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Research Article

The Neutron Lifetime Puzzle and a Tube Test for Velocity-dependent and Geometry-dependent Contributions

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Abstract

This article presents a conservative phenomenological framework for discussing the free-neutron lifetime discrepancy in terms of possible geometry-dependent transport and storage contributions superposed on a common intrinsic time scale. The purpose is not to replace the standard weak-decay description, but to formulate an experimentally testable discriminator capable of separating predominantly velocity-dependent from configuration-dependent effects in the extraction of the neutron lifetime. As a starting point, a compact intrinsic-scale layer is used to introduce a working reference value $\tau_0 \approx 877.77$s. On top of this baseline, two effective correction channels are added. The first is a weak transport or alignment term for a straight tube geometry, suppressed in first approximation approximately as $1/v^2$. The second is a configuration-mixing term associated with storage or bottle setups, isotropization, and wall-induced scrambling. This leads to a direct and testable expectation: in one and the same straight decay-tube geometry, measurements across a broad speed interval should show either near constancy or only a weak residual speed dependence, whereas larger deviations would point more naturally to storage-specific mixing effects. The formulation is intentionally moderate. It is not presented as derived from QED, nor as a replacement for the standard theory of beta decay. Instead, it is proposed as an effective test framework written in notation-compatible form with respect to the standard operator language and directed toward a concrete straight-tube experiment.

Keywords

Neutron Lifetime, Beam-bottle Discrepancy, Tube Test, Transport Effects, Storage Effects, Phenomenological Model, Beta Decay, Extraction Bias

1. Introduction

Since Chadwick's discovery of the neutron [2], the problem of the free-neutron lifetime remains one of the longest-standing experimental tensions in low-energy physics. Historically, beam and bottle measurements have yielded systematically different values [4-9], while the more recent beam/TPC result at J-PARC weakens the simple beam-versus-bottle split without finally closing the question [9]. Recent discussions and updates, including additional beam implementations, simulation work, and alternative interpretations of the discrepancy, further motivate a clean geometry-discriminator experiment [5-9, 12-15].

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In this context, it is useful to examine whether part of the observed spread may include not only the true weak-decay rate but also geometry-dependent contributions associated with transport, alignment, storage, isotropization, and wall interaction effects.

The present work proposes a deliberately cautious phenomenological construction. It does not replace the standard description of weak β decay. Instead, it introduces an additional effective layer for analysing how different experimental configurations may shift the extracted value of the neutron lifetime. The central idea is that a common intrinsic lifetime scale may be combined with small configuration-dependent correction terms that manifest differently in a straight tube and in a bottle or storage geometry.

The main practical goal of the article is to formulate a decisive tube test: the same straight geometry, the same detectors, the same analysis, but clearly separated neutron-speed groups. If such a test yields an almost constant extracted lifetime, or only a weak residual term suppressed approximately as $1/v^2$, that would support the view that the large historical discrepancy is not purely kinematic. If, on the contrary, only bottle or storage regimes remain systematically shifted, this would support a storage-specific mixing interpretation layer.

2. Theoretical Framework and Phenomenological Construction

2.1. Standard Operator Language as a Point of Departure

To avoid unnecessary opposition to the standard formalism, the present article is written in a notation-compatible form with respect to the conventional operator language [10, 11].

At the level of state evolution, the starting point is

$$|\Psi(t)\rangle = U(t,t_0)|\Psi(t_0)\rangle \qquad (1)$$

where $\Psi(t)$ is the state at time t and $U(t,t_0)$ is the evolution operator from t_0 to t.

The evolution operator is written as

$$U(t,t_0) = \mathcal{T} \exp\left[-(i/\hbar) \int_{t_0}^{t} H_{eff}(t')\, dt'\right] \qquad (2)$$

where $\mathcal{T}$ is the time-ordering operator and H_{eff} is the effective Hamiltonian of the description.

In the conservative phenomenological layer used in this work, the decomposition

$$H_{eff} = H_0 + H_\beta + H_{geom} \qquad (3)$$

is adopted, where H_0 is the reference unperturbed term, H_β is the effective transition term for neutron β decay, and H_{geom} is a small geometry-dependent phenomenological correction term introduced only at the level of extraction bias, transport, and storage effects.

Meaning of symbols. H_0 — reference internal Hamiltonian; H_β — effective β-decay transition term; H_{geom} — geometry-dependent phenomenological correction term; ħ — reduced Planck constant.

2.2. Standard Weak-decay Benchmark and Conservative Embedding

Strictly speaking, free-neutron β decay belongs to the effective weak interaction rather than to pure QED [3-5]. At low energy, the standard transition term may be represented in compact form as

$$\mathcal{L}_{int} = -(G_F V_{ud} / \sqrt{2}) [\bar{p} \gamma^\mu (1 - g_A \gamma^5) n] [\bar{e} \gamma_\mu (1 - \gamma^5) \nu_e] + h.c. \qquad (4)$$

where G_F is the Fermi constant, V_{ud} is the effective CKM element, and g_A is the axial coupling parameter.

The corresponding standard reference decay rate may be written as

$$\Gamma_n^{(std)} = (G_F^2 |V_{ud}|^2 / 2\pi^3) (1 + 3g_A^2) m_e^5 f_R \qquad (5)$$

where f_R is a compact phase-space and radiative-correction factor.

Meaning of symbols. $\Gamma_n^{(std)}$ — standard reference neutron decay rate; G_F — Fermi constant; V_{ud} — effective up-down mixing parameter; g_A — axial coupling parameter; m_e — electron mass; f_R — phase-space and radiative-correction factor.

The key conservative step is the following: the present work does not modify this benchmark vertex directly. Instead, it introduces an observable-level correction layer.

$$\Gamma_{obs}(v, \mathcal{G}) = \Gamma_n^{(std)} + \delta\Gamma_{tube}(v) + \delta\Gamma_{geom}(\mathcal{G}) \qquad (6)$$

where v is the neutron speed and $\mathcal{G}$ is the class of the experimental geometry. In this way, the standard weak-decay structure remains the reference basis, while the present model enters only through a small configuration-dependent correction layer at the level of the extracted value.

2.3. Density Operator and Effective Mixing Terms

A convenient phenomenological representation of geometry-dependent effects is obtained through the density operator.

$$\rho = |\Psi\rangle\langle\Psi| \qquad (7)$$

and the effective evolution equation.

$$d\rho/dt = -(i/\hbar)\,[H\_eff, \rho] + \mathcal{D}\_mix\,[\rho] \quad (8)$$

where [H_eff, ρ] is the commutator term and $\mathcal{D}$_mix [ρ] is an effective mixing or scrambling operator.

A minimal phenomenological form is

$$\mathcal{D}\_mix\,[\rho] = \lambda\_mix\,(L\rho L^\dagger - ½\{L^\dagger L, \rho\}) \quad (9)$$

where L is an effective geometry-dependent mixing operator and λ_mix is the corresponding rate constant.

Meaning of symbols. ρ — density operator; [,] — commutator; {, } — anticommutator; L — effective mixing operator; λ_mix — mixing strength. This form is not presented as a microscopic derivation. It serves only as an operator-compatible way of describing storage-dependent isotropization, wall scrambling, and loss of directional coherence.

2.4. Intrinsic Time-scale Layer

On top of the operator language above, a compact intrinsic-scale layer is introduced. The numerical reference values employed in the benchmark discussion are consistent with standard CODATA/NIST constants [1].

$$\nu = 1/t \quad (10)$$

$$\omega = 2\pi/t \quad (11)$$

$$\lambda\_C = ct \quad (12)$$

$$R\_bare = \lambda\_C / 2\pi \quad (13)$$

$$W = h/t = h\nu \quad (14)$$

Meaning of symbols. t — characteristic internal time; ν — frequency; ω — angular frequency; λ_C — characteristic Compton length; R_bare — inner characteristic radius; W — characteristic energy scale; h — Planck constant; c — speed of light. These relations are used here as a compact internal parametrization layer rather than as a full first-principles derivation of all observables.

2.5. Gauss–Riemann Nonlinear Correspondence Layer

To give the geometry-dependent correction layer a more structured mathematical form, an additional Gauss–Riemann nonlinear correspondence method is introduced. It does not replace the weak vertex; rather, it parametrizes possible corrections through a relation among flux quantities, energy density, and an effective curvature functional.

The electric flux through a closed surface is

$$\Phi\_E = \oint\_S E \cdot dA \quad (15)$$

and Gauss's law gives

$$\oint\_S E \cdot dA = Q\_enc / \varepsilon_0 \quad (16)$$

where Q_enc is the enclosed charge and ε_0 is the vacuum permittivity.

The electric-energy density is

$$u\_E = ½\, \varepsilon_0 E^2 \quad (17)$$

where u_E is the field-energy density.

On this basis an effective curvature functional is introduced:

$$\mathcal{K}\_eff = \mathcal{K}_0 + \chi_1\, u\_E + \chi_2\, |\nabla u\_E| + \chi_3\, \Xi\_conf \quad (18)$$

where $\mathcal{K}_0$ is a baseline geometric value, |∇u_E| is the gradient of the field-energy density, Ξ_conf is a configuration factor, and χ_1, χ_2, χ_3 are phenomenological coefficients.

The visible extraction rate of the lifetime is then written as

$$\Gamma\_obs = \Gamma_0 + \Delta\Gamma\_GR \quad (19)$$

with

$$\Delta\Gamma\_GR = a_1\, \mathcal{K}\_eff + a_2\, \mathcal{K}\_eff^{\,2} + a_3\, (v, \mathcal{G}) \quad (20)$$

where Γ_0 is the baseline rate and $\mathcal{A}(v,\mathcal{G})$ is an alignment or geometry function.

Meaning of symbols. $\mathcal{K}$_eff — effective geometric or curvature measure; $\mathcal{K}_0$ — baseline value; u_E — field-energy density; Ξ_conf — configuration factor; a_1, a_2, a_3, χ_1, χ_2, χ_3 — phenomenological parameters; (v,) — velocity and geometry function. This layer allows geometry-dependent contributions to be described not only verbally, but also through a compact nonlinear mathematical ansatz.

2.6. Effective Channel Weights and Energy Partition

To represent the distribution of observable contributions in a notation-compatible form, effective projectors are introduced:

$$P\_e + P\_\nu + P\_r = I \quad (21)$$

where P_e, P_ν, and P_r correspond respectively to an electron-like visible channel, a neutrino-like weakly observable release channel, and a recoil channel.

The corresponding channel weights are

$$\Pi\_e = Tr(\rho P\_e),\ \Pi\_\nu = Tr(\rho P\_\nu),\ \Pi\_r = Tr(\rho P\_r) \quad (22)$$

with

$$\Pi\_e + \Pi\_\nu + \Pi\_r = 1 \quad (23)$$

The beta-decay mismatch energy is written as

$$Q\_\beta = W\_n - W\_p - W\_e \quad (24)$$

and numerically is

$$Q\_\beta \approx 0.78233356 \text{ MeV} \quad (25)$$

The effective partition into channels is expressed in the softest form as

$$W\_e\hat{}(obs) = Q\_\beta \, \Pi\_e \quad (26)$$

$$W\_\nu\hat{}(rel) = Q\_\beta \, \Pi\_\nu \quad (27)$$

$$W\_r\hat{}(recoil) = Q\_\beta \, \Pi\_r \quad (28)$$

This notation is better suited to the article than a stronger ontological language, because it reads the channels as effective projected observables.

3. Materials and Methods

3.1. Reference Intrinsic Lifetime Scale

A reference intrinsic lifetime scale is introduced as

$$\tau_0 = T\_cl \cdot \exp(\Sigma_0) \quad (29)$$

where T_cl is a characteristic closure-cycle time and Σ_0 is an effective dimensionless correction factor.

In the working calibration used in the present article,

$$\tau_0 \approx 877.77 \text{ s} \quad (30)$$

This value serves as a baseline reference rather than as a claim that the standard theory of weak decay has been replaced.

3.2. Tube Phenomenology

For a straight tube, a weak transport or alignment term is introduced:

$$\Gamma\_tube(v) = 1/\tau_0 + A\_t / v^2 \quad (31)$$

and correspondingly

$$\tau\_tube(v) = 1 / \Gamma\_tube(v) \quad (32)$$

where v is the neutron speed and A_t is a small phenomenological transport coefficient.

In the language of the Gauss–Riemann correspondence method, the same relation may also be read as

$$\Gamma\_tube(v) = \Gamma_0 + A\_t/v^2 + a_1\mathcal{K}\_eff + a_2\mathcal{K}\_eff^{\,2} \quad (33)$$

if a more general nonlinear correction layer is desired.

3.3. Bottle or Storage Phenomenology

For a storage or bottle geometry one uses

$$\Gamma\_bottle = 1/\tau_0 + \Gamma\_mix \quad (34)$$

and

$$\tau\_bottle = 1 / \Gamma\_bottle \quad (35)$$

A more detailed phenomenological ansatz is

$$\Gamma\_mix \propto \nu\_mix \cdot \chi\_m \cdot N\_n \cdot (\delta\_mix/\rho\_eff) \cdot \sin^2\theta\_m \cdot \Xi\_wall \quad (36)$$

where ν_mix is the mixing frequency, χ_m is the mixing factor, N_n is a neutron-count factor, δ_mix is a characteristic mixing length, ρ_eff is an effective scale parameter, θ_m is a mixing angle, and Ξ_wall is a wall-induced scrambling factor.

3.4. Proposed Straight-tube Test

The proposed decisive test is not a generic beam-versus-bottle comparison, but a comparison performed in one and the same straight tube geometry at several clearly separated speeds, using the same detectors and the same analysis. The working fit is

$$\tau\_tube(v) = 1 / (\Gamma_0 + A\_t/v^2) \quad (37)$$

If the extracted lifetime remains almost constant across a broad speed interval, this supports the view that pure kinematics is not the main source of the historical discrepancy. If a small residual dependence is observed, it should remain compatible with a weak $1/v^2$ term rather than with a multi-second effect.

Table 1. *Proposed working setup for the straight-tube test.*

Test element	Working setup
Geometry	One and the same straight decay tube / guide geometry

Test element	Working setup
Velocity regimes	Approximately 8 m/s, 50 m/s, 200 m/s, and 1000 m/s
Detection	The same detectors and the same analysis chain
Systematics	Wall interactions minimized as far as possible; magnetic guiding where feasible
Test function	$\tau\_tube(v) = 1 / (\Gamma_0 + A\_t/v^2)$

4. Results

The principal lifetime benchmark of the model is $\tau_0 \approx 877.77$ s. Internally, this value lies close to the modern bottle or UCN cluster and remains clearly separated from the larger value reported in the proton-counting beam update [6-9]. Within the same framework, a tube geometry is expected to show either an almost constant extracted lifetime or only a weak residual speed dependence, whereas storage or bottle configurations may exhibit an additional mixing contribution.

Table 2. *Compact lifetime benchmark relative to the model and the main experimental references.*

Regime / experiment	τ_n [s]	Deviation from τ_0 [s]	Note
Model baseline	877.77	+0.00	model baseline
UCNτ 2021	877.75	-0.02	magneto-gravitational bottle
UCN average 2025	877.82	+0.05	averaged UCN result
J-PARC 2024	877.20	-0.57	electron-counting beam / TPC
Beam 2013 update	887.70	+9.93	proton-counting beam update

To first approximation, an expansion around the standard benchmark may also be used:

$$\Gamma\_obs(v, \mathcal{G}) = \Gamma\_n\hat{}(std)\ [1 + \varepsilon\_t\ v^{-2} + \varepsilon\_g\ \chi(\mathcal{G}) + O(\varepsilon^2)] \quad (38)$$

where ε_t and ε_g are small dimensionless coefficients and $\chi(\mathcal{G})$ is a geometry functional. For the apparent lifetime this gives

$$\tau\_obs(v, \mathcal{G}) \approx \tau\_n\hat{}(std)\ [1 - \varepsilon\_t\ v^{-2} - \varepsilon\_g\ \chi(\mathcal{G})] \quad (39)$$

which makes the experimental interpretation transparent: the effect being sought is small, testable, and layered on top of the standard benchmark rather than replacing it.

5. Discussion

The present construction is intentionally moderate. It is not presented as a derivation of β-decay amplitudes from QED or from the Standard Model, nor as a replacement for the established description of weak decay. Its role is narrower: to propose an effective phenomenological layer with which one may test whether part of the spread in free-neutron lifetime measurements arises from geometry-dependent extraction effects.

The strength of the approach is methodological. It formulates one and the same straight-tube geometry as a clean discriminator between a weak speed-suppressed transport term and a bottle-specific mixing or storage term. If a nearly speed-independent lifetime is confirmed in the tube regime, while bottle regimes remain shifted, this would support a storage-dependent interpretation layer. If, on the contrary, the straight tube shows a large speed effect, then the central hypothesis of the present article must be restricted or abandoned. Recent beam-type implementations and simulation frameworks may be particularly useful in planning or benchmarking such a straight-tube discriminator [12, 14].

The Gauss–Riemann nonlinear correspondence layer has value beyond the specific neutron-lifetime problem. It provides a compact mathematical scheme in which flux quantities, field-energy density, and an effective curvature functional may be linked to observable extraction terms. In that sense, the method may be developed further for other projects, although in the present paper it is used only in a limited and phenomenological form.

6. Conclusions

This article proposes a cautious test framework for the free-neutron lifetime puzzle. A working intrinsic lifetime scale near $\tau_0 \approx 877.77$ s is combined with a weak velocity-suppressed tube term and a storage-related mixing term. In addition, a Gauss–Riemann nonlinear correspondence layer is introduced so that geometry-dependent corrections may be written in a more structured mathematical form.

The final message remains moderate: the text does not replace the standard theory of β decay, but it does propose a clear experimental discriminator. A straight-tube measurement performed in one and the same geometry over a broad range of velocities can cleanly separate predominantly kinematic from configuration-dependent extraction effects.

Abbreviations

QED Quantum Electrodynamics
TPC Time Projection Chamber
UCN Ultracold Neutrons

Author Contributions

Alexandar Balevsky: Conceptualization, Formal Analysis, Methodology, Writing – original draft, Writing – review & editing

Krasimira Ivanova: Investigation, Validation, Visualization, Writing – review & editing

Data Availability Statement

The data necessary for understanding the results reported in this work are included in the present manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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