The Role of Decoherence in the Foundations of Quantum Mechanics*

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*These transparencies differ in two main respects from the ones used in Vancouver: (a) they include revisions prompted by questions or discussion in Vancouver, partly in the text but mostly in the form of remarks in small type; (b) they are typed rather than being a sample of my awful handwriting. A full version of this paper (including references) will appear in the on-line Stanford Encyclopedia of Philosophy (http://plato.stanford.edu/).

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Structure of the talk:

- Introduction
- Decoherence and its possible role in foundations
- Role of decoherence in:
  - GRW
  - Bohm
  - Everett
  - Modal interpretations
- Concluding remarks

1 Introduction

Theory of decoherence: study of spontaneous interactions with environment that suppress interference.

'Suppress interference': phase relations are *not* destroyed, but now well-defined only for larger system.

For this reason, claims that *simultaneously*

- the measurement problem is real
- decoherence solves it

are confused at best.

Remark: The measurement problem is not that e.g. by looking at a measurement device at the end of an experiment we think that we are performing an interference experiment between the different pointer states and are surprised that we see no interference effects. Decoherence would explain that. Instead, the measurement problem is that the possibility (in principle) of doing an interference experiment shows that the apparatus is described by none of these pointer states [just as the (easily realisable) possibility of doing an interference experiment in a two-slit set-up shows that the electron is not described by wave functions that go through one or the other slit]. Decoherence does not affect this possibility. But if the apparatus does not exhibit definite readings (in the sense of being described by these definite pointer states), why does it appear to exhibit definite readings (in the everyday sense of the word)?

Thus, the motivation for foundational approaches (GRW, Bohm, Everett, modal...) is unchanged.

Question: is decoherence nevertheless important to these approaches?

Answer: it can indeed play a useful role, partly depending on which approach.

(In the lab, decoherence may be your enemy; in foundations, it may be your friend!)

Remark: Approaches to the foundations of quantum mechanics can range from largely or purely physical (e.g. modifications of the Schrödinger equation) to largely or purely interpretational (e.g. interpreting the wave function as describing 'many worlds'). Common usage is loose, but the term 'approach to the foundations of quantum mechanics' is thus more accurate than the term 'interpretation of quantum mechanics'.

2 Decoherence and its possible role in foundations

Our focus: theory of decoherence.

Not our focus: decoherent histories.

Remark: There are controversial claims about the latter as a foundational approach in its own right. Stripped of controversial claims, it is an interpretationally neutral abstract framework that can be useful as a language for describing situations of suppression of interference.

Features of special interest in decoherence:

- shortness of decoherence times
- preferred sets of states
- robustness of preferred states
- localisation
- analogy with measurements (environment monitors the system)
- redundancy of information in environment
- trajectories at the level of preferred states
- classicality of trajectories

In particular, localisation and classicality of trajectories lead to claims about the emergence of classical behaviour from quantum mechanics.

Example: quantum chaos as discussed by Zurek.

- No chaos for pure states if evolution is unitary;
- at the level of components perfectly compatible with unitary evolution of the total system (and explicitly modelled)

Remark: None of these features are claimed to obtain in all cases of interactions with an environment. It is a matter of detailed physical investigation to assess which systems exhibit which features, and how general the lessons are that we might learn from studying specific models. In particular, one should beware of overgeneralising any conclusions: for instance, it now seems that it is possible to sufficiently shield SQUIDS from decoherence for the purpose of observing superpositions of different macroscopic currents.

Decoherence is relevant (or is claimed to be relevant) to a variety of questions.

We wish to focus on the possible relevance to questions in foundations.

Paraphrasing Bohr, the 'existence of the classical world' is a precondition for us defining, doing and in fact discovering quantum mechanics.

Thus, any foundational approach that considers quantum mechanics (or any proposed variants) to be applicable to the entire universe, *must* explain the emergence of the classical world.

Remark: From this point of view, the measurement problem is a case where quantum mechanics appears to be incompatible with a feature of the classical world, namely definite measurement results, that is crucial in setting up quantum mechanics in the first place.

One of our main questions will thus be: can foundational approaches use decoherence to explain the emergence of the classical world (*modulo* detailed physical questions about the generality of the results)?

Problem?

- Any classicality is at the level of components.
- Re-run of the measurement problem!
- Indeed, it makes the problem *more* general: even normal macrosystems (not just measureing apparatus) get entangled with other quantum systems.
- The everyday world is full of Schrödinger kittens!

Turning the tables around:

- Approaches to quantum mechanics take superpositions containing different pointer states (or live/dead states of a cat), and try to get definite pointer readings one way or another (new physics, new interpretation, both).
- Apply these approaches to superpositions containing trajectories of classical-like states. Do we get definite classical trajectories?

As it turns out, the answer is somewhat different for different approaches. Decoherence may be relevant but more or less crucial (GRW, Bohm, Everett), or an approach may fail to explain classicality in the presence of decoherence (some modal interpretations)

3 Decoherence and GRW

Let A_x be multiplication with a (real) Gaussian with centre x and some width a.

A particle spontaneously collapses at random times ($\sim \tau$):

$$|\psi\rangle \mapsto \frac{1}{\langle\psi|A_x^* A_x|\psi\rangle} A_x|\psi\rangle$$

with probability density in x given by $\langle\psi|A_x^* A_x|\psi\rangle$.

($\int A_x^* A_x dx = \mathbf{1}$, i. e. the $A_x^* A_x$ form a POVM.)

Original GRW theory: independent processes for each particle (given a and τ leading to desired macroscopic effects). Later modifications: (a) tied to mass density, (b) continuous spontaneous localisation (Pearle).

Particles undergo spontaneous approximate position measurements. Formally (esp. mass density version) much like in some of the models of decoherence.

But:

- 'True' collapse: only one component survives.
- No interaction with any environemnet involved.

Remarks: From this evolution for the state vector one can derive the evolution for the density matrix, which may be mathematically convenient (e.g. linear), but not equivalent to it!

In the version that uses mass density there are further speculations that the collapse might be tied to gravity. These speculations are inessential to the theory, but will be important to our discussion below.

Can decoherence be put to use in GRW?

In those situations in which decoherence is also describable in terms of approximate position measurements performed by the environemnt, there are two cases:

(1) when GRW collapse is faster than suppression of interference, the latter becomes irrelevant;

(2) when suppression of interference is faster than GRW collapse, the collapse selects ‘classical structures’ already prepared by decoherence.

Quantitative comparisons in fact yield (2) in many cases, so that decoherence does play an active role also in GRW.

Remark: In those situations in which decoherence is described in terms other than approximate position measurements, i.e. selects states defined other than in terms of localisation (e.g. currents in a SQUID), one can imagine either: (a) collapse kicking in when applied to the environment (records in the environment have different localisation properties), leading to a situation similar to (2); or (b) collapse and decoherence pulling in different directions.

Relevance to experimental tests of GRW:

Assume that alternative approaches to QM (e.g. Bohm, Everett) can explain the appearance of collapse using decoherence. Then an experiment in which GRW predicts collapse and standard QM predicts 'merely' suppression of interference will not distinguish between GRW and standard QM.

Only experiments in which GRW predicts collapse and standard QM predicts *no* suppression of interference will do, i.e. need situations of type (1) (or possibly (b)), which are typically difficult to realise.

One disastrous scenario for experimental testability:

(True) collapse is indeed tied to gravity, but one expects *exactly* the same (apparent) collapse from decoherence because gravitation is quantised

(e. g. a terrestrial experiment could not be shielded from decoherence, while in an orbiting experiment no GRW collapse could be expected either!)!

Remark: B. Kay takes what he describes as conservative assumptions about what the low-energy limit of quantum gravity might look like, and obtains decoherence effects remarkably similar to the GRW collapse.

4 Decoherence and the Bohm theory

De Broglie 1927:

Modify Hamiltonian mechanics. Action S becomes the phase of a wave.

$$\mathbf{p}_i = \boldsymbol{\nabla}_i S(\mathbf{x}_1, \ldots, \mathbf{x}_n)$$

Non-Hamiltonian theory of particles in motion. How to get:

- collapse, uncertainty, EPR correlations?
- Hamiltonian motions?

Remark: Since the theory is first-order (momentum not a free variable), possible trajectories cannot cross, so trajectories are qualitatively different from Hamiltonian ones, and the problem of the 'classical limit' is highly non-trivial (as emphasised by Holland).

Bohm 1952:

Apply to measurements. Wave of system and apparatus separates into non-overlapping components in configuration space:

- the particle is 'trapped', only one component guides its motion;
- effective collapse.

From this follow already: uncertainty (qualitatively) and (perfect) EPR correlations.

Remark: The quantitative aspects of the theory concern the use of $|\psi|^2$ as particle distribution. The justification of this 'equilibrium' follows the analogous discussion in classical statistical mechanics (and is equally hotly debated).

Later variants:

Use different notion of configurations: fermion number density (Bell), fields (Valentini) etc.

Decoherence?

Idea: apply Bohm's analysis to 'spontaneous position measurements' by the environment.

If there is separation in configuration space, particles will be 'trapped' inside the localised components and will follow approximately Hamiltonian trajectories.

(That is, the *same* strategy would recover both quantum and classical phenomena!)

Would explain also why Bohm works in position representation and not, say momentum. (In later variants: decoherence as criterion for choice of correct configuration space?)

idea seems plausible but needs working out.

Appleby (1999): partial results (under special assumptions).

Allori (2001): classical limit as geometric optics limit; decoherence is crucial in *maintaining* classical behaviour, which otherwise would break down (as soon as classical S becomes multi-valued).

5 Decoherence and Everett

Closest to views of practitioners of decoherence (esp. Zeh, also recent papers by Zurek).

'Purist' Everett:

Just take the universal $|\Psi\rangle$. Reinterpret the superposition of components as describing coexisting 'worlds' in the one universe. No modification of the Schrödinger equation, no additional variables, no need for non-locality (arguably). Price to pay: personality splits.

Questions:

- which components correspond to worlds ('preferred basis problem')?
- meaning of probabilities?

(Partial?) solution to preferred basis:

natural to identify worlds with trajectories of decoherence (e.g. S. Saunders).

Meaning of probabilities:

more to be done (I believe), but taking over worlds from decoherence gives at least well-defined frequencies along worlds.

Zeh ('many-minds interpretation'):

von Neumann introduced collapse to save psycho-physical parallelism. In a decohering no-collapse quantum universe one needs to introduce a *new* psycho-physical parallelism, in which individual minds supervene on non-interfering *components* of the wave.

Zurek ('existential interpretation'):

robust states have 'relatively objective existence'. Observers use redundant information in the environment. Since they possess different information, they *are* different observers.

6 Decoherence and modal interpretations

Van Fraassen: ‘constructive empiricism’, aim of science is empirical adequacy (not truth).

QM without collapse and with ‘Dirac-von Neumann rule’ (system has a property iff the quantum probability is 1) is *not* empirically adequate.

Therefore change the Dirac-von Neumann rule. To say that the state is ρ at time t means to give a catalogue of *possibilities* for the properties of the system at t, namely all properties corresponding to any pure $|\psi\rangle$ in *any* decomposition of ρ.

Empirical adequacy:

$$\frac{1}{2}(|\text{pointer up}\rangle\langle\text{pointer up}| + |\text{pointer down}\rangle\langle\text{pointer down}|)$$

is compatible with both ‘pointer up’ being true and ‘pointer down’ being true (i. e. with our empirical evidence).

Very *modest* approach: no extra theory, no extra dynamics (possible ‘histories’ are sequences of single-time possibilities).

Decoherence guarantees having possibilities that look classical (and indeed contain records of sequences of measurements with the right frequencies).

Solves the measurement problem in the sense of making QM compatible with the possibility of definite measurement results, but does not explain why measurements should *actually* have definite results. QM constrains possibilities and the world happens to be one of these possibilities.

Remark: Could such a 'modest' foundational approach have more appeal to practising physicists than GRW, Bohm or even Everett?

Other variants of modal interpretations attempt *more*.

In particular, Kochen (1985), Healey (1989), Dieks (1989): restriction to orthogonal (diagonal) decomposition of ρ.

G. B. and M. Dickson (1996): addition of dynamics (à la Bohm-Bell).

Measurement problem/problem of classical world?

- von Neumann measurements: OK, since $\rho_{\text{apparatus}}$ is indeed diagonal in the pointer basis
- Albert and Loewer: what about POVMs? $\rho_{\text{apparatus}}$ is not diagonal!
- G. B. and M. Hemmo: through decoherence, $\rho_{\text{apparatus}}$ becomes almost diagonal; states in the orthogonal decomposition are close to pointer states unless the state is close to degeneracy
- G. B., M. Donald, and P. Vermaas (1995), M. Donald (1998): the orthogonal decomposition is very unstable close to degeneracies; expect problems in infinite dimensions
- G. B. (2000): take model from Joos and Zeh (1985), ρ from their master equation and its orthogonal decomposition. While the coherence length of ρ is tiny (decoherence is telling us to expect very localised properties), the states in the orthogonal decomposition are essentially spread over the entire spread of ρ (this modal interpretation picks out delocalised states).

Conclusions to be drawn:

- This is an approach that solves the measurement problem in the simple models of von Neumann measurements, but fails to mesh with decoherence in more general situations.
- Van Fraassen's version is still fine. Other newer versions (Spekkens and Sype, Gyula and Dieks) may also be (?).

7 Concluding remarks

There are further claims about what decoherence can give us, which would also need to be discussed in the context of various foundational approaches (in QFT: charge superselection, emergence of 'particles'; in QG: might give us GR!).

Discussion of decoherence may be very important for discussing the arrow of time.

Decoherence is needed in order to move the von Neumann 'cut' between observed and observer.

What about Bohr?

How to have Bohr's cake and eat it:

Bohr's intuition: if we lack a classical world, we lack the tools for doing, talking about and finding out about QM.

Bohr's conclusion: this forces us to postulate the classical world prior to QM.

If decoherence together with some foundational approach shows that one can derive the classical world from QM, then this postulate is unnecessary. We could recognise the correctness of Bohr's intuition (*having Bohr's cake*), but incorporate it in a rounded-off picture of the world that is entirely quantum mechanical (*eating it*).