REVIEW

Decoherence: the view from the history and philosophy of science

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We present a brief history of decoherence, from its roots in the foundations of classical statistical mechanics, to the current spin bath models in condensed matter physics. We then analyse the philosophical importance of decoherence in three different foundational problems, and find that its role in their solutions is less than that commonly believed. What makes decoherence more philosophically interesting, we argue, are the methodological issues it draws attention to, and the question of the universality of quantum mechanics.

Keywords: decoherence; dephasing; dissipation; entanglement; irreversibility; universality

1. Introduction

All objects in the Universe interact with each other to a greater or lesser degree. In classical physics, the Hamiltonian \( H_{\text{sys}}(q, p, t) \) that determines the evolution of a local system described by canonical coordinates depends on the actual state \{\( q_{\text{env}}(t), p_{\text{env}}(t) \}\) of the environment. In a statistical description, ensembles of Hamiltonians may be more appropriate because the effect of the environment is treated as ‘uncontrollable perturbation’. Nevertheless, in classical physics, a unique state of the system is still supposed to exist, even though we are dealing with such an ensemble.

In quantum physics, the situation is completely different: there are no definite states of the subsystem; interactions generally lead to a non-separable global state for the whole system; phase relations delocalize extremely fast first into the composite system (system + apparatus) and finally into the total Universe (system + apparatus + environment). This delocalization of phase relations into the environment has come to be known as ‘decoherence’.

Within the standard formalism of quantum theory, the only possible description of an interacting system is by means of a reduced density matrix,

\[
\left( \sum_n c_n |n\rangle |\Phi_n\rangle \right) |E_0\rangle \quad \rightarrow \quad \sum_n c_n |n\rangle |\Phi_n\rangle |E_n\rangle
\]  

(1.1)

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One contribution of 11 to a Theme Issue ‘Decoherence’.
and

\[ \rho_{SA} \approx \sum_n |c_n|^2 |n\rangle \langle n| \otimes |\Phi_n\rangle \langle \Phi_n| \quad \text{if} \quad \langle E_n | E_m \rangle \approx \delta_{nm}, \]  

(1.2)

where \( \rho_{SA} \) yields the same statistics for observables of \( S, A \) or \( S + A \), and these are indistinguishable from the statistics given by a classical mixture. However, we should bear in mind that the formal ensemble of states characterizing the reduced density matrix is not a ‘real’ ensemble in the sense of classical physics. Even if a complete set of density matrices for all subsystems were given, such a description would remain incomplete in an essential way, in contrast to classical physics (where a specification of the state of each degree of freedom implies a complete characterization of the global state). To distinguish between entanglement and lack thereof, we need specific observables of the composite system \( S_n + A + E \) (of which the entangled composite state is an eigenstate).\(^1\) As the number of subsystems \( S_n \) increases, however, this distinction becomes more and more difficult, and for all practical purposes (FAPPs) impossible. Yet even if this distinction is practically hard to attain, quantum theory itself tells us that this is not impossible in principle.

Using cutting-edge technology and ingenious experimental set-ups, for example [5,6], attempts to suppress decoherence in tests of quantum mechanics on the large scale have been going on for many years, but in this article, we will not address these technical details. Rather, we shall concern ourselves with issues more conceptual: from a philosophical perspective, decoherence is often thought as relevant to the solution of some of the foundational puzzles in quantum theory, namely the measurement problem, the ‘quantum to classical’ transition and the (quantum) arrow in time. The purpose of this study is to lay down a brief history of the concept of ‘decoherence’, which has it roots in the foundations of statistical mechanics (SM henceforth), and to analyse its relevance to these three philosophical problems. We will try to show that the role decoherence plays in this context is less instrumental than is commonly believed. To substantiate this thesis, we shall demonstrate that the solutions of each of the three problems either involve additional assumptions and mechanisms or, at least in principle, can be achieved without invoking decoherence.

We next argue that what makes decoherence philosophically interesting is the methodological distinction that it draws attention to, namely, the distinction between what is impossible in practice but possible in principle, in the ongoing attempts to test the universality of quantum mechanics. In particular, in these attempts, one must be able to distinguish between ‘environmental’ decoherence—the delocalization of phase relations in the state of one’s system into the environment owing to interactions with additional degrees of freedom—and ‘intrinsic’ decoherence—sometimes called ‘wave function collapse’, which involves no interaction and signifies the breakdown of quantum mechanics. The former mechanism implies a practical limit to the applicability of quantum theory, one that has to do with the technological capacities of

\(^1\)The inability to distinguish the statistics of a reduced state of a composite system from the corresponding classical mixture with operators whose degrees of freedom are confined to those of the observed system alone was mentioned for the first time in Furry [2] and Schrödinger [3]. The reduced state and the corresponding classical mixture would later be termed ‘improper’ and ‘proper’ mixtures, respectively [4].
the experimenter in controlling her environment; the latter, on the other hand, signifies that the theory’s applicability is limited in principle. To clarify this point further, we draw an analogy between quantum theory and thermodynamics.

2. (A very brief) history

(a) The statistical mechanical roots of decoherence

The idea that a physical system behaves differently when closed or open to interactions with its environment has its roots in the nineteenth century science of thermodynamics, and is commonly attributed to the interventionist school in the foundations of SM. Interventionism is premised on an indisputable fact and on a controversial thesis (for a review and analysis, see [7,8] and references therein). The indisputable fact is that, apart from the Universe as a whole, all systems are ‘open’ to interactions with their environment. The controversial thesis is that this fact is responsible for the normal thermodynamic behaviour of physical systems, namely, their relaxation to equilibrium.

Interventionist ideas appear already in the discussions on the plausibility of the probabilistic assumptions behind Maxwell’s derivations of the velocity distribution and in Boltzmann’s formulation of ergodicity. Maxwell, for example, mentions ‘interactions with the surroundings’ as a possible justification for his equipartition theorem (quoted in Brush [9]), and Boltzmann [10] points out that the special (highly ordered) initial conditions that lead to abnormal thermodynamic behaviour, i.e. to entropy decrease, ‘could be destroyed at any time by an arbitrarily small change in the form of the container’.

While Maxwell and Boltzmann were ambivalent with respect to the character of these external perturbations—they were, after all, working within the framework of deterministic Hamiltonian mechanics—Boltzmann’s advocates in the debate on the validity of his $H$-theorem that took place on the pages of Nature between 1894 and 1895 [11,12] explicitly claimed that random external perturbations led to the desired randomization of molecular motion—a randomization that was at the heart of Boltzmann’s derivation of Maxwell’s velocity distribution. Here is Burbury, an English barrister, who took on himself the task of defending Boltzmann’s views:

Any actual material system receives disturbances from without, the effect of which coming at haphazard, is to produce the very distribution of coordinates which is required to make $H$ diminish, so there is a general tendency for $H$ to diminish, although it may conceivably increase in particular cases, just as in matters political change for the better is possible but the tendency is for all change to be from bad to worse. \[13, \text{p. 320}\]

Several years later, Borel explained why external interventions should be instrumental in the construction of classical mechanical models of thermodynamic phenomena:

The representation of gaseous matter composed of molecules with position and velocities which are rigorously determined at a given instant is therefore a pure abstract fiction; as soon as one supposes the indeterminacy of the external forces, the effect of collisions will
very rapidly disperse the trajectory bundles which are supposed to be infinitely narrow, and the problem of the subsequent movement of the molecules becomes, within a few seconds, very indeterminate, in the sense that an enormously large number of different possibilities are a priori equally probable.\footnote{14, pp. 179–180}

According to Borel, even the gravitational effects resulting from shifting a small piece of rock with a mass of one gram as distant as Sirius by a few centimetres would change the \textit{microscopic} state of a gas—the positions and momenta of its molecules—in a vessel here on Earth within a fraction of a second after the retarded field of force has arrived, thus altering the trajectory of gas in phase space. In most cases, such perturbations are negligible, but they can have dramatic consequences for a system whose dynamics are \textit{unstable}. Berry \footnote{15, p. 95} has calculated that an electron in the limits of the observable Universe will disturb the motion of two colliding oxygen molecules here on Earth to the extent that predictability of the motion would be lost after 56 collisions. Berry notes that we should not go as far as the end of the Universe. Even a medium-sized billiard player situated 1 m from a billiard table would do the same for two elastic billiard balls after nine collisions.

Note that Boltzmann and Borel both limit the effect of the external intervention to the instability of those initial microstates that lead to abnormal thermodynamic behaviour. However, it seems unfair to bring external perturbations as \textit{deus ex machina} to save the foundations of SM and then neglect them in the subsequent dynamics. Interventionist models that have appeared in the 1950s have subsequently modified the \textit{dynamics} of thermodynamic systems to include random external perturbations,\footnote{2Famous milestones after Borel’s calculation are the spin echo experiments \cite{16} and the subsequent models they initiated \cite{17,18}. A revival of this approach within the foundations of SM has been recently championed in earlier studies \cite{19–21}, and discussed in Sklar \cite{22}.} arguing that these perturbations are absolutely necessary for the construction of realistic mechanical models for thermalization:

\begin{quote}
Statistical mechanics is not the mechanics of large, complicated systems; rather it is the mechanics of limited, not completely isolated systems. \footnote{18, p. 749}
\end{quote}

In such models, one can demonstrate, e.g. that just by taking into account the walls of a container in which a gas approaches equilibrium, one can achieve realistic time scales for this process. The counterfactual claim, however, that ‘without’ external intervention, physical systems would not relax to equilibrium remains unsubstantiated.

\subsection*{(b) Quantum theory}

The interventionist attitude towards the role of the environment in the behaviour of an observed physical system is prevalent in the foundations of quantum mechanics too. The earliest evidence for it is Mott’s famous remark:

\begin{quote}
The difficulty that we have in picturing how it is that a spherical wave can produce a straight track arises from our tendency to picture the wave as existing in ordinary three dimensional space, whereas we are really dealing with wave functions in the multispaces formed by the co-ordinates both of the $\alpha$-particle and of every atom in the Wilson’s chamber. \footnote{23, p. 79}
\end{quote}
But one can find it also in, e.g. von Neumann’s famous division of quantum processes to unitary and non-unitary in the context of the analysis of the measurement procedure [24], or in Schrödinger’s and Furry’s remarks on the Einstein, Podolosky and Rosen thought experiment [2,3], where the inability to distinguish the statistics of a reduced state of a composite system from the corresponding classical mixture with operators whose degrees of freedom are confined to those of the observed system alone is mentioned for the first time.

von Neumann’s treatment and his thermodynamic analogies, as well as a similar discussion on the measurement process by were followed in the 50s and early 60s by Ludwig [26] and Born & Ludwig [27], Green [28] and, more famously, by Hugh Everett’s PhD dissertation—published only in 1973 [29])— in which the interaction with the environment plays a key role in the formalism. The unifying theme in these papers was that, analogous to thermalization, environmental dephasing (the delocalization of phase factors to the environment) would destroy large-scale quantum behaviour.

One domain in which the statistical mechanical roots of decoherence played a constitutive role is nuclear magnetic induction. Starting with Bloch [30], and following Hahn’s spin echo experiments [16], two relaxation times—the first, called $T_1$, owing to energy dissipation and thermalization, and the second, called $T_2$, owing to dephasing—were defined, studied and carefully distinguished:

The transversal relaxation time $[T_2]$ can be many orders of magnitude smaller than the longitudinal time $[T_1]$ and [...] serious errors may be committed by assuming $T_1 = T_2$. There are, on the other hand, also cases where this equality is justified, particularly those where both relaxation times are due to impacts which last during a time short compared to the Larmor period, so that the distinction between collisions change the spin energy and those which leave it unaltered becomes immaterial. [30, p. 468]

This important distinction notwithstanding, in 1962, Daneri, Loinger & Prosperi (DLP henceforth) published an article [31] in which the measurement process is modelled as an irreversible thermalization. The DLP paper was strongly criticized by Bub [32], and prompted a German nuclear physicist, H. D. Zeh, to suggest [33] an alternative research programme to thermalization that would dynamically explain why macroscopic superpositions are never observed.

(c) Condensed matter: oscillator bath

These early treatments of the interaction of a quantum system with its environment, necessarily leading to dephasing, were confined to discussions on the foundations of quantum theory, and in particular, to discussion on the notorious measurement problem, involving only simple, almost toy, models. For this reason, it seems that working physicists paid little attention to them (in effect, most of the earlier-mentioned discussions were published in journals such as Nuovo Cimento and Foundations of Physics, clearly not the mainstream physics journals at that time). But in the beginning of the 1980s, the situation changed. The now well-known work of Leggett et al. [34–36] demonstrated that in fact one could expect superconducting quantum interference devices (SQUIDs) to show quantum tunnelling and interference properties at the macroscopic scale, and that, moreover, one could test quantum theory at the macroscopic scale in this...
way. The shift from qualitative theory and crude models to precise experimental designs, quantitatively testable in many domains, as well as the rebuttal of the prevalent view about the ubiquity of environmental dephasing, drew a lot of attention, and completely changed the nature of both the scientific and the philosophical debates.

To model the environment Leggett et al. used a general representation of an ‘oscillator bath’. This representation was described first in a paper from the 60s [37], and qualitatively resembles a much earlier treatment of the environment—in the context of classical SM—by Planck [38]. As Stamp [39] notes, these models clearly lend themselves to problems in particle and string physics, quantum optics and cosmology, and they are also often used in condensed matter systems at low temperatures, but the decoherence rates they predict do not agree with those measured in solid-state systems. This discrepancy led experimentalists to search for a better fit with other models.

(d) Condensed matter: spin bath

The oscillator bath models, used in the work of Leggett et al., describe some of the low-energy modes of the environment, and usually break down at higher energies. Robust and general as they are, these models nevertheless infer the quantum dynamics from an effective quantum Hamiltonian whose form is derived from the observed classical or quantum behaviour. In this approach, the environment is modelled with delocalized, extended states, i.e. wave-like oscillations of some background field, and so the strength of the effective coupling between the system and the environment decreases with energy. This decrease is a general feature of such a model of the environment’s states, whose density always goes down with energy because of decreasing available phase-space volume—there are simply fewer oscillator modes at lower energies (see Stamp [39] for more details). This means that at lower energies and temperatures close to zero, one may expect decoherence rates to also decrease.

In recent years, advances in condensed matter physics and the attempt to describe real many-body quantum systems at low energies have led to the development of alternative models, generally called ‘spin bath’ [41]. In these models, the environment is represented by localized modes. Spin bath models reduce back to the model of delocalized environmental modes of the oscillator bath when, e.g. the interaction between the spins is very strong, but in general, they form a very different background. In particular, the spin bath modes of the environment tend to cluster at low energy; so they dominate decoherence, even in systems that are almost pure. Another, separate, feature of these models is that they predict decoherence with very little dissipation, and so would mostly be ignored by experiments that focus on thermalization and energy transfer (e.g. tunnelling experiments), and would become rather obvious for experiments that probe quantum coherence.

3As an anonymous referee remarks, decoherence is still possible within such models even in $T = 0$, owing, e.g. to the emission of radiation into the vacuum, or to correlations between subsystems, as is evidenced by the Unruh effect [40], where observers of a subregion of space in the vacuum state see a highly incoherent thermal state.

Phil. Trans. R. Soc. A (2012)
These differences between the two types of models are evident in the decoherence mechanism they portray. In the oscillator bath models, the main assumption is that the bath modes and the system are only weakly coupled, so that the environment as a whole is not perturbed by the system, in the sense that the total change in the bath’s temperature or in the oscillator distribution function is small. On the other hand, while each oscillator couples only weakly to the system, the system can be strongly affected by the combined effect of all the bath modes. Decoherence (and its thermodynamic analogue, dissipation) both arise here from energy exchange between the system and the bath. This connection between dissipation and decoherence is one of the most remarkable results of the oscillator bath model.

In contrast, in the spin bath models, the system and the environment are strongly entangled, and—instead of energy—they both exchange phases. This means that decoherence resulting from a spin bath may proceed almost in the absence of environmental noise (though there is always some—albeit very small—dissipation), and that one can expect spin bath decoherence to dominate over oscillator bath decoherence at low temperature. In particular, there is no reason to expect it to decrease, even as $T \to 0$. This feature of ‘quantum noise’ has serious practical implications on the question of the feasibility of fault-tolerant and large-scale quantum computers [42].

Cursory as this historical sketch of the development of the concept of decoherence is, it nevertheless emphasizes the importance of understanding the sources of decoherence. This understanding is crucial to many experimental tests of quantum mechanics on the large scale, and, as we shall see, it is from here the main philosophical lessons from decoherence should be drawn. But before we develop this point further, let us discuss other philosophical issues to which decoherence is thought to be relevant.

3. Philosophy

(a) The quantum measurement problem

The birth of the concept of decoherence lies—both historically and conceptually—within the foundations of SM. Its penetration into quantum theory was mainly in the context of the coupling of the system to a measurement apparatus. In particular, the FAPP irreversible delocalization of phase relations into the environment, and the description of the observed open system with a reduced density matrix whose statistics is FAPP indistinguishable from a classical mixture, makes it tempting to connect decoherence with the quantum measurement problem. In fact, in many popular expositions of decoherence, e.g. Zurek [43], and even in more sophisticated treatments within quantum information theory [44], the claim is being repeated that decoherence actually solves the measurement problem. Now, does it?

Let us recall what this problem is all about. In its essence, the quantum measurement problem is a problem of theoretical completeness, namely, a theory (in our case, quantum theory) predicts certain phenomena (in our case, interference phenomena) that are nevertheless never observed for certain physical objects (in our case, macroscopic massive objects), which raises the obvious question whether the theory is complete. To solve this problem, several
alternatives to the theory were presented [45–47]. All these alternatives reproduce the predictions of quantum theory in all the experiments we have empirical data on so far, and one of them also gives different predictions in experimental set-ups yet to be tested, but they all share the same feature, namely they aim to complete quantum theory by dynamically explaining how measurement results come about.

The first two ‘no-collapse’ alternatives [45,46] keep the (deterministic and unitary) Schrödinger dynamics unaltered, and hence do require decoherence in order to give sense to their kinematical picture, i.e. to make sense of the one-time probability they assign to any given macroscopic state. Such a requirement is not necessary in the alternative ‘collapse’ theory [47], which alters the Schrödinger dynamics, as the one-time probabilities it assigns are regarded as transition probabilities and thus result naturally from the altered dynamics. But note that in the first case, decoherence is not sufficient to solve the measurement problem because it must be accompanied by a detailed dynamical account of the measurement process, given by the respective alternatives to quantum theory. So, decoherence alone, without any alternative to quantum theory, does not solve the problem.

In the case of the third, ‘collapse’, alternative, decoherence may still be instrumental, but its importance shifts from the philosophical to the practical: if one is willing to entertain collapse, or ‘intrinsic decoherence’ (see Stamp [48]), then the measurement problem is solved regardless of environmental decoherence, but here we trade one problem for another, and the different problem to which decoherence becomes relevant now is the problem of distinguishing ‘true’ from ‘false’ collapse [49]—real collapse due to some intrinsic mechanism, from apparent collapse owing to ‘noise’ or environmental interaction. In other words, the issue shifts from the philosophical question about interpretation to the empirical question about the universality of quantum theory. We shall say more on this issue later.

The relevance of decoherence to solving the measurement problem is even more questionable in the quantum information theoretic view, where measurement results are taken as primitive, and do not require any further dynamical analysis [44]. Here, the measurement problem does not arise by fiat; one simply ignores it and accepts measurement results as primitive brute facts to which no explanation—let alone dynamical explanation—is required. On this view, the quantum state is regarded as an epistemic construct, a catalogue of knowledge, and the Hilbert space supplies the kinematical space for those primitive measurement events (analogously to Minkowsky’s space–time and the space–time events thereon). Decoherence is summoned here to explain the emergence of an effectively classical probability space of macro-events to which the Born probabilities refer. As we shall see later, this effectiveness could also be explained otherwise, without decoherence, and so on both counts—the kinematical and the dynamical—the problem is solved, by fiat or not, regardless of decoherence.

(b) The ‘emergence’ of the classical world

In many of the popular presentations of decoherence [43,50], and even within the decoherence programme itself [1], one finds the claim that decoherence is
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responsible for the ‘emergence of the classical world’. What one means by ‘the classical world’ remains mostly vague, but as a minimum requirement, one could at least ask for an effective classical behaviour of macroscopic objects that generally presents no interference.

The delocalization of phase relations into the environment is indeed a feature of decoherence, and the inability (in practice) to re-interfere two macroscopic quantum states can be regarded as fulfilling the requirement for effectiveness. However, if the question is why we do not observe massive macroscopic objects in entangled states, then a dynamical explanation that involves decoherence is but one possible option. One can also give a combinatorial, non-dynamical, story [51], similar to the one that was given by Boltzmann in the foundation of SM for the ubiquity of ‘normal’ thermodynamic phenomena, according to which, as the size of the system under investigation grows, we need an ever more precise knowledge of the state and an ever more carefully designed experiment, in order to recognize entanglement of massive macroscopic bodies. This increasing ‘rarity’ of witnesses for entangled states of massive macroscopic objects—operators that can reveal entanglement and distinguish separable from non-separable states [52]—can be proved under some additional assumptions that may require further justification and may look suspect (e.g. an assumption about the equiprobability of possible experimental arrangements), but at least it serves to show, again, that decoherence is not the only game in town as an explanation for effective classical behaviour: even if it could be ‘turned off’, under the combinatorial view here mentioned, we would still not be able to recognize massive macroscopic objects in entangled states.

To put this point in a more historical context, the combinatorial approach is non-dynamical, and as such it, resembles Khinchin’s famous approach to the foundations of SM [53]. One may strive for a dynamical explanation for the relaxation to equilibrium, says Khinchin, e.g. invoking ergodicity and mixing, but if the purpose of SM is to reproduce the thermodynamic functional relations, then such a project is an overkill. In a similar vein, decoherence, as a dynamical explanation of ‘the emergence of the macroscopic world’, is not forced upon us: there is an alternative, non-dynamical, explanation or a consistency proof, for the unobservability of quantum coherence in massive macroscopic objects, and in this strict sense, i.e. if all we are looking for is an explanation for this unobservability, then there exists an alternative to decoherence.4

That decoherence is not sufficient for the emergence of classicality is evident in the fact that, again, it must be supplemented with an ontological account of what this world consists of. That phase relations decohere and therefore a classical world emerges is an incomplete statement; it presupposes that the wave function alone is sufficient to account for the result of any measurement. But the wave function lives in a high-dimensional configuration space, and so to complete such an account of the emergence of the classical world, one must add particles, i.e. localized objects in low-dimensional space-time, into the ontology [55], and supply

4Note that recent results in observing SQUIDs, e.g. Chiorescu et al. [54], do not suffice to falsify the combinatorial story, as the entanglement observed there, albeit macroscopic and involving many particles, is of magnetic fluxes, and not of massive objects. These results serve, however, to constrain the combinatorial research programme by narrowing the set of appropriate entanglement witnesses.
these with an appropriate dynamics. Our everyday classical world, after all, is not composed of wave functions, not even of wave functions whose branches have decohered, and is not depicted in multi-dimensional configuration space. Rather, or so the story goes, it is composed of particles whose dynamics is depicted in space-time, and both accounts require more than lack of interference.

Failure to recognize this fact leads to a kind of epistemic incoherence: on the one hand, one would like to have empirical confirmation for one’s theory; on the other hand, if the ontology of one’s theory is limited to the wave function alone, it falls short of postulating the basic ingredients such a confirmation relies on.

(c) The quantum arrow in time

Another received view is that decoherence is responsible for the (quantum) arrow in time [56] because it involves, for all practical purposes, an irreversible process, similar to dissipation. Here, our historical prelude becomes important, as this view of decoherence shares a common mistake with the interventionist approach to the foundations of SM, from which it stems.

That many things are easier to do than to reverse has been known to mankind from time immemorial. In contrast, the fundamental laws of physics are believed to be indifferent to the directionality in time, allowing in principle such a reversal. One of the great challenges to mathematical physics in the twenty-first century is thus to construct a rigorous mathematical derivation of equations that describe irreversible behaviour, e.g. Fourier’s law of heat conductivity, from a classical or quantum model with a Hamiltonian microscopic dynamics [57]. In this respect, the fundamental question with which the founding fathers of the kinetic theory struggled in the second half of the nineteenth century remains open: can a reversible and deterministic dynamics fully explain the behaviour of macroscopic matter?

The premise behind the interventionist school in the foundations of SM is that a positive answer to this question requires acknowledging an undeniable fact, namely, that all physical systems are ‘open’, in the sense that they interact with their environment. On this view, external noise is regarded as necessary for the validity of thermodynamics, and in particular for the process of thermalization; if this noise is removed, no such process can take place. The problem, of course, is that while the dynamics of the system is altered by the noise, the total dynamics (of the system + the environment) is still time-reversal invariant, and so (i) we can—at least in principle—reverse the noise and (ii) we must rely on initial conditions to explain irreversibility in this background.

If we now make the analogy from thermodynamics to quantum mechanics (or from thermalization to decoherence), we find that this twofold problem persists. The point here is that while the dynamics of the reduced density matrix is not time-reversal invariant, the dynamics of the total system is still unitary and reversible. This means that (i) the perturbations (or noise)—responsible for irreversibility—can be reversed, and so the reason for the observed irreversibility is the practical inability to control all degrees of freedom of the environment and (ii) if the initial conditions in the Universe that are responsible for decoherence (namely that the system’s Hamiltonian and the environment’s Hamiltonian form a tensor product) are such that the wave function of the total, composed, system formations.
would one day re-cohere, then it will re-cohere, no matter what the dynamics of the reduced density matrix is, which means that the sole culprit behind the observed irreversibility are these initial conditions.

Consequently, we find again that—according to (i)—decoherence is not sufficient as an explanation of the quantum arrow in time, and that—according to (ii)—it is also unnecessary. The latter verdict should not be surprising, given the lesson learned already within the foundations of SM that if one wants to explain irreversibility with time-reversal-invariant dynamics, one must invoke initial conditions.

(d) Upshot

The upshot of this brief discussion is that decoherence as a physical concept—important as it may be to the solutions of the three problems here mentioned—is less instrumental to them than that commonly advertised, at least to the extent that it needs to be (and in some cases also is) supplemented with additional explanations. What I would like to draw attention to next, however, is another question to which decoherence is actually crucial. This empirical question is the question of the universality of quantum theory, and the arena for answering it is not the armchair, but the laboratory.

4. Methodology

(a) The decoherence double bind

Schrödinger is famous for, among other things, coining the term ‘entanglement’, and for singling it out as ‘not one but rather the characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought’ [58]. Tests of entanglement are thus tests of quantum mechanics. Those have been formulated and performed for almost four decades now, mostly in the context of Bell’s inequality [59], and in some cases Marciki et al. [60], have shown entanglement to persist over many kilometres (thus refuting the idea—once voiced by Schrödinger himself—that entanglement may weaken with distance). None of these tests, however, has involved a large number of particles; rather, they have involved small molecules or a few entangled photons or ions.

Tests of quantum mechanics on the large scale have been suggested within the framework of Leggett et al. that involve superconductors with a large number of particles, and experiments have verified the predictions of that model to a remarkable degree of accuracy [61]. More recently, macroscopic coherence of SQUIDs was found [54], but although baby steps have been made in this direction [62], at least to the knowledge of the author, entanglement of massive macroscopic objects—the elusive ‘Schrödinger cat’—has never been observed. The reason, many believe, is decoherence.

Decoherence, however, is not only the ‘inverse’ of entanglement; it is also—as far as we know—a result of entanglement. We thus find ourselves in an interesting double bind: on the one hand, we would like to confirm the universality of quantum mechanics, extending its validity from the well-tested microscopic scale to the yet-to-be-tested macroscopic scale; on the other hand, what stands in our
way of doing so is exactly this universality, namely, the fact that entanglement persists also in the macroscopic scale and leads to decoherence, which in turn prevents (or at least makes it difficult to) testing quantum mechanics.

Another way to see this double bind is this. Suppose that crucial experiments similar to those which are being carried out under Leggett’s research programme, which are capable of distinguishing between, say, intrinsic decoherence such as the mechanism proposed in the collapse alternative to quantum theory known as the Ghirardi, Rimini and Weber (GRW) theory [47], and environmentally induced decoherence, were to come out in accordance with the predictions of the GRW theory—and not with those of quantum theory—to a very good approximation. Nevertheless, it is often argued that standard non-relativistic quantum mechanics would remain intact for the following reason.

Let us suppose that an open system \( S \) is subject to perfect decoherence, namely, to interactions with some degrees of freedom in the environment \( E \), such that the states of the environment become strictly orthogonal. Suppose further that we have no access whatsoever (as a matter of either physical fact or law) to these degrees of freedom. In this case, the GRW dynamics for the density operator of \( S \) would be indistinguishable from the dynamics of the reduced density operator of \( S \) obtained by evolving the composite quantum state of \( S + E \) unitarily and tracing over the inaccessible degrees of freedom of \( E \). It turns out that this feature is mathematically quite general because the GRW dynamics for the density operator is a completely positive linear map [63,64]. From a physical point of view, this means that the GRW theory is empirically equivalent to a quantum mechanical theory with a unitary (and linear) dynamics of the quantum state defined on a larger Hilbert space. In other words, one could always introduce a new quantum mechanical ancilla field whose degrees of freedom are inaccessible, and cook up a unitary dynamics on the larger Hilbert space that would simulate the GRW dynamics on the reduced density operator. Therefore, experimental results that might seem to confirm GRW-like dynamics could always be re-interpreted as standard quantum mechanics on larger Hilbert spaces.

Now, there is little merit in claiming that a theory cannot be proved wrong, as this also means that it cannot be proved right: one of the features of quantum mechanics is that it purports to describe the world as it is, and so one would not only have to show that those additional degrees of freedom with which the system interacts could explain the evolution of that system, but that those additional degrees of freedom actually exist as independent physical entities, which means that understanding the source of decoherence and its mechanisms is extremely important to physicists and philosophers alike:

[No experiment purporting to test quantum mechanics, according to any of these scenarios, can afford to ignore disagreements between experimental and theoretical decoherence rates; these are no longer a question of detail. One certainly cannot treat any disagreement as a ‘dirt’ or some other uncontrolled extrinsic effect. This would automatically dismiss any real breakdown of quantum mechanics as a dirt effect and make tests of large-scale quantum mechanics impossible in principle. [39, p. 489]

\( b \) An analogy with thermodynamics

Quantum mechanics has been tested again and again, and has never been found wanting. But suppose that, as a matter of fact, the theory is not universal,
and applicable only up to a certain scale. Some physicists might regard this as blasphemy, but non-universality of this sort is not unheard of in the history of physics. Consider thermodynamics. The theory is widely applicable in large—some may say even cosmological—scales, but at least one of its postulates, namely the second law, is regarded only as a statistical generalization, the validity of which in the small scale is kept intact because of practical reasons alone.\(^5\) Quantum mechanics, on the other hand, is widely applicable in the small scale, but, for all that we know, its validity in the larger scale might as well be limited \textit{in principle}. As in the case of thermodynamics, it may appear that the theory is valid on all scales simply because of practical reasons. The analogy here goes even further: the \textit{in principle} limitation to the applicability of both theories is consistent with the view that, so far, both have been protected from direct experimental refutation by the practical inability—sometimes called ‘coarse graining’—to control certain degrees of freedom. In thermodynamics, these degrees of freedom pertain to the system at hand; in quantum mechanics, they pertain to the environment that surrounds it.

We thus arrive to the final point of this study: another reason to view decoherence as a subject matter worthy of philosophical investigation is the methodological distinction that it draws attention to, namely the distinction between what is impossible \textit{in practice} but possible in principle—in our case, the isolation of one’s system from environmental noise, be its origin in oscillator baths or spin baths—in the ongoing attempts to test the universality of quantum mechanics. Failure to acknowledge this distinction, or attempts to blur it, results in an untenable scientific position: if one argued that systems are always ‘open’ as a matter of principle, and that any disagreement between experiment and the decoherence rates predicted by environmental models is just ‘noise’, then one would end up turning quantum mechanics into an unfalsifiable theory, true by fiat, no matter what.

\section{Conclusion}

Decoherence is an important quantum phenomenon that carries wide applications, both theoretical and experimental. Owing to its roots in the foundations of SM, philosophical discussions on decoherence focused so far on its alleged relevance to foundational problems such as the quantum measurement problem, the emergence of the classical world and the problem of irreversibility. In this study, I have argued that decoherence is less instrumental to the solutions of these problems than one might believe. Furthermore, I have tried to draw attention to another question to which decoherence is crucial, namely the question of the universality of quantum mechanics. In the context of this question, there exists an interesting methodological double bind that decoherence saddles us with, representing as it does both the universality of the theory and the difficulty in testing such a universality. Only a better acquaintance with the mechanisms that underlie decoherence can free us from this double bind, as they will allow us to shield physical systems from it, and thus to test quantum mechanics on larger

\(^5\)See the recent discussions in the philosophical literature on the consistency of Maxwell’s demon with Newtonian and statistical mechanics [65].

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and larger scales. Such tests might help us solve some of the earlier-mentioned foundational problems; or they might raise more, unforeseen, ones. But this is what makes science so exciting: one can never know a priori what nature is like.

References

11 Culverwell, E. P. 1894 The kinetic theory of gases. Nature 51, 78–79. (doi:10.1038/051078b0)
13 Burbury, S. H. 1895 Boltzmann’s minimum function. Nature 51, 320. (doi:10.1038/051320a0)


