Emergence of a classical Universe from quantum gravity and cosmology

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I describe how we can understand the classical appearance of our world from a universal quantum theory. The essential ingredient is the process of decoherence. I start with a general discussion in ordinary quantum theory and then turn to quantum gravity and quantum cosmology. There is a whole hierarchy of classicality from the global gravitational field to the fluctuations in the cosmic microwave background, which serve as the seeds for the structure in the Universe.

Keywords: quantum mechanics; gravity; decoherence

1. Introduction

Modern physics is reigned by quantum theory. Originally devised as a theory of atoms and molecules, it has become evident that its range of application comprises almost all phenomena, from the behaviour of elementary particles to processes determining the properties of stars. All experiments and observations performed so far support quantum theory, which thus assumes more the role of a universal theoretical framework than the role of a particular theory for particular interactions. The only interaction that has not yet been fully accommodated into quantum theory is gravity, but arguments can be put forward in favour of a quantum theory of gravity, too (see later text). We shall thus assume here the universal validity of quantum theory.

In §2, I first present the central features of quantum theory. I then discuss the interpretational difficulties that arise from the measurement problem. In §3, I address and answer one of the central questions: how can we understand the appearance of our classical world from a fundamental quantum theory? The key to the answer is the process of decoherence, which is the emergence of classical properties through the irreversible interaction of a quantum system with its environment. In §4, I argue that a fundamental understanding cannot be attained without the application of quantum theory to the Universe as a whole, for which a theory of quantum gravity is needed. Section 5 is devoted to decoherence in quantum cosmology and the origin of structure in the Universe. Section 6 contains a brief conclusion.

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One contribution of 11 to a Theme Issue ‘Decoherence’.
2. The physical essence of quantum theory

The heart of quantum theory is the superposition principle. If \( \Psi_1 \) and \( \Psi_2 \) are allowed quantum states of a system, then \( \alpha_1 \Psi_1 + \alpha_2 \Psi_2 \), where \( \alpha_1 \) and \( \alpha_2 \) are arbitrary complex numbers, is again a possible physical state. In contrast to classical physics, where the superposition principle holds for particular situations (e.g. when linear wave equations hold approximately), its validity in quantum theory is assumed to be exact. Quantum states ('wavefunctions') are thus described by elements of a linear space. More specifically, they are members of a Hilbert space. Such a space is characterized by the fact that it is a linear space with a scalar product. The demand for a scalar or inner product arises from the probability interpretation of quantum theory: probabilities and transition rates are calculated by evaluating the scalar product for the wavefunctions in question.

A state \( \Psi \) can describe a quantum system consisting of many degrees of freedom ('subsystems'), for example, a collection of particles. An important fact is that it is in general not possible to write this state as a product of wave functions pertaining to the various subsystems. Erwin Schrödinger has called this feature Verschränkung or entanglement. The degree of entanglement does not depend on the spatial separation of the subsystems. For example, if two particles are entangled, they must be described by one common quantum state, even if they are far apart. This is the case in the famous Einstein–Podolsky–Rosen situation. In general, therefore, the state of the whole is more than the sum of its parts: one cannot ascribe separate states to the subsystems. This is often called the holistic nature of quantum theory and the world described by it.

The central role of entanglement was clearly emphasized by Schrödinger:

I would not call that one but rather the characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought. By the interaction the two representatives (or \( \psi \)-functions) have become entangled. ...Another way of expressing the peculiar situation is: the best possible knowledge of a whole does not necessarily include the best possible knowledge of all its parts, even though they may be entirely separated ... [1, p. 555]

Entanglement is a pure kinematic property, but it is, of course, consistent with the dynamics. The Schrödinger equation, which describes the evolution of the quantum states in time, is a linear equation; therefore, the sum of two solutions is again a solution.

A superposition of quantum states must not be confused with a classical ensemble of different possibilities. The latter describes mutually exclusive options, whereas in the superposition, all components are equally real. The difference is thus between the or and the and, which is the difference between classical and quantum physics and which lies at the origin of the paradoxical features often associated with quantum theory.

The superposition principle has so far passed all experimental tests [2]. Let me mention some examples. Entangled photon pairs have been created over a distance of many kilometres. One can perform double-slit experiments with large biomolecules [3], and serious suggestions were made even for tests of the superposition principle with living organisms [4]. In superconducting quantum interference devices, it is possible to superpose a current in one direction with the same current in the other direction and to observe the resulting interference.

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Entanglement is also the central feature in the emerging field of quantum information. For example, in 2007, a safe key in quantum cryptography has been transmitted over a distance of 144km. In particle physics, application of the superposition principle leads to experimentally well-established facts such as the $K^0 - \bar{K}^0$ and neutrino oscillations.

In the macroscopic regime, however, the direct application of the superposition principle seems to lead to paradoxes—the famous ‘measurement problem’ \cite{2,5}, which has been popularized in particular by the Gedanken experiment of Schrödinger’s cat: a quantum superposition in the atomic realm is transferred to a macroscopic state describing a cat that is simultaneously alive and dead. Superpositions of macroscopic states can result in any situation in which a microscopic system is in interaction with a macroscopic apparatus. Since such weird states are never observed, John von Neumann, who presented the measurement problem in 1932, proposed to introduce a new dynamical mechanism by hand (called by him Erster Eingriff or ‘first intervention’) in addition to the Schrödinger equation: whenever a measurement situation occurs, the superposition principle and the Schrödinger equation are violated, and one component of the initial superposition is selected with the probability given by the quantum formalism (‘Born’s rule’). This new dynamics is called the ‘collapse of the wave function’. However, neither von Neumann nor any other person in the early days of quantum theory made a concrete proposal (that is, a proposal with a dynamical equation) for the collapse mechanism. Today, various scenarios for a dynamical collapse are discussed, but none has been established in any experiment, so far \cite{2,5}.

The assumption that the superposition principle and the Schrödinger equation are universally valid leads directly to what is called the Everett or many-world interpretation of quantum theory: all components (‘branches’) of the quantum state are equally real. This has, of course, drastic consequences for our view of the world because it means that one and the same observer exists in various components of a wave function, in a very realistic sense. Can such a view be taken seriously? After all, no one has ever seen a superposition of different observers. The answer to this question relies very much on our understanding of how the classical appearance of our world arises in quantum theory.

3. The classical appearance of our world

It has been tacitly assumed since the days of Galileo that systems can be isolated, at least in principle. The mechanical laws for freely falling bodies, for example, exhibit themselves clearly in a situation where air resistance can be neglected. It is thus not surprising that the idea of an isolated system was thought to be generically applicable to quantum systems, too. This is, however, not the case. As shown by Zeh \cite{7}, quantum systems are extremely sensitive to the presence of an environment; the interaction between system and environment can be switched off only for micro- and mesoscopic systems.

This sensitivity goes beyond the direct disturbance of the system as it is known already from classical physics. The point is that the system can become quantum entangled with the environment even in cases where the interaction

\footnote{This section is adapted from §3 of my paper \cite{6}.}
is so weak that a direct disturbance cannot happen. For example, the cross section of a small dust grain in intergalactic space with the photons of the cosmic microwave background (CMB) is too weak to cause a direct disturbance of the grain but sufficiently strong to generate an entangled state between grain and photons [8].

It is, amazingly, this entanglement with the environment that is responsible for the classical appearance of the quantum system. The process of this emerging classicality is called decoherence [2,5,9]. How can this happen? Does the entanglement with the environment not lead to an even weirder non-classical state involving zillions of degrees of freedom, thus making the measurement problem even more severe?

It is indeed true that quantum mechanics predicts the emergence of a highly entangled state between system and environment. The crucial point, however, is that the environmental degrees of freedom are, in general, not accessible. For example, in a scattering situation where photons interact with a quantum system (such as the dust grain mentioned above), the photons usually escape in an irreversible way and cannot be subject to observation. What then happens is the following. The components of a local superposition (such as a pointer of a measuring apparatus being simultaneously at different positions) become separated in the huge configuration space of system and environment, and therefore the interferences between these components cannot be seen by a local observer who has access only to the system itself. But all realistic observers have this property of being localized (although we do not understand why this is ultimately the case)! Therefore, the interferences in the system cannot be seen, although they are there (in the entanglement with the unaccessible environment). This is decoherence. Entanglement is thus not only at the heart of quantum theory, but is also obligatory to understand the classical appearance of our world.

It is clear that the environment must be able to discriminate between the various components of a local superposition in order to cause decoherence. But this is usually the case because, for example, in a scattering process, the state of the scatterer (e.g. an escaping photon) is correlated with the position of the scattered object (e.g. a large molecule). For this process to occur, it is by no means necessary that the measured system is disturbed; all one needs is the imprint of the information about the system in the environment. In this sense, it is the environment that is ‘disturbed’ by the system and not the other way round. The process of decoherence allows one to substitute the quantum and by the classical or for the local system. The interaction with the environment distinguishes a certain basis for the local system with respect to which interferences are unobservable. This basis is called ‘pointer basis’ [2,5,9]. In the important case of scattering, the pointer basis is given by narrow Gaussians approximating the position basis.

Decoherence must not be confused with dissipation. Although dissipation is also an effect caused by an environment, the time scales for both effects are widely separated. Decoherence usually acts much quicker than dissipation, a typical number for the decoherence time scale in macroscopic situations being about $10^{-40}$ times the dissipation time scale. It is because of this tiny time scale that continuous quantum processes appear discontinuously, for example, in the form of ‘quantum jumps’ or ‘particles’ [10].
As long as one sticks to the present formalism of quantum theory—that is, as long as one assumes the exact validity of its linear structure and the Schrödinger equation, one arrives at a consistent interpretation—the Everett or many-worlds interpretation mentioned earlier. Given some assumptions (which, however, are of a contentious nature), one can then attempt to derive Born’s rule—that is, the probability interpretation of quantum theory—from relative frequencies in the Everett picture. Such attempts were made from different perspectives in papers, including [11] and, more recently [12–14].

If used in the framework of the Everett interpretation, decoherence can solve the measurement problem. But, as David Wallace has emphasized [15], ‘It does not, however, in any way blunt the metaphysically shocking aspect of Everett’s proposal: no one quasi-classical branch is singled out as real; all are equally part of the underlying quantum reality’.

From a pragmatic point of view, one could argue that the process of decoherence justifies the ‘Copenhagen viewpoint’, which postulates the existence of classical measuring agencies from the outset. In my opinion, such an attitude is too positivistic. Adopting a realist interpretation, the only alternatives to the Everett interpretation are models that describe a dynamical collapse of the wave function (aside from approaches such as the Bohm interpretation that introduce additional kinematic structures). In such models, the linear structure of the theory breaks down in situations corresponding to a measurement—that is, in situations where a macroscopic number of variables is involved. As mentioned earlier, there exist several collapse models in the literature, but so far none has received experimental support. The problem of experimentally testing these models faces the difficulty that decoherence itself mimics an apparent collapse: one has to construct a situation in which the environment is weak enough to avoid decoherence, but strong enough to cause a genuine collapse. This has not yet been achieved, although concrete proposals exist [16]. As long as no empirical decision is possible, one has to choose between the simplicity of the equations (here, the exact validity of the Schrödinger equation) and the simplicity (or parsimony) of our world view (our Weltanschauung).

Among the many applications of decoherence is also its relevance for brain processes. In the context of claims made by Roger Penrose and others to the extent that the emergence of consciousness can be understood from the occurrence of quantum superpositions in the brain, it was found by Max Tegmark in 2000 that decoherence happens too quickly for this to be allowed [2,5,17]. Still, investigating the role of quantum theory for living organisms is a promising avenue for the future [17].

4. The role of quantum gravity

As the discussion of decoherence demonstrates, quantum systems cannot, in general, be considered as isolated. Only microscopic and, to some extent, mesoscopic systems can be efficiently shielded from their environment. Only for them, therefore, is the description by wave functions (which refers to isolated systems) correct. In all other cases, one must take the environment into account and can assign a quantum state only to the total system, including the environment. But because the environment is a system with many degrees of

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freedom, it is again coupled to its environment, and so forth, leading to the Universe as a whole as the only closed quantum system in the strict sense. One thereby arrives at the concept of a ‘wave function of the Universe’ and to the field of quantum cosmology. Quantum cosmology is thus needed for a consistent description of the world.

Since gravity is the dominating interaction at cosmic scales, quantum cosmology must be based on a theory of quantum gravity [18]. But such a theory is also needed for other reasons.

On the one hand, general relativity is incomplete in that it predicts the occurrence of singularities in a wide range of situations. This concerns the origin of the Universe (‘big bang’) but also its potential final fate. Some of the models that use dark energy for an explanation of the current acceleration of the Universe predict singularities in the future; other models still allow for a recollapsing Universe and a ‘big crunch’. A more general theory is therefore needed in order to describe such situations. It is generally believed that such a theory should be a quantum theory of gravity, for it was, after all, quantum mechanics that rescued the atom from the singularities of classical electrodynamics.

On the other hand, one faces the problem of time (see [19,20] and references therein). Whereas time in quantum theory is absolute (the parameter $t$ in the Schrödinger equation has been inherited from Newtonian mechanics), time as part of the space–time obeying Einstein’s equations is dynamical. A more fundamental theory is therefore needed in order to gain a coherent concept of time.

Although a complete quantum theory of gravity is not yet at our disposal, some general remarks on the concept of time can be made. Let us consider the following analogy. A central concept in classical mechanics is a particle trajectory. There are, however, no trajectories in quantum mechanics because the states depend either on position or on momentum (or some other representation), but not on both. In addition, the Newtonian time parameter $t$ is still present. In general relativity, the analogue of a particle trajectory is a whole space–time, with three-dimensional space as the analogue of position. Using standard quantization rules, one thus obtains quantum states that depend only on the spatial geometry (using the position representation). But, in contrast to quantum mechanics, there is no external time $t$ anymore because general relativity employs a dynamical concept of space–time. Therefore, time has disappeared completely from the scene; the problem of time is solved by the absence of time in quantum gravity. The fundamental equation for the quantum state is of the form $\hat{H}\psi = 0$ and thus has the form of a stationary wave equation. If one uses the metric variables suggested by general relativity, this equation is called the Wheeler–DeWitt equation. One can use other variables, for example, the holonomy and the field flux of loop quantum gravity, but the timeless form of this equation remains. This should also apply to string theory, once it is fundamentally understood.

The standard time parameter $t$ can be recovered from the fundamental timeless equation as an approximate concept in special ‘semiclassical’ situations [18,19]. The emergent time bears some resemblance to the notion of ephemeris time in astronomy [21]; time in Newtonian theory is reconstructed from the observed positions of the celestial objects. In quantum gravity, the time parameter emerges for the behaviour of quantum variables with respect to macroscopic degrees of freedom of the gravitational field.
5. Decoherence in quantum cosmology and the origin of structure

Quantum cosmology is the application of quantum theory to the Universe as a whole. As we have seen already, such a framework is needed for consistency. For its description, we can use a wave function that satisfies the Wheeler–DeWitt equation or its generalization in loop quantum cosmology. One assumes that one can approximate the Universe by a homogeneous and isotropic background plus small inhomogeneities. This assumption may not be valid at the fundamental level, but one expects it to be sufficient for a wide range of applications. For definiteness, by using the Wheeler–DeWitt approach, one can write the wave function as

$$\Psi(a, \phi, \{x_n\})$$

where $a$ denotes the scale factor of the Universe, $\phi$ denotes a homogeneous background field (e.g. the inflaton field in an inflationary scenario of the early Universe) and the $\{x_n\}$ denote symbolically a collection of small inhomogeneities (they can describe density fluctuations, weak gravitational waves, or other fields).

In any linear theory of quantum gravity (and practically all existing approaches belong to this class), one faces the consequences of the superposition principle at the macroscopic level. A generic quantum state is a superposition of macroscopically different universes, a variant of Schrödinger’s cat at the cosmic level. Again, the question arises whether the non-observation of such configurations can be understood. In the case of quantum mechanics, decoherence by the irreversible interaction with the environment leads to the emergence of classical behaviour. But what is the situation in cosmology? After all, the Universe as a whole has no environment. The key to an answer is provided by the observation that decoherence is a process in configuration space. This is the high-dimensional (probably infinite-dimensional) space on which the total wave function is defined. It is in this space where the separation between system (relevant degrees of freedom) and environment (irrelevant degrees of freedom) must be made.

So what are the irrelevant and the relevant variables in quantum cosmology? It has been suggested in Zeh [22] that the main relevant variables are the global ones such as the scale factor $a$ and the inflaton field $\phi$, while the irrelevant ones are the small fluctuations described by the $\{x_n\}$. There are, of course, also situations where some of the fluctuations become relevant; we shall describe such a situation shortly. The general formalism of treating such fluctuations (‘higher modes’ or ‘multipoles’) in quantum cosmology was set up in Halliwell & Hawking [23]. On the basis of this formalism, it was shown in Kiefer [24] and in later papers (cf. [18]) that the interaction between the higher modes and $a$ and $\phi$ leads to a strong entanglement and thus provokes $a$ and $\phi$ to decohere. Calculations show that the scale factor is the first variable to assume classical properties; this classicality of $a$ then serves as a prerequisite for the classicality of $\phi$. It is in this sense that the emergence of space can be understood in quantum cosmology. If, in addition, the special ‘semiclassical’ situation holds, in which time has emerged as an approximate quantity, one could speak of the emergence of space–time from quantum theory.

The semiclassical limit, together with decoherence, could also provide the means for an understanding of the arrow of time in the Universe [20]. The Wheeler–DeWitt equation is asymmetric with respect to $a$; more precisely, it assumes the form of a free wave equation in the limit $a \to 0$, but develops

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a complicated potential for large $a$. The equation is thus compatible with a simple boundary condition that leads, for small $a$, to a wave function being a product state of each variable separately. There is thus no entanglement in this limit, and tracing out degrees of freedom is ineffective. There is thus also no decoherence, and the entanglement entropy vanishes. As $a$ becomes larger, entanglement becomes stronger, and the entropy increases. Because entanglement entropy can be connected with the ordinary entropy (e.g. ch. 9 in Peres [25]), this generates an arrow of time. The magnitude of the entropy is then directly correlated with the size of the Universe. The origin of irreversibility could thus in principle be understood from quantum gravity. This picture, if it were true, would have amazing consequences for the arrow of time in a classically recollapsing Universe [26]. The arrow of time would formally reverse at the region of the classical turning point, but global quantum effects would forbid any observer to continue his existence beyond that region.

In the decoherence process discussed earlier, the fluctuations serve as an irrelevant environment for the global degrees of freedom such as the scale factor. But some of the fluctuations are observable and can thus become relevant. These are the fluctuations that manifest themselves in the anisotropy spectrum of the CMB radiation. According to the inflationary scenario of the early Universe, these fluctuations have their origin in the ubiquitous quantum fluctuations during inflation. But how does the transition from these primordial quantum fluctuations to the observed classical anisotropies in the CMB proceed? The answer to this question contains two parts. First, the peculiarity of the inflationary phase yields the result that for late times, the quantum expectations values for these fluctuations become indistinguishable from their classical counterparts [27,28]. Second, the interaction of the fluctuations with other degrees of freedom (‘environment’) distinguishes the field-amplitude basis for the fluctuations in the sense of decoherence [28,29]. This happens as follows.

During inflation, the quantum state of the primordial fluctuations develops from the ground state to a highly squeezed state; the squeezing is in the ‘momentum’, while the elongation is in the ‘position’ (i.e. the field amplitude). Such a state is strongly prone to decoherence. The environmental degrees of freedom can be the nonlinear parts of the fluctuations or other fields that interact with them; the details of the interaction are of secondary nature. The behaviour of the primordial fluctuations then becomes indistinguishable from a classical stochastic system, where the classicality arises with respect to the field amplitude—that is, it is the field-amplitude basis that is the pointer basis in the sense of decoherence. The standard calculations describing the CMB anisotropies are based on this classical stochastic nature for the fluctuations.

6. Conclusion

We have assumed throughout this article that quantum theory is universally valid. This assumption may, of course, be wrong, but all empirical evidence so far supports its validity. The emergence of classical properties can be understood from within the formalism, by the process of decoherence. Because the linear structure of quantum theory is not violated, this corresponds to an Everett interpretation of the theory. Decoherence then describes an
apparent collapse only. One can, of course, modify the theory by hand to accommodate a real collapse, but this is presently done for philosophical, not empirical, reasons.

All quantum systems carry energy; so they all interact with the gravitational field. It is thus natural to assume that gravity has to be described by a quantum theory, too. A theory of quantum gravity is not yet available in final form, but various approaches are at our disposal. Practically all of them preserve the linear structure of ordinary quantum theory. Because only the Universe as a whole can be considered to be truly isolated, quantum gravity must be applied to cosmic scales, and a framework of quantum cosmology is needed for consistency. The prevalent interpretation is the Everett interpretation because no real alternative for cosmology is in sight. Again, the emergence of classical properties can be understood by decoherence, with the separation of irrelevant and relevant degrees of freedom being performed in configuration space. We can thus understand from a universal quantum theory why we observe a classical Universe.

There is, in fact, a whole hierarchy of classicality. The first variables to assume classical behaviour are global gravitational degrees of freedom such as the scale factor of the Universe. This arises from their strong entanglement with all other variables. The next level is the global matter degrees of freedom such as the inflaton field. On this semiclassical background, then, one can understand the emergence of classicality for the primordial quantum fluctuations of gravitational field and matter. These then serve as the seeds for the origin of structure in the Universe, leading eventually to the galaxies and clusters of galaxies. On the basis of a universal quantum theory, we can thus obtain a consistent picture of our world. We do not know, of course, whether this picture will ultimately be the correct one.

References

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