James Evans · Alan S. Thorndike

QUANTUM MECHANICS AT THE CROSSROADS

New Perspectives from History, Philosophy and Physics

With 46 Figures

Springer 2007

7

Decoherence and the Foundations of Quantum Mechanics

Maximilian Schlosshauer and Arthur Fine

7.1 Introduction

Over the past quarter-century, decoherence has become an omnipresent term in the literature on quantum mechanics. Even named part of the "new orthodoxy" [1] in understanding quantum mechanics, it has attracted widespread attention among experimental and theoretical physicists as well as philosophers of physics. The burgeoning field of quantum computing [2] and research into the realization of mesoscopic and macroscopic superposition states [3] has made decoherence a more widely studied field than ever. Although decoherence per se does not introduce anything particularly new into the formalism of standard quantum mechanics, it is capable of yielding surprising results that, when properly interpreted, can contribute crucially to a proper understanding of the connection between the quantum-mechanical formalism and the world of our perception. Anyone working in the field of quantum mechanics today needs to know the basics of decoherence and its conceptual implications. This article is intended as a primer that reviews those basics [4].

Decoherence studies the ubiquitious interactions between a system and its surrounding environment. These interactions lead to a rapid and strong entanglement between the two partners that has crucial consequences for what we can observe at the level of the system. Studies have shown that even the microwave background radiation can have a significant impact on systems of sizes as small as a dust particle [5]. The decoherence program describes such environmental interactions and evaluates their formal, experimental, and conceptual consequences for the quantum-mechanical description of physical systems. In the following, we will introduce the main concepts of decoherence and discuss some of their implications for foundational aspects and interpretations of quantum mechanics.

7.2 Basics of Decoherence

The key idea promoted by decoherence is rather simple, although its consequences are far-reaching and seem to have been overlooked for a surprisingly long time: To give a correct quantum-mechanical account of the behavior and properties of a physical system, we must include the interactions of this system with its omnipresent environment, which generally involves a large number of degrees of freedom.

Classical physics typically studies systems that are thought of as being separated from their surroundings. The environment is generally viewed as a "disturbance" or "noise." In many cases, the influence of the environment is neglected, usually in accordance with the relative sizes of system and environment. For instance, the scattering of air molecules on a bowling ball is ignored when the motion of the ball is studied, while surrounding molecules have a crucial influence on the path of a small particle in Brownian motion.

By contrast, in quantum mechanics, environmental interactions amount to more than a simple delivery of "kicks" to the system. They lead to the formation of a nonlocal entangled state for the system–environment combination. Consequently, no individual quantum state can be attributed to the system anymore. Such entanglement corresponds to establishing correlations that imply properties for the system–environment combination that are not derivable from features of the individual parts themselves and that change the properties that we can "assign" to the individual system. Thus interactions between a given system and its large, ubiquitous environment, must not be neglected if the system is to be described properly in quantum-mechanical terms.

The theory of decoherence typically involves two distinct steps: a dynamical step, namely, the interaction of the system with its environment and the resulting entanglement, and a coarse-graining step in form of a restriction to observations of the system only. The latter step can be motivated by the (nontrivial) empirical insight that all observers, measuring devices, and interactions are intrinsically local [6]. In any realistic measurement performed on the system, it is practically impossible to include all degrees of freedom of the system and those of the environment that have interacted with the system at some point. In other words, inclusion of the environment is needed to arrive at a

complete description of the time evolution of the system, but we subsequently "ignore" at least a part of the environment by not observing it. For example, light that scatters off a particle will influence the behavior of the particle, but we will intercept (i.e., observe) only a tiny part of the scattered photons with our visual apparatus; the rest will escape our observation. The key question that decoherence investigates can then be put as follows: What are the consequences of *nonlocal* environmental entanglement for *local* measurements?

To formalize matters, let us assume that the system $\mathcal{S}$ can be described by state vectors $|s_k\rangle$, and that the interaction with the environment $\mathcal{E}$ leads to a formation of product states of the form $|s_k\rangle \otimes |e_k(t)\rangle$, where the $|e_k(t)\rangle$ are the corresponding "relative" states of $\mathcal{E}$ (representing a typically very large number of environmental degrees of freedom). If the initial state of the system at $t = 0$ is given by the pure-state superposition $|\Psi_\mathcal{S}\rangle = \sum_k \lambda_k |s_k\rangle$, and that of the environment by $|e_0\rangle$, the initial state of the system–environment combination has the separable form

$$|\Psi\rangle = |\Psi_\mathcal{S}\rangle \otimes |e_0\rangle = \left(\sum_k \lambda_k |s_k\rangle \right) \otimes |e_0\rangle. \tag{7.1}$$

Here, the system has the well-defined individual quantum state $|\Psi_\mathcal{S}\rangle$. However, the interaction between $\mathcal{S}$ and $\mathcal{E}$ evolves $|\Psi\rangle$ into the nonseparable entangled state

$$|\Psi(t)\rangle = \sum_k \lambda_k(t) |s_k\rangle \otimes |e_k(t)\rangle. \tag{7.2}$$

In essence, the dynamical evolution $|\Psi\rangle \rightarrow |\Psi(t)\rangle$ corresponds to von Neumann's account of quantum measurement [7] that models the measurement process within unitary (no-collapse) quantum mechanics as the formation of appropriate quantum correlations between the system and the measuring apparatus (where the latter is here represented by the environment). Accordingly, decoherence was initially only referred to as "continuous measurement by the environment."

Since the state $|\Psi(t)\rangle$ in general can not be expressed anymore in a separable product form $|\Psi_\mathcal{S}(t)\rangle \otimes |\Psi_\mathcal{E}(t)\rangle$, no individual state vector can be attributed to $\mathcal{S}$. The phase relations λ_k, describing the coherent superposition of $\mathcal{S}$-states $|s_k\rangle$ in the initial state, have been "dislocalized" into the combined state $|\Psi(t)\rangle$ through the interaction; i.e., coherence has been "distributed" over the many degrees of freedom of the system–environment combination and has become unobservable at the level of the system. To paraphrase Joos and Zeh [8], the superposition still *exists* (in fact, it now even pertains to the environment), but it is not *there* (at the individual system). In this sense, we can speak of the decoherence process as describing a local suppression (or rather: inaccessibility) of interference.

Since the interaction is strictly unitary, decoherence can in principle always be reversed. However, due to the large number of degrees of freedom of the environment (that are typically not controlled and/or controllable), decoherence can be considered irreversible for all practical purposes. It also turns out that, for the same reason, the states $|e_k(t)\rangle$ rapidly approach orthogonality (i.e., macroscopic distinguishability) as t increases,

$$\langle e_k(t)|e_{k'}(t)\rangle \longrightarrow 0 \quad \text{if } k \neq k'. \tag{7.3}$$

To see more directly the phenomenological consequences of the processes described thus far in the context of actual measurements, let us consider the density matrix $\rho_{\mathcal{SE}}(t)$ corresponding to the state $|\Psi(t)\rangle$:

$$\rho_{\mathcal{SE}}(t) = |\Psi(t)\rangle\langle\Psi(t)| = \sum_{k,k'} \lambda_k(t)\lambda_{k'}^*(t)|s_k\rangle|e_k(t)\rangle\langle s_{k'}|\langle e_{k'}(t)|. \tag{7.4}$$

(We shall from here on omit the tensor-product symbol "$\otimes$" to simplify our notation.) The presence of terms $k \neq k'$ represents interference (quantum coherence) between different product states $|s_k\rangle|e_k(t)\rangle$ of the system–environment combination $\mathcal{SE}$. By contrast, if we dealt with a classical ensemble of these states, our density matrix would read

$$\rho_{\mathcal{SE}}^{\text{class}}(t) = \sum_k |\lambda_k(t)|^2|s_k\rangle|e_k(t)\rangle\langle s_k|\langle e_k(t)|. \tag{7.5}$$

Such an ensemble is interpreted as describing a state of affairs in which $\mathcal{SE}$ is in one of the states $|s_k\rangle|e_k(t)\rangle$ with (ignorance-based) probability $|\lambda_k(t)|^2$.

Let us now include the coarse-graining component, i.e., we assume that we do not (cannot, do not need to) have full observational access to all the many degrees of freedom of the environment interacting with the system. The restriction to the system can be represented by forming the so-called reduced density matrix, obtained by averaging over the degrees of freedom of the environment via the trace operation:

$$\begin{aligned}\rho_{\mathcal{S}}(t) &= \operatorname{Tr}_{\mathcal{E}}(\rho_{\mathcal{SE}}(t)) \\ &= \sum_l \langle e_l|\rho_{\mathcal{SE}}(t)|e_l\rangle \\ &= \sum_{k,k'} \lambda_k(t)\lambda_{k'}^*(t)\langle e_{k'}(t)|e_k(t)\rangle|s_k\rangle\langle s_{k'}|,\end{aligned} \tag{7.6}$$

where the $\{|e_l\rangle\}$ forms a basis of the Hilbert space of $\mathcal{E}$. Density matrix $\rho_{\mathcal{S}}$ suffices to compute probabilities and expectation values for all local observables $\widehat{O}_{\mathcal{S}}$ that take into account only the degrees of freedom of $\mathcal{S}$. In this sense, it contains all the relevant information about the "state" of $\mathcal{S}$ that can be found out by measuring $\mathcal{S}$ (while, of course, no individual quantum state vector can be attributed to $\mathcal{S}$).

Now, since the decoherence process makes the environmental states $|e_k(t)\rangle$ approximately mutually orthogonal, as in (7.3), the reduced density matrix approaches the diagonal limit

$$\rho_{\mathcal{S}}(t) \longrightarrow \sum_k |\lambda_k(t)|^2|s_k\rangle\langle s_k|. \tag{7.7}$$

Since this density matrix *looks like* that for a classical ensemble of $\mathcal{S}$-states $|s_k\rangle$ [cf. (7.5)], it is often referred to as describing an "apparent ensemble." As a consequence, the expectation value of observables $\widehat{O}_{\mathcal{S}} = \sum_{k,k'} O_{kk'}|s_k\rangle\langle s_{k'}|$ computed via the trace rule $\langle\widehat{O}_{\mathcal{S}}\rangle = \operatorname{Tr}_{\mathcal{S}}\left[\rho_{\mathcal{S}}(t)\widehat{O}_{\mathcal{S}}\right]$ approaches that of a classical average, i.e., the contribution from interference terms $k \neq k'$ becomes vanishingly small.

While the dislocalization of phases can be fully described in terms of unitarily evolving, interacting wavefunctions [see (7.2)], the reduced density matrix has been obtained by a nonunitary trace operation. The formalism and interpretation of the trace presuppose the probabilistic interpretation of the wave function and ultimately rely on the assumption of the occurence of an (if only apparent) "collapse" of the wave function at some stage. We must therefore be very careful in interpreting the precise meaning of the reduced density matrix, especially if we would like to evaluate the implications of decoherence for the measurement problem and for no-collapse interpretations of quantum mechanics. It is probably fair to say that early misconceptions in this matter have contributed to the confusion and criticism that has surrounded the decoherence program over the decades. So we will discuss this point in some detail in the next section.

7.3 Decoherence and the Measurement Problem

The measurement problem relates to the difficulty of accounting for our perception (if not the objective existence) of definite outcomes at the conclusion of a measurement. It follows from the linearity of the Schrödinger equation that when the (usually microscopic) system $\mathcal{S}$ is described by a superposition of states $|s_k\rangle$ which the (typically macroscopic) apparatus $\mathcal{A}$ (with corresponding states $|a_k\rangle$) is designed to measure, the final composite state of the system–apparatus combination $\mathcal{SA}$ will be a superposition of product states $|s_k\rangle|a_k\rangle$. This is basically the state of affairs described by (7.1) and (7.2) (representing the von Neumann-type measurement scheme), with the environment $\mathcal{E}$ now replaced by the measuring device $\mathcal{A}$.

The usual rules of quantum mechanics then imply that no single, definite state can be attributed to the apparatus, and that in general we have (1) a multitude of possible outcomes (not just one), and (2) interference between these multiple outcomes. That a superposition must not be interpreted as an ensemble has also been widely confirmed in numerous experiments, in which superpositions are observed as individual physical states where all components of the superposition are simultaneously present [9].

So how is it, then, that at the conclusion of a measurement we always observe the pointer of the apparatus to be in a single definite position, but never in a superposition of positions? This "measurement problem" actually contains of two separate questions: (A) Why is it that always a particular quantity (usually position) is selected as the determinate variable (the "preferred-basis problem")? And (B), why do we perceive a single "value" (outcome) for the determinate variable (the "problem of outcomes")? We shall discuss these questions and their connection with decoherence in the following.

7.3.1 The Preferred-Basis Problem

As a simple example for the preferred-basis problem, consider a system $\mathcal{S}$ consisting of a spin-1/2 particle, with spin states $|\uparrow_z\rangle_\mathcal{S}$ and $|\downarrow_z\rangle_\mathcal{S}$ corresponding to the eigenstates of an observable σ_z that measures whether the spin points up or down along the z axis. Now, let $\mathcal{S}$ be measured by an apparatus $\mathcal{A}$ in the following way: If the system is in state $|\uparrow_z\rangle_\mathcal{S}$, the apparatus ends up in the state $|\uparrow_z\rangle_\mathcal{A}$ at the conclusion of the measurement, i.e., the final system–apparatus combination can be described by the product state $|\uparrow_z\rangle_\mathcal{S}|\uparrow_z\rangle_\mathcal{A}$ (and similarly for $|\downarrow_z\rangle_\mathcal{S}$). Since we may think of the $|\uparrow_z\rangle_\mathcal{A}$ and $|\downarrow_z\rangle_\mathcal{A}$ as representing different pointer positions on a dial (say "pointer up" and "pointer down"), the $|\uparrow_z\rangle_\mathcal{A}$ and $|\downarrow_z\rangle_\mathcal{A}$ are often referred to as the "pointer states" of the apparatus.

Suppose now that the state of $\mathcal{S}$ before the measurement is given by the superposition $\frac{1}{\sqrt{2}}(|\uparrow_z\rangle_\mathcal{S} - |\downarrow_z\rangle_\mathcal{S})$. Then, at the conclusion of the measurement, the combined (entangled) state of $\mathcal{S}$ and $\mathcal{A}$ is

$$|\Psi\rangle_{\mathcal{SA}} = \frac{1}{\sqrt{2}}(|\uparrow_z\rangle_\mathcal{S}|\uparrow_z\rangle_\mathcal{A} - |\downarrow_z\rangle_\mathcal{S}|\downarrow_z\rangle_\mathcal{A}). \tag{7.8}$$

We note that this again represents the final state of a typical von Neumann measurement [cf. (7.1) and (7.2)]. Looking at the state $|\Psi\rangle_{\mathcal{SA}}$, the answer to the question "what observable has been measured by $\mathcal{A}$?" seems obvious: σ_z, of course, i.e., the spin in z direction. But as the reader may easily verify, $|\Psi\rangle_{\mathcal{SA}}$ can in fact be rewritten using any other basis vectors $\{|\uparrow_{\hat{n}}\rangle_\mathcal{S}, |\downarrow_{\hat{n}}\rangle_\mathcal{S}\}$ of $\mathcal{S}$, where now $\hat{n}$ is a unit vector that can point into any arbitrary direction in space, and still $|\Psi\rangle_{\mathcal{SA}}$ will maintain its initial form. For example, if we choose $\hat{n}$ to point along the x axis, (7.8) becomes

$$|\Psi\rangle_{\mathcal{SA}} = \frac{1}{\sqrt{2}}(|\uparrow_x\rangle_\mathcal{S}|\uparrow_x\rangle_\mathcal{A} - |\downarrow_x\rangle_\mathcal{S}|\downarrow_x\rangle_\mathcal{A}). \tag{7.9}$$

What would we now deduce from this form of $|\Psi\rangle_{\mathcal{SA}}$ as the measured observable? Apparently σ_x, i.e., a measurement of the spin in x direction. So it appears that once we have measured the spin in *one* direction (again, interpreting the formation of correlations between $\mathcal{S}$ and $\mathcal{A}$ as a measurement), we seem to also have measured the spin in *all* directions. But wait, the reader may now object, σ_z and σ_x do not commute, so they can't be measured simultaneously!

The conclusion to be drawn is that quantum mechanics, in the form of the von Neumann measurement scheme applied to the isolated system–apparatus combination, does not automatically specify the observable that has been measured. This is certainly hard to reconcile with our experience of the workings of measuring devices that seem to be designed to measure highly specific physical quantities. We can generalize this problem by asking why (especially macroscopic) objects are usually found in a very small set of eigenstates, most prominently in position eigenstates. In fact, the observation that "things around us" always seem to be in definite spatial locations, whereas the linearity of the Hilbert space of the quantum mechanical formalism would in principle allow for arbitrary superposition of positions, is maybe the most intuitive and direct illustration of the preferred-basis problem.

The inclusion of interactions with an environment suggests a solution to this problem. The system $\mathcal{S}$ and the apparatus $\mathcal{A}$ will, in all realistic situations, never be fully isolated from their surrounding environment $\mathcal{E}$. Thus, in addition to the desired measurement interaction between $\mathcal{S}$ and $\mathcal{A}$, there will also be an interaction between $\mathcal{A}$ (and $\mathcal{S}$) and $\mathcal{E}$, leading to the formation of further correlations. Many such $\mathcal{A}$–$\mathcal{E}$ interactions will, however, result in a disturbance of the initial correlations between $\mathcal{S}$ and $\mathcal{A}$, thus altering, or even destroying, the measurement record, which would render it impossible for an observer to perceive the outcome of the measurement.

Zurek therefore proposed the definition of a "preferred pointer basis" of the apparatus as the basis that "contains a reliable record of the state of the system $\mathcal{S}$" [10], that is, the basis $\{|a_k\rangle\}$ of $\mathcal{A}$ in which the correlations $|s_k\rangle|a_k\rangle$ are least affected by the interaction between $\mathcal{A}$ and $\mathcal{E}$ (for simplicity, we shall assume here that $\mathcal{S}$ interacts directly only with $\mathcal{A}$ but not with $\mathcal{E}$). A sufficient (but not necessary) criterion for such a pointer basis would then be given by requiring all the projectors $|a_k\rangle\langle a_k|$ to commute with the apparatus–environment interaction Hamiltonian $H_{\mathcal{AE}}$ (the so-called "commutativity criterion"), that is,

$$[\,|a_k\rangle\langle a_k|,\, H_{\mathcal{AE}}\,] = 0 \qquad \text{for all } k. \tag{7.10}$$

In other words, the apparatus would be able to measure (i.e., be designed to measure) observables reliably that are linear combinations of the $|a_k\rangle\langle a_k|$, but not necessarily certain other observables. Thus, the environment – or more precisely, the form of the apparatus–environment interaction Hamiltonian – determines the preferred basis of the apparatus, and in turn also the preferred basis of the system ("environment-induced superselection").

Of course, we can generalize these findings from a setup explicitly containing measuring devices to the more general situation of entanglement between arbitrary systems and their environment. The fact that physical systems are usually observed to have determinate values only with respect to a small number of quantities (typically position for macroscopic objects) can then be explained by the fact that the system–environment interactions depend on precisely these quantities, e.g., distance (relative position). The commutativity criterion then implies that the system will preferably be found in (approximate) eigenstates of observables corresponding to those quantities. Since this selection mechanism is based on standard unitary quantum mechanics, it avoids the necessity to postulate ad hoc basis selection criteria, and it can therefore also be expected to be in agreement with our observations.

Apart from the most simple toy model cases, the commutativity criterion holds usually only approximately [11], and general operational methods have therefore been proposed to determine (at least in principle) the preferred basis in more complex situations [12]. One remaining conceptual problem concerns the question of what counts as the "system" and what as the "environment," and where to place the cut (see the discussion in Sect. 7.4 below). Nonetheless, environment-induced selection can be considered as the most promising approach toward explaining the emergence and stability of preferred states.

7.3.2 The Problem of Outcomes

Let us again consider the situation of von Neumann quantum measurement in form of an interaction that entangles the state of the system with the state of the measuring apparatus. We now also include the environment into the chain of interactions. That is, the apparatus $\mathcal{A}$ interacts with the system $\mathcal{S}$; in turn, the $\mathcal{SA}$ combination then interacts with the environment $\mathcal{E}$. The linearity of the Schrödinger equation yields the following time evolution of the entire system $\mathcal{SAE}$:

$$\begin{aligned}\Big(\sum_n \lambda_n |s_n\rangle\Big)|a_0\rangle|e_0\rangle &\longrightarrow \Big(\sum_n \lambda_n |s_n\rangle|a_n\rangle\Big)|e_0\rangle \\ &\longrightarrow \sum_n \lambda_n |s_n\rangle|a_n\rangle|e_n\rangle.\end{aligned} \tag{7.11}$$

Here $|a_0\rangle$ and $|e_0\rangle$ are the initial states of the apparatus and the environment, respectively. Evidently, after the interaction has taken place, the combined system $\mathcal{SAE}$ is described by a coherent pure-state superposition at all times. While the dislocalization of the phases λ_n into the $\mathcal{SAE}$ combination resulting from the interaction between $\mathcal{S}$, $\mathcal{A}$, and $\mathcal{E}$ "dissolves" local interference into the global system (see Sect. 7.2), this decoherence process by itself does not automatically explain why definite outcomes are perceived. Since superpositions represent individual quantum states in which all components of the superposition "exist" simultaneously, we cannot (and must not) isolate a single apparatus state $|a_m\rangle$ that would indicate an actual outcome of the measurement.

We can break free from the persistence of coherence in the $\mathcal{SAE}$ combination only when the dynamics of the open subsystem $\mathcal{SA}$ in terms of its reduced density matrix is considered. And, of course, all that we really need is the ability to ascribe a definite value to $\mathcal{A}$ (to be precise, to the $\mathcal{SA}$ combination, if the measurement is to be considered faithful), rather than to the total system $\mathcal{SAE}$. The time evolution of the reduced density matrix will in general be nonunitary, since it is not only influenced by the Hamiltonian of $\mathcal{SA}$, but also by the interacting (but averaged-out) environment. As indicated before, decoherence leads to the formation of "classical-looking" density matrices for $\mathcal{SA}$: The reduced density matrix $\rho_{\mathcal{SA}}$ becomes rapidly diagonal in a set of stable, environment-selected basis states. In other words, the decohered density matrix of the local system–apparatus combination becomes *operationally* indistinguishable from that of an ensemble of states, and it correctly describes the time evolution of the open system $\mathcal{SA}$.

It would then seem that decoherence could account for the existence of a local ensemble of potential measurement outcomes with definite probabilities (that in turn could then be related to the occurence of single outcomes in individual measurements). The problem with this argument has already been briefly touched upon earlier: The averaging-out of environmental degrees of freedom by means of the trace operation needed to arrive at the reduced density matrix relies on the probabilistic interpretation of the state vector (i.e., on the interpretation of $|\langle\varphi_k|\Psi\rangle|^2$ as the probability for the system described by the state vector $|\Psi\rangle$ to be found in the state $|\varphi_k\rangle$ upon measurement). In turn, this is related to the assumption of some form of wavefunction "collapse" at a certain stage of the observational chain. In this sense, taking the trace essentially "amounts to the statistical version of the projection postulate" [13]. Of course we do not want to presuppose some sort of collapse that would solve the measurement problem trivially without even necessarily having to worry about the role of decoherence.

We therefore conclude that, by itself, decoherence does not directly solve the measurement problem. After all, this might not come as a surprise, as decoherence simply describes unitary entanglement of wavefunctions – and since the resulting entangled superpositions are precisely the source of the measurement problem, we cannot expect the solution to this problem to be provided by decoherence. However, the fact that the reduced density matrices obtained from decoherence describe observed open-system dynamics and the emergence of quasiclassical properties for these systems perfectly well, decoherence is extremely useful in motivating solutions to the measurement problem. This holds especially when the physical role of the observer is correctly taken into account in quantum-mechanical terms of system–observer correlations, making more precise what the "perception of definite outcomes" and the related measurement problem actually *mean* in terms of physical observations.

Accordingly, we shall describe in Sec. 7.5 how decoherence can be put to use in various interpretations of quantum mechanics, especially with respect to a resolution of the measurement problem. Before that, however, we shall discuss in the next section a couple of conceptual issues related to decoherence.

7.4 Resolution into Subsystems and the Closed-Universe Objection

The application of the theory of decoherence requires a decomposition of the total Hilbert space into subsystems. As long as we consider the universe as a whole, it is fully described by its state vector $|\Psi\rangle$ that evolves strictly deterministically according to the Schrödinger equation, and no interpretive problem seems to arise here. The notorious measurement problem only comes into play once we decompose the universe into subsystems (thus forming the joint product state $|\Psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle \otimes \cdots$), and attempt to attribute *individual* states to the subsystems.

However, there exists no general criterion that would determine where the splitting cuts are supposed to be placed. Of course, in a standard laboratory-like measurement situation, the physical setup might lead to an easy identification of "the system of interest," "the measuring device," and "the external environment." But this is a rather special and subjective rule for the splitting, and confronted with a more complex state space (encompassing, say, larger contiguous parts of the universe), there is neither a general rule for decomposition (given, for example, a total Hilbert space and its Hamiltonian) nor a definition for what counts as a "system." This issue becomes particularly important if one would like to use decoherence to define "objective macrofacts" of the universe as a whole. On the other hand, one might of course adopt the view that all correlations (and the resulting properties) should be considered as intrinsically relative to a given local observer, and that therefore a general rule for "objective" state-space decompositions need not be required.

Also, the ignorance-based coarse-graining procedure required by decoherence to obtain the reduced density matrix requires the openness of the system. But what about if we take this system to be the universe as a whole? (Quantum cosmology, for example, is all about studying the evolution of the universe in its entirety.) By definition, the universe is a closed system, and thus no external environment exists whose "unobserved" degrees of freedom could be averaged over. This has become known as the "closed-universe problem." From the point of view of talking about "events" or "facts" as the result of observations, this does however not necessarily constitute a problem, since every observation is inherently local and presupposes the ignorance of certain other parts. As Landsman [14] put it, "the essence of a 'measurement', 'fact' or 'event' in quantum mechanics lies in the non-observation, or irrelevance, of a certain part of the system in question.... A world without parts declared or forced to be irrelevant is a world without facts."

7.5 Decoherence and Interpretations of Quantum Mechanics

There are numerous interpretive approaches to quantum mechanics. On the "standard" (textbook) side, we have the "orthodox" interpretation with its infamous collapse postulate, together with the similar (and often not distinguished) Copenhagen interpretation. As "alternative" interpretations, we can name several main categories: the relative-state interpretation, introduced by Everett [15] (and further developed as "many-worlds" and "many-minds" interpretations); the class of modal interpretations, first suggested by van Fraassen [16]; physical collapse theories like the Ghirardi–Rimini–Weber (GRW) approach [17]; the consistent-histories approach introduced by Griffiths [18]; and the de Broglie–Bohm pilot-wave theory, a highly non-local hidden-variable interpretation [19]. Common to all of the alternative approaches is their attempt to dispose of the collapse postulate of the orthodox (and Copenhagen) interpretation. Some of them are just alternative readings of the formalism of standard quantum mechanics (Everett), others modify the rules that connect the formalism to the actual physical properties (modal interpretations), postulate new physical mechanisms (GRW), and introduce additional governing equations (de Broglie–Bohm).

The necessity to include environmental interactions for a realistic description of the behavior of physical systems is an objective one, independent of any interpretive framework. But the effects (and their proper interpretation) arising from such interactions have much to do with conceptual and interpretive stances. For instance, we might ask whether decoherence effects alone can already solve some of the foundational problems without the need for certain interpretive "additives," or whether decoherence can motivate (or falsify) some approaches – or even lead to a unification of different interpretations. In the following, we discuss some of the connections between decoherence and the main interpretations of quantum mechanics [20].

7.5.1 The Orthodox and the Copenhagen Interpretations

A central element of orthodox interpretations is the well-known collapse (or projection) postulate which prescribes that every measurement,

represented by some suitably chosen observable, leads to nonunitary reduction of the total state vector to an eigenstate of the measured observable. To avoid the preferred basis problem, measurements are assumed to be carried out by an "observer" that can freely "choose" an observable before the measurement, and thus determine what properties can be ascribed to the system after the measurement (a strongly positivist, observer-dependent viewpoint).

A major problem with this approach is that it is not clearly defined what counts as a "measurement," and that the measuring process has a strong "black box" character. It does not explain why measuring devices seem to be designed to measure certain quantities but not others. Taking into account environmental interactions can provide the missing physical description of measurements. According to the stability criterion of the decoherence program, for a measurement to count as such, it must lead to the formation of stable records in spite of immersion into the environment. Therefore, the structure of the interaction between the apparatus and its environment singles out the preferred observables of the apparatus (and thereby also determines what properties can be assigned to the measured system). In this sense, decoherence and environment-induced selection can augment, if not replace, the formal and vague concept of measurement employed by the orthodox interpretation with general observer-independent criteria that specify what observables can actually be measured by a given apparatus.

The most distinctive feature of the Copenhagen interpretation (compared to the orthodox interpretation) is its postulate of the necessity for classical concepts to describe quantum phenomena. Instead of deriving classicality from the quantum world, e.g., by considering some macroscopic limit, the requirement for a classical description of the "phenomena," which comprise the whole experimental arrangement, is taken to be a fundamental and irreducible element of a complete quantum theory. Specifically, the Copenhagen interpretation postulates the existence of intrinsically classical measuring devices that are not to be treated quantum mechanically. This introduces a quantum–classical dualism into the description of nature and requires the assumption of an essentially nonmovable boundary (the famous "Heisenberg cut") between the "microworld," containing the objects that are to be treated as quantum systems, and the "macroworld" that has to be described by classical physics.

However, the studies of decoherence phenomena demonstrate that quasiclassical properties, across a broad range from microscopic to macroscopic sizes, can emerge directly from the quantum substrate through environmental interactions. This makes the postulate of an a priori existence of classicality seem unnecessary, if not mistaken, and it renders unjustifiable the placement of a fixed boundary to separate the quantum from the classical realm on a fundamental level.

7.5.2 Relative-State Interpretations

The core idea of Everett's original relative-state proposal, and of its interpretive extensions into a many-worlds or many-minds framework, is to assume that the physical state of an isolated system (in particular, that of the entire universe) is described by a state vector $|\Psi\rangle$, whose time evolution is given by the Schrödinger equation that is assumed to be universally valid. All terms in the superposition of the total state correspond in some way to individual physical states (realized, for instance, in different "branches" of the universe or "minds" of an observer). One major difficulty of this approach is the preferred basis problem, which is here particularly acute since each term in the state vector expansion is supposed to correspond to some "real state of affairs." Thus, it is crucial to be able to define uniquely a particular basis in which to expand the continuously branching (since new quantum correlations are formed constantly and everywhere) state vector at each instant of time.

It has frequently been suggested to use the environment-selected basis to define the preferred branches. This has several advantages. Instead of having simply to postulate what the preferred basis is, the basis arises through the interaction with the environment and the natural criterion of "robustness." Clashes with empirical evidence are essentially excluded, since the selection mechanism is based on well-confirmed Schrödinger dynamics. Finally, and maybe most importantly, the environment-preferred components of the decohered wavefunction can be reidentified over time, which yields stable, temporally extended branches.

There have been several criticisms of this idea. First, as we have pointed out before, there exists no objective rule for what counts as a system and what can be considered as the environment. Therefore, decoherence-induced selection of branches is often promoted in the context of an observer-based (subjective) interpretation [21]. Typically this includes the observer's neuronal (perceptional) apparatus in the full description of observations, instead of assuming the existence of "external" observers that are not treated as interacting quantum systems. Each neuronal state then becomes correlated with the states corresponding to the individual terms in the superposition of the observed system, and decoherence between these different brain states [22] is assumed to prevent the different "outcome records" from interfering and thus to lead to a perception of individual outcomes.

Second, decoherence typically yields only an approximate ("for all practical purposes" [23]) definition of a preferred basis and therefore does not provide an "exact" specification of branches [24]. Responses to this criticism suggest that it is fully sufficient for a physical theory to account for our experiences, which does not entail the necessity for exact rules as long as the emerging theory is empirically adequate [25].

7.5.3 Modal Interpretations

The main characteristic feature of modal interpretations is to abandon the rule of standard quantum mechanics that a system must be in an eigenstate of an observable in order for that observable to have a definite value. In its place, new rules are introduced that specify lists of possible properties (definite values) that can be ascribed to a system given, for example, its density matrix $\rho(t)$. The results of the theory of decoherence have frequently been used to motivate and define such rules of property ascription. Some [26] have even suggested that one of the main goals of modal interpretations is to provide an interpretation of decoherence. The basic approach consists of using environment-selected preferred bases (in which the decohered reduced density matrix is approximately diagonal) to specify sets of possible quasiclassical properties associated with the correct probabilities. This provides a very general and entirely physical rule for property ascriptions that can be expected to be empirically adequate. The rule could also be used to yield property states with quasiclassical, continuous "trajectory-like" time evolution (since the decohered components of the wavefunction are stable and can thus be reidentified at over time) that is in accordance with unitary quantum mechanics [27].

The difficulty with this approach lies in the fact that determining the environment-selected robust basis states explicitly is nontrivial in more complex systems. The aim of modal interpretations, however, has been to formulate a general rule from which the set of possible properties can be directly and straightforwardly derived. Frequently, instead of explicitly finding preferred states on the basis of the stability criterion (or a similiar measure), the orthogonal decomposition of the decohered density matrix has been used to determine the property states directly. When applied to discrete models of decoherence (that is, for systems described by a finite-dimensional Hilbert space), this method has in most cases been found to yield states with the desired quasiclassical properties, similar to those obtained from the stability criterion, at least when the final composite state was sufficiently nondegenerate [28]. In the continuous case, however, it has been demonstrated that the predictions of decoherence (e.g., as measured by the coherence length of the density matrix) and the properties of the states determined from the orthogonal decomposition do not mesh [29]. Thus decoherence can here be used to indicate that certain methods of property ascription might be physically inadequate [30].

7.5.4 Physical Collapse Theories

These are theories that modify the unitary Schrödinger dynamics to induce an actual collapse of the wavefunction based on a physical mechanism. The most popular version has probably been the one proposed by Ghirardi, Rimini and Weber (GRW) [31] which postulates the existence of instantaneously and spontaneously occurring "hits" that lead to a spatial localization of the wavefunction. The frequency of the hits is chosen such that macroscopic objects are localized faster than any observation could resolve, while preserving an effectively unitary time evolution on microscopic scales.

Decoherence provides a physical motivation for the a priori choice of position as the universal preferred basis in the GRW theory. Many physical interactions are described by distance-dependent terms, which according to the stability criterion of the decoherence program leads to the selection of (at least approximate) eigenstates of the position operator as the preferred basis. On the other hand, however, decoherence also demonstrates that in many situations position will *not* be the preferred basis. This occurs most commonly on microscopic scales, where systems are typically found in energy rather than position eigenstates [32], but also for instance in superconducting quantum interference devices [33] that exhibit superpositions of macroscopic currents. As far as microscopic systems are concerned, the GRW theory avoids running into empirical inadequacies by having the spatial localization hits occur so rarely that state vector reduction in the position basis is effectively suppressed. However, this has certainly an ad hoc character in comparison with the more sensitive, general, and physically motivated basis selection mechanism of the decoherence program. Furthermore, since decoherence will always be present in any realistic system, the assumption that the GRW theory holds means that we can expect to have two selection mechanisms that either act in the same direction (if decoherence also leads to a spatial localization) or compete with each other (in cases where decoherence predicts a different preferred basis than position).

It also has been found that the governing equations for the time evolution of the density matrix of a system in the GRW theory bear remarkable similarity to the evolution equations obtained from an inclusion of environmental interactions. This has raised the question whether it is necessary to postulate an explicit collapse mechanism, or whether at least the free parameters in the equations of the GRW approach could be directly derived from the study of environmental interactions [34]. (Of course, the GRW theory achieves true state vector reduction, whereas decoherence only leads to improper ensembles, so they are not on the same interpretive footing.) Assuming the simultaneous presence of decoherence and GRW effects, one could imagine an experimental falsification of the GRW theory by means of a system for which GRW predicts a collapse, but decoherence leads to no significant loss of coherence [35]. However, since any realistic system is extremely hard to shield from decoherence effects, such an experiment would presumably be very difficult to carry out [36].

7.5.5 Consistent-Histories Interpretations

The central idea of this approach is to dispose of the fundamental role of measurements (that assume the existence of external observers) in quantum mechanics and instead study quantum "histories," i.e., sequences of quantum events represented by sets of time-ordered projection operators, and to attribute probabilities to such histories. A set of histories is called consistent (judged by an appropriate mathematical criterion) when all its members are independent, that is, when they do not interfere and the classical probability calculus can be applied.

One major problem of this approach has been that the consistency criterion appears to be insufficient to single out the quasiclassical histories that would correspond to the world of our experience – in fact, most consistent histories turn out to be highly nonclassical [37]. To overcome this difficulty, decoherence has frequently been employed in proposals that would lead to a selection of quasiclassial histories, and also in attempts to provide a physical motivation for the consistency criterion [38]. Interestingly, this move has also introduced a conceptual shift. While the original aim of the consistent-histories program had been to define the time evolution of a single, closed system (often the entire universe, where standard quantum mechanics runs into problems as no external observers can be present), wedding decoherence to the consistent-histories formalism requires a division of the total Hilbert space into subsystems and the openness of the local subsystems.

The decoherence-based approach commonly consists of using the environment-selected pointer states that (approximately) diagonalize the reduced density matrix as the projectors of histories. This leads typically to the emergence of histories that are stable and exhibit quasiclassical properties, since the pointer basis is "robust" and corresponds well to the determinate quantities of our experience. Moreover, such histories defined by projectors corresponding to the pointer basis also turn out to fulfill the consistency criterion automatically, at least approximately. This has led to the argument that the consistency criterion is both insufficient and overly restrictive in singling out histories with quasiclassical properties, and to a questioning of the fundamental role and relevance of this criterion in consistent-histories interpretations in general [39].

7.5.6 Bohmian Mechanics

Bohm's approach describes the deterministic evolution of a system of particles, where the system is described both by a wavefunction $\psi(t)$, evolving according to the standard Schrödinger equation, and by the particle positions $\mathbf{q}_k(t)$, whose dynamics are determined by a simple "guiding equation" for the velocity field, essentially the gradient of $\psi(t)$. Particles then follow well-defined trajectories in configuration space represented by the configuration $\mathcal{Q}(t) = (\mathbf{q}_k(t), \dots, \mathbf{q}_N(t))$, whose distribution is $|\psi(t)|^2$.

Bohm's theory has been criticized for attributing fundamental ontological status to particles. It has been argued that, since decoherence typically leads to ensembles of wavepackets that are narrowly peaked in position space, one can identify these wavepackets with our (subjective) perception of particles, i.e., spatially localized objects [40]. This suggests that the explicit assumption of the existence of actual particles at a fundamental level of the theory might be rendered superfluous (modulo the basic question of how to go from an apparent to a proper ensemble of wavepackets).

Another problem is how to relate the Bohmian particle trajectories to quasiclassical trajectories that emerge on a macroscopic scale. Going back to studies of Bohm himself [41], it has been suggested that the inclusion of environmental interactions could provide the missing ingredient to arrive at quasiclassical trajectories. Typically the idea has been to identify the Bohmian trajectories $\mathcal{Q}(t)$ with the temporally extended, spatially localized wavepackets of the decohered density matrix

that describe macroscopic objects. While this approach is highly intuitive and has been demonstrated to yield promising results in some of the explicitly studied examples, in other cases this identification turns out to be insufficient to sustain the classical limit [42].

7.6 Outlook

The key idea of the decoherence program relies on the insight that, in order to properly describe the behavior of a physical system in quantum-mechanical terms, the omnipresent interactions of the system with the degrees of freedom of its environment must be taken into account. The application of the formalism of decoherence to numerous model systems has led to many experimentally verified results, so the idea has proven to be very successful. Interestingly, however, the rather straightforward and well-studied approach of decoherence, both experimentally and theoretically, has led to several fundamental interpretive and conceptual questions.

By itself, decoherence simply describes environmental entanglement and the resulting practically irreversible dislocalization of local phase relations (i.e., of quantum-mechanical superpositions). Since the entangled pure state makes it impossible to assign an individual state vector to the system, the dynamics of the system must be described by a nonunitarily evolving reduced density matrix. While decoherence transforms such density matrices into apparent ensembles of quasiclassical states (which, when properly interpreted, may be used to obtain a physically motivated resolution of the measurement problem), the formalism and interpretation of reduced density matrices *presume* the probabilistic interpretation of the wavefunction. Thus decoherence alone (i.e., without being augmented by some additional interpretive elements) cannot solve the measurement problem. Furthermore, the requirement for a division of the universe into "systems" and "environments" introduces a strong flavor of subjectivity, since no general and objective rule exists for how and where to place the cuts. Also, the necessity for an "external" environment leads to difficulties when one would like to apply the theory to the universe as a whole, as in quantum cosmology.

This situation requires and motivates interpretive frameworks beyond the "orthodox" interpretation, frameworks that might provide some of the missing steps toward a conceptually complete and consistent interpretation of the decoherence program, and of quantum mechanics as a whole. Conversely, the assumptions made by an interpretation must be consistent with the results obtained from decoherence, thus narrowing down the spectrum of possible (empirically adequate) interpretations – maybe even making the choice between different such interpretations "purely a matter of taste, roughly equivalent to whether one believes mathematical language or human language to be more fundamental," as Tegmark [43] put it in a comparison between the orthodox interpretation and decoherence-based relative-state interpretations. Clearly, the rather simple idea of including environmental interactions as promoted by decoherence has an extremely important impact on the foundations of quantum mechanics, suggesting solutions to fundamental problems as well as posing new conceptual questions.

References

1. J. Bub, *Interpreting the Quantum World* (Cambridge University Press, Cambridge 1997), p 212
2. M. A. Nielsen and I. L. Chuang, *Quantum Computation and Quantum Information* (Cambridge University Press, Cambridge 2000)
3. M. Schlosshauer, "Experimental motivation and empirical consistency in minimal no-collapse quantum mechanics," Annals of Physics **321**, 112–149 (2006)
4. For more detailed reviews of decoherence, we recommend the following. For a review paper that that deals comprehensively with many of the more technical aspects of decoherence, including an overview of recent experimental advances, see W. H. Zurek, "Decoherence, einselection, and the quantum origins of the classical," Reviews of Modern Physics **75**, 715–775 (2003). E. Joos, H. D. Zeh, C. Kiefer, D. Giulini, J. Kupsch, and I.-O. Stamatescu, *Decoherence and the Appearance of a Classical World in Quantum Theory*, 2nd edn (Springer, New York 2003) provides an extensive description of the decoherence program as a whole. Finally, a recent review paper of one of us discusses in great detail the foundational implications of decoherence: M. Schlosshauer, "Decoherence, the measurement problem, and interpretations of quantum mechanics," Reviews of Modern Physics **76**, 1267–1305 (2004).
5. E. Joos and H. D. Zeh, "The emergence of classical properties through interaction with the environment," Zeitschrift für Physik B **59**, 223–243 (1985); M. Tegmark, "Apparent wave function collapse caused by scattering," Foundations of Physics Letters **6**, 571–590 (1993)
6. H.-D. Zeh, "On the interpretation of measurement in quantum theory," Foundations of Physics **1**, 69–76 (1970). H.-D. Zeh, "The problem of conscious observation in quantum mechanical description," Foundation of Physics Letters **13**, 221–233 (2000). N. P. Landsman, "Observation and superselection in quantum mechanics," Studies in the History and Philosophy of Modern Physics **26**, 45–73 (1995)
7. J. von Neumann, *Mathematische Grundlagen der Quantenmechanik* (Springer, Berlin 1932)
8. Joos and Zeh, "The emergence of classical properties" (Ref 5)
9. An overview of such experiments involving mesoscopic "Schrödinger kittens" can be found in Schlosshauer, "Experimental motivation and empirical consistency" (Ref 3).
10. W. H. Zurek, "Pointer basis of quantum apparatus: Into what mixture does the wave packet collapse?," Physical Review D **24**, 1516–1525 (1981), p 1519
11. W. H. Zurek, "Preferred states, predictabilty, classicality, and the environment-induced decoherence," Progress of Theoretical Physics **89**, 281–312 (1993). W. H. Zurek, S. Habib, and J. P. Paz, "Coherent states via decoherence," Physical Review Letters **70**, 1187–1190 (1993)
12. Zurek, "Preferred states"(Ref 11); Zurek, "Decoherence, einselection, and the existential interpretation" (The Rough Guide)," Philosophical Transactions of the Royal Society of London, Series A **356**, 1793–1821 (1998); Zurek, "Decoherence, einselection, and the quantum origins of the classical" (Ref 4); and Zurek, et al., "Coherent states via decoherence" (Ref 11)
13. O. Pessoa, Jr., "Can the decoherence approach help to solve the measurement problem?," Synthese **113**, 323–346 (1999), p 432
14. Landsman, "Observation and superselection in quantum mechanics" (Ref 6) pp 45–46
15. H. Everett, "'Relative state' formulation of quantum mechanics," Reviews of Modern Physics **29**, 454–462 (1957)
16. B. van Fraassen, *Quantum Mechanics: An Empiricist View* (Clarendon Press, Oxford 1991)
17. G. C. Ghirardi, A. Rimini, and T. Weber, "Unified dynamics for microscopic and macroscopic systems," Physical Review D **34**, 470–491 (1986)
18. R. B. Griffiths, "Consistent histories and the interpretation of quantum mechanics," Journal of Statistical Physics **36**, 219–272 (1984). For a review see R. Omnès, "Consistent interpretations of quantum mechanics," Reviews of Modern Physics **64**, 339–382 (1992).
19. D. Bohm, "A suggested interpretation of the quantum theory in terms of 'hidden variables'," I and II, Physical Review **85**, 166–193 (1952). D. Bohm and J. Bub, "A proposed solution of the measurement problem in quantum mechanics by a hidden variable theory," Reviews of Modern Physics **38**, 453–469 (1966)
20. For a more detailed treatment, see Schlosshauer, "Decoherence" (Ref 4).
21. See, for example, Joos and Zeh, "The emergence of classical properties" (Ref 5); W. H. Zurek, "Decoherence, einselection, and the existential interpretation" (Ref 12); M. Tegmark, "The interpretation of quantum mechanics: Many worlds or many words?," Fortschritte der Physik **46**, 855–

862 (1998); Zeh, "The problem of conscious observation" (Ref 6); H.-D. Zeh, "Toward a quantum theory of observation," Foundations of Physics **3**, 109–116 (1973); and Zurek, "Decoherence, einselection, and the quantum origins of the classical" (Ref 4).
22. M. Tegmark, "Importance of quantum decoherence in brain processes," Physical Review E **61**, 4194–4206 (2000)
23. J. S. Bell, "Against 'measurement'," in A. I. Miller (ed), *Sixty-Two Years of Uncertainty* (Plenum Press, New York 1990) pp 17–31
24. A. Kent, "Against many worlds interpretations," International Journal of Modern Physics A **5**, 1745 (1990); and Zeh, "Toward a quantum theory of observation," (Ref 21)
25. B. d'Espagnat, "A note on measurement," Physics Letters A **282**, 133–137 (2000); D. Wallace, "Everett and structure," Studies in the History and Philosophy of Modern Physics **34**, 87–105 (2003)
26. D. Dieks, "Modal interpretation of quantum mechanics, measurements, and macroscopic behavior," Physical Review A **49**, 2290–2300 (1994); D. Dieks, "Objectification, measurement and classical limit according to the modal interpretation of quantum mechanics," in I. Busch, P. Lahti and P. Mittelstaedt (eds), *Proceedings of the Symposium on the Foundations of Modern Physics* (World Scientific, Singapore 1994) pp 160–167
27. M. Hemmo, *Quantum Mechanics Without Collapse: Modal Interpretations, Histories and Many Worlds*, PhD thesis, University of Cambridge, Department of History and Philosophy of Science (1996); G. Bacciagaluppi and M. Hemmo, "Modal interpretations, decoherence and measurements," Studies in the History and Philosophy of Modern Physics **27**, 239–277 (1996)
28. G. Bene, "Quantum origin of classical properties within the modal interpretations," http://arxiv.org/abs/quant-ph/0104112 (2001); and Bacciagaluppi and Hemmo, "Modal interpretations" (Ref 27)
29. G. Bacciagaluppi, "Delocalized properties in the modal interpretation of a continuous model of decoherence," Foundations of Physics **30**, 1431–1444 (2000)
30. M. Donald, "Discontinuity and continuity of definite properties in the modal interpretation," in D. Dieks and P. Vermaas (eds), *The Modal Interpretation of Quantum Mechanics* (Kluwer, Dordrecht 1998) pp 213–222
31. Ghirardi, Rimini and Weber, "Unified dynamics" (Ref 17)
32. J. P. Paz and W. H. Zurek, "Quantum limit of decoherence: Environment induced superselection of energy eigenstates," Physical Review Letters **82**, 5181–5185 (1999)
33. J. R. Friedman, V. Patel, W. Chen, S. K. Yolpygo, and J. E. Lukens, "Quantum superposition of distinct macroscopic states," Nature **406**, 43–46 (2000)
34. E. Joos, "Comment on 'Unified dynamics for microscopic and macroscopic systems'," Physical Review D **36**, 3285–3286 (1987)

35. A. I. M. Rae, "Can GRW theory be tested by experiments on SQUIDS?," Journal of Physics A **23**, L57–L60 (1990); E. J. Squires, "Wavefunction collapse and ultraviolet photons," Physics Letters A **158**, 431–432 (1991)
36. F. Benatti, G. C. Ghirardi, and R. Grassi, "Quantum mechanics with spontaneous localization and experiments," in E. G. Beltrametti and J.-M. Lévy-Leblond (eds), *Advances in Quantum Phenomena* (Plenum Press, New York 1995); and Tegmark, "Apparent wave function collapse" (Ref 5)
37. A. Albrecht, "Following a 'collapsing' wave function," Physical Review D **48**, 3768–3778 (1993); F. Dowker and A. Kent, "Properties of consistent histories, Physical Review Letters **75**, 3038–3041 (1995); F. Dowker and A. Kent, "On the consistent histories approach to quantum mechanics," Journal of Statistical Physics **82**, 1575–1646 (1996); M. Gell-Mann and J. Hartle, "Quantum mechanics in the light of quantum cosmology," in S. Kobayashi, H. Ezawa, Y. Murayama and S. Nomura (eds), *Proceedings of the 3rd International Symposium on the Foundations of Quantum Mechanics in the Light of New Technology (Tokyo, Japan, August 1989)* (Physical Society of Japan, Tokio 1990) pp 321–343; J. P. Paz and W. H. Zurek, "Environment-induced decoherence, classicality and consistency of quantum histories," Physical Review D **48**, 2728–2738 (1993); and Zurek, "Preferred states" (Ref 11)
38. See, for example, Gell-Mann and Hartle, "Quantum mechanics in the light of quantum cosmology" (Ref 37); F. Dowker and J. J. Halliwell, "Quantum mechanics of history: The decoherence functional in quantum mechanics," Physical Review D **46**, 1580–1609 (1992); A. Albrecht, "Investigating decoherence in a simple system," Physical Review D **46**, 5504–5520 (1992); Albrecht, "Following a 'collapsing' wave function" (Ref 37); Zurek, "Preferred states" (Ref 11); Paz and Zurek, "Environment-induced decoherence" (Ref 37); J. Twamley, "Phase-space decoherence: A comparison between consistent histories and environment-induced superselection," Physical Review D **48**, 5730–5745 (1993); J. Finkelstein, "On the definition of decoherence," Physical Review D **47**, 5430–5433 (1993); C. Anastopoulos, "Decoherence and classical predictability of phase space histories," Physical Review E **53**, 4711–4728 (1996); M. Gell-Mann and J. B. Hartle, "Strong decoherence," in D. H. Feng and B. L. Hu (eds), *Quantum Classical Correspondence: The 4th Drexel Symposium on Quantum Nonintegrability* (International Press, Cambridge, Mass. 1998) pp 3–35; and J. J. Halliwell, "Decoherent histories for spacetime domains," in J. G. Muga, R. S. Mayato and I. L. Egususquiza (eds), *Time in Quantum Mechanics* (Springer, Berlin 2001).
39. Albrecht, "Investigating decoherence" (Ref 38); Albrecht, "Following a 'collapsing' wave function" (Ref 37); Gell-Mann and Hartle, "Quantum mechanics in the light of quantum cosmology" (Ref 37); Griffiths, "Consistent histories and the interpretation of quantum mechanics" (Ref 18); Omnès, "Consistent interpretations of quantum mechanics" (Ref 18); R.

Omnès, *The Interpretation of Quantum Mechanics* (Princeton University Press, Princeton 1994); Paz and Zurek, "Environment-induced decoherence" (Ref 37); Twamley "Phase-space decoherence" (Ref 38); and Zurek, "Preferred states" (Ref 11)
40. H.-D. Zeh, "There are no quantum jumps, nor are there particles!," Physics Letters A **172**, 189–192 (1993); H.-D. Zeh, "Why Bohm's quantum theory?," Foundations of Physics Letters **12**, 197 (1999); H.-D. Zeh, "There is no 'first' quantization," Physics Letters A **309**, 329–334 (2003)
41. D. Bohm and B. Hiley, *The Undivided Universe* (Routledge, London 1993)
42. V. Allori, *Decoherence and the Classical Limit of Quantum Mechanics*, PhD thesis, Physics Department, University of Genova (2001); V. Allori, D. Dürr, S. Goldstein, and N. Zanghì, "Seven steps towards the classical world," Journal of Optics B: Quantum and Semiclassical Optics **4**, S482–S488 (2002); V, Allori, and N. Zanghì, "On the classical limit of quantum mechanics," Biannual IQSA Meeting (Cesena, Italy, 2001), http://arxiv.org/abs/quant-ph/0112009; D. M. Appleby, "Bohmian trajectories of an isolated particle," Foundations of Physics **29**, 1863–1884 (1999); A. S. Sanz and F. Borondo, "A Bohmian view on quantum decoherence," http://arxiv.org/abs/quant-ph/0310096 (2003); and Zeh, "Why Bohm's quantum theory?" (Ref 40)
43. Tegmark, "The interpretation of quantum mechanics: Many worlds or many words?" (Ref 21), p 855

8

What Are Consistent Histories?

Alan Thorndike

8.1 Introduction

In the standard interpretation, quantum mechanics answers questions about the probabilities of obtaining such and such a value for such and such a measurement in such and such an experiment. A particle released from location a at a certain time has a certain probability of being detected at location b at some later time. This is a rather restricted view. It has nothing to say about quantities that aren't measured as part of the experiment, such as locations at intermediate times. And it is quiet about plausible physical processes that are not accessible to measurement, events that happened long ago or far away, for example. Finally, in the standard interpretation, the act of measurement forces a system to assume one of its several possible states, and thus interrupts the natural evolution of the system.

Over the last twenty years, a new interpretation of quantum mechanics has been developed that addresses these restrictions. The new interpretation – consistent histories – allows one to assign probabilities to sequences of states without actually perturbing the system with measurements at each time in the sequence. But this is only possible if certain conditions are satisfied. Consistent histories play an important role in current discussions of the foundations and interpretation of quantum mechanics, not the least by helping us sharpen our thinking about what constitutes a meaningful question and what does not. In this chapter, I provide an introduction to the notion of consistent histories and show how the mathematics works in a few examples.