COMPLEMENTARITY AND CONTEXTUALITY IN THE SPIRIT OF COPENHAGEN

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***ABSTRACT*. The aim of this talk it to outline Bohr's concept of complementarity in the context of Bohr's epistemology of quantum mechanics. Taking this epistemology into account, I argue, is essential for understanding how complementarity, which can, as a concept, be defined more generally and applies elsewhere, is specifically used by Bohr in quantum mechanics.**

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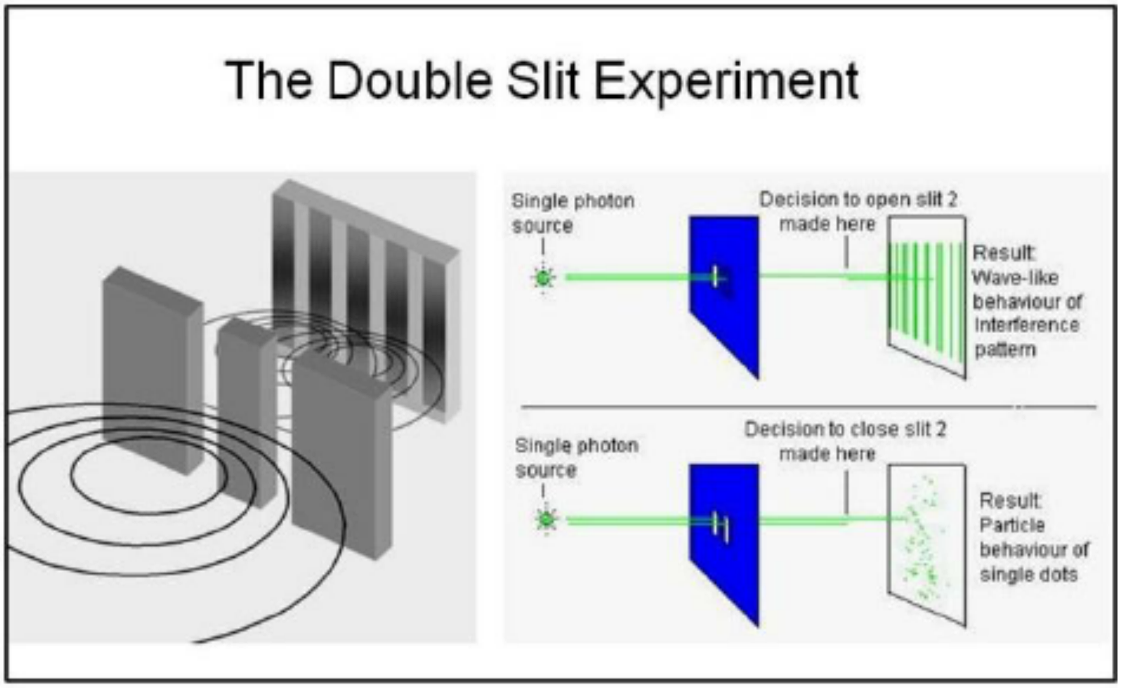
"In quantum mechanics, we are not dealing with an arbitrary renunciation of a more detailed analysis of atomic phenomena [=Wheeler's elementary acts of observer-participancy], but with a recognition that such an analysis is *in principle* excluded"
--N. Bohr, "Discussion with Einstein on Epistemological Problems in Atomic Physics" (1949)

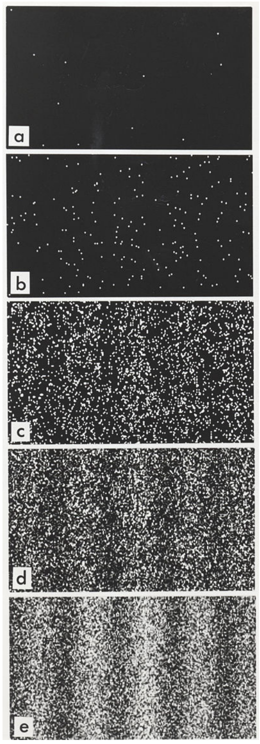
"We can ask ourselves if it is not absolutely preposterous to put into a formula anything as first sight so vague as law without law and substance without substance. How can we hope to move forward with no solid ground at all under our feet? Then we remember that Einstein had to perform the same miracle. His curved space seemed to take all definitive structure away from anything we can call solidity. In the end physics, after being moved bodily [sic: boldly?] over onto the new underpinnings, shows itself as clear and useful as ever. We have to demand no less here. We have to move the imposing structure of science over onto the foundation of elementary acts of observer-participancy."
--J. Wheeler, "Law Without Law" (1983).

As this indeterminacy is an unavoidable element of every initial state of a system [a quantum object] that is at all possible according to the new [quantum-mechanical] law, the development of the system even can never be determined as was the case in classical mechanics. The theory predicts only the *statistics* of the results of an experiment, when it is repeated under a given condition. Like the ultimate fact without any cause, the *individual* outcome of a measurement is, however, in general not comprehended by laws.
--W. Pauli, "Matter" (1952)

OUTLINE

1. **Introduction**
2. **Quantum Epistemology**
3. **Complementarity**
4. **The EPR Experiment and the EPR Complementarity**


The Double Slit Experiment
Single photon source
Decision to open slit 2 made here
Result: Wave-like behaviour of Interference pattern
Single photon source
Decision to close slit 2 made here
Result: Particle behaviour of single dots



In order to make correct predictions, one must take into account that an electron can go through both slits, which, however, never happens: it is never observed and assuming this introduces contradictions with several accepted physical principle, specifically (physical) locality.

We don't know and cannot imagine how this happens, in Bohr's and related interpretations.

Remark: It is different in Bohmian theory (or in some alternative interpretations of quantum mechanics), where we have the account of how quantum objects behave. These cases will not be considered here.

1. Quantum Epistemology

"The renunciation of the ideal of causality in atomic physics which has been forced on us is founded logically only *on our not being any longer in a position to speak of the autonomous behavior of a physical object*, due to the unavoidable interaction between the object and the measuring instruments which [interaction] in principle cannot be taken into account, if these instruments according to their purpose shall allow the unambiguous use of the concepts necessary for the description of experience. *In the last resort <u>an artificial word like "complementarity"</u> <u>which does not belong to our daily concepts</u> serves only briefly to remind us of the epistemological situation here encountered, which at least in physics is of an entirely novel character*."
--N. Bohr, "Causality and Complementarity" (1937)

"the very existence of the quantum of action [the Planck constant, *h*, which, physically, defines all quantum phenomena] entails . . . the necessity of a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality."
--N. Bohr, "Can the Quantum-Mechanical Description of Physical Reality Be Considered Complete?" (a reply to A. Einstein, B. Podolsky, and N. Rosen (EPR), "Can the Quantum-Mechanical Description of Physical Reality Be Considered Complete?") (1935)

Two key points:

1. **The impossibility of representing *"the autonomous [independent] behavior of a physical [quantum] object*, due to the unavoidable interaction between the object and the measuring instruments," which defines the nonrealist epistemology of quantum phenomena and quantum theory.**

"In quantum mechanics, we are not dealing with an arbitrary renunciation of a more detailed analysis of atomic phenomena, but with a recognition that such an analysis is *in principle* excluded"
--N. Bohr, "Discussion with Einstein on Epistemological Problems in Atomic Physics" (1949)

Nobody has ever observed, at least thus far, an electron or photon as such, in motion or at rest, to the degree that such a concept, as opposed to a change of a state of an electron or photon, ultimately applies to them, or any quantum objects, qua quantum objects, no matter how large. (Photons, of course, only exist in motion.) It is only possible to observe traces, such as spots on photographic plates, left by their interactions with measuring instruments.

2. **The character *of "complementarity," which does not belong to our daily concepts, and hence is a different type of concept,* as reflecting this epistemology.**

“In contrast to ordinary mechanics, *the new quantum mechanics does not deal with a space–time description of the motion of atomic particles*. It operates with manifolds of quantities [matrices] which replace the harmonic oscillating components of the motion and symbolize the possibilities of transitions between stationary states in conformity with the correspondence principle [which requires that quantum and classical predictions coincide in the classical limit]. These quantities satisfy certain relations which take the place of the mechanical equations of motion and the quantization rules [of the old quantum theory].”
--N. Bohr 1987, “Quantum Theory and Mechanics” (1925)

“What I really like in this scheme [his new quantum mechanics] is that one can really reduce *all interactions* between atoms and the external world ... *to transition probabilities*”
--W. Heisenberg, Letter to R. Kronig, 5 June 1925

Heisenberg's approach may be thought of in quantum-informational terms because the quantum-mechanical situation, as he conceived of it (initially dealing with hydrogen spectra), was in effect defined by:

(a) certain *already obtained* information, concerning the energy of an electron, derived from spectral lines (due to the emission of radiation by the electron), *observed* in measuring instruments; and

(b) certain possible future information, concerning the energy of this electron, *to be obtainable* from spectral lines *to be observed* in measuring instruments and predictable, unavoidably (on experimental grounds) in probabilistic or statistical terms, by means of the mathematical formalism of one or another quantum theory.

Heisenberg's strategy was to develop a mathematical formalism that would connect these two sets of data, manifested in measuring instruments, only in predictive terms, moreover (in accord with what is actually observed in quantum experiments), in strictly probabilistically or statistically predictive terms, without assuming that this formalism needed to represent how these two sets of data or information are connected by a spatiotemporal process or how each set comes about, in the first place. Heisenberg's mathematical scheme did not represent anything at the time of measurement either: it only predicted transition probabilities between situations defined by measurements, those already performed, which provide the numerical data that serve as the experimental basis for these predictions, and possible future ones.

Any quantum-mechanical situation was now defined in terms of events and probabilistic or statistical connections between events, as manifested only in the measuring instruments involved. Heisenberg's scheme was about the *interactions* between atoms in the observed external world, specifically the measuring instruments involved. It is this view eventually became the foundation of Bohr's concepts of phenomena, defined by these interactions, and complementarity, and his interpretation of quantum mechanics.

“There is no description of what happens to the system between the initial observation and the next measurement. …The demand to ‘describe what happens’ in the quantum-theoretical process between two successive observations is a contradiction in adjecto, since the word ‘describe’ refers to the use of classical concepts, while these concepts cannot be applied in the space between the observations; they can only be applied at the points of observation.”

--W. Heisenberg, *Physics and Philosophy* (1958)

“But the problem of language is really serious. We wish to speak in some way about the structure of the atoms and not only about ‘facts’—the latter being, for instance, the black spots on a photographic plate or the water droplets in a cloud chamber. But we cannot speak about the atoms in ordinary language.”

--W. Heisenberg, *Physics and Philosophy* (1958)

The absence of causality is automatic under these conditions.

"Causality" refers, ontologically, to the conception that the state of the system considered is determined at all future moments of time, once it is determined at a given moment of time, and by

"Determinism" refers, epistemologically, to the possibility of predicting the outcomes of such processes ideally exactly, although both concepts are connected and, at bottom, are co-defining in classical physics.

The lack of causality implies the lack of determinism, but the opposite is not true. A theory may be causal without being deterministic, as in the case in classical statistical physics, chaos theory, or Bohmian mechanics.

On the other hand, the lack of realism implies the lack of causality.

"if a classical state does not exist at any moment, it can hardly change causally,"
--E. Schrödinger, "The Present Situation in Quantum Theory" (1935)

"It is most important to realize that the recourse to probability laws under such circumstances is essentially different in aim from the familiar application of statistical considerations as practical means of accounting for the properties of mechanical systems of great structural complexity. In fact, in quantum physics we are presented not with intricacies of this kind, but with the inability of the classical frame of concepts to comprise the peculiar feature[s] of the elementary [quantum] processes."

The probabilistic or statistical character of quantum predictions must, however, be equally maintained by realist interpretations of these theories or alternative theories (such as Bohmian mechanics), to accord with what is observed in quantum experiments, where only probabilistic or statistical predictions are possible. This is because the repetition of identically prepared experiments in general leads to different outcomes, and, unlike in classical physics, this difference cannot be diminished beyond the limit defined by Planck's constant, *h*, by improving the capacity of our instruments, as manifested in the uncertainty relations, which would remain valid even if we had perfect instruments.

Alternative concepts of causality:

Relativistic causality = locality

Quantum (Probabilistic) Causality

TWO VIEWS OF THE WORLD

"Inquiry into nature is a search for the causes of each thing; why each thing comes into existence, why it goes out of existence, why it exists"
--Plato, *Phaedo*, 96 a 6–10, 5-th century BC.

"If, therefore, we experience that something happens, then we always presuppose that something else precedes it, which it *follows* in accordance with a rule."
--Kant 1997, pp. 305, 308).

This presupposition also defines the *concept* of classical causality (proceeding from causes to effects), and, in Kant and beyond, it is accompanied by and even arises from another presupposition, that of the possibility of forming a representation or at least a conception of the mechanism responsible for this rule, which presupposition defines realism.

Quantum phenomena, in nonrealist, the spirit-of-Copenhagen interpretation, interpretations, violate this principle, because the cause of a given event could not in general be ascertained, even ideally or in principle. Only statistical correlations between events could be ascertained, correlations that defy classical causality.

The spirit of Copenhagen does not stop thinking and knowledge. Indeed, it leads to thinking and knowledge that would not be possible otherwise, QFT theory, beginning with Dirac's work (Bohr's favorite illustration of this claim), but it also changes the nature of thinking and knowledge, but making that which is beyond thought part of thinking and knowledge. Fundamental physics, thus understood, is, in Heisenberg's title phrase, always "physics and beyond," not the least because it is also a physics of the beyond. It is the physics of that which is beyond the reach of the physics available at a given moment of time, and beyond physics itself, for example, if one adopts the RWR principle, which, in its strongest version, places the ultimate constitution of nature beyond thought itself, but not beyond existence or reality.
This "beyond the reach of physics," makes possible new physics, physics that would not be possible otherwise.

3. COMPLEMENTARITY

Complementarity is defined by:

(a) a mutual exclusivity of certain phenomena, entities, or conceptions; and yet

(b) the possibility of considering each one of them separately at any given point, and

(c) the necessity of considering all of them at different moments for a comprehensive account of the totality of phenomena that one must consider in quantum physics.

Remark: In quantum mechanics, the concepts of complementarity and contextuality are, while different, correlative and imply each other.

Digression: Bohr vs. Bell

"[Bohr] seemed to revel in contradiction, for example, between 'wave' and 'particle.' … Not to resolves these contradictions and ambiguities, but rather to reconcile us to them, he put forward a philosophy which he called 'complementarity." … There is very little I can say about 'complementarity.' But I wish to say one thing. It seems that Bohr used this word with the reverse of its usual meaning. Consider for example the elephant. From the front she is head, trunk, and two legs. From the sides she is bottom, tail, and two legs. They supplement one another, they are consistent with one another and they are all entailed by the unifying concept 'elephant.' It is my impression that to suppose Bohr used the word 'complementarity' in this ordinary way would have been regarded by him as missing his point and trivializing his thought. He seems to insist rather that we must use in our analysis elements which *contradict* one another, which do not add up or derive from a whole. By 'complementarity' he meant, it seems to me, the reverse: contradictoriness. … Perhaps he a subtle satisfaction in the use of a familiar word with the reserve of its familiar meaning.'
--J. Bell, *Speakable and Unspeakable in Quantum Mechanics* (1987)

While Bell in fact reasonably cogently comment on Bohr's conception of complementarity his criticism of it puzzling. One can understand Bell's discontent with Bohr, and it is not my intention to reproach Bell *for this discontent* itself. Expressly siding with Einstein, Bell does not favor Bohr's interpretation or for that matter quantum mechanics itself, which attitude is legitimate and, again, far from uncommon. On the other hand, leaving aside Bell's psychological surmise, Bell's comments themselves are misleading. Bell is not wrong is saying that "to suppose Bohr used the word 'complementarity' in this ordinary way would have been regarded by him as missing his point and trivializing his thought." It would indeed, because it is. Bell is also not accurate on this point: While "complementary" as an adjective is a familiar word, "complementarity" as a noun is not, and in fact it was never used as a noun before Bohr.

“an artificial word like ‘complementarity’ which does not belong to our daily concepts serves only … to remind us of the epistemological situation here encountered, which at least in physics is of an entirely novel character.”
N. Bohr, “Causality and Complementarity” (1937)

Complementarity is a new physical concept, which must be understood in the specific sense Bohr gives it. There is no point in attempting to relate it to a meaning it may be given in our daily life, as Bell does, by defining complementary parts as adding up to a whole. This is precisely what Bohr wants to avoid, because he needs a new concept to account for a “new feature of natural philosophy,” and not, as Bell suggests, for the reason of some “subtle satisfaction in the use of a familiar word with the reverse of its familiar meaning.” There is no evidence that Bohr ever had such a satisfaction. On the other hand, there is plenty of evidence for his physical reasons for defining complementarity in the way he did: the uncertainty relations, the double-slit and other iconic quantum experiment, or the EPR experiment. Complementarity was introduced in the spirit of resolving contradictions and not reveling in them.

The quantum-mechanical situation and Bohr's interpretation of it were eventually recast by Bohr in terms of his concept of "phenomenon," defined by what is observed in measuring instruments under the impact of quantum objects, in contradistinction to quantum objects themselves, which could not be observed or represented, or even conceived of:

"I advocated the application of the word phenomenon exclusively to refer to the *observations* obtained under specified circumstances, including an account of the whole experimental arrangement. In such terminology, the observational problem is free of any special intricacy since, in *actual* experiments, all observations are expressed by unambiguous statements referring, for instance, to the registration of the point at which an electron arrives at a photographic plate. Moreover, speaking in such a way is just suited to emphasize that the appropriate physical interpretation of the symbolic quantum-mechanical formalism amounts only to predictions, of determinate or statistical character, pertaining to individual phenomena appearing under conditions defined by classical physical concepts [describing the observable parts of measuring instruments]."
--N. Bohr, "Discussion with Einstein on Epistemological Problems in Atomic Physics" (1949)

By contrast, quantum objects themselves and their behavior are beyond representation or even conception:

"In quantum mechanics, we are not dealing with an arbitrary renunciation of a more detailed analysis of atomic phenomena, but with a recognition that such an analysis is *in principle* excluded"
--N. Bohr, "Discussion with Einstein on Epistemological Problems in Atomic Physics" (1949)

Complementarity may be seen as a reflection of the fact that, in a radical departure from classical physics or relativity, the behavior of quantum objects of the same type, say, electrons, is not governed, individually or collectively, by the same "physical law," in all possible contexts, specifically in complementary contexts. That is, the behavior of quantum objects leads to mutually incompatible observable physical effects in complementary setups or contexts, an incompatibility not found in classical physics or relativity. On the other hand, quantum mechanics offers correct probabilistic *or* statistical predictions (no other predictions are, again, possible) of quantum phenomena *in all contexts*, in nonrealist, RWR-type, interpretations under the assumption that quantum objects, states, and behavior are beyond representation or even conception. Speaking of "*physical* law" in this connection requires caution, because, in Bohr's and related nonrealist interpretations, there is no physical law representing this behavior, not even a probabilistic law if one adopts a statistical, rather than a Bayesian, view.

As this indeterminacy is an unavoidable element of every initial state of a system [a quantum object] that is at all possible according to the new [quantum-mechanical] law, the development of the system even can never be determined as was the case in classical mechanics. The theory predicts only the *statistics* of the results of an experiment, when it is repeated under a given condition. Like the ultimate fact without any cause, the *individual* outcome of a measurement is, however, in general not comprehended by laws.

--W. Pauli. "Matter" (1952)

If one adopts this type of interpretation, the nature of both experimental and theoretical physics, and with them, the philosophy of physics, change. Experimentally we no longer track, as we do in classical physics or relativity, the independent behavior of the systems considered, track what happens in any event. Instead we define what *will* happen in the experiments we perform, by *how* we experiment with nature by means of our experimental technology, even though and because we can only predict what will happen probabilistically or statistically. Thus, in the double-slit experiment, the two alternative setups of the experiment, whether we, respectively, can or cannot know, even in principle, through which slit each particle, say, an electron, passes, we obtain two different outcomes of the statistical distributions of the traces on the screen (with which each particle collides). Or, in effect equivalently to the double-slit experiment, while also giving a rigorous physical meaning to the uncertainty relations, we can set up our apparatus so as to measure and correspondingly predict, again, probabilistically or statistically, either the position or the momentum of a given quantum object, but never both together. Either case requires a separate experiment, incompatible with the other, rather than representing an arbitrary selection of either type of measurement within the same physical situation, by tracking either one of its aspects or the other, as in classical mechanics. There, this tracking is possible because we can, in principle, assign simultaneously both quantities within the same experimental arrangement. In quantum physics, we cannot. Quantum physics changes what experiments do: they define what will or will not happen, while allowing for probabilistic or statistical predictions concerning what will happen, rather than follow what is bound to happen in accordance with classical causality.

4.The EPR Experiment and the EPR Complementarity

"When two systems, of which we know the states by their respective representatives, enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems separate again, then they can no longer be described in the same way as before, viz. by endowing each of them with a representative of its own. *I would not call that* one *but rather* the *characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought.* By the interaction the two representatives [the quantum states] have become entangled. Another way of expressing the peculiar situation is: the best possible knowledge of a *whole* does not necessarily include the best possible knowledge of all its *parts,* even though they may be entirely separate and therefore virtually capable of being 'best possibly known,' i.e., of possessing, each of them, a representative of its own. *The lack of knowledge is by no means due to the interaction being insufficiently known—at least not in the way that it could possibly be known more completely—it is due to the interaction itself.*"
--E. Schrödinger, "Discussion of probability relations between separated systems" (1935)

"*I would not call that* one *but rather* the *characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought.*"

“The lack of knowledge is by no means due to the interaction being insufficiently known—at least not in the way that it could possibly be known more completely—it is due to the interaction itself” is strictly in accord with Bohr’s view. Bohr gives this point a nonrealist interpretation (which Schrödinger resists) as concerns the ultimate character of this interaction, which is “finite [quantum] and uncontrollable.”

There are further profound connections to complementarity, which in fact would allow us to refine Schrödinger’s point, but I am

“Out of Space, Out of Time!”
--Edgar Allan Poe

THANK YOU!