Oscillatory Memory Corrections to Exponential Decay: A Testable Signature of Non-Markovian Commitment Dynamics

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For the General Reader

When a radioactive atom decays, standard physics tells us it has no memory — it doesn't "know" how long it has been waiting, and each moment it faces exactly the same probability of decaying as the moment before. This memoryless property is called the Markov assumption, and it leads to the familiar exponential decay law: half the atoms decay in one half-life, half of those in the next, and so on.

But what if that assumption is wrong — not globally, but in a specific, detectable way?

This paper explores the possibility that past irreversible events leave a faint but real imprint on the present. In the VERSF framework, when a physical system makes a definite, irreversible transition — what we call a *commitment event* — that event doesn't simply vanish from the universe's causal ledger. It seeds a field, the *κ-field*, which propagates forward in time and continues to influence the system's future behaviour. The system, in effect, carries a fading memory of its own history.

The observable consequence is striking: instead of pure exponential decay, a system with this kind of memory should show a decay rate that oscillates slightly — rising and falling in a regular rhythm superimposed on the overall exponential falloff. Crucially, these oscillations should *weaken over time* as the memory fades, distinguishing them from other possible causes of oscillatory signals (such as measurement artefacts, which would produce constant-strength oscillations, or certain particle-physics effects, which produce a different characteristic pattern).

A tentative experimental hint that something like this might be occurring appeared in experiments at a facility called GSI in Germany, where the decay of exotic stored ions seemed to show a puzzling oscillatory modulation. Those results remain unconfirmed and contested. But whether or not they turn out to be real, they provide a useful template: a specific frequency, amplitude, and timescale against which the theoretical predictions of this paper can be tested.

We derive the expected form of the memory-induced oscillations from first principles, show what measurements would confirm or rule out the effect, and make two hard numerical predictions that go beyond merely fitting the shape of the data — predictions that can be checked independently and that would falsify the framework if they fail. The theory also predicts that the effect should be absent in atoms embedded in ordinary matter (where the causal environment is too crowded for long-lived memory) and most likely to be observable in systems with extremely sparse causal environments — isolated single atoms or ions in near-perfect vacuum, atoms coupled to optical cavities, or superconducting qubits in engineered low-interaction environments.

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Abstract

Standard quantum decay is modeled as a Markovian, memoryless process, yielding strict exponential decay laws. Known deviations at short and long times are smooth and non-oscillatory — they arise from spectral threshold singularities and carry no phase structure. This paper derives a class of decay laws from commitment-based dynamics in the VERSF framework, in which past irreversible commitment events remain dynamically active and influence present evolution through the κ-field. The resulting memory kernel is not phenomenological: it is the retarded Green's function of the κ-field, and its two limiting forms — exponential-oscillatory and power-law-oscillatory — are the unique minimal kernels consistent with causal decay, finite or scale-free memory, and oscillatory κ-field feedback.

The decay law in the transient regime takes the form:

$$\mathbf{R(t) = R_0\, e^{-\Gamma t}\, [1 + \varepsilon\, e^{-t/\tau_m} \cos(mt + \varphi)]}$$

and in the geometric regime:

$$\mathbf{R(t) \sim e^{-\Gamma t} + \cos(mt)/t}$$

Beyond the shape of these forms, the framework makes two hard predictions: **(i)** the memory timescale is determined by the committed record density alone via $\tau_m = (\hbar/(\rho c^3))^{1/4}$, derived directly from the CCC threshold condition with no free parameters — g enters the oscillation amplitude ε but not τ_m; **(ii)** the observed decay rate is shifted from the bare rate by $\Gamma_{obs} - \Gamma = \varepsilon/(m^2\tau_m^2)$, testable against precision lifetime measurements. Both predictions apply generically to any exponentially decaying quantum system — nuclear, atomic, or mesoscopic — whenever the system's causal environment is sufficiently sparse that τ_m is comparable to the decay lifetime. We test these predictions against the reported GSI storage-ring anomaly and propose a complete falsification protocol.

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1. Introduction

Exponential decay is among the most robust predictions of quantum mechanics. When an unstable system couples to a continuum of final states, the Wigner-Weisskopf approximation reduces the full non-Markovian integro-differential equation to an effective memoryless evolution:

$$\mathbf{N(t) = N_0\, e^{-\Gamma t}}$$

at intermediate times. This reduction is accurate when environmental memory timescales are far shorter than the decay lifetime.

The approximation is not exact. Two classes of deviation are well-established:

- **Short-time (Zeno) deviations:** For $t \ll 1/\Delta E$, the survival probability evolves quadratically: $P(t) \approx 1 - (\Delta E)^2 t^2$.
- **Long-time power-law tails:** For $t \to \infty$, the survival amplitude decays as ~t^{−n}, arising from non-analyticities in the spectral density at threshold.

Both deviations share a common origin: **spectral structure** — the energy spectrum of the final-state continuum. Crucially, both are strictly monotone. Standard long-time deviations arise from spectral threshold singularities and carry no phase structure; the present effect arises from temporal causal feedback — the κ-field of past committed facts — and necessarily introduces phase structure. This is the distinction that makes oscillatory corrections a qualitatively new phenomenon, not a quantitative refinement of known physics.

The reported **GSI storage-ring anomaly** [Litvinov et al., Phys. Rev. Lett. 99, 262501 (2007)] — oscillatory modulation of electron-capture decay rates with period $T \approx 7.1$ s and amplitude $A \approx 18$–23% in $^{142}\mathrm{Pm}^{61+}$ and $^{122}\mathrm{I}^{49+}$ — is taken here as a phenomenological template, not as established evidence. Whether or not the GSI anomaly is confirmed, the framework developed here makes predictions applicable to nuclear, atomic, and mesoscopic quantum systems generally, wherever the committed record density of the causal environment is sufficiently sparse.

This effect arises beyond the Wigner–Weisskopf approximation and does not contradict standard QFT predictions within their domain of validity. The Wigner–Weisskopf result — pure exponential decay — is recovered exactly in the limit $\rho \to \infty$ (dense causal environment, $\tau_m \to 0$), where κ-field memory is suppressed on timescales far shorter than Γ^{-1}. The present prediction is an additional structure that becomes observable only in the complementary regime of sparse causal environments where $\tau_m \sim \Gamma^{-1}$.

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2. From Commitment Dynamics to Memory Kernel

2.1 The Ontological Foundation

In the VERSF framework, irreversible commitment events are not merely past states that cease to influence the future — they are **dynamically active facts** that continue to propagate causal structure forward via the κ-field. The κ-field $\kappa(x, t)$ encodes the local density of irreversible commitments, and its dynamics govern how those past commitments exert residual influence on subsequent evolution. The κ-field should be understood as an effective dynamical mode of the commitment density field $\rho(x,t)$ at the scale relevant to the decay process — analogous to how phonons are effective modes of atomic displacement fields, not fundamental fields themselves.

An unstable ion does not decay against a static vacuum. It decays against the background κ-field generated by all prior commitment events in its causal history: preparation, storage, and the as-yet-uncommitted potential for the decay event itself. The oscillatory correction to exponential decay is the observable signature of this structured background — the interference between present decay probability and the standing causal wave left by past commitments.

2.2 Derivation of the Memory Kernel

We derive the memory kernel from four steps.

Step 1 — Commitment events as κ-field sources. An irreversible commitment event at time t_0 seeds the κ-field with a source:

$$J(t) = g \cdot \delta(t - t_0)$$

where g is the coupling between the commitment event and the κ-field. The κ-field equation of motion is:

$$(\partial^2\_t + 2\gamma_m \partial\_t + m^2)\, \kappa(t) = J(t)$$

where m is the κ-field's characteristic frequency and γ_m its dissipation rate.

The κ-field is not introduced ad hoc. It is the propagating fluctuation mode of the committed record density field ρ(x,t) developed in prior VERSF work [Taylor, *CCC Threshold Derivation*, VERSF Technical Note]. The relationship mirrors the distinction between thermodynamic pressure (static scalar field) and acoustic modes (its propagating fluctuations): ρ(x,t) characterizes the background committed record density at each point, while κ(x,t) carries the local dynamical perturbations — individual commitment events propagating their causal influence forward through the medium of established facts. The CCC threshold $\chi(L) = \rho L^4/\hbar c$ constrains the static sector of ρ; the damped wave equation above governs the dynamic sector κ.

Step 2 — Causal propagation. The retarded Green's function of the κ-field equation is:

$$G\_\kappa(\tau) = \theta(\tau) \cdot (e^{-\gamma_m \tau}/\omega\_\kappa) \sin(\omega\_\kappa \tau),\quad \omega\_\kappa = \sqrt{m^2 - \gamma_m^2}$$

For $\gamma_m \ll m$ (underdamped regime):

$$G\_\kappa(\tau) \approx \theta(\tau) \cdot (e^{-\gamma_m \tau}/m) \sin(m\tau)$$

A commitment event at t_0 therefore induces a κ-field contribution at later time $t_0 + \tau$ of $\kappa\_\text{induced}(\tau) = g \cdot G\_\kappa(\tau)$. The influence propagates outward at speed c, reaching spatial scale $L = c\tau$ after elapsed time τ.

Step 3 — Causal capacity threshold. The causal capacity $\chi(L) = \rho L^4/\hbar c$ [Taylor, *CCC Threshold Derivation*, VERSF Technical Note] measures whether the committed record density ρ at scale L is sufficient to sustain dynamically active structure. The κ-field influence from a past commitment remains physically active while $\chi(c\tau) \geq 1$:

$$\rho(c\tau)^4/\hbar c \geq 1 \Longrightarrow \tau \leq \tau_m$$

Solving at equality:

$\tau_m = L/c = (\hbar/(\rho c^3))^{1/4}$*

This is the **memory lifetime** predicted from the committed record density of the system's causal environment. It is not a free parameter: given ρ, τ_m is determined.

Step 4 — The memory kernel. The rate at which past commitment events influence present decay probability is proportional to the temporal derivative of the κ-field contribution, integrated over the system's causal history within the active window $\tau \leq \tau_m$:

$$\mathbf{K(\tau) = \Gamma\, \delta(\tau) + g \cdot \partial_\tau G_\kappa(\tau) \cdot \theta(\tau_m - \tau)}$$

The choice of $\partial_\tau G_\kappa$ rather than G_κ here is for notational convenience — the primary derivation in §2.4 shows the kernel from first principles is $g^2 G_\kappa(\tau)$, with the $\partial_\tau G_\kappa$ form being accurate to $O(\gamma_m/m)$ and differing only by a $\pi/2$ phase shift in the free parameter φ. Both forms produce identical decay law structure; see §2.4 for the full derivation.

For $\tau \ll \tau_m$ (deep within the active window):

$$\mathbf{\partial_\tau G_\kappa(\tau) \approx e^{-\gamma_m \tau} [\cos(m\tau) - (\gamma_m/m) \sin(m\tau)] \approx e^{-\gamma_m \tau} \cos(m\tau)}$$

giving:

$$\mathbf{K(\tau) = \Gamma\, \delta(\tau) + \varepsilon\, \gamma_m\, e^{-\gamma_m \tau} \cos(m\tau)}$$

where ε is the dimensionless oscillation coupling parameter, treated as a phenomenological observable in this step. Its microscopic identification in terms of the underlying κ-field coupling constant g is given in §2.4 as $\varepsilon \sim g^2/(\gamma_m m)$ — the quadratic dependence on g arises because the coupled-ODE elimination applies the coupling twice. The kernel structure follows directly from the κ-field dynamics: given the equation of motion in Step 1 with parameters (m, γ_m), the Green's function form is fixed with no further freedom. The κ-field equation of motion with these parameters is itself motivated by VERSF commitment dynamics as described in §2.1; a full derivation from the VERSF action principle will appear in a companion paper.

In the scale-free limit — when $\rho \to 0$ so that $\tau_m \to \infty$ and the CCC threshold is never reached — the kernel acquires the form $K(\tau) \sim \cos(m\tau)/\tau$ (see §3.2 and Appendix A).

2.3 Minimality of the Kernel Forms

A referee may ask: why these two kernels and not infinitely many others that also produce oscillations?

Lemma (Kernel Minimality). *The unique minimal memory kernels consistent with (i) causal decay, (ii) finite or scale-free memory, and (iii) oscillatory κ-field feedback are:*

$K(\tau) = \Gamma\, \delta(\tau) + \varepsilon\, \gamma_m\, e^{-\gamma_m \tau} \cos(m\tau)$ *[finite ρ, transient regime]*

$K(\tau) \sim \Gamma\,\delta(\tau) + C\cos(m\tau)/\tau$ [$\rho \to 0$, geometric regime]

Any causal memory kernel consistent with requirements (i)–(iii) must take one of these forms, or be expressible as a superposition thereof.

Proof sketch. The three requirements constrain the kernel as follows:

(i) Causal decay. $K(\tau)$ must decay for large τ — the influence of a past commitment cannot grow indefinitely. This requires the envelope to be integrable: $\int_0^\infty |K(\tau)|\, d\tau < \infty$.

(ii) Memory scale. If the system has a characteristic causal memory scale τ_m determined by the CCC threshold (§2.2 Step 3), the minimal integrable decaying envelope consistent with a single characteristic timescale is exponential: $e^{-\tau/\tau_m}$. If $\rho \to 0$ and no such scale exists, the envelope must be a power law $\tau^{-\alpha}$. The exponent $\alpha = 1$ is selected as the **unique boundary case** on two grounds: for $\alpha < 1$, the kernel diverges at large τ, violating requirement (i); for $\alpha > 1$, the Laplace transform $\tilde{K}(s)$ acquires an algebraic branch cut near $s = im$ of the form $(s-im)^{\alpha-1}$, yielding $R(t) \sim t^{-\alpha}\cos(mt)$ — a qualitatively different functional form with faster algebraic decay, not the logarithmic branch cut that characterises the scale-free limit. $\alpha = 1$ is the unique value consistent with both causal decay and the logarithmic branch-cut structure that arises from the $\rho \to 0$ limit of the CCC threshold, as derived in Appendix A.

(iii) Oscillatory feedback. The κ-field is a massive oscillatory field with characteristic frequency m. Its retarded Green's function $G_\kappa(\tau)$ is oscillatory (§2.4), and the memory kernel — being g^2 times $G_\kappa(\tau)$ from the coupled-ODE elimination — inherits this oscillatory character. A kernel without oscillatory structure would require a massless κ-field ($m = 0$), which produces $G_\kappa(\tau) = \theta(\tau)\tau$ — a monotone ramp, giving only damping corrections with no oscillatory modulation. ■

The kernels derived in §2.4 from the explicit coupled-ODE system confirm this lemma constructively: the elimination procedure produces exactly these forms and no others.

2.4 Minimal Dynamical Derivation of the Memory Kernel

To demonstrate that the oscillatory memory kernel arises from a well-defined dynamical mechanism rather than a motivated choice, we present an explicit coupled-system derivation. This bridges the κ-field dynamics of §2.1–2.2 and the non-Markovian evolution equation used throughout.

Coupled equations. Let $a(t)$ denote the survival amplitude of the unstable system and $q(t)$ represent the local κ-field response generated by past commitment events. The minimal coupled system is:

$$\dot{a}(t) = -\Gamma\, a(t) - g\, q(t)$$

$$\ddot{q}(t) + 2\gamma_m\, \dot{q}(t) + m^2\, q(t) = g\, a(t)$$

where Γ is the bare decay rate, g is the coupling between the decay channel and the κ-field, m is the characteristic κ-field frequency, and γ_m is the κ-field dissipation rate. The second equation is the minimal linear equation consistent with causal propagation (second-order time evolution), finite memory (damping term $2\gamma_m\dot{q}$), and oscillatory response (mass term $m^2 q$). No additional structure is assumed.

Elimination of the κ-mode. Let $G_\kappa(\tau)$ be the retarded Green's function satisfying:

$$(\partial^2_\tau + 2\gamma_m \partial_\tau + m^2)\, G_\kappa(\tau) = \delta(\tau), \quad G_\kappa(\tau < 0) = 0$$

In the underdamped regime $\gamma_m < m$:

$$G_\kappa(\tau) = \theta(\tau) \cdot (e^{-\gamma_m\tau}/\omega_\kappa) \sin(\omega_\kappa\tau), \quad \omega_\kappa = \sqrt{m^2 - \gamma_m^2}$$

Setting the homogeneous solution to zero (no pre-existing κ-field excitation), the κ-mode is:

$$q(t) = g \int_0^t G_\kappa(t - s)\, a(s)\, ds$$

Substituting into the survival amplitude equation yields the **non-Markovian evolution equation**:

$$\dot{a}(t) = -\Gamma\, a(t) - g^2 \int_0^t G_\kappa(t - s)\, a(s)\, ds$$

The system's evolution now depends on its full causal history through the κ-field's retarded response.

Memory kernel identification. Writing this in convolution form $\dot{a}(t) = -\int_0^t K(t - s)\, a(s)\, ds$:

$$K(\tau) = \Gamma\, \delta(\tau) + g^2\, G_\kappa(\tau)$$

This is the **primary form** of the kernel, derived directly from the coupled-ODE elimination. It is already oscillatory: $G_\kappa(\tau) = e^{-\gamma_m\tau}\sin(\omega_\kappa\tau)/\omega_\kappa$ carries oscillatory structure at frequency $\omega_\kappa \simeq m$. The $\partial_\tau G_\kappa$ form used elsewhere in this paper is not an independent derivation — it is the leading-order approximation to $g^2 G_\kappa$ in the underdamped regime $\gamma_m \ll m$. Specifically, since $G_\kappa(\tau) = e^{-\gamma_m\tau}\sin(m\tau)/m + O(\gamma_m/m)$, we have:

$$g^2 G_\kappa(\tau) \simeq (g^2/m) e^{-\gamma_m\tau}\sin(m\tau) = \varepsilon\gamma_m e^{-\gamma_m\tau}\sin(m\tau)$$

and $\partial_\tau G_\kappa(\tau) \simeq e^{-\gamma_m\tau}\cos(m\tau)$ to the same order. The two forms therefore produce oscillations at the same frequency m with the same exponential envelope, differing only by a $\pi/2$ phase shift $\sin \to \cos$ — i.e., a shift in the free parameter φ. Since φ is not predicted by the framework, both kernels give the same decay law structure. The $\partial_\tau G_\kappa$ form is retained in §3.1 for notational convenience; the primary G_κ form is the result of the elimination. The condition for the equivalence is $\gamma_m \ll m$ — the underdamping condition established independently — with no requirement on the relationship between Γ^{-1} and τ_m.

Sourcing: discrete events and continuum coupling. In §2.2, past commitment events source the κ-field via discrete δ-function terms $J(t_0) = g\cdot\delta(t - t_0)$; in §2.4, the source is the continuous coupling $g\cdot a(t)$. These are consistent: the continuous coupling $g\cdot a(t)$ is the continuum limit of the discrete sourcing in which the rate of new commitment events is proportional to the survival amplitude — a system with amplitude $a(t)$ has probability $|a(t)|^2\, dt$ of committing in interval dt, and in the linear (small-depletion) regime this maps to a source rate proportional to $a(t)$.

Explicit kernel in the underdamped limit. Using $\partial_\tau G_\kappa$:

$$\partial_\tau G_\kappa(\tau) = \theta(\tau)\, e^{-\gamma_m \tau} \left[\cos(\omega_\kappa \tau) - (\gamma_m/\omega_\kappa) \sin(\omega_\kappa \tau)\right]$$

For $\gamma_m \ll m$ (so $\omega_\kappa \simeq m$):

$$K(\tau) \simeq \Gamma\, \delta(\tau) + \varepsilon\, \gamma_m\, e^{-\gamma_m \tau} \cos(m\tau), \quad \varepsilon \sim g^2/(\gamma_m m)$$

This is precisely the transient oscillatory memory kernel of §3.1, now derived rather than postulated. The coupling $\varepsilon \sim g^2/(\gamma_m m)$ is identified with the dimensionless coupling in the phenomenological notation of §3.1.

What this derivation establishes. The memory kernel follows from three minimal physical ingredients:

- *Commitment sourcing:* irreversible events act as sources $g\cdot a(t)$ for the κ-field.
- *Causal propagation:* the κ-field evolves via a retarded Green's function, not instantaneously.
- *Dissipation:* finite causal memory enters through γ_m, which controls the envelope decay rate.

The oscillatory structure in $K(\tau)$ arises from the κ-field's intrinsic frequency m. The envelope decay arises from dissipation γ_m. Neither is imposed by hand — both emerge from the coupled equations. The geometric regime $K(\tau) \sim \cos(m\tau)/\tau$ arises from a distinct physical limit — $\rho \to 0$, scale-free κ-field with no CCC threshold — derived via the Tauberian argument in Appendix A; it is not recovered by taking $\gamma_m \to 0$ in the transient kernel, which instead yields $G_\kappa(\tau) = \sin(m\tau)/m$, an undamped sinusoid with no $1/\tau$ decay.

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3. Memory Regimes and Their Signatures

3.1 Transient Memory Regime (Massive κ-Field, Finite ρ)

Kernel (from §2.2):

$$K(\tau) = \Gamma\, \delta(\tau) + \varepsilon\, \gamma_m\, e^{-\gamma_m \tau} \cos(m\tau)$$

Laplace transform. Using the standard result $\mathscr{L}\{e^{-\gamma_m\tau}\cos(m\tau)\}(s) = (s + \gamma_m)/[(s + \gamma_m)^2 + m^2]$:

$$\tilde{K}(s) = \Gamma + \varepsilon\, \gamma_m \cdot (s + \gamma_m)/[(s + \gamma_m)^2 + m^2]$$

This can equivalently be written as $\Gamma + \varepsilon\gamma_m \cdot \mathrm{Re}[(s + \gamma_m - im)^{-1}]$, since $\mathrm{Re}[(s + \gamma_m - im)^{-1}] = (s + \gamma_m)/[(s + \gamma_m)^2 + m^2]$ by direct expansion; the first form is more transparent for readers checking the algebra.

Pole structure. The survival amplitude $\tilde{N}(s) = N_0/(s + \tilde{K}(s))$ has a primary pole at $s^* \approx -\Gamma$ shifted by first-order perturbation theory in ε. The pole shift is real at first order in ε; the phase φ is a free parameter set by initial conditions, not determined by the framework at this level of approximation. Evaluating $\tilde{K}(s)$ at $s = -\Gamma$:

$$\delta\Gamma = \varepsilon\, \gamma_m(\gamma_m - \Gamma) / [(\gamma_m - \Gamma)^2 + m^2]$$

Sign structure and the $\gamma_m = \Gamma$ prediction. This formula has a sign that depends on the relationship between γ_m and Γ — equivalently, between τ_m and Γ^{-1}:

- **$\gamma_m > \Gamma$ ($\tau_m < \Gamma^{-1}$):** $\delta\Gamma > 0$ — κ-field memory *accelerates* decay relative to the bare rate.
- **$\gamma_m = \Gamma$ ($\tau_m = \Gamma^{-1}$):** $\delta\Gamma = 0$ to first order — the shift vanishes and requires second-order perturbation theory.
- **$\gamma_m < \Gamma$ ($\tau_m > \Gamma^{-1}$):** $\delta\Gamma < 0$ — κ-field memory *slows* decay relative to the bare rate.

This sign flip at $\gamma_m = \Gamma$ is itself a falsifiable prediction: systems with τ_m slightly above Γ^{-1} should exhibit a reduced effective decay rate, while those with τ_m slightly below should exhibit an increased rate. The transition through $\delta\Gamma = 0$ at $\tau_m = \Gamma^{-1}$ is in principle measurable via precision lifetime comparison across different environmental conditions (varying ρ) in the same ion species.

In the limit $\Gamma \ll \gamma_m$ ($\tau_m \ll \Gamma^{-1}$):

$$\delta\Gamma \to \varepsilon\, \gamma_m^2/(\gamma_m^2 + m^2) \simeq \varepsilon/(m^2\tau_m^2) \ [\Gamma \ll \gamma_m \text{ limit}, \delta\Gamma > 0]$$

which is the form used in §4.2. This applies only in the $\tau_m \ll \Gamma^{-1}$ tail, and gives a positive shift. For $\tau_m > \Gamma^{-1}$ the shift is negative — the simplified formula then has the wrong sign, not merely imprecise magnitude. The general formula must be used when $\tau_m \sim \Gamma^{-1}$. Inverting:

$$R(t) = R_0\, e^{-\Gamma_{obs} \cdot t}\, [1 + \varepsilon\, e^{-t/\tau_m} \cos(mt + \varphi)]$$

with $\Gamma_{obs} = \Gamma + \delta\Gamma$ using the general expression. The oscillatory amplitude envelope predictions are unaffected by the sign structure — they arise from the residue of the oscillatory correction and remain valid across the full observability window.

Validity condition. The pole shift is computed to first order in ε, requiring $\varepsilon \ll 1$. For the GSI case, the observed modulation amplitude $A \approx 0.18$–0.23 implies $\varepsilon \cdot e^{-t^*/\tau_m} \approx 0.20$. With $\tau_m \gtrsim$

30 s and $t^* \sim 50$ s, the suppression factor $e^{-50/30} \approx 0.19$ gives $\varepsilon \sim 1.05$. However, these estimates are mutually consistent but not independently derived: $\tau_m \gtrsim 30$ s was obtained by setting $\varepsilon \sim 1$ in §5.1, so the $\varepsilon \sim 1.05$ back-computation is not an independent check — (ε, τ_m) are degenerate from amplitude data alone without additional time-resolution. A full joint fit of (ε, τ_m) from the time-resolved amplitude evolution $A(t)$ would resolve this degeneracy. Subject to this caveat, the GSI regime is likely $\varepsilon \sim \mathcal{O}(1)$, meaning the perturbative calculation captures the correct functional form but the quantitative coefficient predictions (rate shift, amplitude normalization) carry an implicit $\mathcal{O}(\varepsilon)$ systematic uncertainty.

Underdamped regime. The derivation assumes $\gamma_m \ll m$. Underdamping is not an additional assumption: it is the condition required for oscillatory structure to appear at all. In the overdamped regime ($\gamma_m \gtrsim m$), the κ-field response is monotone and the kernel produces only a damping correction to Γ — no oscillations. The observation of oscillatory modulation therefore self-selects the underdamped regime; any system exhibiting the predicted oscillatory decay is by definition underdamped. This is confirmed for GSI ($\gamma_m/m \lesssim 0.04$).

Status of the κ-field mass m. The oscillation frequency m is the κ-field's intrinsic mass parameter. Unlike τ_m, which is derived from ρ via the CCC threshold, m is not yet determined from VERSF first principles for a specific ion species — it is an intrinsic property of the κ-field dynamics at the relevant nuclear scale, analogous to a particle mass that must be measured rather than derived at current theoretical precision. For a given system, m is read off directly from the observed oscillation period: $m = 2\pi/T$. The VERSF framework predicts that m should be **universal across decay channels of the same ion species** — since m is a κ-field property of the nucleus, not of the specific decay mode — and that it should be **independent of environmental conditions** (storage ring vs. laboratory frame). These universality predictions are falsifiable: if different decay channels of the same ion yielded different oscillation frequencies, the framework would be ruled out. A first-principles calculation of m from the VERSF nuclear κ-field Lagrangian is identified as a priority for future work.

Envelope constraint. For the oscillation to appear approximately sinusoidal over observation window Δt:

$$e^{-\Delta t/\tau_m} \approx 1 \Longrightarrow \tau_m \gg \Delta t$$

Combined with the τ_m prediction from §2.2, this constrains ρ: the committed record density must be low enough that $(\hbar/(\rho c^3))^{1/4} \gg \Delta t$.

3.2 Geometric Memory Regime (Scale-Free κ-Field, ρ → 0)

When $\rho \to 0$ the CCC threshold is never reached and the κ-field influence is scale-free. The kernel takes the power-law form $K(\tau) \sim C \cos(m\tau)/\tau$ for large τ. The Laplace transform acquires a logarithmic branch cut at $s = \pm im$ (see Appendix A), and Bromwich inversion yields:

$$R(t) \sim e^{-\Gamma t} + \cos(mt)/t$$

The cos(mt)/t form is the specific consequence of the scale-free ($\alpha = 1$) propagator: the $1/\tau$ kernel maps to a logarithmic branch cut, and logarithmic branch cuts invert to 1/t asymptotics by the Tauberian correspondence. For $\alpha \neq 1$, the form is cos(mt)/t^α; the case $\alpha = 1$ is the unique scale-free limit.

Regime separation. The transient and geometric regimes arise from distinct κ-field dynamics — finite ρ (massive underdamped field) vs. $\rho \to 0$ (scale-free field). They are not sequential phases of a single system.

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4. Hard Predictions

4.1 Memory Timescale from Committed Record Density

From §2.2 Step 3, the memory timescale follows directly from the CCC threshold $\chi(c\tau_m) = 1$:

$$\tau_m = (\hbar/(\rho c^3))^{1/4}$$

where ρ is the **committed record energy density** [J/m³] in the system's local causal past light cone. This formula contains no free parameters beyond ρ: the CCC threshold condition $\chi(L) = \rho L^4/\hbar c = 1$ at $L = c\tau_m$, solved for τ_m, yields the above expression with no g appearing — g enters the memory kernel through the oscillation coupling $\varepsilon \sim g^2/(\gamma_m m)$, but not through the threshold condition that sets τ_m. The memory timescale is therefore a **direct prediction from ρ alone**.

Concrete mapping of ρ across system types. The committed record energy density can be operationally estimated as:

ρ ≈ (characteristic energy per commitment event) × (commitment event rate) / (causal volume)

where the causal volume is $V\_causal \sim (4\pi/3)(c\tau_m)^3$:

System	Dominant commitment events	ρ (order of magnitude)	Predicted τ_m ordering
Nucleus in solid matter	~10^{28} inter-atomic interactions/m³ × ~MeV each	~10^{18} J/m³	Sub-femtosecond — no observable oscillations
Atom in optical cavity	Photon absorption/emission events × cavity mode energy	~10^{-6} – 10^{-2} J/m³ (tunable)	Microseconds–milliseconds
Ion in storage ring (beam mode)	Residual gas scattering + frequent detector interactions across a multi-ion beam × ~eV per event	~10^{-12} J/m³	Nanoseconds–picoseconds

System	Dominant commitment events	ρ (order of magnitude)	Predicted τ_m ordering
Single stored ion (GSI-like)	Passive Schottky noise monitoring — no hard detector interactions between decay events; ρ dominated by the ion's own rare commitment events	Extremely low	Long — potentially seconds

The distinction between the bottom two rows is physically important: a storage ring operating with a beam of ions and conventional detectors registers frequent hard interactions (each ion pass through a detector element constitutes a committed record), driving ρ up and τ_m down. The GSI-like single-ion case uses **passive non-demolition monitoring** (Schottky pickup of the ion's revolution frequency), which does not constitute a strong commitment event. Between decay events, the single stored ion undergoes almost no irreversible commitment interactions — this is what makes ρ extremely low and τ_m potentially macroscopic. The prediction is therefore sensitive to the measurement mode, not just the vacuum quality.

The ordering is the testable claim: **τ_m increases monotonically as ρ decreases**, i.e., as the system's causal environment becomes more sparse and isolated. More formally, comparing any two systems A and B:

$\tau_m(A)/\tau_m(B) = (\rho(B)/\rho(A))$^{1/4}

This ratio prediction requires no knowledge of g.

The g-dependence principle. To state this precisely once: *τ_m itself is g-independent — it is determined by ρ alone via the CCC threshold. The coupling g enters only through the dimensionless oscillation amplitude $\varepsilon \sim g^2/(\gamma_m m)$ and therefore through the decay rate shift Γ_obs − $\Gamma = \varepsilon/(m^2\tau_m^2)$.* All ratio predictions $\tau_m(A)/\tau_m(B) = (\rho(B)/\rho(A))$^{1/4}, all functional-form tests of envelope shape, and the memory timescale itself are g-independent. The decay rate shift requires knowing ε, which depends on g, but can also be expressed in terms of observables once (m, τ_m, Γ_obs) are measured directly from the decay curve.

On the physical interpretation of ρ and its scale. The committed record energy density ρ differs from conventional energy densities such as the CMB (~4×10^{-14} J/m^3) or the cosmological constant (~10^{-10} J/m^3) because it counts only irreversible commitment events — physically realized, record-creating transitions that have definitively occurred. Quantum vacuum fluctuations, zero-point field energy, thermal radiation, and uncommitted superpositions do not contribute, because they have not undergone irreversible commitment. This is an ontological distinction, not a technical one: pre-factual fluctuations, by definition, have not committed and therefore do not seed the κ-field. ρ_committed is to ρ_total as recorded signal is to background noise — the latter may be energetically dominant while contributing nothing to the causal record.

4.2 Observed Decay Rate Shift

From the pole calculation in §3.1, the general first-order rate shift is:

$$\delta\Gamma = \varepsilon\, \gamma_m(\gamma_m - \Gamma) / [(\gamma_m - \Gamma)^2 + m^2]$$

As established in §3.1, this formula changes sign at $\gamma_m = \Gamma$: positive (memory accelerates decay) for $\tau_m < \Gamma^{-1}$, negative (memory slows decay) for $\tau_m > \Gamma^{-1}$. In the $\Gamma \ll \gamma_m$ limit ($\tau_m \ll \Gamma^{-1}$):

$$\Gamma\_obs - \Gamma \approx \varepsilon/(m^2\tau_m^2) > 0 \; [\tau_m \ll \Gamma^{-1} \text{ only}]$$

Regime note. This simplified formula applies only in the $\tau_m \ll \Gamma^{-1}$ tail where the shift is positive. For $\tau_m \sim \Gamma^{-1}$ (the observable regime), the general formula must be used; the simplified form gives the wrong sign for $\tau_m > \Gamma^{-1}$ and vanishes at $\tau_m = \Gamma^{-1}$. The sign of the measured shift relative to Γ is therefore itself a probe of whether τ_m is above or below Γ^{-1} — a qualitative prediction requiring no parameter fitting. The rate shift is **independently testable** against the theoretically computed or non-oscillatory-regime bare rate Γ, with the sign carrying physical information about the memory regime.

4.3 Over-Determination and Falsification Structure

The transient regime has four observable quantities — m, ε, τ_m, Γ_obs — constrained by:

1. $m = 2\pi/T$ (from oscillation period, directly measured)
2. $\varepsilon e^{-t^*/\tau_m} = A\_obs$ (from oscillation amplitude at known t*)
3. Envelope time-evolution → τ_m (from amplitude decay rate)
4. $\Gamma\_obs - \Gamma = \delta\Gamma$ using the general formula of §4.2 (sign and magnitude depend on whether $\tau_m \lesseqgtr \Gamma^{-1}$; the simplified $\varepsilon/(m^2\tau_m^2)$ applies only for $\tau_m \ll \Gamma^{-1}$)
5. $\tau_m = (\hbar/(\rho c^3))^{1/4}$ (from committed record density; requires independent estimate of ρ)

Constraints (1)–(3) use three observables to fix three parameters. Constraints (4) and (5) are then **two independent parameter-free predictions**, each falsifiable by measurement. A model with this structure is not curve-fitting — it is over-determined.

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5. Application to GSI-Type Anomalies

5.1 Parameter Extraction

The GSI measurements of $^{142}\mathrm{Pm}^{61+}$ [Litvinov et al. 2007] covered t ≈ 0–100 s with visible oscillatory modulation over t ≈ 20–100 s:

- Oscillation period: **$T \approx 7.1$ s → $m \approx 0.884\ \mathrm{s}^{-1}$**
- Modulation amplitude: **$A \approx 0.18$–0.23**

Taking t* ~ 50 s as an illustrative midpoint of the modulation window:

$\varepsilon\, e^{-t/\tau_m} \approx 0.20 \Longrightarrow \tau_m \gtrsim 30$ *s* ($\varepsilon \sim 1$); $\tau_m \gtrsim 60$ *s (full 100 s window)**

Confirming the underdamped regime:

$$\boldsymbol{\gamma_m = 1/\tau_m \lesssim 0.033\ \mathrm{s}^{-1} \ll m \approx 0.884\ \mathrm{s}^{-1} \Longrightarrow \gamma_m/m \lesssim 0.04}$$

Committed record energy density: Back-computing directly from the CCC threshold formula $\tau_m = (\hbar/(\rho c^3))$^{1/4} with $\tau_m \sim 30$ s:

$$\boldsymbol{\rho \sim \hbar/(c^3\tau_m^4) \sim (10^{-34})/((3\times10^8)^3 \times (30)^4) \sim 5\times10^{-66}\ \mathrm{J/m^3}}$$

This requires no assumption about g — the formula is a direct inversion of the CCC threshold condition. The committed record energy density is extraordinarily low, consistent with a single ion in near-vacuum undergoing rare commitment interactions. The ordering ρ_GSI ≪ ρ_bulk is the robust prediction; the absolute value follows without free parameters.

Decay rate shift: For $\Gamma \approx 0.017\ \mathrm{s}^{-1}$ (^{142}Pm half-life ~40 s) and $\tau_m \sim 30$ s ($\gamma_m \approx 0.033\ \mathrm{s}^{-1} \approx 2\Gamma$):

$$\boldsymbol{\delta\Gamma = \varepsilon\gamma_m(\gamma_m - \Gamma)/[(\gamma_m - \Gamma)^2 + m^2] \approx \varepsilon \times (0.033)(0.016)/[(0.016)^2 + (0.884)^2] \approx 6\times10^{-4}\varepsilon\ \mathrm{s}^{-1}}$$

For $\varepsilon \sim 1$ this gives $\delta\Gamma \sim 4\%$ of Γ — indicative only, since $\gamma_m \approx 2\Gamma$ places the GSI case in the breakdown region of the simplified formula, and the sign is positive (memory accelerates decay) because $\gamma_m > \Gamma$. See §4.2 for the sign structure and regime conditions. The rate shift magnitude is measurable in principle at the level of precision accessible to storage-ring lifetime experiments.

5.2 Phase Coherence Requirement

The data span ~60–100 s of modulation, giving **N ~ 10–14 oscillation cycles** and requiring:

$$\boldsymbol{T_2 \gtrsim N\cdot T \sim 70\text{–}100\ \mathrm{s}}$$

In the present framework, **T_2 is identified with $\tau_m = 1/\gamma_m$** — the κ-field dephasing time. The same dissipation parameter γ_m that governs the exponential decay of the oscillatory amplitude envelope also controls the phase coherence lifetime: as the κ-field loses amplitude, it loses phase, at the same rate. The constraint $T_2 \gtrsim 70$–100 s is therefore equivalent to $\tau_m \gtrsim 70$–100 s — a stronger lower bound than the $\tau_m \gtrsim 30$ s derived from the amplitude data in §5.1 alone, and consistent with the full 100 s observation window. There is no additional free parameter: phase coherence and amplitude decay are governed by the single κ-field dissipation rate γ_m.

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6. Predictions and Experimental Discrimination

6.1 Scope: Beyond GSI

The predictions of this framework do not depend on the GSI anomaly being real. They apply to any exponentially decaying quantum system where the committed record density ρ in the causal environment is low enough that $\tau_m \sim \Gamma^{-1}$. The observability condition is:

$\tau_m \sim \Gamma^{-1}$ and $m\tau_m \gg 1$

This effect exists only in the narrow regime where memory and decay timescales are comparable. For $\tau_m \ll \Gamma^{-1}$, the memory fades before the system has a chance to decay and the correction is negligible. For $\tau_m \gg \Gamma^{-1}$, the system decays before the oscillation completes a cycle and no modulation is observable. The window $\tau_m \sim \Gamma^{-1}$ is therefore a necessary condition — which explains why the effect has not been seen everywhere: it requires both extreme environmental isolation (to achieve long τ_m) and a decay process slow enough to match it.

Three classes of candidate system:

Nuclear decay: Electron-capture and β-decay in hydrogen-like ions stored in ring traps. The near-vacuum environment gives low ρ. The prediction: oscillatory corrections should be **absent** in nuclei embedded in matter (ρ large, $\tau_m \ll \Gamma^{-1}$) and potentially **present** in isolated stored ions (ρ small). This is a testable environmental dependence.

Atomic decay: Radiative transitions in atoms trapped in optical lattices or cavities. The photon-field commitment density ρ_photon can be controlled by varying the cavity mode population. The prediction: τ_m and oscillation amplitude should depend on the cavity photon number in a specific way determined by $\tau_m \sim (\hbar/(\rho\_photon\ c^3))$^{1/4}.

Mesoscopic quantum systems: Superconducting qubits, nitrogen-vacancy centers, and quantum dots all exhibit exponential T_1 decay. Their controlled, engineered environments allow ρ to be varied systematically. The prediction: oscillatory corrections to T_1 should scale with environmental isolation according to $\tau_m \sim (\hbar/(\rho c^3))$^{1/4}.

The VERSF framework thus generates a **universality prediction**: the same scaling $\tau_m \sim$ ρ^{−1/4} should govern oscillatory memory corrections across all three system classes, with no free parameters beyond ρ.

6.2 Amplitude Decay: The Primary Distinguishing Prediction

Both memory regimes predict a monotonically decreasing oscillation amplitude A(t):

Regime	A(t)
Transient (massive κ-field)	ε e^{−t/τ_m}
Geometric (scale-free κ-field)	A_0/t

No competing hypothesis produces monotone amplitude decay:

Hypothesis	Oscillation?	Amplitude envelope	Functional form
Standard QM (Markovian)	No	—	—
Instrumental systematics	Possible	Non-monotone	Constant or erratic
κ-field memory — transient	Yes	**Strictly monotone**	e^{-t/τ_m}
κ-field memory — geometric	Yes	**Strictly monotone**	$1/t$
Neutrino mixing	Yes	Non-monotone	$\mathrm{sinc}(\delta \cdot L/E)$

A strong statement is warranted here, with careful scope: **no single-channel Markovian quantum system within standard quantum theory can produce a decaying oscillatory modulation of the exponential envelope.** In a single-channel Markovian process, the future conditional probability depends only on the present state; oscillatory corrections to the decay rate cannot carry a history-dependent phase by construction. More precisely: **a strictly monotone decay of oscillation amplitude cannot arise from any single-channel Markovian process within standard quantum theory, and requires specific near-degenerate spectral structure in multi-channel cases — independently testable via spectroscopy as noted in point (c) below.** This is the anchor prediction of the framework.

Multi-channel interference is the one standard-QM mechanism that can produce oscillations in a decay curve: two interfering near-degenerate decay channels with amplitudes A_1, A_2 and parameters (Γ_1, E_1), (Γ_2, E_2) give:

$$N(t) = |A_1 e^{(-\Gamma_1/2 - iE_1)t} + A_2 e^{(-\Gamma_2/2 - iE_2)t}|^2$$

which oscillates at frequency $\Delta E = E_1 - E_2$. For $\Gamma_1 \approx \Gamma_2$ the envelope is approximately monotone over short times. However, this mechanism is distinguishable from κ-field memory on three grounds: **(a)** the oscillation amplitude evolves as a ratio of sums of exponentials — specifically ~ $\cosh(\Delta\Gamma \cdot t/2)$ weighting — not as a pure e^{-t/τ_m} or $1/t$ form; in particular, no two-channel interference model produces a pure exponential or power-law envelope over extended time intervals without additional fine-tuning; **(b)** for $\Gamma_1 \neq \Gamma_2$ the envelope is never strictly monotone — it exhibits partial recovery at late times as one channel dominates; **(c)** the mechanism requires a specific near-degeneracy $\Delta E \approx 2\pi/T$ in the nuclear spectrum, an additional spectroscopic prediction independently testable. The functional form discrimination in §6.5 step 2 directly tests (a); the late-time amplitude behaviour tests (b); independent spectroscopy tests (c). The κ-field model therefore remains distinguishable from multi-channel interference even when the latter produces qualitatively similar oscillatory signals.

6.3 The Neutrino Mixing Alternative: A Sharp Distinction

The neutrino oscillation survival probability is:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta) \cdot \sin^2(\Delta m^2 L / 4E)$$

At a storage ring, the ion beam has an energy (velocity) spread $\delta v/\langle v\rangle$. Averaging over this distribution, the oscillation amplitude acquires an envelope:

$$\boldsymbol{\langle \sin^2(\Delta m^2 L/4E) \rangle \sim \tfrac{1}{2}[1 - \mathrm{sinc}(\Delta m^2 \cdot \delta(L/4E)) \cdot \cos(\Delta m^2 \langle L/4E \rangle)]}$$

This envelope is a function of path length L and velocity spread. Crucially:

1. The sinc envelope has **zeros and partial revivals** — it is not monotonically decreasing.
2. The dependence is on **L/E** (a spatial/energy ratio), not on elapsed time t through an intrinsic decoherence mechanism.
3. **Dephasing ≠ monotonic envelope decay.** Velocity-spread dephasing produces a sinc pattern in L that can exhibit partial recovery beyond the first zero. The κ-field model predicts strict exponential or power-law monotone decrease at all times — a qualitatively different functional form with no zeros or sidelobes.

This is the functional kill shot: the two mechanisms produce amplitude envelopes with qualitatively different topologies (monotone vs. oscillatory), distinguishable without any parameter estimation beyond measuring A(t) at multiple time points.

6.4 Minimum Viable Experiment

Before outlining the full protocol, we specify the minimum experiment capable of discriminating the κ-field model from alternatives:

System: Any isolated quantum system with exponential decay lifetime $\Gamma^{-1} \gtrsim 10$ s and a suspected oscillatory signal — $^{142}\mathrm{Pm}^{61+}$ in a storage ring is the primary candidate, but a long-lived metastable atomic state in a cryogenic trap (e.g., $^{207}\mathrm{Pb}^{81+}$ or trapped Yb^+ in the $^2F_{7/2}$ manifold, $\tau \sim$ years) could also serve.

Measurement duration: T_obs ≥ 10 oscillation periods. For T ≈ 7 s: T_obs ≥ 70 s. For an unknown oscillation period, the minimum requirement is T_obs ≥ 10/Γ (ten decay lifetimes).

Required statistical precision: The oscillation amplitude A(t) must be resolvable at ≤5% precision per oscillation period. This allows a 3σ discrimination between constant amplitude (A_0, systematics) and exponentially decaying amplitude ($A_0 e^{-t/\tau_m}$ with $\tau_m \sim 30$ s) within the observation window.

Expected signal: The amplitude A(t) decreases by a factor of $e^{-1} \approx 0.37$ over the memory timescale τ_m. For $\tau_m \sim 30$ s and T_obs = 70 s, the final amplitude should be $A(70)/A(0) \approx e^{-70/30} \approx 0.10$ — a factor of 10 decrease. This is unambiguous if the early-amplitude precision is ≤5%.

Decision criterion: Compute the ratio A(t_late)/A(t_early) for the first and last third of the time series. If this ratio is consistent with unity within 2σ, the κ-field model is rejected (for that τ_m range). If consistent with $e^{-\Delta t/\tau_m}$, fit τ_m and proceed to the hard-prediction test.

6.5 Full Observational Protocol

1. **Measure** N(t) with high statistics spanning ≥10 oscillation periods (≳ 70 s for T ≈ 7 s).

2. **Fit** the residual (after subtracting best-fit exponential) with $A(t) \cos(mt + \varphi)$, simultaneously testing:
    - $A(t) = A_0$ — systematics
    - $A(t) = A_0$ e^{−t/τ_m} — transient κ-field
    - $A(t) = A_0/t$ — geometric κ-field
    - $A(t) = A_0 \operatorname{sinc}(\beta\cdot t)$ — neutrino dephasing (mapping $L = \bar{v}t$)
3. **Select** among models via BIC; extract (m, ε, τ_m) for the winning memory model.
4. **Test hard prediction (i):** Compute $\delta\Gamma$ using the general formula of §4.2 with measured $(m, \varepsilon, \tau_m, \Gamma)$; note that the sign of the predicted shift (positive for $\tau_m < \Gamma^{-1}$, negative for $\tau_m > \Gamma^{-1}$) is itself a qualitative prediction. Compare against precision lifetime measurement relative to bare rate Γ.
5. **Test hard prediction (ii):** Compute $\rho = \hbar/(c^3\tau_m^4)$ from the measured τ_m; assess against independent estimates of committed record density in the experimental environment.
6. **Hold out** the latest 20% of the time series; predict $A(t)$ from early-time fit parameters and compare.

Steps 4–6 are decisive: they test predictions independent of the curve being fit.

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7. Physical Interpretation

7.1 Past Committed Facts as Dynamically Active Structure

The central VERSF claim is precise: **past committed facts are not erased — they remain dynamically active.** A commitment event at t_0 seeds the κ-field with source $J(t_0) = g\cdot\delta(t - t_0)$. The κ-field then propagates that commitment's causal structure forward through the retarded Green's function G_κ(τ), influencing the system's subsequent dynamics at all later times $\tau > 0$ within the causal window $\tau \leq \tau_m$. This is not metaphorical — it is encoded in the equation of motion (∂²_t + 2γ_m∂_t + m²)κ = J and its solution.

In ordinary quantum mechanics, the pre-measurement amplitude structure is replaced by the post-measurement eigenstate. The VERSF picture differs: the commitment event does not erase the past state, it records it. The record persists in the κ-field and continues to interfere with the system's future evolution. The oscillatory correction to exponential decay is the observable signature of this interference — not a correction to quantum mechanics, but a consequence of the causal structure of irreversible commitment.

7.2 Why Oscillations and Not Just Damping

Non-Markovian corrections generically produce damping corrections to Γ (the real part of the pole shift). Oscillatory corrections require a *complex* pole shift — i.e., a kernel with imaginary parts in its Laplace transform. This requires the kernel to have oscillatory character, which in turn requires the κ-field to be massive (ω_κ > 0). A massless κ-field ($m = 0$) would produce only damping corrections, not oscillations. The presence of oscillations is therefore a direct probe of the κ-field mass — an intrinsic property of the VERSF commitment structure.

7.3 Distinction from Quantum Oscillations

Standard quantum oscillations (Rabi, neutrino mixing) persist indefinitely in the absence of external decoherence — their amplitude depends on the initial superposition, not on elapsed time. The oscillations here are fundamentally different:

- Amplitude decays **intrinsically** through κ-field dissipation, independent of external decoherence
- They are corrections to a **decaying baseline**, not to a stationary amplitude
- They reflect **non-local temporal correlations** — past committed states interfering with present decay probability

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8. Discussion

8.1 Status of the GSI Anomaly

The GSI anomaly remains unconfirmed. Subsequent experiments have not reproduced the oscillatory signal, and instrumental explanations remain viable. The present analysis does not depend on the GSI result. The framework's predictions — $\tau_m \sim \rho^{-1/4}$ scaling, decay rate shift, monotone amplitude decay — are testable independently of GSI in any sufficiently isolated quantum decay system (§6.1).

What the GSI data does provide, taken at face value, is a concrete numerical template: $m \approx 0.884\ s^{-1}$, $\tau_m \gtrsim 30$ s, $\rho \lesssim 5\times10^{-66}\ m^{-3}$. These numbers are consistent and physically coherent within the VERSF framework. If the anomaly is re-examined with higher statistics and longer time baselines, the primary test is not the presence of oscillations but the **monotone decay of their amplitude** — a functional signature that neither systematics nor neutrino mixing can replicate.

The present analysis is restricted to single-channel decay with weak-to-moderate coupling ($\varepsilon \sim \mathcal{O}(1)$) to a structured κ-field environment. Extensions to strongly coupled multi-channel systems and to the non-perturbative regime $\varepsilon \gg 1$ will be addressed in separate work.

8.2 Zeno Cross-Prediction: A Bonus Falsification Test

The VERSF reinterpretation of the Quantum Zeno Effect [Taylor, *Quantum Zeno Effect as Suppression of Irreversible Commitment*, VERSF Technical Note] treats measurement as an irreversible commitment event that resets the κ-field background. In the present framework, each measurement seeds $J(t_{meas}) = g\cdot\delta(t - t_{meas})$, interrupting the kernel $K(\tau)$ by initiating a new causal epoch. When measurement events occur at intervals $\Delta t \ll \tau_m$, the kernel never accumulates oscillatory feedback, and Zeno suppression of decay emerges naturally.

This yields a **cross-prediction that is independent of the primary oscillation measurement** and cannot be produced by any of the competing hypotheses (neutrino mixing, multi-channel interference, instrumental systematics): the commitment interval required to suppress the κ-field oscillatory memory feedback satisfies:

$\Delta t\_Zeno \lesssim 1/m$

Critical distinction from standard Zeno suppression. This is not the standard Quantum Zeno suppression of the nuclear decay amplitude, which for electron-capture transitions operates at the timescale $\hbar/\Delta E \sim 10^{-22}$ s (for MeV Q-values) — entirely inaccessible to sub-second measurements. What is predicted here is specifically **κ-field memory Zeno suppression**: measurements at intervals $\Delta t \lesssim 1/m$ interrupt the accumulation of oscillatory κ-field feedback by resetting the causal epoch, suppressing the oscillatory correction to the decay rate (the ε-term) without affecting the base decay rate Γ. The two effects operate on completely different timescales and through completely different mechanisms. We use the term "κ-field Zeno suppression" to distinguish this from the standard nuclear Zeno effect. For the GSI system, $m \approx 0.884\ s^{-1}$ gives:

$\Delta t\_Zeno \lesssim 1.1$ s

The concrete prediction: Zeno suppression of the electron-capture rate in $^{142}Pm^{61+}$ should onset when the ion is subjected to commitment events at sub-second intervals — achievable via controlled photon scattering or charge-state interrogation at the storage ring. The onset timescale is directly linked to m, which is independently measurable from the oscillation period. If Zeno suppression is observed at $\Delta t \sim 1/m$ and the oscillation period $T \sim 7$ s are measured in the same system, their product $m \times \Delta t\_Zeno \sim \mathcal{O}(1)$ is a dimensionless prediction requiring no free parameters.

This cross-prediction is the most distinctive consequence of the κ-field framework: no other explanation for GSI-type oscillations predicts a specific Zeno onset timescale tied to the oscillation frequency. Stated concisely: **this links two independent observables — oscillation frequency m and Zeno onset interval Δt_Zeno — through a single κ-field parameter, $m \times \Delta t\_Zeno \sim \mathcal{O}(1)$, with no free parameters.** This is a unification result, not an add-on: the same κ-field mass m that sets the oscillation period also determines the measurement rate at which memory feedback is suppressed.

9. Conclusion

We have derived, from commitment dynamics in the VERSF framework, oscillatory corrections to exponential decay with a time-dependent, decreasing amplitude. The decisive test is not the presence of oscillations, but the time-dependence of their amplitude. The key results are:

1. **Kernel derivation (§2.2):** The memory kernel $K(\tau) = \Gamma\delta(\tau) + \varepsilon\gamma_m e^{-\gamma_m\tau} \cos(m\tau)$ follows from the κ-field's retarded Green's function with parameters m (κ-field frequency) and $\gamma_m = 1/\tau_m$ (κ-field dissipation). The scale-free limit gives $K(\tau) \sim \cos(m\tau)/\tau$.

   Both forms are the unique minimal kernels consistent with causal decay, characteristic or scale-free memory, and oscillatory κ-field feedback (§2.3).

2. **Hard prediction — memory timescale (§4.1):** $\tau_m = (\hbar/(\rho c^3))^{1/4}$, where ρ is the committed record density in the system's causal environment. This is not a free parameter. It predicts τ_m should be **universally short in bulk matter and potentially long in isolated stored ions**, with a specific $\rho^{-1/4}$ scaling across system types.
3. **Hard prediction — decay rate shift (§4.2):** $\Gamma_{obs} - \Gamma = \varepsilon/(m^2\tau_m^2)$. For GSI parameters, this is a ~2% shift in the ^{142}Pm lifetime. Combined with the τ_m prediction, the model is over-determined by two independent parameter-free tests.
4. **Functional distinction (§6.3):** The neutrino dephasing envelope is a sinc function in L with zeros and sidelobes. The κ-field memory envelope is strictly monotone — exponential or power-law. **Dephasing ≠ monotonic envelope decay.** This topological distinction requires no parameter fitting to verify.
5. **Universality (§6.1):** The predictions apply to nuclear, atomic, and mesoscopic systems via the same $\tau_m \sim \rho^{-1/4}$ scaling. The GSI anomaly is a test case, not a precondition.
6. **Zeno cross-prediction (§8.2):** Zeno suppression of the decay rate in $^{142}\mathrm{Pm}^{61+}$ should onset at measurement intervals $\Delta t \lesssim 1/m \approx 1.1$ s. The dimensionless product $m \times \Delta t_{Zeno} \sim \mathcal{O}(1)$ is a parameter-free cross-prediction linking the oscillation frequency to a Zeno timescale in the same ion — a signature no competing hypothesis can produce.

Appendix A: Tauberian Argument for R(t) ~ cos(mt)/t

Kernel: $K(\tau) = \Gamma\,\delta(\tau) + C\cos(m\tau)/\tau$ for $\tau > \tau_c$, arising from the scale-free ($\rho \to 0$) κ-field.

Laplace transform. Using the exponential integral $E_1(z) \sim -\ln(z) - \gamma_E$ for small $|z|$:

$$\mathscr{L}\{\cos(m\tau)/\tau\}(s) = \mathrm{Re}[E_1((s - im)\tau_c)] \approx \mathrm{Re}[-\ln((s - im)\tau_c) - \gamma_E]$$

This introduces a **logarithmic branch cut** at $s = im$ (and conjugate at $s = -im$):

$$\tilde{K}(s) \approx \Gamma + C \cdot \mathrm{Re}[-\ln((s - im)\tau_c) - \gamma_E]$$

Survival amplitude: $\tilde{N}(s) = N_0/(s + \tilde{K}(s))$ inherits branch points at $s = \pm im$.

Bromwich inversion. Wrapping the contour around the branch cut at $s = im$:

$$N_{bc}(t) \sim C' \cdot t^{-1} \cdot e^{imt} + \text{c.c.} \Longrightarrow N_{bc}(t) \sim \cos(mt + \delta)/t$$

Combined with the main exponential from the pole at $s \approx -\Gamma$:

$$R(t) \sim e^{-\Gamma t} + \cos(mt)/t$$

Why 1/t and not $1/t^{3/2}$: The exponent $\alpha = 1$ gives a logarithmic branch point ($\tilde{K}(s) \sim \ln(s-im)$), which inverts to t^{-1}. For $\alpha = 3/2$, $K(\tau) \sim \tau^{-3/2}$ and the branch cut gives $\tilde{K}(s) \sim$

(s−im)^{1/2}, inverting to t^{−3/2}. The scale-free case α = 1 is uniquely selected by the ρ → 0 limit of the CCC threshold.

Scope and completeness. This is a schematic argument demonstrating the mechanism. Two points on its status: first, the cos(mt)/t asymptotics are **insensitive to the UV cutoff τ_c** — the branch-cut contribution that determines the large-t behavior is controlled by the behavior of K̃(s) near s = im (the low-frequency, long-time region), which is logarithmic regardless of τ_c. The UV regularization by τ_c affects K̃(s) only for |s| ≫ m, which maps to short times and does not contribute to the leading asymptotics. The cutoff is therefore a technical device for handling the τ → 0 divergence of 1/τ and does not affect the predicted large-t functional form. Second, a complete treatment — including the subleading terms, the crossover between the exponential and algebraic regimes, and the renormalization of the kernel coefficients under τ_c → 0 — will appear in a dedicated technical note on the VERSF κ-field Lagrangian.