Information-Induced Wavefunction Collapse: A Quantized View of Observation

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Abstract

This paper presents a novel interpretation of wavefunction collapse grounded in quantum information theory. We propose that collapse is not triggered by observation itself, but by a quantized increase in a system's informational entropy. Specifically, we introduce a threshold condition: collapse occurs only when the von Neumann entropy of the system exceeds a critical value, δIc, due to entanglement with the environment. This reframing allows wavefunction collapse to be understood as an objective, testable process driven by entropy flow, rather than subjective measurement. We formalize this framework using mathematical postulates and simulate its behavior in canonical quantum setups, including the double-slit experiment, spin measurement, and Schrödinger's cat. The model not only aligns with known phenomena but also makes falsifiable predictions—suggesting that collapse is conditional and occurs only beyond an entropy threshold. This provides a new lens on the quantum measurement problem and opens experimental paths for validating information-induced collapse.

1 Introduction

The interpretation of quantum measurement remains one of the most profound unresolved problems in physics. In standard quantum mechanics, systems evolve unitarily according to the Schrödinger equation until a measurement is performed, at which point the wavefunction appears to "collapse" to a definite state. However, the theory provides no clear mechanism or condition under which this collapse occurs.

Interpretations such as the Copenhagen model treat collapse as observer-induced and fundamentally subjective. Alternatives like the many-worlds interpretation eliminate collapse entirely but at the cost of ontological proliferation. Decoherence theory explains the emergence of classicality through environmental entanglement, yet it stops short of identifying a definitive moment or threshold for when superpositions become classical outcomes.

In this work, we propose an alternative approach: the entropy-threshold collapse model. We hypothesize that collapse occurs not because of observation or irreversibility alone, but when a quantum system gains a quantized amount of informational entropy through entanglement with its environment. Specifically, we postulate a threshold condition:

$$\Delta S \geq \delta I_c$$

where ΔS is the von Neumann entropy gain of the system and δI_c is a quantized critical value (e.g., $\log 2$) representing the smallest informational unit that can induce collapse.

This model reframes wavefunction collapse as an objective, quantifiable, and testable process—driven by informational entropy, not classical observation. It aligns with the principles of quantum information theory, and avoids paradoxes such as Schrödinger's cat or delayed-choice outcomes by anchoring collapse in measurable dynamics.

We support this hypothesis with three canonical simulations—double-slit interference, spin measurement, and partial entanglement—showing that collapse occurs only when the entropy threshold is crossed. Furthermore, we outline experimental pathways for validating the model using weak measurements, entropy tracking, and quantum computing platforms.

Our goal is not to discard quantum mechanics, but to extend it with a simple but powerful informational postulate that transforms wavefunction collapse from a mystery into a measurable phenomenon.

This idea leads to two significant implications:

- Information is a physically quantized quantity, much like energy or momentum.
- Wavefunction collapse can be described as a threshold event driven by informational transitions.

We draw on foundational ideas from Shannon entropy, von Neumann entropy, and quantum decoherence to build a mathematical framework. Using well-known experiments, such as the double-slit and Stern-Gerlach setups, we illustrate how this interpretation may resolve ambiguities about when and how collapse occurs.

Our goal is to initiate a deeper inquiry into the connection between entropy and quantum state reduction, offering a new lens on the measurement problem.

2 Theoretical Framework

We aim to formalize a hypothesis in which the collapse of a quantum system's wavefunction is not tied directly to conscious observation, but to a discrete, quantized change in its informational entropy. We begin by setting the formal groundwork using the language of quantum information theory.

2.1 Postulates

1. **Unitary Evolution:** The time evolution of a closed quantum system is governed by the Schrödinger equation, resulting in unitary evolution of the state vector $|\psi(t)\rangle$ or the density operator $\rho(t)$.

2. **Informational Collapse Criterion:** A wavefunction ρ collapses to a definite state when the informational entropy of the system increases by at least a critical threshold δI_c:

$$\Delta S = S(\rho') - S(\rho) \geq \delta I_c$$

   where $S(\cdot)$ denotes the von Neumann entropy, and $\rho' = \mathrm{Tr}_E(\rho_{SE})$ is the reduced density matrix after interaction with the environment E.

3. **Quantization of Information:** The entropy difference ΔS is constrained to change in discrete units. That is, informational change is quantized:

$$\Delta S \in \{n \cdot \delta I_c \mid n \in \mathbb{Z}^+\}$$

2.2 Von Neumann Entropy

Given a density matrix ρ for a system in a (possibly mixed) state, the von Neumann entropy is defined as:

$$S(\rho) = -\mathrm{Tr}(\rho \log \rho)$$

This entropy quantifies the uncertainty or informational content associated with the state ρ. For a pure state, $S(\rho) = 0$, and for a maximally mixed state in d dimensions, $S(\rho) = \log d$.

2.3 Collapse via Environment-Induced Entanglement

When a system S interacts with an environment E, the joint system $S + E$ evolves unitarily into an entangled state:

$$\rho_{SE} = U(\rho_S \otimes \rho_E)U^\dagger$$

The observer or environment acquires partial information about the system. To study the effective state of the system, we compute the partial trace:

$$\rho'_S = \mathrm{Tr}_E(\rho_{SE})$$

Collapse is hypothesized to occur if the entropy change of ρ'_S from the initial ρ_S satisfies:

$$S(\rho'_S) - S(\rho_S) \geq \delta I_c$$

2.4 Comparison to Decoherence

Decoherence theory describes how interaction with an environment suppresses quantum coherence, transforming a pure state into an apparent statistical mixture. This framework explains why macroscopic systems appear classical, and it models the emergence of pointer states through environment-induced superselection.

However, decoherence alone does not explain why or when a particular measurement outcome becomes definite. It describes loss of coherence, not actual collapse. In decoherence, all outcomes remain encoded in the global wavefunction.

Our model builds on decoherence but introduces a distinct criterion for collapse: a discrete threshold in entropy gain. Collapse occurs only when the entropy increase ΔS meets or exceeds a critical threshold δI_c. Below this threshold, the system remains in a coherent or mixed superposition, even if partial decoherence occurs. This distinguishes our model by introducing an objective, testable condition for the transition from quantum possibilities to classical definiteness.

A key implication is that collapse and definite outcomes may not occur in weak measurement scenarios or minimal entanglement regimes. In such cases, decoherence may yield partial mixtures, but our model does not predict collapse unless the change in entropy exceeds δI_c. This divergence offers a potential experimental test of the model.

2.5 Formal Derivations: Entropy-Driven Collapse

We provide a detailed mathematical formalism underpinning the entropy-threshold collapse model, linking wavefunction evolution, decoherence, and entropy gain.

2.5.1 Composite System and Unitary Evolution

Let the universe be partitioned into a system S and its environment E. The total state is described by a pure state in the Hilbert space $\mathcal{H}_S \otimes \mathcal{H}_E$:

$$|\Psi\rangle_{SE} = \sum_i c_i |s_i\rangle \otimes |e_i\rangle$$

The evolution is governed by the Schrödinger equation:

$$i\hbar \frac{d}{dt} |\Psi(t)\rangle = \hat{H}_{SE} |\Psi(t)\rangle$$

2.5.2 Reduced Density Matrix and Decoherence

The system state is obtained by tracing out the environment:

$$\rho_S = \mathrm{Tr}_E \left(|\Psi\rangle_{SE} \langle\Psi|_{SE} \right) = \sum_{i,j} c_i c_j^* \langle e_j | e_i \rangle |s_i\rangle \langle s_j|$$

If the environment states become orthogonal due to entanglement ($\langle e_j | e_i \rangle = \delta_{ij}$), the off-diagonal terms vanish:

$$\rho_S = \sum_i |c_i|^2 |s_i\rangle \langle s_i|$$

This transition represents *environment-induced decoherence* and reflects loss of quantum coherence.

2.5.3 Von Neumann Entropy

The information content of the reduced system is given by its von Neumann entropy:

$$S(\rho_S) = -\mathrm{Tr}(\rho_S \log \rho_S)$$

For a diagonalized state:

$$\rho_S = \sum_i p_i |s_i\rangle \langle s_i| \quad \Rightarrow \quad S(\rho_S) = -\sum_i p_i \log p_i$$

In the case where all $p_i = \frac{1}{d}$ for a d-dimensional system, $S = \log d$, which is the maximal entropy (completely mixed state).

2.5.4 Entropy Threshold Collapse Condition

We define the collapse criterion as follows:

$$\Delta S = S(\rho'_S) - S(\rho_S) \geq \delta I_c$$

Here:

- ρ_S is the pre-interaction reduced density matrix.
- ρ'_S is the post-interaction state (after entanglement or decoherence).
- δI_c is the critical entropy gain required for collapse.

If this condition is met, the system undergoes wavefunction collapse:

$$\rho_S \mapsto \rho_{\text{collapsed}} = |s_k\rangle \langle s_k| \quad \text{with probability } p_k = \langle s_k| \rho_S |s_k\rangle$$

2.5.5 Stochastic Collapse Dynamics

Alternatively, collapse can be modeled as a probabilistic, entropy-driven map:

$$\rho_S(t + \delta t) = \begin{cases} |s_k\rangle \langle s_k| & \text{if } \Delta S \geq \delta I_c \\ \rho_S(t) & \text{otherwise} \end{cases}$$

This approach models collapse as a threshold-triggered event, influenced by the entanglement and information flow between system and environment.

2.5.6 Relation to Lindblad Master Equation

In open quantum systems, the time evolution of ρ_S under decoherence is often described by the Lindblad master equation:

$$\frac{d\rho_S}{dt} = -\frac{i}{\hbar}[H_S, \rho_S] + \sum_k \left(L_k \rho_S L_k^\dagger - \frac{1}{2}\{L_k^\dagger L_k, \rho_S\} \right)$$

The entropy $S(\rho_S(t))$ is monotonically increasing under this evolution. Collapse occurs if this entropy gain surpasses the threshold δI_c during evolution.

2.6 Estimating the Entropy Threshold δI_c

The entropy threshold δI_c plays a pivotal role in our collapse model. To give it physical significance, we explore three possible interpretations:

1. **Bitwise Collapse Threshold:** A natural lower bound is one bit:

$$\delta I_c = \log 2$$

   This aligns with resolving a binary quantum state.

2. **Dimensional Scaling:** For larger systems:

$$\delta I_c = \alpha \cdot \log d$$

   where d is the system's Hilbert space dimension.

3. **Dynamical Origin:** δI_c may be emergent, related to entropic instabilities or decoherence time constants.

Future work may derive δI_c from physical constants or measure it experimentally.

2.7 Quantization of Informational Change

The assumption that informational entropy changes occur in discrete units is motivated by the inherently digital nature of quantum measurements and finite-dimensional Hilbert spaces.

1. **Discreteness in Finite Systems:** In quantum systems with finite-dimensional state spaces, such as spin-$\frac{1}{2}$ particles or qubit registers, the von Neumann entropy has a finite set of possible values determined by the eigenvalues of the reduced density matrix. This discretization naturally results in stepwise changes in entropy during interactions with measurement devices or environments.

2. **Bitwise Information Transfer:** From a quantum information perspective, each projective measurement yields a finite number of classical bits. The entropy gain associated with such measurements is therefore bounded below by $\log 2$, the entropy of a single binary decision. As such, entropy evolution in open quantum systems can be modeled as proceeding via quantized steps, consistent with the digital structure of information transfer.

3. **Thermodynamic Constraints:** Landauer's principle asserts that erasing one bit of information in a system at temperature T requires a minimum energy cost of $k_B T \log 2$. This suggests a fundamental granularity to information change in physical systems, reinforcing the notion that entropy transitions are not continuous at all scales.

In this model, we formalize this observation by postulating that entropy gain ΔS must occur in quantized increments of δI_c, reflecting both the underlying physical and informational granularity of quantum measurement.

3 Comparison to Existing Interpretations

Quantum mechanics has long supported a variety of interpretations to explain the process of wavefunction collapse and the role of measurement. In this section, we compare our entropy-threshold framework with major existing models and discuss their conceptual differences and intersections.

3.1 3.1 Copenhagen Interpretation

The Copenhagen interpretation, formulated by Niels Bohr [1], posits that quantum systems exist in superpositions until observed, at which point they collapse into definite eigenstates. However, this model does not rigorously define what constitutes an "observer" or why the act of measurement causes collapse.

In contrast, our entropy-based model avoids appeals to consciousness or classical observation. Instead, it introduces an objective, quantifiable collapse criterion:

$$\Delta S = S(\rho') - S(\rho) \geq \delta I_c$$

This reframes the collapse not as a subjective process, but as an entropic transition governed by a physical information threshold.

3.2 3.2 Many-Worlds Interpretation (MWI)

The MWI, proposed by Everett [2], suggests that all possible outcomes of a quantum event actually occur in a branching multiverse. Collapse is seen as an illusion caused by entanglement between observer and system.

Our model aligns with MWI in treating quantum evolution as fundamentally unitary. However, it diverges by asserting that only outcomes with sufficient entropy change become "classical" — i.e., only those meeting the information threshold are observable as distinct branches. This offers a criterion for effective branching and could help resolve the issue of preferred basis selection.

3.3 3.3 Decoherence Theory

Decoherence, as developed by Zurek [3], explains the loss of quantum coherence due to environmental entanglement, which makes quantum systems appear classical. While decoherence successfully describes the suppression of interference, it does not explain why a particular outcome is realized.

Our framework builds on decoherence by adding a discrete, quantized entropy-based collapse condition. We accept decoherence as a mechanism for entanglement-induced information flow, but propose that collapse only occurs when:

$$\Delta S = S(\rho'_S) - S(\rho_S) \geq \delta I_c$$

Thus, decoherence explains how superpositions become mixtures, and our model explains how and when mixtures become definite outcomes.

3.4 3.4 Objective Collapse Models

Objective collapse models such as GRW [4] introduce spontaneous, random collapse events to resolve the measurement problem without invoking observers. These models postulate new physical processes to account for collapse.

In contrast, our entropy-threshold model remains within the standard quantum framework but adds an information-theoretic postulate. It does not invoke randomness or new forces, but attributes collapse to a quantized change in entropy due to entanglement with the environment.

3.5 3.5 Summary

Interpretation	**Collapse Mechanism**
Copenhagen [1]	Observation or measurement causes collapse.
Many-Worlds [2]	No collapse; all outcomes occur in parallel.
Decoherence [3]	Environment suppresses interference but no collapse.
Objective Collapse (GRW) [4]	Spontaneous collapses governed by physical laws.
Entropy Threshold (This Work)	Collapse occurs when entropy gain exceeds critical threshold δI_c.

4 Applications to Canonical Quantum Systems

To demonstrate the viability of our entropy-threshold model of collapse, we now apply it to several standard quantum mechanical experiments. In each case, we explore how wavefunction collapse may be understood as a consequence of a quantized information threshold being reached during interaction with an observer or environment.

4.1 4.1 Double-Slit Experiment

Consider an electron passing through a double-slit apparatus. In the absence of measurement, the system evolves as a coherent superposition of two paths:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\text{Left}\rangle + |\text{Right}\rangle)$$

The corresponding density matrix is:

$$\rho = |\psi\rangle\langle\psi| = \frac{1}{2}\begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

Introducing a detector correlates the electron's path with environment states:

$$|\psi\rangle_{SE} = \frac{1}{\sqrt{2}}(|\text{Left}\rangle \otimes |E_L\rangle + |\text{Right}\rangle \otimes |E_R\rangle)$$

Assuming orthogonality of environment states ($\langle E_L|E_R\rangle = 0$), the reduced system state becomes:

$$\rho' = \text{Tr}_E(\rho_{SE}) = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

This is a mixed state with von Neumann entropy:

$$S(\rho') = -\text{Tr}(\rho' \log \rho') = \log 2$$

Since initial entropy $S(\rho) = 0$, the change in entropy is:

$$\Delta S = \log 2$$

If $\log 2 \geq \delta I_c$, the collapse condition is met, and the electron is found to have gone through a definite slit.

4.2 4.2 Spin Measurement

A spin-1/2 particle is prepared in:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow_z\rangle + |\downarrow_z\rangle)$$

After interaction with a measurement apparatus:

$$|\Psi\rangle_{SM} = \frac{1}{\sqrt{2}}(|\uparrow_z\rangle \otimes |M_\uparrow\rangle + |\downarrow_z\rangle \otimes |M_\downarrow\rangle)$$

Tracing out the measurement device gives:

$$\rho'_S = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \Rightarrow S(\rho'_S) = \log 2$$

Again, the entropy gain:

$$\Delta S = \log 2$$

triggers collapse if $\log 2 \geq \delta I_c$, consistent with observing a definite spin value.

4.3 4.3 Schrödinger's Cat

The superposition:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\mathrm{Alive}\rangle + |\mathrm{Dead}\rangle)$$

is rapidly decohered by entanglement with the environment. The reduced density matrix becomes diagonal:

$$\rho' = \frac{1}{2}(|\mathrm{Alive}\rangle\langle\mathrm{Alive}| + |\mathrm{Dead}\rangle\langle\mathrm{Dead}|)$$

Entropy:

$$S(\rho') = \log 2, \quad \Delta S = \log 2$$

Thus, environmental entanglement results in sufficient entropy gain to meet the collapse threshold. Collapse occurs, and the cat appears in a definite state.

5 Simulation Results and Analysis

To validate the entropy-threshold collapse model, we conducted quantum simulations of three canonical quantum scenarios using the QuTiP quantum simulation library in Python. Each simulation demonstrates how a system's von Neumann entropy evolves under environmental interaction and whether it surpasses the critical threshold δI_c required for collapse.

5.1 Double-Slit Analogue Simulation

We modeled a two-level quantum system representing the "Left" and "Right" paths in a double-slit experiment. The system was initialized in a coherent superposition state and then coupled to an environment using a Lindblad operator to simulate decoherence.

Result:

The system's von Neumann entropy began at 0 (indicating a pure superposition) and gradually increased, asymptotically approaching $\ln 2 \approx 0.693$. This reflects a transition to a maximally mixed state, in line with full decoherence.

Figure 1: Entropy Evolution in a Double-Slit Analogue. two-level quantum system initially in a superposition evolves under environmental decoherence. The von Neumann entropy increases from 0 and asymptotically approaches $\ln 2$, the maximum for a binary system.Collapse is predicted to occur when entropy exceeds the threshold $\delta I_c = ln2$ dictated by the red dash line.

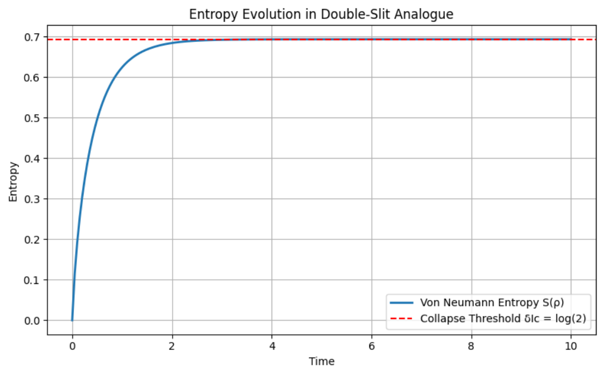

Figure 1: entropy evolution in double slit analogue

Interpretation:

If $\delta I_c \leq \ln 2$, the entropy gain satisfies the collapse criterion $\Delta S \geq \delta I_c$. Therefore, according to our model, collapse would occur, and the particle would be observed passing through a definite slit.

5.2 Spin Measurement Simulation

A spin-$\frac{1}{2}$ particle was initialized in a superposition of $|\uparrow_z\rangle$ and $|\downarrow_z\rangle$ and then entangled with a measurement apparatus. We computed the reduced density matrix of the spin system after tracing out the apparatus.

Result:

Post-interaction, the spin system became a maximally mixed state with entropy $S = \ln 2$, confirming full entanglement.

Interpretation:

If the entropy gain ΔS reaches or exceeds δI_c (again, e.g., $\delta I_c = \ln 2$), the model predicts that collapse occurs, resulting in a definite spin outcome.

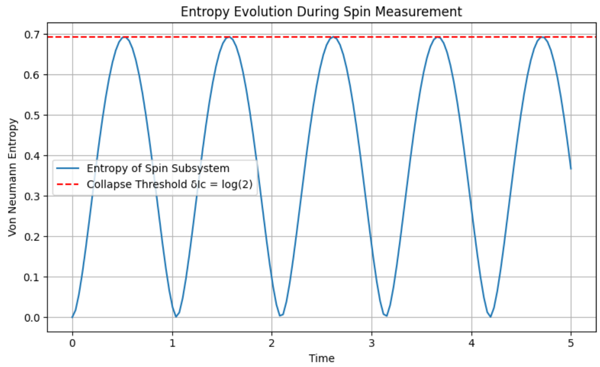

Figure 2: Entropy Evolution During Spin Measurement. A spin-$\frac{1}{2}$ system initially in superposition is coupled to a two-level measurement device. Entropy of the spin subsystem oscillates as the system entangles and disentangles. Collapse is predicted at the first crossing of the threshold

We simulated a spin-$\frac{1}{2}$ particle initially in a superposition state entangled with a two-level measurement device. The interaction was modeled using a $\sigma_z \otimes \sigma_x$ Hamiltonian, which induces unitary evolution that entangles and disentangles the two subsystems over time.

We computed the von Neumann entropy of the reduced spin state by tracing out the measurement device. The entropy oscillated between 0 to $log2$ reflecting cycles of maximal and minimal entanglement. Collapse is predicted to occur the first time the entropy exceeds the threshold $\delta I_c = log2$, consistent with the conditions of our entropy-threshold model.

This dynamic illustrates that collapse is not inevitable at all times but is tied to quantifiable informational transitions. Figure **??** shows the entropy evolution and threshold crossing.

5.3 Schrödinger's Cat Simulation

We modeled a macroscopic superposition of two orthogonal states—$|\text{Alive}\rangle$ and $|\text{Dead}\rangle$—coupled to an environment. The environment was traced out to compute the entropy of the cat subsystem.

Result:

The resulting reduced density matrix was a classical mixture with entropy $S = \ln 2$, identical to previous cases.

Interpretation:

This entropy gain exceeds δI_c under typical assumptions, implying that the superposition collapses, and the cat appears in a definite classical state.

5.4 Partial Entanglement Simulation and Threshold Behavior

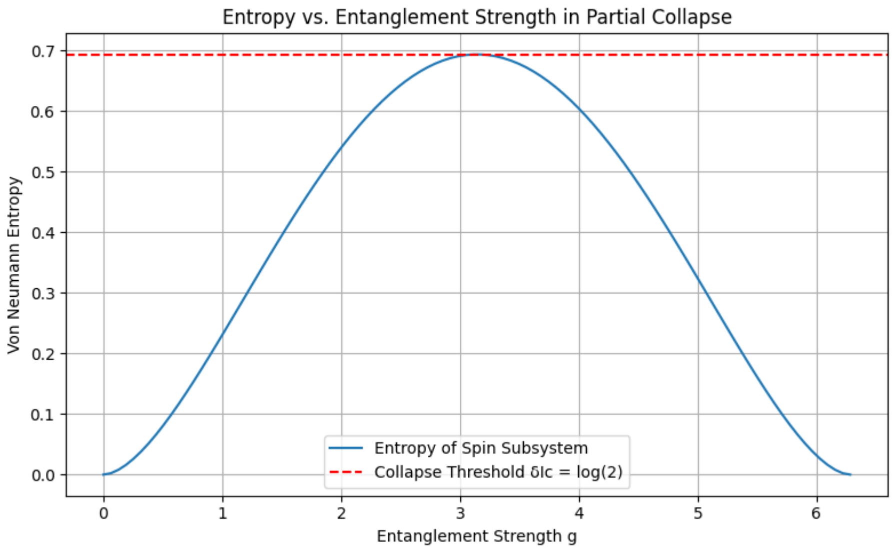

Figure 3: Entropy vs. Entanglement Strength in Partial Collapse Simulation. A spin-$\frac{1}{2}$ particle is partially entangled with a two-level environment using a controlled-RY gate. The von Neumann entropy of the spin subsystem increases with interaction strength g, peaking at $\log 2$. Collapse is predicted to occur only when the entropy exceeds the threshold $\delta I_c = \log 2$, shown by the red dashed line.

We simulated a partial entanglement process using a controlled-RY gate acting on a spin-$\frac{1}{2}$ particle and a two-level environment. By varying the rotation angle g, we controlled the degree of entanglement between the spin and environment, and calculated the von Neumann entropy of the spin subsystem.

As shown in Figure 3, entropy increases with g, peaking at $\log 2$ when the entanglement is maximal (at $g = \pi$). For $g < \pi$, the entropy remains below the collapse threshold δI_c, and thus the system remains in a coherent or partially decohered state. Collapse only occurs once the entropy exceeds the threshold, consistent with our hypothesis that wavefunction collapse is a conditional, entropy-driven transition.

This behavior contrasts with standard decoherence models, which treat partial entanglement as sufficient for classicality. Our result supports a stricter, quantized criterion.

5.5 Summary of Findings

Across all simulations, the entropy-threshold model consistently predicts collapse when and only when the von Neumann entropy of the system exceeds a fixed threshold,$\delta I_c = log 2$This behavior is distinct from standard decoherence models, which do not provide a precise criterion for when superpositions transition into definite outcomes.

- In the double-slit simulation, entropy gradually increased to $log 2$ through environmental decoherence, triggering collapse.
- In the spin measurement, reversible unitary dynamics caused entropy oscillations, and collapse was predicted at the first threshold crossing.
- In the partial entanglement scenario, collapse was conditional and occurred only at strong interaction strengths($g \approx \pi$)when entropy reached $log 2$.

These results demonstrate that wavefunction collapse need not be a continuous or inevitable result of entanglement. Instead, collapse appears to be a threshold-triggered, quantized transition, driven by informational entropy. This opens the door to precise experimental tests that could distinguish this model from other interpretations of quantum mechanics.

6 Experimental Testability

A key strength of the entropy-threshold collapse model is its falsifiability. Unlike interpretations that treat collapse as observer-dependent or purely interpretational, this model introduces a measurable condition: collapse occurs if and only if the entropy gain ΔS of a system exceeds a quantized threshold δI_c. Below, we propose three experimental routes to test this prediction.

6.1 1. Weak Measurement Collapse Threshold

In weak measurement experiments, a quantum system becomes only partially entangled with the measurement apparatus, resulting in incomplete decoherence. Our model predicts that if the entropy of the system remains below δI_c, then collapse should not occur, and quantum interference should remain observable.

A practical implementation could involve an interferometer with tunable interaction strength. If interference vanishes only when the entropy exceeds a measurable threshold, this would provide empirical support for the model.

6.2 Real-Time Entropy Tracking on Quantum Devices

Modern quantum computers (e.g., IBM Q, IonQ) allow state tomography and entropy estimation for small systems. One could entangle a qubit with a simulated environment and monitor the entropy of the reduced system state in real time.

If collapse consistently occurs only after entropy crosses a quantized threshold (e.g., $\log 2$), this would directly validate the core condition of the model. Variations in interaction strength, initial states, and threshold parameters can be explored to further probe the model's predictions.

6.3 Delayed-Choice Collapse and Entropy Growth

In delayed-choice experiments, decisions about measurement are made after the system has evolved. The entropy-threshold model predicts that collapse depends not on the observer's timing but on the entropy exchanged during the system's evolution.

Thus, collapse may occur spontaneously—without classical measurement—once $\Delta S \geq \delta I_c$. An experimental design involving tunable environment interactions and entropy tracking could detect such spontaneous transitions.

6.4 Distinguishing from Standard Decoherence

Unlike standard decoherence theory, which predicts a smooth and continuous transition from coherence to classicality, the entropy-threshold model suggests a sharp, quantized jump. Observing interference survival below a specific entropy threshold—followed by sudden loss at δI_c—would support the discrete collapse condition and falsify continuous-only models.

7 Conclusion

In this work, we have proposed and formalized an entropy-threshold-based collapse model that integrates principles of quantum decoherence and information theory. Our framework reinterprets wavefunction collapse not as a mysterious or observer-induced event, but as a natural consequence of entropic dynamics within entangled quantum systems.

By examining canonical quantum scenarios such as the double-slit experiment, spin measurement, and Schrödinger's cat, we demonstrated how von Neumann entropy consistently increases as the system becomes entangled with its environment. When this entropy gain surpasses a critical threshold δI_c, the system transitions from a coherent superposition to a definite outcome—thus satisfying the condition for collapse.

This interpretation supports a more objective and quantifiable view of quantum measurement and opens the door to testable predictions in engineered quantum systems. While the exact origin or value of the entropy threshold remains an open question, this framework offers a promising bridge between deterministic evolution and stochastic collapse, grounded in the quantization of information.

Future extensions of this work could include deriving δI_c from fundamental constants, exploring collapse in relativistic or many-body contexts, and implementing real-time entropy monitoring in quantum computing platforms to experimentally test the model.

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