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► **To cite this version:**

Michel Bitbol, Stefano Osnaghi. Bohr's complementarity and Kant's epistemology. O. Darrigol; B. Duplantier; J.M. Raimond; V. Rivasseau. Niels Bohr 1913-2013, 9783319143156, Birkhauser, 2014. <hal-04719934>

**HAL Id: hal-04719934**

**<https://hal.science/hal-04719934v1>**

Submitted on 3 Oct 2024

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# Bohr's complementarity and Kant's epistemology

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In: O. Darrigol, B. Duplantier, J.M. Raimond, & V. Rivasseau (eds.), *Niels Bohr 1913-2013*, Birkhauser, 2016 (Progress in Mathematical Physics 68, pp. 199-221)

## 1. Introduction

Contrary to received wisdom, Bohr's views on quantum mechanics did not gain universal acceptance among physicists, even during the heyday of the so-called "Copenhagen interpretation" (spanning approximately between 1927 and 1952). The "orthodox" approach generally referred to as "the Copenhagen interpretation" was in fact a mixture of elements borrowed from Heisenberg, Dirac, and von Neumann, with a few words quoted from Bohr and due reverence for his pioneering work, but with no unconditional allegiance to his ideas.<sup>3</sup> Indeed, Bohr's unpaired physical insight and mastery in devising effective models did not prevent many of his colleagues from finding his reflections about the epistemological status of theoretical schemes, and his considerations on the limits of the representations employed by science, obscure and of little practical moment – in a word: too philosophical.<sup>4</sup> In addition, it proved somehow uneasy to reach definite conclusions as to the true nature of this philosophy.

Although Bohr's views have occasionally been criticized for their alleged positivistic leaning,<sup>5</sup> a number of commentators have more aptly pointed out their pragmatist aspects, especially in view of Bohr's apparently operationalist definition of microphysical phenomena, and of his documented interest for William James.<sup>6</sup> We know that Bohr had a lifelong friendship with the Danish philosopher Harald Høffding (who was a close friend of his father, and taught a course at the university of Copenhagen, which Bohr attended as a student).<sup>7</sup> Through Høffding, Bohr was exposed to Kantian influences (partly reshaped by Høffding's own rather pragmatist views). Such influences are arguably responsible for the Kantian pattern that can be discerned amidst Bohr's mixture of blurred philosophical styles. Even though Bohr himself did not bother to pinpoint his debt towards Kant, a very important component of Kant's theory of knowledge had clearly, albeit indirectly, made its way in Bohr's interpretation of

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<sup>3</sup> Maybe it's here worth quoting Howard, Camilleri and others who discuss in detail the historical and psychological context in which what is called "the Copenhagen interpretation" came to occupy a central place in the literature on the foundations of quantum mechanics.

<sup>4</sup> See e.g. the attitude of Enrico Fermi, described by G.J. Holton, *The Scientific Imagination : Case Studies*, Cambridge University Press, 1978, p. 162; I can add references

<sup>5</sup> Bunge, 1957; J. Faye, "Niels Bohr and the Vienna circle", in : J. Manninen & F. Stadler (eds.), *The Vienna Circle in the Nordic Countries*, Springer, 2009

<sup>6</sup> Stapp, 1972; D. Murdoch, *Niels Bohr's Philosophy of Physics*, Cambridge University Press, 1987, p. 225

<sup>7</sup> J. Faye, *Niels Bohr, his Heritage and Legacy*, Kluwer, 1991

quantum mechanics. It had filtered through Bohr's scattered philosophical background, only to reemerge clandestinely but very recognizably in his epistemological reflection on quantum mechanics. Early neo-Kantian analyses of quantum mechanics, such as Carl-Friedrich von Weizsäcker's,<sup>8</sup> Grete Hermann's,<sup>9</sup> and Ernst Cassirer's,<sup>10</sup> thus took advantage of Bohr's position, instead of distancing themselves from it.

The Kantian element in Bohr's thought was subsequently recognized by a number of historians and philosophers of physics,<sup>11</sup> while being minimized or denied by others.<sup>12</sup> The reasons for such disagreement are easy to understand: on the one hand, the Kantian component of Bohr's epistemology is buried in his idiosyncratic remarks about the role of measuring devices and the boundaries of theoretical domains; and on the other hand, after more than three centuries of erudite commentaries, the gist of Kant's philosophy remains a matter of debate. Any attempt to bring out the affinities and differences between Bohr and Kant can, therefore, hardly avoid engaging in a twofold process of clarification.<sup>13</sup>

The present paper will undertake this task by showing that some of Bohr's crucial moves, while seemingly conflicting with the letter of Kant's work, are in fact very much in tune with its spirit. The first section sorts out the various dimensions of Kant's theory of knowledge, and identifies what was retained and what was left out by Bohr. We insist in particular on the striking analogy between, on the one hand, Kant's strategy to "disentangle" the object and the subject from the cognitive relation which lies at the heart of our experience, and, on the other hand, Bohr's endeavor to come to grips with the "indivisibility" of quantum phenomena. In the subsequent sections we analyze in turn Bohr's notion of a "cut" between the measuring instrument and the measured object (that we relate to Kant's general reflection upon the subjective conditions of possibility of knowledge), Bohr's concept of complementarity (that we relate to Kant's theory of the object), and the peculiar role of classical concepts within Bohr's approach

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<sup>8</sup> W. Heisenberg, *Physics and Beyond*, Harper and Row, 1971, chapter X

<sup>9</sup> G. Hermann, *Les fondements philosophiques de la mécanique quantique*, Vrin, 1996. The original German version was published in 1935

<sup>10</sup> E. Cassirer, *Determinism and Indeterminism in Modern Physics*, Yale University Press, 1956. The original German version was published in 1936

<sup>11</sup> C.A. Hooker, "The nature of quantum mechanical reality", in R. G. Colodny (ed.), *Paradigms and Paradoxes*, University of Pittsburgh Press, 1972, 135-172 ; J. Honner, "The transcendental philosophy of Niels Bohr", *Studies in the History and Philosophy of Sciences*, **13**, 1-30, 1982 ; C. Chevalley, *Le dessin et la couleur*, in : N. Bohr, *Physique atomique et connaissance humaine*, Gallimard, 1991 ; D. Kaiser, "More roots of complementarity : Kantian aspects and influences", *Studies in the History and Philosophy of Science*, **23**, 213-239, 1992 ; S. Brock, *Niels Bohr's Philosophy of Quantum Physics*, Logos Verlag, 2003

<sup>12</sup> H. Folse, "Kantian aspects of complementarity", *Kant-Studien*, **69**, 58-66, 1978 ; H. Folse, *The Philosophy of Niels Bohr : The Framework of Complementarity*, North-Holland, 1985 ; D. Murdoch, *Niels Bohr's Philosophy of Physics*, Cambridge University Press, 1987 ; A. Pais, *Niels Bohr's Time in Physics, Philosophy, and Polity*, Oxford University Press, 1991

<sup>13</sup> C. Held, "Bohr and Kantian idealism", in : H. Robinson & G. Brittan (eds.), *Proceedings of the Eighth International Kant Congress*, Marquette University Press, 1995, P. Kauark-Leite, *Théorie quantique et philosophie transcendantale : dialogues possibles*, Hermann, 2012 ; H. Pringe, *Critique of the Quantum Power of Judgment. A Transcendental Foundation of Quantum Objectivity*, de Gruyter, 2007 ; M. Cuffaro, "The Kantian Framework of Complementarity", *Studies in History and Philosophy of Modern Physics*, **41**, 309-317, 2010

(that we relate to the *a priori* forms by which, according to Kant, the subject contributes the objectivity of knowledge).

## 2. Kant's and Bohr's "Copernican" turns

It is our task in this section to document some essential features of Kant's theory of knowledge, and to find equivalent moves or clear differences in Bohr's philosophy of quantum physics.

As a way to characterize what he regarded as a radical rupture with previous philosophical traditions (empiricists and rationalists alike), Kant described his epistemology as a "Copernican revolution". By this term, Kant meant to emphasize the analogy between his approach and Copernicus' decision to base the explanation of the apparent motion of planets on the *relations* between the motion of our own Earth and the orbit of the planets, instead of sticking to a theory of their *intrinsic* kinematics. Rather than remaining exclusively fascinated by his object of study (the planets), Copernicus focused on the situation *of the astronomer* on planet Earth, and he addressed the problem of how this particular situation contributes to shaping cosmological knowledge. The generalization of this reflective stance to scientific knowledge in general is described by Kant in striking terms:

"Thus far it has been assumed that all our cognition must conform to objects ... Let us try to find out by experiment whether we shall not make better progress ... if we assume that objects must conform to our cognition."<sup>14</sup>

This does *not* mean that objects are so to speak *created* by our cognition, but (i) that one cannot dispense with a proper analysis of our own faculties of knowing, if knowledge is to be understood at all, and (ii) that the form of objects is predetermined by a set of cognitive conditions enabling us to overcome the variegation of fleeting subjective appearances, and to circumscribe some invariant phenomena which can be intersubjectively recognized and designated. In this case, "object" is the name of such experiential invariants, not of something beyond experience. Kant then tried to identify what, in the structure of our cognition, makes the identification of unified invariant phenomenal patterns possible. And he found two classes of such structures. The first one is our continuum of sensory givenness, namely space and time. The second one is the table of general concepts of our understanding (or categories) that are used to bring a variety of sensory appearances under a common organization. Among the latter, we find: (i) the category of *substance*, that permanently unifies a set of attributes and (ii) the category of *causality*, that gives us the possibility of making

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<sup>14</sup> I. Kant, *Critique of Pure Reason*, BXVI, Hackett Publishing Co., 1996, p. 21

a difference between unruly subjective successions and law-like sequences of phenomena that any subject can pick out.

Like Kant, Bohr was thoroughly concerned with the inherent structures of our cognitive apparatus, and he thought that we cannot dispense with studying them, if we want to make sense of the theoretical byproduct of our scientific inquiry. Bohr's notion of experience is definitely Kantian in that "all knowledge presents itself *within a conceptual framework*", where, by "a conceptual framework", Bohr means "an unambiguous logical representation of relations between experiences."<sup>15</sup> As he explains in a letter to Einstein, "...the boundary of our concepts is exactly congruent with the boundary to our possibilities of observation."<sup>16</sup> In his reflective analysis of the general structure of our capability to know, however, Bohr did not address, as Kant did, mental faculties such as sensibility and understanding. Instead, he focused on a technological counterpart of sensibility, namely the measuring apparatus, and on an intersubjective counterpart of understanding, that is, language. On the one hand, Bohr stressed again and again the importance of paying due attention to the experimental context in which phenomena occur, and pointed out the impossibility of conceiving of the latter by extrapolating them altogether from the former.<sup>17</sup> On the other hand, following (and even anticipating) in part the linguistic turn of the philosophy of his time, he saw in the conditions for unambiguous communication an essential feature of scientific objectivity.<sup>18</sup>

Bohr's "Copernican turn" can naturally be understood in the context of the quantum revolution that took place in the first decades of the twentieth century. As long as a certain scientific paradigm (in Kuhn's sense) is generally accepted, the project of science can be understood as characterizing better and better its purported *objects*. However, when the paradigm is crumbling, the ontological status of its very objects comes under suspicion, and the standard procedures for extracting invariant phenomena are also put into question. One then falls down on the only firm ground left, which is experience itself, together with the experimental means of getting definite measurement values on which the manifold of subjective experiences can concur. Bohr's view that "the task of science is both to extend the range of our experience and to reduce it to order"<sup>19</sup> enables him straightforwardly to deal with such a situation. The instrumentalist attitude (which was all but uncommon among the physicists involved in the creation of quantum mechanics) is however decisively supplemented, in Bohr's case, by a careful analysis of the conditions of possibility of experience. He is, in other words, concerned with precisely the sort of reflective knowledge that Kant

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<sup>15</sup> APHK, p. 67-8, our emphasis.

<sup>16</sup> letter to Einstein, 1927, in Honner 1982, p.7

<sup>17</sup> reference

<sup>18</sup> reference

<sup>19</sup> N. Bohr, *Atomic Theory and the Description of Nature*, op. cit. p. 1

called *transcendental* and regarded as the fundamental subject-matter of “post-Copernican” metaphysics.

The word “transcendental” is a variation of the more common word “transcendent”. Both terms point semantically towards something “exceeding experience”. But “exceeding” can be achieved in two antithetical ways. A transcendent *object* exceeds experience insofar as it is said to exist *beyond* experience, as a remote (and intellectually reconstructed) external cause of experienced phenomena. Conversely, a transcendental structure exceeds experience because it is a *precondition* of experience: it shapes up experience without being part of experience. Moreover, as long as the act of knowing develops, such a transcendental structure is bound to remain in the silent background of this act. We bump here into the extraterritorial status of the precondition of knowledge - a status that Kant, who created the very concept of a transcendental epistemology, regarded as a strong logical requirement. In his own terms, the question of how the condition of possibility of knowledge “... is (itself) possible, will not admit of any further solution or answer, because we invariably require it for all answers and for all thought of objects.”<sup>20</sup> To sum up, what plays the role of the knower cannot be known in the very process of knowing; what preconditions the possibility of a quantum description cannot be described quantum-mechanically in the very process of describing.

As we will see in Section 3, Bohr held very similar views with regard to measurement. In particular, he regarded all attempts to treat the process of acquisition of knowledge as if it were an object of the sciences of nature (of the *knowledge* of nature!), as fundamentally misguided. As one of the most accomplished realizations of the ideal of universal description pursued by the sciences, quantum theory can indeed describe any known phenomena. Yet, it cannot avoid leaving *the preconditions for this very description* outside its scope. As a well-known article about the measurement problem of quantum mechanics put it: the quantum theory can describe *anything*, but not *everything*.<sup>21</sup> In his discussions with Einstein, Bohr developed in detail an argument to the effect that the “indivisibility of the quantum of action”<sup>22</sup> precludes the description of the measurement interaction.<sup>23</sup> In other words, the measuring instrument, *qua* measuring instrument, cannot be described by quantum mechanics (for, if it is to serve as a *measuring* instrument, it cannot obey the uncertainty relations). Bohr’s conclusion was that: “It must above all be recognized that, however far quantum effects transcend the scope of classical physical analysis, the account of the experimental arrangement and the record of the observations must always be expressed in common language supplemented with the terminology of classical

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<sup>20</sup> I. Kant, *Prolegomena to any Future Metaphysics*, Pearson, 1994, §36

<sup>21</sup> A. Peres & W. Zurek, “Is quantum theory universally valid?”, *American Journal of Physics*, 50, 807-810, 1982 ; C. Fuchs & A. Peres, “Quantum theory needs no ‘interpretation’”, *Physics Today*, 53, 70-71, 2000

<sup>22</sup> add reference

<sup>23</sup> D. Murdoch, *Niels Bohr’s philosophy of physics*, op. cit., Ch. 5

physics.”<sup>24</sup> This in turn implies that a *cut* must be introduced somewhere in the measuring chain, in order to separate the object-system to be described by the quantum symbolism from the measuring instrument, which is described in classical terms. Characteristically, in Bohr’s writings, this issue is often related to what he calls the “subject-object separation”.<sup>25</sup>

We have thus far focused on the subjective term of the cognitive relation, which is the one towards which the word “transcendental” points. Let us now bring into focus the other, objective term of the relation. Beyond the horizon of experience, when we look in the direction pointed by the word “transcendent”, lies, according to Kant, the ideally conceived “thing in itself”, that is, the thing as it *is* independently of any relation with our faculties of knowledge, which, as such, is doomed to remain undisclosed for ever. Things in themselves are to be contrasted with the objects of experience, which, according to Kant, are intrinsically relational:

“Things ... are given in intuition with determinations that express mere relations without being based on anything intrinsic; for such things are not things in themselves, but are merely appearances. Whatever [characteristics] we are acquainted with in *matter* are nothing but relations (what we call its intrinsic determinations is intrinsic only comparatively); but among these relations there are independent and permanent ones, through which a determinate object is given to us.”<sup>26</sup>

What we call “properties of material objects” are only the expression of the cognitive relations that we establish with our environment; they are not “proper” to some object, but rather arise as an unanalyzable byproduct of our interaction with “it” (the quotation marks surrounding the word “it” is justified by the fact that, in Kant’s approach, there are no such things as preexisting objects waiting for sensorial or experimental study, but that “object” is the name we give to the common focus of a consistent set of “independent and permanent” relations with *what there is*). What exists beyond these cognitive relations and independently of them is *in principle* unreachable, since reaching it would precisely mean establishing a cognitive relation with it. So much so that some commentators concluded that “thing in itself” is only Kant’s word for the impossibility of disentangling ourselves completely from the content of our knowledge;<sup>27</sup> it is only a word for the impossibility to subtract the contribution of the knower from the mass of what is known.

Here too a close analogy with Bohr can be drawn. Although, as we have seen, the influence of Kant on Bohr was arguably only an indirect one, under the pressure of quantum mechanics Bohr came to endorse a position about properties which is remarkably similar to that of the philosopher of Königsberg. Starting

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<sup>24</sup> N. Bohr, “On the notions of Causality and Complementarity”, *Dialectica* 2, 313, 1948

<sup>25</sup> N. Bohr, *Essays 1958-1962*, op. cit., p.12

<sup>26</sup> I. Kant, *Critique of Pure Reason*, B341, op. cit. p. 340

<sup>27</sup> J. Hintikka, “Dinge an sich revisited”, in : J. Hintikka, *Knowledge and the Known*, Reidel, 1974

from the observation “that the properties of atoms are always obtained by observing their reactions under collisions or under the influence of radiation”,<sup>28</sup> Bohr showed that the quantum of action compels us to acknowledge the existence of a fundamental “limitation on the possibilities of measurement”.<sup>29</sup> Unlike Heisenberg and others, however, Bohr did not endorse the interpretation according to which the “disturbance” introduced by the measuring agent prevents us from having complete knowledge of the properties of the object under study. Nor did he suggest that we should regard those properties as intrinsically fuzzy or unsharp. He rather insisted on the “impossibility of a strict separation of phenomena and means of observation”,<sup>30</sup> and accordingly on the unworkability of defining attributes that be *proper* to the atomic object (which conditions the use of the name “property”). Since “... interaction forms an inseparable part of the phenomena”,<sup>31</sup> any discourse about phenomena going on in nature independently of any measuring interaction is meaningless according to Bohr; and the very concept of independent properties of objects accordingly loses any ground.<sup>32</sup> As we will see in Section 4, in his later writings, Bohr took a further step by advocating the “interactionality conception of microphysical attributes”,<sup>33</sup> according to which properties can only be meaningfully *defined* in certain experimental contexts, and not in others.

The consequences of Bohr’s inseparability thesis are exactly the same as those of Kant’s thorough relationism. The two available options are: (i) accepting that there is something like a “micro-object in itself” that we can know only obliquely, by means of successive interactive approaches; (ii) declaring that any term referring to some such obliquely knowable “micro-object in itself” is a fake name for the impossibility of disentangling the wholeness of phenomena. Arguably, Bohr’s concept of *complementarity* was, at least to some extent, intended to make option (i) viable. As in the case of the “cut”, here too we are confronted with an *ad hoc* restriction of the empirical domain available for the quantum description. In this case, the restriction is meant to enable us to conceive of the quantum phenomena as manifestations of the properties *of an object*. It is only within certain well specified sets of experimental situations that the conceptual framework presupposed by certain classes of predicate attributing sentences can be employed without inconsistencies.

The last feature of Kant’s epistemology that we need to point out is the organic articulation of what he identified as the two sources of knowledge, namely sensibility and understanding. Kant considered that the unity brought by concepts could only concern the data of sensory intuition, and he then looked for a proper

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<sup>28</sup> N. Bohr, *Atomic Theory and the Description of Nature*, op. cit., p. 95

<sup>29</sup> Ibid.

<sup>30</sup> N. Bohr, *Atomic Theory and the Description of Nature*, op. cit., p. 96

<sup>31</sup> N. Bohr, *Essays 1958-1962 on Atomic Physics and Human Knowledge*, in: *The Philosophical Writings of Niels Bohr*, Volume 3, Ox Bow Press, 1987, p. 4

<sup>32</sup> I would add references from Bohr’s writings here – I have some [...].

<sup>33</sup> M. Jammer, *The Philosophy of Quantum Mechanics*, John Wiley, 1974, p. 160

locus of connection between the forms of understanding and the contents of intuition. This locus was found in what he called the “schematism of pure imagination”.<sup>34</sup> Schematism can be figured out as the ability to elaborate pictures guiding possible actions that purport to anticipate in a systematic way certain contents of sensory intuition. An example of such connection is *causality*. As a concept of pure understanding, causality applies, according to Kant, to sensory contents pre-ordered by a spatio-temporal structure. And its application is mediated by the scheme of succession according to a rule (a generic term for the trajectories of a dynamics), which allows one to anticipate later phenomena from the knowledge of an appropriate set of earlier phenomena.

It is precisely at this point that Bohr parts company with Kant. Being faced with the puzzling phenomena of atomic physics, Bohr became increasingly diffident of some components of Kant’s account of the constitution of experience. In 1924, he questioned the universal applicability of the category of causality, deeming that this could well prove incompatible with “picturing” of trajectories in space-time; and in view of the failure of his challenge of conservation principles, he endorsed the view that, conversely, no single “picture” could be meaningfully used to represent atomic processes. Pictures were accordingly restricted to the role of purely “symbolic”, not to say “poetical”, approaches of the atomic domain.<sup>35</sup> Later on, Bohr took an even more definite stance according to which the category of causality and the spatio-temporal coordination of phenomena are mutually exclusive (see Section 4). Anticipation of phenomena was no longer performed on the basis of a continuous spatio-temporal representation of phenomena, but rather by using “... a purely symbolic scheme permitting only predictions ... as to results obtainable under conditions specified by means of classical concepts.”<sup>36</sup> Thus, a major keystone of Kant’s theory of knowledge was removed, and, to many physicists of the time, the entire building looked like it was doomed to crumbling.

The divergence between Bohr and Kant can be characterized in a few words. Kant claimed that the forms of sensibility and understanding he had identified were *a priori* conditions of possibility of objective knowledge in general. This suggested that these forms, as well as their articulation, were fixed for ever by way of necessity, and that no scientific knowledge might be conceived which would *not* fit within such a scheme. *A fortiori*, no vicissitude of scientific research might be expected to result in an alteration of those forms. As for Bohr, he accepted the typically Kantian idea of *a priori* forms of knowledge. He stressed that “... in spite of their limitations, we can by no means dispense with those forms of perception which colour our whole language and in terms of which all experience must ultimately be expressed.”<sup>37</sup> But Bohr also considered that, in view of these limitations, “... we must always be prepared ... to expect alterations

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<sup>34</sup> I. Kant, *Critique of Pure Reason*, B177, op. cit. p. 210

<sup>35</sup> W. Heisenberg, *Physics and Beyond*, op. cit., chapter III

<sup>36</sup> N. Bohr, *Essays 1933-1957 on Atomic Physics and Human Knowledge*, op. cit., p. 40

<sup>37</sup> N. Bohr, *Atomic Theory and the Description of Nature*, op. cit., p. 5

in the points of views best suited for the ordering of our experience.”<sup>38</sup> The idea of modifying the so-called “*a priori*” forms of human knowledge according to the advances of scientific research was so averse to Kant, that this alone justified the rejection by many philosophers of science of any similarity between Bohr’s and Kant’s theory of knowledge.<sup>39</sup> However, even in this particular respect, the relation between the two theories is more complex than it at first sight appears.

To begin with, Kant’s epistemology need not be viewed as the static articulation of the ideas displayed in Kant’s own system. One can also regard it as a *research program*. Such a program was developed by an entire school of neo-Kantian philosophy, whose major move was to historicize and relativize the so-called “*a priori* forms of knowledge”.<sup>40</sup> The function of these forms, which is to unify and extract invariants in the midst of appearances, can for instance be ascribed to plastic “symbolic forms” (Cassirer<sup>41</sup>), or to historically relative “principles of coordination” (Reichenbach<sup>42</sup>). Philosophical pragmatism itself can, to a large extent, be traced back to a Kantian framework, provided that the latter’s emphasis on the absolute *a priori* is attenuated.<sup>43</sup> These examples show that Kant’s epistemology, when conceived as a research program, might indeed display the kind of flexibility required for accounting of quantum knowledge.

Conversely, one might argue that Bohr’s epistemology is itself characterized by a sort of *a priori* component, namely “classical concepts”. As we have seen, Bohr employs classical concepts in two different contexts: the description of the measuring apparatus and that of the complementary aspects of a given atomic phenomenon. He was always opposed to replacing classical concepts with new concepts allegedly more suited to deal with atomic phenomena. In his reply to a letter in which Schrödinger urged a “re-organisation involv[ing] the most profound levels of our knowledge, space, time and causality”,<sup>44</sup> Bohr remarked: “...I am scarcely in complete agreement with your stress on the necessity of developing ‘new’ concepts. (...) The ‘old’ experimental concepts seem to me to be inseparably connected with the foundation of man’s powers of visualizing.”<sup>45</sup>

In so far as we confine our analysis to the measuring apparatuses and other massive objects *as considered within ordinary experience*, Bohr thinks that we are allowed to rely on “our accustomed forms of perceptions”, in spite of having learned from quantum mechanics that these are mere “*idealizations*”.<sup>46</sup> In this

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<sup>38</sup> N. Bohr, *Atomic Theory and the Description of Nature*, op. cit., p. 1

<sup>39</sup> Folse, 1978... See discussion in : D. Kaiser, “More roots of complementarity : Kantian aspects and influences”, loc. cit.

<sup>40</sup> M. Friedman, *Kant and the Exact Sciences*, Harvard University Press, 1992 ; M. Bitbol, *Mécanique quantique, une introduction philosophique*, Flammarion, 1996 ; M. Bitbol, “Some steps towards a transcendental deduction of quantum mechanics”, *Philosophia naturalis*, 35, 253-280, 1998 ; D. Pradelle, *Généalogie de la raison*, P.U.F., 2013

<sup>41</sup> E. Cassirer, *Philosophy of Symbolic Forms*, Yale University Press, 1965

<sup>42</sup> H. Reichenbach, *The Theory of Relativity and a priori Knowledge*, University of California Press, 1965

<sup>43</sup> Putnam, etc.

<sup>44</sup> E. Schrödinger, letter of.. , quoted in D. Murdoch,...p. 101

<sup>45</sup> N. Bohr, letter.... Ibid.

<sup>46</sup> N. Bohr, *Atomic Theory and the Description of Nature*, op. cit.,p. 5

sense, Bohr can be thought to acknowledge the enduring pragmatic value of Kant's *a priori* forms. The empirical domain to which such forms apply is nevertheless severely hampered.<sup>47</sup> It does not extend to the whole field of microphysics, but only to ordinary experiences and experiences which fall within the scope of classical physics. It is an anthropological condition of possibility for the technological conditions of possibility of microphysical research. Therefore, as Heisenberg pointed out, it can be called a second-order condition of possibility of microphysical knowledge: "What Kant had not foreseen was that these *a priori* concepts can be the conditions for science and at the same time have a limited range of applicability."<sup>48</sup> The forms that directly precondition knowledge of our familiar experience and of the empirical domain of classical physics, have limited range of applicability, but at the same time they indirectly precondition knowledge of any research beyond this domain. This may be seen as Bohr's simultaneous vindication and confinement of Kant's *a priori*.

One may argue along the same lines that classical concepts can, and must, be applied to microphysics, provided that one considers well-defined *phenomena* in the Bohrian sense, that is, "observations obtained under specified circumstances, including an account of the whole experimental arrangement",<sup>49</sup> such that only sets of compatible observables are measured. But where does the *necessity* of employing classical concepts come from? The need to retain classical concepts can be generically related, as Bohr repeatedly did, to the conditions of possibility of unambiguous communication: "(...) By the word 'experiment' we refer to a situation where we can tell others what we have done and what we learned and (...) therefore, the account of the experimental arrangement and of the results of the observations must be expressed in unambiguous language with suitable application of the terminology of classical physics."<sup>50</sup> As we will see in Section 5, however, Bohr's lack of enthusiasm for any project involving the *replacement* of classical concepts stems less from his attachment to those particular "forms of perception" than from the conviction that what quantum mechanics demands is not so much a new set of concepts as a deeper understanding of the way concepts *in general* enters the construction of objective knowledge. This, once again, sounds like a distinctly Kantian concern. Bohr's suggestion that we should think of "the viewpoint of complementary forms" as "a consistent *generalization* of the ideal of causality"<sup>51</sup> should be understood in this context.

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### 3. Enabling measurement : cut

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<sup>47</sup> M. Bitbol, "Reflective metaphysics: understanding quantum mechanics from a kantian standpoint", *Philosophica*, 83 (2009), 53-83, 2011

<sup>48</sup> W. Heisenberg, *Physics and philosophy*, Penguin, 1990, p. 78

<sup>49</sup> N. Bohr, *Atomic Physics and Human Knowledge*, op. cit., p. 64

<sup>50</sup> *Ibid.*, p. 39

<sup>51</sup> *Ibid.*, p. 27, our emphasis

As we have seen in section 1, Bohr ascribed a kind of extraterritorial status to measuring instruments, measurement outcomes, and experimental activities, by imposing a classical mode of description onto them and cutting them from the quantum mode of description. This was not meant to assert the uncommon *nature* of such macroscopic objects and laboratory procedures, but only to ascribe them an indispensable *function* in the system of knowledge: that of a condition of possibility of intersubjective agreement about experimental results and activities. Such functional rather than substantial status of the classical mode of description is confirmed by Bohr's insistence that the boundary between the classical and quantum domains is by no means fixed, and that we even have a "free choice"<sup>52</sup> of the exact location of this boundary. An advantage of ascribing classical concepts the function of a condition of possibility of quantum knowledge is that this automatically dissolves the measurement problem from the outset. Indeed: (i) in so far as a classic-like actualistic description of a relevant part of the measuring instruments is taken as a fundamental presupposition of any quantum account of phenomena, there is no need to figure out a mechanism for the transition between potentialities and actuality; or (ii) since the quantum description is prevented from extending to the totality of the measurement chain, there is no such thing as a superposition of pointer macrostates.

Saying that Bohr's classic-like extraterritorial status of measuring procedures is not very popular among physicists would be an understatement.<sup>53</sup> In fact, this approach of the measurement problem is frequently *abhorrent* to them, either because it suggests that their discipline has fundamental limits that cannot be overcome, or because it acknowledges that physics cannot account (even retrospectively) for the experimental conditions of its own assessment. The standard bearer of this rejection of Bohr's view is Bell's celebrated paper "Against 'measurement'".<sup>54</sup> What Bell criticizes eagerly in this article is the decision to stick to propositions that are valid only "for all practical purposes (FAPP)". Being the archetype of such propositions, the classic-like status of measuring devices, together with the split between classical apparatuses and quantum world, is the central target of Bell's attack. Bell thus called for a mature quantum mechanics in which the "shifty split" would be completely omitted, and its symbols would "refer to the world as a whole". Bohm's theory and Everett's theory are good candidates to such status: they both claim to be varieties of quantum physics, yet to provide us with descriptions of the world as a whole, including the measuring apparatus. Bell was leaning towards Bohm's theory, while he criticized Everett's for its defense of something like a *solipsism of the present*.<sup>55</sup> More recently,

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<sup>52</sup> N. Bohr, "Can quantum-mechanical description of physical reality be considered complete", *Physical Review*, 48, 696-702, 1935

<sup>53</sup> Here I can provide a couple of nice quotations [...]

<sup>54</sup> J. Bell, "Against 'measurement'", *Physics World*, 8, 33-40, 1990

<sup>55</sup> J. Bell, *Speakable and Unsayable in Quantum Mechanics*, Cambridge University Press, p. 136

decoherence theories have become the most widely accepted realizations of the project of describing the world as a whole, since they claim to derive classical behavior from the quantum formalism, instead of presupposing it.<sup>56</sup>

So, can we now bury safely Bohr's alleged "cut" between the domain of study and the experimental means of investigation; can we just skip completely the presupposition of classical concepts in the foundations of quantum physics? Our answer is negative: the function of the "cut" *has* to be fulfilled somehow. We must repeat that the function of Bohr's cut was to avoid any confusion between the predictive formalism of quantum mechanics and the elementary presuppositions needed for putting it to the test. These two things are logically distinct; they appertain respectively to a theoretical and pre- (or meta-) theoretical level of thought.<sup>57</sup> True, no intrinsic feature of the measuring apparatus forces one to treat it on the pre-theoretical rather than theoretical level,<sup>58</sup> but if the theoretical level is chosen for describing the apparatus, the pretheoretical level has to irrupt at some earlier or later stage of the statement of the project of measurement and the measuring outcome. As a consequence, the shadow of this distinction remains visible, and uneliminable, in *all* the above-mentioned theories. The privilege of space coordinate variables in Bohm's theory is the shadow of the spatio-temporally located classical pointer variables. Everett's frequent changes of standpoint between (i) a purely external description of the "universal state vector" and (ii) an internal description of what is recorded in the "memory bracket" of some given counterpart of the observer on one "branch" of this state vector, is the shadow of the two levels (theoretical and pretheoretical) of any physical description. As for decoherence theories, their ability is only to derive quasi-classical probabilistic structures (namely approximately diagonal reduced density matrices of systems), not a full degree of classicality;<sup>59</sup> moreover, in order to do so, they rely on a deliberate selection of the relevant degrees of freedom of the system within a larger domain of environmental degrees of freedom, which can be seen as the shadow of the system-context cut.

We must ponder some more time on this issue of the shadowy presence of the system-context or theoretical-pretheoretical cut, because it is especially tricky. In classical physics, the indispensibility of the pretheoretical level was usually hidden, because in this very special case, the pretheoretical treatment of the measurement process could easily be made *isomorphic* to its theoretical description. So much so that isomorphism could be taken as a case of identity, and "... the measurement process could be understood as a special case of the

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<sup>56</sup> E. Joos, H. D. Zeh, C. Kiefer, D. Giulini, J. Kupsch, & I.-O. Stamatescu, *Decoherence and the Appearance of a Classical World in Quantum Theory*, Springer, New York, 2003

<sup>57</sup> P. Mittelstaedt, *The Interpretation of Quantum Mechanics and the Measurement Process*, Cambridge University Press, 1998, p. 8

<sup>58</sup> *Ibid.* p. 104

<sup>59</sup> M. Schlosshauer & K. Camilleri, "What classicality? Decoherence and Bohr's classical concepts", *Advances in Quantum Theory, AIP Conference Proceedings*, 1327, 26-35, 2011

general laws applying to the entire universe”<sup>60</sup>. Nothing seemed to hinder the grand project of an entirely *naturalized* theory of knowledge, whereas Kant’s intimation of a *transcendental* conception of knowledge was neglected or taken as optional. By contrast, all we have seen until now inclines us to think that no attempt at elaborating a fully *naturalized* theory of the knowledge process has been successful in the quantum paradigm, and that a *transcendental* approach of knowledge (whose archetype has been formulated by Bohr) becomes more clearly unavoidable in this theory than anywhere else. Let us make one more little pause at this point: what is the difference between a naturalized and a transcendental theory of knowledge? What is the meaning of these two words, “naturalized” and “transcendental”?

Such attempts are based on the idea that the measuring apparatus should obey the same laws of nature as the measured object, so that it should be possible to describe the measurement interaction as a standard natural process. More generally, the whole cognitive operation, including the *decision* to perform an experiment and the *realization* of the outcome of that experiment, is considered as a topic for natural sciences such as neurobiology, biochemistry, optics etc. At first sight, this option of naturalization looks quite reasonable and innocuous. Nothing seems to prevent the continuous expansion of the domain of validity of the sciences of nature towards an increasing disclosure of the knowing process: after all, a measuring apparatus, a sense organ, and a brain are quite standard material objects. Nothing therefore seems to threaten the ideal of sciences, which is to understand in their own terms each element of *what there is*.

Interestingly, this debate between naturalized and transcendental epistemologies overtly took place during a remarkable discussion between Bohr, Wheeler and Everett at the end of the 1950’s, about the latter’s “relative state” interpretation of quantum mechanics. Wheeler, who regarded himself as an orthodox Bohrian, appeared to be convinced that Everett’s proposal might be endorsed by Bohr as a decisive improvement of the Copenhagen interpretation. Bohr and his collaborators, however, far from acknowledging that Everett’s proposal delivered a more *complete* account of experience, regarded it as a deep misunderstanding of their ideas.<sup>61</sup> The main reason for this rejection was precisely that Bohr could not accept Everett’s denial of the classical-like extraterritorial status of (part of) the measurement process. Against Everett’s claim that basing quantum physics upon classical physics was only a provisional step,<sup>62</sup> Rosenfeld replied: “To try (as Everett does) to include the experimental arrangement into theoretical formalism is perfectly hopeless, since this can only shift, but never

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<sup>60</sup> D. Bohm & B. Hiley, *The undivided universe*, Routledge, 1993, p. 13

<sup>61</sup> S. Osnaghi, F. Freitas, & O. Freire, “The origin of the Everettian heresy”, *Studies in History and Philosophy of Modern Physics*, 40, 97-123, 2009

<sup>62</sup> *Ibid.*

remove, this essential use of unanalysed concepts which alone makes the theory intelligible and communicable.”<sup>63</sup> Here, the irreducibly *transcendental* status of the measurement process, manifested by its being described with classical concepts, was clearly reasserted against Everett’s dream of naturalizing everything (including the act of measuring). This transcendental status can be ascribed to any part of the process, its field of application can be extended or shrunk, but it can by no means be eliminated altogether (in Rosenfeld’s terms, it can be “shifted” but not “removed”).

#### 4. From phenomena to objects : complementarity

According to Bohr, a crucial consequence of the “interactionality” conception of microphysical attributes, of the fact that experimental modes of access cannot be separated from phenomena, is *complementarity*. Let us follow Bohr’s reasoning. In classical physics, where the influence of the measuring procedure can easily be subtracted from its outcome, data obtained by using various instruments “... supplement each other and can be combined into a consistent picture of the behaviour of the object under consideration”<sup>64</sup>. But in quantum physics, changing the experimental arrangement is tantamount to changing the holistic phenomenon itself, which therefore turns out to be incompatible with other holistic phenomena. “Combination into a single picture”<sup>65</sup> of various experimental data then yields contradictions. The contradictions are overcome only at the cost of loosely articulating the information derived from various experimental arrangement by a new non-pictorial method called “complementarity”. Indeed, according to complementarity, these variegated pieces of information are taken to be mutually exclusive, yet jointly indispensable to characterize a certain micro-object:

“... 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.”<sup>66</sup>

But Bohr’s complementarity is no simple or unambiguous concept. One may list *three* (disputable) applications of the concept of complementarity in quantum mechanics<sup>67</sup>:

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<sup>63</sup> L. Rosenfeld, letter to S. Bergmann, 21 December 1959, quoted and commented in : S. Osnaghi, F. Freitas, & O. Freire, “The origin of the Everettian heresy”, loc. cit.

<sup>64</sup> N. Bohr, *Essays 1958-1962 on Atomic Physics and Human Knowledge*, in: *The Philosophical Writings of Niels Bohr*, Volume 3, op. cit., p. 4

<sup>65</sup> Ibid.

<sup>66</sup> N. Bohr, *Essays 1933-1957 on atomic physics and human knowledge*, op. cit., p. 40

<sup>67</sup> J. Faye, *Niels Bohr: his heritage and legacy*, Kluwer, 1991; C. Held, “The meaning of complementarity”, *Studies in History and Philosophy of Science*, 25, 871-893, 1994; M. Bitbol, *Schrödinger’s Philosophy of Quantum Mechanics*, Kluwer, 1996

C1- *The complementarity between incompatible variables.* “In quantum physics ... evidence about atomic objects obtained by different experimental arrangements exhibits a novel kind of complementary relationship.”<sup>68</sup> A standard example is the complementarity of the archetypal couple of conjugate variables, namely position and momentum.

C2- *The complementarity between causation and spatiotemporal location of phenomena.* This was the first explicit statement of complementarity in Bohr’s Como lecture of 1927: “The very nature of quantum theory (...) forces us to regard the space-time coordination and the claim of causality, the union of which characterizes the classical theories, as complementary but exclusive features of the description, symbolizing the idealization of observation and definition respectively.”<sup>69</sup>

C3- *The complementarity between the continuous and discontinuous pictures of atomic phenomena, i.e. between the wave model and the particle model:*

“The individuality of the elementary electrical corpuscles is forced upon us by general evidence. Nevertheless, recent experience, above all the discovery of the selective reflection of electrons from metal crystals, requires the use of the wave theory superposition principles in accordance with the original ideas of L. de Broglie. ... In fact, here again we are not dealing with contradictory but with complementary pictures of the phenomena which only together offer a natural generalization of the classical mode of description.”<sup>70</sup>

Let us discuss these three versions of complementarity in turn, starting with the last one, C3. This is at the same time the most popular and the most controversial version of complementarity, since it involves remnants of classical *representations* (rather than classical *variables*, or classical terminology for the description of measuring apparatuses).<sup>71</sup> Moreover, after 1935, Bohr “(...) tacitly abandons the idea of wave-particle complementarity.”<sup>72</sup> From this moment on, the concept of complementarity only allows indirect “clarification” of the dilemma of wave-particle dualism;<sup>73</sup> it does not operate directly on the corresponding couple of representations.

The C1 version of complementarity is likely to be closer to the roots of the concept, yet it is not without difficulties of its own. The most benign difficulty is that, from the incompatibility of experimental arrangements, one cannot derive *immediately* the incompatibility of the corresponding value ascriptions to an object. For nothing precludes that it is only our experimental *knowledge* of position which is incompatible with our experimental *knowledge* of momentum, whereas the object intrinsically “possesses” both properties. But, as we have seen

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<sup>68</sup>N. Bohr, *Essays 1958-1962 on Atomic Physics and Human Knowledge*, op. cit., p. 4

<sup>69</sup>N. Bohr, *Atomic Theory and the Description of Nature*, op. cit., p. 54f

<sup>70</sup>Ibid., p. 56

<sup>71</sup>D. Murdoch, *Niels Bohr's philosophy of physics*, op. cit. p. 79

<sup>72</sup>C. Held, “The meaning of complementarity”, loc. cit.

<sup>73</sup>N. Bohr, *Essays 1958-1962 on atomic physics and human knowledge*, op. cit., p. 25

previously, this narrowly epistemic interpretation of incompatibility was ruled out by Bohr, when he declared that the experimental arrangement is part of the *definition* of the corresponding variable, rather than an instrument for revealing its intrinsic value. A much more serious difficulty bears on the claim that the values of incompatible variables are *jointly* indispensable to exhaust knowledge about the object. How can this be made compatible with Bohr's rejection of the classical thesis according to which two incompatible variables referring to a given object are *simultaneously* endowed with definite values? A way to bypass *simultaneous* possession consists in saying that joint indispensibility concerns *successive* measurements actually performed in order to exhaust knowledge about the object. But this solution is not satisfactory either, because the values can vary according to the *order* of measurements. An alternative, more satisfactory, interpretation is that exhaustiveness concerns the full list of *possibilities* of observation one has, before any experimental arrangement has been chosen.<sup>74</sup> Along this line of thought, one may reconcile mutual exclusion and completion of conjugate variables without logical inconsistency: mutual exclusion pertains to *actual* experimental arrangements, whereas completion (or exhaustiveness) refers to *possible* measurements.

An even deeper problem nevertheless remains unaddressed at this point. What *reason* do we have to impose (and try to justify) the idea that conjugate variables are *jointly indispensable*? According to Bohr, only the complete list of conjugate variables provides exhaustive information *about* the objects under investigation. He mentioned repeatedly this *aboutness* of experimental information as a crucial feature: "(...) evidence obtained under different experimental conditions (...) must be regarded as complementary in the sense that only the totality of the phenomena exhausts the possible information about the objects"<sup>75</sup>; "(...) together (these phenomena) exhaust all definable knowledge about the objects concerned"<sup>76</sup>; "(...) such phenomena together exhaust all definable information about the atomic objects"<sup>77</sup>. But this insistence on aboutness is highly problematic. It presupposes that despite the unanalysability (or interactionality) of micro-phenomena, it is still possible to *refer to* micro-objects as if they were somehow independent of any experimental procedure. It also suggests that these putative atomic objects have the same general predicative structure as the objects of classical mechanics, even though they are not ascribed predicates as such. Just as classical particles, "atomic objects" are indeed construed by Bohr as points of convergence of two families of conjugate features such as position *and* momentum. Conversely, if one did *not* presuppose that experimental outcomes are *about* objects endowed with the same predicative structure as the moving bodies of classical mechanics, one could perfectly accept that position and momentum are mutually exclusive without

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<sup>74</sup>C. Held, "The meaning of complementarity", loc. cit.

<sup>75</sup>N. Bohr, *Essays 1933-1957 on atomic physics and human knowledge*, op. cit., p. 40

<sup>76</sup>ibid. p. 90

<sup>77</sup>ibid. p. 99

being *jointly* indispensable for some *thing*. Once again, we are facing the dilemma of the “object in itself”: should we refer to some such “micro-object in itself” characterized by successive but mutually incompatible interactive probings; or should we rather look for a new mode of objectification that retains *nothing* (not even the adumbration of a predicative structure) of the classical corpuscularian concept? If we follow Bohr in adopting the first (conservative) strategy, we must ascribe a highly non-conventional status to micro-objects. Expressing this status in a Kantian idiom, Bohr’s cloudy “micro-object” should only be considered as a unifying *symbol* used as a regulative-heuristic device,<sup>78</sup> not as a tangible *something*. But if we adopt the “revolutionary” strategy of looking for novel forms of objectification instead of sticking to old object-like pattern, we become free to consider appropriate elements of the quantum formalism as denotations of previously unconceivable objects of knowledge. This was Schrödinger’s strategy, when he ascribed the wave function the latter kind of status.<sup>79</sup>

Let us finally examine complementarity C2 between causality and the use of space-time concepts. According to Bohr, “(...) the use of any arrangement suited to study momentum and energy balance - decisive for the account of essential properties of atomic systems - implies a renunciation of detailed space-time coordination of their constituent particles.”<sup>80</sup> This suggests that, in the same way as complementarity of conjugate variables, complementarity between causality and space-time coordination is related to the incompatibility of experimental arrangements combined with the interactionality thesis. However, other texts of the earlier period,<sup>81</sup> as well as Heisenberg’s lucid interpretation of Bohr’s position, favour another conception of the complementarity between causality and space-time coordination, which does *not* reduce it to the complementarity of pairs of conjugate variables. In his *Physical principles of the quantum theory*, Heisenberg argues that the measurement of *any* variable whatsoever involves spatio-temporal aspects. Thus, it is not only space-time coordination, but any description of phenomena in space-time, which is incompatible with causality. Indeed, one cannot observe *any* kind of spatio-temporally circumscribed phenomena without influencing them; and such an influence makes causal laws inapplicable to the said phenomena.<sup>82</sup> Such Heisenbergian interpretation of the complementarity

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<sup>78</sup> I. Kant, *Critique of Judgment*, §59, Hackett, 1987, p. 227 ; H. Pringe, *Critique of the Quantum Power of Judgment : A Transcendental Foundation of Quantum Objectivity*, op. cit.

<sup>79</sup> M. Bitbol, *Schrödinger’s Philosophy of Quantum Mechanics*, op. cit.

<sup>80</sup>N. Bohr, *Essays 1958-1962 on atomic physics and human knowledge*, op. cit. p. 11

<sup>81</sup>see e.g. N. Bohr, *Atomic Theory and the Description of Nature*, op. cit. p. 54: “(...) 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. The very nature of the quantum theory thus forces us to regard the space-time co-ordination and the claim of causality, the union of which characterizes the classical theories, as complementary but exclusive features of the description, symbolizing the idealization of observation and definition respectively”.

<sup>82</sup>W. Heisenberg, *The physical principles of the quantum theory*, op. cit. p. 63

between causality and space-time location has rapidly spread out. C.F. Von Weizsäcker<sup>83</sup> and P. Mittelstaedt<sup>84</sup> thus interpreted this version of complementarity as a relation of mutual exclusiveness and joint completion between the abstract deterministic law of evolution of  $\psi$ -functions (i.e. the Schrödinger equation) and any measurement result observed in space-time.

As suggested in section 2, this dismantling of Kant's articulation between the category of causality and spatiotemporally-shaped sensory experience is likely to have momentous consequences. It does not only challenge the special architecture of the *Critique of Pure Reason* and its *a priori* conditions of any possible knowledge. At first sight, it also threatens the global Kantian strategy of finding how the chaos of subjective impressions is progressively ordered into an objective pattern, the first step being to embed these impressions into the spatiotemporal web, and the second step being to connect the spatiotemporally located phenomena with one another according to a *law* of succession. How can one objectify phenomena, if the former procedure is no longer available? Bohr's answer is daring, but in line with the spirit (if not the letter) of Kant's epistemology. It consists in turning complementarity into a connecting device that *supplants* causality, beyond ascribing it a limited role within its own scheme of mutual exclusion and joint exhaustivity. According to Bohr, quantum physics "forces us to *replace* the ideal of causality by a more general viewpoint called 'complementarity'".<sup>85</sup> In so far as the standard (causal) connection of phenomena is prevented by the incompatibility of the various modes of experimental access, a new mode of (complementary) connection is offered as a substitute. "Complementarity is called for to provide a frame wide enough to embrace the account of fundamental *regularities* of nature which cannot be comprehended within a single picture."<sup>86</sup> But once again, we wish to point out that this replacement of a causal mode of connection with a complementary mode of connection, is aimed at extrapolating the mode of existence of standard classic-like objects endowed with mutually exclusive attributes well beyond their standard domain of relevance. The revolutionary mode of connection here compensates for a conservative ontology. A diametrically opposed strategy has been proposed, and it consists in sticking to the standard (causal) mode of connection at the cost of redefining the object of microphysics.<sup>87</sup>

## 5. Classical concepts: a remnant of Kant's a priori?

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<sup>83</sup>C. F. Von Weizsäcker, *Aufbau der physik*, Hanser, 1985

<sup>84</sup>P. Mittelstaedt, *Philosophical problems of modern physics*, Reidel, 1976

<sup>85</sup>N. Bohr, "Causality and complementarity", *Philosophy of Science*, 4, 289-298, 1937

<sup>86</sup>N. Bohr, *Essays 1958-1962 on atomic physics and human knowledge*, op. cit., p. 12

<sup>87</sup>P. Mittelstaedt, *Philosophical problems of modern physics*, op. cit.

Reformulate the argument for the cut and complementarity in semantic terms. The cut: a way to allude to the conditional nature of the elementary semantic unit; Complementarity: a way to allude to *conceptual* relations of a *probabilistic* nature. Why classical concepts to describe atomic phenomena? Why classical concepts to describe macroscopic objects (including measuring instruments)? How is this compatible with quantum mechanics? Bohr's model of the atom<sup>88</sup> includes a non-conventional compromise between classical mechanics and electrodynamics on the one hand, and Planck's "quantum rules" on the other hand. It has often been said to be "incoherent", due to its baroque combination of electronic stationary orbits ruled by classical mechanics, quantized transitions from one orbit to another, and overt violation of certain theorems of classical electrodynamics (since electrons on stationary orbits were supposed to emit no radiation despite their angular acceleration). Yet, the accusation of incoherence is excessive, in so far as the rules for using each one of the elements of the model in succession are mostly well-stated. That Bohr's model of the atom is a patchwork does not necessarily entail inconsistency, provided the pieces of this patchwork are ascribed a precise but limited use in certain restricted theoretical contexts.<sup>89</sup> In other terms, it lacks unity rather than logical and practical consistency. Of course, unity is also a major regulative ideal of physics. The natural assumption of those who realized with amazement the efficiency of Bohr's clumsy model for predicting a large range of atomic spectral lines, was that this could only be a *provisional* compromise which would sooner or later be replaced by a fully unified theory. But, to the surprise of many physicists, Bohr's path towards the new quantum theory constantly postponed the banishment of classical physics. During the intermediate phase that separated the old quantum theory and the advent of modern quantum mechanics, say from 1913 to 1925, Bohr was looking for new ways of articulating classical physics with quantum postulates, rather than trying to eliminate classical features altogether. The "correspondence principle" between classical and quantum physics acted as a pivotal element of this strategy. It went far beyond the usual retrospective requirement that the old physical theory be a limiting case of the new theory, and rather irrupted in the very fabric of the new theory. It was taken as a prospective guide towards new theoretical structures, by way of "generalization" and extrapolation. And it was also used as a sort of spare wheel for assessing the value of certain variables that were absent from the hybrid model, such as the line amplitudes. The correspondence principle here worked as a meta-theoretical structure that enabled one theoretical structure (the classical one) to serve as an analogic scaffolding for the elaboration and completion of another theoretical structure (the quantum one).<sup>90</sup> Thus, according to Bohr,

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<sup>88</sup> N. Bohr, "On the constitution of atoms and molecules", *Philosophical Magazine*, 26, 1-25, 1913

<sup>89</sup> P. Vickers, "Bohr's Theory of the Atom: Content, Closure and Consistency", <http://philsci-archive.pitt.edu/4005/>, 2007

<sup>90</sup> O. Darrigol, *From c-Numbers to q-Numbers*, University of California Press, 1992, p. 81

“Although the process of radiation cannot be described on the basis of the ordinary theory of electrodynamics ... there is found, nevertheless, to exist a far-reaching correspondence between the various types of possible transitions between the stationary states on the one hand, and the various harmonic components. ... This correspondence is of such a nature that the present theory of spectra is in a certain sense to be regarded as a rational generalization of the ordinary theory of radiation.”<sup>91</sup>

This non-conventional approach to theorizing has cogently been compared with Kant’s central prescription in his *Critique of Judgment*: bringing seemingly heterogeneous theoretical structures into a unique *system* irrespective of their differences, by way of a hypothetical use of reason.<sup>92</sup> Nevertheless, Bohr was less and less satisfied by the original compromise, and he was systematically varying the boundaries between the classical and quantum elements of his theory in order to find the most appropriate locus of the sought articulation. His strategy was a permanent negotiation between what should be retained and what should be excluded of the old patterns of physics. One crucial (though unsuccessful) step was taken in 1924, when Bohr tried to find a new way to reconcile the continuous spatio-temporal orbits and the discontinuity of quantum jumps in his model. There, he decided to retain the “picture” of orbits, but to jettison the principle of causality and the principles of conservation of energy and momentum, when the connection between each electronic motion and emission / absorption of radiation is at stake. While being no longer valid for individual processes of interaction between radiation and matter, the principles of conservation were still enforced at the statistical level.<sup>93</sup>

However, this new compromise was soon perceived as unsuccessful, and pressure was exerted towards eliminating the very classical “picture” of orbital trajectories in favor of a thoroughly “quantum” kinematics and dynamics. Such revolutionary advance was advocated by Pauli<sup>94</sup> in a letter to Bohr of December 1924, and it was sketched by Born under the newly invented label “*Quantenmechanik* (quantum mechanics)”<sup>95</sup>. The final accomplishment in this direction was, of course, Heisenberg’s “matrix mechanics”,<sup>96</sup> which completely dispensed with the concept of a continuous trajectory, replacing it with a law-like structure applying to spectral observables. Here, a systematic procedure of symbolic translation of classical laws into quantum laws was undertaken, by way of replacing ordinary continuous variables by non-commuting matrices of measurable discontinuous quantities. Yet, Bohr hailed Heisenberg’s quantum

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<sup>91</sup> N. Bohr, *The Theory of Spectra and Atomic Constitution*, Cambridge University Press, 1922, p. 24

<sup>92</sup> H. Pringe, “A transcendental account of correspondence and complementarity”, in : M. Bitbol, J. Petitot & P. Kerszberg (eds.), *Constituting Objectivity, Transcendental Perspectives in Modern Physics*, Springer, 2009

<sup>93</sup> N. Bohr, H. Kramers, & J.C. Slater, “The quantum theory of radiation”, *Philosophical Magazine*, 47, 785-822, 1924

<sup>94</sup> O. Darrigol, *From c-Numbers to q-Numbers*, op. cit., p. 208

<sup>95</sup> M. Born, “Über Quantenmechanik”, *Zeitschrift für Physik*, 26, 379-395, 1924

<sup>96</sup> W. Heisenberg, “Über die Quantentheoretische Umdeutung kinematischer und mechanischer Beziehungen”, *Zeitschrift für Physik*, 33, 879-893

mechanics as a “... precise formulation of the tendencies embodied in the correspondence principle”, and Heisenberg himself called his theory “a quantitative formulation of the correspondence principle”.<sup>97</sup> The vestige of classical physics was still utterly active in the new theory, and the only thing that remained obscure was the *reason* for this stubborn presence.

With a move whose *style* is unmistakably Kantian, Bohr later attempted to clarify this reason by turning away from ontological considerations about nature, and relying on epistemology instead. This about-turn was to become the birth act of the “Copenhagen interpretation” of quantum mechanics. From then on, the footprint of classical physics was not construed as a manifestation of the (possibly semi-classical) essence of micro-objects, but as a constraint that is inherent to us *qua* knowing and speaking subjects able to ascribe meaning to what we observe. One of Bohr’s earliest statements of this cognitive status ascribed to classical physics reads thus:

“No more is it likely that the fundamental concepts of the classical theories will *ever* become superfluous for the description of physical experience. ... It continues to be the application of these concepts alone that makes it possible to relate the symbolism of the quantum theory to the data of experience”<sup>98</sup>.

In other terms, no acceptable account of what is observed in a laboratory, and no acceptable description of the instruments that are used for that purpose, can be given in non-classical terms according to Bohr. Classical physics here remains the theoretical substrate of quantum mechanics, its basic and too often unrecognized background. Not, to repeat, because this old stratum of the history of physics has captured some sort of definitive truth about the world, but because it embodies a set of even more primitive preconditions of knowledge. These preconditions were later expressed by Bohr in a celebrated statement:

“*However far the phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms.* The argument is simply that by the word ‘experiment’ we refer to a situation where we can tell to others what we have done and what we have learned and that, therefore, the account of the experimental arrangement and of the results of the observations must be expressed in unambiguous language with suitable application of the terminology of classical physics.”<sup>99</sup>

It becomes clear from the former sentences that what is needed in full-blown quantum physics is not the integral theoretical contents of classical physics, but its *terminology*, and above all its logical two-valued unambiguous pattern of *communication*. Classical physics is here taken as the proxy of the most elementary conditions of possibility of intersubjective agreement about

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<sup>97</sup> O. Darrigol, *From c-Numbers to q-Numbers*, op. cit., p. 276

<sup>98</sup> N. Bohr, *Atomic Theory and the Description of Nature*, Cambridge University Press, 1934, p. 16

<sup>99</sup> N. Bohr, *Essays 1933-1957 on Atomic Physics and Human Knowledge*, in : *The Philosophical Writings of Niels Bohr*, Volume 2, Ox Bow Press, 1987, p. 39

experimental results as well as about the way to build and to calibrate measuring instruments. This Kant-like status of classical descriptions immediately disposes of so many criticisms of Bohr according to which the latter was a “macro-realist”<sup>100</sup> who ascribed an upper level of reality to macroscopic objects while he downgraded the reality of microscopic objects, or according to which he believed that nature is made of two realms of beings: the classical macro-entities and the quantum micro-entities.<sup>101</sup> Indeed, there is no such ontological divide in Bohr’s conception of quantum mechanics, but only a practical and epistemological divide between the referred to quantum objects and the logico-linguistic tools of reference that happen to be implemented in classical physics. Even in the most advanced attempts at avoiding any mixture of classical elements with quantum physics, the logico-linguistic *function* of the former elements must be fulfilled.

## 6. Conclusion

In his *Critique of Pure Reason*, which addresses our interest for *nature*, Kant explained how, without truly disentangling ourselves with respect to what there is, we can nevertheless elaborate a form of knowledge that works *as if* we were separated from nature. This approach, which ascribes us a role which mimics that of an external *spectator* of nature, is called “objective knowledge”. By contrast, in his *Critique of Practical Reason*, which deals with the issues of freedom, action, and morals, any such separation is precluded and we are ascribed the role of true *actors* of our own deeds<sup>102</sup>. This dialectic of actor and spectator was later taken over by Schopenhauer, in his famous book *The World as Will and Representation*. The will is experienced from the point of view of a living actor, whereas the representation of the world is obtained from a point of view that superficially resembles that of a spectator. But the latent lesson of both Kantianism and post-Kantianism is that there is no *true* spectator’s standpoint (except in a minimalist “as if” sense); that in view of our deep insuperable entanglement with what there is, the standpoint of a spectator of nature is extrapolated out of the only available standpoint, which is that of the actor.

This is exactly what Bohr concluded from his reflection on quantum mechanics, with some additional radicality. He soon discovered that our apparent disentanglement from nature in classical knowledge is only a limiting case, and that we are actually immersed in it as any actor is; he pointed out that, in the quantum domain, there are circumstances in which we cannot even behave *as if* we were spectators; but he also insisted that we must still play the role of a

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<sup>100</sup> For a discussion of macro-realism, see : A.J. Leggett, “Quantum mechanics and macroscopic realism”, AIP Conference Proceedings, 180, 229, 1988; <http://dx.doi.org/10.1063/1.37869>

<sup>101</sup> Here I think it’s worth adding a footnote with some quotations (I have a nice list of those. Everett in particular made this point repeatedly and very explicitly in his discussion with Bohr

<sup>102</sup> L.W. Beck, *A Commentary on Kant’s Critique of Practical Reason*, The University of Chicago Press, 1963, p. 31

classical pseudo-spectator at the macroscopic scale of the laboratory, to enable “unambiguous communication”. This is why “the new situation in physics has so forcibly reminded us of the old truth that we are both onlookers and actors in the great drama of existence.”<sup>103</sup>

Two kinds of wholeness, dynamical and semantic. The former seems more superficial, and somehow contingent in so far as it is based on an analysis of *cinematic* concepts. However, one might argue that all physical concepts can ultimately be traced to cinematic ones in so far as they are to refer to measurable quantities. In which case, the dynamical argument for inseparability would also be general.

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<sup>103</sup> N. Bohr, *Atomic Theory and the Description of Nature*, op. cit., p. 119

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