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Bohr and the Problem of the Quantum-to-Classical Transition

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1. Introduction

Niels Bohr famously insisted on the indispensability of what he called “classical concepts,” as well as on the necessity of giving a classical description of measuring instruments. What is known as Bohr’s “doctrine of classical concepts” refers to the need to use classical concepts (such as position and momentum) in the description of microscopic quantum objects (like electrons) in mutually exclusive experimental arrangements. In perhaps his most frequently quoted account of the doctrine, Bohr declared: “It is decisive to recognize that, however far the phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms,” and to this extent “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” (Bohr 1949, 209).

As we have argued in an earlier publication—from which the present chapter has been adapted (Camilleri and Schlosshauer 2015)—and in another contribution by one of us (K. C.) in this volume, Bohr’s doctrine of classical concepts should be understood as an epistemological thesis based on a functional understanding of experiment. Put simply, it is an attempt by Bohr to elaborate an *epistemology of experiment*. Indeed, it is in this context that one should place Bohr’s contention that the experimental apparatus must be described in terms of the concepts of classical physics. Bohr (1939) acknowledged that the “quantum mechanical formalism” can be applied to “any intermediate auxiliary agency employed in the measuring process.” However, for the purposes of *performing a measurement*, the experimental apparatus and its interaction with the object of investigation “must be described on classical lines” (23–4). Bohr’s central insight was that if a measuring instrument is to serve its purpose of furnishing us with knowledge of an object, it must be described classically. That is to say, any functional description of the experimental apparatus, in which it is treated as a means to an end and not merely as a dynamical system, must make use of the concepts of classical physics.

This view of Bohr's (1948, 317) was significantly motivated by his early recognition that the quantum-mechanical inseparability of measured system and measurement apparatus brought about by entanglement constituted a difficulty as far as the concept of observation is concerned, since the impossibility of "separating the behaviour of the objects from their interaction with the measuring instruments" in quantum mechanics "implies an ambiguity in assigning conventional attributes to atomic objects." While Bohr would be happy to allow that it is always possible to represent the experimental apparatus from a purely structural point of view, without any reference to its function, as a quantum-mechanical system and thus give a quantum-mechanical treatment of the observational interaction, he also recognized that this would render the very distinction between object and instrument ambiguous. However, as Bohr repeatedly emphasized, such a distinction is a necessary condition for empirical inquiry. Therefore, for Bohr measuring instruments must admit of a classical description, otherwise they could not perform their epistemic function as measuring instruments (Camilleri and Schlosshauer 2015).

To this extent, any "quantum mechanical treatment" of a measuring instrument will, by virtue of its *function* as a measuring instrument, "be essentially equivalent with a classical description," as Bohr (1939, 23) explained at the Warsaw conference in 1938. However, this raises the question of why, from a purely dynamical point of view, the quantum-mechanical treatment is "essentially equivalent" to a classical description. Bohr's *epistemological* explanation for why we must use a classical description thus begs the question of what *dynamical* features of a macroscopic system entitle us to neglect the "quantum effects." Bohr (1935, 701) here appears to simply assume that there exists a macroscopic "region where the quantum-mechanical description of the process concerned is effectively equivalent with the classical description." Thus we are led to ask: How is it that classical physics can be employed, at least to a very good approximation, under certain dynamical conditions (typically those corresponding to measuring scenarios)? Bohr never provided a satisfactory answer to this question.

As these introductory remarks should have made clear, it is crucial to distinguish Bohr's doctrine of classical *concepts*, as it applies to the mutually exclusive experimental conditions in the description of quantum objects, from the use of classical dynamical *theories* in the description of macroscopic systems. In this chapter, we will focus on the latter issue—and the associated problem of the quantum-to-classical transition—and recount how a number of Bohr's followers attempted to provide a dynamical reformulation of Bohr's epistemological doctrine (Section 2). These attempts took the form of attempts to explain why macroscopic systems (such as measuring apparatuses) behave "classically" (or at least approximately classically), and they assumed crucial importance in the 1950s and 1960s and generated much debate and discussion. What is perhaps remarkable about this situation is that both critics and defenders of Bohr's viewpoint saw the need to arrive at a deeper understanding of the quantum-to-classical transition. Notably, Heisenberg took the crucial step of emphasizing the importance of the openness of quantum systems in his brief remarks on the problem of the quantum-to-classical transition in the 1950s (Section 3). Yet it was only with the deeper understanding of the role of entanglement with the environment, brought about by decoherence theory (Zeh 1970; Zurek 1981, 1982, 2003; Joos et al. 2003;

Schlosshauer 2007), that the dynamical problem of the quantum-to-classical transition could be properly addressed. In Section 4, we comment on the relationship between Bohr's views and decoherence.

2. Irreversibility and the dynamical problem of the quantum-to-classical transition

As mentioned, Bohr appears to have simply assumed that any macroscopic system serving as a measuring instrument must be describable by means of a classical approximation—otherwise we could not rely on such a system to perform experiments. For him, it is simply the case that without such a presupposition, experimental knowledge would be rendered impossible. The task then fell to Bohr's followers to provide an adequate dynamical account of why this is so. Throughout the 1950s and 1960s, a number of Bohr's disciples, including Rosenfeld, Petersen, and Groenwald, became increasingly preoccupied with the dynamical problem of the quantum-to-classical transition amid the new wave of criticisms of quantum mechanics. While most of these attempts ended in failure, they did not signify a departure from Bohr's general epistemological viewpoint, and they did yield some surprising insights. Commenting on attempts in this direction in 1965, Rosenfeld (1979, 536) argued that "it is understandable that in order to exhibit more directly the link between the physical concepts and their mathematical representation, a more formal rendering of Bohr's argument should be attempted." In spite of their philosophical differences, many of Bohr's followers, such as Weizsäcker and Rosenfeld, pursued this kind of approach to the physics of the quantum-to-classical transition as entirely in keeping with the spirit in which Bohr had intended his doctrine of classical concepts.

As Weizsäcker (1971, 25) put it at a colloquium in 1968, "The crucial point in the Copenhagen interpretation" is captured, "but not very luckily expressed, in Bohr's famous statement that all experiments are to be described in classical terms." As a devotee of Bohr, this was a view that Weizsäcker endorsed wholeheartedly, but which he now wished to justify. "My proposed answer is that Bohr was essentially right" in arguing that the instrument must be classically describable, "but that he did not know why" (28). The paradox at the heart of the Copenhagen interpretation for Weizsäcker is therefore to be stated: "Having thus accepted the falsity of classical physics, taken literally, we must ask how it can be explained as an essentially good approximation" when describing objects at the macrolevel. He spells this out:

> This amounts to asking *what physical condition must be imposed on a quantum-theoretical system in order that it should show the features which we describe as "classical."* My hypothesis is that this is precisely the condition that it should be suitable as a measuring instrument. If we ask what that presupposes, a minimum condition seems to be that irreversible processes should take place in the system. For every measurement must produce a trace of what has happened; an event that goes completely unregistered is not a measurement. Irreversibility implies a description of the system in which some of the information that we may think of as being present

> in the system is not actually used. Hence the system is certainly not in a "pure state"; we will describe it as a "mixture." I am unable to prove mathematically that the condition of irreversibility would suffice to define a classical approximation, but I feel confident it is a necessary condition. (29; emphasis in original)

Weizsäcker's remarks here point to a program of dynamical explanation that had been pursued since the 1950s. After the Second World War, a number of physicists had devoted themselves to investigating the thermodynamic conditions of irreversibility that would need to hold in order for a measurement to be registered macroscopically as "classical." On a number of occasions Bohr (1958b, 310) referred explicitly to "the essential irreversibility inherent in the very concept of observation," but he never suggested, at least in his published writings, that this might hold the key to a thermodynamic explanation of the "classicality" of quantum systems at the macroscopic level. "The amplification of atomic effects," as he noted, "emphasizes the irreversibility characteristic of the very concept of observation" (Bohr 1958a, 170). But such allusions to "irreversibility" were not developed further. Indeed, as Everett pointed out in 1956, "there is nowhere to be found any consistent explanation of this 'irreversibility' attributed to the measuring process" (Everett's notes on Stern's letters 1956, as quoted in Osnaghi, Freitas, and Freire 2009, 106).

A more rigorous "thermodynamic approach" was developed independently by Günther Ludwig in the second half of the 1950s (Jammer 1974, 488). Ludwig attempted to explain measurement by means of a thermodynamic analysis of the irreversible amplification process triggered by a microscopic event (490). As Osnaghi, Freitas, and Freire (2009, 103) explain, many physicists saw Ludwig's approach as opening up "the possibility of providing a rigorous foundation for Bohr's approach, thereby dispelling the misunderstandings surrounding the alleged subjectivism of the Copenhagen view." A number of attempts to develop further Ludwig's basic program of a thermodynamic approach were pursued during the 1960s, the most elaborate of which was the work carried out by Daneri, Loinger, and Prosperi (1962). Their aim was to find the exact ergodicity conditions for the validity of the ergodic theorem in quantum statistical mechanics. As Jeffery Bub (1971, 66) explained, the question the authors wished to answer was, "How does the *theory* guarantee that quantum theoretical macrostates will not exhibit interference effects?" The answer Daneri, Loinger, and Prosperi gave was that the physical structure of a large body implies ergodicity conditions, which in turn prevent the system from exhibiting quantum superpositions at the macroscopic scale (see also Ludwig 1953; 1955).

In Rosenfeld's (1979, 537) view, this work represented a major step forward in clearing up the misunderstandings and the "extravagant speculations" on the measurement problem, which had arisen through "the deficiencies in von Neumann's axiomatic treatment." Importantly, Rosenfeld declared that the Daneri–Loinger–Prosperi approach was "in complete harmony with Bohr's ideas" (539). Jeffery Bub (1968), however, saw it as "basically opposed to Bohr's ideas" insofar as it treated classical mechanics as an approximation to a quantum theory of macroscopic systems (see also Bub 1971, 65). In a similar vein, Max Jammer (1974, 493) called into question whether the approach of Daneri, Loinger, and Prosperi was "really congenial, or at least not incompatible, with the basic tenets of the Copenhagen interpretation." Yet as we have seen, the *epistemological* primacy of classical physics, on which the functional description of experiment rested, was for Bohr perfectly compatible with, and indeed depended on, the view that classical mechanics was an approximation of quantum mechanics. Those physicists closest to Bohr appreciated this point. As Weizsäcker (1987, 283) put it, Bohr's emphasis on "the classical description of an instrument just meant that only so far as it was an approximation would the instrument be of use *as* an instrument." There was never any suggestion for Bohr that measuring instruments could not in principle be described by quantum mechanics, or that classical dynamics was somehow more fundamental in an ontological sense than quantum mechanics.

Yet the subtleties of Bohr's point of view were typically lost on other physicists, many of whom saw little value in Bohr's forays into epistemology. This episode is indicative of the state of confusion surrounding Bohr's doctrine of classical concepts, which persisted well into the 1960s and early 1970s. In a qualified sense, Rosenfeld was right—there was no essential conflict between Bohr's *epistemological* view of the doctrine of classical concepts and the attempt to find a *dynamical* solution to the problem of the quantum-to-classical transition.

Nevertheless, an adequate dynamical solution turned out to be far more complicated than Bohr or many of his followers had originally thought. Rosenfeld's endorsement of the ergodic solution as having provided the solution to the problem was based on his view that "the reduction rule" is "essentially a thermodynamic effect, and, accordingly, only valid to the thermodynamic approximation" (Rosenfeld to Belinfante, July 24, 1972, Rosenfeld Papers, quoted in Osnaghi, Freitas, and Freire 2009, footnote 243). In hindsight, such pronouncements appear to have been overly optimistic. Eugene Wigner (1995, 65), who retained a key interest in foundational questions of quantum mechanics throughout the 1970s, rightly pointed out that the ergodicity conditions of Daneri–Loinger–Prosperi, which purported to explain "the transition to a classical description of the apparatus," rested on "an arbitrary step," which only served to "postulate the miracle which disturbs us." In a similar vein, Bub (1971, 70) argued that the authors had simply reintroduced "von Neumann's infinite regress all over again." The problem of the quantum-to-classical transition remained unsolved. On this point, Wigner and Bub were right.

3. The relation between object, instrument, and the external world

Looking back over the history of the foundations of quantum mechanics, it is easy to see that the crucial obstacle to an understanding of the quantum-to-classical transition was the erroneous assumption that we can treat quantum systems as isolated from the environment. There do, however, appear to be anticipations of the relevance of the environment in the 1950s and 1960s. In his contribution to the Bohr *Festschrift* edited by Pauli in 1955, Heisenberg reminded his readers that a quantum-mechanical treatment of the "interaction of the system with the measuring apparatus" does not of itself "as a rule lead to a definite result (e.g., the blackening of a photographic plate at a given point)" (22). Inclusion of further systems, such as a secondary apparatus or a human observer, will not terminate the resulting von Neumann chain (1955) if these systems are treated as interacting quantum systems.

Heisenberg observed that this situation had prompted a number of physicists to attempt to develop a modified dynamics of wave-packet collapse, or to suggest that the conscious observer plays an essential role in the process of measurement. Yet, as Heisenberg (1955, 22) explained, such attempts failed to grasp the real nature of the problem. In the von Neumann scheme, "the apparatus and the system are regarded as cut off from *the rest of the world* and treated as a whole according to quantum mechanics" (emphasis added). Yet the measuring apparatus is in reality never isolated from its environment: "If the measuring device would be isolated from the rest of the world, it would be neither a measuring device nor could it be described in the terms of classical physics at all" (Heisenberg [1958] 1989, 24). Heisenberg (1955, 27) emphasized that "the connection with the external world is one of the necessary conditions for the measuring apparatus to perform its function." He spelled out this position in more detail in *Physics and Philosophy*. Here it is worth quoting Heisenberg (1989, 121–2) at some length:

> Again the obvious starting point for the physical interpretation of the formalism seems to be the fact that mathematical scheme of quantum mechanics approaches that of classical mechanics in dimensions which are large compared to the size of atoms. But even this statement must be made with some reservations. Even in large dimensions there are many solutions of the quantum-mechanical equations to which no analogous solutions can be found in classical physics. In these solutions the phenomenon of the "interference of probabilities" would show up … [which] does not exist in classical physics. Therefore, even in the limit of large dimensions the correlation between the mathematical symbols, the measurements, and the ordinary concepts is by no means trivial. In order to get at such an unambiguous correlation one must take another feature of the problem into account. It must be observed that the system which is treated by the methods of quantum mechanics is in fact a part of a much bigger system (eventually the whole world); it is interacting with this bigger system; and one must add that the microscopic properties of the bigger system are (at least to a large extent) unknown. This statement is undoubtedly a correct description of the actual situation … The interaction with the bigger system with its undefined microscopic properties then introduces a new statistical element into the description … of the system under consideration. In the limiting case of the large dimensions this statistical element destroys the effects of the "interference of probabilities" in such a manner that the quantum-mechanical scheme really approaches the classical one in the limit.

In this intriguing passage, Heisenberg seems to have recognized that one cannot simply appeal to the macroscopic dimensions or the mass of the measuring apparatus to explain why the apparatus is never found in a quantum superposition. Such a view marks a departure from Bohr's suggestion that the heaviness of the apparatus renders it effectively classical. Heisenberg enlarges the system–apparatus composite to include couplings to further degrees of freedom in the environment (the "external world"). This is a most interesting point. Of course, for practical purposes, Heisenberg admits that we often treat the quantum system and the measuring apparatus as isolated from the rest of the world. But, in Heisenberg's (1955, 23) view, a proper account of the quantum-to-classical transition must in the end rest on "the underlying assumption," which Heisenberg took to be implicit in the Copenhagen interpretation, "that the interference terms are in the actual experiment removed by the partly undefined interactions of the measuring apparatus, with the system and with the rest of the world (in the formalism, the interaction produces a 'mixture')."

4. Decoherence theory and "emergent classicality"

Heisenberg's remarks might be read, somewhat charitably, as anticipating certain results of the decoherence program. After all, it is the hallmark of decoherence that it proceeds from the recognition that it is practically impossible to isolate the quantum system and the apparatus from the surrounding environment, and moreover that it is precisely this feature that results in the emergence of classicality. But while Heisenberg (1955, 23) emphasizes the importance of environmental interactions, he gives no detailed account of precisely how "the interference terms are … removed by the partly undefined interactions of the measuring apparatus, with the system and with the rest of the world." In particular, nowhere does he explicate the specific role of entanglement between the system and the environment as the crucial point in the dynamical emergence of classicality in the system.

While physicists such as Bohr, Heisenberg, and Schrödinger had recognized the nonseparability of quantum systems—that is, entanglement—as a characteristic feature of quantum mechanics as early as the 1920s and 1930s, the feeling prevailed that entanglement was something unusual and a peculiarly microscopic phenomenon that would have to be carefully created in the laboratory (such as in an EPR-type experiment). Entanglement was regarded as an essential quantum feature that would necessarily have to be irreconcilable with classicality. These long-held beliefs likely contributed to the comparably late "discovery" of the theory of decoherence, which has its roots in Zeh's work from the 1970s but did not receive broader attention until Zurek's contributions appeared in the 1980s (Camilleri 2009).

It is indeed a particular irony that entanglement would turn out to be not something that had to be tamed to ensure classicality but would instead assume an important role in our understanding of aspects of the quantum-to-classical transition. Decoherence proceeds from the realization that realistic quantum systems are never completely isolated from their environment (Zeh 1970; Zurek 1981, 1982 and 2003; Joos et al. 2003; Bacciagaluppi 2012; Schlosshauer 2004 and 2007). When a quantum system interacts with its environment, it will in general become entangled with a large number of environmental degrees of freedom. This entanglement influences what we can locally observe upon measuring the system. Thus, decoherence can be viewed as a dynamical filter on the space of quantum states: It provides a quantitative, dynamical explanation, wholly within standard mechanics, of the difficulty of creating and observing many "nonclassical" superposition states and interference phenomena, especially for mesoscopic and macroscopic systems whose many degrees of freedom typically lead to strong coupling to the environment. Thus, decoherence provides a partial solution to the dynamical problem of the quantum-to-classical transition, insofar as it describes effective restrictions on the superposition principle for subsystems interacting with other systems. Decoherence thus addresses what Bub (2012) has called a *consistency problem*: the agreement between the probability distributions obtained from quantum mechanics and classical mechanics in the relevant cases. It is in this narrow qualified sense that we may say that "classicality," so to speak, "emerges" out of the quantum formalism.

Recently, a number of physicists have suggested that Bohr's views on the primacy of classical concepts, and by extension his doctrine of an (ostensibly) fundamental quantum–classical divide, amount to little more than superfluous semantic or philosophical baggage, much of which has been discredited by recent developments. Dieter Zeh, for example, has contrasted the dynamical approach of decoherence with the "irrationalism" of the Copenhagen school (Joos et al. 2003, 27). Erich Joos (2006, 54), who attributes the origins of decoherence to a dissatisfaction with the "orthodoxy of the Copenhagen school" and "the desire to achieve a better understanding of the quantum–classical relation," has argued that "the message of decoherence" is that "we do not need to take classical notions as the starting point for physics," given that "these emerge through the dynamical process of decoherence from the quantum substrate" (77).

However, a purely dynamical account such as decoherence must be viewed in the context of the series of similar attempts made by Bohr's followers as discussed in Section 2. Its relationship to Bohr's views regarding the object–instrument divide and the primacy of classical concepts should therefore be judged in the same way as those earlier attempts: as something that was believed by many of Bohr's followers to be in natural harmony with Bohr's views. The dynamical problem of the quantum-to-classical transition, as many of Bohr's followers recognized, in fact addressed a problem quite different from the chiefly epistemological problem that had preoccupied Bohr. Of course, if classical concepts are understood in a purely pragmatic sense—as something we simply *do* use when we perform a measurement—decoherence may supply a justification for their use. Furthermore, decoherence explains why macroscopic objects, such as measuring apparatus, permit a classical description, in the sense of the applicability of classical dynamical theories. Thus, decoherence can be seen as providing a dynamical (and finally satisfactory) explanation for Bohr's (1935, 701) assumption that there exists a macroscopic "region where the quantum-mechanical description of the process concerned is effectively equivalent with the classical description." As Zurek (1993, 311) put it:

> The role of decoherence is to establish a boundary between quantum and classical. The boundary is in principle moveable, but in practice largely immobilized by the irreversibility of the process of decoherence … The equivalence between "macroscopic" and "classical" is then validated by the decoherence considerations, but only as a consequence of the practical impossibility of keeping objects which are macroscopic perfectly isolated.

It should be kept in mind, however, that while decoherence theory provides a dynamical account of the applicability of classical and quantum-mechanical descriptions and their relationship to the distinction between macroscopic and microscopic, Bohr's (1935, 701) discrimination "between those parts of the physical system … which are to be treated as measuring instruments and those which constitute the objects under investigation" was determined by functional (epistemological) considerations and not by dynamical (ontological) considerations. In Bohr's view, once the aims of the experiment had been decided upon and the experimental apparatus has been set up accordingly, the "cut" between system and apparatus was effectively fixed—it could not be moved around arbitrarily. Indeed this was precisely the point that Bohr insisted upon in an exchange of correspondence with Heisenberg in September 1935 (Camilleri and Schlosshauer 2015, 77–9). To this extent, Bohr argued that the cut corresponds to something "objective" in the sense that the object–instrument distinction was essentially fixed by the *functional-epistemological* considerations dictated by the choice of the particular experimental arrangement.

5. Concluding remarks

Bohr's epistemological thesis concerning a functional description of experiment should be distinguished from the efforts, which gathered momentum in the 1960s, to supply a dynamical explanation of the emergence of classicality from quantum theory. What such approaches have aimed for—and, in the case of decoherence, with great success—is to ensure, through consideration of the dynamics, a consistency between the quantum and classical descriptions (expressed in terms of the relevant probabilistic predictions), particularly for mesoscopic and macroscopic systems.

While such approaches can provide, post facto, a physical, pragmatic justification for the applicability of classical concepts, they do not touch on Bohr's main concern of an epistemology of experiment that underlies his doctrine of classical concepts. Indeed, Bohr's doctrine was premised on the assumption that a quantum-mechanical treatment of the measurement apparatus would be "essentially equivalent with a classical description," an assumption for which decoherence can now provide a dynamical explanation. This suggests that Bohr's philosophy and the insights brought about by decoherence theory may not only coexist peacefully, but also that decoherence may be seen as supplying the dynamical justification for the distinction, which Bohr held to be epistemically necessary, between the "classical system" serving as the measuring apparatus and the "quantum object."

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