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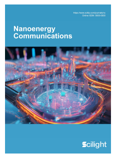

Article

Decoherence as a Local and Realistic Account of the EPR Paradox

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Abstract: Quantum mechanics, despite its extraordinary success in describing microscopic phenomena, continues to raise foundational questions concerning measurement, nonlocality, and the nature of physical reality. These issues are exemplified by the Einstein-Podolsky-Rosen (EPR) paradox and the Bell inequality, which contrast quantum correlations with classical notions of locality and realism. In this work, we critically examine the assumptions underlying Bell's theorem in light of the incompatible and contextual nature of quantum observables. We show that Bell's constraint on simultaneous definite values for incompatible observables, together with the assumption of hidden variables, is not applicable to quantum mechanics itself, which is inherently nonclassical and contextual. When measurement is modeled as a local system-environment interaction within the framework of quantum decoherence, the resulting dynamics remain entirely local and unitary in the EPR scenario. Decoherence naturally selects pointer states and suppresses interference, giving rise to the appearance of wavefunction collapse consistent with quantum predictions. Importantly, the Bell correlations obtained in this framework reproduce the standard quantum results and are independent of both system-bath and inter-bath interactions, which affect only the rate of decoherence. Our analysis suggests that, in the EPR scenario, quantum mechanics can be both local and realistic when the wavefunction is treated as an ontic description of reality within the decoherence framework, offering a potential route toward a locally realistic quantum theory aligned with Einstein's vision. This work contributes to a more rigorous foundation for quantum mechanics, providing insights that can accelerate progress in quantum computing and nanoenergy harvesting.

Keywords: EPR paradox; bell-inequality; quantum decoherence; nanoenergy; locality; reality

1. 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 profoundly challenged our deepest philosophical assumptions about reality. Yet, despite its predictive power, quantum mechanics remains one of the most counterintuitive theories ever formulated. Phenomena such as nonlocal correlations, entanglement, and the apparent instantaneous collapse of the wavefunction upon measurement continue to defy classical intuition and have motivated a wide range of interpretations among physicists 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 the quantum formalism, a measurement performed on one particle appears to instantaneously determine the state of the distant partner, regardless of the spatial separation between them. EPR regarded this as evidence that the quantum-mechanical description of physical reality must be incomplete. Einstein argued [3–5] that the expected value of a quantum observable should correspond to an element of physical reality, and that a measurement on one subsystem should not instantaneously influence the state of another. He suggested that a more complete theory—possibly one incorporating additional parameters or hidden variables—might restore determinism and locality to physical description. His reasoning was rooted in the principles of locality and realism [6].

The principles of *locality* and *realism* assert that physical systems are influenced only by their immediate surroundings and that physical properties exist with definite values independent of observation. In 1964, Bell formulated a theorem [7] showing that any hidden-variable theory consistent with local realism must satisfy a specific constraint—now known as Bell's inequality [8,9]. Applying the reasoning of the EPR scenario, Bell demonstrated that quantum mechanics predicts correlations that violate this inequality. Over the past decades, increasingly sophisticated experiments [10–15] have tested these predictions while closing both detection and locality loopholes. The robust experimental violations of Bell inequalities agree precisely with quantum mechanics and strongly rule out *local hidden-variable* theories. Importantly, the inferred nonlocality pertains to hidden-variable models, not to the quantum formalism itself.

Nevertheless, Bell's result is sometimes misinterpreted—even by distinguished physicists [16–18]—as demonstrating that quantum mechanics cannot be both local and realistic. However, Bell's theorem presupposes the existence of predefined values for observables—a condition not realized in quantum mechanics. The quantum contextuality established by the Kochen–Specker theorem [19–23], together with later developments such as the Greenberger–Horne–Zeilinger (GHZ) argument [24–28], demonstrates that it is impossible to assign predefined, measurement-independent values to quantum observables in a way that is consistent with the structure of the theory. These results show that even for sets of observables that are jointly measurable, the assumption of simultaneous definite values conflicts with the foundations of quantum mechanics [29]. Moreover, two of the spin observables appearing in Bell correlation are mutually incompatible (not commuting) and this incompatibility is the reason that quantum correlation exceeds classical bound [30]. Thus, Bell-type tests constrain *classical, local-realist hidden-variable extensions* of quantum mechanics, rather than quantum mechanics itself [31–35].

Although Bell's theorem does not prove that quantum mechanics must be nonlocal, most physicists accept nonlocality primarily due to the postulated instantaneous collapse of the wavefunction upon measurement. Within the standard Copenhagen interpretation, wavefunction collapse is viewed as a nonphysical update of information rather than a dynamical process [36]. However, recent work such as the Pusey–Barrett–Rudolph (PBR) theorem [37] argues in favor of an ontic interpretation, suggesting that the quantum state corresponds to a real physical entity. Whether the wavefunction represents knowledge (epistemic) or an element of physical reality (ontic) remains an open question. The ambiguous ontological status of the wavefunction, the absence of a physical mechanism for collapse, and the apparently nonlocal character of quantum measurement remain central controversies in the field. These issues are tied to the measurement problem and manifest in well-known paradoxes such as Schrödinger's cat [38] and Wigner's friend [39–41]. Clarifying these issues is also relevant for applied systems where quantum coherence and decoherence at material interfaces determine performance, such as in triboelectric nanogenerators (TENGs).

Since the 1970s, quantum decoherence [42–44] has been proposed as a framework for addressing the measurement problem. It provides a dynamical mechanism explaining the apparent collapse of the wavefunction through local system–environment interactions (see recent reviews [45–47]). Spin-environment models, introduced by Zurek [44,48], focus on the decoherence of a single spin (qubit) interacting with a spin bath.

The quantitative predictions of quantum decoherence theory have been subjected to rigorous and successful experimental testing across multiple physical platforms. A foundational prediction is the exponential decay of quantum coherence, governed by rates proportional to the system's coupling to its environment. This has been precisely verified in controlled experiments with trapped ions, where engineered noise sources induce dephasing whose timescales match theoretical models of the spectral noise density [49]. Matter-wave interferometry with large molecules and nanoparticles provides a direct test of spatial decoherence, where the loss of interference fringe visibility as a function of particle size, internal temperature, and background gas pressure quantitatively confirms theoretical decoherence rates [50]. Perhaps the most stringent tests come from superconducting qubits, where the ability to tailor dissipation channels allows for a side-by-side comparison between the predicted and observed decay of quantum states, demonstrating agreement over many orders of magnitude in environmental coupling strength [51]. These experiments collectively validate decoherence theory's core tenet: the transition from quantum to classical behavior is not instantaneous but follows a dynamical, predictable process dictated by the system-environment interaction.

In recent years a compelling alternative and more fundamental perspective has emerged, suggesting that gravity itself may be the underlying origin of decoherence, macroscopic irreversibility, and the arrow of time [52]. Unlike standard environmental decoherence, which necessitates an a priori division of the universe into a system and its surroundings, this approach posits spacetime geometry as an intrinsic, universal source of stochasticity.

Theoretical models, such as the stochastic extension of the Madelung quantum hydrodynamic framework [53,54], show that fluctuations in the spacetime curvature—potentially linked to phenomena like a gravitational wave background—can directly modulate the quantum potential, leading to the irreversible decay of quantum superpositions [55,56]. This framework naturally addresses conceptual challenges in the standard theory, such as the issue of noncollapsing of global wavefunction, by attributing an intrinsic stochastic character to the dynamics, which breaks time-reversal symmetry. Crucially, conventional "deterministic" quantum mechanics is recovered as the flat-spacetime, zero-noise limit of this more general stochastic quantum-gravitational description, thereby providing a foundational basis for the measurement postulate which otherwise appears ad hoc. Consequently, gravity is reframed not merely as another potential decoherence channel, but as a fundamental mechanism that couples quantum evolution to spacetime dynamics, driving the emergence of classical reality from a self-decohering quantum whole.

In this work, we first examine the assumptions required in the derivation of Bell's inequality in light of the incompatibility of quantum observables and the contextual nature of quantum measurements (Section 2). In Section 3, we investigate two entangled spin-1/2 particles in the EPR setting using a decoherence-based framework to compute Bell-type correlations. The resulting correlations are shown to be independent of both system–bath and inter-bath interactions, which influence only the rate of decoherence. Section 4 analyzes a general dynamic solution in EPR-Bell scenario, when one of the entangled particles interacts with its local environment. From this solution, we study the wavefunction collapse, entanglement, decoherence, and their implications for locality and realism. Section 5 presents numerical simulations and examines the impact of stochastic fluctuations arising from system–bath coupling strengths and from the initial microstates of the environment. We discuss the reality and locality in the light of decoherence framework in Section 6 and finally, we discuss our conclusions in Section 7.

2. Contextuality and Observable Incompatibility in Bell's Inequality

Bell's theorem [8,9] provides a profound result: no local hidden-variable theory can reproduce all statistical predictions of quantum mechanics. The theorem follows from a set of assumptions, many of which appear natural from a classical standpoint, yet several of them stand in tension with the orthodox formulation of quantum theory. In this section, we review the role and implications of these assumptions in detail.

Both the original EPR argument and Bell-type scenarios consider experiments involving two entangled spin-1/2 particles that, once having interacted, remain correlated in their measurable properties even when separated by large spatial distances. According to the standard quantum measurement postulate, a measurement performed on one particle *instantaneously* determines the corresponding outcome of its distant partner. This seems to imply an influence that propagates faster than light—Einstein's "spooky action at a distance"—and appears to conflict with the principle of locality. It also challenges the notion that physical properties possess definite values independent of measurement, i.e., the existence of "elements of reality."

Building on the EPR thought experiment, Bell formulated a strict inequality that transforms Einstein's philosophical critique into an experimentally testable condition within local hidden-variable models. In the commonly used CHSH form, the Bell parameter is defined as

$$S = E(a,b) - E(a,b') + E(a',b) + E(a',b'), \tag{1}$$

where $E(a,b)$ denotes the expectation value of the correlation between measurement outcomes of observables $\hat{A}$ and $\hat{B}$ with detector settings a and b, respectively. Within Bell's framework, the measurement outcomes $\hat{A}(a)$ and $\hat{B}(b)$ are represented by deterministic functions $A(a,\lambda)$ and $B(b,\lambda)$, where λ denotes hidden variables that uniquely predetermine all outcomes.

The expectation value of the correlation can then be written as

$$E(a,b) = \int A(a,\lambda)B(b,\lambda)\,\rho(\lambda)\,d\lambda, \tag{2}$$

where $\rho(\lambda)$ is a normalized probability density over hidden variables. Bell showed that any theory satisfying these assumptions must obey $S \leq 2$. This inequality can be tested experimentally.

2.1. Existence of Local Hidden Variables

Instead of expectation value of the correlation in Equation (2) by integration over hidden variables, orthodox quantum mechanics posits no hidden variables; the quantum state encodes the complete statistical information about the system. Quantum mechanics computes correlations as

$$E_{\mathrm{QM}}(a,b) = \langle\psi|\hat{A}(a)\hat{B}(b)|\psi\rangle, \tag{3}$$

where $|\psi\rangle$ is the quantum state. Crucially, quantum observables are not generally commuting: $\hat{A}\hat{B} \neq \hat{B}\hat{A}$. As a result, $E_{\mathrm{QM}}(a,b) \neq E_{\mathrm{QM}}(b,a)$. In contrast, the hidden-variable expression in Equation (2) always implies that all observables are commutable, $E_{\mathrm{HV}}(a,b) = E_{\mathrm{HV}}(b,a)$. Furthermore, quantum theory contains no underlying ontic variable λ that predetermines measurement outcomes. Thus, Bell's assumption of hidden variables introduces additional conceptual structure absent from standard quantum mechanics and fails to capture the fundamental noncommutativity of observable operators.

2.2. Local Hidden Variables Violate Quantum Contextuality

Bell's hidden-variable framework implicitly assumes noncontextuality in Equations (1) and (2): the outcome of measuring a correlation observable is assumed to be independent of the others. Quantum mechanics, however, is contextual. The Kochen–Specker theorem establishes that measurement outcomes in quantum mechanics cannot be understood as revealing pre-existing, context-independent properties of a system.

In Hilbert spaces of dimension three or greater, it is mathematically impossible to assign noncontextual hidden variables to all observables without contradiction. Measurement outcomes depend on which other commuting observables are simultaneously measured. As Peres noted [23]: "If three operators A, B, and C satisfy $[A,B] = [A,C] = 0$ and $[B,C] \neq 0$, the result of a measurement of A cannot be independent of whether A is measured alone or together with Bor C." This illustrates that contextuality of observables mark a fundamental departure from classical realism.

2.3. Violation of Bell Inequality as a Consequence of Observable Incompatibility

The violation of Bell-type inequalities can be understood not as evidence for intrinsic nonlocality, but as a consequence of the incompatibility of quantum observables [30]. The CHSH inequality assumes the existence of simultaneous, definite values for all observables involved, thereby implying a joint probability distribution. Quantum mechanics violates this bound because such joint distributions do not exist when observables correspond to noncommuting operators.

Consider the four observables $\hat{A}, \hat{A}', \hat{B}, \hat{B}'$ used in EPR–Bell experiments. The spin observables can be expressed using Pauli matrices:

$$\hat{A} = \mathbf{a} \cdot \boldsymbol{\sigma}^A, \hat{A}' = \mathbf{a}' \cdot \boldsymbol{\sigma}^A, \hat{B} = \mathbf{b} \cdot \boldsymbol{\sigma}^B, \hat{B}' = \mathbf{b}' \cdot \boldsymbol{\sigma}^B, \tag{4}$$

where $\mathbf{a}$, $\mathbf{a}'$, $\mathbf{b}$, $\mathbf{b}'$ are unit vectors describing detector orientations. Observables on distinct particles commute:

$$[\hat{A}, \hat{B}] = [\hat{A}, \hat{B}'] = [\hat{A}', \hat{B}] = [\hat{A}', \hat{B}'] = 0. \tag{5}$$

However, within each particle's subsystem, the operators are not commutable:

$$[\hat{A}, \hat{A}'] \neq 0, [\hat{B}, \hat{B}'] \neq 0.$$

The CHSH operator is defined as

$$\hat{S} = \hat{A}\hat{B} - \hat{A}\hat{B}' + \hat{A}'\hat{B} + \hat{A}'\hat{B}'. \tag{6}$$

Using $\hat{A}^2 = \hat{A}'^2 = \hat{B}^2 = \hat{B}'^2 = I$, Landau derived the identity [57,58]

$$\hat{S}^2 = 4I + [\hat{A}, \hat{A}'][\hat{B}, \hat{B}'], \tag{7}$$

where I is the identity operator. If either $[\hat{A}, \hat{A}'] = 0$ or $[\hat{B}, \hat{B}'] = 0$, then $\langle\psi|\hat{S}^2|\psi\rangle = 4$, and the Cauchy–Schwarz inequality yields

$$-2 \leq \langle\psi|\hat{S}|\psi\rangle \leq 2. \tag{8}$$

In EPR–Bell scenarios, however, both commutators in Equation (7) are non-zero. From Equation (4) and the Pauli algebra, we obtain

$$[\hat{A}, \hat{A}'] = 2i(\mathbf{a} \times \mathbf{a}') \cdot \boldsymbol{\sigma}^A, [\hat{B}, \hat{B}'] = 2i(\mathbf{b} \times \mathbf{b}') \cdot \boldsymbol{\sigma}^B. \tag{9}$$

Thus,

$$\hat{S}^2 = 4I - 4(\mathbf{a} \times \mathbf{a}') \cdot \boldsymbol{\sigma}^A\ (\mathbf{b} \times \mathbf{b}') \cdot \boldsymbol{\sigma}^B.$$

When $\mathbf{a} \perp \mathbf{a}'$ and $\mathbf{b} \perp \mathbf{b}'$, these cross products are maximized, and $\langle\psi|\hat{S}^2|\psi\rangle \leq 8$. Applying Cauchy–Schwarz again yields the Tsirelson bound [59]:

$$-2\sqrt{2} \leq \langle \psi | \hat{S} | \psi \rangle \leq 2\sqrt{2}. \quad (10)$$

Landau's inequality provides necessary and sufficient conditions for embedding correlations into a classical probability model. When observables are compatible, Equation (8) holds, and no Bell violation occurs. When observables are incompatible—noncommuting—no such embedding exists, and quantum correlations can exceed the classical bound.

Thus, the observed violations of CHSH inequalities arise from the incompatibility and contextuality of quantum measurements, rather than from any inevitable appeal to nonlocal mechanism.

In addition, the Greenberger-Horne-Zeilinger (GHZ) theorem [24–28], which demonstrates that merely assuming definite values for three commutable spin observables leads to a direct contradiction with quantum predictions [29]. Bell inequality violations arise from the incompatibility and contextuality of quantum observables, not from any intrinsic nonlocal influence. Because quantum observables cannot be assigned simultaneous, definite values, the classical assumptions underlying Bell's theorem do not apply to standard quantum mechanics.

3. Decoherence Framework for Bell-Type Correlations in the EPR Scenario

To analyze Bell-type correlations within a strictly local dynamical framework, we consider two entangled spin-1/2 particles, A and B, initially prepared in the singlet state and separated by a spacelike interval. Particle B interacts with an environmental bath consisting of $N > 0$ spins, while particle A remains isolated (Figure 1).

The total Hamiltonian is taken to be

$$H = H_{SE} + H_E + H_{E-E},$$

where H_E is free Hamiltonian of the environment and H_{E-E} describes internal bath interactions. The system-environment interaction is assumed to be a linear spin–spin coupling along the z-direction between spin B and environmental spins [44,48]:

$$H_{SE} = \frac{1}{2}\sigma_z^{(B)} \otimes \sum_{k=1}^{N} g_k \, \sigma_z^{(k)} \quad (11)$$

where $\sigma_z^{(B)}$ and $\sigma_z^{(k)}$ denote the Pauli z-operators of particle B and kth environment spin, respectively, and g_k is the coupling strength.

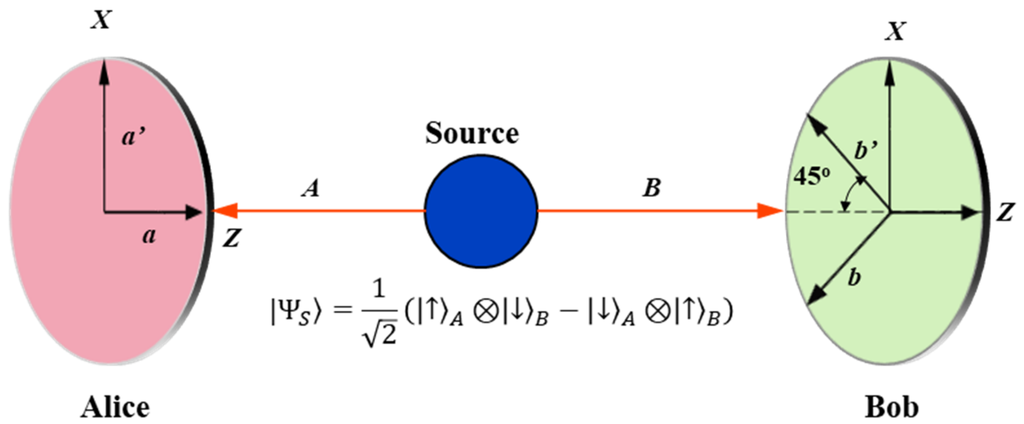

Figure 1. Schematic of Bell-EPR scenario with local decoherence. Two entangled spin-1/2 particles, A and B, are emitted in opposite directions toward Alice and Bob, who independently choose their spin-measurement settings $\mathbf{a}$, $\mathbf{a}'$ and $\mathbf{b}$, $\mathbf{b}'$ respectively. In this model, particle B interacts locally with a spin environment (bath) via a linear system–environment coupling H_{SE}, while particle A remains isolated.

The initial wavefunction of the system plus environment can be written as:

$$|\Psi_{SE}(0)\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle_A \otimes |\downarrow\rangle_B - |\downarrow\rangle_A \otimes |\uparrow\rangle_B) \otimes |E(0)\rangle, \quad (12)$$

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.

Under very general physical condition that H_{SE} acts only on spin *B*, H_E and H_{E-E} act solely on environment, the unitary evolution retains a two-branch form

$$|\Psi_{SE}(t)\rangle = \frac{1}{\sqrt{2}}[|\uparrow\rangle_A \otimes |\downarrow\rangle_B \otimes |E_\downarrow(t)\rangle - |\downarrow\rangle_A \otimes |\uparrow\rangle_B \otimes |E_\uparrow(t)\rangle], \tag{13}$$

No approximation is used—Equation (13) follows exactly from linear Schrödinger evolution with conditional environmental coupling to *B*.

The time-dependent state in Equation (13) allows us to evaluate Bell correlations under environmental decoherence. Within the CHSH formalism, the quantum Bell correlation is defined as:

$$S^{QM}(t) = E(\hat{A},\hat{B}) - E(\hat{A},\hat{B}') + E(\hat{A}',\hat{B}) + E(\hat{A}',\hat{B}'), \tag{14}$$

where $\hat{A},\hat{A}',\hat{B},\hat{B}'$ are defined in Equation (4). To maximize the Bell violation, we choose the standard optimal configuration (Figure 1):

$$\mathbf{a} = \hat{z},\ \mathbf{a}' = \hat{x},\ \mathbf{b} = -\frac{1}{\sqrt{2}}(\hat{z}+\hat{x}),\ \ \mathbf{b}' = \frac{1}{\sqrt{2}}(\hat{z}-\hat{x}),$$

which correspond to

$$\hat{A} = \sigma_z^A,\ \hat{A}' = \sigma_x^A,\ \hat{B} = -\frac{1}{\sqrt{2}}(\sigma_z^B + \sigma_x^B),\ \hat{B}' = \frac{1}{\sqrt{2}}(\sigma_z^B - \sigma_x^B)$$

Using the state in Equation (13), the expectation values evaluate to

$$E(\hat{A},\hat{B}) = \frac{1}{\sqrt{2}}, E(\hat{A},\hat{B}') = -\frac{1}{\sqrt{2}}, E(\hat{A}',\hat{B}) = \frac{1}{\sqrt{2}}, E(\hat{A}',\hat{B}') = \frac{1}{\sqrt{2}}$$

Substituting these into (14) gives:

$$S^{QM}(t) = 2\sqrt{2} \tag{15}$$

Remarkably, the Bell correlation $S^{\mathrm{QM}}(t)$ remains constant throughout the decoherence process and is independent of system-bath coupling as well as bath internal dynamics. This indicates that quantum correlations, as captured by the CHSH quantity, are robust to the internal dynamics of the environment and do not decay with the loss of coherence in the local reduced states.

This result is fully consistent with the Born rule and reproduces the standard quantum prediction ($2\sqrt{2}$) for the Bell-CHSH parameter in the limit of ideal, decoherence-free conditions. Crucially, and as demonstrated by our model, this ideal correlation value remains robust independent of decoherence strength for a class of environmentally induced dephasing. This prediction of decoherence-independent nonlocality aligns with high-precision, loophole-free Bell tests [10–15,60,61], where violations persist at the theoretical maximum despite inevitable experimental noise. Our framework thus shows that the correct measurement statistics of quantum theory can be recovered *without invoking instantaneous wavefunction collapse or superluminal influences*. The measurement process is instead treated as a local, dynamical evolution in the Schrödinger picture, where decoherence selectively suppresses specific coherences while leaving the entangled correlations that underpin nonlocal statistics intact.

4. Dynamics of Entanglement and Decoherence in the EPR Scenario

The time dependent state in Equation (13) can be used to study the dynamical wavefunction collapse under decoherence. 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. 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.

$$|\uparrow\rangle_A \to |\uparrow\rangle_A$$

$$|\downarrow\rangle_A \to |\downarrow\rangle_A$$

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

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

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:

$$z(t) = \langle E_\downarrow(t)|E_\uparrow(t)\rangle$$

This decoherence factor $z(t)$ depends on is the interacting strength g_k between particle B and kth spin in the bath, the initial bath states, as well as bath self and internal Hamiltonians H_E, H_{E-E}. Notably, the expressions for the environment states remain identical to those in ref. [48], despite the fact that our system comprises two entangled particles—one of which interacts with the environment—whereas the system in ref. [48] 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.

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 [48] following the approximation for $z(t) \doteq e^{iat-bt^2}$, 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 [44] 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:

$$\rho_s(t) = \frac{1}{2}\{|\uparrow\rangle_A\langle\uparrow|_A \otimes |\downarrow\rangle_B\langle\downarrow|_B + |\downarrow\rangle_A\langle\downarrow|_A \otimes |\uparrow\rangle_B\langle\uparrow|_B\} \quad (16)$$

In Zurek's terminology, Equation (16) indicates that the environment dynamically selects two product 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 [45]. The environmental interaction progressively suppresses the coherence between these two branches, eliminating any physically accessible superposition. As a result, the system approaches a statistical mixture in which each pointer state occurs with 50% probability, in agreement with the Born rule and the standard quantum measurement postulate.

This result highlights a key feature of decoherence: the global entangled pair evolves into an improper mixture, even though subsystem A never directly couples to the environment. Crucially, the local quantum state of A remains unaltered. Our analysis demonstrates that for two entangled particles separated by a space-like interval, decoherence in one subsystem induces no physical change—no dynamical collapse, no superluminal signaling, and no "spooky action at a distance"—in the other (Figure 2). All evolution is accounted for by local interactions. The final step of the measurement occurs when Bob's apparatus, having rapidly decohered, registers a definite outcome. At this point, Alice's knowledge of the global state updates instantaneously, revealing to her the definite pointer state of her distant particle. This final update is not a physical process but a purely epistemic one, reflecting a change in information rather than a change in the physical state of her subsystem

It is commonly stated that a measurement on one particle of an entangled pair instantaneously determines, or "reveals," the quantum state of its distant partner, regardless of spatial separation or the absence of any mediating physical interaction—an implication that Einstein famously regarded as unsatisfactory. The present analysis suggests a more nuanced picture. Within the decoherence framework studied here, the emergence of (improperly) mixed state can be accounted for through local system–environment interactions alone, without invoking a superluminal interaction.

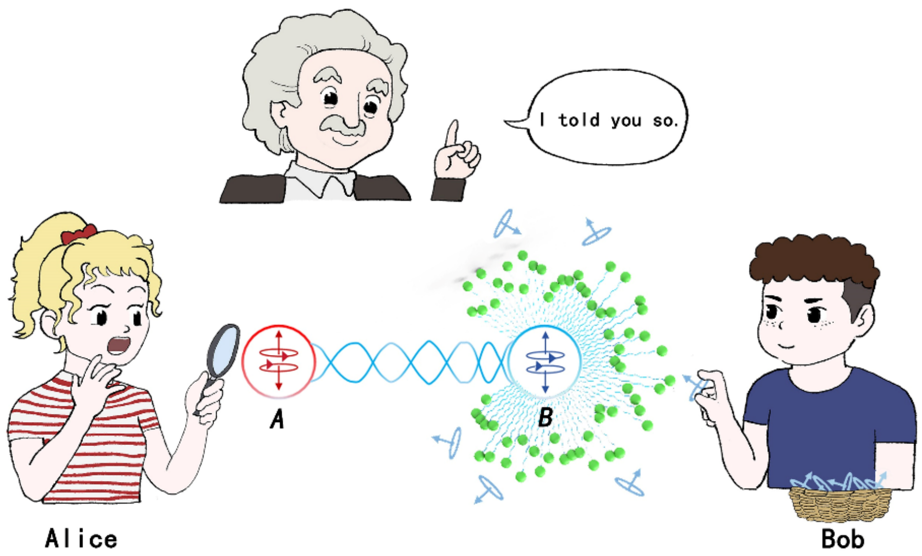

Figure 2. Schematic of an EPR-like system. Two entangled spin-1/2 particles, *A* and *B*, propagate in opposite directions toward Alice and Bob. Bob allows *N* = 6 environmental spins, corresponding to 2^N environmental basis states (green spheres), to interact with particle *B*, Meanwhile, Alice observes the spin state of particle *A*—under the watchful supervision of Einstein.

5. Numerical Simulations of Decoherence under Stochastic Environmental Dynamics

Having showed the decoherence framework for EPR scenario in a bath model independent manner, we now applying a simple analytic and numerical model to the decoherence factor $z(t)$ and show the impact of randomness of environment. Assume the inter-bath interaction is zero, thus the total Hamiltonian is

$$H = H_{SE} = \frac{1}{2}\sigma_z^{(B)} \otimes \sum_{k=1}^{N} g_k\, \sigma_z^{(k)} \tag{17}$$

This model can be solved analytically with arbitrary $\{g_k\}$ and *N*. Here we assume the bath spins are initially entangled. The wavefunction of the system plus environment is still the same as Equation (13) with the two environment states explicitly as:

$$|E_\uparrow(t)\rangle = \sum_{n=0}^{2^N-1} c_n e^{-\frac{iB_n t}{2}} |n\rangle,$$
$$|E_\downarrow(t)\rangle = \sum_{n=0}^{2^N-1} c_n e^{\frac{iB_n t}{2}} |n\rangle. \tag{18}$$

where $B_n = \sum_{k=1}^{N} (-1)^{n_k} g_k$ and $n_k = 0$ if the *k*th spin in the bath is aligned with *z* and $n_k = 1$ if it is anti-aligned. $|E(0)\rangle = \sum_{n=0}^{2^N-1} c_n |n\rangle$, c_n are complex numbers for bath computational basis state $|n\rangle, n = 0 \ldots 2^N - 1$, corresponds uniquely to its associated spin configuration $\{n_k\}$, as determined by its binary representation given in Equation (19):

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

$$\ldots\ldots$$

$$|n\rangle = |\downarrow\rangle_1 |\uparrow\rangle_2 |\uparrow\rangle_3 \ldots |\downarrow\rangle_k \ldots |\uparrow\rangle_N \tag{19}$$

$$\ldots\ldots$$

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

The above solution can be verified by substituting it to the Schrödinger equation with the Hamiltonian $H = H_{SE}$. The decoherence factor $z(t)$ is expressed by

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

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 *k*th spin in the bath.

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 uniformly distributed [48] in [−2, 2]. In this analysis, we disregard the randomness associated the initial distribution of environment spins by assuming that each spin has 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 [48] (Curve A and B in Figure 3). 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 [62], induces decoherence on a nanosecond timescale.

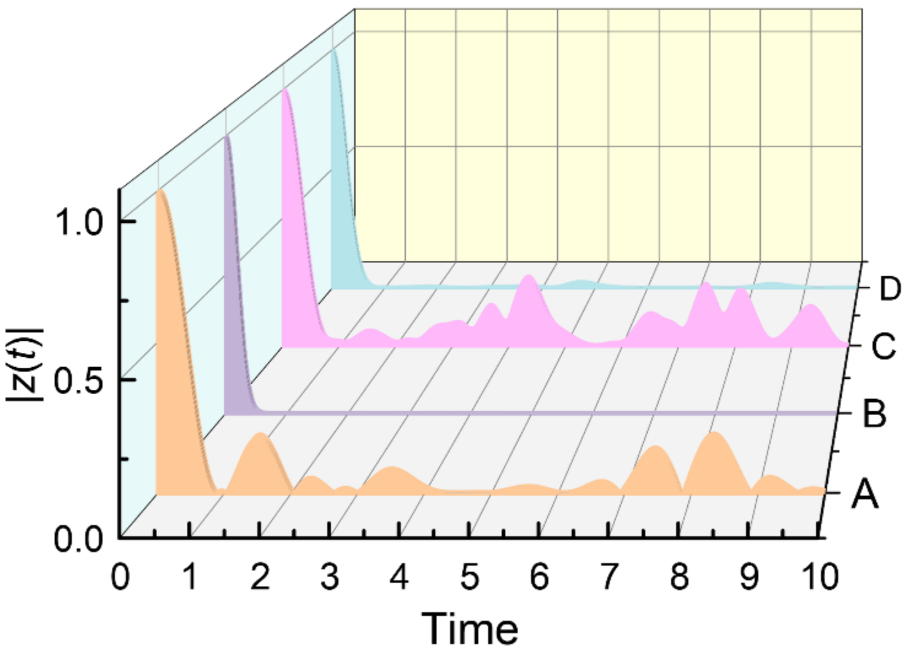

Figure 3. Monte Carlo simulations of decoherence induced by the environment. A, B are with random interaction strengths g_k with N = 6 and 24, respectively. C, D add random distribution of bath initial states with N = 6 and 24, respectively. The unit of time is roughly in nanosecond for electron spin in GaAs quantum dot.

The impact of randomness from initial environment spins are considered in Figure 3 curve 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.

The individual contributions from all $2^6 = 64$ basis states are illustrated in Figure 4, which corresponds to curve C in Figure 3. These contributions account for both the inherent stochasticity in the initial spin states of the environment and the variability in their interaction strengths. The results reflect the combined effects of random sampling over environmental spin states and the heterogeneous coupling parameters governing their interactions with the system.

Beyond the analytic model presented here, a variety of more sophisticated theoretical frameworks—including models incorporating non-Markovian dynamics, structured or correlated spin environments, and stochastic fluctuations in system–bath coupling—have been developed to study spin-bath–induced decoherence [63–67]. State-of-the-art numerical techniques such as multiscale simulations, tensor-network methods, and hierarchical equations of motion further enable accurate modeling of strongly coupled or non-Markovian spin environments [68–70].

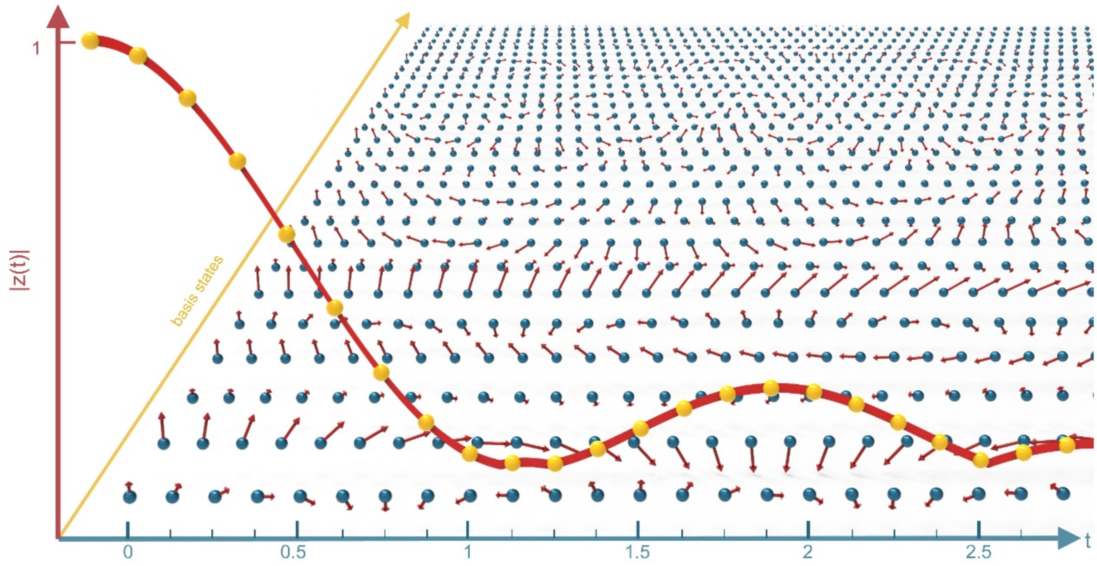

Figure 4. Contributions of the decoherence factor from $2^6 = 64$ basis states in Figure 2C. Each basis state has different magnitude c_n, representing random initial states from environment, and different rotation rates, representing random interaction strength. At $t = 0$, all basis states are aligned up, producing a large $|z(t)| = 1$. 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 3.

More general decoherence models, extending beyond spin-bath interactions, likewise demonstrate that decoherence typically occurs on extremely short timescales. For a macroscopic object with mass 1 g and size 1 cm, the ratio of decoherence time to thermal relaxation time is on the order of 10^{-40}, implying effectively instantaneous decoherence. In mesoscopic systems—for example, dust particles of mass 10^{-15} kg and radius 0.1 μm—exposure to the 3 K cosmic microwave background leads to decoherence within approximately 10^{-7} s. Even microscopic systems, including large molecules, experience a rapid loss of coherence due to interactions with ambient thermal radiation, with timescales far shorter than can be experimentally resolved [71–73].

Although these models differ in mathematical formulation and computational complexity, their quantitative predictions for the decoherence process remain broadly consistent with our results: coherence decays rapidly, the off-diagonal elements of the reduced density matrix are suppressed, and the system evolves into an effectively mixed state. This convergence across distinct approaches strongly reinforces the robustness of the decoherence mechanism and supports the reliability of the analytic framework developed in this work.

6. Reality and Locality within the Decoherence-Based Framework

The nature of physical reality has been a central question in quantum foundations since the inception of quantum mechanics. Einstein famously insisted on an objective reality that exists independently of observation—captured in his often-quoted question: "Is the Moon there when nobody looks?" His conviction reflected a realist position in which physical quantities such as position, momentum, or spin possess definite, observer-independent values. In this view, measurement merely reveals pre-existing properties of a system. However, this assumption conflicts with quantum contextuality [19–23] and is further ruled out by the Greenberger–Horne–Zeilinger (GHZ) results [24–29], which show that noncontextual, value-definite assignments of measurement outcomes are incompatible with quantum predictions.

By contrast, the orthodox Copenhagen interpretation rejects this form of realism. It holds that quantum properties do not have context-independent existence, and that measurement plays a constitutive role in bringing such properties into being [74,75]. In this viewpoint, "reality" is contextual and measurement-dependent: the wavefunction is taken to represent information or knowledge about the system, and wavefunction collapse corresponds to the observer's update of information rather than a physical process [36].

Whether the wavefunction is fundamentally epistemic or ontic—whether it describes knowledge or reality itself—remains a central open question. Recent theoretical developments, most notably the Pusey–Barrett–Rudolph (PBR) theorem [37], together with advances in quantum state tomography [76–79], provide strong evidence that the quantum state cannot merely represent information or subjective knowledge. Quantum tomography allows the full reconstruction of a system's quantum state from a complete set of measurements performed on identically prepared ensembles, indicating that the wavefunction encodes objective physical features rather than just observers' beliefs. These results strengthen the case for an ontic view of the wavefunction, suggesting that realism may be reconciled with quantum theory by treating the wavefunction as a real physical entity, rather than by assuming pre-existing values for observables. This offers a path toward preserving Einstein's aspiration for an objective physical world, but through a conceptually distinct route.

A key observation is that the Schrödinger equation is fundamentally *local:*

$$i\hbar\frac{\partial}{\partial t}\psi(x,t)=\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}+V(x,t)\right]\psi(x,t),$$

where the evolution of the wavefunction at a space-time point depends only on the Hamiltonian and potential in its immediate vicinity. In our decoherence-based model, all interactions—including those between system, apparatus, and environment—are treated within this local unitary evolution. If the wavefunction is taken as ontic, this suggests that quantum mechanics can be interpreted as a *local realist theory,* provided the measuring apparatus and its environment are included as physical degrees of freedom in the dynamics.

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 mixed pointer states, regardless of whether Wigner later inquiries about the outcome.

Although decoherence does not collapse the global wavefunction of the system and environment, as shown in Equation (13), nor fully resolves the measurement problem, 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. Thus, decoherence provides a natural account of measurement statistics without invoking instantaneous, nonlocal collapse, and does so within the standard Schrödinger evolution.

7. Discussion and Conclusions

In this work, we revisited the foundational assumptions underlying the derivation of Bell's inequality and argued that Bell's theorem—together with the experimental violations of the inequality—rules out only *local realistic hidden-variable theories,* not quantum mechanics itself. The derivation of the Bell inequality presupposes the simultaneous existence of definite values for incompatible, noncommuting observables, as well as underlying hidden variables that determine all measurement outcomes. Both assumptions are foreign to quantum mechanics, particularly in the EPR–Bell setting where observables are noncommutative. Moreover, the assumption of predefined observable values conflicts directly with quantum contextuality, as demonstrated by the Kochen–Specker and Greenberger–Horne–Zeilinger (GHZ) theorems.

Recent advances—most notably the Pusey–Barrett–Rudolph (PBR) theorem—further support an *ontic interpretation of the wavefunction,* in which the quantum state represents a genuine element of physical reality rather than merely encoding knowledge or information. This perspective offers a conceptual route for restoring realism within quantum theory without invoking hidden variables or nonlocal influences.

To substantiate this view, we developed a quantum decoherence model for an EPR-like system in which system–environment interactions are treated as intrinsic components of the measurement process. Both analytical derivations and Monte Carlo simulations demonstrate that a measurement performed on one particle neither instantaneously collapses the global wavefunction nor determines the state of its distant partner. Instead, the local wavefunction of the measured particle evolves unitarily together with its environment through entirely local interactions, while the remote particle remains unaffected. Decoherence induced by the local environment dynamically selects stable pointer states and rapidly suppresses interference terms, producing the *appearance* of wavefunction collapse without requiring any nonlocal physical mechanism.

Importantly, our results show that quantum correlations between the two entangled particles remain fully consistent with standard quantum predictions and are independent of the intra-bath and system-bath coupling strengths, which influence only the decoherence rate. This indicates that entanglement and its statistical manifestations are intrinsic properties of the initial quantum state, not artifacts of environmental dynamics.

The framework presented here is fully compatible with standard quantum mechanics, including predictions derived from the measurement postulate in the EPR scenario. This agreement emerges naturally from the density-matrix formalism underlying decoherence, which already incorporates the Born rule. For an open quantum system interacting with an environment possessing many degrees of freedom, the observable statistics become indistinguishable from those predicted by the conventional measurement postulate. The only difference arises at the earliest stages of interaction, where decoherence provides a continuous, unitary description that smoothly evolves toward an effectively mixed state on extremely short timescales.

Looking forward, the principles elucidated here could inform the design of next-generation nano-energy harvesting systems. For instance, in Triboelectric Nano-generators (TENGs) [80], the initial charge separation event is a quantum surface process that is rapidly influenced by its local environment. Our detailed account of decoherence dynamics invites the question of whether the quantum coherence of charge carriers, however brief, could be harnessed or protected to enhance triboelectric efficiency, opening a new path for quantum-informed energy materials.

While our analysis within the standard decoherence framework correctly describes the phenomenology of classical emergence, the gravitational decoherence perspective suggests a deeper origin. The effective 'environment' responsible for decoherence in our model could be understood as emerging from the universal dynamics of spacetime geometry. This viewpoint naturally addresses conceptual challenges of the standard framework, such as the issue of noncollapsing of global wavefunction, by attributing an intrinsic stochastic character to quantum evolution via curvature fluctuations [52–54].

Overall, these findings suggest that quantum mechanics can, in principle, be reconciled with *local realism* if the wavefunction is regarded as an ontic element of reality in the EPR–Bell scenario. This interpretation yields a coherent and physically grounded framework aligned with Einstein's original aspiration for an objective account of physical phenomena. Beyond foundational implications, our results offer conceptual clarity relevant to quantum information science, where a precise understanding of measurement, decoherence, and the ontology of quantum states is essential for quantum communication and computation.

Author Contributions

The author solely conceived the study, conducted the research, analyzed the results, and wrote the manuscript.

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Data Availability Statement

All data generated or analyzed during this study are included in this article. The MATLAB scripts used to generate Figures 3 and 4 are available from the corresponding author upon reasonable request.

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Conflicts of Interest

The author declares no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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