Entropy-Drift Dynamics in Nonlinear Quantum Measurement: A Thermodynamic Constraint on Outcome Statistics

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Abstract

The quantum measurement problem persists because standard linear, completely positive trace-preserving (CPTP) dynamics account for decoherence but fail to explain outcome fixation in the **unconditional ensemble mean**. While Lindblad evolutions commuting with measurement projectors suppress coherences, they leave diagonal populations invariant: $\frac{d}{dt}\langle w_j \rangle = 0$. Here we derive a **nonlinear entropy-drift equation** acting exclusively as a **phenomenological description of unconditional ensemble-averaged populations**. Crucially, this dynamics does not modify the underlying Schrödinger evolution of individual quantum states but constrains the macroscopic probability flow. The drift is generated by a thermodynamic principle and exhibits an unstable fixed point at the Born weight. We show that the dynamics is active only in measurement regimes, preserves standard unitary evolution for isolated systems, forbids superluminal signaling, and is consistent with experiments exhibiting purification and asymmetric drift in unconditional ensembles.

1 Introduction

1.1 The measurement problem in unconditional ensembles

Standard quantum mechanics postulates probabilistic collapse, while decoherence theory explains suppression of interference through entanglement with the environment. However, decoherence alone does not explain why **unconditional ensemble averages** evolve toward definite outcomes. Linear CPTP dynamics describe dephasing but cannot generate diagonal drift in ensemble-averaged populations.

Throughout this work, “ensemble” refers strictly to unconditional averages over all measurement records, without postselection or conditioning.

1.2 Limitations of linear open-system dynamics

For a density operator ρ and projectors P_j, populations are defined as $w_j = \mathrm{Tr}(P_j \rho)$. If all Lindblad operators commute with the P_j, one obtains pure dephasing:

$$\frac{d}{dt}\rho_{ij} = -\gamma_{ij}\rho_{ij} \quad (i \neq j), \qquad \frac{d}{dt} w_j = 0. \tag{1}$$

Thus, **linear CPTP maps cannot generate diagonal drift** in the unconditional ensemble mean.

1.3 Contribution of this work

We derive a nonlinear entropy-drift equation for measurement weights that:

- Acts on unconditional ensemble averages (no postselection).
- Generates diagonal drift ($\frac{d}{dt}\langle w_j \rangle \neq 0$) from a thermodynamic principle.
- Reproduces the Born rule as an unstable fixed point.
- Is compatible with experiments showing purification and asymmetric drift in unconditional averages (e.g., [1–3]).
- Provides a phenomenological ensemble description without modifying the microscopic Schrödinger equation.

2 Theoretical Framework

2.1 Reduced relative entropy

For a binary measurement with subspace dimensions N_1 and N_2, define

$$S_{\mathrm{Red}}(w) = -w \log\left(\frac{w}{N_1}\right) - (1-w)\log\left(\frac{1-w}{N_2}\right). \tag{2}$$

The entropy is maximized at $w^* = \frac{N_1}{N_1+N_2}$.

2.2 Entropy-drift equation

We postulate an entropy-gradient-driven drift,

$$\dot{w} = -\Gamma\, w(1-w)\,\frac{\partial S_{\mathrm{Red}}}{\partial w} = \Gamma\, w(1-w)\log\left(\frac{w/N_1}{(1-w)/N_2}\right). \tag{3}$$

The nonlinear term breaks the linear no-drift constraint while preserving normalization.

2.3 Born rule as a dynamical relaxation point

The Born rule is usually introduced as a static axiom, $\rho = |\psi|^2$, implicitly assuming that probabilistic weights instantaneously satisfy equilibrium conditions. Recent theoretical work, however, suggests that deviations from the Born distribution may occur transiently and relax only asymptotically in time.

In particular, scenarios have been discussed in which interference effects persist prior to full relaxation, giving rise to anomalous interference patterns before the equilibrium distribution is reached. Within our framework, such phenomena admit a natural interpretation.

We identify the entropy-driven drift Γ as the effective *thermodynamic force* that drives the ensemble probabilities toward the Born weights. Crucially, this force acts in time and is not assumed to be instantaneous. The observation of residual interference before full relaxation is therefore not a contradiction, but direct evidence that the drift constitutes a genuine dynamical process.

2.4 Thermodynamic drift and osmotic velocity

In stochastic formulations of quantum mechanics, such as Nelson-type approaches, quantum dynamics is described in terms of two velocities: a current velocity and an osmotic velocity. Standard quantum mechanics corresponds to the equilibrium condition in which these contributions balance exactly, yielding $\rho = |\psi|^2$ at all times.

From this perspective, the entropy-drift introduced here can be interpreted as the *macroscopic manifestation of an imbalance in the osmotic velocity*. While conventional quantum theory postulates this balance as exact and timeless, our model explicitly allows for situations in which thermodynamic constraints drive the system *out of equilibrium*.

The entropy-drift equation then governs the relaxation back toward equilibrium, with the Born weight emerging not as an axiom, but as a dynamically selected symmetry point of the ensemble evolution.

3 Fixed-Point Structure and Visualization

3.1 Born weight as unstable symmetry point

The drift vanishes at $w = w^*$. Linear stability analysis yields instability: arbitrarily small asymmetries are amplified by the drift.

3.2 Pre-relaxation regime and interference anomalies

The entropy-drift dynamics predicts that the approach to quantum equilibrium occurs over a finite relaxation time whenever the drift rate Γ is nonzero. As a consequence, the Born weight does not need to be satisfied instantaneously, but can emerge dynamically as the endpoint of an irreversible ensemble process.

In this pre-relaxation regime, where $\dot{w} \neq 0$, residual interference effects may persist even though decoherence is already effective. Such interference does not contradict quantum mechanics, but indicates that the unconditional ensemble has not yet reached thermodynamic equilibrium.

This behavior provides a natural interpretation of interference anomalies reported in stochastic and relaxation-based approaches to quantum mechanics: they correspond to transient ensemble states evolving toward the Born fixed point. The entropy-driven drift thus acts as the effective thermodynamic force governing this relaxation.

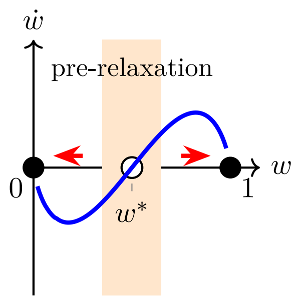

Figure 1: Phase portrait of the entropy-driven ensemble drift. The Born weight w^* appears as an unstable fixed point corresponding to quantum equilibrium. For finite drift rate Γ, the approach to this point requires a nonzero relaxation time. Within the pre-relaxation window, residual interference effects may occur. Such anomalies are interpreted as signatures of an active thermodynamic probability flow rather than violations of quantum mechanics.

3.3 Interference anomalies as a test scenario

The entropy-drift dynamics naturally suggests experimental test scenarios. If the drift rate Γ is finite, the approach to equilibrium requires a nonzero relaxation time. In measurement or gravitational contexts where Γ is enhanced or suppressed, the ensemble may temporarily reside away from the Born fixed point.

In such regimes, deviations from standard interference patterns are expected. These anomalies would not signal a breakdown of quantum mechanics, but rather indicate that the unconditional ensemble has not yet completed its thermodynamic relaxation.

Within this interpretation, previously discussed interference anomalies acquire a clear physical meaning: they constitute the experimental signature of an active entropy-driven probability flow.

4 Consistency Constraints

4.1 Measurement-dependent dissipation

The dissipation constant Γ encodes irreversible coupling. In the absence of such coupling, $\Gamma \to 0$, and isolated systems obey standard unitary evolution.

4.2 No-signaling and locality

The equation does not act on the global state. It evades the Gisin theorem by focusing on locally decohered, diagonal populations.

4.3 Ensemble determinism vs. event indeterminism

The drift equation deterministically governs probability flow at the ensemble level. It does not specify which individual outcome is realized.

> Determinism applies to ensemble evolution, not to individual events.

5 Conclusion

We have derived a nonlinear entropy-drift equation for unconditional ensemble averages. The framework preserves unitary quantum mechanics for isolated systems, forbids superluminal signaling, and reproduces the Born rule as a symmetry constraint. In this view, the Born rule is no longer a static postulate but the endpoint of a relaxation process. Quantum mechanics describes the equilibrium structure, while the entropy-drift governs the irreversible approach toward it in measurement contexts.

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