Convergences in the Measurement Problem in Quantum Mechanics

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Abstract

This paper presents arguments purporting to show that von Neumann’s description of the measurement process in quantum mechanics has a modern day version in the decoherence approach. We claim that this approach and the de Broglie-Bohm theory emerge from Bohr’s interpretation and are therefore obliged to deal with some obscure ideas which were anticipated, explicitly or implicitly and carefully circumvented, by Bohr.

I. INTRODUCTION

The existence of quantum physics imposes on physicists an unavoidable ambiguity when describing atomic and subatomic systems. On his/her daily activity in the laboratory, the physicist describes and calculates classical trajectories of particles in order not only to interpret the data, but also to design the apparatus producing that data. Witness, for example, how a high energy physicist reconstructs events involving a maze of particles produced in a complex subatomic collision. He/She rarely uses any quantum mechanics at all, determining trajectories, lifetimes, vertex positions, trigger algorithms, all with classical relativistic mechanics. Bohr was perfectly aware of this necessity of using classical language for describing the results of experiments and constructed his interpretation of quantum mechanics based on this (Bohr 1939). The need for a classical language is imposed, according to him, by the classical nature of observers and experimental apparatuses. It is fair to say that for Bohr there was no measurement problem, as classical apparatuses are not described by wave functions, avoiding superpositions of macroscopic states. Wave functions pertain only to the microscopic world. The problem as it is recognized today can be traced back to von Neumann.
We argue in this paper that von Neumann’s interpretation of quantum mechanics (von Neumann 1955) originated in an attempt to remove the somewhat arbitrary division between the classical and the quantum world introduced by Bohr. In so doing, von Neumann shifted the cut by introducing an observer, who was not required by Bohr.

Modern attempts to solve the measurement problem introducing the environment to dissipate macroscopic coherence do not explain the collapse of the wave function. We argue in the text that decoherence models (Zurek 1998) are true descendants of von Neumann and therefore will ultimately bring the observer to the forefront. Consequently, the decoherence approaches are not a solution of the measurement problem if one’s standing point is that the observer should not play a role in the interpretation.

We further argue that the causal approach, introduced by de Broglie and developed by Bohm and collaborators (Bohm 1952 and 1995), also originated in an effort to better deal with the division of the world. The causal approach removed it by combining classical and quantum concepts in a single description of nature: from the classical world it takes the position of the particles (be they part of the system or of the measuring device), while keeping from the quantum world the wave function and its Schrödinger’s evolution.

We also bring forward our view that von Neumann’s (and its modern day version - decoherence) and the de Broglie-Bohm interpretation, though corresponding to two different branches emerging from Bohr’s elaborate world view, dealt in their own specific way with the vague concept of information and the quite obscure notion of its disappearance.

II. BOHR

With a long historical hindsight, we can now see Bohr’s position as one that intended to provide an interpretation, whose main purpose was to protect the successful formalism of quantum mechanics. We might say that Bohr anticipated many of the problems that would be faced by those who would later try to analyze in detail the measurement process. As we will show below, the attempts presented here to solve the measurement have to answer questions that do not pertain to the daily activity of an experimenter in the laboratory. Bohr somehow foresaw these inextricable difficulties and cut them short by declaring (Bohr 1939):

‘In the system to which the quantum mechanical formalism is applied, it is of course possible to include any intermediate auxiliary agency employed in the measuring process [but] some ultimate measuring instruments must always be described entirely on classical lines, and consequently kept outside the system subject to quantum mechanical treatment.’

Although Bohr’s position was a strong and deeply intricate one, it was challenged by one simple criticism: where is the demarcation between system and apparatus, quantum and classical?

‘The ‘Problem’ then is this: how exactly is the world to be divided into speakable apparatus ... that we can talk about ... and unspeakable quantum system that we can not talk about? How many electrons, or atoms, or molecules, make an ‘apparatus’? The mathematics of the ordinary theory requires such a division, but says nothing about how it is to be made. In practice the question is resolved by pragmatic recipes which have stood the test of time, applied with discretion and good taste born of experience. But should not fundamental theory permit exact mathematical formulation?’ (Bell 1987, 171)
Though simple, this question has a devastating effect on Bohr’s interpretation. This quotation from Bell summarizes the challenge and motivation for those who felt the urge to explain the measurement process despite the best advice against it by Bohr.

III. VON NEUMANN

Von Neumann was probably the first to attempt a unified quantum description of system and apparatus. Contrary to Bohr, who avoided the danger of such a description by constructing a philosophical fortress around quantum mechanics, von Neumann made a formal analysis of the measurement process and ended up by arriving at an altogether new interpretation of quantum mechanics, which no wonder is frequently misidentified with Bohr’s philosophical constructs. As stressed by Feyerabend (Feyerabend 1962, 237):

‘when dealing with von Neumann’s investigation, we are not dealing with a refinement of Bohr - we are dealing with a completely different approach.’

Like Bohr, von Neumann attributed importance to the apparatus as part of the measurement process, but he examined the evolution of the joint system (system + apparatus) with a single wave function governed by Schrödinger’s evolution, which establishes a correlation between them in such a way that any result pertaining to the system is inferred from the reading of the apparatus.

In doing so, the states of the apparatus are also subjected to the superposition principle. Clearly von Neumann managed to move the classical/quantum cut from the system/apparatus boundary, but at the price of leaving the apparatus in a coherent superposition of states which is not observed. No matter how many apparatuses are included, the superpositions will remain. At this stage von Neumann distinguished two types of processes in quantum mechanics: the one described above, leading to undesirable macroscopic superpositions as a consequence of the reversible unitary evolution of Schrödinger’s equation and the other one, corresponding to our knowledge of the result of the measurement, which is irreversible. Following Bohr,

‘it is also essential to remember that all unambiguous information concerning atomic object is derived from the permanent marks... left on the bodies which define the experimental conditions. Far from involving any special intricacy, the irreversible amplification effects on which the recording of the presence of atomic objects rests rather remind us of the essential irreversibility inherent in the very concept of observation.’ (Bohr 1964, 3)

Von Neumann formalized the irreversibility in quantum mechanics by postulating the collapse of the wave function. Notice, though, that he deals with ensembles and therefore uses density matrices in his formalism. To avoid imposing the postulate without any physical justification, the observer is introduced and his/her subjective perception becomes essential. This interpretation is thereby weakened and open to severe criticisms. The cut is still present, but has now moved to a position between joint system/observer.

In addition to interpretative and epistemological problems, this interpretation also has problems in its formalism. The need to consider instantaneous interactions in the measurement process, so that the unitary evolution does not move the state vector away from the position of measurement, implies that the Hamiltonian for the joint system commutes with the observable which is being measured $[H, O] = 0$. This could be a demanding condition on the Hamiltonian, but not an excessive one, as we will make clear when discussing
Von Neumann’s approach is taken one step further in the decoherence models. These models invoke the inevitable interaction between joint system and environment to help solving, it is claimed, the measurement problem. Following von Neumann’s tradition, system, apparatus and environment are treated quantum mechanically and, as for von Neumann, the unavoidable superposition of macroscopically different states will still be present. As the environment has a large number of degrees of freedom, the observer has no access to them and therefore, they must be traced over, ignored. Notice that the observer still plays a crucial role in this approach, for the trace must be done by someone and the cut is maintained as the boundary between the degrees of freedom which are traced over and those which are not. The inevitability of this division of the world is acknowledged by the proponents of this approach as illustrated by Zurek in a recent paper (Zurek 1998, 1794):

‘We can mention two such open issues right away: both the formulation of the measurement problem and its resolution through the appeal of decoherence require a universe split into systems.’

The trick of tracing over the unaccessible degrees of freedom brings the density matrix of the total system to a diagonal form removing the undesirable macroscopic superpositions and this is von Neumann’s postulate presented in a more elaborate dynamical way. However, there is a subjective element in the whole procedure: how far does the environment reach?

Von Neumann’s condition of commutativity of the Hamiltonian and the observable to be measured, now acquires a complex meaning: \( [H_{\text{int}}, A] \), where now \( A \) is the pointer basis of the apparatus and the Hamiltonian refers to the interaction between joint system and environment, for which there is even less control by an experimental physicist. It is as if a measuring instrument should bring in its instruction manual recommendations on the appropriate environment where to operate. Von Neumann’s condition only indicated the adequate apparatuses for measuring a certain observable. Demands put on the experimenter do not stop here however, he/she - according to the decoherence procedure known as the predictability sieve (Zurek 1993) - should refer to a list to decide which observable can be measured, those on the top of the list are more classical in appearance and thus preferable for measurement. The existence of such a list brings back the subjectivity in the choice of where to put the quantum/classical cut, which is ‘to be decided by circumstances’ (Zurek 1993). Besides, how is it possible to know the environment well enough to decide which observable can be measured, but at the same time to be so ignorant about it that one is obliged to trace it over?

One of the worst aspects of the decoherence approach, taken to its ultimate consequence, is thus to introduce a set of procedures that should be obeyed when measuring a quantity, procedures which no experimentalist on his/her right mind would recognize as what goes on in the laboratory. The appeal to notions far remote from the reality of the laboratory experiments is well illustrated in the following passages in a recent paper on decoherence (Zurek 1998, 1796 and 1799).

‘Correlations [between states of the joint system and environment] are both the cause of decoherence and the criterion used to evaluate the stability of the states...Moreover, stability
of the correlations between the states of the system monitored by their environment and of some other ‘recording’ system (i.e. an apparatus or a memory of an observer) is a criterion of the ‘reality’ of these states.’

or still,

‘the observer can know beforehand what (limited) set of observables can be measured with impunity. He will be able to select measurement observables that are already monitored by the environment.’

The above passages clearly show some subjective elements of this approach, invoking memory of observer or a priori knowledge of the interaction between the environment and joint system.

One last criticism is that decoherence, as well as von Neumann, deals with the density matrix, which is by force in the realm of the ensemble interpretation and as Bell says:

‘If one were not actually on the look-out for probabilities, I think the obvious interpretation of even [the butchered density matrix] would be that the system is in a state in which the various [wave functions] somehow co-exist...This is not at all a probability interpretation, in which the different terms are seen not as co-existing, but as alternatives.’ (Bell 1990, 36 [ref.2] and Whitaker 1996, 289)

V. DE BROGLIE - BOHM

A description of individual events was proposed by de Broglie-Bohm (Bohm 1952). In it, an individual system is described by a wave function and a particle. The particle is guided by the wave function, which works, to a certain extent, like a field. One could say that this theory corresponds to a refinement of Bohr’s duality - the use of quantum concepts in a scale and classical concepts in another one - taken to an extreme. The wave function and the particle position are now used at the same time in all scales. It thus eliminates the division quantum/classical and apparently has no measurement problem, as the particle has always a definite position. Moreover, it claims to be free from problems connected with the act of observation, contrary to what we will suggest below.

It is arguably that this theory is subjected to some serious criticisms (Holland 1993), but the only one we want to emphasize here is related to the infamous empty wave and more specifically, to the information carried by it. Whenever the wave splits up into parts which do not have spatial overlap, such as in the trajectories of the double-slit experiment, one part will be with the particle and the other one will be empty, though it can still influence the particle motion. The empty wave carries information on the superpositions of states, but as soon as a measurement is realized, the empty wave loses any overlap it had before with the branch that carries the particle.

‘Perhaps we shouldn’t talk about it actually disappearing from the universe. Rather the information in the ‘empty’ wave packet no longer has any effect, because during the act of measurement the irreversible process introduces a stochastic or random disturbance which destroys the information of quantum potential of the wave packet.’ (Hiley 1986, 146)

Suddenly the superpositions are destroyed, this only happens thanks to the measurement which identifies which branch corresponds to the empty wave. How this happens, where the empty wave information is taken to, what are the effects of its disappearance on the surroundings are left unspecified. This sends us back to the similar problem encountered
in the decoherence models, where information - as before, information on superpositions of states - was dissipated into an environment with no observable effects on it, but only on the system.

At this point the convergence of these two apparently different interpretations becomes clear. If one accepts the concept of information as they do, the act of measurement implies its loss, be it dissipated in the environment or in the arbitrary sterilization of the empty wave, whose information is now declared passive:

‘we’ve tried to introduce a distinction between active information and inactive information. That is, when an apparatus has undergone this irreversible change, one wave packet becomes inactive.’ (Hiley 1986, 146)

This vague notion of information is central to both causal and decoherence interpretations. Its vagueness has been nicely expressed by Bell (Bell 1990, 8 [ref.3]):

‘I don’t have a concept of disembodied information - it must be located and represented in the material world, and I don’t know how to formulate the concept of how much information there is in an arbitrary space region - I think the concept of information is again a very useful one in practice but not in principle...’

This concludes our arguments. It is certainly frustrating that the measurement problem in quantum mechanics, after six decades of being delineated, remains open. Perhaps this indicates a fundamentally new epistemological obstacle to be overcome jointly by physicists and philosophers, an obstacle that was not present in classical physics.

VI. CONCLUSION

We argued in this paper that von Neumann’s approach (and its modern version: decoherence) and the causal interpretation have many points in common, despite being so different in formalism and in language. Remarkably the common points are the problematic ones springing from Bohr’s deep analysis of the interface quantum/classical. These elaborated attempts to define quantitatively what happens in this boundary have exposed open unsurmountable problems which Bohr carefully avoided by his radical separation of classical and quantum.

NOTES

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