



Review Article

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Entanglement Breaking and Punctuated Unitary Evolution: A Dynamical Perspective on the Quantum Measurement Problem

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Abstract

Despite its extraordinary empirical success, quantum mechanics rests on two dynamically incompatible postulates: continuous, deterministic unitary evolution and the discontinuous, probabilistic reduction of the wavefunction during measurement. We propose a dynamical framework in which a quantum measurement is identified with a spontaneous Entanglement Breaking (EB) event between an observable subsystem and the remainder of the system. An EB event is represented by a singular source term in an extended Schrödinger equation. Solving the equation exactly using a retarded Green's function, we show that the apparent collapse of the wavefunction arises from destructive interference between the freely evolving state and a source induced component at the EB event. The post event state reduces to a disentangled product state corresponding to a definite outcome. The Born rule emerges from norm conservation and projector completeness, and the post measurement density matrix acquires a nonzero von Neumann entropy without invoking coarse graining or subjective tracing. The resulting dynamics is a punctuated unitary evolution that reconciles unitary quantum dynamics with definite outcomes and intrinsic irreversibility.

Introduction

The central foundational challenge of Quantum Mechanics (QM) is the measurement problem, arising from the apparent conflict between two of its core postulates: the deterministic, reversible unitary evolution of the quantum state and the irreversible, probabilistic reduction to a definite outcome during a measurement. While environmental decoherence [1,2] explains the practical suppression of interference and the emergence of stable pointer states, it does not account for the occurrence of a single definite outcome in an individual measurement.

This gap has motivated a variety of interpretational and dynamical proposals. The Many Worlds Interpretation retains

global unitarity at the cost of proliferating noninteracting branches [3], while objective collapse models such as GRW and CSL introduce nonlinear and stochastic modifications of quantum dynamics [4–6]. Despite their differences, these approaches reflect the absence of a precise physical characterization of what constitutes a measurement at the quantum level [7].

In this work, we propose a dynamical framework in which a quantum measurement is identified with a spontaneous Entanglement Breaking (EB) event between an observable subsystem and the rest of the system, including the measurement apparatus and environment. An EB event completes the

decoherence process by discontinuously terminating entanglement and producing a definite outcome. The physical evolution consists of unitary intervals punctuated by EB events, resulting in what we may call punctuated unitary evolution.

We formulate this idea by introducing a singular source term into an extended Schrödinger equation. Its exact solution reveals that the apparent wavefunction collapse emerges dynamically as a destructive interference effect. We further show that the Born rule follows from norm conservation and that EB events generate an intrinsic increase in von Neumann entropy, providing a microscopic source of irreversibility.

Extended Schrödinger Equation

We postulate that a quantum measurement corresponds to a spontaneous entanglement breaking (EB) event occurring at a time $t = t_c$. The state vector $\psi(t)$ satisfies the extended Schrodinger equation

$$i\hbar \frac{\partial}{\partial t} \psi(t) = [H_{QM} - i\hbar(1 - P_n)\delta(t - t_c)]\psi(t), \quad (1)$$

where H_{QM} is the standard Hamiltonian of the system and

$$P_n = |n\rangle\langle n| \quad (2)$$

is the projector associated with the outcome n of an observable $\hat{o}$ satisfying $\hat{o}|n\rangle = o_n|n\rangle$.

The EB term acts only at $t = t_c$. It does not represent a typical Hamiltonian interaction but a singular dynamical event.

Exact Solution

The retarded Green's function associated with H_{QM} satisfies

$$\left(i\hbar \frac{\partial}{\partial t} - H_{QM}\right)G(t, t') = \delta(t - t'), \quad (3)$$

with solution

$$G(t, t') = -\frac{i}{\hbar} \theta(t - t') U(t, t'), \quad (4)$$

where $U(t, t') = \exp[-iH_{QM}(t - t')/\hbar]$.

The solution of Eq. (1) is

$$\psi(t) = \psi_i(t) - \theta(t - t_c) U(t, t_c) (1 - P_n) \psi_i(t_c), \quad (5)$$

where $\psi_i(t) = U(t, t_0) \psi_i(t_0)$ is the freely evolving state determined by the initial condition; the Heaviside step function $\theta(t - t_c)$ is defined:

$$\theta(t - t_c) = \begin{cases} 0, & \text{for } t \leq t_c, \\ 1, & \text{for } t > t_c, \end{cases} \quad (6)$$

Wavefunction Reduction by Destructive Interference and Punctuated Unitary Evolution

For $t \leq t_c$, the Heaviside function vanishes and $\psi(t) = \psi_i(t)$. For $t > t_c$, $\theta = 1$, the freely evolving component is exactly canceled by the source induced $U(t, t_c)(1 - P_n)\psi_i(t_c) = \psi_i(t)$ term, yielding

$$\psi(t_c^+) = P_n \psi_i(t_c). \quad (7)$$

Thus, the apparent collapse of the wavefunction arises dynamically as a destructive interference between the unitary evolution and the EB induced contribution. The post event state is a disentangled product state corresponding to a definite outcome. The physical evolution therefore consists of unitary segments punctuated by EB events.

Emergence Of the Born Rule

The squared norm immediately after the EB event is

$$\|\psi(t_c^+)\|^2 = \langle \psi_i(t_c) | P_n | \psi_i(t_c) \rangle = p_n. \quad (8)$$

Using the completeness relation $\sum_n P_n = 1$, we obtain

$$\sum_n p_n = 1. \quad (9)$$

The nonnegative quantities

$$p_n = |\langle n | \psi_i(t_c) \rangle|^2 \quad (10)$$

satisfy the axioms of probability and coincide with the Born rule [8]. In this framework, the Born rule emerges from the dynamics and normalization of the quantum state, rather than being an independent postulate.

Relation To Measurement Theory and Entanglement Breaking Channels

The present formulation bears a close but conceptually distinct relation to the standard theory of quantum measurements developed in terms of projection postulates and quantum operations. In the traditional approach, an ideal measurement of an observable $\hat{O}$ with spectral projectors $\{P_n\}$ induces a state transformation described by the Luders rule [9],

$$\rho \rightarrow \rho_n = \frac{P_n \rho P_n}{\text{Tr}(P_n \rho)}, \quad (11)$$

with outcome probabilities $\text{Tr}(P_n \rho)$. While operationally successful, this rule is introduced as an additional postulate, independent of the unitary Schrödinger dynamics. More generally, the operational formulation of quantum mechanics describes measurements as completely positive trace preserving (CPTP) maps, represented by Kraus operators [10, 11],

$$\rho \rightarrow \sum_n K_n \rho K_n^\dagger, \quad \sum_n K_n^\dagger K_n = 1. \quad (12)$$

Projective measurements correspond to the special case $K_n = P_n$. These frameworks provide a powerful and internally consistent description of measurement statistics, but they remain agnostic about the physical mechanism that selects a single outcome in an individual measurement event. The entanglement breaking (EB) events postulated here are closely related to, but conceptually distinct from, the notion of entanglement breaking quantum channels studied in quantum information theory [12, 13]. An entanglement breaking channel is defined as a completely positive map that destroys all entanglement between a system and any ancillary system.

In contrast, the EB events introduced in the present work are not continuous quantum channels acting over finite time intervals, but singular dynamical events that interrupt unitary evolution

at a specific instant. Their role is to complete the decoherence process by converting an entangled system–environment state into a disentangled product state corresponding to a definite outcome. While the statistical ensemble of EB events reproduces the structure of a projective measurement channel, the individual EB event is a fundamentally stochastic physical occurrence rather than an effective description of information loss.

In this sense, the present framework provides a dynamical underpinning for the projection postulate and for entanglement breaking operations. The standard measurement rules emerge as statistical consequences of punctuated unitary evolution rather than as independent axioms.

Post EB Density Matrix and Intrinsic Entropy

The ensemble of EB events yields the density matrix

$$\rho^+ = \sum_n \rho_n |n\rangle\langle n| \otimes |X_n\rangle\langle X_n|, \quad (13)$$

where $|X_n\rangle$ are normalized states of the rest system. The eigenvalues of ρ^+ are p_n , and the corresponding von Neumann entropy [14] is

$$\begin{aligned} S_{vN}^+ &= -\text{Tr}(\rho^+ \log \rho^+) \\ &= -\sum_n p_n \log p_n \geq 0. \end{aligned} \quad (14)$$

For the preEB pure state, $S_{vN}^- = 0$. Each EB event therefore produces an intrinsic, irreversible increase in entropy without invoking coarsegraining or subjective ignorance.

Statistical Conservation of Energy

If the measured observable coincides with the Hamiltonian, $[H_{QM}, P_n] = 0$, then

$$\langle E \rangle(t_c^+) = \text{Tr}(\rho^+ H_{QM}) = \langle E \rangle(t_c) \langle \psi_i(t_c) | H_{QM} | \psi_i(t_c) \rangle = \langle E \rangle(t_c^-). \quad (15)$$

Thus, energy is conserved statistically across EB events. The same holds for other conserved quantities commuting with the Hamiltonian.

Interpretational and Cosmological Implications

The intrinsic entropy increase associated with EB events provides a microscopic arrow of time and suggests a possible quantum foundation for macroscopic irreversibility. If EB events are fundamental, the universe may initially reside in a pure state prior to the first such event, offering a perspective on the low entropy past hypothesis [15]. More speculatively, horizons in gravitational systems may act as loci of EB events, potentially offering a new

viewpoint on the black hole information problem [16]. These lie beyond the present note and to be further considered elsewhere.

Conclusions

We have proposed a dynamical framework in which quantum measurement is identified with a spontaneous entanglement breaking event. The resulting punctuated unitary evolution accounts dynamically for state reduction, the Born rule, and intrinsic entropy increase and perspective on quantum measurement and irreversibility.

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