Article

Not peer-reviewed version

Quantum Collapse in an Isolated Laboratory

David Ring *

Posted Date: 20 August 2024

doi: 10.20944/preprints202408.1434.v1

Keywords: quantum mechanics; quantum measurement; quantum foundations doi:10.20944/preprints202408.1434.v1

Article

Quantum Collapse in an Isolated Laboratory

David W. Ring

Independent Researcher; physicspapers@davering.com

Abstract: A simple model of a measurement in a laboratory isolated from the environment is analyzed in detail, demonstrating the features of the collapse effect. Such an experiment can readily be implemented today under the idealization of an observer's memory as a simple quantum system. The central role of loss of information is emphasized.

Keywords: quantum mechanics; quantum measurement; quantum foundations

---

1. Introduction

From the earliest days of quantum theory, physicists have been troubled by its implications. Schrödinger, for example, pointed out the "absurd" conclusion that a cat could be in a superposition of alive and dead states [1]. We have never seen an alive/dead cat so, according to the Copenhagen interpretation, something in the act of observation must collapse the system into one or the other state.

The many-worlds interpretation [2], on the other hand, insists that observers themselves must be treated quantum mechanically and evolve into superpositions. In this picture, the collapse effect is an illusion and the universe splits into different branches corresponding to different outcomes.

Microscopic branches can recombine and interfere, as in the double-slit experiment. It is important, therefore, that coherence between branches is eliminated when observers are involved. Environmental interactions are known to effectively eliminate the coherence between branches [3], and human observers are necessarily in close thermal contact with their environment, thus satisfying the requirements for the collapse effect.

On the other hand, there is no barrier in principle to the existence of an observer who is isolated from the environment and can maintain coherence. Today's quantum computers are not sophisticated enough to implement intelligent thought, but a measurement can be as simple as recording a single bit of information. A single qbit or multilevel quantum system can therefore serve as a model for a quantum observer's memory.

In this paper, the collapse effect is demonstrated in a purely unitary evolution without the presence of an environment. Loss of information serves the role of eliminating coherence between the branches. The model includes a system, prepared in a pure state superposition. A general measurement is performed using a probe. The observer's memory is updated by a von Neumann measurement of the probe. The probe is discarded to destroy coherence. Finally, the collapse effect is demonstrated by showing that a projection has no effect on the observer's future experience.

2. Measurement Theory

The density operator formulation of quantum mechanics, equivalent to the usual wavefunction formalism, will be used. A measurement postulate is not assumed. The density operator simply evolves according to the von Neumann equation

$$i\hbar\frac{\partial}{\partial t}\rho = [H, \rho]\,. \tag{1}$$

Since all outcomes with support under ρ actually occur, there is no inherent statistical interpretation of ρ. It is simply a state that may or may not be pure.

The laboratory, minus the observer, starts in a pure state

$$\sigma_0 = \rho_0 \otimes |0\rangle\langle 0| \tag{2}$$

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 20 August 2024 doi:10.20944/preprints202408.1434.v1

where the system state ρ_0 satisfies $tr(\rho_0^2) = 1$ and the probe starts in a reference state. The probe is allowed to interact with the system for a time. This arbitrary unitary interaction may be written

$$U_1 = \sum_{aa'} A_{aa'} \otimes |a\rangle \langle a'| \ . \tag{3}$$

where $A_{aa'}$ acts in the system Hilbert space, a indexes a basis for the probe Hilbert space corresponding to the possible results of the measurement. The unitary operator can be thought of as the result of the integration of an interaction Hamiltonian over time. Since the probe starts in the reference state, we define $A_a = A_{a0}$. The A_a satisfy

$$\sum_a A_a^\dagger A_a = I_s \tag{4}$$

but are otherwise arbitrary linear operators. I_s is the identity in the system Hilbert space. After the interaction, the state becomes

$$\begin{aligned} \sigma_1 &= U_1 \sigma_0 U_1^\dagger \\ &= \sum_{aa'} A_a \rho A_{a'}^\dagger \otimes |a\rangle \langle a'| \ . \end{aligned} \tag{5}$$

The off diagonal terms in this expression allow interference between the different branches. It is possible in principle, for example, to exactly reverse the unitary interaction, restore the system to its starting state, and determine the initial superposition. That task would be impossible if collapse has occurred. Something must happen while the observer's memory is being updated.

Measurement theory does not usually treat the observer quantum mechanically. Instead a von Neumann measurement of the probe is postulated, including a projection operator which depends on what result was observed. For example, if result a was observed, the projection

$$\Pi_a = I_s \otimes |a\rangle \langle a| \tag{6}$$

is applied and the final state is

$$\sigma_2 = N_a \rho_a \otimes |a\rangle \langle a| \tag{7}$$

where

$$\rho_a = A_a \rho A_a^\dagger \tag{8}$$

and a normalization

$$N_a = Tr(A_a \rho A_a^\dagger)^{-1} \tag{9}$$

is added because the projection changes the trace. The projection (6) is non-unitary and if quantum states actually evolve this way, new physics is needed.

3. Quantum Observers

Our observer is required to remain isolated from the environment. We can contemplate a sophisticated quantum computer AI, but the important features of collapse can be demonstrated by modeling the observer's memory as a single quantum system. This has the added advantage that the model can be implemented today. For simplicity the probe and memory Hilbert spaces have the same finite dimensionality and their bases will be aligned so that a memory state of $|a\rangle_m \langle a|_m$ corresponds to knowledge that the probe is in state $|a\rangle_p \langle a|_p$.

The von Neumann measurement of the probe can be described similarly to the above. The observer's memory is updated by an interaction

$$U_2 = I_s \otimes \sum_{bb'} B_{bb'} \otimes |b\rangle_m \langle b'|_m \ , \tag{10}$$

 doi:10.20944/preprints202408.1434.v1

where $B_{bb'}$ acts in the probe Hilbert space. Again, the memory starts in a reference state $|0\rangle_m \langle 0|_m$ so we define $B_b = B_{b0}$. In a von Neumann measurement the $B's$ are orthogonal projections.

The resulting state includes off-diagonal components entangling different results:

$$\begin{aligned}\sigma_2 &= U_2 \sigma_1 U_2^\dagger \\ &= \sum_{aa'} A_a \rho A_{a'}^\dagger \otimes |a\rangle_p \langle a'|_p \otimes |a\rangle_m \langle a'|_m\end{aligned} \tag{11}$$

where the alignment of the probe and memory Hilbert spaces has been used.

In order to justify a projection without new physics, it is necessary to first lose information. One simple choice is to discard the probe. For example, if the probe is the state of a spin, the spin particle may be released to outer space.

The subsequent evolution of the laboratory includes contributions from all the possible states of the decoupled probe. These contributions can be quantified by taking the partial trace over the decoupled degrees of freedom. The partial trace procedure is commonly justified because it is the only operation that produces the correct measurement statistics for observables. That reasoning is not available here. Instead we note that the partial trace is the only operation that has the proper unitary transformation properties in the decoupled tensor product Hilbert space [4].

After the probe is discarded, the state becomes

$$\sigma_3 = \sum_a A_a \rho A_a^\dagger \otimes |a\rangle_m \langle a|_m \ . \tag{12}$$

There are no longer off-diagonal terms. This state may be considered an incoherent superposition where the observer's memory is correlated with the state of the system. In fact, the observer in branch "a" of the superposition is confident that result "a" occurred. Such an observer would not object if a projection

$$\Pi_a = I_s \otimes |a\rangle_m \langle a|_m \tag{13}$$

were applied so that the state is described by

$$\sigma_4 = N_a A_a \rho A_a^\dagger \otimes |a\rangle_m \langle a|_m \ . \tag{14}$$

From her perspective, the state of the system is given by the collapsed state (8), suitably normalized. She may believe a non-unitary collapse has occurred even though the global evolution is entirely unitary. A subsequent experiment, or in fact any future time evolution, must remain consistent with her understanding, as

$$U \sigma_3 U^\dagger = \sum_a U A_a \rho A_a^\dagger U^\dagger \otimes |a\rangle_m \langle a|_m \tag{15}$$

where we have assumed her memory register of the original result is preserved. In this way the collapse effect and the illusion of a projection are caused by the inaccessibility to an observer of other branches of the evolution.

4. Information Loss

Loss of information is required to silo the branches so that they cannot interfere. This can be seen by noting that the entropy has changed between (11) which is a pure state and (12) which is not. The specifics of when information is lost is not critical. A long chain of interactions between the system and the observer can lose information at any stage and still silo the branches.

What *is* critical is that the loss carries which-way information. Consider a general post-interaction density matrix in a now decoupled tensor product Hilbert space:

$$\rho_{a\alpha, b\beta} \tag{16}$$

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 20 August 2024 doi:10.20944/preprints202408.1434.v1

where a and α are indices for the two Hilbert spaces, as are b and β. In general this state is entangled. In some cases the entanglement will be *faithful*, meaning there is a correspondence between the basis elements, *i.e.* the matrix (16) is non-zero only when a and α corresponds to the same observational result and similarly for b and β. In such a case, one could inspect either subsystem to determine the measurement result. We say the discarded subsystem carries which-way information. It is clear that the reduced state

$$\rho_{ab} = \sum_{\alpha} \rho_{a\alpha,b\alpha} \tag{17}$$

is diagonal. For off diagonal terms, either a or b will not correspond with α.

5. Discussion

Discarding a probe to outer space is a somewhat contrived example, but the effect is robust. If multiple layers of observation are present, loss of any probe carrying which-way information is sufficient to destroy coherence. In fact, more complex and realistic models offer more opportunities to discard which-way information. By far the most common way to lose information in measurement is through interactions with the environment. There is extensive literature on this subject with results consistent with ours [3], but authors in this area rarely make clear claims regarding the measurement problem, possibly because proving claims that involve the messy business of environmental interactions is challenging. Understanding environmental decoherence as a special case of information loss offers a simpler analysis.

The picture that emerges for measurement in a unitary universe is as follows: a system entangles with an observer through multiple layers of interaction, information is lost, and the resulting correlated state of system and memory is diagonal among various results which evolve in such a way that an imagined collapse projection does not impact correlated observations.

Funding: This research received no external funding.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Schrödinger, E. Die gegenwärtige Situation in der Quantenmechanik. *Naturwissenschaften* **1935**, *23*, 807–812. doi:10.1007/BF01491891.
2. Everett, H. "Relative State" Formulation of Quantum Mechanics. *Reviews of Modern Physics* **1957**, *29*, 454–462. doi:10.1103/RevModPhys.29.454.
3. Schlosshauer, M. Quantum decoherence. *Physics Reports* **2019**, *831*, 1–57. Quantum decoherence, doi:10.1016/j.physrep.2019.10.001.
4. Ring, D. Partial Trace Reduction Without the Born Rule. *Preprints* **2024**. doi:10.20944/preprints202408.1312.v1.