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ARTICLE

Bohr as a Phenomenological Realist

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Abstract There is confusion among scholars of Bohr as to whether he should be categorized as an instrumentalist (see Faye 1991) or a realist (see Folse 1985). I argue that Bohr is a realist, and that the confusion is due to the fact that he holds a very special view of realism, which did not coincide with the philosophers' views. His approach was sometimes labelled instrumentalist and other times realist, because he was an instrumentalist on the theoretical level, but a realist on the level of models. Such a realist position is what I call phenomenological realism. In this paper, and by taking Bohr's debate with Einstein as a paradigm, I try to prove that Bohr was such a realist.

Keywords Instrumental Bohr · The realist Bohr · Phenomenological realism · Quantum mechanics · Bohr's philosophical position · Bohr–Einstein debate · J. Faye · H. Folse

1 Introduction

I think that the most puzzling point in the well-known debate between Bohr and Einstein is Bohr's apparent lack of understanding of Einstein's points, which are clear. Why, in spite of its clarity, was Bohr's starting remark on Einstein's thought experiments: 'I cannot understand it'? Bohr had a very good idea of Einstein's objections and yet it seems he could not understand Einstein's simple presentations! Why did Bohr exert a great effort to reconstruct Einstein's thought experiments? Why was it important to do so? Had Einstein missed any point in his presentation or were there other important factors? I think that by searching for answers to such questions, we will arrive at Bohr's realist perspective, provided that we understand the way Bohr was convinced that theoretical physics ought to be conducted. He presented an understanding of theoretical physics that can be encapsulated in what I call phenomenological realism.

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Einstein and Bohr had different perspectives on theoretical physics. While Einstein was a fundamental theorist who approached theory building on a top-down basis, Bohr was a bottom-up theorist. The crucial difference between Bohr and Einstein was the *point of departure* from which theoretical physicists ought to build their theoretical understanding of physical phenomena and the *process* by which such theoretical representation is built.

Einstein believed in a unified theory. This kept him thinking that there would be a simple and beautiful theory that would encompass all the phenomena of nature. He believed that the mathematical structure of such unified theory is the ultimate representation of nature. Einstein wanted theory to give complete answers for all the problems facing it without the need to use any other method. Hence, in the debate, his examples originated in the theoretical structure of quantum mechanics. On the contrary, Bohr started by putting hypothetical situations into plausible (if not possible at the time) experimental set-ups, and used quantum mechanics as a tool to build models that can capture these set-ups.

Einstein tried to prove the inconsistency of quantum theory by starting from its premises to arrive at a hypothetical experimental situation where the inconsistency was visible. This was the direct opposite of Bohr's approach. Bohr always, as I argue, started from the experimental and phenomenal in order to build theoretical representations and descriptions of physical reality, which can be termed phenomenological models. To him, these models represented physical reality. Hence, Bohr was a realist on the level of phenomenological models but instrumentalist on the theory level.

Moreover, Bohr was concerned mainly with the way we can articulate these phenomenological models. He thought that we ought to present a coherent "story" that could fully explain and represent the quantum mechanical phenomena. His concern wasn't the formalism of quantum mechanics, but the physical meanings that would be ascribed to such formalism. The important point for him was to find the correct way in which formalism could model any suggested experimental set-up. In his view, mathematical schemes do not give us descriptive power but models do.

Henry Folse[1] asserts that Bohr was a realist, but he falters in defending this position, because he restricts it to the existence of atomic systems and overall acceptance of a realistic interpretation of science. Although Folse asserts that Bohr's realism is not compatible with standard realism, Folse himself could not represent a coherent realist position of Bohr. He admits that he had "to reconstruct what Complementarity must assume about the nature of physical reality with only the barest minimum of direct statements from Bohr" (Folse 1985, p. 223). Had he not dismissed a phenomenological understanding of Bohr, he would have arrived at accepting that Bohr's realist stands are phenomenological realism. Nonetheless, Folse's position is fully understandable, since what Bohr accepted as phenomenological was not only the surface of physical reality, but, as we will see below, an interpretation that insisted on the motto of "what you see is what you get," i.e., there is nothing behind the phenomenon.[2] As Bohr put it: "Indeed it is difficult for me to associate any meaning with the question of what is behind the phenomena, beyond the corresponding features of the formalism …" (Bohr, quoted in Folse 1985, p. 248).

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[1] See Folse (1985, 1986, 1990, 1993). Others agree on this: see Krips (1993), Mackinnon (1993), and Honner (1987).

[2] Which Folse himself admits in 1985, pp. 247–249.

2 What is Phenomenological Realism[3]

> Yet it is to some such conclusion that we shall have to come if we wish to define the philosophy of scientific knowledge as an open philosophy, as the consciousness of a mind which constitutes itself by working upon the unknown, by seeking within reality that which contradicts anterior knowledge.[4]
>
> Gaston Bachelard

In order to be able to overcome the pessimistic meta-induction, most realists accept that a kind of dichotomy is needed on the theoretical level. Phenomenological realism asserts that such a dichotomy ought to be horizontal, whereby low-level theoretical representations are what represent physical reality, and therefore have a better chance to survive through theory change than high-level ones.

The overall strategy of phenomenological realism can be described as being realist on the empirical and phenomenological levels, but not at the theory level. It might be described as a middle-way approach between instrumentalism, which asserts that theories are mere instruments, and realism which claims that theories represent or approximate nature. Phenomenological realism accepts that phenomenological models, which are a kind of low-level "theoretical description" are representative of physical reality, while fundamental, high-level theories are mere tools.

Models serve as mediators between high theories on the one hand, and either hypothetical situations (theoretical models) or real concrete situations[5] (phenomenological models) on the other. Models in physics, as I use the term, whether theoretical or phenomenological, have three parts: (1) a set of mathematical equations; (2) a description of the experimental set-up and/or the boundary conditions in which the phenomenon under study can exhibit itself (it is necessary here to present a clear referential assertion between the data acquired or expected in the case of thought experiments, and the mathematical symbols used); and (3) a story.

The third point requires elaboration. Usually, a story fulfils the following criteria:

(a) It presents a coherent account of the phenomenon's behaviour. In doing so, the story might either adhere to the need for theory coherency (in the case of theoretical models), or for physical coherency in relation to the phenomenal facts (in the case of phenomenological models).

(b) In order to present such a coherent account, the story must relate the mathematical formalism with the real features of nature (or the hypothetical situation). This might be done by accepting the terminology of a certain theoretical framework (theoretical models), or by associating the symbols with certain properties exhibited by the phenomenon without strictly accepting the existing terminology (phenomenological models).

(c) A story gives an account of how the model can represent the known properties of the phenomenon under study.

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[3] For further details consult Shomar (1998).

[4] From Bachelard (1968, p. 9).

[5] I accept models as mediators between theories and experiments in special way as dialectical mediators (see Gramsci 1980; Bachelard 1984a, b). The development of this idea I follow is not Margaret Morrison's idea of mediator models (1990, 1999) although in many respects I agree with her, but that of Gaston Bachelard.

It should be stated here that all models (theoretical and phenomenological) use concepts whose criteria of application are not exhausted by measurement procedures but include constraints taken from the body of formerly presupposed theories. Consider acceleration. We can measure the time, distance and the change in distance with respect to the change in time. These are our data. At this level alone, there is very little theorisation, but as soon as we introduce the concept of acceleration or speed or force, there will be.

Theoretical models and phenomenological models share some general characteristics, yet phenomenological models are more likely to be accurate representations of nature. Phenomenological realism accepts that on the level of theorisation, theoretical descriptions do represent nature. This is the basic difference between phenomenological realism and instrumentalism which usually asserts that theoretical descriptions at all levels are mere instruments.

Usually, fundamental theories are used in constructing models, either by derivation (theoretical models) or merely as tools[6] (phenomenological models). In some cases, the theory predicts a certain phenomenon and suggests a theoretical model to represent it. Then, after experimentally testing the hypothesis, physicists, most of the time, would be able to rebuild the suggested model using a bottom-up approach. Phenomenological realism insists that the models which can be constructed by applying the bottom-up approach are phenomenological models, even in cases where only one fundamental theory is used as a tool in their construction, and even if that fundamental theory is itself the theory which could produce the same mathematical equations of the model by derivability. Nonetheless, such models are not the only kind of phenomenological models.

In a lot of situations in physics we do not have a fundamental theory that provides a set of theoretical models. Rather, we have a set of observations of which we have little understanding. In these cases, we also try to build models that represent the phenomenon under study. In most cases, the model needs to employ more than one fundamental theory. Phenomenological realism considers these models phenomenological as well. In fact, most of what intuitively seem to be phenomenological models in physics are built in this way.

Hence, a phenomenological model is a type of theoretical representation which stems from the phenomenological level. It provides a description of the experimental set-up of a phenomenon using a mathematical structure to express the relations between its different aspects, and a story to present a coherent account of the relations between the mathematical structure and the phenomenon under study. However, the theoretical account provided by a phenomenological model is not as abstract as the one provided by a theoretical model.

Phenomenological realism asserts that phenomenological models are generally the best vehicles of representation. These models are closely related to the empirical findings. Therefore, it is more probable that what they say about nature is correct. It must be said that even if phenomenological models, when constructed, take the phenomenal facts as their starting point, they should nevertheless encompass more than just the facts they start off with. They ought to be able to predict unknown properties of the phenomenon. This is an important point, because it is obvious that a theoretical representation can get an empirical fact right if it was constructed with this empirical fact as a presupposition. So, in order to give the no-miracle argument weight in favour of phenomenological models, it is important that these models are able to predict previously unknown properties of the phenomenon. By accepting this idea, phenomenological realism is able to escape the

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[6] See Cartwright et al. (1995).

pessimistic meta-induction critiques[7] while at the same time holding to the no-miracle argument.

It is important here to differentiate between observations and phenomenal facts. Observations are raw sense-data that can be interpreted in various ways depending on one's prior theoretical understanding of such data, while phenomenal facts are a set of data that are already loaded with a specific prior theoretical understanding. Hence, phenomenal facts are not raw observations.

3 Bohr's Philosophical Grounds

In order to understand Bohr's position, it is important to understand his philosophical position. Bohr contended that any complete "theoretical description" ought to have a pictorial description[8] that links it to physical reality. This idea is expressed in quantum mechanics by the quantum postulate and the complementary principle. Bohr accepts that the new physics forces a new understanding of natural phenomena. These elements, along with his idea of objectivity, would shape his attitude toward realism.

3.1 The "Theoretical Description"

Bohr accepted a dialectical concept of knowledge stressing the importance of human intervention as part of objective reality. He accepted that "theoretical descriptions" are real representations of nature. In Bohr's view, such "theoretical descriptions" were not restricted to one theory but use all accepted theories in physics as tools to construct them. These "theoretical descriptions" are phenomenological models.[9] Moreover, Bohr asserted that "theoretical descriptions" contain another important element: the story that links them to real situations.

Bohr was a theoretical physicist who thought that "theoretical descriptions" were not constructed from simple mathematical formalism, like the principle of least action, but built up on experimental and phenomenological grounds.[10] Heisenberg acknowledged this when he said that Bohr's

> insight into the structure of the theory was not a result of mathematical analysis of the basic assumptions, but rather of an intense occupation with the actual phenomena, such that it was possible for him to sense the relationships intuitively rather than derive them formally.
>
> Thus I understood: knowledge of nature was primarily obtained in this way, and only as the next step can one succeed in fixing one's knowledge in mathematical form and subjecting it to complete rational analysis. (Heisenberg 1967, pp. 94–95)

This is one of the major ways Bohr's standpoint differs from that of Einstein, who thought that theories should give a *'complete' description of the physical system by virtue*

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[7] This is so because phenomenological models survive through theory change, because of the way they are built.

[8] This is similar, as I will argue, to the story associated with phenomenological realism.

[9] This connotation between the theoretical description and models in Bohr's work was also suggested by both Mackinnon (1993) and Murdoch (1987). Nonetheless I think that my approach to the issue differs from theirs.

[10] I will argue below that Bohr's concept of phenomena is different from that of a phenomenalist like Mach.

of mathematical formalism. The difference between the two standpoints is crucial for understanding their debate. While Bohr's concern was the quantum phenomena and how they ought to be represented, Einstein's concern was consistency between new theory and other existing theories in physics. For now, let us see Bohr's idea of "theoretical description" at work.

The first important theoretical work for Bohr was the model of the atom, or, as it is known now, the old quantum theory (or sometimes, Bohr's model). In 1911, Bohr was a newly graduated physicist, searching for a research project to work on. He went to Cambridge to work at the Cavendish with Thomson, and there he met Rutherford.[11]

At that time, Rutherford was working on his model of the atom in Manchester. As we know, he had suggested, in line with a series of experiments, that an atom must consist of a massive, positively charged nucleus with negatively charged particles surrounding it. The problem with Rutherford's model was its inconsistency with the mechanical representations known at that time. The classical picture dictates that if such a description is ascribed to a system, the electrons ought to collapse in a spiral-like path toward the nucleus when a loss of energy by radiation occurs. This means that the resulting spectrum should be a continuous spectrum of radiated light. Experimental evidence shows instead that the radiation spectrum is a discrete 'line spectrum.'

In his PhD thesis, Bohr did not accept classical mechanics as a suitable framework for all situations. He claimed that classical mechanics could not provide a solution for the chemical atom. In his view, a break with the classical picture was inescapable. Electrons are not free, reacting with different particles, but are bound. This attitude made him a suitable candidate to tackle the challenge of the experimental facts provided by Rutherford's experiments, and he was able to find a solution.

Newly discovered phenomenological facts indicated the fallacy of theories then current. Bohr used these facts as a starting point to construct a new model. Then, given the well-corroborated fact that classical mechanics could not explain these new facts, Bohr searched for other tools and models that could be used to construct a descriptive model of the atomic system. These tools are:

(1) *Quantum of action*: As Bohr stated in his 1913 paper, "it seems necessary to introduce" into the process of building the atom-model "a quantity foreign to the electrodynamics, i.e., Plank's constant." Experiments show that the resulting spectrum is linear with discontinuity in the distribution of energy. Such a result justifies the claim that there is an analogy between such a distribution and Planck's "quantum of action" (Bohr 1913).
(2) *Rutherford's atom model*: Bohr agreed with Rutherford's claim that electrons move in orbits around a heavy nucleus, but asserted that it was essential to modify this assumption.
(3) *The planetary system*: Bohr suggested a solution using the planetary system. He suggested that the electrons orbit round the nucleus on closed orbits with different energy levels.
(4) *Photoelectric effect*: In order to better understand the energy levels, Bohr used yet another tool, relying on a reformulation of Einstein's 1905 paper on the photoelectric effect. He stated that when an atom radiates energy, electrons jump from one energy level to another, emitting photons with energy equal to Planck's constant multiplied by frequency.

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[11] For more details see Pais (1991).

Bohr also tried to clarify his assumptions in a way best suited to building a "theoretical description" (the atom-model). Therefore, he articulated his postulates and assumptions using a detailed description of the experimental and/or experimental set-up of that postulate or assumption (Bohr 1913, pp. 11–12). For Bohr, this process was not a simple description of the boundary conditions of a physical system, but essential to developing his theory.

In technical terms, Bohr's model stated the following:

(1) Electrons move in circular orbits of radius r. They are restricted to these orbits due to the requirement that the angular momentum be an integer multiple of Planck's constant:

$$mvr = \frac{nh}{2\pi} \tag{1}$$

This use of Planck's notion of quanta allowed Bohr to define his concept of the quantum postulate for the first time. Bohr used the quantum postulate to state a major difference between classical systems and quantum systems: quantum systems have an inherited property of being discrete. According to Bohr,

> the quantum postulate attributes to any atomic process an essential discontinuity, or rather individuality, completely foreign to the classical theories and symbolised by Planck's quantum of action. (Bohr 1928, p. 89)

(2) The electrons in their orbits do not radiate even if they are in rapid movement; they are in a stationary state with a definite value of energy E.

(3) Electrons can transfer from one stationary state to another, either by absorbing or radiating energy with a frequency:

$$f = \frac{E - E'}{h} \tag{2}$$

(4) As a consequences of points 1–3, the energy of each level (each possible orbit) can be given for an atom with a nuclear charge Z_e and electron charge $-e$ and mass m:

$$E = -\frac{2\pi^2 e^4 Z^2 m}{h^2 n^2} = -\frac{\text{const.}}{n^2} eV \tag{3}$$

This point is another instance of Bohr's quantum postulate: that energy, in this case, is not continuous but jumps by an integer factor ($n = 1, 2, 3\ldots$).

Here, the importance of the quantum postulate, in the process of building the atom model, is apparent. Bohr did not think that numerical agreement between mathematical and experimental results was a sufficient reason to accept the mathematical model as a representative model. He felt that it was important to present a clear pictorial description of the quantum system. This picture ought to be presented in unambiguous language. The quantum postulate provides the physical picture of the mathematical equations.

The essential basis for Bohr's model was his suggestion that although classical language and models are used in constructing the quantum models, the phenomena we encounter at the atomic level are 'completely foreign' to those of the classical level, where a description of discontinuity and individuality is brought in to account for the puzzling results of experiments. Bohr continued to adhere to this kind of dual description of quantum systems:

On the one hand, he accepted that these systems were alien to classical ones, but on the other hand, he still acknowledged the importance of classical language in order to present the quantum system. Bohr believed, as Folse claims (Folse 1985, 1986), that the quantum postulate was a real (true) description of situations in the quantum world. Bohr accepted that a true "theoretical description" consisted of:

(1) A description of the experimental set-up of the 'natural phenomena.' In his construction of the model of the atom, he gave a detailed description of the experimental set-up of the atom and the reasons he thought that such set-up could not be represented using classical mechanics (Bohr 1913, pp. 1–25).
(2) Mathematical formalism. These are tools chosen from more than one of the currently accepted theories. In Bohr's model, they were: the planetary system, Einstein's photoelectric effect and Planck's quantum of energy.
(3) A pictorial description that would represent the phenomenon in everyday language. An example of such a pictorial description is the quantum postulate in Bohr's model.
(4) A story that relates the mathematical formalism with the physical reality. This is conveyed in his discussion of the movement of the electron orbits around the nuclei, the excitation of the electrons and their movement from one orbit to another. Bohr questioned whether the suggested mathematical formalism could explain experimental findings, like the line spectrum and why electrons stay in their orbits and do not collapse into the nuclei.

Such a "theoretical description" is a low-level theoretical representation that satisfies the definition of a phenomenological model. This way of doing physics, i.e., trying to capture an intuitive description of physical phenomena as a first step, then searching for a mathematical scheme which might fit the description—not the other way round—was the way Bohr did physics from the early stages of his work and throughout his life. Heisenberg indicates this by saying:

> "Bohr was not a mathematical minded man, but he thought about the connection in physics … one doesn't bother too much about the mathematical scheme. That is a later trouble. One-first tries to see how things are connected—what they really mean." (Heisenberg 1963, p. 30)

Each model in any theoretical representation contains a story that helps link it to the real physical system. Bohr accepted that each system had its model relative to its experimental set-up. This model was a representative one. This is essentially what he meant by the term "individuality" that he persistently used in his writings. Here, it is crucial to notice the importance of the process whereby such a model is derived, because this process constitutes the essential difference between Bohr's theoretical approach and other approaches. For Bohr, the approach had to be bottom-up, in order to reflect his vision of how the "theoretical description" would be a representation of nature. Hence, even if the mathematical equations of the model could be derived from the theory's first principles, Bohr would not want the representative models to be associated with such first principles. As he later in life stated clearly in his reply to Rosenfeld: "it appeared difficult to define what one should understand by first principles in a field of knowledge where our starting point is empirical evidence of different kind that is not directly combinable" (as formulated by Mackinnon 1993, p. 281).

Such reasoning clarifies why Bohr changed his tone when speaking about quantum mechanics as a theory; he put his instrumental hat on. I will come back to this point below, but let us now turn our attention to the complementarity principle, which Bohr viewed as the second important tool that would shape the pictorial description associated with models of the quantum world.

3.2 The Complementarity Principle

As mentioned earlier, Bohr's main interest was to present a physical pictorial description that helped to clarify the meaning of the mathematical equations adopted from quantum mechanics to account for the phenomena. As discussed by many scholars (Jammer 1966, pp. 323–361; Beller 1992, pp. 171–175; Folse 1985, 1986, 1993; Krips 1987, 1993; Pais 1991; Murdoch 1987), Bohr was dissatisfied with both the contradictory pictures of quantum systems entailed in wave mechanics and matrix mechanics, and the uncertainty principle as presented by Heisenberg. In this section I want to explore how complementarity stemmed from Bohr's disagreement with the mathematically minded approach in quantum mechanics. "Bohr would not like to say that nature imitates a mathematical scheme, that nature does only things which fit into a mathematical scheme"[12] (Heisenberg 1963, p. 15). In line with this conviction, he wanted to think about the real quantum phenomena at the atomic level.

In the Como lecture, Bohr, countering Heisenberg, tried to present the uncertainty principle not as the consequence of a mathematical scheme, but as arising from well-established experience. The dispute with Heisenberg was related to the underlying ontology of the quantum world. The world of natural phenomena is rich and it is not possible to capture it within one mathematical scheme. Even if we can capture the behaviour of the quantum systems in terms of matrix mechanics, it is still necessary to understand why it is possible to capture it by wave mechanics. Bohr considered both schemes as mathematical tools to deal with the richness of nature. Heisenberg, on the contrary, thought that if it were possible to prove mathematically that the two might be equivalent, then there is no cause for concern.[13] It would be a matter of preference whether we talk in terms of wave mechanics or matrix mechanics.

Bohr was not worried about the equivalency between wave and matrix mechanics but about the physical description of the phenomena in the quantum world. In Bohr's view, the experimental evidence at the time clearly indicated that particles behave as 'waves' and as 'particles.' Moreover, the experimental set-up always has a measuring instrument which cannot be interpreted as a quantum mechanical device. From this accumulation of layers of complexity, the complexity of Bohr's argument of complementarity emerges.

Bohr started by indicating that the observation of a classical phenomenon could occur without disturbing it:

> Indeed, our usual description of physical phenomena is based entirely on the idea that the phenomena concerned may be observed without disturbing them appreciably. (Bohr 1928, p. 88)

In contrast:

> The quantum postulate implies that any observation of atomic phenomena will involve an interaction with the agency of observation not to be neglected.

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[12] This is not to say that a mathematical scheme cannot represent nature as an integrated element of the theoretical representation.

[13] At that time, Schrödinger's proof of compatibility between the two schemes was not yet known.

> Accordingly, an independent reality in the ordinary physical sense can neither be ascribed to the phenomena nor to the agencies of observation. (Bohr 1928, p. 89)

It is important to see how carefully Bohr worded his sentences: “any observation of atomic phenomena will involve an interaction with the agency of observation not to be neglected.” This interaction will not affect the existence of an independent reality, but this independent reality will not be independent “in the ordinary physical sense.” Later he rephrased the idea by specifying that the interaction was real physical interaction of the measuring instruments with the quantum system, and that this interaction would serve as the objective conditions that “define the conditions under which the phenomena appear.” In his words:

> The crucial point, which was to become a main theme of the discussions…, implies the impossibility of a *sharp separation between the behaviour of atomic objects and the interaction with the measuring instruments which serve to define the conditions under which the phenomena appear*. (Bohr 1949, p. 210)

Hence, Bohr had a particular sense of objectivity, which at face value appears irrational if viewed from a classical perspective. However, it is far from being irrational. The only difference is that it has a dynamic concept of objectivity, as we will see below. Moreover, such objectivity means seeing the observer as part of the system, not as an independent observer looking at the system. As he said:

> “it must never be forgotten that we ourselves are both actors and spectators in the drama of existence.” (Bohr 1948, p. 318)

This leads us to the next layer of complexity. Bohr accepted that each particular set-up provides the ways in which we ought to apply the quantum postulate:

> The circumstances, however, that in interpreting observations use has always to be made of theoretical notions entails that for every particular case it is a question of convenience at which point the concept of observation involving the quantum postulate with its “irrationality” is brought in. (Bohr 1928, p. 89)

The classical notion of observing a physical system does not (necessarily) involve disturbance, and the classical description of the physical system can be presented in an unambiguous way. However, due to the interaction with the measurement instrument, an “unambiguous definition of the state of the system” in the classical sense “is naturally no longer possible,” in Bohr’s view. In order to restore clarity, we ought to change the way we think about the description of the physical system. Bohr saw the change in terms of the possibilities of combining dialectically both theoretical entities with empirical outcomes:

> Indeed, in the description of the atomic phenomena, the quantum postulate presents us with the task of developing a “complementarity” theory the consistency of which can be judged only by weighing the possibilities of definition and observation. (Bohr 1928, p. 90)

That is, there is a complementarity between the theoretical “definition” and empirical “observation.” This “complementarity mode of description” is not a subjective judgement in which the observer can, by merely wishing or thinking, decide whether to observe this or that aspect (i.e., whether we want, in the case of the wave and particle duality, to observe the wave aspect of the system or the particle aspect of it). Rather, it is a matter of objective conditions in which there would be one possible observation (of two non-commuting observers) in a particular set-up (see Bohr 1948, p. 317).

The complexity increases as another factor is brought in: the experimental evidence. At the experimental level, for example, it did not seem possible at that time[14] that a single experimental set-up could observe both the particle aspect and the wave aspect of a quantum system. In his discussion of this point, Bohr started with the nature of light:

> The two views of the nature of light are rather to be considered as different attempts at an interpretation of experimental evidence in which limitation of the classical concepts is *expressed* in complementary ways. (Bohr 1928, p. 91)

Of course, the same can be said about the elementary particles. "Recent experiments" and "the very expression of experimental evidence" prove that "here again we are not dealing with contradictory but with complementary pictures of the phenomena."

Let me put this argument in an experimental perspective. In the two-slit experiment, there were two possible experimental set-ups (at that time). The first was related to fixing the two-slit frame and losing the momentum information while gaining position information. The second was leaving the two-slit frame loose in a way that could give information about the momentum, while losing information about the position of the particle. Bohr accepted that the first experimental set-up gave the particle picture, while the second experimental set-up gave the wave picture. Both pictures are important in order to describe the quantum phenomena. Therefore, it is important to have a complementarity mode of description that incorporates these two kinds of experimental evidence, without needing to change the existing mathematical tools. This point is crucial in Bohr's discussion with Einstein, as we will see below.

Here we have a quantum system that cannot be described in the same way as the classical system. Each experimental set-up allows the observation of one of two non-commuting pictures. But we have a classical language that is essential to present an unambiguous description of the quantum system. To illustrate this point, Heisenberg told a story about a discussion between Bohr, Bloch, Carl Friedrich [v. Weizsäcker] and himself. They were on a skiing holiday. One night, while washing the dishes after supper, they were discussing the importance of language in scientific discourse. The discussion reached a peak, at which point Bohr said:

> Our washing up is just like our language. We have dirty water and dirty dishcloth, and yet we manage to get the plates and glasses clean. In language, too, we have to work with unclear concepts and a form of logic whose scope is restricted in an unknown way, and yet we use it to bring some clarity into our understanding of nature. (Heisenberg 1972, p. 137)

In this simple paragraph, Bohr summarised his idea of an unambiguous language. He accepted that our daily language and the need for unambiguous communication forces us to use classical concepts to express concepts alien to classical physics by using complementary pictorial techniques:

> For this purpose, it 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. (Bohr 1949, p. 209)

In classical physics language, we have two pictures: waves and particles. Both of these pictures are important to the quantum system. Here comes Bohr's bright idea: complementarity.

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[14] Even now, it is not clear that we can have such a set-up. The current experiments related to quantum optics that are claimed to have such a combination are, to say the least, controversial.

This complementarity can be expressed at all these levels: complementarity between two experimental set-ups, complementarity of modes of description, and complementarity of pictures combining the two classical pictures in presenting the quantum system: waves and particles. In sum, such a model is a phenomenological model. The only missing element is the mathematical expression. This, as Bohr argues, can be found in the uncertainty principle.

Bohr wanted to relate complementarity to Heisenberg's bright idea of uncertainty. He did not accept Heisenberg's way of representing uncertainty. Nevertheless, he was very enthusiastic about it, to the extent that he sent a copy of Heisenberg's paper to Einstein with a letter, wherein he said: 'This article probably marks a very momentous contribution to the discussion of the general problems of quantum theory.' Here Bohr chose the phrase, 'the general problems of quantum theory,' precisely because he thought of the uncertainty principle, as it was formulated by Heisenberg, as a theoretical contribution to the language of the quantum theory which would help it overcome some of its disadvantages in contrast to the clarity of classical theory. Bohr added:

> Through [Heisenberg's] new formulation we are given the possibility to harmonize the demand for conservation of energy with the wave theory of light, while in accord with the nature of description, the different sides of the problem never come into appearance simultaneously. (Bohr to Einstein, April 1927, in Folse 1985, p. 97)

Here, it is clear that Bohr wanted to have the uncertainty principle as a theoretical tool connected to his idea of complementarity [i.e., the mathematical element in his "theoretical description" (phenomenological model)]. Yet, the important point for Bohr was the way such an element ought to be brought into the picture. He accepted that the experimental evidence, and not any theoretical justification, was what lead to belief in the use of the uncertainty principle. Speaking about Heisenberg, Bohr said:

> In particular, he has stressed the peculiar reciprocal uncertainty which affects all measurements of atomic quantities. Before we enter upon his results, it will be advantageous to show how the complementary nature of the description appearing in this uncertainty is unavoidable already in an analysis of the most elementary concepts employed in interpreting experience. (Bohr 1928, p. 92)

The uncertainty principle is the outcome of the complementarity picture (i.e., the picture that combines the two non-commuting instants: waves and particles), not the mathematical schemes. So, in his reconstruction of the uncertainty principle, Bohr started from the many experimental situations that would demonstrate the ultimate uncertainty of finding the value of any two complementary properties of the system. In this presentation, he insisted on the view that the uncertainty relation is an outcome of the "theoretical description" of the quantum system, such as in this statement:

> 'the essence of this consideration is the inevitability of the quantum postulate in the estimation of the possibilities of measurement.' (Bohr 1928, p. 98)

This would be demonstrated by the different ways the accuracy of measurement of position or momentum might be affected by the measuring equipment. About the relation between momentum measurement and position measurement, Bohr said:

> Just this situation brings out most strikingly the complementary character of the description of atomic phenomena which appears as an inevitable consequence of the

> contrast between the quantum postulate and the distinction between object and agency of measurement, inherent in our very idea of observation. (Bohr 1928, p. 103)

Bohr accepted that in the case of different experimental conditions, 'however far the phenomena transcend the scope of classical physical explanation,' we need to use classical terms in describing the phenomena. He accepted that the classical concepts were sufficient tools. In this he was exhibiting another feature of his realism. It is possible to use any previously accepted tools in physics in order to represent a physical phenomenon. Bohr employed the classical concepts in order to present unambiguous complementary pictures which exhausted all possible information about the object (i.e., the information produced by the different experimental set-ups which implies that the quantum system behaves as particles in particular cases and as a wave in others). In Bohr's words:

> [Consequent] evidence obtained under different experimental conditions cannot be comprehended within a single picture, but must be regarded as complementary in the sense that only the totality of the phenomena exhausts the possible information about the objects. (Bohr 1949, p. 210)

For Bohr, complementarity was the only way to exhaust the information about the quantum phenomena.

However, although complementarity was presented as an unambiguous solution to the phenomena in the quantum world, it generated deep confusion in both the physics and philosophy communities.[15] Even Heisenberg, who believed that he and Bohr agreed that the uncertainty principle was a special case of the more general complementarity principle, said in 1959 that the complementarity principle

> has encouraged the physicists to use an ambiguous language, to use the classical concepts in a somewhat vague manner in conformity with the principle of uncertainty… When this vague and unsystematic use of the language leads into difficulties, the physicist has to withdraw into the mathematical scheme and its unambiguous correlation with the experimental facts. (Heisenberg 1959, p. 154)

It should be stated at this point that while the uncertainty principle[16] is a mathematical relation which puts an epistemic limitation on what can be measured in principle in quantum mechanics from two non-commuting observables, the complementarity principle acknowledges the importance of using both "observables" in describing the quantum mechanical systems.

As any quantum mechanics textbook will explain, the relation between any two non-commuting observables is given by a general commutative relation {if $[A, B] \neq 0$ then A and B are said to be non-commuting}, which expresses the general idea of not being able to ascribe an exact measured value to two observables represented by non-commuting operators at the same time. The wave-particle duality, or let us say the relation between the position operator and momentum operator, will be just one of many, and it will have no

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[15] Many philosophers have discussed this point. See, for instance, Folse (1985), Howard (1993), Beller and Fine (1993), and Krips (1987).

[16] Here I do not want to enter into a fundamental debate about the uncertainty principle and its role in quantum mechanics, but only point out that there are many ways in which it is possible to get around the limitations imposed by the uncertainty principle to get readings of two non-commuting observables. See the work of Busch (1987) and also the experiments conducted by Chiao et al. (1993), Kwiat et al. (1990, 1992, 1993), Greenberger and Yasin (1988, 1989), Greenberger et al. (1990, 1993), Ghose et al. (1991), and Home and Kalayerou (1989) in relation to the principle.

special place as a quantum postulate. In quantum mechanics, if you pick any two observables, the possibility of them being non-commutative is high. In a 1963 interview Wigner reported that after the Como lecture, von Neumann said: “Well, there are many things which do not commute and you can easily find three operators which do not commute” (quoted in Jammer 1966, p. 354). Bohr knew this fact and was not addressing it in his lecture. His aim was not to address the mathematical schemes of quantum mechanics, but rather to understand how to provide “theoretical descriptions” of quantum systems.

The problem that motivated Bohr to adopt the complementarity principle as a solution to the wave-particle duality might not mean anything from an anti-realist or instrumentalist point of view. An anti-realist or instrumentalist would not care about the underlying ontology of the quantum world, but would be concerned about the extent to which the mathematical scheme was successful in finding empirical results. He or she would be concerned merely about the empirical adequacy of the mathematical (theoretical) scheme. However, this issue is important for a realist because it might differentiate between an acceptable representation of nature and one merely driven by theoretical motivations and not representative of nature.

Hence, if Bohr had been an anti-realist, he could have adopted a position similar to that of Heisenberg and need not have troubled himself with the issue of presenting a clear description of the quantum phenomena. But Bohr’s extreme interest in this issue revealed his priorities. Let us now turn our attention to the next points in Bohr’s philosophical position: natural phenomena and physical reality.

3.3 Natural Phenomena

Bohr had a distinct concept of phenomena. He was one of the first physicists/philosophers to clearly indicate that the concept of phenomena in physics differs in a seminal way from that used in the philosophical tradition. Bohr clearly dissociated himself from the Machian ideas of phenomenalism (see Faye 1991). Furthermore I think that Bohr also was aware of the importance of dissociating himself from the German tradition of phenomenology. Bohr tried over and over throughout his work to clarify what he meant by phenomena. Toward the end of his article, “Discussion with Einstein” (1949), where he tried to condense his arguments for an interpretation of quantum mechanics, he pointed to this explicitly:

> Meanwhile, the discussion of the epistemological problems in atomic physics attracted as much attention as ever…. In this connection I warned especially against phrases often found in the physical literature, such as ‘disturbing of phenomena by observation’ or ‘creating physical attributes to atomic objects by measurements’. Such phrases, which may serve to remind of the apparent paradoxes in quantum theory, are at the same time apt to cause confusion, since words like ‘phenomena’ and ‘observation’, just as ‘attributes’ and ‘measurements’, are used in a way *hardly compatible with common language and practical definition.* (Bohr 1949, p. 237, my emphasis)

He went on to discuss a point which he thought was more puzzling: phenomena, saying:

> As a more appropriate way of expression 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. (Bohr 1949, pp. 237–238)

Bohr's concept of a phenomenon was related to the whole experimental arrangement. Take for example Bohr's favourite example, the electron behaving as a wave. In this case, Bohr would say that the natural phenomenon "electron behaving as a wave" would occur "only if an experimental set-up so and so is in place." The natural phenomenon here is: "the electron behaves as a wave in the case of a certain experimental set-up." Then, the description of a phenomenon would need more than a mere description of an empirical result.[17] Hence, a mathematical scheme that would yield the empirical result would not be sufficient as a description of the phenomena. The experimental conditions are crucial in building the model:

> It is certainly more in accordance with the structure and interpretation of quantum mechanical symbolism, as well as with elementary epistemological principles, to reserve the word 'phenomenon' for the comprehension of the effects observed under given experimental conditions.
>
> These conditions, which include the account of the properties and manipulation of all measuring instruments essentially concerned, constitute in fact the only basis for the definition of the concepts by which the phenomenon is described. (Bohr as quoted in Folse 1985, pp. 157–158)

A phenomenon, according to Bohr, is not to be interpreted without the whole experimental set-up and the concepts related to it. In the case of Bohr's example, "electron behaves as a wave," the electron will exhibit the wave aspect only if the experiment is set up in such a way as to allow the electron to exhibit the wave aspect. There might be a different set-up which prevents the possibility of the occurrence of the wave aspect. If this happens, then Bohr would conclude that these two set-ups are "mutually exclusive experimental arrangements."

Bohr accepted that the "theoretical description" was a real representation of the natural phenomena and that the elements described were elements of those phenomena. For him every element in the mathematical formalism of the "theoretical description" should have a counterpart in physical reality. In the case at hand, he would say that the "theoretical description"—which represents the phenomenon of 'electron behaving as a wave' with the experimental set-up that produces such a phenomenon—is a real representation of the natural phenomenon, and every element in the description refers to its counterpart in reality: a real electron, wave-like behaviour, and so on.

Bohr believed that there were electrons, as well as photons and other quantum particles, and therefore certain attributes should be assigned to them. Moreover, he believed that the quantum mechanical phenomena related to the electrons could give two mutually exclusive attributes to the electrons (particles and waves); he accepted that all possible outcomes related to electrons must be part of any complete description of the quantum mechanical system. Therefore, he asserted that complementarity might help in capturing these two descriptions in one complete description of the quantum system. In his words:

> phenomena defined by different concepts, corresponding to mutually exclusive experimental arrangements, can be unambiguously regarded as complementary aspects of the whole obtainable evidence concerning the object under investigation. (Bohr 1938, pp. 24–25)

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[17] An implicit premise here is the acceptance of instrumentalists that mathematical schemes yield successful empirical results; for that, it would be a successful description.

Bohr thought that human intervention was crucial in dictating the experimental set-up of a phenomenon; nevertheless, he wanted an objective criterion for defining a phenomenon. Physics ought to be ‘independent of individual subjective judgement and therefore objective.’ But Bohr was very much aware that some of the methods in physics would probably not be able to provide objective knowledge in the sense of ‘corresponding’ to the world as it is, for all physics knowledge is fallible and likely to change:

> Only by our experience itself do we come to recognize those laws which grant us a comprehensive view of diversity of phenomena. As our knowledge becomes wider, we must always be prepared, therefore, *to expect alterations in the point of view best suited for ordering of our experience*…. The great extension of our experience in recent years has brought to light the insufficiency of our simple mechanical conceptions and, as a consequence, has shaken the foundation on which the customary interpretation was based, thus throwing new light on old philosophical problems. (Bohr 1934, pp. 1–2)

In this sense, even quantum theory would be one of the ordering schemes in which we should be prepared to expect alteration.

Folse indicates such understanding of Bohr’s conception of phenomenon; he asserts that Bohr does not use the term “phenomena” in the usual sense and that he “considers the entire experiment from preparation to detection to be a single phenomenon.” The quantum mechanical description[18] “allows us to understand the single phenomenon which is the whole experiment from preparation to detection” (Folse 1993, p. 132). Or, to put it better, in the master’s own words:

> As a more appropriate way of expression, one may strongly advocate limitation of the use of the word phenomenon to refer exclusively to observations obtained under specific circumstances, including an account of the whole experiment. (Bohr 1948, p. 317)

3.4 Realism

Bohr’s philosophical grounds were those of a realist. Nevertheless, Bohr accepted that some theoretical concepts were not realisable. These are elements of high-level theoretical representations. I agree with Folse that there is an anti-realist tendency in Bohr’s writing connected to his instrumental attitude toward theories:

> Thus this ‘instrumentalist’ tendency in complementarity could support characterising Bohr as an anti-realist with respect to theories. But this form of anti-realist does not compromise Bohr’s robust realism with respect to the reality of atomic systems. (Folse 1986, p. 102)

Folse asserts that Bohr’s realism is ‘entity realism,’ i.e., that Bohr was a realist in regard to the existence of the quantum entities. I think that Bohr’s concept of realism went beyond “entity realism;” to him, the theoretical descriptions were representations of nature. Hence, he accepted that theoretical representations could be representative of nature, but only those terms that might potentially be referring beyond the “theoretical description.” In his reply to the 1935 Einstein–Podolsky–Rosen paper (EPR) as we shall see in the next section, he insisted on accepting their reality criterion, but he re-phrased it to say that every

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[18] This consists of the atomic object, the preparation, the quantum theory, the interaction and complementarity.

element in the quantum mechanical description—as opposed to quantum theory—should have a counterpart in physical reality. Bohr was a realist in relation to both the existence of elementary particles and atomic structure. This means that, for Bohr, the models described the natural phenomena and represented them.

In order to understand his insistence on the relation between the elements of reality and theoretical description, we ought to look at Bohr's understanding of knowledge. Bohr asserted that it was important to understand knowledge in the proper context:

> …For objective description and harmonious comprehension it is necessary in almost every field of knowledge to pay attention to circumstances under which evidence is obtained. (Bohr as quoted in Beller 1992, p. 147)

He thinks that knowledge is obtained by a process of interaction between natural phenomena and experience. Knowledge is objective only to the extent that humans can communicate it in an unambiguous way. In Bohr's words:

> The lesson of atomic physics has been that we are not simply co-ordinating experience arranged in given general categories for human thinking, as one might have liked to say in expressions of physical philosophy, but we have learned that our task is to develop human concepts to find a way of speaking which is suited to bringing order into new experience and, so to say, being able to put questions to nature in a manner in which we can get some help with answer. (Bohr, a transcript of Compton Lectures 1957, quoted in Folse 1985, pp. 235–236)

Our task is to develop concepts that bring order to new experience, and to state the right questions, that is, the question for which nature can help in finding answers. The relation between theoretical description and empirical observation can "lead to the recognition of relations between formally unconnected groups of phenomena." When such recognition occurs, it

> "demands a renewed revision of the presupposition for the unambiguous application of even our elementary concepts." (Bohr 1938, p. 28)

In another place, Bohr makes an even stronger claim:

> The main point to realise is that all knowledge presents itself within a conceptual framework adapted to account for previous experience and that any frame may prove too narrow to comprehend new experience. Scientific research in many domains of knowledge has indeed time and again proved the necessity of abandoning or re-moulding points of view which, because of their fruitfulness and apparently unrestricted applicability, were regarded as indispensable for rational explanation. (Bohr 1958, pp. 67–68)

These revisions are associated with developments in science which contribute to the "clarification of the principle underlying human knowledge" (Bohr 1937, pp. 289–290). The new experience should be established on an objective basis. This needs a new 'means of communication' that can represent it in an unambiguous way. Let us recall the way Bohr understood objectivity, whereby humans are simultaneously spectators and actors.

Moreover, Bohr accepted that our descriptions of physical objects reveal the internal properties even if these internal properties are not directly observed. Bohr says that:

> in fact all our knowledge concerning the internal properties of atoms is derived from experiments on their radiation or collision reactions, such that the interpretation of

> experimental facts ultimately depends on abstractions of radiation in free space and free material particles. Hence our whole space-time view of physical phenomena, as well as the definition of energy and momentum depends ultimately on these abstractions. (Bohr 1927, p. 112)

Let us examine Bohr's use of abstraction here. He concentrated only on elements directly related to the physical phenomena. It is obvious here that Bohr presented a realist perspective on the relation between our knowledge and nature. He clearly indicated that our abstract presentation of nature is related to real elements of reality.

Moreover, Bohr dismissed Machian scepticism of what might be known about atoms:

> We know now, it is true, that the often expressed scepticism with regard to the reality of atoms was exaggerated; for, indeed the wonderful development of the art of experimentation has enabled us to study the effects of individual atoms.
> However, at the same time as every doubt regarding the reality of atoms has been removed and as we gained a detailed knowledge of the inner structure of atoms, we have been reminded in an instructive manner of the natural limitation of our forms of perception. (Bohr 1934, p. 103)

Hence, Bohr undoubtedly believed in the reality of atoms. Nonetheless, we ought to be careful about Bohr's reality concept when he insisted on renouncing an independent reality in favour of a reality of "actors and spectators at the same time." In his words:

> an independent reality in the ordinary physical sense can neither be ascribed to the phenomena nor to the agencies of observation. (Bohr 1928, p. 89)

Before turning to the debate between Bohr and Einstein, it is important to comment on Folse's position. It is very difficult to distinguish my position from that of Folse in brief, because basically we both insist that Bohr cannot be understood as an anti-realist. We agree that Bohr's realism was different from conventional realism. Yet, although Folse agrees that Bohr had a distinct concept of phenomena, he dismissed a phenomenological interpretation of Bohr. Folse based his position on Bohr's rejection of the standard phenomenalist position (Folse 1985, pp. 227–241). I think that all the points raised by Folse can be easily reinterpreted in a way that gives a clearer understanding of Bohr's position by accepting that Bohr was a phenomenological realist. Let me give an example, Folse says:

> Bohr holds that in describing experience, the task of science is to bring order into an ever growing range of phenomena. From the definition of the state of an isolated system derived from theoretical formalism, we make predictions about the phenomena which will be experienced by describing them as observational interactions between observing instruments and microsystems. When theoretical predictions are confirmed by experienced phenomena, we regard the theoretical description as adequate. (Folse 1985, p. 228)

Here Folse presents Bohr as if he started by accepting theoretical formalism and theoretical prediction, and then searched for confirmation of such prediction in order to count the theoretical description as adequate. This is directly opposite to Bohr's process. As I already indicated, the process of doing theoretical physics is essential in presenting an adequate theoretical description of the physical systems. Bohr exhausted great efforts to reconstruct Einstein's arguments precisely because he was beginning from theoretical predictions and theoretical formalism. Hence, if I were to present the same statement on the relation between theory and the adequacy of theoretical description, I would put it as follows:

> *Bohr holds that in describing experience, the task of science is to bring order into an ever growing range of phenomena. Depending on the facts collected from our experience of the phenomena and our observations, we look for the best possible instruments derived from theoretical formalism that can help in describing the observational interactions between observing instruments and Microsystems, and present a theoretical description that can make predictions about the phenomena under study. When theoretical predictions are confirmed by experienced phenomena, we regard the theoretical description as adequate.*

Here, it is clear that the difference between the two statements is the point of departure and the process whereby the theoretical description is formalised. The way Folse articulated his statement led him directly into presenting Bohr as an instrumentalist: "Bohr's viewpoint appears in Bohr's strong insistence that we cannot visualize through wave and particle pictures the properties of an atomic system which produces the phenomena that confirm quantum theory, Bohr is led into making claims with which any instrumentalist would agree." Then he quoted Bohr saying: "we agree here in a new light the old truth that in our description of nature the purpose is not to disclose the essence of the phenomena but only to track down, so far as it is possible, relations between the manifold aspects of our experience" (Folse 1985, p. 228). Folse interpreted this quote in the light of his line of argumentation as "certainly compatible with anti-realism," although he continued to say that such interpretation is "not consistent" with Bohr's concept of complementarity.

The quote from Bohr can be interpreted in a different way. If we accept that Bohr's "phenomenon" is the whole experiment from preparation to detection, and that there is nothing behind the phenomenon, then his statement "not to disclose the essence of the phenomena" would be a direct consequence of such a position. Hence such a statement would not imply an instrumentalist position.

I fully agree with the rest of Folse's argument highlighting the point that I started with, i.e., that Bohr's theorizing was derived from the facts of nature: "[Bohr's] arguments are *never* based on purely mathematical reasoning from the theoretical formalism, but always are derived from what he regarded to be a fact of nature" (Folse 1985, p. 229). We can see clearly the difference between this statement and the previous one.

Having presented Bohr's philosophical grounds, let us turn to the Bohr–Einstein debate, which has prompted an industry of papers and yet is still an unsolved puzzle. I will try here to understand it from the perspective of Bohr's being a phenomenological realist. I think that such a position would help to resolve many misunderstandings and a lot of vague points associated with the heated discussions on the issues of the debate.

4 The Debate

The first round of the debate took place during the 1920s. Two versions of quantum theoretical models existed: Schrödinger's wave mechanics and matrix mechanics. At the time, the compatibility between the two formulas was not known. Bohr and Heisenberg worked on a daily basis to resolve the non-compatibility between these two schemes. While Heisenberg's concern was to find the mathematical compatibility, Bohr's worries were much deeper. He needed to understand how it was possible to have two such schemes to express one and the same physical system. The main point was to arrive at an unambiguous understanding of the physical system. Bohr found a solution through his presentation of complementarity, while Heisenberg wrote his paper on the uncertainty principle.

Bohr's theorising technique stems from the phenomenological and experimental level, but in 1927 the experimental information gave theoretical physicists a very shallow picture of the quantum world. The main experiments which had an impact on the theoretical debate were the Stern–Gerlach effect in 1922 and the Compton experiments in 1924. This left theoretical physicists open to a different type of game: that of suggesting and debating hypothetical situations in which quantum mechanics should be applied, and trying to figure out if the answer given for these hypothetical situations was satisfactory from a theoretical point of view.

Einstein was not happy with either the uncertainty principle or the complementarity principle. He thought that in spite of the mathematical accuracy of quantum mechanics and its agreement with (a handful of) experiments, it could not be considered as a complete theory. For him, there had to be another theory that would give the same level of accuracy in mathematical results, but without the related philosophical jargon.[19]

In his attempt to disprove quantum mechanics, Einstein tried hard to suggest thought experiments that would demonstrate the incompleteness of quantum mechanics. For him, a theory was complete only if it could account for every element in physical reality.

Einstein's concern was related to the coherency between the new theory and previously accepted physics theory. As Arthur Fine argues in his book, *The Shaky Game*, Einstein's criticisms of quantum theory during its early years were expressed in five points. These are:

> (1) the equations of the theory are not relativistically invariant; (2) it does not yield the classical behaviour of macroscopic objects to a good approximation; (3) it leads to correlations among spatially separated objects that appear to violate action-by-contact principles; (4) it is an essentially statistical theory that seems incapable even of describing the behaviour of individual systems; and (5) the scope of the commutation relations may not in fact be so broad as the theory supposes. (Fine 1986, p. 28)

It is clear from this list that Einstein's concern was with what type of theory quantum mechanics was, and whether it would be compatible with other fundamental theories. Here Einstein viewed mathematical formalism as the major element in the theory. This standpoint motivated his construction of a series of thought experiments.

Bohr presented his recollection of the events of the first round of the debate in his contribution to Schilpp's 1949 volume,[20] *Albert Einstein: philosopher-scientist*. Einstein did not attend Bohr's presentation of his famous "Como lecture," but later that year they met in the fifth Solvay conference. Einstein started the debate, according to Bohr's reconstruction, with a very simple experimental set-up:

According to quantum theory, in the case of a single slit between a source and a photographic plate, if a particle is shot at the slit, the theory cannot provide an accurate prediction of the exact point at which the particle will hit the photographic plate. The best it can provide is a probabilistic percentage for the particle to hit any given region. In this case, there will be agreement between the theory and the experiment if the experiment is repeated a sufficient number of times. Einstein pointed out that if in a single given experiment, the particle is recorded at point (A) on the plate, this directly leads to the impossibility of observing any effect of that particle at any other point (B) which lies at a

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[19] For a discussion of Einstein's position see Fine (1986).

[20] Bohr (1949, pp. 201–241).

distance from (A). This would create a contradiction: The theory predicts that there is a possibility that the particle will hit (B), while if the particle was found to be at (A), then it is impossible that any trace of the particle can be found at (B). According to Bohr, Einstein's main concern was that the 'causal account in space and time' was abandoned.

Here Einstein raised two points: one was about the statistical nature of the experimental set-up and whether this statistical nature was associated with the system itself or with the description of the system. Einstein wanted to maintain that the statistical nature ought to be similar to that occurring in classical situations. He thought that quantum mechanics with its statistical nature left plenty of questions unanswered, especially the question of defining the exact energy and momentum of the particle at all times. He thinks that there ought to be a "fuller description of the phenomena" which can "bring into consideration the detailed balance of energy and momentum in individual processes" (Bohr 1949, p. 213). That is to say, the particle could have a definite position with a definite energy, while at the same time having a precise momentum. This brings us to the second point: the wave-particle duality and how the theory constrains ascribing both the particle aspect and the wave aspect to the system at the same time. Einstein asserted that any theory that could not ascribe both aspects to the system at the same time could not give a full description of all the elements in physical reality.

Bohr replied to Einstein's arguments, beginning, as he usually did, by reconstructing the whole argument; he started by stating the experimental set-up and analysing whether it was consistent, given the quantum postulate, to accept such argument. In this simple case, Bohr stated that the experimental set-ups that might provide information about the position and the momentum of the particle were, in fact, different. He explained that two possible set-ups existed.

The first would provide the basis for the phenomenon 'particle behaving as a wave.' In this phenomenon, when the particle interacts with the slit, it will undergo a change of momentum (Δp) which, according to the uncertainty principle, would make it impossible to find the energy of the particle. This means that the experimental set-up would exhibit latitude in the location of the particle. If the particle is behaving as a wave, this means that there is a possibility that it might hit the photographic plate at any point within a given region. But at the moment of measurement of the particle (where it hits the photographic plate), there would be another interaction between the particle and the measuring instrument, and at that point the particle would behave as a particle.

Now the model of the phenomenon 'particle behaving as a wave' uses tools from quantum mechanics to give us a general prediction of where the particle might hit the photographic plate. But also it contains a description of the experimental set-up and the story that tells why the particle behaves like a wave after interacting with the slit and how the particle alters its momentum when interacting with the slit. The story also tells us how we can detect that the particle is really behaving as a wave. This detection is not done on a single-experiment basis but on a set of experiments. Now Einstein said that in a single experiment, the theory could not give us a description of both the wave and the particle aspects of the particle. Bohr answered this by saying that what counted was not the theory but the model which described one of the two aspects at a time. And because it is a model of the phenomenon 'particle behaving as a wave,' it need not account for any other phenomenon like 'particle behaving as a particle.' Also, the statistical nature of the model is not associated with the quantum theory but, according to Bohr, with the ability to detect experimentally the wave behaviour of the particle.

The second set-up suggests a shutter in front of the slit. In this case, the interaction between the shutter and the particle would allow additional latitude in the kinetic energy of the particle. This set-up has an uncertainty in the energy ΔE. Then, in accordance with the uncertainty relation, there is a latitude in the exact time when the particle interacts with the shutter (the outcome of such an interaction would be $\Delta E \Delta T \approx h$).

Einstein's question was to what extent we can control our knowledge of the momentum and energy so that we would obtain a specification of the state of the particle after passing through the slit. Bohr, in reply, claimed that:

> As soon as we want to know the momentum and energy of these parts [the shutter and the diaphragm] of the measuring arrangement with an accuracy sufficient to control the momentum and energy exchange with the particle under investigation, we shall, in accordance with the indeterminacy relations, lose the possibility of their accurate location in space and time. (Bohr 1949, p. 215)

In the case presented by Einstein, it was the assumption that both the diaphragm (with the slit) and the plate had a well-defined position that would not allow, in accordance with quantum mechanics, an exact prediction of the point where the particle might hit the plate. However, if in a similar case we have a sufficient latitude in knowing the position of the diaphragm (with the slit), then it is possible (in principle) to control the interaction between the slit and the particle. This would lead to the possibility of predicting the path of the particle from the slit to the plate.

Although this experimental arrangement is very simple and was familiar to physicists working in the field at that time, Bohr's first reaction to Einstein's example was to say that he could not understand what Einstein meant. The notes taken by Kramers and kept in Bohr archives show that Bohr's reply to Einstein's simple objections started by saying: 'I feel myself in a very difficult position because I don't understand what precisely is the point which Einstein wants to [make]. No doubt it is my fault.'[21]

What Bohr did not understand was not the experiment, but the process in which the experiment was presented. Einstein complained about the theory while Bohr's own concern was the description. Because of that, Bohr insisted on reconstructing the whole setting every time he wanted to reply to any of Einstein's critiques. He accepted that each particular experiment had its own description—its "individuality." So, in every case, he needed to explain the detailed circumstances related to that case and how it was possible to construct the related quantum mechanical description.

In this particular case, after explaining in detail the experimental and phenomenological facts (i.e., the way the experiment was set up and the way the particle would react to the different set-ups: e.g., the loose diaphragm versus the fixed one), he asserted that in the quantum mechanical description,

> we have to deal [..] with a two-body system consisting of the diaphragm as well as the particle, and it is just with an explicit application of conservation laws to such a system that we are concerned in the Compton effect where, for instant, the observation of the electron by means of a cloud chamber allows us to predict in what direction the scattered photon will eventually be observed. (Bohr 1949, p. 216)

It is clear that this quantum mechanical description is pretty much related to the experiments at hand. Here Bohr does not talk about the quantum formalism; rather his concern is how to capture the intuition behind the experiment and what would be in fact possible to be performed experimentally. Moreover, Bohr insisted that these two experimental set-ups, the one with fixed diaphragm and the one with loose diaphragm, were

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[21] In Pais (1991, p. 318).

mutually exclusive. For him this point ‘clearly brings out the complementary character of the phenomena’ (Bohr 1949, p. 215).

Einstein took the debate a step further and suggested another simple argument: It should be possible to suggest an experimental set-up in which it would be possible to measure through which of the two holes the particle entered. Here we see the theory-driven attitude of Einstein at its best. He asserted that the framework of contemporary physics does not accept that the act of observation affects the observed system in a way which we cannot control. The ultimate challenge is to plot the set-up that might give us the exact knowledge without affecting the observed object in an uncontrolled way. He suggested the following experiment.

In the last suggested set-up, another diaphragm with two slits was installed between the first diaphragm and the photographic plate. An electron source (or photon source) would emit electrons to the first diaphragm (with one slit). Then the output electrons’ beam would target the second diaphragm (with two slits), lying at a distance d from the first diaphragm. This distance was at most twice the electrons’ beam wavelength. If the first diaphragm were fixed, quantum mechanics predicts that the outcome on the screen would exhibit an interference pattern.

Einstein proposed supporting the first diaphragm with a spring which could be affected by the slightest movement of the diaphragm. The momentum exchange between the particle and the first diaphragm would, presumably, define the position of the particle at that point, and then decide through which of the two slits it would pass toward the screen without distorting the interference pattern. In his reply, Bohr used the uncertainty principle in the case of position and momentum to prove that the first diaphragm would be affected. The change in momentum of the diaphragm would eventually change the position by an unknown factor; the more precise the momentum measurement, the less we can predict the position of the slit. That affects the interference on the photographic plate by a factor equal to the uncertainty in the position of the first diaphragm.

Einstein’s other experiments suggested in that period evolved within the same argumentation, even if they were more complex in form. One of these other experiments, which was suggested in 1930 at the sixth Solvay congress, was the clock in a box with a radioactive source, even though Einstein tried to use a complex line of argumentation, deploying the special theory of relativity. Once more Bohr’s reply used the uncertainty principle to prove the impossibility of finding two non-commuting variables simultaneously (in this case, time and energy). The last attempt in this first round was made in a very short paper published in *Physical Review* in 1931, entitled ‘Knowledge of Past and Future in Quantum Mechanics’[22] with Tolman and Podolsky, using concepts from the theory of relativity.

4.1 The EPR Paper

After a long period of silence, Einstein started the second round. In this round, he refined his strategy and made it more complex. His paper written in collaboration with Podolsky and Rosen (EPR), entitled “Can quantum-mechanical description of the physical reality be considered complete?”, concentrated on the question of the ability of quantum theory to represent the physical reality.

The paper used Einstein’s style of theorising, i.e., going from theory to experiment. In their attempt to prove the incompleteness of quantum mechanics, the writers started by laying out their philosophical position on the nature of “physical reality”:

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[22] Einstein et al. (1931, pp. 780–781).

(1) In a complete physical theory, "*every element of physical reality must have a counterpart in the physical theory.*" [The condition of completeness]
(2) In any physical theory, "the elements of the physical reality cannot be determined by a priori philosophical consideration, but must be found by an appeal to the results of experiments and measurements." [The empirical assumption]
(3) Regarding the second point, "*If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.*" [The reality criterion] (Einstein et al. 1935, p. 777)

The EPR writers tried to prove a contradiction between the condition of completeness and the reality criterion. To this end, they suggested a thought experiment which allows one of two conclusions:

> "either (1) the description of reality given by the wave function in quantum mechanics is not complete, or (2) when the operators corresponding to two physical quantities don't commute the two quantities cannot have simultaneous reality." (Einstein et al. 1935, p. 778)

The paper has continued to prompt many discussions and papers up until now.[23] Hence, I do not want here to go into a detailed description of the paper, or enter into a debate as to whether its presentation was right or wrong.[24] Instead, I will present its basic argument in a nutshell before turning my attention to Bohr's reaction to it.

Basically the EPR argument goes into detailed theoretical representation of the quantum theory to prove that it is incomplete, because it fails to give a theoretical account of two non-commuting physical attributes of a particle at the same time: position and momentum. The premise is a system where two particles, A and B, interact for a specific time and then emit in two different directions. Theoretically, if we perform a position measurement on A, then we can conclude the position of B (assuming that the source is located at the origin). Similarly, if we perform a momentum measurement on A, then we can conclude the momentum of B. If we run such measurements on A and not on B, then we do not in any way "disturb" B. Moreover, the measurement of position on A informed us that there exists an element of physical reality: "position of the particle B." Similarly, measuring the momentum on A informed us that there exists an element of physical reality: "momentum of the particle B." In other words, particle B definitely has two elements of physical reality: position and momentum. Since we did not disturb B, the theory ought to be able to represent these two elements of physical reality at the same time in its formalism. Quantum mechanics fails to do so; therefore, quantum mechanics is incomplete.[25]

4.2 Bohr's Reply

The first important remark on Bohr's reply is that it did not contain any mathematical formalism in the main body, except the uncertainty relation (p. 697). His comments on the deduction presented in the EPR was tucked away in a footnote. His problem was not with the formalism or whether the theory was complete.

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[23] See for instance Landsman (2005) and the references therein, Fine (2004), Halvorson and Clifton (2001), and Dickson (2001).

[24] Dickson (2001).

[25] A more general discussion of EPR can be found in Fine (1986, Chap. 3).

Here, as in his previous replies to Einstein, Bohr went back to discuss the basic ideas of quantum mechanics in an attempt to mount what could be considered an "adequate" argument corresponding to the actual situation. Such an argument should, from Bohr's perspective, revolve around the understanding of complementarity.

His first reaction toward the EPR paper was that it was ambiguous and the authors were not clear about what they wanted. As his assistant Rosenfeld recollects, when Bohr heard about the paper, he put all other work aside and sat down to construct an answer. As Rosenfeld recalls:

> A new worry could not come at less propitious time. Yet, as soon as Bohr heard my report of Einstein's argument, everything else was abandoned: we had to clear up such misunderstanding at once. We should reply by taking up the same example and showing the right way to speak about it. In great excitement, Bohr immediately started dictating to me the outline of such reply. Very soon, however, he became hesitant: "No, this won't do, we must try all over again… we must make it quite clear…" So it went on for a while, with growing wonder at the unexpected subtlety of the argument. Now and then, he would turn to me: "What can they mean? Do you understand it?"(Rosenfeld 1967, p. 128)

Again and again, we see this great mind articulating his puzzlement with seemingly simple arguments: 'What can they mean? Do you understand it?' Despite all his effort, he could not build an argument using the same example: 'No, this won't do, we must try all over again.' He returned to his usual technique in order to present a clear reply: reconstructing the whole argument, flipping it, so to speak, and going from experiments to theoretical representation, rather from theory to experiment.

Bohr argued that the EPR thought experiment didn't meet the situation occurring in the quantum world; their thought experiment could not be actualised. In his words, "The trend of their argumentation, however, does not seem to me adequately to meet the actual situation with which we are faced in atomic physics."[26] Therefore, he started by outlining a set of experimental procedures that occurs in atomic physics. Here he is saying: This is what we have experimentally; how can we describe such systems theoretically? In this sense, Bohr was thinking of the quantum mechanical description of physical reality. This description should be taken individually; we cannot by any means speak of all systems at all times; this classical concept is foreign to the quantum reality. Systems have their own individuality that is dictated by the experimental arrangement. The "symbolic representation" of such systems "will imply an uncertainty" in the properties that are being measured, and hence the "quantum-mechanical formalism is a direct consequence of the commutation relation for any pair of conjugate variables." (Bohr 1935, pp. 696–697)

Nonetheless, Bohr insisted on accepting the reality criteria: the elements of physical reality must have a counterpart in physical description regardless of our measurement. Here, it was essential from Bohr's point-of-view to renounce forever the classical conception of independent physical reality, in favour of a humanised physical reality. Our choice of the experimental arrangement will dictate what we can actually measure. Hence, merely by choosing to measure position, we renounce the possibility of finding an accurate value of the momentum. It is important here to understand that Bohr was not saying that

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[26] It is important here to note that the possibility of carrying out real experiments did not occur until after Bohm's (1952, 1957) reconstruction of the EPR to involve spins (up and down) rather than position and momentum, and Bell's (1964) suggestions. The real experiments started only in 1973, and the real breakthrough came with Aspect et al. (1982).

the system lacked the element of momentum, but that this element would not be able to exhibit itself in the chosen arrangement due to the inevitable interaction with the experimental apparatus.

After presenting many simple arrangements to demonstrate his ideas of “individuality,” “complementarity,” “quantum mechanical description” and his own insistence on considering the measuring instrument as part of the physical system, Bohr emphasised that:

> in the phenomena concerned we are not dealing with an incomplete description characterised by arbitrary picking out of different elements of physical reality at the cost of sacrifying other such elements, but with a rational discrimination between essentially different experimental arrangement and procedures which are suited either for an unambiguous use of the idea of space location, or for a legitimate application of the conservation theorem of momentum. (Bohr 1935, p. 699)

We rationally discriminate between different experimental arrangements. Our chosen intervention does not actualise the existence of an element of physical reality, but it does limit our ability to find its value. The choice of the experimental set-up will lead us to one of two possible outcomes:

> “we are, in the “freedom of choice” offered by the last [experiment] arrangement, just concerned with a discrimination between different experimental procedures which allow of the unambiguous use of complimentary classical concepts.” (Bohr 1935, p. 699)

We have the freedom to decide which element of physical reality we wish to measure. This decision must be taken before setting up the experiment, in order to take the interaction between the measuring apparatus and the quantum system into consideration. This situation is essential in quantum mechanics, and we must consider it as a part of the physical reality. The final representation of the physical reality must deploy the concept of complementarity. Since we are forced to renounce the ability to know the exact value of one of the two possible elements of physical reality in any given experimental situation, we need complementarity in order to present the whole description of the quantum system using our classical language. Here the complementarity is between these two experimental arrangements, which will force us into a complementarity in the quantum mechanical description in order to describe these two elements of reality.

Bohr’s next step was to combine the quantum mechanical description with the quantum formalism. He insisted that the quantum mechanical description was essentially complete. Such a description is “compatible” with the quantum theory formalism of the interaction between the object and the measuring instruments. Hence, the link with the theory is only because it is compatible with the description that is related to the experimental arrangements. As he said:

> On the contrary this description, as appears from the preceding discussion, may be characterized as a rational utilization of all possibilities of unambiguous interpretation of measurements, compatible with the finite and uncontrollable interaction between the objects and the measuring instruments in the field of quantum theory. (Bohr 1935, p. 700)

It is clear that Bohr does not care about the completeness of the theory itself but about the completeness of the ‘quantum mechanical description.’ This is the most important difference in terminology between EPR and Bohr. This difference exemplifies the different theorisation techniques adopted by the two giants. While EPR started with a theoretical statement: "Any serious consideration of a physical theory…," Bohr started with the quantum mechanical description, which is a low-level theoretical representation. Bohr assumed that it was a description of the phenomena at hand at the atomic level, consisting of the empirical data; the experimental setup; the measuring instruments; and the quantum mechanical formalism.

Bohr highlighted the importance of the measuring instruments as a part of the phenomena under study, saying:

> the action of the measuring instruments on the object under investigation cannot be disregarded and will entail a mutual exclusion of the various kinds of information required for a complete mechanical description of atomic phenomena issues ultimately from the ignorance of the reaction of the object on the measuring instruments inherent in any measurement. (Bohr, in Beller and Fine 1993, p. 5)

The last point made by Bohr involved a justification for changing our classical understanding in favour of a modern understanding. He reminded Einstein that his theory of relativity renounced the classical separation of space and time in favour of a space-time "system of reference." Hence, there was nothing strange or unacceptable about renouncing the classical concept of causality in favour of the notion of complementarity.

In conclusion: I have showed in this paper that Bohr was a realist of a special kind. Then I showed that the main difference between Bohr and Einstein was their treatment of the theoretical structure. While Einstein insisted on a top-down approach, Bohr adopted a bottom-up approach. I think that the spirit of the Bohr–Einstein debate is a debate between a structural realist[27] exemplified by Einstein and a phenomenological realist exemplified by Bohr.

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[27] Zahar (1988).

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