Collapse Completeness in Open Quantum Systems

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Abstract

Collapse is often treated as an interpretive addendum to quantum mechanics rather than as a structural feature subject to analysis. In this work, collapse is approached instead as instead as a classificatory lens for organizing dynamical regimes already present in orthodox quantum theory. Focusing on open quantum systems governed by Lindblad generators, we examine how the spectral structure of the Liouvillian distinguishes regimes of complete selection, partial selection, and degeneracy. Using a recently analyzed dissipative large-spin model as a concrete example, we show that fixed points, limit cycles, and Hopf bifurcations correspond, respectively, to collapse completion, residual phase admissibility, and degeneracy of selection. In this framework, time emerges not as an external parameter but as motion along degrees of freedom left unsuppressed by collapse, while algebraic relaxation signals a loss of discriminating power in the generator itself. No modification to quantum mechanics is proposed, and no claim of objective collapse is made. Rather, the results demonstrate that collapse completeness is a meaningful organizing principle within standard open-system dynamics, providing a bridge between generative collapse ontology and the limits of quantum description explored at the Planck scale.

1 Motivation

Discussions of collapse in quantum theory are often polarized between two unsatisfactory extremes. On one hand, collapse is treated as a purely epistemic artifact—an update rule reflecting incomplete knowledge rather than a feature of dynamics. On the other, collapse is introduced as an additional physical process, appended to quantum mechanics through new postulates whose necessity and empirical status remain contested. Both approaches obscure a more basic question: whether collapse-like selection already functions as an organizing principle within the dynamics of standard quantum systems.

Open quantum systems provide a natural setting in which to revisit this question. Once unitary evolution is abandoned in favor of generator-based dynamics, the long-time behavior of a system is no longer determined by trajectories but by the spectral structure of the generator itself. Fixed points, oscillatory modes, and critical slowing are not imposed by interpretation but emerge directly from the properties of the Liouvillian operator. In this context, the suppression or persistence of degrees of freedom is governed by the generator's discriminating power rather than by measurement postulates.

The framework of Quantum Collapse Geometry proposes that this discriminating power can be meaningfully characterized by a collapse index: a measure of how completely a given generator suppresses alternative configurations. Importantly, the collapse index is not introduced as a new observable or dynamical term. It functions instead as a classificatory parameter, allowing distinct regimes of behavior to be compared on common structural grounds. Collapse, in this sense, names a property of selection already present in the dynamics, rather than an additional mechanism layered on top of it.

The purpose of this paper is to demonstrate that such a classification is not merely philosophical. By examining well-understood models in open quantum dynamics, we show that regimes corresponding to complete selection, partial selection, and degeneracy can be identified directly from the generator's spectrum. These regimes align naturally with fixed-point behavior, limit-cycle persistence, and critical transitions characterized by algebraic relaxation. No claim is made that collapse is objective or fundamental at this level; rather, the goal is to establish collapse completeness as a precise organizing concept within orthodox quantum theory.

2 Generators, Spectra, and Selection

The dynamics of open quantum systems are naturally expressed in terms of generators rather than trajectories. When a system is coupled to an environment, its reduced state ρ evolves according to

$$\frac{d\rho}{dt} = \mathcal{L}[\rho],$$

where $\mathcal{L}$ is a Liouvillian superoperator, typically of Lindblad form. Long-time behavior is governed by the spectral properties of $\mathcal{L}$.

Eigenvalues with negative real parts correspond to decaying modes, while purely imaginary eigenvalues generate persistent oscillations. Steady states are associated with eigenvalues whose real parts vanish, and the approach to equilibrium is controlled by the spectral gap separating these modes from the rest of the spectrum. The generator acts globally on the space of states, selectively suppressing or preserving entire directions in state space.

This structure naturally defines a notion of selection. Degrees of freedom associated with rapidly decaying modes are eliminated from late-time dynamics, while modes with vanishing or near-vanishing decay rates remain dynamically relevant. The distinction between suppression and persistence is therefore structural rather than interpretive.

Three broad spectral regimes are particularly relevant. In the first, a finite gap isolates a unique steady state, and all deviations decay exponentially. In the second, a discrete or continuous set of imaginary eigenvalues survives, supporting persistent motion along a low-dimensional manifold. In the third, the gap closes and an extensive family of modes acquires arbitrarily small decay rates, leading to algebraic relaxation and critical behavior.

Within Quantum Collapse Geometry, these regimes are organized by the collapse index, which characterizes the effective discriminating power of the generator. High collapse index corresponds to sharp suppression and rapid convergence, while lower collapse index admits residual degrees of freedom. degeneracy of selection arises when the generator can no longer efficiently distinguish among competing configurations. This language does not modify the underlying mathematics; it provides a structural classification of familiar spectral phenomena. From an experimental standpoint, selection manifests in which observables retain coherence at late times.

3 Spin Model as a Tunable Collapse Environment

A particularly clear realization of these ideas is provided by a dissipative large-spin system governed by a Lindblad master equation with competing linear and nonlinear jump operators [1]. The model is fully orthodox, analytically tractable, and admits a well-defined classical limit.

The system consists of a single spin of magnitude S evolving under a simple Hamiltonian and two dissipative channels. One channel induces relaxation toward a polarized state, while the other introduces a nonlinear, state-dependent excitation controlled by a dimensionless parameter γ. Varying γ produces a phase diagram containing a unique fixed point, stable limit cycles, and a critical transition separating them.

The spin length S controls the approach to the classical limit and sets the scale of quantum fluctuations. Diffusion, spectral curvature, and decoherence rates scale as inverse powers of S, so increasing S sharpens the generator's discriminating power. In this sense, S functions as a proxy for the collapse index: larger S corresponds to more complete selection, while finite S admits residual fluctuations. This identification is operational rather than ontological.

By contrast, γ controls the topology of selection. It determines whether the generator suppresses all degrees of freedom except a single steady configuration, leaves a continuous phase direction admissible, or becomes unable to efficiently discriminate at a critical threshold. Together, (S, γ) define a minimal environment in which collapse completeness, partial collapse, and degeneracy can be explored without modifying quantum mechanics.

4 Fixed Points and Collapse Completion

For $\gamma < 1$, the classical dynamics admit a unique stable fixed point. The corresponding Liouvillian spectrum exhibits a finite gap separating the steady state from all other modes, ensuring exponential relaxation [1].

This structure reflects maximal discriminating power of the generator. All deviations decay at finite rates, and no persistent oscillatory degrees of freedom remain. In collapse-index terms, this regime corresponds to collapse completion: selection resolves the system onto a single admissible configuration.

Fluctuations around the attractor scale as $S^{-1/2}$, consistent with increasing collapse sharpness at large S. Because selection is complete, no persistent motion survives once transients decay. Geometry stabilizes to a point, and no internal temporal degree of freedom emerges.

5 Limit Cycles and Partial Collapse

For $\gamma > 1$, the generator no longer enforces convergence to a unique steady state. Instead, the dynamics stabilize onto a closed orbit, while motion along the azimuthal direction persists indefinitely. The Liouvillian spectrum develops a ladder of eigenvalues with evenly spaced imaginary parts and real parts that vanish as $S \to \infty$ [1].

This structure signals partial collapse. Radial degrees of freedom are selectively suppressed, fixing the geometry of the attractor, while the phase direction remains dynamically admissible. Motion along this direction persists and constitutes an emergent notion of time.

At finite S, small negative real parts introduce slow dephasing, reflecting incomplete sharpness of selection. As S increases, this curvature diminishes and temporal coherence becomes exact. Geometry and time thus arise from different aspects of the same selective process.

6 Hopf Bifurcation and degeneracy of selection

At $\gamma = 1$, the system undergoes a Hopf bifurcation. The Liouvillian gap closes, and an infinite family of eigenvalues accumulates near the imaginary axis, producing algebraic relaxation [1].

This behavior reflects degeneracy of selection. The generator loses the ability to efficiently discriminate among competing configurations, leaving many slow modes dynamically comparable. Neither a unique attractor nor a sharply defined manifold emerges. Dynamics are governed by collective, entropy-driven relaxation rather than selective suppression.

The Hopf point thus marks a boundary between regimes of selection itself: beyond it, the generator's discriminating power is insufficient to impose structure.

7 Synthesis and Role in the QCG Framework

This analysis demonstrates that collapse completeness is a meaningful classifier of dynamical regimes already present within orthodox open quantum systems. Fixed points, limit cycles, and critical slowing correspond to complete selection, partial selection, and degeneracy of selection, respectively.

Geometry and time emerge as distinct outcomes of selection. Where collapse suppresses all alternatives, geometry stabilizes and motion ceases. Where collapse leaves a phase direction admissible, persistent motion emerges as time. Where collapse becomes degenerate, neither geometry nor time is sharply resolved.

The role of this paper within the Quantum Collapse Geometry program is diagnostic rather than foundational. It establishes that collapse completeness is a precise organizing principle within standard quantum dynamics, motivating the possibility that quantum mechanics itself represents a regime of partial collapse. This perspective prepares the ground for the analysis of fundamental limits undertaken in the following work on the Planck horizon.

References

[1] Shovan Dutta, Shu Zhang, and Masudul Haque. "Quantum Origin of Limit Cycles, Fixed Points, and Critical Slowing Down". In: *Phys. Rev. Lett.* 134 (5 Feb. 2025), p. 050407. DOI: `10.1103/PhysRevLett.134.050407`. URL: `https://link.aps.org/doi/10.1103/PhysRevLett.134.050407`.