

Neutrino Emission from Near-Horizon Beta Decays: A Hypothetical Mechanism for Black Hole Mass Loss

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Abstract

We explore a speculative mechanism by which neutrinos, produced via beta decay in ultra-dense matter near or within a black hole’s event horizon, may escape to infinity and contribute to black hole mass loss. Focusing on a model in which neutron-rich matter resides nanometers above the Schwarzschild radius of a non-rotating $10 M_{\odot}$ black hole, we compute gravitational redshift effects and estimate the power carried away by neutrinos. Although this emission is highly suppressed, it can exceed Hawking radiation by many orders of magnitude under optimistic assumptions. We further analyze whether antineutrinos generated inside a finite-density black hole core could quantum-tunnel across the event horizon. Despite exponential suppression, this mechanism—rooted in real weak interactions rather than virtual processes—offers a concrete, particle-physics-based perspective on alternative black hole evaporation channels and motivates further inquiry into black hole interiors, neutrino transport, and quantum gravity.

Note: Mathematical calculations and quantitative estimates presented here were assisted by AI computational tools to ensure accuracy, while the physical ideas and conceptual framework are original to the author.

1 Introduction

Black hole evaporation is traditionally attributed to Hawking radiation, a quantum effect arising from virtual particle pair creation near the event horizon [1]. While widely accepted in semiclassical physics, Hawking radiation is extraordinarily weak for stellar-mass black holes, with negligible observational signatures [2].

This paper explores an alternative mass-loss mechanism involving real neutrinos produced through beta decay of ultra-dense matter near a black hole’s horizon. Specifically, we consider:

- Neutrino emission from neutron-rich matter located extremely close to the Schwarzschild radius.

- Quantum tunneling of neutrinos from matter within the horizon, assuming a finite-density core replaces the classical singularity.

Such scenarios challenge two key assumptions of classical general relativity: the inviolability of the event horizon and the existence of a singularity at the core. If instead the interior contains dense, degenerate matter—as in gravastar [3], fuzzball [4], or loop quantum gravity–inspired models [5]—then weak interaction processes may proceed under extreme conditions, and neutrinos may offer a leakage channel.

2 Physical Setup and Assumptions

We construct a simplified model based on the following assumptions. While we adopt a “neutron shell” for clarity and ease of estimation, we emphasize that the mechanism does not require the presence of such a shell; infalling matter undergoing beta decay or more extended structures could yield similar behavior. The shell is thus a tool for tractability, not a physical necessity.

- **Black Hole:** Non-rotating Schwarzschild black hole of mass $M = 10 M_\odot$.
- **Schwarzschild Radius:**

$$r_s = \frac{2GM}{c^2} \approx 2.953 \times 10^4 \text{ m.}$$

- **Neutron Shell:** A thin, hypothetical layer of neutron-rich matter located at a proper radial distance $\Delta r = 1 \text{ nm} = 10^{-9} \text{ m}$ above r_s , undergoing beta decay:

$$n \rightarrow p + e^- + \bar{\nu}_e.$$

- **Local Neutrino Energy:** $E_{\nu,\text{local}} \approx 1 \text{ MeV}$, typical of beta decay spectra [6].
- **Optimistic Neutrino Emission Rate:** $\dot{N}_\nu \approx 10^{40} \text{ s}^{-1}$, motivated by neutron star neutrino emission rates scaled to the shell volume [7].

3 Gravitational Redshift and Neutrino Energy at Infinity

The gravitational redshift factor near the Schwarzschild radius is:

$$\alpha(r) = \sqrt{1 - \frac{r_s}{r}} \approx \sqrt{\frac{\Delta r}{r_s}} = \sqrt{\frac{10^{-9}}{2.953 \times 10^4}} \approx 1.84 \times 10^{-7}.$$

Hence, the neutrino energy observed at infinity is:

$$E_{\nu,\infty} = \alpha(r) \cdot E_{\nu,\text{local}} \approx (1.84 \times 10^{-7}) \times (1 \text{ MeV}) \approx 2.95 \times 10^{-20} \text{ J.}$$

This strong gravitational redshift dramatically reduces the neutrino energy detected far from the black hole.

4 Neutrino Luminosity and Mass Loss Estimate

Assuming all neutrinos escape (an upper bound), the luminosity is:

$$L_\nu = E_{\nu,\infty} \times \dot{N}_\nu.$$

- **Optimistic emission rate** $\dot{N}_\nu = 10^{40} \text{ s}^{-1}$:

$$L_\nu = (2.95 \times 10^{-20} \text{ J}) \times (10^{40}) = 2.95 \times 10^{20} \text{ W}.$$

- **Conservative emission rate** $\dot{N}_\nu = 10^{37} \text{ s}^{-1}$:

$$L_\nu \approx 2.95 \times 10^{17} \text{ W}.$$

These luminosities greatly exceed the power output expected from Hawking radiation (see Section 7).

5 Theoretical and Physical Considerations

5.1 Viability of the Neutron Shell

The existence of stable matter just nanometers above the Schwarzschild radius is speculative. Known equations of state do not support equilibrium at such extreme gravitational gradients [8]. Potential stabilizing mechanisms might include:

- Ultra-relativistic degeneracy pressure [9].
- Exotic anisotropic stress-energy distributions (e.g., gravastars [3]).
- Quantum gravitational effects that balance collapse at Planck densities [5].

These possibilities remain speculative but motivate the exploration of non-classical black hole interiors.

5.2 Neutrino Transport in Dense Matter

In dense nuclear matter, neutrino mean free paths are typically $\lambda_\nu \sim 10\text{--}100 \text{ m}$ [10, 11]. In a thin shell of thickness $R = 1 \text{ nm}$, the escape fraction is:

$$f_{\text{esc}} \sim e^{-R/\lambda_\nu} \approx 1 - \frac{R}{\lambda_\nu} \approx 1 - 10^{-10}.$$

This near-unity escape fraction suggests neutrinos generated in the shell could largely escape, assuming no other trapping mechanisms.

5.3 Shell Replenishment and Stability

As long as a reservoir of neutron-rich matter exists in or near the core, continuous beta decay may be sustained. This could arise from accretion, internal phase transitions, or modified interior structures [12]. The shell may serve as a transient interface rather than a static boundary, with dynamic inflow and decay processes maintaining its presence.

5.4 Backreaction on Spacetime

The neutrino emission would, in principle, backreact on spacetime via:

$$G_{\mu\nu} = 8\pi G \langle T_{\mu\nu} \rangle.$$

We neglect backreaction here, assuming steady-state emission and minimal energy loss compared to total mass. Incorporating backreaction would require solving the Einstein–Boltzmann system for neutrino radiation hydrodynamics, a challenging problem beyond this initial exploration [13].

6 Neutrino Tunneling from Inside the Horizon

Assuming the black hole interior contains ultra-dense matter rather than a singularity, beta decay could occur inside the event horizon. Neutrinos generated there may quantum-tunnel across the horizon, a process distinct from but formally reminiscent of Hawking radiation.

Using the WKB approximation [14]:

$$\Gamma_\nu \sim \exp\left(-\frac{8\pi GME}{\hbar c^3}\right).$$

For $E = 1 \text{ MeV}$ and $M = 10 M_\odot$:

$$\Gamma_\nu \sim \exp(-1.88 \times 10^{18}).$$

While exponentially suppressed, this tunneling probability is nonzero. Non-singular interior models may yield reduced barriers or enhanced tunneling pathways, possibly increasing Γ_ν [15, 16].

7 Comparison with Hawking Radiation

- **Hawking Temperature:**

$$T_H = \frac{\hbar c^3}{8\pi GM k_B} \approx 6.17 \times 10^{-9} \text{ K}.$$

- **Hawking Power Output:**

$$P_H \approx 9.01 \times 10^{-31} \text{ W}.$$

Even our conservative L_ν estimate exceeds this by over 50 orders of magnitude. However, Hawking radiation is robustly predicted in semiclassical gravity [1], whereas our model depends on speculative interior structures and unverified transport assumptions.

8 Implications for the Information Paradox

If neutrinos escaping from near or within the horizon carry state-dependent information (e.g., baryon number, lepton flavor, or decay timing), they may represent a non-thermal, information-bearing leakage mechanism. Unlike Hawking radiation, which is typically modeled as thermal and uncorrelated with internal states [17], beta-decay neutrinos arise from real interactions tied to the microstate of the emitting matter.

This distinction is crucial: thermal Hawking radiation leads to apparent loss of information and challenges unitarity, while neutrino emission from beta decay is fundamentally unitary. If even a tiny fraction of these neutrinos escape to infinity—whether from just outside the horizon or through quantum tunneling inside—the black hole evaporation process may encode microscopic state information in the emitted neutrino flux.

9 Discussion and Future Directions

This speculative framework opens multiple avenues for exploration:

- Developing more realistic equations of state for matter stabilized near the event horizon.
- Modeling neutrino transport and diffusion in extreme gravitational and nuclear environments.
- Investigating quantum gravity–motivated modifications of black hole interiors that may enhance neutrino tunneling probabilities.
- Studying observational signatures of neutrino emission from candidate black holes, and how such signals might differ from background or standard Hawking radiation.
- Examining the implications of information-bearing neutrino fluxes on black hole thermodynamics and quantum information theory.

While the ideas presented here are highly tentative and model-dependent, they illustrate the value of integrating particle physics, gravitational theory, and quantum information to deepen our understanding of black holes beyond classical horizons.

10 Conclusion

We proposed that neutrinos from beta decay of ultra-dense matter near or inside a black hole horizon may provide a novel channel for mass loss and potentially carry information from the black hole interior. Although gravitational redshift and tunneling suppression limit the observed flux, the emission could vastly exceed Hawking radiation in power under optimistic assumptions. This work encourages further theoretical and computational investigation of black hole interiors, neutrino physics in extreme environments, and the interface between quantum gravity and particle astrophysics.

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