On the interpretation of quantum theory – from Copenhagen to the present day

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Abstract
A central feature in the Copenhagen interpretation is the use of classical concepts from the outset. Modern developments show, however, that the emergence of classical properties can be understood within the framework of quantum theory itself, through the process of decoherence. This fact becomes most crucial for the interpretability of quantum cosmology – the application of quantum theory to the Universe as a whole. I briefly review these developments and emphasize the importance of an unbiased attitude on the interpretational side for future progress in physics.
Ich bin nicht damit zufrieden, wenn man eine Maschinerie hat, die zwar zu prophezeien gestattet, der wir aber keinen klaren Sinn zu geben vermögen.

Albert Einstein in a letter to Max Born (3.12.1953)

1 Copenhagen interpretations and alternatives

A physical theory contains both a mathematical formalism and an interpretational scheme. Although their relation may be subtle already for classical physics, it becomes highly non-trivial in quantum theory. In fact, although the mathematical framework had been basically fixed by 1932, the debate about its meaning is going on. As we shall see, this is due to the possibility of having conflicting concepts of reality, without contradicting the formalism. This is why all physicists agree on the practical application of the formalism to concrete problems such as the calculation of transition probabilities.

It is often asserted that the orthodox view is given by the Copenhagen interpretation of quantum theory. This is the standpoint taken by most textbooks. What is this interpretation? It is generally assumed that it originated from intense discussions between Bohr, Heisenberg, and others in Copenhagen in the years 1925-27. However, there has never been complete agreement about the actual meaning, or even definition, of this interpretation even among its main contributors. In fact, the Copenhagen interpretation has remained until today an amalgamation of different views. As has been convincingly argued in [1], it is the incompatibility between Bohr’s and Heisenberg’s views that sometimes gives the impression of inconsistencies in the Copenhagen interpretation.

Historically, Heisenberg wanted to base quantum theory solely on observable quantities such as the intensity of spectral lines, getting rid of all intuitive (anschauliche) concepts such as particle trajectories in space-time [2]. This attitude changed drastically with his paper [3] in which he introduced the uncertainty relations – there he put forward the point of view that it is the theory which decides what can be observed. His move from positivism to operationalism can be clearly understood as a reaction on the advent of Schrödinger’s wave mechanics [1] which, in particular due to its intuitiveness, became soon very popular among physicists. In fact, the word anschaulich (intuitive) is contained in the title of Heisenberg’s paper [3].

Bohr, on the other hand, gave the first summary of his interpretation in his famous lecture delivered in Como in September 1927, cf. [4]. There he introduced the notion of complementarity between particles and waves –
according to von Weizsäcker the core of the Copenhagen interpretation \cite{5}. As is well known, he later extended complementarity to non-physical themes and advanced it to a central concept of his own philosophy. Complementarity means that quantum objects are neither particles nor waves; for our intuition we have to use both pictures, in which the range of applicability of one picture necessarily constrains the range of applicability of the other. Heisenberg, as a mathematical physicist, was not at ease with such an interpretation. He preferred to use one coherent set of concepts, rather than two incompatible ones, cf. \cite{1}. In fact, it was known by then that particle and wave language can be converted into each other and are transcended into the consistent formalism of quantum theory. As Heisenberg wrote in his book \cite{6}: “Licht und Materie sind einheitliche physikalische Phänomene, ihre scheinbare Doppelnatur liegt an der wesentlichen Unzulänglichkeit unserer Sprache. . . . Will man trotzdem von der Mathematik zur anschaulichen Beschreibung der Vorgänge übergehen, so muß man sich mit unvollständigen Analogien begnügen, wie sie uns Wellen- und Partikelbild bieten.”

Even Bohr’s own interpretation did change in the course of time. This happened in particular due to the influence of the important paper by Einstein, Podolsky and Rosen in 1935 (EPR) \cite{7}. Before EPR, an essential ingredient of his interpretation was the uncontrollable disturbance of the quantum system by the apparatus during a measurement. The analysis of EPR demonstrated, however, that the issue is not the disturbance, but the non-separability (the entanglement) of a quantum system over in principle unlimited spatial distances. Therefore, in his response to EPR \cite{8}, Bohr adopted a strong operationalistic attitude, concealing the crucial concept of entanglement. Taking the indispensability of classical concepts for granted, he argued that even without any mechanical disturbance there is an “influence of the very conditions which define the possible types of predictions regarding the future behavior of the system” \cite{8}, i.e. no simultaneous reality for measurements of noncommuting variables such as position and momentum should exist. This attitude leads eventually to the consequence that quantum systems would not possess a real existence before interacting with a suitable measurement device (“only an observed phenomenon is a phenomenon”).

A somewhat ambiguous role in the Copenhagen interpretation(s) is played by the “collapse” or “reduction” of the wave function. This was introduced by Heisenberg in his uncertainty paper \cite{3} and later postulated by von Neu-

\footnote{“Light and matter are unique physical phenomena, their apparent double nature is due to the essential inadequacy of our language. . . . If one nevertheless wants to proceed from the mathematics to the intuitive description of the phenomena, we have to restrict ourselves to incomplete analogies as they are offered by the wave and particle pictures.”}
mann as a dynamical process independent of the Schrödinger equation, see Sec. 2. Most proponents of the Copenhagen interpretation have considered this reduction as a mere increase of knowledge (a transition from the potential to the actual), therefore denying that the wave function is a kinematical concept and thus affected by dynamics. The assumption of a dynamical collapse would definitely be in conflict with Bohr’s ideas of complementarity which forbid a physical analysis of the measurement process. To summarise, one can identify the following ingredients as being characteristic for the Copenhagen interpretation(s):

- Indispensability of classical concepts for the description of the measurement process
- Complementarity between particles and waves
- Reduction of the wave packet as a formal rule without dynamical significance

This set of rules has been sufficient to apply the quantum formalism pragmatically to concrete problems. But is it still sufficient? And is it satisfactory?

Modern developments heavily rely on the concept of entanglement, in order to describe satisfactorily the precision experiments that are now being performed in quantum optics and other fields. From the experimental violation of Bell’s inequalities it has become evident, that quantum theory cannot be substituted by a theory referring to a local reality. This is of course a consequence of the superposition principle – the heart of quantum theory. Among recent developments employing entanglement are quantum computation and quantum cryptography [9] and the reversible transition from the (coherent) superfluid phase to an (incoherent) Mott insulator phase in a Bose-Einstein condensate [10], during which interference patterns appear and disappear. The superposition principle is indispensable for describing $K - \bar{K}$ and neutrino oscillations. It would be hard to imagine how all this can be understood by denying any dynamical nature of the wave function and to interpret it as describing mere knowledge. Moreover, it is now clear, both theoretically and experimentally, that the classical appearance of our world can be understood as a dynamical process within quantum theory itself, without any need to postulate it. Therein, entanglement plays the crucial role. This will be discussed in the next section.

There have been, in the course of history, various attempts to come up with an alternative to the Copenhagen interpretation [11] [12]. Here I want to mention two of them, the de Broglie-Bohm interpretation and the Everett interpretation. Many other interpretations are some variant or mixture
of these two and the Copenhagen interpretation. The consistent-histories interpretation, for example, contains elements from both Copenhagen and Everett, see e.g. Chap. 5 in [13]. Different from these interpretations are attempts which aim at an explicit change of the Schrödinger equation in order to get a dynamical collapse of the wave function, see e.g. Chap. 8 in [13]. Up to now, however, there is no experimental hint that the Schrödinger equation has to be modified.

In the de Broglie-Bohm interpretation (or “theory”), the wave function \( \Psi \) is supplemented with classical variables (particles and fields) possessing definitive values of position and momentum. Whereas the wave function obeys an autonomous dynamics (obeying the Schrödinger equation without additional collapse), the particle dynamics depends on \( \Psi \) (often called a guiding field). Assuming that the particles are distributed according to \( |\Psi|^2 \), the predictions of this theory are indistinguishable from the ordinary framework, at least within non-relativistic quantum mechanics. After a measurement, the particle is trapped within one particular wave packet with the usual quantum-mechanical probability. Because the other wave packets are spatially separated from it after the measurement, they can no longer influence the particle. This represents an apparent collapse of the wave function and the occurrence of a definite measurement result. In principle, however, the remaining packets, although empty, can interfere again with the packet containing the particle, but the probability for this is tiny in macroscopic situations.

John Bell called the Everett interpretation a Bohm interpretation without trajectories. In fact, Everett assumes just as Bohm that the wave function is part of reality and that there is never any collapse. Therefore, after a measurement, all components corresponding to the different outcomes are equally present. It is claimed that the probability interpretation of quantum theory can be derived from the formalism (which is, however, a contentious issue). Von Weizsäcker calls this interpretation \( ^{22} \)... die einzige, die nicht hinter das schon von der Quantentheorie erreichte Verständnis zurück-, sondern vorwärts über es hinausstrebt.\(^4\)” The open question is of course when and how these different components (“branches”) become independent of each other. This leads me to the central topic – the emergence of classical behaviour in quantum theory.

\(^{22} \)... the only one that does not fall back behind the understanding already achieved by quantum theory but which strives forwards and even beyond.”
2 The emergence of classical properties in quantum theory

If classical concepts are not imposed from the outset, they have to be derived from the formalism, at least in an approximate sense. John von Neumann was the first who analysed in 1932 the measurement process within quantum mechanics. He considers the coupling of a system (S) to an apparatus (A), see Fig. 1.

Figure 1: Original form of the von Neumann measurement model.

Let the states of the measured system which are discriminated by the apparatus be denoted by $|n\rangle$ (for example, spin up and spin down), then an appropriate interaction Hamiltonian has the form (see Chap. 3 in [13], or [14])

$$H_{int} = \sum_n |n\rangle \langle n| \otimes \hat{A}_n . \quad (1)$$

The operators $\hat{A}_n$, acting on the states of the apparatus, are rather arbitrary, but must of course depend on the “quantum number” $n$. Eq. (1) describes an “ideal” interaction during which the apparatus becomes correlated with the system state, without changing the latter. There is thus no disturbance of the system by the apparatus – on the contrary, the apparatus is disturbed by the system (in order to yield a measurement result).

If the measured system is initially in the state $|n\rangle$ and the device in some initial state $|\Phi_0\rangle$, the evolution according to the Schrödinger equation with Hamiltonian (1) reads

$$|n\rangle|\Phi_0\rangle \rightarrow e^{t} \exp (-iH_{int}t) |n\rangle|\Phi_0\rangle = |n\rangle \exp \left(-i\hat{A}_nt\right) |\Phi_0\rangle =: |n\rangle|\Phi_n(t)\rangle . \quad (2)$$

The resulting apparatus states $|\Phi_n(t)\rangle$ are often called “pointer states”. A process analogous to (2) can also be formulated in classical physics. The essential new quantum features now come into play when we consider a superposition of different eigenstates (of the measured “observable”) as initial state. The linearity of time evolution immediately leads to

$$\left(\sum_n c_n |n\rangle\right)|\Phi_0\rangle \rightarrow e^{t} \sum_n c_n |n\rangle|\Phi_n(t)\rangle . \quad (3)$$
But this state is a superposition of macroscopic measurement results (of which Schrödinger’s cat is just one drastic example)! To avoid such a bizarre state, and to avoid the apparent conflict with experience, von Neumann introduced the dynamical collapse of the wave function as a new law. The collapse should then select one component with the probability $|c_n|^2$. He even envisaged that the collapse is eventually caused by the consciousness of a human observer, an interpretation that was later also adopted by Wigner. In the Everett interpretation, all the branches (each component in $\sum_n |c_n|^2$) are assumed to co-exist simultaneously.

Can von Neumann’s conclusion and the introduction of the collapse be avoided? The crucial observation [15], which enforces an extension of von Neumann’s measurement theory, is the fact that macroscopic objects (such as measurement devices) are so strongly coupled to their natural environment, that a unitary treatment as in (2) is by no means sufficient and has to be modified to include the environment.

![Figure 2](image)

Figure 2: Realistic extension of the von Neumann measurement model including the environment. Classical properties emerge through the unavoidable, irreversible interaction of the apparatus with the environment.

Fortunately, this can easily be done to a good approximation, since the interaction with the environment has in many situations the same form as given by the Hamiltonian $H$: The measurement device is itself “measured” (passively recognised) by the environment, according to

$$
\left( \sum_n c_n |n\rangle \langle \Phi_n | \right) |E_0\rangle \rightarrow \sum_n c_n |n\rangle \langle \Phi_n | E_n\rangle.
$$

This is again a macroscopic superposition, now including the myriads of degrees of freedom pertaining to the environment (gas molecules, photons, etc.). However, most of these environmental degrees of freedom are inaccessible. Therefore, they have to be integrated out from the full state (4). This leads to the reduced density matrix for system plus apparatus, which contains all the information that is available there. It reads

$$
\rho_{SA} \approx \sum_n |c_n|^2 |n\rangle \langle n| \otimes |\Phi_n\rangle \langle \Phi_n| \quad \text{if} \quad \langle E_n|E_m\rangle \approx \delta_{nm}.
$$
since under realistic conditions, different environmental states are orthogonal to each other. Eq. (5) is identical to the density matrix of an ensemble of measurement results $|n\rangle|\Phi_n\rangle$. System and apparatus thus seem to be in one of the states $|n\rangle$ and $|\Phi_n\rangle$, given by the probability $|c_n|^2$.

Both system and apparatus thus assume classical properties through the unavoidable, irreversible interaction with the environment. This dynamical process, which is fully described by quantum theory, is called decoherence [13]. It is based on the quantum entanglement between apparatus and environment. Under ordinary macroscopic situations, decoherence occurs on an extremely short timescale, giving the impression of an instantaneous collapse or a “quantum jump”. Recent experiments were able to demonstrate the continuous emergence of classical properties in mesoscopic systems [16, 17]. Therefore, one would never ever be able to observe a weird superposition such as Schrödinger’s cat, because the information about this superposition would almost instantaneously be delocalised into unobservable correlations with the environment, resulting in an apparent collapse for the cat state. The concept of decoherence motivated Wigner to give up his explanation of the collapse as being caused by consciousness [18]. In fact, decoherence makes it evident that living creatures play no particular role in the interpretation of quantum theory.

The interaction with the environment distinguishes the local basis with respect to which classical properties (unobservability of interferences) hold. This “pointer basis” must obey the condition of robustness, i.e. it must keep its classical appearance over the relevant timescales [19, 20]. Classical properties are thus not intrinsic to any object, but only defined by their interaction with other degrees of freedom. In simple (Markovian) situations the pointer states are given by localised Gaussian states [21]. They are, in particular, relevant for the localisation of macroscopic objects.

To summarise, these developments have shown that classical concepts are not an indispensable input to the theory, as required by the Copenhagen interpretation, but a natural consequence of the theory itself when applied to realistic conditions.

## 3 Quantum gravity

The modern developments discussed in the last section show that the main assumptions of the Copenhagen interpretation, such as complementarity and the demand for a priori classical concepts, are not obligatory. Still, one might argue, it could be possible to adopt this interpretation as a convenient background for pragmatic use.
While this may be true for ordinary laboratory situations, it may become impossible if quantum effects of the gravitational field are involved. It must be admitted that no effects of quantum gravity have yet been seen, or identified as such, and that no final consensus about such a theory has emerged. However, there exist many models with important applications in cosmology; without an appropriate and consistent interpretation, such models would be void of interest.

In ordinary quantum theory, time is given as an external parameter and not subject to quantisation. On the other hand, the gravitational field is described by Einstein’s theory of general relativity, in which space and time are dynamical and not absolute. I have discussed elsewhere the reasons why one generally believes that gravity must be described by a quantum theory at the most fundamental level \[22\]. If one quantises a theory that classically possesses no absolute time – be it general relativity or some alternative theory – the ensuing quantum theory does not contain any time parameter at all. Since the role of time in general relativity is merely to parametrise spacetimes (the “trajectories” in the corresponding configuration space), the absence of time in quantum gravity is the consequence of the absence of trajectories in quantum theory. The central equation of quantum gravity is of the general form

$$\hat{H} \Psi = 0,$$

where $\hat{H}$ is the total Hamilton operator of both gravitational and non-gravitational fields. The total quantum state is thus of a stationary form. Since quantum degrees of freedom are very sensitive to their environment (see Sec. 2), and since the dominant interaction in the Universe on large scales is gravity, one is immediately led to consider a quantum theory of the whole Universe – quantum cosmology \[22\]. Since the Universe naturally contains all of its observers, the problem arises to come up with an interpretation of quantum theory that contains no classical realms on the fundamental level.

How can a temporal dynamics be understood from the stationary equation \(\hat{H} \Psi = 0\)? It has been demonstrated that a concept of time re-emerges in a semiclassical limit as an approximate concept \[22, 24\]. In this limit, an effective time-dependent Schrödinger equation holds along formal WKB trajectories. Since different semiclassical branches usually decohere from one another, an observer cannot experience the other branches which only together form the one wave function $\Psi$ in \(\hat{H} \Psi = 0\).

Clearly, the Copenhagen interpretation cannot cope with quantum cosmology. This is the reason why most people working in this field, at least implicitly, adopt the Everett interpretation, since it is hard to imagine from where a conceivable collapse could emerge. The problems that are addressed
in quantum cosmology include the quantum origin of the Universe, the quantum probability for the occurrence of an inflationary phase, and the quantum-to-classical transition for primordial fluctuations which serve as the seeds for structure formation in the Universe, giving rise to galaxies [22]. With the advent of precision measurements for the spectrum of the cosmic microwave background radiation, some of these questions gain observational significance. It would thus be unsatisfactory to avoid a theoretical description of such processes just because some pre-conceived interpretation of quantum theory does not fit this purpose.

4 Conclusion

The Copenhagen interpretation needs classical concepts as prerequisites. On the other hand, quantum theory itself predicts the occurrence of decoherence through which systems such as measurement devices can appear classically to local observers. This can be, and has been, interpreted as a quantum justification for at least part of the original Copenhagen programme [19]. This explains, in retrospect, why the Copenhagen interpretations can serve as a background for pragmatic calculations, at least in non-gravitational situations.

The process of decoherence is based on the validity of the Schrödinger equation and can thus not describe any real collapse. For local experiments, this is definitely not needed, because decoherence can explain why we seem to observe a collapse or a “quantum jump”. It would seem unnatural and ad hoc to introduce a real collapse at this stage, where an apparent collapse is predicted anyway by the Schrödinger equation. The concept of quantum jumps thus plays the role of epicycles in astronomy [23] – it describes naively what is observed, but it becomes redundant at the fundamental, theoretical, level.

Still, the measurement problem is not resolved for the total system including the environment. The only alternatives so far are to either assume an additional real collapse in violation of the Schrödinger equation (for which there is not yet any experimental hint), or to adopt an Everett interpretation with its simultaneous reality of all branches. It seems hard to imagine that an experimental decision between these alternatives can be made in the foreseeable future. However, it is important to keep an open mind and to avoid the burden of a pre-imposed interpretation – “sonst wäre ernstlich zu befürchten, daß es dort, wo wir das Weiterfragen verbieten, wohl doch noch einiges Wissenswerte zu fragen gibt” [24].

3“Otherwise it would be seriously feared that just there, where we forbid further ques-
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