Decoherence and reality
Hanneke Janssen memorial lecture

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In honor and memory of Hanneke Janssen

Reconstructing Reality

environment-induced decoherence, the measurement problem, and the emergence of definiteness in quantum mechanics

A critical assessment

Hanneke Janssen

philsci-archive.pitt.edu/archive/00004224/01/scriptie.pdf

But above all he feared imagination, that companion with its two faces; one friendly and one hostile. All the more friendly as long as you don't believe her. But hostile when you succumb to her lovely whispering... [I.A. Gontcharov, Oblomov (1859)]

1. Introduction: the measurement problem

- Do measurements have a special status in quantum mechanics? Or can they be seen as (a special case of) ordinary physical interactions?
  (The term appears as a primitive term in the axioms!)
- Modelling measurement as ordinary interaction between a system $\mathcal{S}$ and a measurement apparatus $\mathcal{A}$, Von Neumann presented an (idealized) scheme for a measurement process for an observable $\hat{S}$ of the system:

$$|\psi\rangle|a_0\rangle \longrightarrow \sum_i c_i|s_i\rangle|a_i\rangle \equiv |\Psi_f\rangle_{\mathcal{SA}}$$

  where
  - $|\psi\rangle \equiv \sum c_i|s_i\rangle$ is an arbitrary (pure) state of $\mathcal{S}$, and $\{|s_i\rangle\}$ the eigenbasis of the observable S,
  - $\{|a_i\rangle\}$ is the basis of the "pointer observable" $\hat{A}$ of apparatus $\mathcal{A}$, and $|a_0\rangle$ is the "ready" initial state of $\mathcal{A}$.

Apects of the measurement problem

- The problem of outcomes: How do we account in VN's scheme that measurements actually have definite outcomes?
- The problem of interference: Can one can rid of the interference terms in the final state? I.e.: Can we replace

$$|\Psi_f\rangle\langle\Psi_f| \equiv \sum_{ij} c_i c_j^* |s_i\rangle\langle s_j| \otimes |a_i\rangle\langle a_j| \text{ by } \rho = \sum_i |c_i|^2 |s_i\rangle\langle s_i| \otimes |a_i\rangle\langle a_i|$$

- The preferred basis problem: In the above scheme it is assumed that the observables $\hat{S}$ and $\hat{A}$ is given beforehand. But, if $|c_i| = |c_j|$, it can happen that

$$\sum_i c_i |s_i\rangle|a_i\rangle = \sum_i c_i |\tilde{s}_i\rangle|\tilde{a}_i\rangle$$

for different orthonormal bases on system and apparatus. (Schmidt's Bi-orthogonal Decomposition Theorem)

Decoherence: a phenomenon or a program?

- Qua phenomenon: the ubiquity and unavoidability of interactions of the apparatus with an environment.
- Qua programme: the claim that taking account of such interactions will solve aspects of the measurement problem or explain the emergence of classicality.
- The "No interpretation Interpretation"
  Some authors claim that these results can be achieved without involving any additional interpretation beyond the orthodox axioms (e.g.: Zurek (?) Joos, Schlosshauer)
  As a consequence, this version of the decoherence programme will not yield a realist interpretation of QM, but promises to show how and when our observations fit a realist interpretation.
- Others authors (Zeh, Wallace) do invoke an additional interpretational stance (Many worlds).

Decoherence in action

$$
\begin{aligned}
|\psi\rangle|a_0\rangle|e_0\rangle &\xrightarrow{\mathcal{SA}} \sum_i c_i|s_i\rangle|a_i\rangle|e_0\rangle \\
&\xrightarrow{\mathcal{AE}} \sum_i c_i|s_i\rangle|a_i\rangle|e_i\rangle \equiv |\Psi_f\rangle_{\mathcal{SAE}}
\end{aligned} \tag{1}
$$

Under plausible assumptions on the $\mathcal{AE}$ interaction (and the size of $\mathcal{E}$) model calculations show that the states $|e_i\rangle$ very, very rapidly become (almost) orthogonal: $\langle e_i|e_j\rangle = \delta_{ij}$.

Hence, granting all these assumptions, we obtain, by tracing out over $\mathcal{E}$, the reduced state

$$\rho_{\mathcal{SA}} = \sum_i |c_i|^2 |a_i\rangle\langle a_i| \otimes |s_i\rangle\langle s_i|$$

So what does decoherence claim to solve?

1. The problem of outcomes: how to account that only one outcome is realized? (and if so which one?)
   It is be now generally acknowledged that decoherence by itself offers no solution.

   However, if we assume a Locality Condition:

   all observables measurable take the form $\hat{O}_{\mathcal{SA}} \otimes I_{\mathcal{E}}$.

   then we can argue: $|\Psi_f\rangle_{\mathcal{SAE}}$ is empirically indistinguishable from a proper mixture of states in which $\mathcal{S}$ is in some state $|s_i\rangle$ and $\mathcal{A}$ is (simultaneously) in $|a_i\rangle$, as given by $\rho_{\mathcal{SA}}$. In other words: our experience will be as if there is a definite outcome. (Schlosshauer: "subjective reality")
2. The problem of interference is then also solved: Assuming the Locality Condition and $\langle e_i|e_j\rangle = \delta_{ij}$, the pure state $|\Psi_f\rangle_{\mathcal{SAE}}$ is empirically equivalent to the mixture $\rho_{\mathcal{SA}}$.

Zurek, (1993, p. 293):

> *"The ability to describe the state of the [total system] in terms of [$\rho_{\mathcal{S}\mathcal{A}}$] is the essence of effective classicality: it corresponds to the assertion that the system already has its own state, which is not necessarily known to the observer prior to the measurement, but is nevertheless, already quite definite.*

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It is important to emphasize here that while this statement is strictly speaking incorrect (there is actually a very messy entangled state vector . . .) it cannot be falsified by any feasible measurement."

3. The preferred basis problem Can the pointer observable of the apparatus be "read off" from the final state after measurement?

   Claim: Decoherence solves the preferred basis problem.
   The dynamics itself selects the unique (basis of the) pointer observable $\hat{A} that is being measured.$. ("Einselection" Zurek)
   The substance of this claim follows from:

The tri-decomposition theorem (Elby & Bub).
Let $|\Psi\rangle$ be any state on the Hilbert space $\mathcal{H}_1 \otimes \mathcal{H}_2 \otimes \mathcal{H}_3$. If there is a decomposition of $|\Psi\rangle$ such that

$$|\Psi\rangle = \sum_i c_i |\psi_i\rangle |\phi_i\rangle |\chi_i\rangle$$

where $\{|\psi_i\rangle\}$ and $\{|\phi_i\rangle\}$ are orthonormal bases in $\mathcal{H}_1$ and $\mathcal{H}_2$ respectively, and $\{|\chi_i\rangle\}$ a set of non-collinear unit vectors on $\mathcal{H}_3$, then this decomposition is unique.

3. Hanneke's analysis of these claims

a. The problem of outcomes. The "No interpretation" version of the decoherence program lays pride in not needing any interpretational statement beyond those of orthodox quantum theory.
Hence, its proposed solution to the problem of outcomes is not a realist one: instead it aims to explain only why our experience could be such as if we perceive definite results in many cases, while they are not really there.

Many authors have criticized this type of argument as
"FAPP" (Bell) or
"Getting away with a crime by hiding the evidence" (Leggett).

But it is a feasible approach to this part of the measurement problem anyway.

b. The proposed solution to the Preferred Basis Problem is guaranteed by the Elby-Bub tri-decomposition theorem. This theorem also implies that existence of such decompositions is rare amongst states on $\mathcal{H}_{\mathcal{S}} \otimes \mathcal{H}_{\mathcal{A}} \otimes \mathcal{H}_{\mathcal{E}}$.

This raises a further question:

- Is the interaction with the environment responsible for the existence of this decomposition?

No! Rather, it is the choice of initial state + dynamics: Problem: while it may be plausible to assume that system state and apparatus state factorize initially, there is no good reason to assume the same for apparatus and environment. The $\mathcal{A}\mathcal{E}$ interaction is not " switched on" by the experimenter.

Open problem: would the decoherence dynamics still lead to a final state of the desired form if we start with a more general initial state, e.g. $|\psi\rangle \otimes \sum_j |a_j\rangle|e_j\rangle$?

c. The Problem of Interference: Given that Elby-Bub settles the Preferred Basis Problem, why should one even want to solve the Problem of Interference as well?
Orthogonality of the environmental states ($\langle e_i | e_j \rangle = \delta_{ij}$) is not needed for a unique preferred basis!

Why are interference terms troubling, to begin with?
Let's go back to the VN scheme:
In orthodox quantum theory the empirical meaning of a quantum state is fixed by the Born postulate. Hence, the distinction between the pure state:

$$(|\Psi_f\rangle\langle\Psi_f|)_{\mathcal{SA}} = \sum_{ij} c_i c_j^* |s_i\rangle\langle s_j| \otimes |a_i\rangle\langle a_j|$$

and the mixed state:

$$\rho_{\mathcal{SA}} = \sum_i |c_i|^2 |s_i\rangle\langle s_i| \otimes |a_i\rangle\langle a_i|$$

is not emprically relevant if we measure $\hat{A} = \sum_i a_i |a_i\rangle\langle a_i|$, (or indeed, any observable on $\mathcal{S} + \mathcal{A}$ compatible with $\hat{A}$.

Interference terms only mark their presence (i.e., empirical distinctions between $(|\Psi_f\rangle\langle\Psi_f|)_{\mathcal{SA}}$ and $\rho_{\mathcal{SA}}$ can only be found if we contemplate measuring another observable $\tilde{A}$ that does not commute with $\hat{A}$.

But the solution to the preferred basis problem already fixes what the observable being measured is. But then, any reason to replace $(|\Psi_f\rangle\langle\Psi_f)$ by $\rho_{\mathcal{SA}}|_{\mathcal{SA}}$ seems to evaporate.

4. Conclusions

1. The No Interpretation Interpretation, taken literally, is self-defeating as a solution to the measurement problem. "No interpretation" ultimately relies on the minimal orthodox interpretation given by Born's postulate. And, thus, "measurement" retains its *status aparte* as a primitive notion in the theory.

   What decoherence adds to the story, however, is that the choice of an observable to interpret the quantum state is not up to the discretion of an observer but seen as fixed by the state itself.

   This still leaves many problems: The unique preferred basis does not exist for most states.
   Its dependence on the state can be wildly discontinuous. (cf. Bacciagaluppi and Donald on the modal interpretation)

2 If the above analysis is correct, then the effort within decoherence to solve the Problem of Interference is irrelevant! That is, even if we have $\langle e_i | e_j \rangle \neq \delta_{ij}$, and even without assuming the Locality Condition, the idea that the empirical meaning of

$$|\Psi_f\rangle_{\mathcal{SAE}} = \sum_i c_i |s_i\rangle |a_i\rangle |e_i\rangle$$

is to be cashed out in terms of a measurement of the preferred basis $\{|a_i\rangle\}$, this leads to the probabilities $|c_i|^2$.
In other words, the non-diagonal terms $(i \neq j)$in the final state

$$|\Psi_f\rangle\langle\Psi_f|_{\mathcal{SAE}} \sum_{ij} c_i c_j^* |s_i\rangle |a_i\rangle |e_i\rangle \langle s_i| \langle a_i| \langle e_i|$$

would be devoid of empirical meaning anyway.
The only reason for demanding their disappearance seems cosmetic: it may be esthetically pleasing when quantities that lack empirical meaning are zero.

Hanneke Janssen (1982 - 2008)