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Quantum Measurement Problems, Decoherence, and Spontaneous Symmetry Breaking

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Quantum Measurement Problems, Decoherence, and Spontaneous Symmetry Breaking

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Abstract: In this paper, we propose a mechanism analogous to the spontaneous symmetry breaking combined with the quantum decoherence theory to explain the collapse of the wave function after the quantum measurement. We show that a wave function in a superposition of several eigenstates reduces to a single eigenstate due to the spontaneous-symmetry-breaking-like kinetic effect.

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1. Introduction

In quantum mechanics, the measurement problem is the problem of definite outcomes: quantum systems have superpositions as predicted by the Schrödinger equation but quantum measurements always give definite outcomes. To resolve the measurement problem and more generally explain the quantum-to-classical transition behavior, many objective collapse theories, including the Ghirardi–Rimini–Weber (GRW) model [1] and the continuous spontaneous localization (CSL) model [2], have been proposed. The GRW theory proposes that each constituent of a physical system independently undergoes a random "hit" on the order of once every hundred million years. In the CSL theory, the Schrödinger equation is supplemented with additional nonlinear and stochastic terms and the nonlinear modification induces the collapse of the wave function. Instead of introducing some vague concept of the unknown environmental degrees of freedom, Penrose (and Diósi, independently) suggested that the wave function collapse is induced by the gravity, the so-called DP model [3–6]. The wave function describing the state of a quantum system progressively loses its validity when the mass of the system becomes large enough. Although the DP model is the most influential model including gravity, it appears to have been ruled out in recent experiments [7].

All models listed so far cannot be described within quantum mechanics. On the other hand, quantum decoherence has been studied to understand how the classical world emerges from the quantum theory. In quantum mechanics, systems can exist in a superposition of states, described by a wave function that represents the probability amplitude of finding the system in each possible state. As long as there exists a definite phase relation between the components of the superposition, the system is said to be coherent and exhibits interference effects, as seen in the famous double-slit experiment. An isolated system always evolves according to unitary evolution and maintain coherence. But as soon as a system becomes entangled with its surroundings, the information about the relative phases between the quantum states leaks into the environment. This loss of information results in the destruction of quantum coherence, which in turn suppresses interference effects, the so-called environment-induced decoherence proposed by Zeh [8] (for a review see Ref. [9–11]). Quantum decoherence is a fundamental process that plays a crucial role in the transition from quantum to classical behavior. However, quantum decoherence does not describe the actual collapse of the wave function, but it explains the conversion of the quantum probabilities that exhibit interference effects to the ordinary classical probabilities.

Quantum phase transitions and spontaneous symmetry breaking (SSB) are fundamental concepts in condensed matter physics, connecting microscopic quantum mechanics with macroscopic properties of materials. When the temperature approaches the quantum critical point, the states of the system might be effectively decoupled by a large energy barrier separating them. To interconvert between the different states and hence sample them in the ensemble average, we would need require to quantum mechanically tunnel through this large barrier. The wider and the higher the potential energy barrier separating two states, the longer it takes to quantum mechanically tunnel between them. Therefore the time scale for the tunneling is extremely long. It will take an infinitely long time to get to a different region of the phase space. The averages over a finite amount of time and therefore not necessarily equal to the averages over all states in phase space at an instant in time. In this case, we should compute our ensemble expectation values using only a part of the phase space and the phase space becomes fragmented. Therefore, SSB occurs when the system in a mixed state gets stuck in a certain state.

In this paper, we argue that the basic origin of the wave function collapse is the same as the SSB. We propose a mechanism as a supplement to the decoherence theory to provide a solution to the measurement problem of quantum mechanics. Thus, quantum mechanics is itself applicable to the description of measurements.

This paper is organized as follows. In Sec.2, we make a brief review of the decoherence theory. In Sec.3, we demonstrate how the wave function collapses due to the spontaneous-symmetry-breaking-like kinetic effect. Finally, in Sec.4 we summarize the main results obtained.

2. A Brief Review of Quantum Decoherence Theory

Let us first make a brief review of the decoherence theory. Consider the double-slit experiment and denote the quantum states of the particle (call it S, for "system") corresponding to passage through slit 1 and 2 by $|s_1\rangle$ and $|s_2\rangle$, respectively. Suppose that the particle interacts with a detector or an environment E such that if the quantum state of the particle before the interaction is $|s_1\rangle$, then the quantum state of E will become $|E_1\rangle$ (and similarly for $|s_2\rangle$). Then for an initial superposition state $\alpha|s_1\rangle + \beta|s_2\rangle$ the final composite state $|\Psi\rangle$ will be entangled. That is

$$|\Psi\rangle = \alpha|s_1\rangle|E_1\rangle + \beta|s_2\rangle|E_2\rangle. \tag{1}$$

For the composite state vector described by Eq. (1), the reduced density matrix of the particle is

$$\rho_S = \mathrm{Tr}_E\, |\Psi\rangle\langle\Psi| = |\alpha|^2|s_1\rangle\langle s_1| + |\beta|^2|s_2\rangle\langle s_2| + \alpha\beta^*|s_1\rangle\langle s_2|\langle E_2 \mid E_1\rangle + \alpha^*\beta|s_2\rangle\langle s_1|\langle E_1 \mid E_2\rangle \tag{2}$$

Now suppose, for example, that we measure the particle's position by letting the particle impinge on a distant detection screen. Then the resulting particle probability density $P(x)$ is given by

$$P(x) = \mathrm{Tr}_S(\rho_S\hat{x}) = |\alpha|^2|\psi_1(x)|^2 + |\beta|^2|\psi_2(x)|^2 + 2\,\mathrm{Re}\{\alpha\beta^*\psi_1(x)\psi_2^*(x)\langle E_2 \mid E_1\rangle\} \tag{3}$$

where $\psi_a(x) \equiv \langle x|s_a\rangle$. The last term represents the interference contribution. Thus, the visibility of the interference pattern is quantified by the overlap $\langle E_2|E_1\rangle$, i.e., by the distinguishability of $|E_1\rangle$ and $|E_2\rangle$. In the limiting case of perfect distinguishability ($\langle E_2|E_1\rangle = 0$), the interference pattern vanishes and we obtain the classical prediction. Two states which were previously the same can become different as soon as the information that distinguishes between them is created. Physically, we interpret this as a flow of information from the system to the environment and hence information becomes delocalized. Conversely, if the interaction between S and E is such that E is completely unable to resolve the path of the particle, then $|E_1\rangle$ and $|E_2\rangle$ are indistinguishable and full coherence is retained for the system S.

3. Wave Function Collapse and Spontaneous Symmetry Breaking

We now arrive at the central result of the quantum decoherence that open systems are effectively described by diagonal reduced density matrices, generally called an "improper mixture". The improper mixture refers to that we view the pure state of the total entangled system as an effective mixed state for the subsystem while the proper mixture is an ensemble of pure states. Although they are defined differently, no physically realizable measurements can distinguish between a proper mixture ensemble and an improper mixture ensemble described by the same density matrix. Therefore, the time evolutions of the corresponding ensemble statistics are also indistinguishable. For simplicity, we still consider a quantum system with two eigenstates $|s_1\rangle$ and $|s_2\rangle$. The reduced density matrix and the particle probability density $P(x)$ becomes

$$\rho_S = |\alpha|^2 |s_1\rangle\langle s_1| + |\beta|^2 |s_2\rangle\langle s_2| \tag{4}$$

and

$$P(x) = \langle \hat{x} \rangle = \sum_{s=1}^{2} p_i \langle s_i | \hat{x} | s_i \rangle, \tag{5}$$

where $p_1 = |\alpha|^2$ and $p_2 = |\beta|^2$. In fact, the expressions of Eq. (5) follow from the ergodic principle, which states that all states of the system are accessible and eventually explored in the dynamical evolution of the system. To derive the expression for the particle probability density $P(x)$, we have used the fact that the behavior averaged over time is the same as the behavior averaged over states in phase space at a given instant in time, known as the ensemble average. However, in certain cases, the formula of the ensemble average is incorrect when the ergodic principle does not hold. To sample the two states s_1 and s_2 in our ensemble average, we would need require to interconvert between the two states. Since the interference is suppressed due to the quantum decoherence, it will take an infinitely long time to get to a different eigenstate at the classical level. For our two-dimensional system, the phase space becomes fragmented and the particle in a mixed state gets stuck in a certain eigenstate s_1 or s_2 with the corresponding probability. Thus, actual measurements always find the physical system in a definite state. It should be noted here that the improper mixture shows differences from the usual proper mixture. For the proper thermal ensemble, it allows different states to interconvert with different Boltzmann factors.

In the case of the continuous eigenvalues, we cannot precisely locate a quantum particle due to Heisenberg's uncertainty principle and hence the particle still exhibit a faint interference effect and has some nonzero probability of passing through the potential barrier. As a result, it would instantly spread out after we locate this particle.

4. Conclusions

In this paper, we model a quantum measurement within quantum theory and propose a mechanism similar to the SSB to provide possible explanations of how quantum measurements always give definite outcomes. It is actually a new supplementation of the quantum decoherence theory. This result strictly adheres to quantum mechanics and does not modify any fundamental statements of quantum mechanics. Based on these considerations, all the fundamental statements of quantum mechanics reduces to one—the superposition principle.

References

1. Ghirardi, G.C.; Rimini, A.; Weber, T. Unified dynamics for microscopic and macroscopic systems. *Physical review D* **1986**, *34*, 470.
2. Pearle, P. Combining stochastic dynamical state-vector reduction with spontaneous localization. *Physical Review A* **1989**, *39*, 2277.
3. Diósi, L. Models for universal reduction of macroscopic quantum fluctuations. *Physical Review A* **1989**, *40*, 1165.
4. Penrose, R. On gravity's role in quantum state reduction. *General relativity and gravitation* **1996**, *28*, 581–600.
5. Penrose, R. Wavefunction collapse as a real gravitational effect. In *Mathematical physics 2000*; World Scientific, 2000; pp. 266–282.
6. Penrose, R. On the gravitization of quantum mechanics 1: Quantum state reduction. *Foundations of Physics* **2014**, *44*, 557–575.
7. Donadi, S.; Piscicchia, K.; Curceanu, C.; Diósi, L.; Laubenstein, M.; Bassi, A. Underground test of gravity-related wave function collapse. *Nature Physics* **2021**, *17*, 74–78.
8. Zeh, H.D. On the interpretation of measurement in quantum theory. *Foundations of Physics* **1970**, *1*, 69–76.
9. Schlosshauer, M. Quantum decoherence. *Physics Reports* **2019**, *831*, 1–57.

doi:10.20944/preprints202409.2405.v2

10. Zurek, W.H. Decoherence, einselection, and the quantum origins of the classical. *Reviews of modern physics* **2003**, *75*, 715.
11. Schlosshauer, M. Decoherence, the measurement problem, and interpretations of quantum mechanics. *Reviews of Modern physics* **2004**, *76*, 1267–1305.