Environmental Decoherence

Environmental decoherence is the interaction of a coherent system with the external particles in the environment, in a manner that destroys the system coherence. External orthogonalization can be used to model decoherence in which the Hamiltonian of Equation (4.1) is utilized such that H_D represents the environmental particles that are external to the system.

Assume that the system initially has coherence which can be represented by the off-diagonal terms of the density matrix of the system. Let us assume that there are two degrees of freedom of the system, and that the system is initially in the state $|\psi_S\rangle = \sqrt{a}|\phi_1\rangle + \sqrt{1-a}|\phi_2\rangle$, for which the density matrix of the system denoted $\rho^{(0)}$ is given by

$$\rho^{(0)} = \begin{pmatrix} a & \sqrt{a(1-a)} \\ \sqrt{a(1-a)} & 1-a \end{pmatrix}.$$

For any value of a not equal to either 0 or 1 one can see that the system possesses a non-zero off-diagonal coherence term. After the system interacts with the environment, and undergoes external orthogonalization, the final state of system plus environment is given by Equation (4.2) where the $|\Psi_r\rangle$ are orthogonal states of the environment. Such states can be considered in environmental decoherence theory as environmental *pointer* states, similar to a device read-out state that results for the corresponding system state $|\phi_r\rangle$. Now if one computes the partial density matrix of the system after environment decoherence occurs, denoted by $\rho^{(1)}$, it is found via Equation (4.3) to result in

$$\rho^{(1)} = \begin{pmatrix} a & 0 \\ 0 & 1-a \end{pmatrix}.$$

At this point, one might expect that the measurement problem is resolved because the system coherence is completely eliminated. That is, one can interpret the system to be in either state $|\phi_1\rangle$ with probability a and in state $|\phi_2\rangle$ with probability $1-a$; that it is only our ignorance of the actual state that prevents us from knowing the correct state. And this is quite correct if the system is isolated from its environment and either follow-up unitary evolution or measurements are performed on the system alone.

However, even after separating the system from its environment, the system remains entangled with the environment under unitary evolution. The case of entanglement versus the case for which the system is definitely either in $|\phi_1\rangle$ or $|\phi_2\rangle$ can in fact be differentiated via a UMDT. Under unitary evolution and environmental decoherence, the original first-order off-diagonal system coherence $\sqrt{a(1-a)}$ does indeed vanish, but instead becomes second-order coherence or entanglement between the system and environment. Simply because one transferred first-order coherence into entanglement does not resolve the measurement problem one iota. However, one might be inclined to proclaim to have resolved the measurement problem because when the system is isolated all follow-up operations performed on the system-only do indeed produce results consistent in a manner that the environment did measure the system in the environmentally determined pointer basis $\{|\Psi_r\rangle\}$. But this requires ignoring the unitarily predicted entanglement between system and environment which still can, in principle, be differentiated from measurement via a UMDT.

Environmental decoherence predicts a pointer basis but does not tell us the conditions for which measurement will occur. Consider a system composed of an electron with up or down spin that is moving in an inhomogeneous magnetic field. Suppose that the environment consists of one or more electrons which can interact with and scatter the first electron. It is well known that the unitary solution of interacting electrons can produce entangled electron states. Helium can be found in states such as the material parahelium, which is found when the two electrons are in an entangled singlet state. Another possibility is that the state of the two electrons is in the triplet entangled state for which a different material results, orthohelium. Scattering of electrons is generally modeled unitarily for example using Feynman diagrams, so one would be hard pressed to produce real theoretical or experimental evidence that would prove that a few electrons interacting with a single spin electron is sufficient to produce measurement. That is, if UMDT were performed in most such cases, we expect that the interactions are largely unitary and the results would agree with unitary theory. Although evidence would suggest that elementary electron scattering is unitary in most cases, one has to be careful not to leap to the final conclusion that this implies that all interactions are unitary. Such logically incorrect conclusions are often drawn by the quick-witted inductionist.

Moreover, consider the replacement of the devices in the UMDT of Chapter 3 by the local environment. Suppose that one were to speculate that environmental decoherence with some particular characteristic time or characteristic environmental size, resolved the measurement problem. As we can make the distance d between the two devices as large as desired in Figure 3.4, we can include both longer-and-longer interaction times and/or larger-and-larger local environments with increasing d and preclude interaction between the two respective local environments. Hence a UMDT can be designed in principle to investigate experimentally whether or not this is the case. As to date, there is substantial experimental evidence that indicates that minimal environmental interaction does not result in measurement. If at some point the environment can be considered a measurement device, then experimental investigation using UMDT would be needed to specify the conditions for which measurement would occur under such an environmental decoherence theory. Furthermore, these conditions would necessitate a substantial revision of quantum mechanics.

Decoherence by Stipulation

Bub claims in [120, p. 20]:

> *…we can take the decoherence pointer as definite by stipulation, and that decoherence then guarantees the objectivity of the macroworld, which resolves the measurement problem without resorting to*

Copenhagen or neo-Copenhagen instrumentalism.

Bub appears to be attempting to shift the definition of the measurement problem from the physical definition to the philosophical definition by taking the decoherence pointer basis as definite by stipulation.

Although Bub did not propose that decoherence by stipulation resolves the physical measurement problem it is still a useful exercise to analyze. To see that this does not resolve the physical measurement problem as we have defined it, let us consider several cases. In Case 1, we consider a system of particles that for the time interval $[0, t_1]$ is unitarily predicted to evolve in a manner that provides a decoherence pointer, which is equivalent to the process of external orthogonalization. Now suppose that such a system is predicted to continue to decohere in the same pointer basis without any further interaction in the time interval $[t_1, t_3]$, and that this could be continued indefinitely if desired. Bub's approach is that this is sufficient to guarantee objectivity of the state that existed at time t_1. Consider now Case 2 in which the same exact set of particles in the same state as Case 1 at time t_1 can interact with a new set of particles in a future time interval $[t_2, t_3]$. It is entirely possible that the unitary predicted state for this new set of particles effects an interaction between the pointer states such that the new pointer states that emerge are different from what they were in time interval $[0, t_1]$, and it is these new states that continue on to represent the new pointer basis. Hence if one applied Bub's methodology, in Case 1 the state after time t_1 represents an objective state, and in Case 2, the state after time t_2 is also an objective state.

Now, we apply the UMDT test of Chapter 3 to Cases 1 and 2 for which we will consider three possible outcomes—Case 3, 4, and 5. Case 3 is defined as the particles from Case 1 for which Step 2 and Step 3 of the UMDT test are applied at time t_3 and the CHSH value is $2\sqrt{2}$. Case 4 is defined as the particles from Case 1 for which Step 2 and Step 3 of the UMDT test are applied at time t_3, and the CHSH value is $\sqrt{2}$. Case 5 is defined as the particles from Case 2 for which Step 2 and Step 3 of the UMDT test are applied at time t_3, and the CHSH value is $\sqrt{2}$. If Case 3 is found to occur, then similarly in Case 2 the CHSH value if a Bell experiment were made at time t_1 would be expected to be $2\sqrt{2}$ as these are the same particles in the same state as in Case 1. However, suppose Case 5 is found to occur. Then we can conclude from the UMDT test that after time t_1 such a set of particles composing the device did not constitute a bona fide measurement of the photon while in Case 2 that the interaction with the set of the old plus the new particles does constitute a bona fide measurement of the photon in the interval $[0, t_3]$.

It can be seen from this example that UMDT tests provides us with a manner to gather true experimental evidence for the conditions under which a device is a bona fide measurement device. Bub's methodology would claim in Case 1 after time t_1 that the state is a classical state such as a cat being alive or dead because the state continued to decohere in that basis. On the other hand, suppose the UMDT test (in this example) shows that these particles are still in a superposition and that cat is neither alive nor dead at time t_1, while the follow-up test at t_3 shows measurement. In this case the correct decoherence pointer would be that given by the former case at time t_3. We have demonstrated the possibility that Bub's methodology, applied to the measurement problem as we have defined it, could give ambiguous results at time t_1, because of the *mere existence* of the possibility that unitarily one can always in the future interact particles in a manner to change the pointer basis that results from decoherence.

One can further ask whether or not Bub's methodology constitutes a necessary condition and/or a sufficient condition for measurement. Let us consider first the condition of sufficiency with the prior Cases 1 and 2 that have already been defined. In Case 1 Bub's methodology would claim that the state after time t_1 is an objective state such as a cat being alive or dead. Yet suppose that when the particles are subject to a UMDT is Case 3 with the result of the CHSH $2\sqrt{2}$ with the same particles as in Case 1, we would conclude that the state after time t_1 was in an entangled state and not in a product state. From this argument, Bub's methodology cannot be considered to be proven to be a sufficient test for a set of particles being a bona fide measurement device. Now, suppose that we applied the UMDT test at time t_3 to the particles from Case 1 and Case 4 results. Then we can conclude that the particles composing the device in Case 1 are a bona fide measurement device and the state after time t_1 is an objective state. But suppose that none of these experiments are performed except Case 5. Then we can conclude that the entire configuration of the original particles plus the new particles constitutes a bona fide device. Furthermore, as the original particles were interacted with new particles in Case 2 so that the original particles are not a decoherence pointer state, Bub's criterion would not apply to the original set of particles. Yet if we then conducted the experiment in Case 4 we would know that the original set of particles constitutes a bona fide measurement device. Because of these counterexamples that have not been ruled out by experiment, Bub's criterion cannot be considered to be a necessary condition for measurement at this time.

Bub's condition at this time has not been proven to be either a necessary or a sufficient condition for measurement in the manner that we have defined the measurement problem. Now one might go beyond Bub's formalism and claim that it is ultimately impossible to interact or reverse decoherence, even in a unitary theory. In this case such a theory could be classified as a Category 2 theory. However, there are systems that can undergo the process of external orthogonalization, for which a measurement does not occur. For example, suppose that a photon interacts with a single atom in a cavity, under conditions that have been utilized in the work of Haroche [121]. There is substantial experimental evidence that such interactions (with the experimental parameters considered in [121]) are unitary and that entanglement would be maintained if one conducted the UMDT test on such systems. Hence if such Category 2 arguments are to be made, they demand much more theoretical and experimental evidence as to what constitutes Category 2 irreversible decoherence.

In the paper [3] Bell states regarding the Landau and Lifshitz formulation (which is similar to the orthodox von Neumann quantum mechanics):

And the Landau and Lifshitz formulation, with vaguely defined wave *function collapse, when used with good taste and discretion, is adequate FAPP. It remains that the theory is ambiguous in principle, about exactly when and exactly how the collapse occurs, about what is microscopic and what is macroscopic, what quantum and what classical. We are allowed to ask: is such ambiguity dictated by experimental facts? Or could theoretical physicists do better if they tried harder?*

When Bell wrote his paper [116] in 1990, Quantum Information had not seriously begun other than a handful of entanglement experiments, and some expected in the early days of quantum information that mesoscopic entangled multipartite states might be impossible to observe due to the theoretically expected complete loss of entanglement when even a single particle of a maximally entangled state is lost through decoherence. However, mesoscopic experiments have proven such thoughts ill conceived. In light of quantum information technologies continuing to improve [122] [123] [124] and with each passing year progressively larger and larger systems being coherently manipulated [125] [26] [126] [127] [27] [128] [129], invoking environmental decoherence by stipulation in this day and age is not a satisfactory argument for resolution of the physical measurement problem. One would need to theoretically and experimentally investigate what conditions of environmental decoherence are bona fide measurements in order to begin to address the requirements of resolving the physical measurement problem. Unfortunately, Bell died at the age of 62. Had Bell been alive to witness the explosion in entanglement related areas, one has to wonder if he would not have reconsidered the possibility of experimentally investigating the issue of the measurement problem, rather than considering the conventional theory correct—FAPP.