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Statement

and

Readings

Decoherence and Entanglement

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Since the inception of quantum mechanics entanglement has been acknowledged, as Schrödinger had put it, as "not one, but The" characteristic feature of the theory that sets it apart from classical physics. Decoherence, on the other hand, was recognized only recently as the "new orthodoxy", crucial to the consistency of quantum theory with our everyday notions of the classical world. In this short introduction I shall present the basic concepts underlying this "new orthodoxy", and place these in the broader context of the philosophy of physics, touching upon topics such as (1) the methodological role of decoherence in the philosophy of quantum theory, (2) the conceptual and historical relation between the foundations of statistical mechanics and decoherence, and (3) the impact of decoherence on quantum information theory, especially on the question of the feasibility of large-scale and computationally superior quantum information processing devices. Finally, I shall also try to raise some doubts about the claim that decoherence plays a role in the so-called "emergence of the classical world".

Readings:

Bacciagaluppi, Guido, "The Role of Decoherence in Quantum Mechanics", The Stanford Encyclopedia of Philosophy (Fall 2008 Edition), Edward N. Zalta (ed.), URL = <http://plato.stanford.edu/archives/fall2008/entries/qm-decoherence/

Joos, Eric, "Elements of Environmental Decoherence", arXiv:quant-ph/9908008v1.

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The Role of Decoherence in Quantum Mechanics

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Interference phenomena are a well-known and crucial feature of quantum mechanics, the two-slit experiment providing a standard example. There are situations, however, in which interference effects are (artificially or spontaneously) suppressed. We shall need to make precise what this means, but the *theory of decoherence* is the study of (spontaneous) interactions between a system and its environment that lead to such suppression of interference. This study includes detailed modelling of system-environment interactions, derivation of equations ('master equations') for the (reduced) state of the system, discussion of time-scales etc. A discussion of the concept of suppression of interference and a simplified survey of the theory is given in Section 2, emphasising features that will be relevant to the following discussion (and restricted to standard non-relativistic particle quantum mechanics.[1] A partially overlapping field is that of *decoherent histories*, which proceeds from an abstract definition of loss of interference, but which we shall not be considering in any detail.

Decoherence is relevant (or is claimed to be relevant) to a variety of questions ranging from the measurement problem to the arrow of time, and in particular to the question of whether and how the 'classical world' may emerge from quantum mechanics. This entry mainly deals with the role of decoherence in relation to the main problems and approaches in the foundations of quantum mechanics. Section 3 analyses the claim that decoherence solves the measurement problem, as well as the broadening of the problem through the inclusion of environmental interactions, the idea of emergence of classicality, and the motivation for discussing decoherence together with approaches to the foundations of quantum mechanics. Section 4 then reviews the relation of decoherence with some of the main foundational approaches. Finally, in Section 5 we mention suggested applications that would push the role of decoherence even further.

Suppression of interference has of course featured in many papers since the beginning of quantum mechanics, such as Mott's (1929) analysis of alpha-particle tracks. The modern beginnings of decoherence as a subject in its own right are arguably the papers by H. D. Zeh of the early 1970s (Zeh 1970; 1973). Very well known are also the papers by W. Zurek from the early 1980s (Zurek 1981; 1982). Some of these earlier examples of decoherence (e.g., suppression of interference between left-handed and right-handed states of a molecule) are mathematically more accessible than more recent ones. A concise and readable introduction to the theory is provided by Zurek in *Physics Today* (1991). This article was followed by publication of several letters with Zurek's replies (1993), which highlight controversial issues. More recent surveys are Zeh 1995, which devotes much space to the interpretation of decoherence, and Zurek 2003. The textbook on decoherence by Giulini *et al*. (1996) and the very recent book by Schlosshauer (2007) are also highly recommended.[2]

2. Basics of Decoherence

2.1 Interference and suppression of interference

The two-slit experiment is a paradigm example of an *interference* experiment. One repeatedly sends electrons or other particles through a screen with two narrow slits, the electrons impinge upon a second screen, and we ask for the probability distribution of detections over the surface of the screen. In order to calculate this, one cannot just take the probabilities of passage through the slits, multiply with the probabilities of detection at the screen conditional on passage through either slit, and sum over the contributions of the two slits.[3] There is an additional so-called interference term in the correct expression for the probability, and this term depends on *both* wave components that pass through the slits.

Thus, the experiment shows that the correct description of the electron in terms of quantum wave functions is indeed one in which the wave passes through both slits. The quantum state of the electron is not given by a wave that passes through the upper slit *or* a wave that passes through the lower slit, not even with a probabilistic measure of ignorance.

There are, however, situations in which this interference term is not observed, i.e., in which the classical probability formula applies. This happens for instance when we perform a detection at the slits, whether or not we believe that measurements are related to a ‘true’ collapse of the wave function (i.e., that only *one* of the components survives the measurement and proceeds to hit the screen). The disappearence of the interference term, however, can happen also spontaneously, even when no ‘true collapse’ is presumed to happen, namely if some other systems (say, sufficiently many stray cosmic particles scattering off the electron) suitably interact with the wave between the slits and the screen. In this case, the interference term is not observed, because the electron has become *entangled* with the stray particles (see the entry on quantum entanglement and information).[4] The phase relation between the two components which is responsible for interference is well-defined only at the level of the larger system composed of electron and stray particles, and can produce interference only in a suitable experiment including the larger system. Probabilities for results of measurements are calculated *as if* the wave function had collapsed to one or the other of its two components, but the phase relations have merely been distributed over a larger system.

It is this phenomenon of suppression of interference through suitable interaction with the environment that we refer to by ‘suppression of interference’, and that is studied in the theory of decoherence.[5] For completeness, we mention the overlapping but distinct concept of *decoherent* (or *consistent*) *histories*. Decoherence in the sense of this abstract formalism is defined simply by the condition that (quantum) probabilities for wave components at a later time may be calculated from those for wave components at an earlier time and the (quantum) conditional probabilities, according to the standard classical formula, i.e., as if the wave had collapsed. There is some controversy, which we leave aside, as to claims surrounding the status of this formalism as a foundational approach in its own right. Without these claims, the formalism is interpretationally neutral and can be useful in describing situations of suppression of interference. Indeed, the abstract definition has the merit of bringing out two conceptual points that are crucial to the idea of decoherence and that will be emphasised in the following: that wave components can be reidentified over time, and that if we do so, we can formally identify 'trajectories' for the system.[6]

2.2 Features of decoherence

The *theory of decoherence* (sometimes also referred to as 'dynamical' decoherence) studies concrete spontaneous interactions that lead to suppression of interference.

Several features of interest arise in models of such interactions (although by no means are all such features common to all models):

- Suppression of interference can be an extremely fast process, depending on the system and the environment considered.[7]
- The environment will tend to couple to and suppress interference between a preferred set of states, be it a discrete set (left- and right- handed states in models of chiral molecules) or some continuous set ('coherent' states of a harmonic oscillator).
- These preferred states can be characterised in terms of their 'robustness' or 'stability' with respect to the interaction with the environment. Roughly speaking, while the system gets entangled with the environment, the states between which interference is suppressed are the ones that get *least* entangled with the environment themselves under further interaction. This point leads us to various further (interconnected) aspects of decoherence.
- First of all, an intuitive picture of the interaction between system and environment can be provided by the analogy with a measurement interaction (see the entries on quantum mechanics and measurement in quantum theory): the environment is 'monitoring' the system, it is spontaneously 'performing a measurement' (more precisely letting the system undergo an interaction as in a measurement) of the preferred states. The analogy to the standard idealised quantum measurements will be very close in the case of, say, the chiral molecule. In the case, say, of the coherent states of the harmonic oscillator, one should think instead of *approximate* measurements of position (or in fact of approximate joint measurements of position and momentum, since information about the time of flight is also recorded in the environment).
- Secondly, the robustness of the preferred states is related to the fact that information

about them is stored in a *redundant* way in the environment (say, because the Schrödinger cat has interacted with so many stray particles — photons, air molecules, dust). This can later be accessed by an observer without further disturbing the system (we measure — however that may be interpreted — whether the cat is alive or dead by intercepting on our retina a small fraction of the light that has interacted with the cat).

- Thirdly, one often says in this context that decoherence induces 'effective superselection rules'. The concept of a (strict) superselection rule is something that requires a generalisation of the formalism of quantum mechanics, and means that there are some observables — called 'classical' in technical terminology — that *commute* with all observables (for a review, see Wightman 1995). Intuitively, these observables are infinitely robust, since no possible interaction can disturb them (at least as long as the interaction Hamiltonian is considered to be an observable). By an effective superselection rule one means that, roughly analogously, certain observables (e.g., chirality) will not be disturbed by the interactions that actually take place. (See also the comments on the charge superselection rule in Section 5 below.)
- Fourthly and perhaps most importantly, robustness has to do with the possibility or reidentifying a component of the wave over time, and thus talking about *trajectories*, whether spatial or not (the component of the electron's wave that goes through the upper slit hits the screen at a particular place with a certain probability; the left-handed component of the state of a chiral molecule at some time t evolves into the left-handed component of the perhaps slightly altered state of the molecule at some later time t'). Notice that in many of the early papers on decoherence the emphasis is on the preferred states themselves, or on how the (reduced) state of the system evolves: notably on how the state of the system becomes approximately diagonal in the basis defined by the preferred states. This emphasis on (so to speak) *kinematical* aspects must not mislead one: the *dynamical* aspects of reidentification over time and trajectory formation are just as important if not the *most* important for the concept of decoherence and its understanding.
- In the case of decoherence interactions of the form of approximate joint position and momentum measurements, the preferred states are obviously Schrödinger waves localised (narrow) in both position and momentum (essentially the 'coherent states' of the system). Indeed, they can be *very* narrow. A speck of dust of radius $a = 10^{-5}$cm floating in the air will have interference suppressed between (position) components with a width ('coherence length') of 10^{-13}cm.[8]
- In this case, the trajectories at the level of the components (the trajectories of the preferred states) will approximate surprisingly well the corresponding classical (Newtonian) trajectories. Intuitively, one can explain this by noting that if the preferred states, which are 'wave packets' that are both narrow in position and remaining narrow (because narrow in momentum), tend to get entangled least with the environment, they will tend to follow more or less undistrubed the Schrödinger equation. But in fact, narrow wave packets will follow approximately Newtonian trajectories (if the external potentials in which they move are uniform enough along the width of the packets: results of this kind are known as 'Ehrenfest theorems'.) Thus, the resulting 'histories' will be close to Newtonian ones (on the relevant

scales).[9] The most intuitive physical example for this are the observed trajectories of alpha particles in a bubble chamber, which are indeed extremely close to Newtonian ones, except for additional tiny 'kinks'.[10]

None of these features are claimed to obtain in all cases of interaction with some environment. It is a matter of detailed physical investigation to assess which systems exhibit which features, and how general the lessons are that we might learn from studying specific models. In particular one should beware of common overgeneralisations. For instance, decoherence does *not* affect only and all 'macroscopic systems'. True, middle-sized objects, say, on the Earth's surface will be very effectively decohered by the air in the atmosphere, and this is an excellent example of decoherence at work. On the other hand, there are also very good examples of decoherence-like interactions affecting microscopic systems, such as in the interaction of alpha particles with the gas in a bubble chamber. And further, there are arguably macroscopic systems for which interference effects are not suppressed. For instance, it has been shown to be possible to sufficiently shield SQUIDS (a type of superconducting devices) from decoherence for the purpose of observing superpositions of different macroscopic currents — contrary to what one had expected (see e.g., Leggett 1984; and esp. 2002, Section 5.4). Anglin, Paz and Zurek (1997) examine some less well-behaved models of decoherence and provide a useful corrective as to the limits of decoherence.

3. Conceptual Appraisal

3.1 Solving the measurement problem?

The fact that interference is typically very well suppressed between localised states of macroscopic objects suggests that it is relevant to why macroscopic objects in fact appear to us to be in localised states. A stronger claim is that decoherence is not only relevant to this question but by itself already provides the complete answer. In the special case of measuring apparatus, it would explain why we never observe an apparatus pointing, say, to two different results, i.e., decoherence would provide a solution to the measurement problem. As pointed out by many authors, however (recently e.g., Adler 2003; Zeh 1995, pp. 14-15), this claim is not tenable.

The measurement problem, in a nutshell, runs as follows. Quantum mechanical systems are described by wave-like mathematical objects (vectors) of which sums (superpositions) can be formed (see the entry on quantum mechanics). Time evolution (the Schrödinger equation) preserves such sums. Thus, if a quantum mechanical system (say, an electron) is described by a superposition of two given states, say, spin in x-direction equal +1/2 and spin in x-direction equal -1/2, and we let it interact with a measuring apparatus that couples to these states, the final quantum state of the composite will be a sum of two components, one in which the apparatus has coupled to (has registered) x-spin = +1/2, and one in which the apparatus has coupled to (has registered) x-spin = -1/2. The problem is that while we may accept the idea of microscopic systems being described by such sums, we cannot even begin to imagine what it would mean for the (composite of electron and) apparatus to be so described.

Now, what happens if we include decoherence in the description? Decoherence tells us, among other things, that there are plenty of interactions in which differently localised states of macroscopic systems couple to different states of their environment. In particular, the differently localised states of the macroscopic system could be the states of the pointer of the apparatus registering the different *x*-spin values of the electron. By the same argument as above, the composite of electron, apparatus and environment will be a sum of a state corresponding to the environment coupling to the apparatus coupling in turn to the value +1/2 for the spin, and of a state corresponding to the environment coupling to the apparatus coupling in turn to the value -1/2 for the spin. So again we cannot imagine what it would mean for the composite system to be described by such a sum.

We are left with the following choice *whether or not* we include decoherence: either the composite system is not described by such a sum, because the Schrödinger equation actually breaks down and needs to be modified, or it is, but then we need to understand what that means, and this requires giving an appropriate interpretation of quantum mechanics. Thus, decoherence as such does not provide a solution to the measurement problem, at least not unless it is combined with an appropriate interpretation of the wave function. And indeed, as we shall see, some of the main workers in the field such as Zeh (2000) and Zurek (1998) suggest that decoherence is most naturally understood in terms of Everett-like interpretations (see below Section 4.3, and the entries on Everett's relative-state interpretation and on the many-worlds interpretation).

Unfortunately, naive claims of the kind above are still somewhat part of the 'folklore' of decoherence, and deservedly attract the wrath of physicists (e.g., Pearle 1997) and philosophers (e.g., Bub 1999, Chap. 8) alike. (To be fair, this 'folk' position has the merit of attempting to subject measurement interactions to further physical analysis, without assuming that measurements are a fundamental building block of the theory.)

3.2 Compounding the measurement problem

Decoherence is clearly neither a dynamical evolution contradicting the Schrödinger equation, nor a new interpretation of the wave function. As we shall discuss, however, it does both reveal important dynamical effects *within* the Schrödinger evolution, and may be *suggestive* of possible interpretations of the wave function.

As such it has other things to offer to the philosophy of quantum mechanics. At first, however, it seems that discussion of environmental interactions even exacerbates the problems. Intuitively, if the environment is carrying out, without our intervention, lots of approximate position measurements, then the measurement problem ought to apply more widely, also to these spontaneously occurring measurements.

Indeed, while it is well-known that localised states of macroscopic objects spread very slowly under the free Schrödinger evolution (i.e., if there are no interactions), the situation turns out to be different if they are in interaction with the environment. Although the different components that couple to the environment will be individually incredibly localised, collectively they can have a spread that is many orders of magnitude larger. That is, the state of the object and the environment could be a superposition of zillions of very well localised terms, each with slightly different positions, and which are collectively spread over a *macroscopic distance*, even in the case of everyday objects.[11]

Given that everyday macroscopic objects are particularly subject to decoherence interactions, this raises the question of whether quantum mechanics can account for the appearance of the everyday world even beyond the measurement problem in the strict sense. To put it crudely: if everything is in interaction with everything else, everything is entangled with everything else, and that is a worse problem than the entanglement of measuring apparatuses with the measured probes. And indeed, discussing the measurement problem without taking decoherence (fully) into account may not be enough, as we shall illustrate by the case of some versions of the modal interpretation in Section 4.4.

3.3 Emergence of classicality

What suggests that decoherence may be relevant to the issue of the classical appearance of the everyday world is that *at the level of components* the quantum description of decoherence phenomena can display tantalisingly classical aspects. The question is then whether, if viewed in the context of any of the main foundational approaches to quantum mechanics, these classical aspects can be taken to explain corresponding classical aspects of the phenomena. The answer, perhaps unsurprisingly, turns out to depend on the chosen approach, and in the next section we shall discuss in turn the relation between decoherence and several of the the main approaches to the foundations of quantum mechanics.

Even more generally, one could ask whether the results of decoherence could thus be used to explain the emergence of the entire *classicality of the everyday world*, i.e., to explain both kinematical features such as macroscopic localisation and dynamical features such as approximately Newtonian or Brownian trajectories, *whenever they happen to be* phenomenologically adequate descriptions. As we have mentioned, there are cases in which a classical description is not a good description of a phenomenon, even if the phenomenon involves macroscopic systems. There are also cases, notably quantum *measurements*, in which the classical aspects of the everyday world are only kinematical (definiteness of pointer readings), while the dynamics is highly non-classical (indeterministic response of the apparatus). In a sense, the everyday world is the world of classical concepts as presupposed by Bohr (see the entry on the Copenhagen interpretation) in order to describe in the first place the 'quantum phenomena', which *themselves* would thus become a consequence of decoherence (Zeh 1995, p. 33; see also Bacciagaluppi 2002, Section 6.2). The question of explaining the classicality of the everyday world becomes the question of whether one can *derive* from within quantum mechanics the conditions necessary to *discover and practise* quantum mechanics itself, and thus, in Shimony's (1989) words, closing the circle.

In this generality the question is clearly too hard to answer, depending as it does on how far the physical *programme of decoherence* (Zeh 1995, p. 9) can be successfully developed.

We shall thus postpone the (partly speculative) discussion of how far the programme of decoherence might go until Section 5.

4. Decoherence and Approaches to Quantum Mechanics

There is a wide range of approaches to the foundations of quantum mechanics. The term 'approach' here is more appropriate than the term 'interpretation', because several of these approaches are in fact *modifications* of the theory, or at least introduce some prominent new theoretical aspects. A convenient way of classifying these approaches is in terms of their strategies for dealing with the measurement problem.

Some approaches, so-called collapse approaches, seek to modify the Schrödinger equation, so that superpositions of different 'everyday' states do not arise or are very unstable. Such approaches may have intuitively little to do with decoherence since they seek to suppress precisely those superpositions that are created by decoherence. Nevertheless their relation to decoherence is interesting. Among collapse approaches, we shall discuss (in Section 4.1) von Neumann's collapse postulate and theories of spontaneous localisation (see the entry on collapse theories).

Other approaches, known as 'hidden variables' approaches, seek to explain quantum phenomena as equilibrium statistical effects arising from a theory at a deeper level, rather strongly in analogy with attempts at understanding thermodynamics in terms of statistical mechanics (see the entry on philosophy of statistical mechanics). Of these, the most developed are the so-called pilot-wave theories, in particular the theory by de Broglie and Bohm (see the entry on Bohmian mechanics), whose relation to decoherence we discuss in Section 4.2.

Finally, there are approaches that seek to solve the measurement problem strictly by providing an appropriate *interpretation* of the theory. Slightly tongue in cheek, one can group together under this heading approaches as diverse as Everett interpretations (see the entries on Everett's relative-state interpretation and on the many-worlds interpretation), modal interpretations and Bohr's Copenhagen interpretation (Sections 4.3, 4.4 and 4.5, respectively).

We shall be analysing these approaches specifically in their relation to decoherence. For further details and more general assessment or criticism we direct the reader to the relevant entries.

4.1 Collapse approaches

4.1.1 Von Neumann

It is notorious that von Neumann (1932) proposed that the observer's consciousness is somehow related to what he called Process I, otherwise known as the collapse postulate or the projection postulate, which in his book is treated on a par with the Schrödinger equation (his Process II). There is some ambiguity in how to interpret von Neumann. He may have been advocating some sort of special access to our own consciousness that makes it appear to us that the wave function has collapsed, thus justifying a phenomenological reading of Process I. Alternatively, he may have proposed that consciousness plays some causal role in precipitating the collapse, in which case Process I is a physical process fully on a par with Process II.[12]

In either case, von Neumann's interpretation relies on the insensitivity of the final predictions (for what we consciously record) to exactly where and when Process I is used in modelling the evolution of the quantum system. This is often referred to as the *movability of the von Neumann cut* between the subject and the object, or some similar phrase. Collapse could occur when a particle impinges on a screen, or when the screen blackens, or when an automatic printout of the result is made, or in our retina, or along the optic nerve, or when ultimately consciousness is involved. Before and after the collapse, the Schrödinger equation would describe the evolution of the system.

Von Neumann shows that all of these models are equivalent, as far as the final predictions are concerned, so that he can indeed maintain that collapse is related to consciousness, while in practice applying the projection postulate at a much earlier (and more practical) stage in the description. What allows von Neumann to derive this result, however, is the assumption of *absence of interference* between different components of the wave function. Indeed, if interference were otherwise present, the timing of the collapse would influence the final statistics, just as it would in the case of the two-slit experiment (collapse behind the slits or at the screen). Thus, although von Neumann's is (at least on some readings) a true collapse approach, its reliance on decoherence is in fact crucial.

4.1.2 Spontaneous collapse theories

The best known theory of spontaneous collapse is the so-called GRW theory (Ghirardi Rimini & Weber 1986), in which a material particle spontaneously undergoes *localisation* in the sense that at random times it experiences a collapse of the form used to describe approximate position measurements.[13] In the original model, the collapse occurs independently for each particle (a large number of particles thus ‘triggering’ collapse much more frequently); in later models the frequency for each particle is weighted by its mass, and the overall frequency for collapse is thus tied to mass density.[14]

Thus, formally, the effect of spontaneous collapse is the same as in some of the models of decoherence, at least for one particle.[15] Two crucial differences on the other hand are that we have ‘true’ collapse instead of suppression of interference (see above Section 2), and that spontaneous collapse occurs *without* there being any interaction between the system and anything else, while in the case of decoherence suppression of interference obviously arises through interaction with the environment.

Can decoherence be put to use in GRW? The situation may be a bit complex when the decoherence interaction does not approximately privilege position (e.g., currents in a SQUID instead), because collapse and decoherence might actually ‘pull’ in different directions.[16] But in those cases in which the main decoherence interaction also takes the form of approximate position measurements, the answer boils down to a quantitative comparison. If collapse happens faster than decoherence, then the superposition of components relevant to decoherence will not have time to arise, and insofar as the collapse theory is successful in recovering classical phenomena, decoherence plays no role in this recovery. Instead, if decoherence takes place faster than collapse, then (as in von Neumann's case) the collapse mechanism can find 'ready-made' structures onto which to truly collapse the wave function. This is indeed borne out by detailed comparison (Tegmark 1993, esp. Table 2). Thus, it seems that decoherence does play a role also in spontaneous collapse theories.

A related point is whether decoherence has implications for the *experimental testability* of spontaneous collapse theories. Indeed, provided decoherence can be put to use also in no-collapse approaches such as pilot-wave or Everett (possibilities that we discuss in the next sub-sections), then in all cases in which decoherence is faster than collapse, what might be interpreted as evidence for collapse could be reinterpreted as 'mere' suppression of interference (think of definite measurement outcomes!), and only cases in which the collapse theory predicts collapse but the system is shielded from decoherence (or perhaps in which the two pull in different directions) could be used to test collapse theories experimentally.

One particularly bad scenario for experimental testability is related to the speculation (in the context of the 'mass density' version) that the cause of spontaneous collapse may be connected with gravitation. Tegmark 1993 (Table 2) quotes some admittedly uncertain estimates for the suppression of interference due to a putative quantum gravity, but they are quantitatively very close to the rate of destruction of interference due to the GRW collapse (at least outside of the microscopic domain). Similar conclusions are arrived at by Kay (1998). If there is indeed such a quantitative similarity between these possible effects, then it would become extremely difficult to distinguish between the two (with the above proviso). In the presence of gravitation, any positive effect could be interpreted as support for either collapse or decoherence. And in those cases in which the system is effectively shielded from decoherence (say, if the experiment is performed in free fall), if the collapse mechanics is indeed triggered by gravitational effects, then no collapse might be expected either. The relation between decoherence and spontaneous collapse theories is thus indeed far from straightforward.

4.2 Pilot-wave theories

Pilot-wave theories are no-collapse formulations of quantum mechanics that assign to the wave function the role of determining the evolution of ('piloting', 'guiding') the variables characterising the system, say particle configurations, as in de Broglie's (1928) and Bohm's (1952) theory, or fermion number density, as in Bell's (1987, Chap. 19) 'beable' quantum field theory, or again field confugurations, as in Valentini's proposals for pilot-wave quantum field theories (Valentini, in preparation; see also Valentini 1996).

De Broglie's idea had been to modify classical Hamiltonian mechanics in such a way as to make it analogous to classical wave optics, by substituting for Hamilton and Jacobi's action function the phase *S* of a physical wave. Such a ‘wave mechanics’ of course yields non-classical motions, but in order to understand how de Broglie's dynamics relates to typical quantum phenomena, we must include Bohm's (1952, Part II) analysis of the appearance of collapse. In the case of measurements, Bohm argued that the wave function evolves into a superposition of components that are and remain separated in the total configuration space of measured system and apparatus, so that the total configuration is ‘trapped’ inside a *single component* of the wave function, which will guide its further evolution, as if the wave had collapsed (‘effective’ wave function). This analysis allows one to recover qualitatively the measurement collapse and by extension typical quantum features such as the uncertainty principle and the perfect correlations in an EPR experiment (we are ignoring here the well developed quantitative aspects of the theory).

A natural idea is now that this analysis should be extended from the case of measurements induced by an apparatus to that of the ‘spontaneous measurements’ performed by the environment in the theory of decoherence, thus applying the same strategy for recovering both quantum and classical phenomena. The resulting picture is one in which de Broglie-Bohm theory, in cases of decoherence, would describe the motion of particles that are trapped inside one of the extremely well localised components selected by the decoherence interaction. Thus, de Broglie-Bohm trajectories will partake of the classical motions on the level defined by decoherence (the width of the components). This use of decoherence would arguably resolve the puzzles discussed e.g., by Holland (1996) with regard to the possibility of a ‘classical limit’ of de Broglie's theory. One baffling problem is for instance that possible trajectories in de Broglie-Bohm theory differing in their initial conditions cannot cross, because the wave guides the particles by way of a first-order equation, while Newton's equations are second-order, as well-known, and possible trajectories do cross. However, the non-interfering components produced by decoherence can indeed cross, and so will the trajectories of particles trapped inside them.

The above picture is natural, but it is not obvious. De Broglie-Bohm theory and decoherence contemplate two a priori *distinct* mechanisms connected to apparent collapse: respectively, separation of components in configuration space and suppression of interference. While the former obviously implies the latter, it is equally obvious that decoherence need not imply separation in configuration space. One can expect, however, that decoherence interactions of the form of approximate position measurements will.

If the main instances of decoherence are indeed coextensive with instances of separation in configuration, de Broglie-Bohm theory can thus *use* the results of decoherence relating to the formation of classical structures, while providing an interpretation of quantum mechanics that explains why these structures are indeed observationally relevant. The question that arises for de Broglie-Bohm theory is then the extension of the well-known question of whether all apparent *measurement* collapses can be associated with separation in configuration (by arguing that at some stage all measurement results are recorded in macroscopically different configurations) to the question of whether *all* appearance of classicality can be associated with separation in configuration space.[17]

A discussion of the role of decoherence in pilot-wave theory in the form suggested above is still largely outstanding. An informal discussion is given in Bohm and Hiley (1993, Chap. 8), partial results are given by Appleby (1999), and a different approach is suggested by Allori (2001; see also Allori & Zanghì 2001). Appleby discusses trajectories in a model of decoherence and obtains approximately classical trajectories, but under a special assumption.[18] Allori investigates in the first place the ‘short wavelength’ limit of de Broglie-Bohm theory (suggested by the analogy to the geometric limit in wave optics). The role of decoherence in her analysis is crucial but limited to *maintaining* the classical behaviour obtained under the appropriate short wavelength conditions, because the behaviour would otherwise break down after a certain time.

4.3 Everett interpretations

Everett interpretations are very diverse, and possibly only share the core intuition that a *single* wave function of the universe should be interpreted in terms of a *multiplicity* of ‘realities’ at some level or other. This multiplicity, however understood, is formally associated with *components* of the wave function in some decomposition.[19]

Various Everett interpretations, roughly speaking, differ as to how to *identify* the relevant components of the universal wave function, and how to *justify* such an identification (the so-called problem of the ‘preferred basis’ — although this may be a misnomer), and differ as to how to *interpret* the resulting multiplicity (various ‘many-worlds’ or various ‘many-minds’ interpretations), in particular with regard to the interpretation of the (emerging?) *probabilities* at the level of the components (problem of the ‘meaning of probabilities’).

The last problem is perhaps the most hotly debated aspect of Everett. Clearly, decoherence enables reidentification over time of both observers and of results of repeated measurement and thus definition of empirical frequencies. In recent years progress has been made especially along the lines of interpreting the probabilities in decision-theoretic terms for a ‘splitting’ agent (see in particular Wallace 2003b, and its longer preprint, Wallace 2002).[20]

The most useful application of decoherence to Everett, however, seems to be in the context of the problem of the preferred basis. Decoherence seems to yield a (maybe partial) solution to the problem, in that it naturally identifies a class of ‘preferred’ states (not necessarily an orthonormal basis!), and even allows to reidentify them over time, so that one can identify ‘worlds’ with the trajectories defined by decoherence (or more abstractly with decoherent histories).[21] If part of the aim of Everett is to interpret quantum mechanics without introducing extra structure, in particular without *postulating* the existence of some preferred basis, then one will try to identify structure that is already present in the wave function at the level of components (see e.g., Wallace, 2003a). In this sense, decoherence is an ideal candidate for identifying the relevant components.

A *justification* for this identification can then be variously given by suggesting that a ‘world’ should be a *temporally extended* structure and thus reidentification over time will be a necessary condition for identifying worlds, or similarly by suggesting that in order for observers to *evolve* there must be *stable records* of past events (Saunders 1993, and the unpublished Gell-Mann & Hartle 1994 (see the Other Internet Resources section below), or that observers must be able to access *robust states*, preferably through the existence of redundant information in the environment (Zurek's ‘existential interpretation’, 1998).

In alternative to some global notion of ‘world’, one can look at the components of the (mixed) state of a (local) system, either from the point of view that the different components defined by decoherence will separately affect (different components of the state of) another system, or from the point of view that they will separately underlie the conscious experience (if any) of the system. The former sits well with Everett's (1957) original notion of relative state, and with the relational interpretation of Everett preferred by Saunders (e.g., 1993) and, it would seem, Zurek (1998). The latter leads directly to the idea of many-minds interpretations (see the entry on Everett's relative-state interpretation and the website on ‘A Many-Minds Interpretation of Quantum Theory’ referenced in the Other Internet Resources). If one assumes that mentality can be associated only with certain decohering structures of great complexity, this might have the advantage of further reducing the remaining ambiguity about the preferred ‘basis’.

The idea of many minds was suggested early on by Zeh (2000; also 1995, p. 24). As Zeh puts it, von Neumann's motivation for introducing collapse was to save what he called psycho-physical parallelism (arguably supervenience of the mental on the physical: only one mental state is experienced, so there should be only one corresponding component in the physical state). In a decohering no-collapse universe one can instead introduce a *new* psycho-physical parallelism, in which individual minds supervene on each non-interfering component in the physical state. Zeh indeed suggests that, given decoherence, this is the most natural interpretation of quantum mechanics.[22]

4.4 Modal interpretations

Modal interpretations originated with Van Fraassen (1973, 1991) as pure reinterpretations of quantum mechanics (other later versions coming to resemble more hidden variables theories). Van Fraassen's basic intuition was that the quantum state of a system should be understood as describing a collection of possibilities, represented by components in the (mixed) quantum state. His proposal considers only decompositions at single instants, and is agnostic about reidentification over time. Thus, it can directly exploit only the fact that decoherence produces descriptions in terms of classical-like states, which will count as possibilities in Van Fraassen's interpretation. This ensures ‘empirical adequacy’ of the quantum description (a crucial concept in Van Fraassen's philosophy of science). The dynamical aspects of decoherence can be exploited indirectly, in that single-time components will exhibit *records* of the past, which ensure adequacy with respect to observations, but about whose veridicity Van Fraassen remains agnostic.

A different strand of modal interpretations is loosely associated with the (distinct) views of Kochen (1985), Healey (1989) and Dieks and Vermaas (e.g., 1998). We focus on the last of these to fix the ideas. Van Fraassen's possible decompositions are restricted to one singled out by a mathematical criterion (related to the so-called biorthogonal decomposition theorem), and a dynamical picture is explicitly sought (and was later developed). In the case of an ideal (non-approximate) quantum measurement, this special decomposition coincides with that defined by the eigenstates of the measured observable and the corresponding pointer states, and the interpretation thus appears to solve the measurement problem (in the strict sense).

At least in Dieks's original intentions, however, the approach was meant to provide an attractive interpretation of quantum mechanics also in the case of decoherence interactions, since at least in simple models of decoherence the same kind of decomposition singles out more or less also those states between which interference is suppressed (with a proviso about very degenerate states).

However, this approach fails badly when applied to other models of decoherence, e.g., that in Joos and Zeh (1985, Section III.2). Indeed, it appears that in general the components singled out by this version of the modal interpretation are given by *delocalised* states, as opposed to the components arising naturally in the theory of decoherence (Bacciagaluppi 2000; Donald 1998). Notice that van Fraassen's original interpretatioin is untouched by this problem, and so are possibly some more recent modal or modal-like interpretations by Spekkens and Sipe (2001), Bene and Dieks (2002) and Berkovitz and Hemmo (in preparation).

Finally, some of the views espoused in the decoherent histories literature could be considered as cognate to Van Fraassen's views, identifying possibilities, however, at the level of possible courses of world history. Such ‘possible worlds’ would be those temporal sequences of (quantum) propositions that satisfy the decoherence condition and in this sense support a description in terms of a probabilistic evolution. This view would be using decoherence as an essential ingredient, and in fact may turn out to be the most fruitful way yet of implementing modal ideas; a discussion in these terms still needs to be carried out in detail, but see Hemmo (1996).

4.5 Bohr's Copenhagen interpretation

It appears that Bohr held more or less the following view. Everyday concepts, in fact the concepts of classical physics, are indispensable to the description of any physical phenomena (in a way — and terminology — much reminiscent of Kant's transcendental arguments). However, experimental evidence from atomic phenomena shows that classical concepts have fundamental limitations in their applicability: they can only give partial (complementary) pictures of physical objects. While these limitations are quantitatively negligible for most purposes in dealing with macroscopic objects, they apply also at that level (as shown by Bohr's willingness to apply the uncertainty relations to parts of the experimental apparatus in the Einstein-Bohr debates), and they are of paramount importance when dealing with microscopic objects. Indeed, they shape the characteristic features of quantum phenomena, e.g., indeterminism. The quantum state is not an ‘intuitive’ (*anschaulich*, also translated as ‘visualisable’) representation of a quantum object, but only a ‘symbolic’ representation, a shorthand for the quantum phenomena constituted by applying the various complementary classical pictures.

While it is difficult to pinpoint exactly what Bohr's views were (the concept and even the term ‘Copenhagen interpretation’ appear to be a later construct; see Howard 2003), it is clear that according to Bohr, classical concepts are autonomous from, and indeed conceptually prior to, quantum theory. If we understand the theory of decoherence as pointing to how classical concepts might in fact emerge from quantum mechanics, this seems to undermine Bohr's basic position. Of course it would be a mistake to say that decoherence (a part of quantum theory) *contradicts* the Copenhagen approach (an interpretation of quantum theory). However, decoherence does suggest that one might want to adopt alternative interpretations, in which it is the quantum concepts that are prior to the classical ones, or, more precisely, the classical concepts at the everyday level emerge from quantum mechanics (irrespectively of whether there are even more fundamental concepts, as in pilot-wave theories). In this sense, if the programme of decoherence is successful as sketched in Section 3.3, it will indeed be a blow to Bohr's *interpretation* coming from quantum physics itself.

On the other hand, Bohr's *intuition* that quantum mechanics as practised requires a classical domain would in fact be *confirmed* by decoherence, if it turns out that decoherence is indeed the basis for the phenomenology of quantum mechanics, as the Everettian and possibly the Bohmian analysis suggest. As a matter of fact, Zurek (2003) locates his existential interpretation half-way between Bohr and Everett. It is perhaps a gentle irony that in the wake of decoherence, the foundations of quantum mechanics might end up re-evaluating this part of Bohr's thinking.

5. Scope of Decoherence

We have already mentioned in Section 2.2 that some care has to be taken lest one overgeneralise conclusions based on examining only well-behaved models of decoherence. On the other hand, in order to assess the programme of explaining the emergence of classicality using decoherence (together with appropriate foundational approaches), one has to probe *how far* the applications of decoherence can be pushed. In this final section, we survey some of the further applications that have been proposed for decoherence, beyond the easier examples we have seen such as chirality or alpha-particle tracks. Whether decoherence can indeed be successfully applied to all of these fields will be in part a matter for further assessment, as more detailed models are proposed.

A straightforward application of the techniques allowing one to derive Newtonian trajectories at the level of components has been employed by Zurek and Paz (1994) to derive *chaotic trajectories* in quantum mechanics. The problem with the quantum description of chaotic behaviour is that *prima facie* there should be none. Chaos is characterised roughly as extreme sensitivity in the behaviour of a system on its initial conditions, where the distance between the trajectories arising from different initial conditions increases exponentially in time. Since the Schrödinger evolution is *unitary*, it preserves all scalar products and all distances between quantum state vectors. Thus, it would seem, close initial conditions lead to trajectories that are uniformly close throughout all of time, and no chaotic behaviour is possible (‘problem of quantum chaos’). The crucial point that enables Zurek and Paz' analysis is that the relevant trajectories in decoherence theory are at the level of *components* of the state of the system. Unitarity is preserved because the vectors in the environment to which these different components are coupled, are and remain orthogonal: how the components themselves evolve is immaterial. Explicit modelling yields a picture of quantum chaos in which different trajectories branch (a feature absent from classical chaos, which is deterministic) and then indeed diverge exponentially. As with the crossing of trajectories in de Broglie-Bohm theory (Section 4.2), one has behaviour at the level of components that is qualitatively different from the behaviour derived from wave functions of an isolated system.

The idea of effective superselection rules was mentioned in Section 2.2. As pointed out by Giulini, Kiefer and Zeh (1995, see also Giulini *et al*. 1996, Section 6.4), the justification for the (strict) superselection rule for charge in quantum field theory can also be phrased in terms of decoherence. The idea is simple: an electric charge is surrounded by a Coulomb field (which electrostatically is infinitely extended; the argument can also be carried through using the retarded field, though). States of different electric charge of a particle are thus coupled to different, presumably orthogonal, states of its electric field. One can consider the far-field as an effectively uncontrollable environment that decoheres the particle (and the near-field), so that superpositions of different charges are indeed never observed.

Another claim about the significance of decoherence relates to time asymmetry (see e.g., the entries on time asymmetry in thermodynamics and philosophy of statistical mechanics), in particular of whether decoherence can explain the apparent time-directedness in our (classical) world. The issue is again one of time-directedness at the level of components emerging from a time-symmetric evolution at the level of the universal wave function (presumably with special initial conditions). Insofar as (apparent) collapse is indeed a time-directed process, decoherence will have direct relevance to the emergence of this ‘quantum mechanical arrow of time’ (for a spectrum of discussions, see Zeh 2001, Chap. 4; Hartle 1998, and references therein; and Bacciagaluppi 2002, Section 6.1). Whether decoherence is connected to the other familiar arrows of time is a more specific question, various discussions of which are given, e.g., by Zurek and Paz (1994), Hemmo and Shenker (2001) and the unpublished Wallace (2001) (see the Other Internet Resources Section below).

In a recent paper, Zeh (2003) argues from the notion that decoherence can explain ‘quantum phenomena’ such as *particle detections* that the concept of a particle in quantum field theory is itself a consequence of decoherence. That is, only fields need to be included in the fundamental concepts, and ‘particles’ are a derived concept, unlike what is suggested by the customary introduction of fields through a process of ‘second quantisation’. Thus decoherence seems to provide a further powerful argument for the conceptual primacy of fields over particles in the question of the interpretation of quantum field theory.

Finally, it has been suggested that decoherence could be a useful ingredient in a theory of quantum gravity, for two reasons. First, because a suitable generalisation of decoherence theory to a full theory of quantum gravity should yield suppression of interference between different classical spacetimes (Giulini *et al*. 1996, Section 4.2). Second, it is speculated that decoherence might solve the so-called *problem of time*, which arises as a prominent puzzle in (the 'canonical' approach to) quantum gravity. This is the problem that the candidate fundamental equation (in this approach) — the Wheeler-DeWitt equation — is an analogue of a time-*independent* Schrödinger equation, and does not contain time at all. The problem is thus simply: where does time come from? In the context of decoherence theory, one can construct toy models in which the analogue of the Wheeler-DeWitt wave function decomposes into non-interfering components (for a suitable sub-system) each satisfying a time-*dependent* Schrödinger equation, so that decoherence appears in fact as the source of time.[23] An accessible introduction to and philosophical discussion of these models is given by Ridderbos (1999), with references to the original papers.

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- The Pittsburgh Phil-Sci Archive. This is the main philosophy of science preprint archive; some of the links above are to this archive.
- A Many-Minds Interpretation Of Quantum Theory, maintained by Matthew Donald (Cavendish Lab, Physics, University of Cambridge). This page contains details of his many-minds interpretation, as well as discussions of some of the books and papers quoted above (and others of interest). Follow also the link to the ‘Frequently Asked Questions’, some of which (and the ensuing dialogue) contain useful discussion of decoherence.
- Quantum Mechanics on the Large Scale, maintained by Philip Stamp (Physics, University of British Columbia). This page has links to the available talks from the Vancouver workshop mentioned in footnote 2; see especially the papers by Tony Leggett and by Philip Stamp.
- Decoherence Website, maintained by Erich Joos. This is a site with information, references and further links to people and institutes working on decoherence, especially in Germany and the rest of Europe.

Related Entries

Einstein, Albert: Einstein-Bohr debates | quantum mechanics | quantum mechanics: Bohmian mechanics | quantum mechanics: collapse theories | quantum mechanics: Copenhagen interpretation of | quantum mechanics: Everett's relative-state formulation of | quantum mechanics: many-worlds interpretation of | quantum theory: measurement in | quantum theory: quantum entanglement and information | quantum theory: quantum field theory | quantum theory: quantum gravity | quantum theory: the Einstein-Podolsky-Rosen argument in | statistical physics: philosophy of statistical mechanics | time: thermodynamic asymmetry in | Uncertainty Principle

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Elements of Environmental Decoherence*

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Abstract

In this contribution I give an introduction to the essential concepts and mechanisms of decoherence by the environment. The emphasis will be not so much on technical details but rather on conceptual issues and the impact on the interpretation problem of quantum theory.

1 What is decoherence?

Decoherence is the irreversible formation of quantum correlations of a system with its environment. These correlations lead to entirely new properties and behavior compared to that shown by isolated objects.

Whenever we have a product state of two interacting systems - a very special state - the unitary evolution according to the Schrödinger equation will lead to entanglement,

$$\begin{aligned} |\varphi\rangle|\Phi\rangle \quad \stackrel{t}{\longrightarrow} \quad & \sum_{n,m} c_{nm}|\varphi_n\rangle|\Phi_m\rangle \\ = \quad & \sum_n \sqrt{p_n(t)}|\tilde{\varphi}_n(t)\rangle|\tilde{\Phi}_n(t)\rangle. \end{aligned} \tag{1}$$

The rhs of (1) can no longer be written as a single product in the general case. This can also be described by using the Schmidt representation, shown in the second line, where the presence of more than one component is equivalent to the existence of quantum correlations.

If many degrees of freedom are involved in this process, this entanglement will become practically irreversible, except for very special situations. Decoherence is thus a quite normal and, moreover, ubiquitous, quantum mechanical process. Historically, the important observation was that this de-separation of quantum states happens extremely fast for macroscopic objects [17]. The natural environment cannot simply be ignored or treated as a classical background in this case.

Equation (1) shows that there is an intimate connection to the theory of irreversible processes. However, decoherence must not be identified or confused with

*To be published in the proceedings of the Bielefeld conference on "Decoherence: Theoretical, Experimental, and Conceptual Problems", edited by P. Blanchard, D. Giulini, E. Joos, C. Kiefer, and I.-O. Stamatescu (Springer 1999).

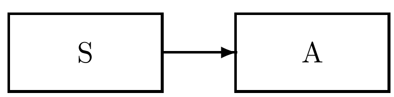
dissipation: decoherence precedes dissipation by acting on a much faster timescale, while requiring initial conditions which are essentially the same as those responsible for the thermodynamic arrow of time [18].

When we consider observations at one of the two systems, we see various consequences of this entanglement. First of all, our considered subsystem will no longer obey a Schrödinger equation, the local dynamics is in general very complicated, but can often be approximated by some sort of master equation (The Schmidt decomposition is directly related to the subsystem density matrices). The most important effect is the disappearance of phase relations (i.e., interference) between certain subspaces of the Hilbert space of the system. Hence the resulting superselection rules can be understood as emerging from a dynamical, approximate and time-directed process. If the coupling to the environment is very strong, the internal dynamics of the system may become slowed down or even frozen. This is now usually called the quantum Zeno effect, which apparently does not occur in our macroscopic world.

The details of the dynamics depend on the kind of coupling between the system we consider and its environment. In many cases – especially in the macroscopic domain – this coupling leads to an evolution similar to a measurement process. Therefore it is appropriate to recall the essential elements of the quantum theory of measurement.

1.1 Dynamical Description of Measurement

The standard description of measurement was laid down by von Neumann already in 1932 [15]. Consider a set of system states $|n\rangle$ which our apparatus is built to discriminate.



Original form of the von Neumann measurement model. Information about the state of the measured system S is transferred to the measuring apparatus A.

For each state $|n\rangle$ we have a corresponding pointer state $|\Phi_n\rangle$ (more precisely, for each "quantum number" n there exists a large set of macrostates $|\Phi_n^{(\alpha)}\rangle$, α describing microscopic degrees of freedom). If the measurement is repeatable or ideal the dynamics of the measurement interaction must look like

$$|n\rangle|\Phi_0\rangle \quad \xrightarrow{t} \quad |n\rangle|\Phi_n(t)\rangle \ . \tag{2}$$

From linearity we can immediately see what happens for a general initial state of the measured system,

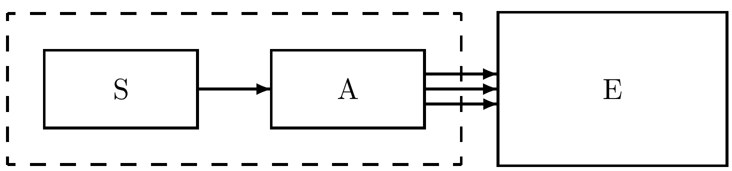
$$\left(\sum_n c_n|n\rangle\right)|\Phi_0\rangle \quad \xrightarrow{t} \quad \sum_n c_n|n\rangle|\Phi_n(t)\rangle \ . \tag{3}$$

We do not find a certain measurement result, but a superposition. Through unitary evolution, a correlated (and still pure) state results, which contains all possible results as components. Of course such a superposition must not be interpreted as an ensemble. The transition from this superposition to a single component – which is what we observe – constitutes the quantum measurement problem. As long as there is no collapse we have to deal with the whole superposition – and it is well known that a superposition has very different properties compared to any of its components. Quantum correlations are often misinterpreted as (quantum) noise. This is wrong, however: Noise would mean that the considered system is in a certain state, which may be unknown and/or evolve in a complicated way. Such an interpretation is untenable and contradicts all experiments which show the nonlocal features of quantum-correlated (entangled) states.

Von Neumann's treatment, as described so far, is unrealistic since it does not take into account the essential openness of macroscopic objects. This deficiency can easily be remedied by extending the above scheme.

1.2 Classical Properties through Decoherence

If one takes into account that the apparatus A is coupled to its environment E, which also acts like a measurement device, the phase relations are (extremely fast) further dislocalized into the total system – finally the entire universe, according to



Realistic extension of the von Neumann measurement model. Information about the state of the measured system S is transferred to the measuring apparatus A and then very rapidly sent to the environment E. The back-reaction on the (local) system S+A originates entirely from quantum nonlocality.

$$\left(\sum_n c_n|n\rangle|\Phi_n\rangle\right)|E_0\rangle \quad \stackrel{t}{\longrightarrow} \quad \sum_n c_n|n\rangle|\Phi_n\rangle|E_n\rangle. \tag{4}$$

The behavior of system+apparatus is then described by the density matrix

$$\rho_{SA} \approx \sum_n |c_n|^2|n\rangle\langle n| \otimes |\Phi_n\rangle\langle\Phi_n| \qquad \text{if} \qquad \langle E_n|E_m\rangle \approx \delta_{nm} \tag{5}$$

which is identical to that of an ensemble of measurement results $|n\rangle|\Phi_n\rangle$.

Of course, this does not resolve the measurement problem! This density matrix describes only an "improper" ensemble, i.e., with respect to all possible observations at S+A it *appears* that a certain measurement result has been achieved. Again, classical notions like noise or recoil are not appropriate: A acts dynamically on E, but the back-action arises entirely from quantum nonlocality (as long as the measurement is "ideal", that is, (4) is a good approximation). Nevertheless, the system S+A acquires classical behavior, since interference terms are absent with respect to local observations if the above process is irreversible [19, 10].

Needless to say, the interference terms still exist globally in the total (pure) state, although they are unobservable at either system alone – a situation which may be characterized by the statement

The interference terms still exist, but they are not there.[10]

2 Do we need observables?

In most treatments of quantum mechanics the notion of an observable plays a central role. Do observables represent a fundamental concept or can they be derived? If we describe a measurement as a certain kind of interaction, then observables should not be required as an essential ingredient of quantum theory. In a sense this was also done by von Neumann, but not used later very much because of restrictions enforced by the Copenhagen school (e.g., the demand to describe a measurement device in classical terms instead of seeking for a consistent treatment in terms of wave functions).

Two elements are necessary to derive an observable that discriminates certain (orthogonal) system states $|n\rangle$. First, one needs an appropriate interaction which is diagonal in the eigenstates of the measured "observable" and is able to "move the pointer", so that we have as above

$$|n\rangle|\Phi_0\rangle \quad \stackrel{H_{int}}{\longrightarrow} \quad |n\rangle|\Phi_n\rangle \ . \tag{6}$$

This can be achieved by Hamiltonians of the form

$$H_{int} = \sum_n |n\rangle\langle n| \otimes \hat{A}_n \tag{7}$$

with appropriate $\hat{A}_n$ leading to orthogonal pointer states (Note that (6) defines only the eigenbasis of an observable; the eigenvalues represent merely scale factors and are therefore of minor importance). The second condition that must be fulfilled is dynamical stability of pointer states against decoherence, that is, the pointer states must only be passively recognized by the environment according to,

$$|\Phi_n\rangle|E_0\rangle \quad \stackrel{decoherence}{\longrightarrow} \quad |\Phi_n\rangle|E_n\rangle \ . \tag{8}$$

Both conditions must be fulfilled. For example, a measurement device which acts according to (6) would be totally useless, if it were not stable against decoherence: Consider a Schrödinger cat state as pointer state! The *same* basis states $|\Phi_n\rangle$ must be distinguished as dynamically relevant in (6) as well as in (8).*

*This explains *dynamically* why certain observables may "not exist" operationally. For a general discussion of the relation between quantum states and observables see Sect. 2.2 of [5]. Arguments along these lines lead to the conclusion that one should not attribute a fundamental status to the Heisenberg picture – contrary to widespread belief – despite its *phenomenological* equivalence with the Schrödinger picture.

3 Do we need superselection rules?

What is a superselection rule? One way to define a superselection rule is to say, that certain states $|\Psi_1\rangle$, $|\Psi_2\rangle$ are found in nature, but never general superpositions $|\Psi\rangle = \alpha|\Psi_1\rangle + \beta|\Psi_2\rangle$. This means that all observations can be described by a density matrix of the form $\rho = p_1|\Psi_1\rangle\langle\Psi_1| + p_2|\Psi_2\rangle\langle\Psi_2|$. Clearly such a density matrix is exactly what is obtained through decoherence in appropriate situations.

3.1 Approximate superselection rules

There are many examples, where it is hard to find certain superpositions in the real world. The most famous example has been given by Schrödinger: A superposition of a dead and an alive cat

$$|\Psi\rangle = |\text{dead cat}\rangle + |\text{alive cat}\rangle \tag{9}$$

is never observed, contrary to what should be possible according to the superposition principle (and, in fact, *must* necessarily occur according to the Schrödinger equation). Another drastic situation is given by a state like

$$|\Psi\rangle = |\text{cat}\rangle + |\text{dog}\rangle \ . \tag{10}$$

Such a superposition looks truly absurd, but only because we never observe states of this kind! (The obvious objection that one cannot superpose states of "different systems" seems to be inappropriate. For example, nobody hesitates to superpose states with different numbers of particles.) A more down-to-earth example is given by the position of large objects, which are never found in states

$$|\Psi\rangle = |\text{here}\rangle + |\text{there}\rangle \ , \tag{11}$$

with "here" and "there" macroscopically distinct. Under realistic circumstances such objects are always well described by a localized density matrix $\rho(x, x') \approx p(x)\delta(x - x')$. A special case of this localization occurs in molecules (except the very small ones), which show a well-defined spatial structure. The Born-Oppenheimer approximation is not sufficient to explain this fact.

Quite generally we have an approximate superselection rule whenever we describe the dynamics of a dynamical variable by some rate equation (that is, without interference) instead of the Schrödinger equation.

3.2 Exact superselection rules

Strict absence of interference can only be expected for discrete quantities. One important example is electric charge. Can this be understood via decoherence? We know from Maxwell's theory, that every charge carries with itself an associated electric field, so that a superposition of charges may be written in the form [16]

$$\begin{aligned} \sum_q c_q|\Psi_q^{total}\rangle &= \sum_q c_q|\chi_q^{bare}\rangle|\Psi_q^{field}\rangle \\ &= \sum_q c_q|\chi_q^{local}\rangle|\Psi_q^{farfield}\rangle \ . \end{aligned} \tag{12}$$

Since we can only observe the local dressed charge, it has to be described by the density matrix

$$\rho = \sum_q |c_q|^2 |\chi_q^{local}\rangle\langle\chi_q^{local}| \tag{13}$$

If the far fields are orthogonal (distinguishable), coherence would be absent locally. So the question arises: Is the Coulomb field only part of the kinematics (implemented via the Gauss constraint) or does it represent a quantum dynamical degree of freedom so that we have to consider decoherence via a retarded Coulomb field? For an attempt to understand part of the Coulomb field as dynamical see [4].

What do experiments tell us? A superposition of the form (11) can be observed for charged particles (cf. the contribution by Hasselbach[6]). On the other hand, the classical (retarded) Coulomb field would contain information about the path of the charged particle, destroying coherence. The situation does not appear very clear-cut. Hence one essential question remains:

What is the *quantum* physical role of the Coulomb field?

A similar situation arises in quantum gravity, where we can expect that superpositions of different masses (energies) are decohered by the spatial curvature.

Another important "exact" superselection rule forbids superposing states with integer and half-integer spin, for example

$$|\Psi\rangle = |\text{ spin } 1\rangle + |\text{ spin } {}^1\!/_2\rangle \ , \tag{14}$$

which would transform under a rotation by 2π into

$$|\Psi_{2\pi}\rangle = |\text{ spin } 1\rangle - |\text{ spin } {}^1\!/_2\rangle \ , \tag{15}$$

clearly a different state because of the different relative phase. If one *demands* that such a rotation should not change anything, such a state must be excluded. This is one standard argument in favor of the "univalence" superselection rule. On the other hand, one *has* observed the sign-change of spin ${}^1\!/_2$ particles under a (relative) rotation by 2π in *certain* experiments. Hence we are left with two options: Either we view the group SO(3) as the proper rotation group also in quantum theory. Then nothing must change if we rotate the system by an angle of 2π. Hence we can derive this superselection rule from symmetry. But this may merely be a classical prejudice. The other choice is to use SU(2) instead of SO(3) as rotation group. Then we are in need of explaining why those strange superpositions never occur. This last choice amounts to keeping the superposition principle as the fundamental principle of quantum theory. In more technical terms we should then avoid using groups with non-unique ("ray" ¶) representations, such as SO(3). In supersymmetric theories, bosons and fermions are treated on an equal footing, so it would be natural to superpose their states (what is apparently never done in particle theory).

¶ The widely used argument that physical states are to be represented by rays, not vectors, in Hilbert space because the phase of a state vector cannot be observed, is misleading. Since relative phases are certainly relevant, one should prefer a vector as a *fundamental* physical state concept, rather than a ray. Rays cannot even be superposed without (implicitly) using vectors.

In a similar manner one could undermine the well-known argument leading from the Galilean symmetry of nonrelativistic quantum mechanics to the mass superselection rule. In this case we could maintain the superposition principle and replace the Galilei group by a larger group. How this can be done is shown by Domenico Giulini[4].

The final open question for this section then is:

Can *all* superselection rules be understood as decoherence effects?

4 Examples

4.1 Localization

The by now standard example of decoherence is the localization of macroscopic objects. Why do macroscopic objects always appear localized in space? Coherence between macroscopically different positions is destroyed *very* rapidly because of the strong influence of scattering processes. The formal description may proceed as follows. Let $|x\rangle$ be the position eigenstate of a macroscopic object, and $|\chi\rangle$ the state of the incoming particle. Following the von Neumann scheme (2), the scattering of such particles off an object located at position x may be written as

$$|x\rangle|\chi\rangle \stackrel{t}{\longrightarrow} |x\rangle|\chi_x\rangle = |x\rangle S_x|\chi\rangle \ , \tag{16}$$

where the scattered state may conveniently be calculated by means of an appropriate S-matrix. For the more general initial state of a wave packet we have then

$$\int d^3x \ \varphi(x)|x\rangle|\chi\rangle \stackrel{t}{\longrightarrow} \int d^3x \ \varphi(x)|x\rangle S_x|\chi\rangle \ . \tag{17}$$

Therefore, the reduced density matrix describing our object changes into

$$\rho(x,x') = \varphi(x)\varphi^*(x') \left\langle \chi|S_{x'}^\dagger S_x|\chi \right\rangle \ . \tag{18}$$

Of course, a single scattering process will usually not resolve a small distance, so in most cases the matrix element on the right-hand side of (18) will be close to unity. If we add the contributions of many scattering processes, an exponential damping of spatial coherence results:

$$\rho(x,x',t) = \rho(x,x',0) \exp\left\{-\Lambda t(x-x')^2\right\} \ . \tag{19}$$

The strength of this effect is described by a single parameter Λ that may be called "localization rate". It is given by

$$\Lambda = \frac{k^2 N v \sigma_{eff}}{V} \ . \tag{20}$$

Here, k is the wave number of the incoming particles, Nv/V the flux, and σ_{eff} is of the order of the total cross section (for details see [10] or Sect. 3.2.1 and Appendix 1 of [5]). Some values of Λ are given in the table.

Localization rate Λ in $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for three sizes of "dust particles" and various types of scattering processes (from [10]). This quantity measures how fast interference between different positions disappears as a function of distance in the course of time.

	$a = 10^{-3}$cm dust particle	$a = 10^{-5}$cm dust particle	$a = 10^{-6}$cm large molecule
Cosmic background radiation	10^{6}	10^{-6}	10^{-12}
300 K photons	10^{19}	10^{12}	10^{6}
Sunlight (on earth)	10^{21}	10^{17}	10^{13}
Air molecules	10^{36}	10^{32}	10^{30}
Laboratory vacuum (10^3 particles/cm^3)	10^{23}	10^{19}	10^{17}

Most of the numbers in the table are quite large, showing the extremely strong coupling of macroscopic objects, such as dust particles, to their natural environment. Even in intergalactic space, the 3K background radiation cannot simply be neglected.
Hence the main lesson is:

Macroscopic objects are not even approximately isolated.

A consistent unitary description must therefore include the environment and finally the whole universe.*

If we combine this damping of coherence with the "free" Schrödinger dynamics we arrive at an equation of motion for the density matrix that to a good approximation simply adds these two contributions,

$$i\frac{\partial \rho}{\partial t} = [H_{internal}, \rho] + i\frac{\partial \rho}{\partial t}\bigg|_{scatt.} \quad . \tag{21}$$

In the position representation this equation reads in one space dimension

$$i\frac{\partial \rho(x,x',t)}{\partial t} = \frac{1}{2m}\left(\frac{\partial^2}{\partial x'^2} - \frac{\partial^2}{\partial x^2}\right)\rho - i\Lambda(x-x')^2\rho \ . \tag{22}$$

Solutions of this equation can easily be found (see, e.g.[5])

*One of the first stressing the importance of the dynamical coupling of macro-objects to their environment was Dieter Zeh, who wrote in his 1970 Found. Phys. paper [17]: "Since the interactions between macroscopic systems are effective even at astronomical distances, the only 'closed system' is the universe as a whole. ... It is of course very questionable to describe the universe by a wavefunction that obeys a Schrödinger equation. Otherwise, however, there is no inconsistency in measurement, as there is no theory."

This is now more or less commonplace, but this was not the case some 30 years ago, when he sent an earlier version of this paper to the journal Il Nuovo Cimento. I quote from the referee's reply: "The paper is completely senseless. It is clear that the author has not fully understood the problem and the previous contributions in this field." (H.D. Zeh, private communication)

So far this treatment represents *pure* decoherence, following directly the von Neumann scheme. If recoil is added as a next step, we arrive at models including friction, that is, quantum Brownian motion. There are several models for the quantum analogue of Brownian motion, some of which are even older than the first decoherence studies. Early treatments did not, however, draw a distinction between decoherence and friction (decoherence alone does *not* imply friction.). As an example, consider the equation of motion derived by Caldeira and Leggett [2],

$$i\frac{\partial\rho}{\partial t} = [H,\rho] + \frac{\gamma}{2}[x,\{p,\rho\}] - im\gamma k_B T[x,[x,\rho]] \tag{23}$$

which reads for a "free" particle

$$\begin{aligned} i\frac{\partial\rho(x,x',t)}{\partial t} &= \Bigg[\frac{1}{2m}\left(\frac{\partial^2}{\partial x'^2} - \frac{\partial^2}{\partial x^2}\right) - i\Lambda(x-x')^2 \\ &\quad + i\gamma(x-x')\left(\frac{\partial}{\partial x'} - \frac{\partial}{\partial x}\right)\Bigg]\rho(x,x',t)\ , \end{aligned} \tag{24}$$

where γ is the damping constant, and here $\Lambda = m\gamma k_B T$.

If one compares the effectiveness of the two terms representing decoherence and relaxation, one finds that their ratio is given by

$$\frac{\text{decoherence rate}}{\text{relaxation rate}} = mk_B T(\delta x)^2 \propto \left(\frac{\delta x}{\lambda_{th}}\right)^2\ , \tag{25}$$

where λ_{th} denotes the thermal de Broglie wavelength of the considered object. This ratio has for a typical macroscopic situation ($m = 1$g, $T = 300$K, $\delta x = 1$cm) the enormous value of about 10^{40}! This shows that in these cases decoherence is *far more important* than dissipation.

Not only the center-of-mass position of dust particles becomes "classical" via decoherence. The spatial structure of molecules represents another most important example. Consider a simple model of a chiral molecule.

Right- and left-handed versions both have a rather well-defined spatial structure, whereas the ground state is – for symmetry reasons – a superposition of both chiral states. These chiral configurations are usually separated by a tunneling barrier, which is so high that under normal circumstances tunneling is very improbable, as was already shown by Hund in 1929. But this alone does not explain why chiral (and, indeed, most) molecules are never found in energy eigenstates!

In a simplified model with low-lying nearly-degenerate eigenstates $|1\rangle$ and $|2\rangle$, the right- and left-handed configurations may be given by

$$\begin{aligned} |L\rangle &= \frac{1}{\sqrt{2}}(|1\rangle + |2\rangle) \\ |R\rangle &= \frac{1}{\sqrt{2}}(|1\rangle - |2\rangle)\ . \end{aligned} \tag{26}$$

Because the environment recognizes the spatial structure via scattering processes, only chiral states are stable against decoherence,

$$|R,L\rangle|\Phi_0\rangle \stackrel{t}{\longrightarrow} |R,L\rangle|\Phi_{R,L}\rangle \ . \tag{27}$$

The dynamical instability of energy (i.e., parity) eigenstates of molecules represents a typical example of "spontaneous symmetry breaking" induced by decoherence. Additionally, transitions between spatially oriented states are suppressed by the quantum Zeno effect, described below.

4.2 Quantum Zeno Effect

The most dramatic consequence of a strong measurement-like interaction of a system with its environment is the quantum Zeno effect. It has been discovered several times and is also sometimes called "watchdog effect" or "watched pot behavior", although most people now use the term Zeno effect. It is surprising only if one sticks to a classical picture where observing a system and just verifying its state should have no influence on it. Such a prejudice is certainly formed by our everyday experience, where observing things in our surroundings does not change their properties. As is known since the early times of quantum theory, observation can drastically change the observed system.

The essence of the Zeno effect can easily be shown as follows. Consider the "decay" of a system which is initially prepared in the "undecayed" state $|u\rangle$. The probability to find the system undecayed, i.e., in the same state $|u\rangle$ at time t is for small time intervals given by

$$\begin{aligned} P(t) &= |\langle u|\exp(-iHt)|u\rangle|^2 \\ &= 1-(\Delta H)^2t^2+\mathcal{O}(t^4) \end{aligned} \tag{28}$$

with

$$(\Delta H)^2 = \langle u|H^2|u\rangle - \langle u|H|u\rangle^2 \ . \tag{29}$$

If we consider the case of N measurements in the interval $[0,t]$, the non-decay probability is given by

$$P_N(t) \approx \left[1-(\Delta H)^2\left(\frac{t}{N}\right)^2\right]^N > 1-(\Delta H)^2t^2 = P(t) \ . \tag{30}$$

This is always larger than the single-measurement probability given by (28). In the limit of arbitrary dense measurements, the system no longer decays,

$$P_N(t) = 1-(\Delta H)^2\frac{t^2}{N}+\ldots \stackrel{N\to\infty}{\longrightarrow} 1 \ . \tag{31}$$

Hence we find that repeated measurements can completely hinder the natural evolution of a quantum system. Such a result is clearly quite distinct from what is observed for classical systems. Indeed, the paradigmatic example for a classical stochastic process, exponential decay,

$$P(t) = \exp(-\Gamma t) \ , \tag{32}$$

is not influenced by repeated observations, since for N measurements we simply have

$$P_N(t) = \left(\exp\left(-\Gamma\frac{t}{N}\right)\right)^N = \exp(-\Gamma t)\ . \tag{33}$$

So far we have treated the measurement process in our discussion of the Zeno effect in the usual way by assuming a collapse of the system state onto the subspace corresponding to the measurement result. Such a treatment can be extended by employing a von Neumann model for the measurement process, e.g., by coupling a pointer to a two-state system. A simple toy model is given by the Hamiltonian

$$\begin{aligned} H &= H_0 + H_{int} \\ &= V(|1\rangle\langle 2| + |2\rangle\langle 1|) + E|2\rangle\langle 2| + \gamma\hat{p}(|1\rangle\langle 1| - |2\rangle\langle 2|)\ , \end{aligned} \tag{34}$$

where transitions between states $|1\rangle$ and $|2\rangle$ (induced by the "perturbation" V) are monitored by a pointer (coupling constant γ). This model already shows all the typical features mentioned above.

The transition probability starts for small times always quadratically, according to the general result (28). For times, where the pointer resolves the two states, a behavior similar to that found for Markow processes appears: The quadratic time-dependence changes to a linear one. For strong coupling the transitions are suppressed. This clearly shows the dynamical origin of the Zeno effect.

An extension of the above model allows an analysis of the transition from the Zeno effect to master behavior (described by transition *rates* as was first studied in quantum mechanics by Pauli in 1928). It can be shown that for many (micro-)states which are not sufficiently resolved by the environment, Fermi's Golden Rule can be recovered, with transition rates which are no longer reduced by the Zeno effect. Nevertheless, interference between macrostates is suppressed very rapidly [7].

4.3 Decoherence of Fields

In QED we find two (related) situations,

- "Measurement" of charges by fields;
- "Measurement" of fields by charges.

In both cases, the entanglement between charge and field states leads to decoherence as already described above in the discussion of superselection rules, see also [5] and references therein.

In recent quantum optics experiments it is possible to prepare and study superpositions of different classical field states, quantum-mechanically represented by coherent states, for example Schrödinger cat states of the form

$$|\Psi\rangle = N(|\alpha\rangle + |-\alpha\rangle) \tag{35}$$

which can be realized as field states in a cavity. In these experiments (see [1]) decoherence can be turned on gradually by coupling the cavity to a reservoir. Typical decoherence times are in the range of about 100 μs.

For *true* cats the decoherence time is much shorter (in particular, it is *very much* shorter than the lifetime of a cat!). This leads to the appearance of *quantum jumps*, although all underlying processes are smooth in principle since they are governed by the Schrödinger equation.

In experimental situations of this kind we find a gradual transition from a superposition of different decay times (seen in "collapse and revival" experiments) to a local mixture of decay times (leading to "quantum jumps") according to the following scheme.

theory	experiment
superposition of different decay times	collapse and revivals
$\Downarrow$	$\Downarrow$
local mixture of different decay times	quantum jumps

4.4 Spacetime and Quantum Gravity

In quantum theories of the gravitational field, no classical spacetime exists at the most fundamental level. Since it is generally assumed that the gravitational field has to be quantized, the question again arises how the corresponding classical properties can be understood.

Genuine quantum effects of gravity are expected to occur for scales of the order of the Planck length $\sqrt{G\hbar/c^3}$. It is therefore often argued that the spacetime structure at larger scales is automatically classical. However, this Planck scale argument is as insufficient as the large mass argument in the evolution of free wave packets. As long as the superposition principle is valid (and even superstring theory leaves this untouched), superpositions of different metrics should occur at any scale.

The central problem can already be demonstrated in a simple Newtonian model[8]. Consider a cube of length L containing a homogeneous gravitational field with a quantum state ψ such that at some initial time $t = 0$

$$|\psi\rangle = c_1|g\rangle + c_2|g'\rangle \ , \tag{36}$$

where g and g' correspond to two different field strengths. A particle with mass m in a state $|\chi\rangle$, which moves through this volume, "measures" the value of g, since its trajectory depends on the acceleration g:

$$|\psi\rangle|\chi^{(0)}\rangle \rightarrow c_1|g\rangle|\chi_g(t)\rangle + c_2|g'\rangle|\chi_{g'}(t)\rangle \ . \tag{37}$$

This correlation destroys the coherence between g and g', and the reduced density matrix can be estimated to assume the following form after many such interactions are taken into account:

$$\rho(g, g', t) = \rho(g, g', 0) \exp\left(-\Gamma t (g - g')^2\right) , \tag{38}$$

where

$$\Gamma = nL^4 \left(\frac{\pi m}{2k_B T} \right)^{3/2}$$

for a gas with particle density n and temperature T. For example, air under ordinary conditions, $L = 1$ cm, and $t = 1$ s yields a remaining coherence width of $\Delta g/g \approx 10^{-6}$[8].

Thus, matter does not only tell space to curve but also to behave classically. This is also true in full quantum gravity.

In a fully quantized theory of gravity, for example in the canonical approach described by the Wheeler-deWitt equation,

$$H|\Psi(\Phi,^{(3)}\mathcal{G})\rangle = 0 \ , \tag{39}$$

where Φ describes matter and ${}^{(3)}\mathcal{G}$ is the three-metric, everything is contained in the "wave function of the universe" Ψ. Here we encounter new problems: There is neither an external time parameter, nor is there an external observer. How these problems can be tackled is described in Claus Kiefer's contribution[12].

5 Lessons

What insights can be drawn from decoherence studies? It should be emphasized that decoherence derives from a straightforward application of standard quantum theory to realistic situations. It seems to be a historical accident, that the importance of the interaction with the natural environment was overlooked for such a long time. Certainly the still prevailing (partly philosophical) attitudes enforced by the Copenhagen school played a (negative) role here, for example by outlawing a physical analysis of the measurement process in quantum-mechanical terms.

Because of the strong coupling of macroscopic objects, a quantum description of macroscopic objects *requires* the inclusion of the natural environment. A fully unitary quantum theory is only consistent if applied to the whole universe. This does not preclude local phenomenological descriptions. However, their derivation from a universal quantum theory and the interpretation assigned to such descriptions have to be analyzed very carefully.

We have seen that typical classical properties, such as localization in space, are *created* by the environment in an irreversible process, and are therefore not inherent attributes of macroscopic objects. The features of the interaction define *what* is classical by selecting a certain basis in Hilbert space. Hence superselection sectors emerge from the dynamics. In all "classical" situations, the relevant decoherence time is extremely short, so that the smooth Schrödinger dynamics leads to apparent discontinuities like "events", "particles" or "quantum jumps".

There are certain ironies in this situation. *Local* classical properties find their explanation in the *nonlocal* features of quantum states. Usually quantum objects are considered as fragile and easy to disturb, whereas macroscopic objects are viewed as the rock-solid building blocks of empirical reality. However, the opposite is true: macroscopic objects are extremely sensitive and immediately decohered.

On the practical side, decoherence also has its disadvantages. It makes testing alternative theories difficult (more on that below), and it represents a major obstacle for people trying to construct a quantum computer. Building a really big one may well turn out to be as difficult as detecting other Everett worlds!

5.1 Does decoherence solve the measurement problem?

Clearly not. What decoherence tells us, is that certain objects *appear* classical when they are observed. But what is an observation? At some stage, we still have to apply the usual probability rules of quantum theory. These are hidden in density matrices, for example.

5.2 Which interpretations make sense?

One could also ask: what interpretations are left from the many that have been proposed during the decades since the invention of quantum theory? I think, we do not have much of a choice at present*, *if* we restrict ourselves to use only wavefunctions as kinematical concepts (that is, we ignore hidden-variable theories, for example).

There seem to be only the two possibilities either (1) to alter the Schrödinger equation to get something like a "real collapse" [3, 13], or (2) to keep the theory unchanged and try to establish some variant of the Everett interpretation. Both approaches have their pros and cons, some of them are listed in the following table.

Clearly collapse models face the immediate question of how, when and where a collapse takes place. If a collapse occurs before the information enters the consciousness of an observer, one can maintain some kind of psycho-physical parallelism by assuming that what is experienced subjectively is parallel to the physical state of certain objects, e.g., parts of the brain. The last resort is to view consciousness as *causing* collapse, an interpretation which can more or less be traced back to von Neumann. In any case, the collapse happens with a certain probability (and with respect to a certain basis in Hilbert space) and this element of the theory comprises an *additional* axiom.

How would we want to test such theories? One would look for collapse-like deviations from the unitary Schrödinger dynamics. However, similar *apparent* deviations are also produced by decoherence, in particular in the relevant meso- and macroscopic range. So it is hard to discriminate these *true* changes to the Schrödinger equation from the *apparent* deviations brought about by decoherence[9].

Everett interpretations lead into rather similar problems. Instead of specifying the collapse one has to define precisely how the wavefunction is to be split up into branches. Decoherence can help here by selecting certain directions in Hilbert space as dynamically stable (and others as extremely fragile – branches with macroscopic objects in nonclassical states immediately decohere), but the location of the observer in the holistic quantum world is always a decisive ingredient. It must be assumed that what is subjectively experienced is parallel to certain states (observer states) in a certain *component* of the global wave function. The probabilities (frequencies)

*The following owes much to discussions with Dieter Zeh, who finally convinced me that the Everett interpretation *could* perhaps make sense at all.

collapse models	Everett
traditional psycho-physical parallelism: What is perceived is parallel to the observer's physical *state*	new form of psycho-physical parallelism: Subjective perception is parallel to the observer state in a *component* of the universal wave function
probabilities put in by hand	probabilities must also be postulated (existing "derivations" are circular)
problems with relativity	peaceful coexistence with relativity
experimental check: look for collapse-like deviations from the Schrödinger equation $\Downarrow$ hard to test because of decoherence	experimental check: look for macroscopic superpositions $\Downarrow$ hard to test because of decoherence

we observe in repeated measurements form also an additional axiom [§]. The peaceful coexistence with relativity seems not to pose much problems, since no collapse ever happens and all interactions are local in (high-dimensional) configuration space. But testing Everett means testing the Schrödinger equation in particular with respect to macroscopic superpositions, and this again is precluded by decoherence.

So it seems that both alternatives still have conceptual problems and both are hard to test because of decoherence. We should not be surprised, however, if it finally turned out that we do not know enough about consciousness and its relation to the physical world to solve the quantum mystery [14].

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[§] There exist several claims in the literature that probabilities can be derived in the Everett interpretation. I think these proofs are circular. Consider a sequence of N measurements on copies of a two-state system, all prepared in the initial state $a|1\rangle + b|2\rangle$. The resulting correlated state contains 2^N components, where each pointer state shows one of the 2^N possible sequences of measurement results (e.g. as a computer printout). But these pointer states are *always the same*, independently of the values of a and b! Only if each branch is given a *weight* involving $|a|^2$ and $|b|^2$ one may recover the correct frequencies. See also [11]. In addition, deep (and partially very old) questions about the meaning of probabilities seem to reappear in the framework of Everett interpretations.

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