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Quantum Mechanics and Local Realism: Resolving the EPR Paradox via Decoherence

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Abstract: Despite its remarkable success in describing microscopic phenomena, quantum mechanics continues to pose unresolved foundational questions concerning measurement, nonlocality, wavefunction collapse, and the nature of physical reality. These issues were highlighted by the EPR paradox[1-2], in which Einstein and his co-authors examined the measurement of entangled particles in space-like separation. Quantum mechanics predicts that measuring one particle's observable instantaneously determines the state of the other, seemingly violating special relativity's prohibition of faster-than-light influences and suggesting an incomplete description of physical reality. However, Bell's theorem[3-5], along with the Bell-Kochen-Specker theorem[6-10] and subsequent experiments, has largely ruled out local hidden variable theories. In this work, I apply the quantum decoherence framework[11-13], pioneered by Zeh, Zurek, Joos and Leggett et al. to analyze an EPR-like system using system-environment interactions as a measurement model. I demonstrate that measurement on one entangled particle does not instantaneously collapse the system's wavefunction. Instead, the local wavefunctions of the measured particle and its environment evolve dynamically, while the remote particle's wavefunction remains unchanged. Environment-induced decoherence selects pointer states and rapidly suppresses quantum correlations through local interactions, giving rise to the appearance of wavefunction collapse. These findings suggest that quantum mechanics can be reconciled with local realism if the wavefunction is treated as an ontic entity, offering a potential path toward a locally realistic quantum theory in alignment with Einstein's vision.

Keywords: quantum decoherence; EPR paradox; local realism; wavefunction collapse; quantum measurement; entanglement; quantum foundations; Bell's theorem; Kochen-Specker theorem; ontic wavefunction; physical reality

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Introduction

The success of quantum mechanics is nothing short of extraordinary since its inception a century ago. It has not only revolutionized science and technology but has also challenged our deepest philosophical assumptions about reality. Yet, it remains one of the most counterintuitive theories ever formulated. Phenomena such as nonlocality, entanglement, and the instantaneous collapse of the wavefunction upon measurement have given rise to a diverse array of interpretations among scientists and philosophers.

In 1935, Einstein, Podolsky, and Rosen (EPR) proposed a thought experiment, now known as the EPR paradox [1,2], involving a pair of entangled particles separated by a space-like distance. According to quantum mechanics, measuring one particle instantaneously alters the quantum state of the other particle, even if they are light-years apart. This led the EPR authors to conclude that the quantum description of physical reality must be incomplete. Einstein argued [14–16] that the expectations of measurement value of quantum-mechanical observables should serve as an element of reality and that a measurement on one particle should not instantaneously affect the quantum state of the other. It may need some new theory with extra parameters (hidden variables) in order to make it complete. His argument relied on the principles of locality and realism [17].

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The principles of locality and realism assume that objects are only directly influenced by their immediate surroundings and that their physical properties exist independently of measurement. In 1964, John Bell formulated a theorem 3 demonstrating that a hidden variable theory consistent with local realism must satisfy a specific mathematical inequality—now known as Bell's inequality [3–5]. Using a system similar to the EPR paradox, he showed that quantum mechanics predicts violations of this inequality. Since then, numerous experiments [18–23] have been conducted, progressively closing loopholes in earlier studies. All experimental results have confirmed violations of Bell's inequality, consisting with the predicts from quantum mechanics and ruling out local hidden variable theory.

Since the advent of quantum mechanics, physicists have debated the nature of reality. Einstein and his colleagues argued that quantum observables—such as a particle's position and momentum—should correspond to "elements of reality," possessing definite values independent of measurement. However, quantum mechanics suggests otherwise: observables lack predetermined values before measurement, a principle encapsulated in the Bell-Kochen-Specker theorem [6–9] (also known as the Kochen-Specker theorem). This theorem formalizes quantum contextuality, showing that measurement outcomes depend on the choice of other commutable observables within the same experiment. As Peres noted in ref. [10]: "… if three operators A, B, and C satisfy [A, B] = [A, C] = 0 and [B, C] ≠ 0, the result of a measurement of A cannot be independent of whether A is measured alone or together with B or C." This directly challenges Einstein's concept of local realism.

The issue is further clarified by the Greenberger-Horne-Zeilinger [24–28] (GHZ) theorem, which demonstrates that merely assuming definite values for three commutable spin observables leads to a direct contradiction with quantum predictions [29]. Likewise, Bell's inequality, derived under the assumptions of hidden variables, is incompatible with quantum mechanics, which inherently lacks such variables. Consequently, Bell's theorem—based on the assumption of predefined observables within a hidden-variable framework—does not strictly apply to quantum mechanics [30–33]. This leaves open the possibility that quantum theory may remain fundamentally local [34], provided an alternative formulation of "elements of reality" extends beyond expectation values of observables.

The Copenhagen interpretation of quantum mechanics, often considered the orthodox view, posits that wavefunction collapse is not a physical process but rather a reflection of the observer's changing knowledge. In this framework, the wavefunction serves as a mathematical representation of information, updating instantaneously upon measurement [35]. Whether the wavefunction is fundamentally epistemic or ontic—and whether it constitutes an element of physical reality—remains an open question. In 2012, Pusey, Barrett, and Rudolph (PBR) formulated a theorem 36 challenging purely epistemic interpretations, providing strong evidence in favor of an ontic view of the quantum state.

Although Bell's theorem does not imply that quantum mechanics must be nonlocal, most physicists accept nonlocality primarily due to the instantaneous collapse of the wavefunction during measurement. The ambiguous nature of reality, the lack of a physical mechanism for wavefunction collapse, and the nonlocal characteristics of quantum mechanics remain central controversies in the field. These issues are ultimately tied to the measurement problem and continue to give rise to paradoxes, such as Schrödinger's cat [37], Wigner Friend [38–40].

Since the 1970s, quantum decoherence [11–13] has been proposed as a way to address the measurement problem. It provides a dynamical mechanism explaining the apparent collapse of the wavefunction due to system-environment interactions (see the recently review papers [41–43]). Spin-environment models, introduced by Zurek [13,44] focus on the decoherence of a single spin (qubit) interacting with a spin bath. In this paper, I investigate two entangled spin-1/2 particles in the EPR setting using a simple yet exactly solvable decoherence model. The local components of the system wavefunction for the two spins and the environment spin bath are derived from the Schrödinger equation when one of the entangled particles is measured by the environment. From this dynamic solution, I analyze wavefunction collapse, entanglement, decoherence, and their implications for locality.

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The system under consideration consists of two entangled spin-1/2 particles (A and B) that are space-like separated. They are initially prepared in a maximally entangled singlet state and propagate freely in opposite directions toward Alice and Bob, who can choose to perform quantum spin measurements (Figure 1).

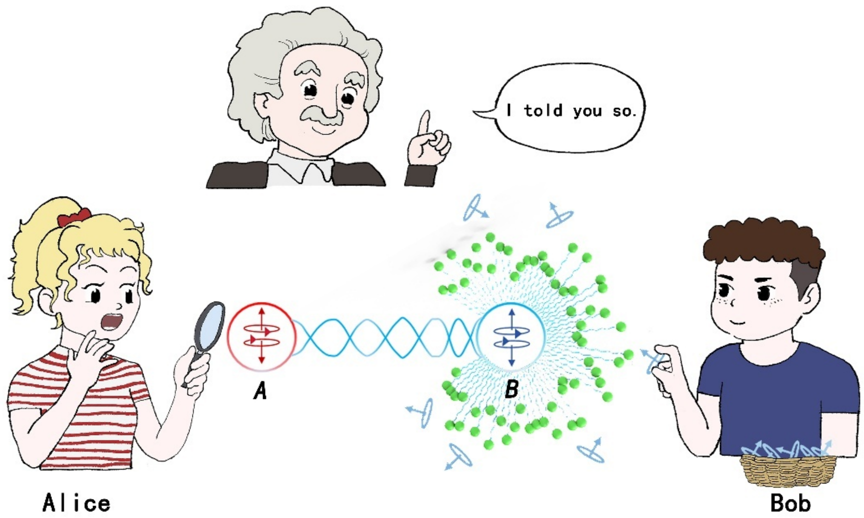

Figure 1. Two entangled spin-1/2 particles propagate in opposite directions toward Alice and Bob. Bob allows N=6 environmental spins, corresponding to 2^N basis states (green spheres), to interact with particle B, while Alice examines the spin state of particle A.

Instead of using a non-uniform magnetic field and a screen, Bob allows particle B in his possession to interact with an environmental bath composed of N spins. This interaction is governed by a linear Hamiltonian [13,44], which mimics a spin measurement in the z-direction for particle B, beginning at t=0:

$$H_{SE} = \frac{1}{2}\sigma_z^{(B)} \otimes \sum_{k=1}^{N} g_k\, \sigma_z^{(k)} \tag{1}$$

where $\sigma_z^{(B)}, \sigma_z^{(k)}$ represent the Pauli matrices of particle B and kth spin in the bath, respectively, while g_k denotes the interaction strength between particle B and bath spin k. Here we study a general case in which the bath spins are initially entangled. The initial wavefunction of the system plus environment can be written as:

$$|\Psi_{SE}(0)\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle_A \otimes |\downarrow\rangle_B - |\downarrow\rangle_A \otimes |\uparrow\rangle_B) \otimes |E(0)\rangle \tag{2}$$

where $|\uparrow\rangle_A$, $|\downarrow\rangle_B$ are the state of particle A and B with their spins pointing in z and anti-z directions, respectively, $|E(0)\rangle = \sum_{n=0}^{2^N-1} \mathrm{c}_n |n\rangle$, c_n are complex number for bath computational base $|n\rangle$, $n = 0 \ldots 2^N - 1$. They can be expressed in terms of individual spin states analogous to a binary encoding:

$$|0\rangle = |\uparrow\rangle_1 |\uparrow\rangle_2 |\uparrow\rangle_3 \ldots |\uparrow\rangle_k \ldots |\uparrow\rangle_N$$

$$|1\rangle = |\downarrow\rangle_1 |\uparrow\rangle_2 |\uparrow\rangle_3 \ldots |\uparrow\rangle_k \ldots |\uparrow\rangle_N$$

……

$$|2^N - 1\rangle = |\downarrow\rangle_1 |\downarrow\rangle_2 |\downarrow\rangle_3 \ldots |\downarrow\rangle_k \ldots |\downarrow\rangle_N$$

The Schrödinger equation with the Hamiltonian for the system and environment can be solved exactly for arbitrary N and time t:

$$|\Psi_{SE}(t)\rangle = \frac{1}{\sqrt{2}}[|\uparrow\rangle_A \otimes |\downarrow\rangle_B \otimes |E_\downarrow(t)\rangle - |\downarrow\rangle_A \otimes |\uparrow\rangle_B \otimes |E_\uparrow(t)\rangle] \quad (3)$$

where two environment states at t are

$$|E_\uparrow(t)\rangle = \sum_{n=0}^{2^N-1} c_n e^{-\frac{iB_n t}{2}}|n\rangle$$

$$|E_\downarrow(t)\rangle = \sum_{n=0}^{2^N-1} c_n e^{\frac{iB_n t}{2}}|n\rangle$$

where $B_n = \sum_{k=1}^{N}(-1)^{n_k} g_k$ and $n_k = 0$ if the kth spin in the bath is aligned with z and $n_k = 1$ if it is anti-aligned.

The solution given in Equation (3) can be verified by substituting it to the Schrödinger equation with the Hamiltonian in Equation (1). Notably, the expressions for the environment states remain identical to those in ref. [44], despite the fact that our system comprises two entangled particles—one of which interacts with the environment—whereas the system in ref. [44] involved only a single particle coupled to the same environment. This similarity arises because particle A, although entangled with particle B, has no direct physical interaction with either the bath spins or particle B. As a result, all dynamical evolution occurs exclusively within particle B and the environment.

After an interaction time t, the environment spins become entangled with both particles A and B, forming a three-way entanglement, due to the fact that wavefunctions for system spins and the environment are no longer factorizable in solution (3). The dynamical solution deviates from the quantum measurement axiom: upon interaction with the environment, the wavefunction does not collapse instantaneously. Instead, it undergoes a continuous evolution governed by the Schrödinger equation. The local wavefunction of particle A, which does not interact with the environment, remains unchanged throughout the decoherence process. In contrast, the wavefunction of particle B and the environment evolves continuously from t=0 onward.

$$|\uparrow\rangle_A \rightarrow |\uparrow\rangle_A$$
$$|\downarrow\rangle_A \rightarrow |\downarrow\rangle_A$$

$$|\uparrow\rangle_B \otimes |E_\uparrow(0)\rangle \rightarrow |\uparrow\rangle_B \otimes |E_\uparrow(t)\rangle$$
$$|\downarrow\rangle_B \otimes |E_\downarrow(0)\rangle \rightarrow |\downarrow\rangle_B \otimes |E_\downarrow(t)\rangle$$

To describe the state of the system for particles A and B alone, we need to "ignore" or "average over" the uncontrollable states of the environment. This is achieved by performing a partial trace over the environmental degrees of freedom (DOF), yielding the reduced density matrix for the system:

$$\rho_s(t) = Tr_E[\rho_{SE}(t)] = Tr_E[|\Psi_{SE}(t)\rangle\langle\Psi_{SE}(t)|] =$$
$$\frac{1}{2}(|\uparrow\rangle_A\langle\uparrow|_A \otimes |\downarrow\rangle_B\langle\downarrow|_B + |\downarrow\rangle_A\langle\downarrow|_A \otimes |\uparrow\rangle_B\langle\uparrow|_B)$$
$$-\frac{1}{2}(z^*(t)|\uparrow\rangle_A\langle\downarrow|_A \otimes |\downarrow\rangle_B\langle\uparrow|_B + z(t)|\downarrow\rangle_A\langle\uparrow|_A \otimes |\uparrow\rangle_B\langle\downarrow|_B)$$

where $z(t)$ is decoherence factor:

$$z(t) = \langle E_\downarrow(t)|E_\uparrow(t)\rangle = \sum_{n=0}^{2^N-1} |c_n|^2 e^{-iB_n t} = \prod_{k=1}^{N}\left(|\alpha_k|^2 e^{-ig_k t} + |\beta_k|^2 e^{ig_k t}\right)$$

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The two expressions for the decoherence factor presented above correspond to the cases where the bath is initially entangled and not entangled, respectively. In the latter case, the initial bath wavefunction $|E(0)\rangle = \prod_{k=1}^{N} \otimes (\alpha_k |\uparrow\rangle_k + \beta_k |\downarrow\rangle_k)$, is characterized by complex coefficients α_k, β_k for the kth spin in the bath.

This decoherence factor $z(t)$ depends on is the interacting strength g_k between particle B and kth spin in the bath, as well as the initial bath states coefficients c_n or α_k, β_k. At $t = 0$, $z(t) = 1$, indicating that the particle A and B remain in their original strongly entangled state. However, it has been shown that $z(t)$ rapidly approaches zero 44 following the approximation for $z(t) \simeq e^{iat - bt^2}$, where a and b are real constants. Furthermore, for large t and N, under a general random distribution of g_k, time average of $z(t)$ remains close to zero 13 with $\langle |z(t)|^2 \rangle \to 0, \langle |z(t)| \rangle \to 0$.

With $z(t)$ approaches 0, the reduced density matrix reveals that environment decoherence of particle B destroys any correlation between two pointer states of the particle A and B, resulting in a density matrix that represents a mixed state:

$$\rho_s(t) = \frac{1}{2}\{|\uparrow\rangle_A\langle\uparrow|_A \otimes |\downarrow\rangle_B\langle\downarrow|_B + |\downarrow\rangle_A\langle\downarrow|_A \otimes |\uparrow\rangle_B\langle\uparrow|_B\} \quad (4)$$

In the terminology of Zurek, equation (4) indicates that the environment dynamically selects two states $|\uparrow\rangle_A \otimes |\downarrow\rangle_B$, and $|\downarrow\rangle_A \otimes |\uparrow\rangle_B$ as pointer states—a process known as environment-induced superselection, or einselection 41—and effectively suppresses any superposition between them. The system exhibits a 50% probability of being in either of the pointer states, precisely as predicted by the Born's rule.

This result is striking: quantum decoherence continuously transforms the two entangled particles into a mixed state, even though the wavefunction component of particle A remains unchanged. Our findings show that for a pair of entangled particles in space-like separation, measuring one has no effect on the wavefunction component of the other. Consequently, there is no instantaneous collapse of the global wavefunction and no superluminal communication. All interactions in the simulation are strictly local, with no indication of "spooky action at a distance".

It is widely assumed that measuring one of a pair of entangled particles instantaneously *reveals* the quantum state of its distant counterpart, irrespective of their spatial separation and without any physical interaction. However, our simulations challenge this view, demonstrating that such an understanding is flawed.

The decoherence factor $z(t)$ can be computed numerically using Monte Carlo simulations. To begin, we consider only the randomness arising from the interaction strength g_k, which are assuming to be uniformed distributed [44] in [-2, 2]. In this analysis, we disregard the randomness associated the initial distribution of environment spins by assuming that each spin equal probability in the spin-up and spin-down state. The results show that the decoherence factor rapidly approaches zero and remains near to zero over the time, ever for small number of the environment spins, consistent with 44 (Figure 2 A and B). The timescale of decoherence is typically very short. For instance, an electron spin in a GaAs quantum dot rapidly loses coherence due to hyperfine interactions with the nuclear spins of Ga and As. This interaction, with a strength of approximately 50 μeV [45], induces decoherence on a nanosecond timescale.

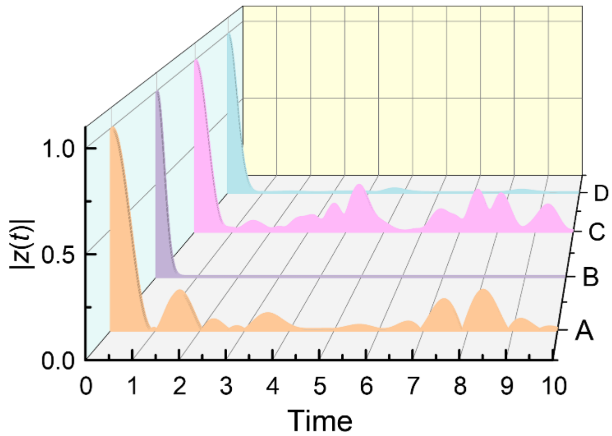

Figure 2. Monte Carlo simulations of decoherence induced by the environment. A, B are with random interaction strengths g_k with *N*=6 and 24, respectively. C, D add random distribution of bath initial states with *N*=6 and 24, respectively. The unit of time is roughly in nanosecond for electron spin in GaAs quantum dot.

The impact of randomness from environment spins are considered in Figure 2 C and D. Instead of fixing the initial state of the spins in the bath, we select the initial states bath spins uniformed distributed on a Bloch sphere. Simulations show that incorporating randomness in initial states of the bath is slightly less effective in suppressing the amplitude of the decoherence factor comparing with A and B.

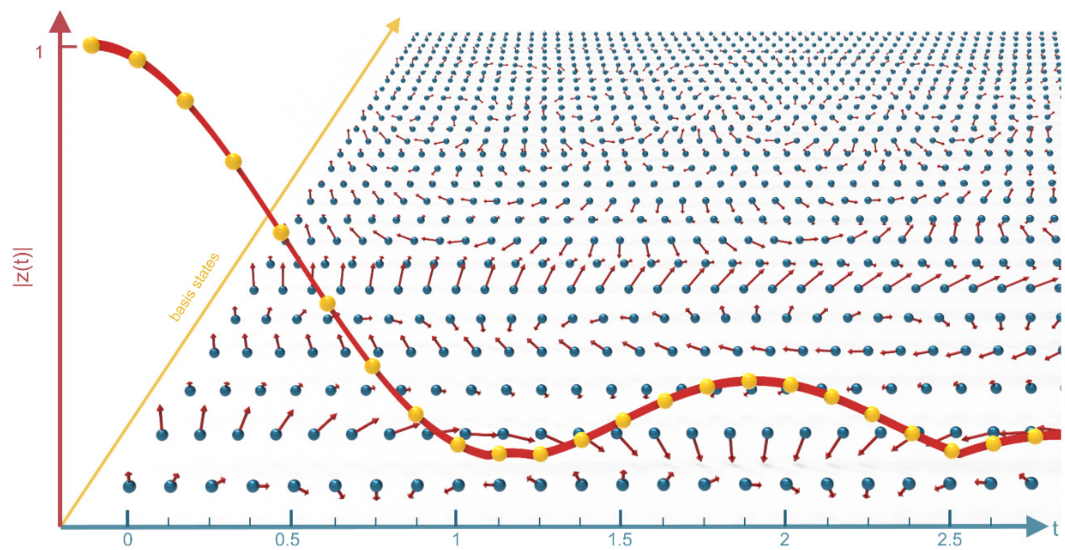

Figure 3. Contributions of the decoherence factor from $2^6 = 64$ basis states in Figure 2 C. Each basis state has different magnitude c_n, representing random initial state, and different rotation rate, representing random interaction strength. At *t*=0, all basis states are aligned up, producing a large $|z(t)|$. As time progresses basis states rotate in different directs with various speeds and system loses its coherence. The time unit is the same as in Figure 2.

More detailed models have shown that decoherence occurs almost instantaneously. For macroscopic object with mass of 1g and size of 1cm, the decoherence time and thermal relaxation time ratio is about $10^{-40,}$ resulting immediate decoherence. In mesoscopic systems, such as dust particles with mass of 10^{-15}kg and radius of 0.1μm, even exposure to the 3K cosmic microwave background radiation induces almost immediate decoherence in about 10^{-7}s. Microscopic systems, including large molecules, also experience rapid decoherence due to interactions with thermal radiation—on timescales far shorter than can be practically observed [46–48].

When considering that all measurement apparatuses are macroscopic systems subject to environmental decoherence, many of quantum mechanics' paradoxes become less problematic. In Schrödinger's cat experiment, decoherence ensures that the cat's state resolves to either alive or dead long before an observer opens the box. Similarly, in Wigner's friend thought experiment, the friend does not remain in a superposition with the electron and measuring device—decoherence rapidly drives large systems into classical states, regardless of whether Wigner later inquires about the outcome.

Although decoherence does not collapse the global wavefunction of the system and environment, the presence of numerous uncontrollable DOF in the environment gives rise to an apparent collapse of the system's wavefunction. This effect emerges because the reduced density matrix, obtained by tracing over these DOF, loses coherence. As a result, quantum decoherence in measurement provides a natural explanation for observed outcomes, eliminating the need for an unphysical, instantaneous wavefunction collapse.

In summary, I present a simple yet exactly solvable decoherence model to examine an EPR-like system, treating system-environment interactions as part of the measurement process. The results demonstrate that measuring one entangled particle neither instantaneously collapses the system's wavefunction nor reveals the state of the distant particle. Instead, the local wavefunctions of the measured particle and its environment evolve dynamically, while the remote particle's wavefunction remains unaffected. Environment-induced decoherence selects pointer states and rapidly suppresses quantum correlations through local interactions, giving rise to the appearance of wavefunction collapse. These findings suggest that quantum mechanics can be reconciled with local realism if the wavefunction is regarded as an ontic entity, offering a path toward a local and realistic quantum theory in alignment with Einstein's vision in the EPR papers.

Author Contribution: E. X. Wang conceived the idea.

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Computer Code: The simulation scripts for Figure 2 and 3 are available at the author upon reasonable request.

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