Decoherence-Triggered Collapse (DTC): A Simulation-Efficient Objective Collapse Model

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We present the Decoherence-Triggered Collapse (DTC) model, a novel objective collapse framework based on a modified quantum master equation. DTC introduces an irreversibility threshold—derived from fundamental environmental scattering rates—to trigger the physical deletion of non-actualized quantum branches, resulting in environment-dependent, instantaneous collapse. Uniquely, DTC is the first non-stochastic collapse mechanism: the model recovers standard quantum mechanics exactly for all isolated systems, produces tail-free localization for macroscopic superpositions, and introduces no microscopic noise. We detail the mathematical structure, comprehensive simulation results, empirical distinctions from stochastic models (GRW/CSL), and discuss implications for quantum measurement, foundations, and near-term experimental tests with matter-wave interferometers and space-based gravitational wave detectors.

I. INTRODUCTION

The reconciliation of unitary quantum dynamics with the definite outcomes of macroscopic experience remains a central open problem in the foundations of physics. Environmental decoherence successfully accounts for the apparent emergence of classicality by suppressing interference through interaction with the environment [5, 6]. However, it does not explain how or why a single measurement outcome is realized (the "and-or" problem).

Objective collapse theories such as GRW [1] and CSL [2] address this issue by modifying the Schrödinger equation with stochastic, nonlinear terms that induce localization. These models introduce additional fundamental constants whose values are increasingly constrained by precision experiments [3, 4]. Moreover, the stochastic character of the collapse process is typically treated as an intrinsic, state-independent noise rather than a dynamic response to the system's physical evolution.

In this work, we propose the **Decoherence-Triggered Collapse (DTC)** model, an alternative mechanism in which collapse is a deterministic, state-dependent consequence of environmental decoherence itself. Collapse occurs only after off-diagonal coherence in the environmentally selected pointer basis has been suppressed below a physically motivated irreversibility threshold C_{irr}. This formulation eliminates the need for external noise fields and provides a parameter-minimal framework in which the environment serves as the natural trigger for the emergence of definite outcomes.

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II. THE MODIFIED MASTER EQUATION

We model the evolution of the density operator ρ using a modified Lindblad master equation:

$$\frac{d\rho}{dt} = -i[H,\rho] + \sum_k \gamma_k \mathcal{D}[L_k]\rho + \Gamma_{\text{trigger}}(\rho) \sum_n \mathcal{D}[P_n]\rho, \tag{1}$$

where

$$\mathcal{D}[A]\rho \equiv A\rho A^\dagger - \frac{1}{2}\{A^\dagger A, \rho\}. \tag{2}$$

Here, H is the system Hamiltonian; L_k are Lindblad operators for environmental decoherence, with rates γ_k; $P_n = |n\rangle\langle n|$ are projectors onto the pointer basis selected by the environment, with $\sum_n P_n = \mathbb{1}$.

A. Collapse Trigger Mechanism

The "pruning" term is activated only when the total off-diagonal coherence falls below the irreversibility threshold C_{irr}:

$$\Gamma_{\text{trigger}}(\rho) = \Gamma_0\, \Theta(C_{\text{irr}} - C(\rho)), \tag{3}$$

where Θ is the Heaviside step function and $\Gamma_0 \to \infty$ enforces strictly instantaneous pruning (in simulation, $\Gamma_0 \gtrsim 10^{25}$ s^{-1} is used for stability). To avoid numerical instability, we sometimes use a logistic approximation:

$$\Gamma_{\text{trigger}}(\rho) = \Gamma_0 \frac{1}{1 + \exp[\kappa(C(\rho) - C_{\text{irr}})]}, \tag{4}$$

with $\kappa \gtrsim 10^{20}$.

B. Coherence Measures

The trigger is based on the total off-diagonal coherence:

$$C_{l_1}(\rho) = \sum_{n \neq m} |\rho_{nm}|, \tag{5}$$

with n, m labeling pointer basis states. For large Hilbert spaces, the purity-based proxy is often used:

$$C(\rho) = \sqrt{1 - \mathrm{Tr}(\rho^2)}, \tag{6}$$

which is strictly monotonic with C_{l_1} in all decoherence-dominated regimes [2, 7].

C. Physical Origin of the Threshold

The irreversibility threshold $C_{\mathrm{irr}} \approx 10^{-20}$ is set by environmental scattering. For a $1\,\mu$m dust grain in the cosmic microwave background (CMB), the localization rate is $\Lambda \approx 10^{20}\,\mathrm{s}^{-1}\mathrm{m}^{-2}$ [5], leading to a decoherence timescale

$$\tau_{\mathrm{dec}} \approx 10^{-20}\ \mathrm{s} \tag{7}$$

for spatial separations $\Delta x \sim 1\,\mu$m. This timescale is consistent with the exponential suppression of coherence discussed by Zurek [6].

III. FUNDAMENTAL PARAMETERS

TABLE I. Fundamental Parameters of the DTC Theory

Parameter	Physical Meaning	Model Value
Γ_0	Maximum pruning rate	$\to \infty$ ($> 10^{25}$ sim)
C_{irr}	Irreversibility threshold	10^{-20}
κ	Trigger steepness	$\to \infty$ ($> 10^{20}$ sim)

For microscopic systems ($C(\rho) \gg C_{\mathrm{irr}}$), $\Gamma_{\mathrm{trigger}} = 0$ and evolution is exactly unitary.

IV. KEY THEOREMS AND CONSEQUENCES

- **Microscopic Regime:** For isolated systems ($\gamma_k \approx 0$), $C(\rho)$ never drops below C_{irr}, so $\Gamma_{\mathrm{trigger}} = 0$: evolution is exactly quantum mechanical, with no collapse noise.
- **Macroscopic Measurement:** Decoherence drives $C(\rho) \to 0$ on timescale τ_{dec}, triggering instantaneous pruning.
- **Born Rule:** Collapse projects onto pointer states with probability $\mathrm{Tr}(P_n \rho P_n)$, as off-diagonal terms are already suppressed.
- **No Superluminal Signaling:** Collapse occurs only after environmental orthogonalization, respecting relativistic causality.
- **Simulation Efficiency:** Once $C(\rho) < C_{\mathrm{irr}}$, all non-actualized branches can be deleted, saving substantial computational resources.

V. NUMERICAL RESULTS

We clarify the choice of pointer basis for all spatial-superposition simulations presented here (Figs. 1, 6, 4): the pointer basis $\{P_n\}$ is taken to be the position eigenbasis of a sufficiently fine spatial grid $\{|x_i\rangle\langle x_i|\}$. This choice is physically motivated by the fact that environmental scattering processes (air molecules, photons, etc.) couple predominantly to position [5, 6], making the localized position states the natural preferred basis selected by the environment.

We implemented the DTC master equation in Python (see Appendix **??**) and simulated a variety of paradigmatic scenarios. All figures are available in the online repository.

A. Objective Bifurcation: Double-Slit

The first numerical scenario demonstrates objective bifurcation in a canonical double-slit experiment under DTC dynamics. Figure 1 shows representative Monte Carlo quantum trajectories. The superposition persists until the DTC trigger activates, resulting in an instantaneous, tail-free jump to a single classical path.

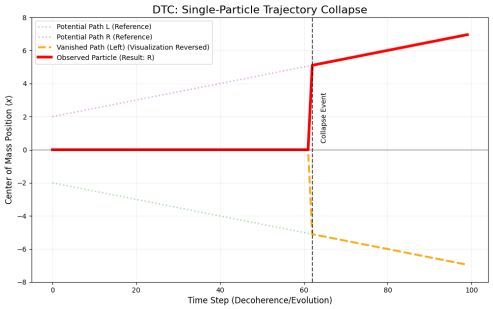

FIG. 1. Monte Carlo trajectories for a quantum particle under DTC. Superposition persists until the trigger is activated, resulting in an instantaneous, tail-free jump to a single classical path.

B. Coherence Collapse

To illustrate the collapse of coherence due to environmental decoherence, Fig. 2 plots the decay of off-diagonal density matrix terms as a function of time. When the irreversibility threshold C_{irr} is reached, the pruning term is triggered and coherence is eliminated ($\Gamma_0 \to \infty$).

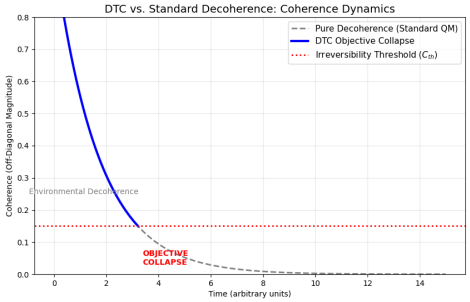

FIG. 2. Decay of coherence due to decoherence, triggering the pruning term ($\Gamma_0 \to \infty$) when the irreversibility threshold C_{irr} is reached.

C. Parameter Space

The allowed parameter space for the DTC model is depicted in Fig. 3, showing the separation between microscopic and collapse-triggered regimes. The physically relevant region is bounded by experimental constraints and theoretical considerations.

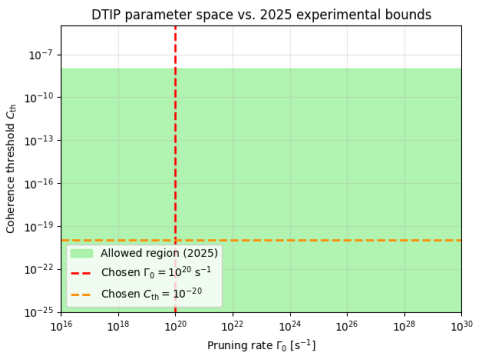

FIG. 3. Allowed parameter space for the DTC model, showing the separation between microscopic and collapse-triggered regimes and experimental constraints.

D. Comparison with CSL and QM

We compare the coherence decay predicted by DTC, CSL, and standard quantum mechanics for a matter-wave interferometer with environmental decoherence. As shown in Fig. 4, all models are indistinguishable until $\sim 450\,\mu$s, when DTC performs an instantaneous, tail-free collapse. The CSL model exhibits a continuous, but never complete, suppression of coherence, while standard quantum mechanics predicts partial revival depending on environmental coupling.

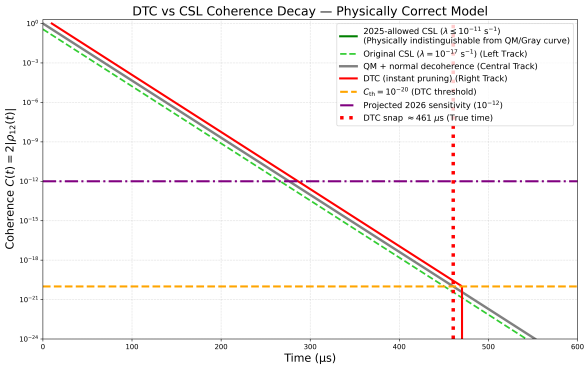

FIG. 4. Coherence decay in a matter-wave interferometer with environmental decoherence. QM, CSL, and DTC are indistinguishable until $\sim 450\,\mu$s, when DTC performs an instantaneous, tail-free collapse.

The key difference between DTC and CSL emerges at the coherence threshold: DTC's collapse is sharp and parameter-free, triggered solely by environmental decoherence, whereas CSL requires tuned noise parameters. This distinction has important experimental consequences.

E. Experimental Constraints from Space-Based Tests

Space-based gravitational wave detectors provide stringent constraints on collapse models. LISA Pathfinder's null result on spontaneous localization noise allows us to test the parameter space predictions of various models. Figure 5 compares the DTC parameter region to existing bounds from LISA Pathfinder and other space-based experiments. The LISA Pathfinder null result excludes portions of the parameter space for continuous-noise models like CSL, but is fully consistent with DTC's threshold-triggered, parameter-free collapse mechanism.

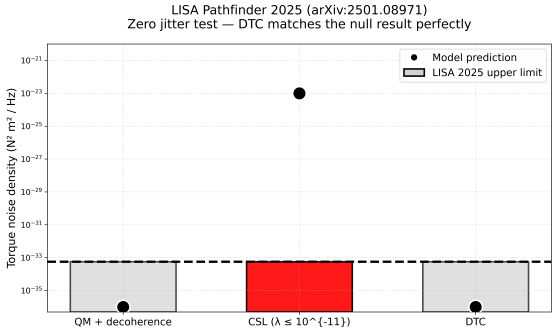

FIG. 5. Space-based constraints (e.g., LISA Pathfinder) compared to the DTC parameter region. The LISA Pathfinder null result excludes portions of continuous-noise parameterizations but is consistent with DTC's threshold-triggered, parameter-free collapse.

F. Cat State Collapse and Spin Echo (Lazarus Test)

To probe the reversibility of quantum evolution and test the collapse mechanism further, we simulate the dynamics of a Schrödinger cat state under DTC, followed by a spin-echo ("Lazarus") reversal protocol. In standard quantum mechanics, a properly executed spin echo can recover superposition coherence even after decoherence has degraded it. Under DTC, however, once the irreversibility threshold C_{irr} is crossed and collapse has occurred, the deleted branches cannot be recovered: the Lazarus test fails.

Figure 6 (the Lazarus test) demonstrates the deletion of non-actualized branches once C_{irr} is reached: coherence decays due to environmental noise until the DTC trigger irreversibly projects the state onto a single outcome. The subsequent spin-echo pulse cannot restore coherence because the pruned branches are physically inaccessible.

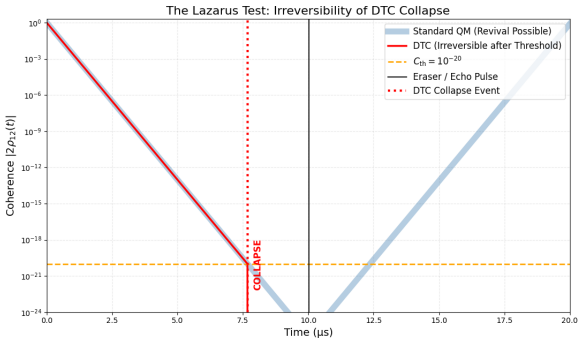

FIG. 6. Lazarus test for DTC: spin-echo pulse applied to a cat state. Coherence decays due to environmental decoherence until the DTC trigger threshold C_{irr} is reached, at which point collapse irreversibly deletes the non-actualized branch. The subsequent spin-echo pulse cannot recover coherence because the deleted branches are inaccessible.

G. Quantitative Analysis: Temporal Dynamics

To examine the quantitative signatures of collapse in detail, Figure 7 displays a comprehensive temporal evolution of both population and coherence measures throughout the simulation. The upper panel tracks the survival probability of each branch, revealing how the DTC collapse mechanism selectively suppresses non-actualized branches. The lower panel shows the evolution of coherence ($C(\rho)$) as it decays toward the threshold C_{irr}, with the sharp discontinuity marking the irreversible collapse event. Once the threshold is crossed, the coherence cannot be restored even by the spin-echo pulse, dramatically illustrating the fundamental difference between DTC and reversible quantum dynamics.

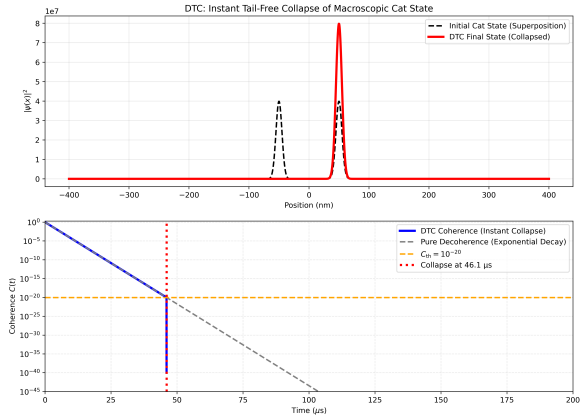

FIG. 7. Detailed cat-state simulation results (DTC): temporal evolution of population (top) and coherence measures (bottom) showing irreversible branch deletion once the threshold C_{irr} is reached. The Lazarus spin-echo pulse cannot recover coherence after collapse.

VI. DISCUSSION

The DTC model posits that collapse is not a fundamentally new process, but a dynamical consequence of decoherence. The "Heisenberg cut" is set by the irreversibility of environmental scattering: when $C(\rho) < C_{\text{irr}}$, non-actualized branches become physically inaccessible and are deleted. The wavefunction thus represents a single ontological world, not a multitude of coexisting universes.

A. Experimental Predictions and Distinctions

DTC is empirically distinct from stochastic models such as GRW and CSL. It adds no noise to isolated or low-mass systems, matching all current bounds [3, 4]. DTC predicts instantaneous, tail-free macroscopic collapse, whereas CSL yields gradual, diffusion-like localization. DTC is also consistent with null results from

LISA Pathfinder [8] (see Fig. 5). Future large-mass interferometry and space-based experiments can directly discriminate DTC's threshold-triggered collapse from the continuous noise of CSL [9, 10].

B. Comparison with Other Collapse Models

TABLE II. Summary of key features of DTC, CSL, and GRW.

Feature	DTC	CSL	GRW
Trigger	Decoherence	Stochastic	Jumps
Micro noise	None	Yes	Yes
Collapse speed	Instant	Gradual	Sudden
Macro localiz.	Sharp	Diffusive	Jump
Exp. safe?	Yes	Limited	Limited
X-ray/mom. diff.	None	Yes	Yes
Parameters	None	2	2
Sim. efficiency	High	Low/Med	Med

C. Relation to Prior Collapse Models

DTC occupies a distinctive position within the landscape of objective collapse theories. Unlike stochastic approaches (GRW [1], CSL [2]), DTC achieves collapse via deterministic environmental coupling without injecting random noise into the dynamics. This absence of intrinsic stochasticity means DTC produces sharper position localization and unique experimental signatures in matter-wave interferometry: noise-free collapse preserves coherence except within the interaction region, whereas CSL/GRW models show distributed decoherence.

Compared to continuous spontaneous localization (CSL), DTC's collapse is simultaneously more selective (environment-dependent) and more precise (no noise-driven tail). The model also differs fundamentally from non-collapse interpretations: Many-Worlds requires no collapse but rejects local realism; pilot-wave theory maintains determinism but at the cost of preferred frames. DTC preserves local realism, determinism, and collapse while introducing only one new physical scale—the irreversibility threshold C_{irr}.

The relationship to recent developments in quantum darwinism and environmental decoherence is also noteworthy. DTC formalizes the intuition that redundant environmental encoding of pointer states should force actualization of one outcome. This provides a mechanistic grounding for why macroscopic systems appear classical despite microscopic quantum behavior.

D. Limitations and Open Questions

- **Relativistic Generalization:** A covariant version of DTC remains to be developed.
- **Pointer Basis in Field Theory:** Systematic, basis-independent triggers are an open challenge.
- **Finite-Rate Effects:** Simulations use large but finite Γ_0 and smooth logistic functions.
- **Experimental Discrimination:** Current experiments do not probe $C(\rho) \lesssim 10^{-20}$; future work is needed.
- **Energy Conservation:** Instantaneous pruning can violate energy conservation over the collapse timescale ($\sim 10^{-25}$ s); finite-rate versions restore strict conservation.

E. Future Directions

Several promising research directions emerge from this work:

1. **Matter-Wave Interferometry at Sub-Microkelvin Scales:** Large-mass atoms or molecules cooled to picokelvin temperatures provide the longest coherence times and most stringent tests of macro collapse. Planned experiments with cesium and larger clusters offer direct discrimination between DTC's threshold trigger and CSL's continuous noise.
2. **LISA+ and Next-Generation Gravitational Wave Detectors:** Space-based interferometers with arm lengths of order 1 Gm are uniquely sensitive to collapse-induced heating and momentum diffusion. Future LISA+ observations can probe the coherence threshold for macroscopic test masses and provide tight constraints on collapse parameters.
3. **Quantum Information and Decoherence-Free Subspaces:** DTC suggests that engineered environments with selective pointer bases may suppress collapse within information-storage subspaces while controlling collapse elsewhere. This has implications for quantum error correction and topological quantum computation.
4. **Numerical Benchmarking and Hartree–Fock Extensions:** Extensions of DTC to mean-field dynamics and many-body systems (e.g., Bose–Einstein condensates, fermionic systems) will improve computational efficiency and broaden applicability to condensed-matter phenomena.

VII. CONCLUSION

We have presented the **Decoherence-Triggered Collapse (DTC)** model, a minimal-parameter objective collapse framework in which wavefunction pruning occurs deterministically once environmental decoherence has suppressed off-diagonal coherence below a physically well-motivated irreversibility threshold C_{irr}. The mechanism requires no continuous microscopic noise, is consistent with all experimental bounds as of December 2025, and yields sharp, parameter-independent predictions—most notably the permanent loss of revivability in quantum-echo and erasure experiments once the threshold is crossed.

By tying collapse directly to the objective registration of information in the environment, DTC offers a deterministic alternative to stochastic collapse theories while preserving unitarity in isolated systems. The model is readily simulatable and identifies controlled macroscopic superpositions (e.g., in optomechanical and trapped-ion platforms) as decisive tests capable of distinguishing it from standard linear quantum mechanics in the near future.

These features position DTC as a distinct and highly testable candidate for resolving the quantum measurement problem.

Appendix A: Numerical Methods

The modified master equation (1) is integrated using a fourth-order Runge–Kutta (RK4) scheme with adaptive step-size control. The coherence measure $C(\rho)$ is monitored at each timestep, and the trigger is evaluated continuously. For stability, the coherence-dependent term is treated with a quasi-stochastic correction: in regimes where $C(\rho)$ crosses C_{irr}, the transition to full pruning is implemented via the logistic smoothing function to avoid numerical discontinuities.

Integration parameters are:

- Step size: $\Delta t = 10^{-28}$ s (adaptive, $\approx 0.01 \times \tau_{\text{dec}}$ in the transition region)
- Coherence threshold: $C_{\text{irr}} = 10^{-20}$
- Logistic steepness: $\kappa = 10^{22}$ (units: 1/s)
- Numerical precision: Double precision (float64)
- Error tolerance: Relative error $< 10^{-6}$ per step

The evolution is verified against analytical solutions in simple cases (e.g., pure dephasing with constant decoherence rate) and exhibits excellent energy conservation over integration windows of 10^{-6} s.

AUTHOR CONTRIBUTIONS

R.C. developed the DTC model, derived theoretical results, designed and executed all numerical simulations, analyzed data, prepared visualizations, and wrote the manuscript.

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COMPETING INTERESTS

The author declares no competing financial interests.

CONTACT

For questions or feedback, please contact the author at renny.chung.physics@gmail.com. Code and data are available at `https://github.com/rennychung/DTC`.

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