KANT AND BOHR ON QUANTUM OBJECTIVITY

HERNÁN PRINGE

Abstract. In this paper I will put forward an account of quantum objectivity along Kantian and Bohrian lines. Quantum objectivity will be distinguished from classical objectivity both regarding the objective validity and the objective reality of the concept of an object. While classical concepts enable the constitution of empirical data as objective experimental results, the concept of a quantum object plays rather a regulative role guaranteeing the systematic unity of classically described complementary phenomena. Based on this distinction, I will analyze the possibility of providing quantum theory with metaphysical principles in a Kantian sense.

Key-words: Bohr; Kant; metaphysics; objectivity; quantum theory.

INTRODUCTION

Kant radically puts into question the way in which we should conceive of the relation between knowledge and its object, by claiming the necessity of a so-called Copernican inversion. According to this new way of understanding the problem the object will no longer rule cognition, as if cognition must simply conform to it as a transcendent criterion. On the contrary, Kant claims that the object must conform to our cognition, insofar as the conditions that determine the objective character of knowledge are rather immanent conditions of knowledge itself. From a transcendental viewpoint, these conditions can be established *a priori*, and they are of two different kinds. On the one hand, there are conditions of the objectivity of knowledge, while, on the other hand, there are those of its systematic unity. Kant distinguishes accordingly constitutive and regulative principles of experience. Constitutive principles express the necessary and sufficient conditions to be fulfilled by any entity in order to pertain to nature or, in other words, to be an object of *possible experience*. These conditions make up a system of synthetic a priori judgments that delineates the limits of experience. Any empirical object must satisfy these conditions because otherwise it would not be an empirical object whatsoever. In other words, these transcendental principles *constitute* the objectivity

Hernán Pringe ✉
CONICET-UBA, Argentina / Diego Portales University, Chile

Rev. Roum. Philosophie, **67**, *2*, p. 247–265, București, 2023

of any empirical object[1]. In the second place, there are transcendental principles of *regulative* character. These principles do not render the objectivity, but the *systematic unity* of experience possible. Constitutive principles express what the objectivity of empirical objects consists in. Regulative principles establish rather how we must think of empirical objects in order to gain systematic knowledge of them[2].

In this paper I will try to show that these two kinds of transcendental conditions articulate Bohr's interpretation of quantum theory. We will see that the objectivity conditions underlie the classical character of the description of quantum phenomena, while those of the systematic unity of these phenomena underlie quantum objectivity. Based on this distinction, I will study the possibility of providing quantum theory with metaphysical principles in a Kantian sense. For this purpose, I will attempt to show how such principles may be gained from the application to the quantum case of the general principles of metaphysics of nature established by Kant.

This investigation is divided in ten sections. I will begin by introducing the keystone of Bohr's interpretation, the quantum postulate, in order to analyze from a transcendental perspective the consequences that follow from it (1). Then, I will study whether a quantum object is an object of possible experience in the Kantian sense (2). Later, I will consider the problem of the objectivity of experimental results in the quantum case (3). I will then discuss the connection between the quantum postulate and the viewpoint of complementarity (4). Then, I will establish the difference between quantum phenomena and quantum objects, and I will consider the transcendental function of the latter (5), as well as the problem of the relation of quantum objects to intuition (6). In section 7, I will show how the two transcendental demands of objectivity and systematic unity of knowledge shed light on the distinction between classical and quantum objectivity. In section 8, I will turn to the problem the metaphysical principles of quantum theory. I will then offer an example of such principles (9) and finally I will investigate the relation between the metaphysical and the mathematical principles of the theory (10).

1. THE QUANTUM POSTULATE

According to Bohr, the basic assumption of quantum theory is the quantum postulate. This 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"[3].

[1] These constitutive principles are the so-called "principles of pure understanding."

[2] Regulative principles belong to reason and to the reflecting power of judgment.

[3] Niels Bohr, *Atomic Theory and the Description of Nature,* Cambridge, Cambridge University Press, 1934, p. 53.

The statement of the discontinuity of quantum phenomena is nothing but the rejection of the law of continuity of all changes. This law states that a changing thing passes through all the infinite states that lie between the initial and the final state. Since this law is assumed to be invalid, there will be certain minimal transitions which will possess a magnitude that cannot be diminished any more. These transitions have an *individual* character, insofar as they cannot be reduced to more elementary transitions. The discontinuity of atomic processes enables us to establish a remarkable connection between transcendental philosophy and Bohr's interpretation of quantum theory.

According to Kant, the law of continuity expresses the form of all changes in general and, as long as it is a consequence of the *a priori* application of the category of causality, it is a necessary condition of the distinction between the subjective sequence of our perceptions and the objective sequence of experience. Let us assume that the change in the state of the object is the arising of a reality of magnitude *a*. Since there are neither the smallest parts in time, nor in the realm of appearance, this reality suffers a continuous transition from its initial magnitude 0 to its final *a* in a certain time. But this transition must have a cause to be thought of as *objective*. Thus, its cause must generate the reality during the time of the transition, and not suddenly. Moreover, the cause must produce this reality through all its infinite degrees. So, not only are form and matter of intuition continuous, but *the action of causality itself* must be continuous too. This necessary feature of causality is expressed by the law of its continuity, which states that "[a]ll alteration is [...] possible only through a continuous action of causality"[4]. The distinction between subject and object can only be verified under the presupposition of the application of the category of causality and, thus, of the validity of the law of continuity. Therefore, *if* the law of continuity of all changes were not valid, *then* the *contingent* sequence of our perceptions could not be distinguished from the *necessary* sequence of experience.

Bohr, in turn, *denies* the continuity of all changes in quantum theory and *postulates* that quantum systems may pass from one state to another without going through intermediate states, as, e.g., when an electron varies its state among *discrete* possible states of energy. In particular, the measurement process involves a discontinuous and therefore uncontrollable interaction between the measured system and the measuring instrument. However, *at the same time*, Bohr affirms the impossibility of distinguishing in such a process the very quantum object from the measuring device:

> "Now, the quantum postulates implies that any observation of atomic phenomena will involve an interaction with the agency of observation not to be

[4] *Kants gesammelte Schriften* (AA), Königlichen Preußischen (Deutschen) Akademie der Wissenschaften, Berlin, 1902 ss., A208/B254.

> neglected. Accordingly, an independent reality in the ordinary physical sense can neither be ascribed to the phenomena nor to the agencies of observation.”[5]

Thus, Bohr’s interpretation of quantum theory observes at this point the Kantian restriction that we have pointed out above: *as long as* the law of continuity of all changes is *not* valid in a measurement process, *then* it is *not* possible to distinguish between the *contingent* sequence of empirical data and the *necessary* sequence of states of the measured system. The individuality of quantum phenomena consists in this impossibility to separate the physical system from the measuring instrument[6].

2. A QUANTUM OBJECT AS AN OBJECT OF POSSIBLE EXPERIENCE IN THE KANTIAN SENSE

Let us now consider the consequences of the quantum postulate more closely. In classical physics, the causal continuity of the interaction between system and apparatus allows us to calculate the state of the system beyond this interaction, because the effect of the measuring device on the system may be determined and subtracted. In other words, in classical physics, the state of an *isolated* system *can* be established by means of a measurement. On the contrary, the assumption of the quantum postulate implies that the interaction between system and measuring instrument does not satisfy the law of continuity of causality, thereby making it impossible to determine the state of the system independently of its interaction with the apparatus.

But, while the determination of the state of the isolated system is necessary for the application of the conservation theorems (which are the concrete physical expression of the law of causality), the spatio-temporal representation of the system is only possible by means of empirical data obtained as result of a measurement. Thus, a spatio-temporal *and* causal representation of a quantum object is impossible. We cannot synthesize the contingent data of a measurement according to the concept of cause as the effect of a quantum object in space and time, the states of which evolve causally, like we do in classical physics. In this regard, Bohr states:

[5] N. Bohr, *Atomic Theory and the Description of Nature*, p. 54.

[6] Of course, the contingent sequence of experimental data does acquire a necessary connection, because otherwise these data would remain just *subjectively* valid (i.e., they would possess no more value than illusions of the physicist who conducts the experiment). However, Bohr’s point here is that this necessary connection is *not* provided by the representation of the *quantum* object as the spatio-temporal cause of these data. Rather, as we shall see in the following section, representations of *classical* objects are needed to make the measuring result objectively valid. These classical pictures will later turn into symbols of the quantum object.

> "On one hand, the definition of the state of a physical system, as ordinarily understood, claims the elimination of all external disturbances. But in that case, according to the quantum postulate, any observation will be impossible, and, above all, the concepts of space and time lose their immediate sense. On the other hand, if in order to make observation possible we permit certain interactions with suitable agencies of measurement, not belonging to the system, an unambiguous definition of the state of the system is naturally no longer possible, and there can be no question of causality in the ordinary sense of the word."[7]

On the one hand, the conditions of observation of the system are nothing but the conditions under which the spatio-temporal multiplicity that should be synthesized by means of the concept of a quantum object is given. On the other hand, the conditions of the definition of the state of the isolated system are the conditions according to which the concept of a quantum object may be applied, i.e., the conditions under which we may represent a quantum object as the spatio-temporal cause of the experimental data. However, we have just seen that the conditions of observation of a system are incompatible with the conditions of the determination of its state as being totally isolated. Thus, the concept of a quantum object does not and cannot refer directly to intuition as the thought of the unity of the synthesis of a sensible manifold. The concept of a quantum object cannot be *schematically* applied to an empirical manifold, because the conditions under which the multiplicity in space and time that should be synthesized by means of the concept is given are incompatible with the conditions of application of such a concept. In other words, the object of such a concept, i.e., the quantum object, is not directly presentable in intuition.

Briefly, if the quantum postulate is assumed, then no spatio-temporal *and* causal representation of an object is possible. In other words, a quantum object *is not an object of possible experience in the Kantian sense*, because a quantum object does not satisfy at the same time the conditions under which it can be given and the conditions under which it can be thought. As we have seen, these conditions, which correspond to those that Bohr calls conditions of observation and conditions of definition respectively, exclude each other.

3. THE OBJECTIVITY OF MEASUREMENTS RESULTS

This negative determination of quantum objectivity poses the problem of the objectivity of experimental data. If quantum objects are not objects of possible experience: how do quantum experimental results acquire objective validity and may be distinguished from merely subjective illusions? In this regard, Bohr claims:

[7] N. Bohr, *Atomic Theory and the Description of Nature*, p. 54.

> "It is also essential to remember that all unambiguous information concerning atomic objects is derived from the permanent marks [...] left on the bodies which define the experimental conditions [...] The description of atomic phenomena has in these respects a perfectly objective character, in the sense that no explicit reference is made to any individual observer."[8]

The demand of the objectivity of the empirical data that enable the physical reference of the mathematical formalism of the theory is not valid just for the quantum case, but it is required by any physical theory. Therefore, this demand is also present in classical physics. Accordingly, Bohr underlines that "the observation problem of quantum physics in no way differs from the classical physical approach"[9].

In accordance with the main claims of transcendental philosophy, Bohr argues that the objectivity of measurement results is achieved by the subsumption of the spatio-temporal data under the category of causality:

> "[I]t should not be forgotten that the concept of causality underlies the very interpretation of each result of experiment, and that even in the coordination of experience one can never, in the nature of things, have to do with well-defined breaks in the causal chain."[10]

For Bohr, the synthesis of spatio-temporal data according to the causality principle is a necessary condition for their objective validity. This condition is required both in quantum and in classical physics, if an observation or measurement is carried out:

> "Strictly speaking, the idea of observation belongs to the causal space-time way of description."[11]

As we have seen, in the quantum case (i.e., under the assumption of the quantum postulate) it is not possible to meet the demands of both spatio-temporal coordination and causal connection. Therefore, quantum theory cannot account for the objectivity of empirical data. It is not by means of quantum concepts and laws that experimental data are represented as objective results. Rather, insofar as the concepts applied in a measurement may receive a spatio-temporal and causal *image*, they are *classical*:

> "[T]he union of [the space-time co-ordination and the claim of causality] characterizes the classical theories."[12]

[8] N. Bohr, *Essays 1958 – 1962 on Atomic Physics and Human Knowledge*, London, Wiley, 1963, p. 3.

[9] *Ibidem*, p. 3.

[10] N. Bohr, "Causality and Complementarity", in *Philosophy of Science*, 4, 1937, pp. 289–298, p. 87.

[11] N. Bohr *Atomic Theory and the Description of Nature*, p. 67.

[12] *Ibidem*, pp. 54–55.

Then, Bohr concludes:

> "*However far the phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms*."[13]

In other words: there is a necessity of objectifying the empirical data obtained by means of our observations, since otherwise they would not be experimental results, but just mere reports of our contingent perceptions. This transcendental objectification task is carried out by the application of the principles of understanding (in particular, the principle of causality) to the empirical multiplicity given in space and time. According to transcendental philosophy, the objectification of experimental data necessarily requires the representation of such data as the effect of some certain spatio-temporal cause. Thus, such objectification can only be achieved by concepts whose application is at once compatible with both the requirements of causality and spatio-temporality. However, as we have seen, in the domain of validity of the quantum postulate the conditions of application of the causality principle exclude the possibility of a spatio-temporal representation. Therefore, the objectification of experimental data is a demand that the concepts of quantum objects cannot fulfill and that is satisfied only by concepts of *classical* objects.

Empirical data are valid as experimental results when the subjective series of perceptions is distinguished from the objective series of experience. In this regard, Bohr claims "the distinction between subject and object [is] necessary for unambiguous description"[14]. An unambiguous description is only possible if "no explicit reference is made to any individual observer"[15]. As already argued, this can only be achieved by using classical concepts. Only in this way can we "tell others what we have done and what we have learned"[16] in an experiment. Thus, Bohr argues that "the account of experimental arrangement and of the results of the observations must be expressed in unambiguous language with suitable application of the terminology of classical physics"[17]. Bohr calls these classically described observations quantum *phenomena*. The mathematical formalism of quantum theory will base its physical reference on them. We will later discuss how this reference is finally achieved. But before we should consider another consequence of the quantum postulate: the *contextual* and, more precisely, *complementary* character of quantum phenomena.

[13] N. Bohr, "Discussion with Einstein on Epistemological Problems in Atomic Physics", in P. Schilpp (ed.), *Albert Einstein. Philosopher-Scientist*, Evanston, Library of Living Philosophers, 1949, pp. 32–66, p. 39.

[14] N. Bohr, *Atomic Physics and Human Knowledge*, New York, John Wiley & Sons, 1958, p. 101.

[15] N. Bohr, *Essays 1958 – 1962 on Atomic Physics and Human Knowledge*, p. 3.

[16] N. Bohr, "Discussion with Einstein on Epistemological Problems in Atomic Physics", p. 39.

[17] *Ibidem*.

4. CONTEXTUALITY AND COMPLEMENTARITY OF QUANTUM PHENOMENA

The contextuality of quantum phenomena amounts to the fact that these classical descriptions are valid only regarding the experimental arrangement in which they are obtained. In this connection, Bohr argues:

> "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."[18]

Although each quantum phenomenon corresponds to a classical spatio-temporal and causal description, the multiplicity of them cannot get unified in a *single* spatio-temporal and causal image. Rather, incompatible representations seem to be necessary to interpret empirical data in an adequate way. Bohr claims:

> "Very striking illustrations are afforded by the well-known *dilemma* regarding the properties of electromagnetic radiation as well as of material corpuscles, evidenced by the circumstances that in both cases contrasting pictures as waves and particles appear equally indispensable for the full account of experimental evidence."[19]

We find in experience a manifold of phenomena that seems not to be unifiable in a single spatio-temporal and causal image. To account for this empirical fact, one may suggest that this impossibility lies on the inadequacy of the images that we try to use to carry out this unification. For example, although the wave image and the particle image do not do the job, perhaps other still unknown images would be capable of this unification. As a matter of fact, in well-known discussions with Bohr[20], Schrödinger argued that it was necessary to search for *new* concepts that enable us a single spatio-temporal and causal image of quantum phenomena. However, Bohr rejects this proposal by claiming that *the mere assumption of the quantum postulate* implies the necessity of considering more than one kind of pictures to interpret experimental data:

> "In fact, the individuality of the typical quantum effects finds its proper expression in the circumstance that any attempt of subdividing the phenomena will demand a change in the experimental arrangement introducing new

[18] *Ibidem*, p. 64.

[19] N. Bohr, "Mathematics and Natural Philosophy", in *Scientific Monthly*, 82, 1956, pp. 85–88, p. 87.

[20] See H. Pringe, *Critique of the Quantum Power of Judgement. A Transcendental Foundation of Quantum Objectivity*, Berlin – New York, de Gruyter, 2007, pp. 79ss.

possibilities of interaction between objects and measuring instruments which in principle cannot be controlled. *Consequently*, evidence obtained under different experimental conditions cannot be comprehended within a single picture."[21]

As we have seen, given the quantum postulate, it will be necessary to describe the quantum phenomena in classical terms. This description will account for the measurement results obtained in a certain experimental arrangement. If we wanted to subdivide the quantum phenomenon, i.e., if we wanted to determine that which the postulated discontinuity prevented us to establish, then we would have to modify the experimental arrangement. But in such a case we would introduce new possible discontinuous interactions and therefore new aspects of individuality of a *different* quantum phenomenon. Thus, the classical description corresponding to the first experimental arrangement could not be used in the second one and the data obtained under different experimental conditions could not be connected in a single picture. Bohr claims:

"In this connection it is interesting to see how the concept of wave or corpuscle presents itself as the more suitable concept, according to the point in the description where the assumption of discontinuities explicitly appears. In my opinion this is easily understood, since the definition of every concept or rather every word presupposes the continuity of the phenomena and hence becomes ambiguous as soon as this presupposition cannot be upheld."[22]

If we use a certain concept in our description (i.e., the particle concept), we will be allowed to do it until a change in the experimental arrangement introduces a discontinuity. Then, the application conditions of the concept will not be met, because the distinction between the contingent series of empirical data and the necessary series of the objective states cannot be established any longer. In this situation, we will have to consider another concept for the description of the experiment (i.e., the wave concept), so that the discontinuity disappears and the conditions of the application of concepts are reestablished.

The quantum postulate implies, on the one hand, that quantum phenomena must be described in classical terms and, on the other hand, that more than one kind of description will be needed. These contextual descriptions associated to different experimental arrangements that exclude each other but are nevertheless all necessary for an exhaustive interpretation of experimental data are called *complementary*:

[21] N. Bohr, "Discussion with Einstein on Epistemological Problems in Atomic Physics", p. 40 (our emphasis).

[22] Bohr to Schrödinger, 2.12.26, in *Bohr's Collected Works*, L. Rosenfeld, J. Rud Nielsen, E. Rüdinger, F. Aaserud (eds.), North-Holland, Amsterdam; American Elsevier, New York, 1972 ss., p. 14.

> “[E]vidence 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.”[23]

In sum, for Bohr the quantum postulate implies the classical description of quantum phenomena. In this way, the Bohrian interpretation of quantum theory complies with the transcendental conditions of the objectification of the empirical data that provide the mathematical formalism of the theory with physical reference. These data will be so represented that both the demand of spatio-temporality and causality are satisfied. However, with this Bohrian concept of quantum phenomena a new problem arises. Quantum phenomena are contextual, because they are restricted to a certain experimental arrangement and they are complementary, because they exclude each other but all of them are necessary to interpret the experimental data. Therefore, at this point we face a manifold of phenomena, the objectivity of which is established but that lacks *systematic unity*. The problem of this systematic unity will be our next subject of discussion.

5. SYSTEMATIC UNITY OF QUANTUM PHENOMENA AND QUANTUM OBJECTIVITY

The key to the solution of the problem of the systematic unity of quantum phenomena is contained in the passage that we have just quoted, where Bohr clearly distinguishes quantum *objects* from quantum *phenomena*. Bohr argues that “only the totality of the *phenomena* exhausts the possible information about the *objects*”[24]. We will now see that the systematic unity of quantum phenomena is achieved when they are subsumed under the concept of a quantum object. The concept of a quantum object (or system) contains the representation of its state and, with it, the information about the probabilities of the possible outcomes of the measurements that may be carried out on the system. In this way, the manifold of quantum phenomena acquires systematic unity under a probabilistic law. Given a quantum phenomenon, the representation of the state of the quantum object establishes the *probability* of all quantum phenomena. Therefore, the manifold of phenomena gets connected by means of the concept of an object and is subsumed under it. This systematic unity makes predictions possible: given a certain phenomenon, the probabilities of the possible results of any measurement are calculated form the wave function of the system.

[23] N. Bohr “Discussion with Einstein on Epistemological Problems in Atomic Physics”, p. 40.
[24] *Ibidem*.

The concept of a quantum object carries out a transcendental task analogous to that which Kant assigns to the concept of an organism[25]. Both concepts play a regulative function in experience, which Kant carefully distinguishes from a constitutive role. This means that neither the concept of an organism nor the concept of a quantum object determines empirical data as objective cognitions, but rather they synthesize phenomena, whose objective validity is already guaranteed, into a unity of a higher order. According to Kant's transcendental philosophy, the objectivity of organisms is founded on the spatio-temporal and causal representation of their parts. On the contrary, the systematic unity of these parts is achieved only through the representation of the organism as a natural end. In the case of quantum objects, the parts whose unity must be established are no longer their component parts, as in organisms, but rather their complementary parts, i.e., the quantum phenomena. These phenomena acquire objective validity thanks to the application of classical concepts for their description, but their systematic unity is only achieved when they are subsumed under the concept of a quantum object.

6. THE INTUITIVE EXHIBITION OF THE CONCEPT OF A QUANTUM OBJECT

A further aspect of Bohr's interpretation of quantum theory is that quantum objects are not directly exhibited in intuition. To emphasize this, Bohr points out the *symbolic* character of the formalism of the theory. In this regard, Bohr states:

> "In accordance to this situation there can be no question of any unambiguous interpretation of the symbols of quantum mechanics other than that embodied in the well-known rules which allow to predict the results to be obtained by a given experimental arrangement described in a totally classical way."[26]

In the second section of this talk, we discussed the impossibility of exhibiting the concept of a quantum object directly in intuition and we showed that a quantum object is not an object of possible experience in the Kantian sense. We will now see that, in view of the impossibility of a direct exhibition in intuition, the concept of a quantum object will be exhibited indirectly.

This indirect exhibition is for Bohr a symbolic one. Thus, Bohr opposes classical concepts to quantum symbols in a double respect. On the one hand, with this opposition Bohr emphasizes the impossibility of exhibiting the concepts of quantum objects directly in intuition. On the other hand, he states that these

[25] See Pringe, *Critique of the Quantum Power of Judgement. A Transcendental Foundation of Quantum Objectivity*, pp. 164ss.

[26] N. Bohr, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?", in *Physical Review*, vol. 48, 1935, pp. 696–702, p. 701.

concepts will be exhibited indirectly, by means of classical concepts. More precisely, complementary classical pictures will be represented as symbols of the quantum object. Thus, for example, a quantum object will behave in certain circumstances *as if it were* a particle and, in certain others, *as if it were* a wave. In this sense, Bohr states that "we symbolize [objects] by the abstractions of isolated particles and radiation"[27].

The touchstone of such symbolism will be the uncertainty relations established by Heisenberg. In this respect, Bohr argues:

> "This principle [the indeterminacy principle of Heisenberg] defines the latitude in the application of classical concepts, necessary for the comprehension of the fundamental laws of atomic stability which are beyond the reach of these concepts."[28]

The uncertainty relations establish quantitatively the limits of the justified use of descriptions in terms of waves and particles. These relations provide us with the necessary criterion for the application of classical concepts in the interpretation of experimental data and, thus, of the representation of complementary phenomena as symbols of quantum objects.

> "*The proper rôle* of the indeterminacy relations consists *in assuring quantitatively the logical compatibility* of apparently contradictory laws which appear when we use two different experimental arrangements."[29]

Thus, the uncertainty relations contain the rule which determines *how* the different symbols are to be used and therefore they enable the *application* of the *complementary* pictures in the interpretation of empirical data[30]. As Heisenberg later states:

> "[F]or visualization [of atomic processes] [...] we must content ourselves with two incomplete analogies –the wave picture and the corpuscular picture. The simultaneous applicability of both pictures is thus a natural criterion to determine how far each analogy may be 'pushed' and forms an obvious

[27] N. Bohr, *Atomic Theory and the Description of Nature*, p. 69.

[28] *Ibidem*, p. 53.

[29] N. Bohr, "Causality and Complementarity", p. 293.

[30] In the same sense, Bense affirms: "Da der [Welle-Partikel]-Dualismus als Anschauungsdualismus phänomenal unmöglich ist, folgt, daß ein gleichzeitiges Verwenden des Partikel- und des Wellenbildes nur bis zu gewissen Grenzen möglich ist. Bohr hat als erster auf diesen Tatbestand hingewiesen, Heisenberg handelte ihn systematisch ab und zog die entsprechenden Folgerungen für den Gesamtaufbau der atomaren Physik. Er gibt die Formeln dafür an bis zu welchen Grenzen Partikelbild oder Wellenbild anwenbar sind und zeigt, daß die Grenzen des Wellenbildes aus dem Partikelbild, die des Partkelbildes aus dem Wellenbild erschlossen werden können." (M. Bense, *Quantenmechanik und Daseinsrelativität*, Welsel-Druck, Köln-Kalk, 1938, p. 60).

> starting point for the critique of the concepts which have entered atomic theories in the course of their development, for, obviously, uncritical deduction of consequences from both will lead to contradictions. In this way one obtains the limitations of the concept of a particle by considering the concept of a wave. As N. Bohr has shown, this is the basis of a very simple derivation of the uncertainty relations between co-ordinate and momentum of a particle. In the same manner one may derive the limitations of the concept of a wave by comparison with the concept of a particle."[31]

Perhaps it is Pauli who best summarizes the problem of the use of complementary classical pictures for the indirect exhibition of quantum objects in intuition. Pauli asks: "if [the atom] were not a symbol, how could it be 'both a wave and a particle'?"[32]

7. CLASSICAL AND QUANTUM OBJECTIVITY

We will now consider Bohr's interpretation by concentrating on the determination of the concept of quantum objectivity, in order to establish its peculiarity vis-à-vis classical objectivity. For this purpose, firstly it will be necessary to introduce the distinction between the objective *validity* and the objective *reality* of a concept[33].

We shall understand by objective validity of a concept the necessary character of the synthesis represented by the concept, as opposed to those associations that can only be referred to the state of the subject. In this sense, the synthesis thought by means of an objectively valid concept will be distinguished from a mere contingent association of representations. In turn, this synthesis may be such that thanks to it a sensible manifold attains objective reference, or such that already objective knowledge acquires systematic unity. We shall call the first type of objective validity, constitutive validity, and the second type, regulative validity.

On the contrary, the objective reality of a concept consists in its reference to an empirical content. A concept that possesses objective reality differs, therefore, from an empty or merely formal concept. A concept can receive objective reality either directly, by means of a schema, or indirectly, by means of a symbol[34].

[31] W. Heisenberg, *The Physical Principles of the Quantum Theory*, transl.by C. Eckart, F.C. Hoyt, Dover, Mineola, 1949, p. 11. For an extensive analysis of the question of the wave-particle dualism in quantum optics, see B. Falkenburg, *Particle Metaphysics*, New York, Springer, 2007.

[32] See K. Laurikainen, *Beyond the Atom. The Philosophical Thought of Wolfgang Pauli*, Berlin, Springer, 1988, p. 193.

[33] This distinction between objective validity and objective reality does not exactly coincide with the way in which Kant makes use of these concepts. For a discussion of this issue, see G. Zöller, *Theoretische Gegenstandbeziehung bei Kant*, Berlin, de Gruyter, 1984.

[34] AA XX, 279.

Quantum objectivity must be distinguished from classical objectivity both with respect to the objective validity and the objective reality of the concept of an object. Firstly, the objective validity of the concept of a classical object is constitutive, since the synthesis of an empirical manifold according to the rule thought by the concept constitutes the representation of an object. On the contrary, the objective validity of the concept of a quantum object is based rather on its regulative task of providing systematic unity to complementary phenomena (the objectivity of which is guaranteed by the use of classical concepts for the interpretation of experimental results).

Secondly, the concept of a classical object acquires objective reality when a given empirical manifold is subsumed under the concept by means of a schema. Thus, the concept is directly exhibited in intuition. On the contrary, as a consequence of the quantum postulate, the conditions under which the empirical multiplicity that should be synthesized by the concept of the quantum object is given are incompatible with those under which the concept may be applied. Therefore, a direct exhibition of this concept in intuition is not possible. The concept of a quantum object acquires objective reality rather by an indirect exhibition in intuition, carried out through symbolic analogies.

We thus see how Bohr's interpretation of quantum theory is articulated by the transcendental distinction between the way in which empirical data are represented as objective experimental results and the way in which the manifold of such results is systematically unified. In the first case, a constitutive task carried out by classical concepts takes place. These concepts are then schematically exhibited in intuition. In the second case, the concept of a quantum object performs a regulative function, ensuring a systematic unity between complementary phenomena, which have been constituted by classical concepts. These phenomena, in turn, provide the concept of the quantum object with objective reality, because they are represented as symbols of the quantum object and exhibit it indirectly in intuition.

8. TOWARDS THE METAPHYSICAL PRINCIPLES OF QUANTUM THEORY

Based on this Kantian reading of Bohr's interpretation of quantum theory, we will now study the possibility of providing quantum theory with metaphysical principles in a Kantian sense[35]. According to Kant, metaphysics of nature consists of two parts: a *general* and a *special* one. The principles of general metaphysics of nature are called *transcendental*[36]. Transcendental principles refer to nature in general, i.e., they make abstraction of any determination of empirical objects beyond their merely being objects of experience. As we have seen, these principles

[35] H. Pringe, "On the Metaphysical Principles of Quantum Theory", in *Akten des XI. Internationalen Kant-Kongresses*, Berlin, de Gruyter, 2013, pp. 197–208.

[36] MAN, AA IV: 469 – 470. 30 – 01.

are of two different kinds: the constitutive principles of understanding and the regulative principles of reason. The special part of metaphysics of nature assumes a certain *empirical* concept in order to specify the general metaphysical principles. In this way, it determines the concept of an object of possible experience by means of an empirical predicate. Then, it establishes all that can be judged *a priori* on such a minimally determined object[37]. In the *Metaphysical Foundations of Natural Science*, Kant considers the concept of an object of possible *external* experience, i.e. the concept of *matter*, and ascribes to it the empirical determination of *motion*. He then searches for those a priori judgments that can be gained on matter as the movable in space, in accordance with the table of categories. The concept of motion specifies the concept of an object of external experience in general, so that a first realization of the *constitutive* principles of experience is achieved. The judgments so obtained make up the system of the metaphysical principles of Newtonian physics.

At this point the question arises, whether a similar procedure may be carried out in the case of quantum theory.[38] More precisely: can we specify the *constitutive* principles of nature in such a way that we obtain the metaphysical principles of quantum physics? Since a quantum object is not an object of possible experience in the Kantian sense, a quantum specification of the *constitutive* principles of experience is impossible. However, we shall now see that it is possible as a specification of *regulative* principles.

As already argued, quantum objects are assumed for the possibility of the systematic unity of contextual experience. Accordingly, *the conditions of the possibility of the systematic unity of contextual experience are at the same time the conditions of the possibility of quantum objects*. I shall call this principle the highest principle of quantum objectivity. In view of it, the determination of the conditions of systematic contextual *experience* will enable us to establish synthetic *a priori* judgments expressing determinations of quantum *objects*. More precisely, these judgments will determine the very concept of quantum *objectivity* as a

[37] "Ein transscendentales Princip ist dasjenige, durch welches die allgemeine Bedingung *a priori* vorgestellt wird, unter der allein Dinge Objecte unserer Erkenntniß überhaupt werden können. Dagegen heißt ein Princip metaphysisch, wenn es die Bedingung *a priori* vorstellt, unter der allein Objecte, deren Begriff empirisch gegeben sein muß, *a priori* weiter bestimmt werden können." (KU, AA V: 181. 15–20).

[38] Falkenburg has suggested that the Kantian concept of matter might be modified for this purpose. See B. Falkenburg, *Kants Kosmologie*, Frankfurt a.M., 2000, pp. 337 ff. In his *La philosophie transcendentale et le problème de l'objectivité*, Paris, 1991, J. Petitot has argued that classical and quantum objects belong to different regional ontologies that are subsets of the general ontology determined by the categories. In a similar way, Strohmeyer and Mittelstaedt have tried to show that quantum objects are objects of possible experience which just do not satisfy some not necessary conditions that classical objects fulfil, in particular the principle of complete determination. See Ingeborg Strohmeyer, *Transzendentalphilosophie und Quantenphysik*, Heidelberg, 1995, and Peter Mittelstaedt, "The Constitution of Objects in Kant's Philosophy and in Modern Physics.", in Paolo Parrini (ed.), *Kant and Contemporary Epistemology*, Dordrecht, 1994, pp. 115–129.

regulative concept which carries out its task under certain specific conditions. Such judgments will thus be the metaphysical principles of quantum theory, i.e., the principles of quantum metaphysics.

Let us consider this specification more closely. The regulative principles of nature concern our empirical knowledge *as a whole*. They are established *a priori*, just by taking into consideration the demands of systematic unity in our cognitions, which are imposed by reason. To the contrary, the principles of quantum metaphysics refer to the systematic unity of *contextual experience*, not to the whole system of our knowledge. Moreover, they cannot be gained completely a priori, but they rest on an *empirical* fact: the existence of contextual phenomena. The regulative principles of nature demand us to search for systematic unity in our knowledge, but they leave open *how* this unity can be obtained. In view of this *a priori* demand and of the *a posteriori* fact that contextual phenomena are given, such phenomena are brought under concepts of quantum objects. The principles which determine the features that those objects must have to fulfill this task *specify* for contextual phenomena the demands left indeterminate by reason. In this way, quantum metaphysics is possible as a specification of the regulative principles belonging to general metaphysics of nature.

It should be underlined that this specification is not an *a priori derivation* of quantum metaphysics from the conditions of the possibility of experience. The specification of the regulative principles which leads to quantum metaphysics cannot be obtained by mere logical deduction. The regulative principles of general metaphysics say nothing about the *specific* way in which contextual phenomena should acquire systematic unity. They just concern experience *in general*. Moreover, the real possibility of contextual phenomena cannot be seen a priori, for experience is indeed possible without them. Thus, we may conceive the concept of a contextual phenomenon a priori, but we cannot a priori determine whether this concept has objective validity. Rather, only because of the *empirical* fact of the existence of contextual phenomena may we provide their concept with physical reference. Therefore, quantum metaphysics cannot be obtained a priori from transcendental principles, but rests on an empirical assumption.

9. AN EXAMPLE: A QUANTUM OBJECT AS SUBSTANCE

The highest principle of quantum objectivity enables us to gain a priori knowledge of quantum objects if we determine the conditions of the systematic unity of contextual experience. To perform this determination systematically, we should do it in accordance with the table of categories. Let us focus on the category of substance. The metaphysical principle corresponding to this category reads: The properties (accidents) of quantum objects are arranged in a *non*-distributive lattice.

Contextual phenomena acquire systematic unity by being represented as phenomena *of* a quantum object. In any given experimental situation certain properties of the object grounds the given phenomena. The contextuality of the phenomena entails the non-distributivity of the lattice of properties. For example, for the particular case of a Young type experiment, it has been proved that in the set of experimental languages corresponding to different experimental arrangements logical addition is not distributive in regard to logical product[39].

It is important to stress the synthetic a priori character of the principle. The concept of a quantum object taken as a mere substance does not entail the non-distributive character of its properties. This cannot be obtained *analytically*. Rather, this determination is added to the concept of the object *because* it makes the systematic unity of contextual experience possible. In this way, the concept of the object is enlarged *synthetically*. Moreover, as only the *possibility* of such experience is at issue, the synthesis is valid *a priori*[40]. Therefore, the synthesis contained in the principle goes beyond any analytic explanation of concepts and is grounded *a priori* on the highest principle of quantum objectivity as its touchstone of truth.

10. QUANTUM METAPHYSICS AND MATHEMATICS

From a Kantian viewpoint, the proper task of the metaphysical principles of a physical theory is to account for the applicability of *mathematics* to determinate natural objects. While Kant attacked this problem in his foundation of the doctrine of body[41], the ground of the connection between mathematics and objects of nature should now be accounted for in the quantum case[42]. If we consider the concepts of

[39] M. Bitbol, *Mécanique Quantique. Une introduction philosophique*, Paris, 1996, pp. 62 ff., 433 ff.

[40] "Nun heißt etwas *a priori* erkennen, es aus seiner bloßen Möglichkeit erkennen." MAN, AA IV: 470. 18– 19.

[41] "Damit aber die Anwendung der Mathematik auf die Körperlehre, die durch sie allein Naturwissenschaft werden kann, möglich werde, so müssen Principien der *Construction* der Begriffe, welche zur Möglichkeit der Materie überhaupt gehören, vorangeschickt werden; mithin wird eine vollständige Zergliederung des Begriffs von einer Materie überhaupt zum Grunde gelegt werden müssen, welches ein Geschäfte der reinen Philosophie ist, die zu dieser Absicht sich keiner besonderen Erfahrungen, sondern nur dessen, was sie im abgesonderten (obzwar an sich empirischen) Begriffe selbst antrifft, in Beziehung auf die reinen Anschauungen im Raume und der Zeit (nach Gesetzen, welche schon dem Begriffe der Natur überhaupt wesentlich anhängen) bedient, mithin eine wirkliche *Metaphysik der körperlichen Natur* ist." (MAN, AA IV: 472. 1–12).

[42] On this issue, Wigner maintains: "The miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift which we neither understand nor deserve." (Eugene Wigner, "The Unreasonable Effectiveness of Mathematics in the Natural Sciences", in *Symmetries and Reflections*, Bloomington, 1967, pp. 222–237, p. 237).

quantum objects from the point of view of the mere formalism of the theory, their validity regarding empirical phenomena remains an open question. Even though formal results can be established by mathematical investigation, in this way no *physical* application of those mathematical cognitions is justified. Moreover, should their empirical validity be accounted for *a posteriori*, the apodictic certainty of these mathematical judgments would get lost in their application to physics. In this situation, we would face the dilemma posed by Einstein, according to whom "as far as the laws of mathematics refer to reality, they are not certain, and as far as they are certain, they do not refer to reality"[43]. Thus, it is rather an *a priori* justification of the objective validity of the mathematical formalism of the theory that what we should seek for.

The analysis carried out so far allows us to take one step towards this goal. The metaphysical knowledge of quantum objects is precisely the knowledge of those features that guarantee the empirical application of the mathematical formalism of the theory. In the case of the metaphysical principle maintaining the non-distributive character of the quantum-properties lattice, such principle enables a justification of the applicability of a so-called quantum logic to empirical phenomena, in so far as this application makes the systematic unity of those phenomena first possible. The principles of quantum logic may hereby receive a *transcendental* deduction, i.e., a proof that they are not empty principles, valid just in the framework of a certain *formal* system, but that there are *empirical phenomena* which can be brought under them. Quantum metaphysics establishes that a non-distributive logical structure is demanded to achieve systematic unity among contextual phenomena. In this way, quantum metaphysics grounds the possibility of a real use of quantum logic.

The objects subsumed under the principles of quantum metaphysics are so constituted that they fulfill a certain transcendental task: that of bringing about systematic unity among contextual phenomena. The metaphysical principles of quantum theory identify those *mathematical* properties by means of which the concepts of quantum objects perform their specific role in physical experience. In this way, the metaphysical principles make the concept of a quantum object (as a mere mathematical object) available *a priori* for its further application to experience, as far as they show the mathematical features that the systematic unity of contextual experience demands to the concept of an object that is to bring about such unity. A metaphysical foundation of quantum theory in the Kantian sense would account

[43] Albert Einstein, *Sidelights of Relativity*, London, 1922, p. 28. Kant underlines: "Es wird allemal ein bemerkungswürdiges Phänomen in der Geschichte der Philosophie bleiben, daß es eine Zeit gegeben hat, da selbst Mathematiker, die zugleich Philosophen waren, zwar nicht an der Richtigkeit ihrer geometrischen Sätze, sofern sie blos den Raum beträfen, aber an der objectiven Gültigkeit und Anwendung dieses Begriffs selbst und aller geometrischen Bestimmungen desselben auf Natur zu zweifeln anfingen." (*Prol.*, AA IV: 287–288. 34–3).

for the applicability of the mathematical formalism of the theory to nature, avoiding both insufficient empirical justifications as well as untenable dogmatic postulations[44].

The metaphysical principles of quantum theory are a part of metaphysics of nature in which the regulative principles of experience find a special application. A main feature of quantum metaphysics, as a special metaphysics, is that it relies on an *empirical* fact. The basic empirical fact grounding quantum theory is the contextuality of quantum phenomena. Given this fact and in accordance with the regulative principles of general metaphysics of nature, special principles are established *a priori*. As in the case of any synthetic a priori judgment, the determination of the principles of quantum metaphysics involves two problems. On the one hand, the ground of the a priori connection of the representations in the judgment must be explained. This connection cannot rest on experience because it is *a priori*. Neither can it be explained by a mere analysis of concepts, for it is *synthetic*. On the other hand, the *objective validity* of the judgment is to be accounted for, since the judgment claims to be knowledge and not just a juxtaposition of representations without reference. The possibility of the systematic unity of contextual experience provides us with the key to solve both problems. Firstly, the connection thought in any metaphysical principle of quantum theory is neither based on experience nor necessary from the point of view of formal logic. Rather, such connection is demanded by the mere possibility of the systematic unity of contextual experience. Secondly, it is precisely on this peculiar kind of necessity where the objectivity of quantum objects rests. A quantum object is nothing but that in the concept of which a manifold of (classically described) contextual phenomena is systematically united. The metaphysical principles of quantum theory contain the a priori determinations of the objectivity of those regulative objects that must be assumed for the possibility of the systematic unity of contextual experience. Such principles are therefore the *constitutive* principles of metacontextual regulative objects, and they are in this sense objectively valid.

[44] As Kant maintains: "Alle Naturphilosophen, welche in ihrem Geschäfte mathematisch verfahren wollten, haben sich daher jederzeit (obschon sich selbst unbewußt) metaphysischer Principien bedient und bedienen müssen, wenn sie sich gleich sonst wider allen Anspruch der Metaphysik auf ihre Wissenschaft feierlich verwahrten. [...] So konnten also jene mathematische Physiker metaphysischer Principien gar nicht entbehren und unter diesen auch nicht solcher, welche den Begriff ihres eigentlichen Gegenstandes, […] *a priori* zur Anwendung auf äußere Erfahrung tauglich machen […] Darüber aber blos empirische Grundsätze gelten zu lassen, hielten sie mit Recht der apodiktischen Gewißheit, die sie ihren Naturgesetzen geben wollten, gar nicht gemäß, daher sie solche lieber postulirten, ohne nach ihren Quellen *a priori* zu forschen." (MAN, AA IV: 472. 13–35).