The Role of Decoherence in the Copenhagen Interpretation of Quantum Mechanics

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What is Copenhagen interpretation?

The **Copenhagen interpretation** is an interpretation of quantum mechanics formulated mainly by Niels Bohr and also Werner Heisenberg while collaborating in Copenhagen. According to a poll in 1997, the Copenhagen interpretation is the most widely-accepted interpretation of quantum mechanics [1] and it was the first general attempt to understand the world of atoms. Since Copenhagen Interpretation was developed by a number of scientists and philosophers in different times there is not very clear statement of the Copenhagen Interpretation. In fact Bohr and Heisenberg never completely agreed on the details of the interpretation of quantum mechanic, and none of them ever used the term "the Copenhagen interpretation" as a joint name for their ideas [2] .However it is possible to summarize some of the main principles of this interpretation based mainly on Bohr's statements. Nowadays, the Copenhagen interpretation is mainly famous for indeterminism, Bohr's correspondence principle as well as his complementarity interpretation and Born's probability rule [2]. It is useful to mention a statement by E.T. Jaynes about the role of Bohr in quantum mechanic [3]:

> "*Our present quantum mechanical formalism is a peculiar mixture describing in part laws of Nature, in part incomplete human information about Nature – all scrambled up together by Bohr into an omelette that nobody has seen how to unscramble. Yet we think the unscrambling is a prerequisite for any further advance in basic physical theory…*"

Main Aspects:

Correspondence principle: In the search for a theory of quantum mechanics, Bohr (and later Heisenberg) believed that any further theory of the atom should predict values, in domains of large quantum numbers, which should be close to the values of classical physics. The correspondence rule was a heuristic principle to make sure that the numerical values predicted by a quantum theory should be the same as what were predicted by classical radiation theory when the influence of Planck's constant could be neglected [2]. The correspondence principle has some other aspects/results which will be discussed in the later parts (Criticism & Main effects on the Copenhagen interpretation) of this paper.

Complementarity: Complementarity is mainly known as matter exhibits a wave-particle duality. And by the experiment it can be shown that it is possible to ascribe either wave or particle properties to a single object but not both at the same times. But on the other hand, complementarity is also known as to attribute either kinematic or dynamic properties to the atom, in which “space-time descriptions” are complementary to “claims of causality”. However the description of light as either particles or waves can be considered a classical dilemma since the momentum of the photon as a particle depends on the frequency of the light as a wave. Beside this particle like properties of matter, or wave-like properties of matter, may occur in a single experiment (e.g., in the double-slit experiment where the interference pattern consists of single dots). Therefore later Bohr tacitly abandoned “wave-particle complementarity” in favor of the exclusivity of “kinematic-dynamic complementarity”. [2, 4]

It is clear that Bohr idea about the complementarity had been changed during time, especially after the EPR paper. For example, while before EPR paper he had often called Heisenberg's “uncertainty relation” as if it were a question of a merely epistemological limitation, he later indicates Heisenberg's “indeterminacy relation” as the ontological consequences of his claim that kinematic and dynamic variables are ill-defined without referring to an experimental outcome. [2]

Indeterminism: Because of some of the main principles of this interpretation (and most of other interpretations), Copenhagen interpretation is considered as a non-deterministic theory. Heisenberg's uncertainty principle ensures that it is not possible to determine all of the properties of the system at the same time (e.g., position and momentum) and those properties that are not known with precision must be described by probabilities, which are related to the square of the amplitude of the wave function (Born rule) [5].

The main reason to consider Copenhagen interpretation as a non-deterministic theory is based on the view that quantum particles do not really have trajectories and any talk of such things is meaningless (according to Heisenberg's uncertainty principle). For several decades it was believed by most physicists that the mathematician John von Neumann had proven, with the utmost mathematical rigor, that a return to any sort of fundamental determinism was impossible. However, in 1952 Bell saw the impossible done and he presented the new deterministic interpretation of quantum mechanics [6].

Main Criticisms:

1. The completeness of quantum mechanics was criticized by the Einstein-Podolsky-Rosen thought experiment (EPR).
2. The Copenhagen Interpretation gives special role to measurement processes and measurement apparatus without clearly defining them and as Steven Weinberg mentioned “The Copenhagen interpretation describes what happens when an observer makes a measurement, but the observer and the act of measurement are

themselves treated classically. This is surely wrong: Physicists and their apparatus must be governed by the same quantum mechanical rules that govern everything else in the universe…" and it is not clear how an undefined measurement process converts probability functions into non-probabilistic measurements (Problem of definite outcome). [5,7] Erwin Schrödinger devised the Schrödinger's cat experiment and by this experiment it makes apparent the fact that the nature of measurement as well as observation, is not well defined in the Copenhagen interpretation. By the supervision principle, if $|1\rangle$ and $|2\rangle$ are two states, quantum mechanics tells us that any linear combination of these two states can be a possible state ($|1\rangle + |2\rangle$). Whereas these states are referred to dead and alive cat in the Schrödinger's cat experiment. [8, 9]
What mentioned above is mainly referred as the problem of definite outcome since after (not well defined) measurement, probability functions (probability of different outcomes) convert into definite results. However there is another problem hidden in the measurement process, which is typically referred as the problem of preferred basis. The expansion of the final composite state is in general not unique however for each different measurement it seems that the measurement defines the set of preferred basis and after the measurement, the system will go to one of those bases. [9]

3. As mentioned the Copenhagen interpretation is a non-deterministic interpretation and because of that many physicists and philosophers have had fundamental problems with that. Some of the main statements against this character of Copenhagen interpretation are made by Einstein such as "I, at any rate, am convinced that He (God) does not throw dice." and "Do you really think the moon isn't there if you aren't looking at it?" However Bohr, in response, said "Einstein, don't tell God what to do". [5, 10]

Decoherence

Introduction:

The theory of decoherence is based on a study of the effects of environment on the physical systems. In the classical physics, the environment is usually viewed as a kind of disturbance, or noise, which negatively influences the study of system's properties. Therefore in order to discover the "true" underlying nature of the system under study, science has established the idealization of isolated systems to eliminate any outer sources of disturbance as much as possible. However it seems that decoherence has significant role in the study of quantum mechanical systems since the non classical phenomenon of quantum entanglement has shown that the correlations between two systems can be of fundamental importance and can lead to properties that are not present in the isolated systems. Generally in quantum mechanical systems, the whole system is different from the sum of its part and this is the key idea why the environment can have such a huge role here. [9]

Why decoherence is important?

While decoherence does not provide a mechanism for the actual wave function collapse, some experts believe that it provides a mechanism for the appearance of wave function collapse. On the other hand, decoherence represents a major problem for the practical usage of quantum mechanics in quantum computers, since quantum computers strongly rely on the undisturbed evolution of quantum coherences. [11] Guido Bacciagaluppi mentioned [12]

"*In the lab decoherence may be your enemy in foundations it may be your friend*"

If many degrees of freedom are involved in the process of decoherence, the entanglements will become practically irreversible (except for very special scenarios).
One of the main important observations about this phenomenon is that this de-separation of quantum states happens extremely fast for macroscopic objects and because of that the natural environment cannot be ignored or treated as a classical background [13, 14].

While the von Neumann's scheme (system-apparatus interaction described by the usual quantum-mechanical formalism) is in sharp contrast to the Copenhagen interpretation, where measurement is an independent component of the theory (represented in fundamentally classical terms), it is useful to use von Neumann model to represent the ideal measurements. By using the von Neumann model for the ideal quantum-mechanical measurement, we can write the mathematics of measurement including decoherence as follows:

Eq.1: $$\left(\sum_n c_n|s_n\rangle\right)|a_r\rangle|e_0\rangle \rightarrow \left(\sum_n c_n|s_n\rangle|a_n\rangle\right)|e_0\rangle \rightarrow \sum_n c_n|s_n\rangle|a_n\rangle|e_n\rangle$$

$|s_n\rangle$ are the basis of the system, $|a_r\rangle$ is the measurement apparatus state and $|e_0\rangle$ is the initial environment state. However as the measurement happens $|a_r\rangle$ will go to the $|a_n\rangle$, which corresponds to the measurement outcome of $|s_n\rangle$ and this is what previously mentioned as the problem of preferred basis. Now by considering the environment, $|e_n\rangle$ are the environment states associated with the different pointer states $|a_n\rangle$ of the measuring apparatus. Each $|e_n\rangle$ represents the product states of many microscopic subsystem states of the environment, i.e., $|e_n\rangle=|e_n\rangle_1|e_n\rangle_2\cdots$. It should be mentioned that while for the two subsystems of S and A, always we can write the second term of the above question (diagonal decomposition of final states of S and A), the last term is not always reachable. This means that a diagonal decomposition of the final state of three subsystems of S, A and E is not always possible and the total Hamiltonian should have a specific form to induce the above time evolution. Note that the above equation implies that the environment can record the state of the system and therefore the state of the system- apparatus composition. [9]

Main Roles of Decoherence

The main features of decoherence, which make it interesting for us, are as follows: suppression of interferences, shortness of decoherence times, super selections (preferred sets of states), robustness of preferred states and preservation of correlations, localization, environment monitors the system (analogy with measurements,) redundancy of information in environment, trajectories at the level of preferred states and classicality of trajectories. [9, 12] and I will try to cover the main ones in bellow.

Local suppression of interference (considering shortness of decoherence times)

In the quantum mechanics a superposition of states is fundamentally different from classical ensembles of states and this can be shown explicitly, especially on microscopic scales, by running the experiments which lead to the direct observation of interference patterns. For example, in a double slit experiment electrons pass individually one at a time through a double slit. This experiment clearly shows that, within the standard quantum mechanical formalism, the electron must not be described by either one of the wave functions but the superposition of both wave functions ($_1+\ _2$).
This happens because the correct density distribution of the pattern on the screen is not given by the sum of the squared wave functions ($|\ _1|^2+|\ _2|^2$) , but only by the square of the sum of the individual wave functions $\left(|\ _1+\ _2|^2\right)$.

It is believed that in the spontaneous interactions with environment, the interference is suppressed. When the interference is suppressed, interference phase relations are not destroyed but well defined only for larger system [12]. If we assume *O* as an observable of *SA* (System& Observer) the expectation value of *O* is given by Tr($_{SAE}$O$_{SAE}$) where $_{SAE}$ (the density matrix of total *SAE*) is described by:

Eq. 2: $$\hat{}_{SAE}=\sum_{mn} c_m c_n^{¿}|s_m\rangle|a_m\rangle|e_m\rangle\langle s_n|\langle a_n|\langle e_n|$$

To do the statistical prediction, we can replace $_{SAE}$ by the reduced density matrix of $_{SA}$. The reduced density matrix can be calculated as by tracing out the unobserved degrees of environment as follows:

Eq. 3: $$\hat{}_{SA}=Tr_E(\ \hat{}_{SAE})=\sum_{mn} c_m c_n^{¿}|s_m\rangle|a_m\rangle\langle s_n|\langle a_n|\langle e_n||e_m\rangle$$

Where there is an interference term in the above equation. However many explicit physical models for the environments-system interactions have shown that because of the large number of subsystems that compose the environment, the environment states become orthogonal rapidly and therefore $\langle e_n||e_m\rangle=0$ (if m≠n) and therefore

Eq. 4: $$\hat{}_{SA}\rightarrow\ \hat{}^{d}_{SA}\approx\sum_n |c_n^2||s_n\rangle|a_n\rangle\langle s_n|\langle a_n|=\sum_n |c_n|^2\hat{P}_n^{(S)}\otimes\hat{P}_n^{(A)}$$

Where the last terms represent the projection operators onto the eigenstates of S and A respectively and as can be seen, the interference terms are vanished. However the full coherence is still retained in the total density matrix $_{SAE}$ and this make us cautious in interpreting this state of affairs. [9]

Super selection & Robustness of preferred states and preservation of correlations

As mentioned in the "main criticisms" of Copenhagen interpretation, there is a problem of preferred basis for interpretation of quantum mechanics and quantum mechanical measurement scheme, as represented in Eq. 1 (the first part of equation), does not uniquely define the expansion of the post measurements state. However because of what mentioned in Eq. 1 (the second part) the situation is changed. The interactions between apparatus and the environment seem to select a set of mutually commuting observables. [9]

In famous paper, "Triorthogonal uniqueness theorem and its relevance to the interpretation of quantum mechanics" [15], Eldy and Bub (1994) shows that a wave-function in a Hilbert space of $H_1 \otimes H_2 \otimes H_3$ has at most one decomposition into a sum of product wave-functions (diagonal form of $\sum_i \; _i| \; _i\rangle_1 | \; _i\rangle_2 | \; _i\rangle_3$) with each set of component wave-functions are linearly independent and normalized. [9, 16] This theorem ensures that the expansion of the final state in Eq. 1 is unique and it seems to solve the problem of the preferred basis. However the tridecompositional uniqueness theorem neither tells us whether Schmidt decomposition exists nor states explicitly the unique expansion itself [9].

Main effects on the Copenhagen interpretation:

While what mentioned above described the effects of decoherence on the standard and Copenhagen interpretations of quantum mechanics, I will try to highlight some of the main effects bellow, considering what discussed previously.

Paraphrasing Bohr the "existence of the classical world" (as described explicitly in the Correspondence principle part) the measurement problem is a case where quantum mechanics appears to be incompatible with a feature of the classical world namely definite measurement. However as described above in the "super selection" part, it seems that decoherence partially solved the problem. But decoherence cannot solve the other part of measurement problem, which is well-known as the problem of definite outcomes. In the state that includes the environment, phase coherence between macroscopically different states is still preserved, and by enlarging the system at least parts of the environment can be included [9]. In other words, the superposition of different states still exists, coherence is only “delocalized into the larger system” [9, 17].

So as Guido Bacciagaluppi mentioned [12]:

“Solves the measurement problem in the sense of making QM compatible with the possibility of definite measurement results but does not explain why measurements should actually have definite results. QM constrains possibilities and the world happens to be one of these possibilities.”

In Copenhagen interpretation, Bohr’s intuition was that we need a classical world if we want to talk and find out about quantum mechanics and therefore he postulates the necessity of classical concepts in order to describe quantum phenomena [12], including the existence of measurement apparatuses that obey classical physics (in sharp contrast to the von Neumann scheme and the standard interpretation). The Copenhagen interpretation postulates that classicality is not to be derived from quantum mechanics (as the macroscopic limit of an underlying quantum structures), but instead that it is viewed as the separate element of a complete quantum theory and (be considered as a concept prior to quantum theory) [9]. If we accept this, decoherence can derive the classical world from quantum mechanics, then this postulate is kind of unnecessary and also irrelevant, because we have an apparatus which behaves classically but obey quantum mechanics rules. And also because of what were gained from decoherence, it seems impossible to uphold the notion of a fixed quantum-classical boundary on a fundamental level of the theory [9]. And as Guido Bacciagaluppi mentioned [12]:

“We could recognize the correctness of Bohr’s intuition (having Bohr’s cake) but incorporate it in a rounded of picture of the world that is entirely quantum mechanical (eating it)”.

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References:

[1] M Tegmark 1998, *Fortschr. Phys.* **46**, 855-862
[2] Jan Faye May 2002, Stanford Encyclopedia of Quantum Mechanic, http://plato.stanford.edu/entries/qm-copenhagen/
[3] Delhotel, Jean-Michel, “Quantum Mechanics Unscrambled”, eprint arXiv:quant-ph/0401063
[4] Held, C. (1994), *Studies in History and Philosophy of Science*, *25*, 871-893.
[5] Copenhagen interpretation, Wikipedia page, edition April 11, 07 http://en.wikipedia.org/wiki/Copenhagen_interpretation
[6] Sheldon Goldstein, http://www.math.rutgers.edu/~oldstein/papers/hr/hr.html
[7] Steven Weinberg, "Einstein's Mistakes", Physics Today, Nov. 2005, page 31
[8] Schrodinger’s cat, Wikipedia page, edition 18:51, April 17, 07 http://en.wikipedia.org/wiki/Schr%C3%B6dinger%27s_cat

[9] Maximilian Schlosshauer, Rev. Mod. Phys. **76**, 1267 (2004)
[10] Albert Einstein, Wikipedia page, edition April 3, 07
http://en.wikiquote.org/wiki/Einstein
[11] Decoherence, Wikipedia, April 4, 07
http://en.wikipedia.org/wiki/Quantum_decoherence
[12] Guido Bacciagaluppi, "The Role of Decoherence in the Foundations of Quantum Mechanics", QMLS Workshop, Vancouver, April 2003
www.physics.ubc.ca/~berciu/PHILIP/CONFERENCES/PWI03/FILES/baccia.ps
[13] Erich Joos, arXiv:quant-ph/9908008v1, Aug. 1999
[14] Zeh, H.D. (1970): On the interpretation of measurement in quantum theory. Found. Phys. 1, 69–76.
[15] Andrew Elby & Jeffrey Bub, Phys. Rev. A 49, 4213 - 4216 (1994)
[16] Donald, Matthew J., "Instability, Isolation, and the Tridecompositional Uniqueness Theorem", arXiv:quant-ph/0412013
[17] Kiefer, C., and E. Joos, 1999, in Quantum Future: From Volta and Como to the Present and Beyond (Proceedings of the Max Born Symposium Held in Przesieka, Poland, 24–27 September 1997), p. 105.