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Decoherence, Quantum Measurement Problem, and Spontaneous Symmetry Breaking

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Decoherence, Quantum Measurement Problem, and Spontaneous Symmetry Breaking

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Abstract: In this paper, we propose a mechanism analogous to the spontaneous symmetry breaking to explain quantum measurement. It is actually a supplement to the decoherence theory. We introduce the effective potential between eigenstates and 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, 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 [1] (for a review see Ref. [2–4]). Environment-induced decoherence is a fundamental process that plays a crucial role in the transition from quantum to classical behavior. In this paper, we propose a mechanism as a supplement to the decoherence theory to explain quantum measurement.

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 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

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

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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. 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

After the environment-induced decoherence, the quantum particle may be regarded as being in a mixed state rather than a pure quantum state. The density matrix of the particle 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. (3-5) 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. The eigenstates of the system might be effectively decoupled by a large energy barrier separating them. To interconvert between the two states s_1 and s_2 and hence sample them in our 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.

For our double-slit experiment, there exists an effective potential energy barrier of the form

$$V(|s_a\rangle) = \begin{cases} 0, & a = 1 \quad \text{or} \quad 2 \\ \infty, & \text{otherwise}\,, \end{cases} \tag{6}$$

where $|s_a\rangle$ denotes a set of orthonormal eigenstates that includes some fictitious eigenstates in addition to $|s_1\rangle$ and $|s_2\rangle$. The form of Eq. (6) implies that a two-dimensional system can be viewed as a higher-dimensional system, but the potential energy corresponding to the other bases is infinite. These fictitious quantum eigenstates and potential energies only play a role during measurement and do not modify any existing quantum theories.

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. Of course, in the limit of an infinite amount of time, these averages should be the same, but in a finite amount of time relevant to our experimental observation of a system, the averages might not be the same. In this case, we should compute our ensemble expectation values using only a part of the phase space. For our double-slit experiment, the phase space becomes fragmented and the particle in a mixed state gets stuck in a certain eigenstate $|s_1\rangle$ or $|s_2\rangle$ with the corresponding probability. The basic origin of the wave function collapse is the same as the spontaneous symmetry breaking. It should be noted here that before the decoherence, the quantum superposition is not affected by this potential. For the system with more than two eigenstates, let $\{|\varepsilon_j\rangle\}$ be a basis of the system Hilbert space $\mathcal{H}_1$, the effective potential energy barrier is given by

$$V(|\lambda_i\rangle) = \begin{cases} 0, & \lambda_i = \varepsilon_j \\ \infty, & \text{otherwise,} \end{cases} \tag{7}$$

where we have introduced the eigenstate variables $|\lambda_i\rangle$. Let $\{|\lambda_i\rangle\}$ be a basis of an extended system Hilbert space $\mathcal{H}_2$, the dimension of $\mathcal{H}_2$ is considerably larger than the dimension of $\mathcal{H}_1$.

In the case of the continuous eigenvalues, we can introduce a series of delta-function potential between eigenstates. However, the particle has some nonzero probability of passing through the delta-function potential when we locate this particle. Hence it would instantly spread out from the location and once a superposition of any two eigenstates is established, they will not be affected by the potential between them.

4. Conclusions

In this paper, we propose a mechanism similar to spontaneous symmetry breaking to explain quantum measurement. It is actually a supplement to the decoherence theory. This result strictly adheres to quantum mechanics and does not modify any fundamental statements of quantum mechanics. One may think that the introduction of effective potential between eigenstates is artificial. In fact, it naturally arises from the discreteness of the eigenstates of the system. Based on these considerations, all the fundamental statements of quantum mechanics reduces to one—the superposition principle.

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