Quantum Decoherence

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1 Introduction: Three Quantum Puzzles

Saturn's moon Hyperion is one of the solar system's strangest bodies. Described in Bokulich (2008, p. 23) as "approximately three times the size of the state of Massachusetts and... roughly the shape of a potato," its irregular shape when coupled with inhomogeneous gravitational forces from Saturn and surrounding moons *should* leave Hyperion in a spatial orientation that is a coherent superposition over 57 degrees (Zurek and Paz, 1997). But this is not what is observed. Hyperion appears to occupy definite orientations – not a superposition of positions – as it chaotically tumbles around Saturn.

Or consider optical isomers like the sugar and ammonia molecules. Optical isomers have identical atomic composition and structure (therefore the same quantum state description) but dissimilar chirality (therefore different optical properties). In the ground state their position eigenstates are "left-handed" or "right-handed"; if these eigenstates are possible states, then coherent superpositions of left- and right-handedness are also possible states. However, while the ammonia molecule is typically observed in a superposition of chiral states, the sugar molecule is observed in a handed eigenstate. Why does nature act according to our expectations regarding the ammonia molecule's spatial position but contrary to our expectations in the case of sugar?

Lastly, consider Bohr's planetary atomic model of 1913. In it, electrons occupy definite energy states and perform instantaneous quantum jumps to transition to higher or lower energy orbitals. This model successfully explained certain atomic spectra despite its incorrect assumption that electrons always occupy an energy eigenstate instead of superpositions of such states.

These puzzles drawn from the macro-, meso- and microscopic domains, respectively, all find an explanation in decoherence. Below these explanations are provided, but first decoherence and relevant concepts are defined (§2). Then (§3) the most widely adopted

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formalism for studying decoherence – that of density matrices – is sketched, followed by an overview of the four canonical models (§4). The latter half of the article examines the explanatory wealth of decoherence when brought to bear on foundational issues such as the question of why certain measurement bases[1] seem to be preferred by nature (§5) – including the pointer basis of measuring apparatuses (§6) –, the old familiar measurement problem (§7) and the emergence of classicality (§8). Because decoherence is prevalent in uncontrolled environments and extraordinarily effective in most circumstances, understanding its theoretical and experimental implications proves a crucial component in any conception of physical bodies and their interactions, philosophical or otherwise.

2 Definition and Basic Concepts

Quantum decoherence, or environmentally-induced decoherence (hereafter simply decoherence) is a physical process resulting from a system's entanglement with an environment. At any given time, systems are interacting quantum-mechanically (as opposed to thermally or mechanically) with external or independent degrees of freedom comprising an environment. The consequence of this interaction is generally entanglement with respect to certain degrees of freedom (hereafter DoFs), and this in turn enables the environment to decohere phases among components of the superposition[2] in the basis or bases of entanglement.[3]

Decoherence is not an interpretation of quantum mechanics nor is it new physics.[4] What is needed for decoherence to occur (within the usual Hilbert space formalism) is a set of three basic postulates, and their consequences when examined apart from several key

[1]For an introduction to the formalism of quantum mechanics including the concept of a basis, see chapter 2 of Albert (1992).

[2]In analogy to classical wave mechanics, a quantum system is said to be in a coherent superposition when the phase relations between individual waves composing the superposed wave are *constant*. (Constant phase relations engender stable constructive and destructive interference patterns). Decoherence can then be understood as the destruction (due to external interactions) of constancy among phase relations (ergo the destruction of interference patterns.

[3]Entanglement is often confused or used interchangeably with the term coupling. This confusion leads to misconceptions about the scope and nature of entanglement as a purely quantum phenomenon, as opposed to the broader class of phenomena related to coupling. Although coupling is, like entanglement, a result of interaction between two or more systems or between different DoFs within a single system, it is unlike entanglement in that the former is not a necessary consequence of interactions whereas the latter typically is. For example, the molecules of gas in a system at thermal equilibrium are not (on average) thermally coupled. These molecules are, however, interacting in a way that will generally lead to entanglement. They can be described independently at the level of classical interactions but are inseparable according to the quantum mechanical description. The confusion between coupling of systems and environments in the classical sense and entanglement as a (or according to Schrödinger, *the*) quantum mechanical property is in part why it took physicists so long to recognize decoherence was a quantum process, distinct from thermal dissipation.

[4]It is important not to confuse the physical process itself with interpretations of quantum mechanics wherein decoherence plays a prominent role, e.g. the decoherent histories approach. On the latter see Gell-Mann and Hartle (1996), Griffiths (2003) and Halliwell (1995).

idealizations. One may begin by assuming (i) pure and mixed states can be represented by density operators in a Hilbert space, (ii) observables are defined as self-adjoint operators acting on that space, and (iii) the Schrödinger equation correctly describes unitary evolution of all closed systems.[5]

Add to these postulates the ubiquity of quantum interactions leading to widespread entanglement and hence the fictitiousness of any truly closed system (apart from the universe as a whole, perhaps) and one has the necessary ingredients for decoherence.[6]

Phase relations and superpositions play an important role in decoherence processes, and though these concepts were conceived in analogy with classical wave mechanics, they are importantly different in quantum systems. In the latter, phase relations mathematically express the degree to which amplitudes of individual waves constituting a superposition can be combined. Bear in mind that this analogy with classical wave mechanics is just that – an analogy. In classical mechanics, a wave packet is analyzable in terms of a superposition of the aggregate individual waves (e.g. electromagnetic field strength is just the sum of wave amplitudes at a spacetime point). In quantum mechanics, although mathematically the superposed state is still described as a sum of the individual component states, a quantum system in such a state may have very different properties.

This is precisely what happens in the puzzle of the sugar and ammonia molecules. In Joos and Zeh (1985), a seminal early work on decoherence, the authors investigated the paradox of optical isomers by entangling a parity eigenstate of each molecular system to a single unpolarized photon. They found that in the case of the sugar molecule, the photon–molecule composite system became strongly entangled to environmental photons. This entanglement led to the decoherence, or prodigious damping, of phase amplitudes in the sugar molecule's polarity, leaving only definite handed states stable under environmental influence. The more stable a state is under evolution, the more measurable it is. Hence the failure to measure sugar in any state *other than* "left-handed" or "right-handed".[7]

Decoherence also satisfactorily explains the behavior of the ammonia molecule. In this case chirality did *not* become entangled with the photon environment, and so no decoherence occurred in the ammonia molecule's basis of polarization. Superpositions of left- and

[5]Quantum mechanics must be assumed universally valid for the explanations from decoherence to have maximal significance. Since, however, the fundamentality of quantum theory is regarded by most to be the only viable working option, additional argumentation in support of this assumption shall not be given here.

[6]In what follows, "system" can be read so weakly as to refer to one or more independent DoFs. For example, decoherence can occur within a single electron when treated as two separate systems: let the electron's spin be the system of interest, while the electron's translational DoFs form the environment. Correspondingly, what is considered the environment can be comprised by any suitable DoFs external to the system of interest.

[7]Further detail: Joos and Zeh calculated rudimentary values for the rate of decoherence of sugar's chiral states and found that it was on a timescale many orders of magnitude faster than the measurement process itself. In other words, before the measurement event on the sugar molecule could be completed (the detection of post-interaction photons indicating the molecule's polarity), decoherence had already practically irreversibly destabilized states in superpositions of polarity, effectively rendering the left- and right-handed eigenstates the only measurable states.

right-handed states of ammonia remain stable under this type of environmental monitoring, and superposed states indeed are what one typically measures. As with sugar molecules, since a chiral state of ammonia has different optical properties than a superposition of chiral states, one can test whether the molecule is in a superposition by studying the specific effect it has on the polarity of incident light.[8] This illustrates the above point that superpositions of quantum systems can give rise to different observable states of affairs.

Of course it is well-known from the double-slit experiment that superpositions are possible states not just for mesoscopic systems like molecules but indeed for individual quanta: "self-interference" explains why spatial interference patterns emerge when particles are sent one at a time through a double-slit apparatus.[9] If the particle's phase relations are constant in the position basis – in which case the wave packet as a whole does not disperse – the system will exhibit interference effects (constructive or destructive) whose strength depends on the character of the phase relations. Nonzero phases whose ratio is constant are defined as coherent superpositions. When system-environment entanglement allows for system monitoring by the environment, the system's phases are delocalized in the basis (or bases) being monitored, an effect which expresses itself in the suppression of interference phenomena. This is what one observes when a detector (that is, a device that can become entangled to and therefore record information about a particle's trajectory) is placed behind one of the slits, interference patterns are destroyed and classical statistical distributions emerge. Absent such a detector, interference patterns are observed, because superposition states of the particle remain coherent long enough to reach the detector and be registered as such.

While quantum theory does not provide a straightforward physical interpretation of superpositions, what is clear from the occurrence of interference phenomena is that a particle within this apparatus cannot be described in terms of a classical statistical ensemble – i.e., it cannot be described as following a classical trajectory – unless one supplements the three basic postulates given above with a collapse mechanism[10] or guiding wave[11] or another suitable physical event.

It is often mistakenly asserted that in order for decoherence processes to correctly explain certain phenomena like self-interference in a double-slit apparatus or the puzzle of the optical isomers, one must assume collapse of the wavefunction.[12] This is decidedly false. It is also frequently claimed that decoherence requires the Born rule (ergo the eigenstate–eigenvalue link). Because of these mistakes – conflation of physical collapse (which decoherence does *not* involve) with effective collapse (which it does – more details

[8]For more detail, see sections 1–5 of Fortin et al. (2016).

[9]That is, as long as the distance between the slits is on the order of the de Broglie wavelength of the particles passing through.

[10]See Lewis (this volume) for discussion of collapse theories.

[11]See Tumulka (this volume) for discussion of theories of this kind.

[12]For a longer discussion of this point as well as expanded discussion on other points of common confusion regarding decoherence, see Crull (2017).

anon) and reliance on the Born rule for assigning definite values to measurement outcomes (which, as shall be argued below, is also unnecessary for decoherence), many have bypassed decoherence theory and experiments without due appreciation for this process' explanatory wealth. Because these misunderstandings run deep even in the professional literature, the remainder of this section is dedicated to a precisification of why decoherence does not need any physical postulate beyond the three listed above.

Regarding the question of collapse, Bacciagaluppi (2012) lists two physical assumptions that collapse theories like GRW require but decoherence does not. It will be instructive to repeat them here. First, collapse theories require true, physical collapse of the wave function; decoherence only entails effective collapse, in that this process renders practically impossible the obtainment of measurement results other than eigenstates of an unperturbed basis. The experimental observation of coherence *revivals* within models of previously decohered systems lends credence to the claim that no physically irreversible mechanism is operating therein.[13]

The second assumption collapse theories require but decoherence does not is the existence of an as-yet undiscovered collapse mechanism that introduces nonlinearity apart from the system-environment Hamiltonian. Decoherence introduces no additional nonlinearity but "simply takes real, inevitable, interaction with external degrees of freedom to bear in the Hamiltonian" (Bacciagaluppi, 2012). To this add a third point, conceded by collapse theorists themselves. Because collapse theories do not explain the privileging of certain bases, decoherence is called upon to explain this piece of the dynamics *within* these interpretations. Indeed, all viable interpretations of quantum mechanics invoke decoherence as a crucial part of their explanatory package on the understanding that this process involves nothing beyond the standard formalism and is not by itself an interpretation. Decoherence is not "empirically complete" in the sense that while it explains why certain bases are more stable than others in a given environment (and hence the states therein more likely measurable, and measurable qua eigenstates of the stable basis), it does not explain why one *particular* apparently definite outcome is measured instead of another.

Hence no physical collapse is needed so long as one stops short (as decoherence explanations do) of attempting to answer the question of why one obtains a specific outcome (as e.g. collapse theories do) instead of simply asking why one obtains an eigenvalue from a preferred basis. *Effective* wave function collapse is all that is required to explain the latter – the question of why certain bases are preferred; this point is discussed in more detail in §5 below.

A similar situation applies to the Born rule and the eigenstate-eigenvalue link: as long as one stops short of declaring the results of measurements to be actually definite – which is a significant ontological step beyond declaring them only apparently definite – then the Born rule can be understood as merely a guide to expectations and not a metaphysical

[13] See Narozhny et al. (1981) for theoretical groundwork and Kokorowski et al. (2001) as an entry point into fascinating work verifying decoherence models through experiments in atomic interferometry.

claim requiring further justification.

3 The Formalisms of Decoherence

The Hamiltonian of a quantum system is unitary only as long as the system is closed; entanglement with an environment therefore destroys local unitarity while preserving it at the level of the newly entangled composite system. Because of this introduced non-unitarity, the maximum information obtainable about one of the entangled subsystems (without introducing collapse or some such physical mechanism) is the complete statistical information about its evolution in a certain basis, and these statistics are obtained using reduced density matrices. The natural utility of reduced density matrices applied to decoherence processes make this formalism the favored one, and will now be briefly introduced.

If a quantum system is said to occupy a pure state, this indicates the state is fully knowable and can be represented by a single vector (or superposition of vectors) in the system's Hilbert space. If on the other hand only statistical information is known about the state it is referred to as a mixture, and can only be represented as a statistical distribution of pure states. However, this statistical distribution does not always describe a classical, or proper, ensemble wherein the system occupies a single state from among possible pure states but it is unknown which one. A mixed state density matrix may instead represent an *improper* ensemble, for which such an ignorance interpretation is incorrect. Entangled states in particular must be considered improper mixtures, as entanglement entails the existence of interference terms, or phase relations, among pure states comprising the ensemble.

It is important to stress that obtaining a diagonalized (interference-free) mixed state does *not* uniquely determine whether one is dealing with a proper or improper mixture. Although both proper and improper mixed states can be written in a variety of ways depending on the basis of measurement, as just described there are importantly different physical properties associated with each. For example, one might choose to write the density matrix for an improper mixture in the most convenient basis – the state's eigenbasis – in which case the density matrix will be diagonal and therefore formally identical to a proper mixture. However, diagonality in this basis is a particular feature of that basis. Because the system is an improper mixture, off-diagonal interference terms must exist in some other basis or bases, and this means that, barring any supplementation of the formalism with e.g. a collapse mechanism, these terms *remain* part of the system's full description.

Give this formal underdetermination of mixed states, when a system's preparation is not fully controllable or not entirely known, one cannot say with any certainty that its density matrix represents a proper classical ensemble with the system occupying a definite pure state. In fact, due to the ubiquity of entanglement, it is likely that a given system (particularly "in the wild") is entangled with some other system, and so must be represented as an improper mixture.[14]

Before describing the aspect of this formalism most useful for decoherence – reduced density matrices – there is another important tool that must be introduced called the trace operation. The trace of a matrix is the sum of its diagonal elements; under the normalization condition, the trace of a density matrix must be equal to one. Reduced density matrices are obtained via *partial* traces over the density matrix of the composite system in order to extract statistical information about a single subsystem. Thus a partial trace over the density matrix of an entangled system-plus-environment with respect to the environment yields the reduced density matrix of the system alone (having "traced out" environmental DoFs). Again one must be careful when interpreting these mathematical results: whatever the form of the system's reduced density matrix – in particular, whether it is diagonalized or not – the physical state to which it corresponds cannot be pure (or a superposition of pure states), as it is in fact a subsystem of an entangled whole. In other words, a mixed state density matrix underdetermines whether the ensemble of states comprising it is proper or improper, and therefore whether the system definitely occupies a single state or not.

The density matrix formalism is the preferred approach in most of the literature for determining system-environment interaction, and thus has received the most detailed explanation here. However, it is important to acknowledge various other approaches adopted for exploring decoherence. For instance, some have studied decoherence from a perspective called coarse-graining, or closed-system approaches.[15] This approach still uses the density matrix formalism but advocates a different treatment of the "cut" between system and measuring apparatus. A few words about the term coarse-graining, which often arises in connection with the closed-system approach, are in order. The switch from using system Hamiltonians to density matrices might in a superficial way be considered coarse-graining as it is a move from fully determinate equations to statistical ensembles. The language of "coarse-graining" here is somewhat misleading, though, as there is no actual loss of information moving from Hamiltonian representations to that of density matrices. Additionally, use of the density matrix formalism does not imply *necessary* coarse-graining, as there exist alternate formalism in which no coarse-graining occurs. For example, no coarse-graining exists in a powerful technique using Feynman path integrals: the restricted path integral (RPI) method.

The RPI method has become increasingly favored by experimentalists of late.[16] While

[14]For discussion of the ubiquity of entanglement and decoherence, see Giulini et al. (1996) (especially Joos' contribution), Joos and Zeh (1985) and Zeh (1970).

[15]The main works advocating and illustrating this approach to decoherence are a suite of papers by Castagnino, Lombardi and Fortin, including Castagnino et al. (2007),Castagnino et al. (2010) and Lombardi et al. (2012).

[16]For an excellent introduction to the theory and experimental practice of the path-integral approach to decoherence, see Mensky (2000). In chapter 5, Mensky provides a nice comparison between the use of

RPIs provide an undeniably powerful tool, this technique essentially relies on mathematical maneuvers whose metaphysical implications are entirely obscure. In particular, the RPI method (as with Feynmen path-integral approaches generally) involves treating the time evolution of a system as an integrand composed of all the possible trajectories (referred to as "channels" in decoherence research) of the system of interest. Obviously, issues arise as to the exact meaning of concepts like trajectories when applied to quantum systems, as one is necessarily dealing with nonlocal entities and quantized parameters. Even maximally coherent wave packets tracing out quasi-Newtonian trajectories in a system's phase space cannot be localized beyond the limit of the uncertainty relations, and so their evolution in accordance with approximately classical trajectories must be understood with significant qualification.

4 The Four Canonical Models

A vast array of physically interesting interactions have been successfully described using only four models, the so-called canonical models of decoherence. These models pair systems with both discrete and continuous DoFs with environments with discrete and continuous DoFs, giving the following permutations (listed as *system type–environment type*): the oscillator-oscillator model (continuous DoFs for both system and environment), the spin-oscillator model, also called the spin-boson model (discrete system DoFs, continuous environment DoFs), the spin-spin model (discrete DoFs for both) and the oscillator-spin model (continuous system DoFs, discrete environment DoFs). Below are tables representing common characteristics for these, where H_S designates the component of the total Hamiltonian (H_{tot}) due to the system's self-dynamics, H_E designates the environment's self-dynamics, and H_{int} is the interaction Hamiltonian for the given system and environment:

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master equations used in tandem with the density matrix approach, and the path-integral approach. He argues that the two approaches are equivalent for nonselective measurements, which are precisely the sort of measurements occurring in nature.

	Continuous DoFs	Discrete DoFs
System	· Mapped as harmonic oscillator in single-well potential · $H_S \approx H_{int}$, thus decoheres fastest in phase-space · E.g.: quantum Brownian particles	· Mapped as spin-1/2 particle in double-well potential · Possible self-entanglement requires complicated H_S · E.g.: fermions & qubits
Environment	· Mapped as continuum of N delocalized harmonic oscillators (bosonic field modes) · $H_E \ll H_S, H_{int}$ gives weak-coupling limit · Dissipation & decoherence of system in this env. is practically irreversible; leads to increased delocalization of field modes · Assume coupling strength of field modes scales as $1/\sqrt{N}$ to ensure well-defined thermodynamic limit for $N \to \infty$ · E.g.: gases	· Mapped as continuum of spin-1/2 particles ("spin bath") · Highly localized energy modes achieved at extremely low T · $H_{tot} \approx H_S$ due to low T env. · All systems – continuous energy spectra (osc. systems) and discrete energy states (spin-1/2 systems) are strongly decohered in spin bath · E.g.: superconducting & quantum computing devices

All four canonical models of decoherence require an important assumption: the initial independence of the system of interest from the relevant environment. Prima facie this seems problematic: if entanglement and decoherence are as effective and ubiquitous as stated, how can it be appropriate to assume for a model's initial conditions that the central system is uncorrelated to the environment? Wasn't decoherence first appreciated as a consequence of *dropping* the idealization of a truly isolated system?

Though the initial assumption of unentangled systems and environments is a nontrivial one, it has been substantiated in a wide variety of models. The earliest justifications of it can be found in Anglin et al. (1997) and Bose et al. (1999). In the former work, the authors convincingly argue that assuming a previously noninteracting system and environment is viable, especially in the most general case of uncontrolled interactions. Anglin et al. found that it is nearly always appropriate to characterize the environment as occupying an approximate pure state prior to interaction with the system due to the fact that uncontrolled environments (and sufficiently large controlled environments) have a prodigious number of DoFs which have been interacting among themselves prior to interaction with the system of interest. Thus the environment is itself already typically decohered in the bases of interest and can be treated as approximately localized therein.

In the latter work, Bose and coauthors investigate decoherence in a Schrödinger cat-type situation where the "cat" is modeled by a macroscopic mirror sitting in an electromagnetic field cavity. They explicitly drops the assumption of an initially unentangled system and environment, and find that the final state of the composite system is similar to that of models which assume *no* initial correlation (Bose et al. 1999).

In sum, the devil remains in the details: the viability of this assumption depends importantly on the nature of a particular system-environment interaction, and on the internal dynamics of both. However, it seems safe to say that in uncontrolled environments such as encountered outside the quantum physics lab, this assumption is justified.

A related question might now arise: if entanglement leads to decoherence, and the effect of decoherence is to suppress quantum correlations beyond observability, how is it that correlations are nevertheless measured? For example, how does decoherence explain Bell-type experiments verifying quantum correlations between EPR pairs? To answer this, one must first remember that decoherence is *basis specific*. Secondly, recall that decoherence occurs at different rates in different bases depending on the nature of the environmental interaction. Thus, while it is indeed true that maximally entangled states like EPR pairs (engineered in carefully controlled environments as they must be) maintain coherence with respect to certain pre-selected bases long enough to be measured by distant detectors, this is not necessarily true for all bases of the pair, and certainly not true for all time. Indeed, were coherence in all bases easily maintained or preserved, quantum computing – which banks on the possibility of maintaing qubit coherence within the computer environment for certain periods of time and over some distances – would not present the enormous engineering difficulties it does.[17]

[17]The possibility of a quantum computer depends upon the ability to engineer environmentally-incorruptible qubits, and this is no trivial feat. A qubit is a quantum system with (effectively) two states that is capable not only of expressing binary language with its two eigenstates, but due to its quantum nature, of encoding additional information via superpositions of its two states *and* via entanglement with other qubits. Such an enriched coding language of course dramatically increases computation power, but at cost: in order to keep the information coherent, qubits must be shielded from decoherence in an environment that is especially decoherence-friendly. Recall the table in section 4 above: quantum computation research heavily relies upon spin-spin decoherence models, for in these models the system (the qubit) is mapped as a spin-1/2 particle in a double-well potential (as a result of which qubits are associated with complicated Hamiltonians that allow for the possibility of self-entanglement), and in addition, this system is surrounded by *other* qubits, so this environment is mapped by a spin bath (as a result of which, the entire quantum computer must be kept at extremely cold temperatures in order to effectively shield qubits from environmental or self-decoherence). Thus quantum computers will require a number of extraordinary engineering feats to overcome the qubit's strong tendency to decohere in this arrangement, a process which scrambles information by (effectively) destroying bit integrity. Unsurprisingly, a particularly active area of investigation regarding the feasibility of quantum computers concerns the engineering of so-called "decoherence-free subspaces" wherein qubits avoid corruption. The literature on quantum computing is already prodigious, but for early discussions focusing on decoherence, see Deutsch (1985), Shor (1995) and Unruh (1995). See also CHRIS TIMPSON CHAP.

5 The Question of the Preferred Basis

The basis-specific nature of decoherence will allow for a satisfying explanation to one of quantum mechanics' oldest mysteries: that of the pointer basis. Why do measuring devices acting on quantum systems "point to" one specific, definite value when the wavefunction describing that system's state is probabilistic? Before answering this, however, it will be instructive to consider the more general underlying question: why do certain bases seem to be preferred over others (e.g., position for macroscopic systems, energy for microscopic systems) when no such preference is evident in the mathematical description?

Perhaps given the solution to the puzzle of optical isomers one can already guess at the answer here. Nature's apparent "preference" for certain bases of measurement is not due to as-yet undiscovered selection rules, but rather to the relative stability of particular bases over others due to decoherence dynamics. The rate at which a system's phase relations become decohered in a particular environment depends on the strength and character of the system-environment entanglement. System DoFs that commute most effectively with environmental DoFs will become most quickly entangled with one another, and therefore most robustly decohered in the associated basis. The dynamical robustness of a given basis under environmental monitoring is another way of describing the effectiveness with which the system's interference terms in that basis are suppressed beyond measurability, leading to the extreme improbability of observing superpositions as opposed to eigenstates in that basis.

As a first approximation of how decoherence provides the dynamics undergirding preferred bases, recall the puzzle of Bohr's atomic model above. There it was asked how a model that did not take superpositions of energy states of the electron into account nevertheless adequately explained empirical data like atomic spectra. It is now understood that by the time an electron's energy can be measured, it has become prodigiously decohered in the energy basis due to interaction and subsequent entanglement with the atomic nucleus. Thus the electron's superposed energy states became prodigiously damped by environmental influence while its energy eigenstates remained largely unaffected. In other words, the energy basis of the electron remains most stable under environmental influence and so becomes the preferred basis.

As a higher-order approximation, consider a quantum Brownian particle weakly interacting with a gas (a common instance of the oscillator-oscillator model). Here the position of the quantum particle decoheres most rapidly, followed by momentum, and momentum in turn decoheres far more rapidly than the rate of thermal dissipation.[18] Thus one observes

[18]Generally speaking, although the canonical coordinate of the system might represent e.g. an electromagnetic variable instead of position, the system will nevertheless be most stable with respect to its position states, because that is the variable whose operator commutes with individual environmental modes of the gas, which are modeled in terms of *their* position coordinates. Thus in the quantum Brownian motion model, the environment is said to continuously monitor the position of the system; when one takes a partial trace over position coordinates of just the environment, one obtains the system's reduced density matrix.

after a very short time the quantum Brownian particle tracing a quasi-Newtonian path in phase-space (as stated in the above table).

An explanation of the remaining quantum puzzle can now be given. Since Hyperion, an object uncontroversially considered "macroscopic," is nevertheless entangled with some environment (the gravitational field, for one), one expects decoherence to be in play. Indeed, in a paper titled "Why We Don't Need Quantum Planetary Dynamics", Zurek and Paz (1997) investigate the dynamics of Hyperion *without* taking decoherence into account, and conclude that the moon should occupy "a very nonclassical superposition, behaving in a flagrantly quantum manner" (pp. 370–371). But as stated above, this is not what is observed. Unsurprisingly, when Zurek and Paz did include decoherence dynamics into their calculations, they found results in agreement with observation. Here decoherence occurs most rapidly in position, probably due to immersion in an inhomogenous gravitational field whose $1/r^2$ dependence commutes with Hyperion's Hamiltonian[19]. This suppresses interference terms in the position basis so effectively that the moon follows an approximately Newtonian trajectory despite its underlying nonlinear quantum dynamics.

In this way decoherence not only provides the dynamics explaining why a certain basis is "preferred" (because it is most stable under interaction with a typical environment), but various models generate parameter-specific decoherence rates indicating the *degree* of a basis's stability through time as compared to other bases.

6 The Question of Pointer Positions

Zurek begins his seminal paper (Zurek, 1981) as follows:

> What does, in the real-world apparatuses, determine this apparently unique *pointer basis...* which records the corresponding relative states... of the system? Interaction with the environment is the key feature that distinguishes the here-proposed model of the apparatus from the manifestly quantum systems. We argue that the apparatus cannot be observed in a superposition of the pointer-basis states because its state vector is being continuously collapsed [sic]. It is the "monitoring" of the apparatus by the environment which results in the apparent reduction of the wave packet. Correlations between states of the pointer basis and corresponding relative states of the system are nevertheless preserved in the final mixed-state density matrix... (p. 1516)

Zurek demonstrates these claims by considering a reversible Stern–Gerlach apparatus (the incident beam of spin-1/2 particles is split into up and down streams by passing through an inhomogeneous magnetic field; the streams are then recombined by passing

[19] Although Hyperion's decoherence in the position basis might best be explained through a combination of interactions (e.g., including the effects of scattering dust and planetary debris), the gravitational field is the most significant – and constant – factor.

through a second inhomogenous magnetic field which is an inversion of the first) where a bistable atom measures the up-stream between the first and second magnet pairs. Zurek first calculates the composite wavefunction resulting from interaction of the spin-up stream (the system) with the atom (the apparatus). The final wavefunction is a pure state, indicating that there could not have been a real collapse of the wave function (ibid., p. 1518).

Zurek then calculates the composite wavefunction of the spin-up stream and the bistable atom in a different, arbitrary basis. Of this new, equally viable wavefunction Zurek writes "the illusion of a collapse may arise" (op. cit.), as this wavefunction is mixed – that is, it encodes maximal system-apparatus correlation, yet measurements will yield *apparently* definite outcomes. Analyzing these results Zurek writes (ibid., p. 1519)

> [T]he pointer basis of the apparatus a is chosen by the form of the apparatus-environment interaction: It is this basis which contains a reliable record of the state of the system. S. This in turn determines uniquely those relative states of the system which are correlated with the apparatus. Moreover, apparatus-environment correlations do not allow one to observe the aS combination in a superposition. Instead, it becomes a mixture diagonal in the basis constructed from the pointer-basis eigenstates... and the corresponding relative state of the system.

A caution that's been given above is worth emphasizing at this juncture: while decoherence explains the *apparent* definiteness of pointer positions, it is a separate claim – and one not substantiated by decoherence qua physical process alone – to insist that pointer positions are *truly* definite. The next two sections aim to clarify misunderstandings of decoherence that frequently arise in connection to this point. The first concerns what decoherence has to say about the measurement problem (broadly construed); the second concerns what is meant by classicality, and by the claim that decoherence explains its emergence.

7 Measurement Problem

The fact that decoherence does not solve the (entire) measurement problem has long been understood. As Joos wrote ((Joos, 2000, p. 14)): "Does decoherence solve the measurement problem? Clearly not. What decoherence tells us, is that certain objects appear classical when they are observed." More specifically, if in addressing the measurement problem one is careful to distinguish between a question about general outcomes ("why was the measurement result a definite state?") and a question about specific outcomes ("why was the measurement result *this* definite state?"), it becomes clear that while the former problem can be explained using decoherence, the latter cannot. For if decoherence could explain why a particular measurement yields the specific result it does, this would indicate decoherence contains the means for predicting the outcomes of quantum measurements. In which case we could pack up and go home...but here we remain.

Yet it is too crude to say decoherence does nothing to help alleviate certain longstanding questions often bound up with "the measurement problem".[20] For example, it has just been described how decoherence explains the problem of the preferred basis, and this is so not only in classical regimes but in a wide array of instances captured by the canonical models. It has also been suggested above that decoherence explains why superpositions are not observed in macroscopic systems like Hyperion, despite their intrinsic dynamics.

Consider the "measurement problem" in terms of both specific and general outcomes as applied to Schrödinger's cat. The general question is: why do we always observe the cat to be either alive or dead, and not a superposition thereof (a possible state according to the cat's wavefunction)? The specific question is: why did I just now observe an alive cat instead of a dead cat? As for the first, decoherence explains why the cat always appears to be *either* alive *or* dead: it's because the "alive-dead" basis is most robust under environmental decoherence. Or to put it another way, the interference between the alive state and the dead state is suppressed so effectively by entanglement with the environment that in practice one only *can* measure either the dead or alive eigenstates. But as for the second question, the quantum formalism (and consequently decoherence) alone provide no answer. And this is where various interpretations enter the story.

8 Emergence of Classicality

The issue of the emergence of an apparently classical world from a fundamentally quantum one seems to have found its resolution in decoherence, though to explain exactly how this happens depends not only on the particular system-environment under investigation, but on what one means by classicality. Here are but a few definitions: as Newtonian or quasi-Newtonian motion (characterized by Ehrenfest's theorem; Ehrenfest (1927)), as classical probability distributions or statistical ensembles (characterized by the Liouville regime; more on which below). in which probability distributions are mapped), as the limit $n \to \infty$, as the limit $\hbar \to 0$, and as mass $\to 0$.

These definitions are, individually, inadequate for universally characterizing the mythological "quantum-to-classical" border. That Ehrenfest's theorem provides neither a necessary nor sufficient condition for defining the classical regime is the central thesis of Ballentine et al. 1994. One is tempted too heartily in the case of the Liouville regime to interpret probabilities incorrectly: although in certain cases using Liouville's theorem one can recover a probability distribution identical to a classical statistical distribution, formal similarity does not always entail ontological similarity. Indeed, the quantum Liouville

[20] The scare quotes are meant to signify the ambiguity with which this phrase is frequently deployed. Precision regarding what the perceived problem *is* is paramount for understanding how, and to what extent, decoherence has something to say about it.

equation is a density matrix which, as discussed above, captures fully the statistics of a system's state-space but cannot be given a unique physical interpretation. Defining classicality as the limit where quantum number n approaches infinity will succeed in some but not all cases. This is proven in Messiah (1965) and Liboff (1984), both of whom draw upon the fact that the uncertainty relations set an insurmountable limit upon the assumption of continuous classical energy spectra. Neither will the limiting case of decreasing Planck's constant suffice, as this quantum-classical borderline is in many cases a singularity.[21] The naivety of relying on mass for one's definition of classicality is evident both through examples of massive systems that nevertheless behave quantum mechanically. One such example (given by Joos in Giulini et al. 1996, p. 135) is the Weber bar, which is a tool for measuring gravitational waves. The bar itself must be quite massive (on the order of tons) for the detection of the waves, and yet the sensitivity of the device is such that it must detect displacements on the order of 10^{-21} meters, or approximately 50 billionths the radius of a ground-state Hydrogen atom. As such, the Weber bar must be treated as a quantum oscillator in order to appropriately characterize its behavior, despite its size. Other examples of macroscopic quantum phenomena are the Josephson effect in superconducting (see for example Yu et al. (2002)) and, trivially, the commonplace laser-pointer: the coherent superposition of numerous emitted monochromatic light quanta are the reason such beams retain focus at great distances.

Because none of the usual definitions of classicality are able to explain its emergence from quantum mechanics in full generality, discussions of the quantum-to-classical transition must never stray far from detailed information about specific system dynamics and their interactions with specific environments. Since decoherence models are designed to examine precisely these dynamics in wide-ranging situations, many consider this the most promising approach to the question of emergent classicality.

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[21]See Batterman (1995), Batterman (2002), Berry (1994), Berry (2001) and Bokulich (2008) for fuller discussions of the failure of this approach to classicality.

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