaphragm is suspended by a spring, and so is allowed to move vertically (Fig. 1).

The movable diaphragm permits control of its momentum before and after the passage of the particle, and therefore the determination of which of the double slits the particle subsequently moves through. However, Bohr (1949, p. 46) observes that "...we are presented with a choice of *either* tracing the path of a particle *or* observing interference effects" [emphasis in original]. The point is that *if* the path is tracked, e.g. by controlling the momentum gain of the spring-suspended diaphragm due to the particle's passage, the position of this diaphragm when the particle passes through becomes uncertain. The uncertainty is the result of an uncontrollable interaction (involving e.g. a momentum change of the diaphragm) when the momentum measurement is made, and it implies a washout of the interference pattern.[3] Bohr (1949, p. 46) concludes

> We have here to do with a typical example of how the *complementary phenomena* appear under mutually exclusive experimental arrangements… and [we] are just faced with the *impossibility*, in the analysis of quantum effects, of drawing any sharp separation between an independent behavior of atomic objects and their interaction with the measuring instruments which serve to define the conditions under which the phenomena occur. [My emphasis]

As we shall see below, one way this impossibility is manifested is through Bohr's idea that the wave function (e.g. of an electron in a double slit experiment) only refers to the object in a given

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[1] In the original 1935 response to Schrödinger (which can be found in Kalckar, 1996, p. 511), Bohr points out that the description of the measurement set-up must "…involve the arrangement of the instruments in space and their functioning in time, if we shall be able to state anything at all about the phenomena". Bohr then argues that the measurement apparatus, in order to serve as such, must be kept outside the system to which quantum mechanics is applied. While this short answer was probably insufficient to satisfy Schrödinger's demand for an explanation, I will attempt to unpack and defend it below.

[2] The relation between complementarity and the uncertainty relations was spelled out already in Bohr's Como lecture (1928, p. 60): "According to the quantum theory a general reciprocal relation exists between the maximum sharpness of definition of the space–time and energy-momentum vectors associated with the individuals. This circumstance may be regarded as a simple symbolical expression for the complementary nature of the space–time description and the claims of causality". For the purposes of this paper, I bypass the controversial issue of whether, and to which extent, Bohr's views on complementarity changed over the years; see e.g. discussion and references in Faye & Folse (1998).

[3] This may suggest that the momentum measurement disturbs some pre-existing definite position of the diaphragm (for instance, Fine & Beller (1994, p. 13) read Bohr this way). However, in this experimental context, Bohr took the particle and the diaphragm to be described by a non-separable (or entangled, see below) state *until* the momentum control is carried out (see also Bohr, 1938, p. 102). For in this case, the diaphragm is part of the system to which quantum mechanics should be applied: "As regards the quantum-mechanical description, we have to deal here with a two-body system consisting of the diaphragm as well as of the particle, …" (Bohr, 1949, p. 45). Hence it is the *combined* system of object and diaphragm (and not the diaphragm alone) which is 'disturbed' by the momentum measurement.