Gravity-Induced Decoherence from Irreversible Interaction Events

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Abstract

The relation between gravity and quantum coherence remains an open problem at the foundations of physics. While several models predict gravity-induced loss of quantum coherence, most rely on mass-dependent mechanisms or stochastic modifications of quantum dynamics, leading to negligible effects for massless particles such as photons. In this work, we propose a minimal and experimentally falsifiable mechanism in which decoherence arises from irreversible interaction events occurring at a rate influenced by gravitational potential differences. The model introduces no collapse postulate and preserves unitary evolution between events. We derive an effective Lindblad-type evolution in which gravitational potential gradients induce visibility loss independently of gravitational phase shifts. A key prediction is that quantum interference of photons exhibits a measurable reduction in visibility proportional to gravitational potential difference and interaction time. We propose concrete experimental tests using existing photon interferometry and satellite–ground quantum communication platforms. The model is decisively falsifiable: the absence of such visibility degradation beyond standard phase effects would rule it out.

1 Introduction

Understanding how gravity influences quantum systems is a central challenge in modern physics. While general relativity describes gravity as spacetime geometry and quantum mechanics governs microscopic dynamics, their conceptual integration remains incomplete. One persistent question concerns the origin of quantum decoherence and its possible connection to gravity.

Several approaches have suggested that gravity may induce decoherence or state reduction. Notable examples include the Penrose–Diósi model, in which gravitational self-energy drives collapse, and continuous spontaneous localization (CSL) models introducing stochastic noise. However, these frameworks typically predict effects that scale with mass and therefore vanish or become unobservable for massless particles such as photons.

In parallel, experimental capabilities in quantum optics and space-based quantum communication have advanced rapidly. High-precision interferometry with photons and atoms now probes regimes where subtle gravitational effects on quantum coherence may be detectable. This motivates the search for models that yield clear, testable predictions within existing experimental platforms.

In this paper, we present a minimal framework in which gravity induces decoherence through irreversible interaction events whose local rate depends on gravitational potential. The approach makes four key claims:

- Decoherence arises from irreversible interaction events rather than stochastic noise or explicit collapse.
- Gravitational potential differences modify the rate of such events.
- The resulting loss of coherence is independent of gravitational phase shifts.
- The effect applies equally to massless particles, including photons.

Crucially, the model is falsifiable. If no gravity-induced visibility degradation beyond standard phase effects is observed, the framework is ruled out.

2 Minimal Framework: Irreversible Interaction Events

2.1 Reversible propagation and irreversible events

We consider quantum dynamics as consisting of two conceptually distinct processes. Between interactions, a system evolves reversibly according to unitary dynamics generated by a Hamiltonian H. This evolution preserves information and von Neumann entropy.

In contrast, interactions are treated as irreversible events represented by completely positive, trace-preserving (CPTP) maps acting on the system state. Such maps cannot be inverted by any physical operation and generally increase entropy. No assumption is made regarding wavefunction collapse; irreversibility is taken as a primitive feature of physical interactions.

The total evolution over a finite interval is thus described as a sequence of unitary propagations punctuated by irreversible events. This structure is standard in open quantum systems, but here the occurrence rate of irreversible events is treated as a physical quantity subject to gravitational influence.

2.2 Event density

We introduce the event density $\rho(x)$ as the average number of irreversible interaction events occurring per unit proper time along a given worldline. In flat spacetime and in the absence of external fields, $\rho(x)$ reduces to a constant background value ρ_0 determined by environmental couplings.

The central assumption of this work is that gravitational potential modifies the local event density. Specifically, differences in gravitational potential lead to differences in the rate at which irreversible events occur, even when standard environmental conditions are held fixed.

No microscopic mechanism is specified at this stage. The role of event density is phenomenological, analogous to the introduction of decay rates or relaxation times in effective theories.

3 Gravity-Induced Decoherence Mechanism

3.1 Gravitational potential and event density

Consider two branches of a quantum superposition propagating through regions with different gravitational potentials Φ_1 and Φ_2. We assume that the local event density depends linearly on the gravitational potential to leading order:

$$\rho(\Phi) = \rho_0 \left(1 + \frac{\Phi}{c^2}\right), \tag{1}$$

where c is the speed of light. The relevant quantity for interference experiments is the difference in event density between the two paths:

$$\Delta\rho = \rho_0 \frac{\Delta\Phi}{c^2}. \tag{2}$$

This dependence is consistent with weak-field gravity and preserves local Lorentz invariance in freely falling frames.

3.2 Effective master equation

The cumulative effect of irreversible events can be described by an effective master equation of Lindblad type. For a reduced density matrix ρ, we write

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] + \rho(x)\mathcal{D}[\rho], \tag{3}$$

where $\mathcal{D}$ is a dissipator characterizing the irreversible interaction. The precise form of $\mathcal{D}$ is not essential for the present argument; it suffices that it suppresses coherence between distinguishable paths.

3.3 Visibility decay

For a two-path interferometer, the off-diagonal elements of the density matrix decay exponentially due to the difference in event density between the paths. The interference visibility $V(t)$ takes the form

$$V(t) = \exp\left(-\gamma\rho_0\frac{\Delta\Phi}{c^2}t\right), \tag{4}$$

where γ is a dimensionless constant determined by the coupling strength of the irreversible events. Importantly, this decay is independent of any gravitationally induced phase shift and affects only the visibility of the interference pattern.

4 Distinction from Existing Models

4.1 Penrose–Diósi model

In the Penrose–Diósi framework, decoherence or collapse is driven by the gravitational self-energy of mass distributions. As a result, the predicted effect vanishes for massless particles such as photons. In contrast, the present model depends on gravitational potential differences rather than mass, and therefore predicts decoherence for photons.

4.2 Continuous spontaneous localization

CSL models introduce stochastic noise fields with phenomenological parameters. While CSL can in principle affect photons, the predicted effects are typically extremely small and depend on poorly constrained parameters. The present framework introduces no stochastic noise and yields a direct, parameter-minimal dependence on gravitational potential.

4.3 Key distinguishing features

Feature	Penrose–Diósi	CSL	This model
Mass dependence	Yes	Yes	No
Stochastic noise	No	Yes	No
Photon decoherence	No	Negligible	Yes
Phase-independent effect	No	No	Yes

Table 1: Comparison of different models

5 Experimental Proposals

5.1 Photon interferometry

A straightforward test uses a photon interferometer with arms separated by a height difference Δh in Earth's gravitational field, corresponding to $\Delta\Phi = g\Delta h$. After accounting for standard gravitational phase shifts, the model predicts an additional reduction in visibility proportional to $g\Delta h$ and interaction time.

5.2 Satellite–ground experiments

Existing satellite-based quantum communication experiments provide an ideal platform. Entangled photon pairs distributed between ground stations and satellites experience large gravitational potential differences while maintaining high phase stability. Any observed visibility degradation beyond known noise sources would directly test the model.

5.3 Falsification criterion

If interference visibility remains invariant under changes in gravitational potential after correcting for phase effects and environmental decoherence, the model is ruled out.

6 Discussion

The proposed mechanism is consistent with the equivalence principle. In a locally freely falling frame, gravitational potential gradients vanish and no additional decoherence is predicted. The effect arises only from relative potential differences between distinct paths.

The framework does not modify quantum mechanics at the level of fundamental dynamics. Instead, it attributes decoherence to the physical rate of irreversible interaction events, offering a new perspective on the interface between gravity and quantum theory.

7 Conclusion

We have presented a minimal and experimentally falsifiable model of gravity-induced decoherence based on irreversible interaction events. The key prediction—a phase-independent loss of quantum interference visibility proportional to gravitational potential difference—distinguishes this approach from existing models and applies to massless particles such as photons. Ongoing and near-future experiments in quantum optics and space-based quantum communication are capable of decisively testing the proposal.

References

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