Bohr and Complementarity

Bohr's complementarity principle is one of the most important historical events regarding wave-particle duality and the measurement problem. A brief examination of complementarity is presented here and elaborated in more detail in Chapter 5.

For Bohr, the issue of whether the statistical Born rule [6] is fundamentally rooted in a physical nondeterminism or whether it is simply a mathematical approximation that is useful to derive a probability or statistical accounting was answered in the following manner. The statistical postulates are not simply useful but are ultimately necessary for an external observer for the following reasons. A physical device is required to make a measurement that necessitates interactions between system and device. This interaction is in-principle uncontrollable and thereby changes one classical variable at the expense of measuring its conjugate because of the uncertainty principle. That is, an external observer ultimately loses the ability in the process of measurement to specify the variable conjugate to the variable being measured. Hence for the external observer there will always be some incomplete knowledge in terms of specifying all measurable classical states of the system.

Bohr believed that *only* a probabilistic description is possible for the external observer in terms of a description of all classical states: no wave function evolution equation can be known to the external observer that uniquely determines the outcome of an experiment when the measured variable is conjugate to an already known variable. It does not matter whether the conjugate variable deterministically evolves with incomplete knowledge afforded to the external observer or is fundamentally nondeterministic. In either case, it is impossible for the external observer to predict with certainty the conjugate variable.

Whether 1) additional variables that are hidden from the external observer and a statistical description is required as proposed by Dirac, or 2) there is a fundamentally nondeterministic substratum, would largely become issues that did not appear to be answered by any experiment at the time of the Copenhagen interpretation. Born states at the end of his 1926 paper [6, p. 54]:

> *Ought we hope later to discover such properties (like phases of the internal atomic motions) and determine them in individual cases? Or ought we to believe that the agreement of theory and experiment—as to the impossibility of prescribing conditions for a causal evolution—is a pre-established harmony founded on the nonexistence of such conditions? I myself am inclined to give up determination in the world of atoms. But that is a philosophical question for which physical arguments are not decisive.*

Many have read these original papers and believe that the wave-particle debate is fully resolved by settling for just such a duality—that is, one can consider the phenomenon as a wave when the momentum becomes known and as a particle when the position becomes known. At this point one might tend to believe that the problem should be relegated to strictly philosophical efforts. In fact, shortly after the Copenhagen interpretation, Bohr and others appeared to have largely abandoned any efforts to model the interactions in a manner to determine both a classical variable and its conjugate.

At this stage, one may be rather content with the explanation of wave-particle duality afforded by complementarity. Suppose that the Copenhagen interpretation is correct—there is no deterministic manner to predict simultaneously a variable and its conjugate. Does this logically imply that the measurement problem is philosophical as stated by Born? Such an inference makes inductive common sense but does not follow to the deductive reasoner. In fact, later in life, Born stated [10, p. 265]:

> *"I should like only to say this: the determinism of classical physics turns out to be an illusion, created by overrating mathematico-logical concepts. It is an idol, not an ideal in scientific research and cannot, therefore, be used as an objection to the essentially nondeterministic statistical interpretation of quantum mechanics."*
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> M. Born, Nobel Prize address, Stockholm, Sweden. ©1954 The Nobel Foundation

The issue of whether or not the problem is philosophical cannot be said to have been resolved conclusively from the issues of wave-particle duality examined so far. For that we need to dig deeper and examine the measurement problem in a different light—that of entanglement. We begin with Schrödinger's cat.