



# Neutrino quantum decoherence engendered by neutrino decay to photons, familons and gravitons

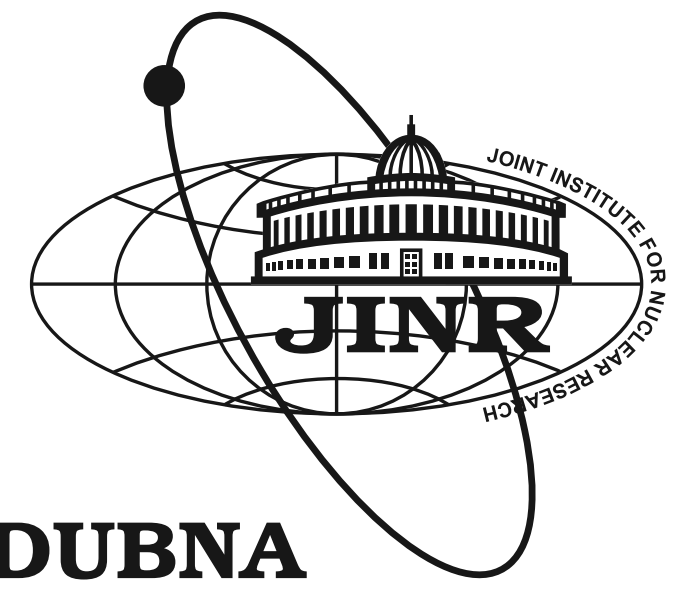
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## 1 Introduction

The phenomenon of neutrino oscillations emerges due to coherent superposition of neutrino mass states. An external environment can modify a neutrino evolution in a way that the coherence will be violated. Such violation is called quantum decoherence of neutrino mass or spin states and leads to the suppression of flavor and spin-flavour oscillations. In our previous paper [1–4], we presented a new theoretical framework, based on the quantum field theory of open systems applied to neutrinos. Within this framework we proposed and considered a new mechanism of the neutrino quantum decoherence engendered by the neutrino radiative decay in an electron background in an extreme astrophysical environment. In the present study we generalize our approach and consider neutrino quantum decoherence engendered by neutrino decay to a lighter neutrino and an arbitrary massless particle.

The quantum neutrino decoherence has attracted a growing interest during the last 20 years. The effect is actively studied in different neutrino experiments in reactor and solar fluxes (see, for example, [5–7]). We also highlight the recent theoretical studies dedicated to neutrino quantum decoherence [8–11]. Previously, we have studied neutrino quantum decoherence in supernovae fluxes [12].

## 2 Neutrino quantum decoherence

For description of the neutrino decoherence we use the formalism of quantum electrodynamics of open systems [1] which was used previously in [13] for evolution of electrons. We start with the quantum Liouville equation for the density matrix  $\rho$  of a system composed of neutrinos and an external environment

$$\frac{d\rho}{dt} = -i[H_\nu + H_{int}(t), \rho], \quad (1)$$

where the Hamiltonian  $H_{int}$  describes the interaction between neutrino system and an external environment,  $H_\nu$  is the free neutrino Hamiltonian. In the most general case it can be written as follows

$$H_{int}(x) = \sum_{\alpha} j_{\alpha}(x) \otimes E_{\alpha}(x), \quad (2)$$

where  $j_{\alpha}$  is the neutrino current and  $E_{\alpha}$  is the vector that describes the external environment. Such a general expression for the interaction Hamiltonians enables one to consider external environment consisted of arbitrary massless particles, such as photons and dark photons, gravitons, axion-like particles and other hypothetical particles.

In order to exclude the environment evolution which we are not interested in, we formally integrate (1) and then trace out the environment degrees of freedom

$$\rho_{\nu}(t_f) = \text{tr}_E \rho(t_f) = \text{tr}_E \left( \text{Exp} \left[ \int_{t_i}^{t_f} d^4x [H_{int}(x), \rho(t_i)] \right] \right), \quad (3)$$

where  $\rho_{\nu}$  is the density matrix for the neutrino system. After calculations similar to those performed in [1] we find the final master equation for the neutrino system

$$\frac{d\rho_{\nu}}{dt} = -i[H_{\nu}, \rho_{\nu}] + D[\rho_{\nu}], \quad (4)$$

The first term on the right hand side describes the neutrino evolution without account for the effect of decoherence. The second term is the dissipative operator in the Lindblad form [14, 15] that appears due to neutrino interaction with external environment  $E_{\alpha}$

$$D[\rho_{\nu}] = \sum_{\omega_n} \Gamma(\omega_n)(1 + N(\omega_n)) \left( j(\omega_n) \rho_{\nu} j^{\dagger}(\omega_n) - \frac{1}{2} \{ j^{\dagger}(\omega_n) j(\omega_n), \rho_{\nu} \} \right) + \sum_{\omega_n} \Gamma(\omega_n) N(\omega_n) \left( j^{\dagger}(\omega_n) \rho_{\nu} j(\omega_n) - \frac{1}{2} \{ j(\omega_n) j^{\dagger}(\omega_n), \rho_{\nu} \} \right), \quad (5)$$

where  $\omega_n$  is the energy difference between neutrino states that are participating in the neutrino decay and  $N(\omega_n)$  is the Planck distribution function

$$N(\omega) = \frac{1}{e^{\beta\omega} - 1}, \quad (6)$$

where  $\beta$  is the temperature of the external environment. The neutrino decoherence parameters are defined by neutrino decay rates  $\Gamma(\omega_n)$ . In equation (5) we have decomposed the neutrino current (2) on the eigenoperators of the neutrino Hamiltonian

$$j(t, \vec{k}) = \sum_{\omega_n} e^{j(\omega_n, \vec{k})}, \quad (7)$$

$$[H_{\nu}, j(\omega_n)] = \omega_n j(\omega_n), \quad (8)$$

where  $\vec{k}$  is the neutrino momenta.

The first term in equation (5) is responsible for the spontaneous and thermally induced emission processes and the second one is responsible for the thermally induced absorption processes. Note that the obtained results can be applied to the description of quantum decoherence both of neutrino mass and spin states.

## 3 Conclusion

We have derived the general dissipative term (5) for the neutrino master equation (4) that describes neutrino quantum decoherence engendered by neutrino decay to arbitrary massless particles. Equation (5) generalizes our previous result [1] where we have considered neutrino radiative decay in matter composed of electrons.

The dissipative term (5) is proportional to the neutrino decay rates  $\Gamma(\omega_n)$ . Thus the obtained results enable one to follow the influence of the neutrino decays through the neutrino quantum decoherence effect on flavour and spin-flavour oscillations. For example, the results can be applied to description of the influence of the recently proposed neutrino spin light ( $SL\nu$ ) (see [16] and references therein) or neutrino decay engendered by the induced magnetic moment [17] through the quantum decoherence on the neutrino spin oscillations.

Neutrino quantum decoherence can also serve as a signature of neutrino nonstandard interaction with dark matter. For example, one can consider neutrino decay to massless familons and other axion-like particles [18–20], to neutrino decay to dark photons [21–23] or to gravitons [24].

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