

Spontaneous Decoherence from Logarithmic Spectral Phase Deformations

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Abstract

We examine a mechanism of spontaneous decoherence in which the generator of quantum dynamics is deformed to a logarithmically modified self-adjoint operator

$$F_\beta(H) = H + \beta H \log \frac{H}{E_*}$$

for a positive self-adjoint Hamiltonian H and a fixed reference scale $E_* > 0$. Dynamical phases acquire energy-dependent factors $\exp[-it\beta E \log(E/E_*)]$, whose rapid variation across the spectrum suppresses interference between distinct energies through a non-stationary-phase mechanism. Stationary-phase analysis shows that oscillatory contributions to amplitudes decay at least as $\mathcal{O}(1/|\beta|)$ when $|\beta|$ is large.

Since $F_\beta(H)$ is self-adjoint for every real β , the evolution operator $U_\beta(t) = \exp[-itF_\beta(H)]$ is unitary. The kinematical structure of quantum mechanics—Hilbert-space inner products, projection operators, the Born rule—remains unchanged. Decoherence arises as suppression of interference terms in coarse-grained observables and decoherence functionals, not as norm loss or stochastic collapse. Physical motivation for logarithmic spectral deformations comes from clock imperfections, renormalization-group and effective-action corrections introducing $\log E$ terms, and semiclassical gravity analyses with complex actions generating spectral factors involving $\log(E/E_P)$. The mechanism is illustrated with two-level systems, quartic oscillators, FRW minisuperspace models, and Schwarzschild-interior-type Hamiltonians. Current superconducting-qubit coherence times constrain $|\beta| \lesssim 10^{-5}$; trapped ions, NV centers, and cold atoms could strengthen this to $|\beta| \lesssim 10^{-8}$.

Contents

1	Introduction	2
1.1	Point of departure	2
1.2	A poetic intuition	3
1.3	Scope of this work	3
2	Logarithmic Spectral Deformations	4
2.1	Definition of the deformation	4
2.2	Unitarity of the deformed dynamics	5
2.2.1	Explicit verification for discrete spectrum	5

3	Non-Stationary Phase and Decoherence	5
3.1	Density matrix and off-diagonal coherence	6
4	Physical Motivation	6
4.1	Clock imperfections and operational time	7
4.2	Renormalization group and effective actions	7
4.3	Semiclassical gravity and complex actions	7
5	Logarithmic vs. Real-Order Fractional Calculus	8
6	Illustrative Examples	8
6.1	Two-level system: worked example	8
6.2	Quartic oscillator	9
6.3	FRW minisuperspace toy model	10
6.4	Curved-background and Schwarzschild interior-type Hamiltonians	10
7	Phenomenology and Experimental Constraints	10
7.1	General scaling and decoherence envelopes	10
7.2	Superconducting qubits as a benchmark platform	11
7.3	Summary table of representative platforms	12
8	Related Work and Novelty	12
8.1	Non-environmental (intrinsic) models	13
8.2	Environmental / open-system models	13
8.3	Structural novelty	14
9	Discussion and Outlook	15

1 Introduction

Standard quantum dynamics evolves states unitarily under $U(t) = e^{-iHt}$, where H is the system Hamiltonian. Interference patterns arise from coherent superpositions of energy eigenstates, each accumulating phase at its own characteristic frequency. These interference terms persist indefinitely in isolated quantum systems.

Yet decoherence—the suppression of quantum interference—is ubiquitous in nature. Conventional explanations invoke environmental coupling [8, 9], stochastic modifications [1, 2, 3, 7], or collapse mechanisms [4, 5, 6, 12, 13, 14, 15]. Each modifies the fundamental dynamics: either through coupling to external degrees of freedom, adding noise, or breaking unitarity.

We explore a different possibility.

1.1 Point of departure

This paper investigates a mechanism in which decoherence arises spontaneously from a deterministic modification of the dynamical generator, without stochastic processes or external degrees of freedom. Instead of replacing H by a non-Hermitian deformation, we consider a self-adjoint spectral deformation of the form

$$F_\beta(H) = H + \beta H \log \frac{H}{E_*}, \quad (1)$$

defined via the spectral theorem for a positive self-adjoint H and a fixed reference scale $E_* > 0$.¹

The evolution operator becomes

$$U_\beta(t) = \exp[-itF_\beta(H)], \quad (2)$$

with eigenstate amplitudes

$$U_\beta(t)|E\rangle = \exp\left[-itE\left(1 + \beta \log \frac{E}{E_*}\right)\right]|E\rangle. \quad (3)$$

The deformation introduces phases depending on $\beta E \log(E/E_*)$. This oscillatory structure suppresses interference between distinct energies by a non-stationary-phase mechanism. The mechanism is deterministic and internal to the system: it does not rely on baths, measurements, or nonlinearity. Hilbert-space inner products, projection operators, and probability assignments via the Born rule remain exactly as in standard quantum mechanics. Only the dynamical phases are modified, through a real spectral function of H .

1.2 A poetic intuition

Wheeler said that space tells matter how to move, and matter tells space how to curve. By analogy:

energy tells time how to tick, and time tells energy how to decohere.

This is not literal—time remains an external parameter. But energies E accumulate phases $\sim tE \log E$, not just $\sim tE$. Different energies thus “experience time” at logarithmically different rates. Interference between them becomes unobservable when these rates diverge.

Physical picture. Imagine an ensemble of clocks, each running at a rate slightly dependent on its energy. Low-energy modes accumulate phase as $\sim tE(1 + \beta \log E)$, while high-energy modes accumulate phase at a different rate. Over time, these clocks drift out of sync by amounts proportional to $\beta tE \log E$. When we measure an observable that involves coherence between different energy components, we see an average over many such drifting clocks, and this average washes out if the drift (the β term) is large enough. The remarkable feature is that this desynchronization occurs even though each clock, individually, keeps perfect time (unitarity is preserved).

1.3 Scope of this work

This work is phenomenological. We do not derive β from first principles, solve the measurement problem, or claim to replace environmental decoherence. Instead, we ask: if logarithmic spectral corrections exist—from renormalization group flow, quantum gravity, or imperfect clocks—what would they do to quantum coherence?

¹The choice of reference scale E_* is arbitrary—shifting it changes $F_\beta(H)$ by βH , which merely redefines the zero of energy. All physical predictions depend only on differences $G(E_m) - G(E_n)$, making E_* drop out.

The answer: they produce observable dephasing even in isolated systems, testable with current experimental precision.

Section 2 introduces logarithmic spectral deformations and establishes basic properties, including self-adjointness and unitarity. Section 3 presents a non-stationary-phase estimate that quantifies interference suppression. Section 4 develops physical motivations from clock imperfections, renormalization-group flow, and semiclassical gravity. Section 5 explains how the present mechanism differs from standard real-order fractional calculus. Section 6 illustrates the mechanism in several simple Hamiltonians. Section 7 discusses phenomenology and experimental constraints. Section 8 situates the proposal among existing decoherence models. Section 9 offers concluding remarks.

2 Logarithmic Spectral Deformations

Let H be a positive self-adjoint operator with spectral resolution

$$H = \int_0^\infty E d\Pi(E), \quad (4)$$

where $\Pi(E)$ is the projection-valued measure associated with H . For any Borel measurable function $f : (0, \infty) \rightarrow \mathbb{R}$, the functional calculus defines the self-adjoint operator

$$f(H) = \int_0^\infty f(E) d\Pi(E). \quad (5)$$

2.1 Definition of the deformation

Choose a reference energy scale $E_* > 0$ (the specific value will not matter). For $\beta \in \mathbb{R}$, define the real spectral function

$$F_\beta(E) = E \left(1 + \beta \log \frac{E}{E_*} \right), \quad (6)$$

and the corresponding operator

$$F_\beta(H) = \int_0^\infty F_\beta(E) d\Pi(E) = H + \beta H \log \frac{H}{E_*}, \quad (7)$$

where $\log(H/E_*)$ is defined via the spectral calculus.

Proposition 2.1. *For each $\beta \in \mathbb{R}$, the operator $F_\beta(H)$ is self-adjoint on a dense domain $D(F_\beta(H)) \subset \mathcal{H}$.*

Proof. The function $F_\beta(E)$ in Eq. (6) is real-valued and measurable on $(0, \infty)$. The spectral theorem then guarantees that $F_\beta(H)$ is self-adjoint on the domain

$$D(F_\beta(H)) = \left\{ \psi \in \mathcal{H} : \int_0^\infty |F_\beta(E)|^2 d\langle \psi, \Pi(E)\psi \rangle < \infty \right\}, \quad (8)$$

which is dense because H is self-adjoint and F_β grows at most linearly times a logarithm. \square

2.2 Unitarity of the deformed dynamics

Define the deformed evolution operator

$$U_\beta(t) = e^{-itF_\beta(H)}, \quad t \in \mathbb{R}. \quad (9)$$

By Stone's theorem, because $F_\beta(H)$ is self-adjoint, $\{U_\beta(t)\}_{t \in \mathbb{R}}$ is a strongly continuous one-parameter unitary group:

$$U_\beta(t)^\dagger U_\beta(t) = U_\beta(t)U_\beta(t)^\dagger = I, \quad U_\beta(t+s) = U_\beta(t)U_\beta(s). \quad (10)$$

In the energy eigenbasis, Eq. (4) implies

$$U_\beta(t)|E\rangle = e^{-itF_\beta(E)}|E\rangle = \exp\left[-itE\left(1 + \beta \log \frac{E}{E_*}\right)\right]|E\rangle. \quad (11)$$

The additional phase is real for all $E > 0$, so the norm of any state is preserved. The Born rule and probabilities assigned to projection operators remain exactly as in the undeformed theory.

2.2.1 Explicit verification for discrete spectrum

For a state in the energy eigenbasis, $|\psi(0)\rangle = \sum_n c_n |E_n\rangle$, the evolved state is

$$|\psi(t)\rangle = \sum_n c_n e^{-itF_\beta(E_n)} |E_n\rangle. \quad (12)$$

The norm is

$$\langle \psi(t) | \psi(t) \rangle = \sum_n |c_n|^2 |e^{-itF_\beta(E_n)}|^2 = \sum_n |c_n|^2 = 1, \quad (13)$$

confirming unitarity at the level of individual states.

3 Non-Stationary Phase and Decoherence

Suppression of interference arises when summations or integrals over energy are dominated by rapidly varying phases induced by $F_\beta(E)$. To capture this, consider an oscillatory integral of the form

$$I_\beta(t) = \int_0^\infty f(E) e^{-itF_\beta(E)} dE, \quad (14)$$

where f is a smooth function with compact support in $(0, \infty)$.

Define the phase

$$\Phi_\beta(E) = tF_\beta(E) = tE\left(1 + \beta \log \frac{E}{E_*}\right), \quad (15)$$

and its derivative

$$\Phi'_\beta(E) = t\left[1 + \beta\left(\log \frac{E}{E_*} + 1\right)\right]. \quad (16)$$

In regimes where $|\Phi'_\beta(E)|$ is large and does not vanish on the support of f , standard non-stationary-phase estimates apply.

Theorem 3.1. *Let $f \in C_c^1((0, \infty))$ and $t \neq 0$. Assume that there exist E_{\min}, E_{\max} with $\text{supp } f \subset [E_{\min}, E_{\max}] \subset (0, \infty)$, and that for $|\beta|$ sufficiently large, $|\Phi'_\beta(E)| \geq c|t||\beta|$ on $[E_{\min}, E_{\max}]$ for some $c > 0$. Then there exist constants $C, \beta_0 > 0$ such that for all $|\beta| \geq \beta_0$,*

$$|I_\beta(t)| \leq \frac{C}{|\beta|}. \quad (17)$$

In particular, $I_\beta(t) \rightarrow 0$ as $|\beta| \rightarrow \infty$ with decay at least of order $1/|\beta|$.

Proof. Assume $\text{supp } f \subset [E_{\min}, E_{\max}]$. Integration by parts yields

$$I_\beta(t) = \int_{E_{\min}}^{E_{\max}} f(E) e^{-i\Phi_\beta(E)} dE = \left[\frac{f(E)}{-i\Phi'_\beta(E)} e^{-i\Phi_\beta(E)} \right]_{E_{\min}}^{E_{\max}} + \int_{E_{\min}}^{E_{\max}} \frac{f'(E)}{i\Phi'_\beta(E)} e^{-i\Phi_\beta(E)} dE. \quad (18)$$

Using $|\Phi'_\beta(E)| \geq c|t||\beta|$ and boundedness of f, f' on $[E_{\min}, E_{\max}]$, we obtain

$$|I_\beta(t)| \leq \frac{\|f\|_\infty}{c|t||\beta|} + \frac{\|f'\|_\infty(E_{\max} - E_{\min})}{c|t||\beta|} \leq \frac{C}{|\beta|} \quad (19)$$

for a suitable constant $C > 0$ independent of β . \square

The theorem shows that oscillatory integrals involving phases $F_\beta(E)$ with large slope are suppressed as $|\beta| \rightarrow \infty$. For interference between two discrete energy levels (E_m, E_n), a natural effective decoherence timescale is

$$\tau_{\text{dec}}(E_m, E_n; \beta) \sim \frac{1}{|\beta||G(E_m) - G(E_n)|}, \quad G(E) := E \log \frac{E}{E_*}, \quad (20)$$

so that interference between those levels is strongly suppressed once $|t| \gg \tau_{\text{dec}}$.

3.1 Density matrix and off-diagonal coherence

Consider the density matrix $\rho(t) = |\psi(t)\rangle\langle\psi(t)|$. For a two-level superposition, the off-diagonal element evolves as

$$\rho_{12}(t) = c_1 c_2^* \exp \left\{ -it[(E_1 - E_2) + \beta(G(E_1) - G(E_2))] \right\}, \quad (21)$$

where $G(E) = E \log(E/E_*)$. While $|\rho_{12}(t)| = |c_1 c_2^*|$ remains constant (reflecting unitarity), the phase oscillates at an effective frequency

$$\omega_{\text{eff}} = (E_1 - E_2) + \beta(G(E_1) - G(E_2)). \quad (22)$$

In measurements that average over time windows Δt or integrate over energy distributions, the β -dependent term causes rapid dephasing, effectively suppressing the interference contribution. This is the mechanism of decoherence in the present framework: not loss of unitarity, but suppression of observable coherence through rapid phase variation.

4 Physical Motivation

Several contexts suggest logarithmic spectral deformations of the form $F_\beta(H)$.

4.1 Clock imperfections and operational time

A physical clock with Hamiltonian H_C may tick at an energy-dependent rate:

$$\frac{dt_{\text{physical}}}{dt_{\text{ideal}}} = 1 + \alpha \log(E/E_0). \quad (23)$$

Effective evolution becomes

$$\exp(-itE) \rightarrow \exp[-itEf(\log E)], \quad (24)$$

with $f(\log E) \approx 1 + \beta \log(E/E_*)$ over some energy window. This leads directly to an effective generator of the form $F_\beta(H)$ in an operational description of time evolution. Here β measures how much physical time deviates from ideal coordinate time. Related ideas appear in clock-induced decoherence and fundamental limits to timekeeping [7].

This connection to clock physics is not merely formal. Any quantum system subjected to external timing—whether a trapped ion interrogated by lasers or a qubit gated by microwave pulses—effectively conditions its evolution on the “ticking” of that external clock. If the clock’s tick rate varies with the system’s energy (even slightly), the net effect is an energy-dependent time dilation. Over many cycles, this accumulates as a phase $\sim \beta E \log E \times t$. The question is whether β is large enough to measure.

4.2 Renormalization group and effective actions

Renormalization-group and effective-action treatments of quantum field theories and quantum gravity frequently produce running couplings and masses of the form

$$g(E) = g_0 + \alpha \log(E/\mu), \quad (25)$$

or effective Hamiltonians

$$H_{\text{eff}}(E) = Ef(\log E), \quad (26)$$

with f a slowly varying function. When these expressions enter the time-evolution factor $\exp[-itH_{\text{eff}}(E)]$, the logarithmic dependence generates spectral phases with $E \log(E/\mu)$ structure. The deformation $F_\beta(H)$ can thus be viewed as a compact representation of RG-induced distortions of the generator, capturing the leading logarithmic behavior in a simple analytic form.

4.3 Semiclassical gravity and complex actions

Anomaly-induced effective actions and semiclassical gravitational calculations often involve operators such as $\log(\square/\mu^2)$, where \square is a covariant d’Alembertian. In minisuperspace or reduced models, these terms translate into logarithmic functions of the effective Hamiltonian or energy. Standard references on quantum fields in curved spacetime [18, 19] contain numerous examples in which logarithmic spectral terms appear.

Likewise, semiclassical WKB analyses of gravitational systems and black-hole spacetimes can yield actions of the form

$$S(E) = S_0(E) + i\hbar\gamma \log \frac{E}{E_P} + \dots, \quad (27)$$

so that the semiclassical wave function

$$\exp\left[\frac{i}{\hbar}S(E)\right] = E^{i\gamma} \exp\left[\frac{i}{\hbar}S_0(E)\right] \quad (28)$$

contains precisely the logarithmic spectral factor motivating deformations like $F_\beta(H)$. In the present framework, this structure is encoded in a real, self-adjoint generator which produces energy-dependent phases proportional to $E \log(E/E_*)$.

$F_\beta(H)$ should be interpreted as a phenomenological stand-in for a more general functional deformation $F(H)$ arising from integrating out gravitational or high-energy degrees of freedom, with the particular form (1) capturing the leading logarithmic behavior without committing to a specific microscopic model.

5 Logarithmic vs. Real-Order Fractional Calculus

The appearance of a logarithmic term in the generator might invite comparison with fractional calculus and fractional quantum mechanics [16, 17]. In standard fractional calculus, one studies real-order derivatives and integrals (e.g. Riemann-Liouville or Caputo derivatives) that act via nonlocal integral kernels and encode memory effects. Real-order fractional dynamics often lead to anomalous diffusion and non-Markovian behavior.

The present construction is of a different type. The deformation

$$F_\beta(H) = H + \beta H \log \frac{H}{E_*} \quad (29)$$

belongs to the spectral functional calculus of a positive operator H . There is no associated real-order memory kernel in time and no direct connection to the Riemann-Liouville or Caputo operators. The logarithmic term appears in the energy domain, not as a fractional time derivative. The resulting dynamics remain unitary, and decoherence arises from oscillatory phase suppression rather than from anomalous diffusion.

In particular, the mechanism here should not be viewed as an instance of fractional Schrödinger dynamics. It is instead a purely spectral deformation in the sense of functional calculus, whose primary consequence is a dephasing of energy eigencomponents governed by energy-dependent phases involving $\log(E/E_*)$.

6 Illustrative Examples

We illustrate how the deformation $F_\beta(H)$ acts on several simple Hamiltonians. The goal is to show concretely how spectral structure feeds into decoherence rates.

6.1 Two-level system: worked example

Consider a qubit with energies E_1, E_2 :

$$H = \begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix}, \quad E_1 = 5 \text{ GHz} \times 2\pi, \quad E_2 = 5.1 \text{ GHz} \times 2\pi. \quad (30)$$

Taking $E_* = 1 \text{ GHz} \times 2\pi$ as reference scale, we have

$$\log(E_1/E_*) = \log 5 \approx 1.61, \quad (31)$$

$$\log(E_2/E_*) = \log 5.1 \approx 1.63. \quad (32)$$

The functions $G(E) = E \log(E/E_*)$ evaluate to

$$G(E_1) = E_1 \times 1.61 = (2\pi \times 5 \times 10^9 \text{ s}^{-1}) \times 1.61 \approx 5.05 \times 10^{10} \text{ s}^{-1}, \quad (33)$$

$$G(E_2) = E_2 \times 1.63 = (2\pi \times 5.1 \times 10^9 \text{ s}^{-1}) \times 1.63 \approx 5.22 \times 10^{10} \text{ s}^{-1}. \quad (34)$$

The difference is

$$G(E_2) - G(E_1) \approx 1.7 \times 10^9 \text{ s}^{-1}. \quad (35)$$

For an initial superposition $|\psi(0)\rangle = (|1\rangle + |2\rangle)/\sqrt{2}$, the off-diagonal density matrix element oscillates as

$$\rho_{12}(t) = \frac{1}{2} \exp \left\{ -it [\Delta E_0 + \beta \times 1.7 \times 10^9 \text{ s}^{-1}] \right\}, \quad (36)$$

where $\Delta E_0 = E_2 - E_1 = 2\pi \times 0.1 \times 10^9 \approx 6.3 \times 10^8 \text{ s}^{-1}$.

The effective oscillation frequency is shifted by

$$\Delta\omega = \beta \times 1.7 \times 10^9 \text{ s}^{-1}. \quad (37)$$

For $\beta = 10^{-6}$, this gives $\Delta\omega/2\pi \approx 270 \text{ Hz}$, which is in principle measurable with modern precision spectroscopy. For $\beta = 10^{-8}$, $\Delta\omega/2\pi \approx 2.7 \text{ Hz}$, requiring sub-Hz frequency resolution.

6.2 Quartic oscillator

As a simple bound-state example, consider the quartic oscillator

$$H = \frac{p^2}{2m} + \lambda x^4, \quad \lambda > 0. \quad (38)$$

Its eigenvalues satisfy asymptotically

$$E_n \sim \kappa n^{4/3}, \quad n \rightarrow \infty, \quad (39)$$

for some constant $\kappa > 0$. Under the deformation, a superposition $\sum_n c_n |n\rangle$ evolves with phases $e^{-itE_\beta(E_n)}$. Interference between levels n and m decays on a timescale

$$\tau_{\text{dec}}(n, m; \beta) \sim \frac{1}{|\beta| |E_n \log(E_n/E_*) - E_m \log(E_m/E_*)|}. \quad (40)$$

For large n, m , the asymptotic form of E_n can be used to obtain explicit scaling relations between decoherence time, level index, and β . One might initially expect the decoherence timescale to scale as $\tau \sim 1/(\beta E)$, treating the logarithm as approximately constant. However, the full expression shows that $G(E) = E \log E$ grows superlinearly, making highly excited states more sensitive to the deformation than this naive estimate would suggest. For $E_n \sim n^{4/3}$, we have $G(E_n) \sim n^{4/3} \log n$, which scales faster than any fixed power of n .

6.3 FRW minisuperspace toy model

In FRW minisuperspace models with a single scale factor a , effective Hamiltonians of the form

$$H = -\frac{d^2}{da^2} + V(a) \quad (41)$$

arise, with potentials $V(a)$ encoding curvature, cosmological constant, and matter content. For simple choices of $V(a)$ (e.g. harmonic-oscillator-like near a minimum), one obtains a discrete spectrum E_n that grows approximately linearly in n . The deformation $F_\beta(H)$ then introduces phases $F_\beta(E_n)$ that dephase superpositions of minisuperspace modes, providing a toy model of spontaneous decoherence in a cosmological setting. The timescales follow the same pattern as in Eq. (20).

6.4 Curved-background and Schwarzschild interior-type Hamiltonians

Effective one-dimensional Hamiltonians modeling motion in curved backgrounds, including toy models of the Schwarzschild interior, often take the form

$$H = -\frac{d^2}{dx^2} + V(x), \quad (42)$$

with potentials such as

$$V(x) = -\frac{\alpha}{x^2} + \beta_1 x^2, \quad \alpha, \beta_1 > 0. \quad (43)$$

This class of potentials admits a discrete spectrum for appropriate boundary conditions and has been used as a simple model of black-hole interior dynamics. Let E_n denote the eigenvalues. Under the deformation, the time evolution of a superposition of interior modes is governed by

$$\sum_n c_n e^{-itF_\beta(E_n)} |n\rangle, \quad (44)$$

and the interference structure can be studied by approximating the sum as an integral over a smooth spectral density. The absence of stationary points in the deformed phase over suitable windows implies $\mathcal{O}(1/|\beta|)$ suppression of cross terms, providing a simple model of spontaneous decoherence in an effective black-hole interior Hamiltonian.

7 Phenomenology and Experimental Constraints

7.1 General scaling and decoherence envelopes

Consider two energy levels E_m and E_n . The decoherence rate is approximately

$$\Gamma_{mn}(\beta) \sim |\beta| |G(E_m) - G(E_n)|, \quad G(E) = E \log \frac{E}{E_*}, \quad (45)$$

with corresponding timescale $\tau_{\text{dec}} \sim 1/\Gamma_{mn}$, cf. Eq. (20). If environmental decoherence produces a standard coherence envelope $C_{\text{std}}(t)$, the present mechanism can be viewed as supplying an additional deterministic decay envelope, so that

$$C_{\text{meas}}(t) \approx C_{\text{std}}(t) e^{-\Gamma_{mn} t}, \quad (46)$$

over timescales where the non-stationary-phase estimate is valid. In an experiment, one would first calibrate $C_{\text{std}}(t)$ using environmental models and then fit the residual decay to extract or bound Γ_{mn} , and hence β . This logic parallels the way collapse-model parameters are bounded by precision experiments [6].

7.2 Superconducting qubits as a benchmark platform

Consider a superconducting-qubit platform where typical transition energies lie in the range $E \sim 5$ GHz and coherence times $T_2 \sim 100$ μs are routinely achieved. Energies are measured in angular-frequency units (setting $\hbar = 1$), so that E and ΔE are understood as angular frequencies in s^{-1} ; numerically, $E \sim 5$ GHz should thus be read as $E \sim 2\pi \times 5 \times 10^9$ s^{-1} .

For two energy levels separated by $\Delta E \sim 100$ MHz, the quantity

$$|G(E_m) - G(E_n)| = \left| E_m \log \frac{E_m}{E_*} - E_n \log \frac{E_n}{E_*} \right| \quad (47)$$

can be approximated by

$$|G(E_m) - G(E_n)| \approx |\Delta E| \left| \log \frac{E}{E_*} + 1 \right|, \quad (48)$$

for E in the relevant range. Taking E_* in the GHz range, $\log(E/E_*)$ is $\mathcal{O}(1)$, and for concreteness one may estimate $|\log(E/E_*) + 1| \sim 20$ in natural units.² Using $\Delta E = 10^8$ s^{-1} , we obtain a characteristic scale

$$|G(E_m) - G(E_n)| \sim 2 \times 10^9 \text{ s}^{-1}. \quad (49)$$

Requiring spontaneous decoherence from the deformation to occur on timescales longer than the experimentally observed coherence time, i.e. $\tau_{\text{dec}} \gtrsim T_2$, gives

$$\frac{1}{|\beta| |G(E_m) - G(E_n)|} \gtrsim T_2, \quad (50)$$

and hence

$$|\beta| \lesssim \frac{1}{T_2 |G(E_m) - G(E_n)|} \sim \frac{1}{(10^{-4} \text{ s})(2 \times 10^9 \text{ s}^{-1})} \sim 5 \times 10^{-6}. \quad (51)$$

Thus, for superconducting qubits, the absence of anomalous decoherence at the $T_2 \sim 100$ μs level constrains the deformation parameter to

$$|\beta| \lesssim 10^{-5}. \quad (52)$$

Platforms with longer coherence times, such as trapped ions or certain cold-atom setups, can in principle provide even stronger bounds.

²We assume $|\log(E/E_*) + 1| \sim 20$ as a rough estimate. The actual value depends on the choice of E_* , but the scaling $\propto \beta \Delta E \log E$ is robust.

Constraining β in superconducting qubits:

1. Prepare equal superposition: $|\psi\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$
2. Measure Ramsey fringe frequency ω_{obs} with precision $\delta\omega$
3. Standard theory predicts: $\omega_0 = E_1 - E_0$
4. LSD modification: $\omega_{\text{LSD}} = \omega_0 + \beta[G(E_1) - G(E_0)]$
5. Any deviation $|\omega_{\text{obs}} - \omega_0| > \delta\omega$ constrains β :

$$|\beta| \lesssim \frac{\delta\omega}{|G(E_1) - G(E_0)|}$$

6. For typical values: $\delta\omega/2\pi \sim 1$ Hz, $|G(E_1) - G(E_0)| \sim 10^9$ Hz $\Rightarrow |\beta| \lesssim 10^{-9}$ (order of magnitude).

Operationally, a practical way for an experimentalist to fit β is to treat the deformation as supplying an additional deterministic decay envelope on top of the usual environmental coherence function. If $C_{\text{std}}(t)$ denotes the standard coherence curve obtained from Ramsey or spin-echo measurements, the prediction of the present mechanism is that the measured signal can be modeled as

$$C_{\text{meas}}(t) = C_{\text{std}}(t)e^{-\Gamma_{mn}t}, \quad \Gamma_{mn} = |\beta||G(E_m) - G(E_n)|. \quad (53)$$

In practice, one fits the residual exponential envelope after independently calibrating $C_{\text{std}}(t)$; the slope of the residual decay yields Γ_{mn} , and thus β , directly. If no statistically significant residual decay is observed, the sensitivity of the fit provides an upper bound on $|\beta|$. In this way, routine coherence measurements become quantitative probes of logarithmic spectral deformations.

7.3 Summary table of representative platforms

Different experimental platforms map into sensitivity to the deformation parameter β . For each, one may identify representative ranges of transition frequencies E , level splittings ΔE , and coherence times T_2 , and then apply the scaling

$$|\beta|_{\text{max}} \sim \frac{1}{T_2|\Delta E||\log(E/E_*) + 1|}, \quad (54)$$

obtained by approximating $|G(E_m) - G(E_n)| \approx |\Delta E||\log(E/E_*) + 1|$.

The values are indicative and are not tied to any specific laboratory implementation. They are meant to convey the relative leverage of different platforms given the same underlying scaling.

8 Related Work and Novelty

We situate the present proposal among existing models of decoherence, both non-environmental (intrinsic) and environmental (open-system) in character.

Platform	Typical E (Hz)	T_2 (s)	Illustrative $ \beta _{\max}$
Superconducting qubits	$\sim 5 \times 10^9$	$\sim 10^{-4}$	$\sim 10^{-5}$
Trapped ions (optical qubits)	$\sim 10^{15}$	~ 1	$\sim 10^{-7}-10^{-8}$
NV centers / solid-state spins	$\sim 3 \times 10^9$	$10^{-3}-10^{-2}$	$10^{-6}-10^{-7}$
Cold atoms in optical lattices	10^4-10^5	1-10	$10^{-5}-10^{-6}$

Table 1: Representative order-of-magnitude parameters for several experimental platforms and corresponding illustrative sensitivities to the deformation parameter $|\beta|$, based on the scaling (54). The values are indicative and are not tied to any specific laboratory implementation.

8.1 Non-environmental (intrinsic) models

Several proposals have attempted to describe intrinsic or spontaneous decoherence without explicit environments. Milburn [1] replaces smooth Schrödinger evolution by a stochastic sequence of unitary kicks characterized by a mean waiting time, leading to a master equation of Lindblad form. Diósi and Penrose [2, 3] argue for gravitational collapse of the wave function based on gravitational self-energy considerations, yielding a characteristic collapse timescale of order $\hbar/E\Delta$. GRW and CSL models [4, 5, 6] implement spontaneous localization events driven by noise, leading to fundamentally nonunitary dynamics. Clock-induced decoherence in quantum-gravity-motivated settings [7] attributes decoherence to the use of physical (imperfect) clocks in place of an ideal external time parameter, leading again to Lindblad-type terms and exponential damping of coherences.

More recently, Snoke and collaborators [12, 13, 14, 15] have developed energy-conserving spontaneous collapse models, extended to nonlocal relativistic quantum field theory and elaborated with explicit experimental predictions and a broader interpretive framework. In these models, collapse occurs in an energy-conserving manner, but the dynamics remains stochastic and nonunitary at the level of state evolution.

All of these intrinsic models introduce nonunitarity through stochastic processes, collapse operators, or explicit Lindblad terms. By contrast, the present model implements decoherence via a unitary spectral deformation: the generator $F_\beta(H)$ is self-adjoint, the dynamics is unitary, and decoherence arises from non-stationary-phase suppression of spectral interference.

8.2 Environmental / open-system models

Standard environment-induced decoherence is modeled by master equations of Lindblad type, Caldeira-Leggett oscillator baths, quantum trajectories, and, more recently, non-Hermitian Hamiltonian deformations. Lindblad master equations [8] describe dissipative evolution of a subsystem coupled to a bath, yielding exponential damping of off-diagonal density-matrix elements, and constitute the canonical form of Markovian open-system dynamics. Caldeira-Leggett-type models [9] implement an oscillator bath linearly coupled to the system, leading to Brownian motion and friction with reduced dynamics that is nonunitary once the bath is traced out. Quantum-trajectory approaches condition evolution on measurement records, with stochastic jumps and nonlinear state updates, providing an unraveling of Lindblad dynamics [8].

Non-Hermitian Hamiltonian deformations in the sense of Matsoukas-Roubeas and collaborators [10, 11] encode energy diffusion and dephasing via effective non-Hermitian

generators $H - i\Gamma$, related to open Markovian dynamics, imperfect timekeeping, and inverse $T\bar{T}$ deformations. In this framework, the imaginary parts of the eigenvalues directly produce decay, and one often restores norm via nonlinear renormalization of the state. In related work, unitarity breaking in self-averaging spectral form factors is analyzed using mixed-unitary channels and non-Hermitian Hamiltonians.

All of these models either explicitly break unitarity (reduced dynamics) or require nonlinear renormalization of the state. They differ from the present proposal, which preserves exact unitarity at the level of the full evolution operator and produces decoherence purely through energy-dependent phases.

8.3 Structural novelty

Feature	Environmental	Collapse models	LSD (this work)
Generator type	Open system	Stochastic	Self-adjoint
Unitarity	No (reduced)	No	Yes
Norm preservation	No	No	Yes
Decoherence origin	Entanglement	Wave collapse	Phase dephasing
Time evolution	Lindblad/master eq.	Jump process	Schrödinger
Free parameter	Bath coupling γ	Collapse rate λ	Phase strength β
Observable signature	Exponential decay	Position localization	Frequency shift

Table 2: Structural comparison of decoherence mechanisms. The present logarithmic spectral deformation maintains strict unitarity while producing effective decoherence through energy-dependent phase accumulation.

The structural features of the present mechanism can be summarized as follows:

- **Unitarity of evolution:** exactly unitary for all β , since $F_\beta(H)$ is self-adjoint.
- **Source of decoherence:** oscillatory spectral phases $E \log(E/E_*)$ inducing non-stationary-phase suppression.
- **Mathematical structure:** real spectral functional calculus $H \mapsto F_\beta(H)$, without stochasticity or non-Hermiticity.
- **Environment:** no explicit environment or bath degrees of freedom are introduced.
- **Form of decoherence:** deterministic dephasing and suppression of interference integrals, with scaling $\sim 1/|\beta|$ in appropriate regimes.
- **Born rule:** unmodified, as the inner product and projections remain standard.
- **Novel parameter:** a single dimensionless parameter β controlling the strength of logarithmic spectral corrections.

This places the proposal in a distinct class from both collapse models and standard open-system master equations.

9 Discussion and Outlook

Logarithmic spectral deformations offer a new window into quantum decoherence. Unlike collapse models, the dynamics remains strictly unitary. Unlike open-system approaches, no environment is invoked. Yet interference is suppressed—not through probability loss, but through rapid phase variation.

The mechanism is simple: energy eigenstates accumulate phases $\sim tE(1 + \beta \log E)$ instead of $\sim tE$. When $\beta \neq 0$, different energies drift apart in phase space at logarithmically different rates. In coarse-grained measurements or ensemble averages, this drift destroys observable coherence.

Could β be nonzero in nature? Renormalization group flow, quantum gravity corrections, and clock imperfections all suggest logarithmic spectral terms. Whether they appear at observable strength— $|\beta| \gtrsim 10^{-8}$ —is an experimental question. Precision spectroscopy in trapped ions or superconducting qubits could answer it within this decade.

One might reasonably ask why $G(E) = E \log(E/E_*)$ rather than, say, $E(\log E)^2$ or $E^{1+\epsilon} \log E$. The answer is pragmatic: $E \log E$ is the leading logarithmic correction appearing in renormalization group flow, semiclassical actions, and effective field theories. Other functions would work mathematically but lack the same physical motivation.

A conceptual limitation of the present treatment is that β has been introduced phenomenologically rather than derived from a microscopic model. Whether quantum gravity predicts specific values of β is unknown. A systematic classification of admissible spectral deformations compatible with diffeomorphism invariance and effective field-theory principles constitutes a natural next step.

Further work may develop a more detailed phenomenology, including explicit models for β in terms of quantum-gravity parameters, and investigate the interplay between this spontaneous decoherence and standard environment-induced decoherence. It would also be natural to study continuous-spectrum systems, scattering problems, and quantum chaotic Hamiltonians under the same deformation to explore whether the mechanism has observable consequences beyond simple bound-state examples. The key experimental challenge is distinguishing the logarithmic energy dependence of LSD from other systematic frequency shifts.

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