XLI International Conference on High Energy Physics (6 - 13 July, 2022, Bologna, Italy)

Neutrino oscillations and quantum decoherence

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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 papers [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 the electrons evolution. We start with the quantum Liouville equation for the density matrix ρ of a system composed of neutrinos and an external environment. In the Dirac picture it reads

$$\frac{d\rho(t)}{dt} = -i\left[H_{int}(x), \rho(t)\right], \tag{1}$$

where the Hamiltonian H_{int} describes the interaction between neutrino system and an external environment. For the general case it can be written as follows

$$H_{int}(x) = \sum_k j_k(x) a_k(x), \tag{2}$$

where j_k is the neutrino current and a_k is the field 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 photos, dark photons, 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

$$\rho_\nu(t_f) = tr_a \rho(t_f) = tr_a\left(Texp\left[\int_{t_i}^{t_f} d^4x\left[H_{int}(x), \rho(t_i)\right]\right]\right), \tag{3}$$

where $\rho_\nu(t)$ 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

$$\frac{d\rho_\nu(t)}{dt} = -i\left[H_\nu(x), \rho_\nu(t)\right] + D[\rho_\nu(t)], \tag{4}$$

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 a_k

$$\begin{aligned} D[\rho_\nu(t)] = \sum_k \left(A_k \rho_\nu(t) A_k^\dagger - \frac{1}{2}\{A_k A_k^\dagger, \rho_\nu(t)\}\right) + \\ + \sum_k \left(B_k \rho_\nu(t) B_k^\dagger - \frac{1}{2}\{B_k B_k^\dagger, \rho_\nu(t)\}\right), \end{aligned} \tag{5}$$

where A_k and B_k are the Lindblad operators. Within our approach we have found the exact formulas for this operators,

$$\begin{aligned} A_k &= \sum_{n:\{m_n<m_k\}} \sqrt{\Gamma^d_{kn}}\, |k\rangle\langle n|, \\ B_k &= \sum_{l:\{m_l>m_k\}} \sqrt{\Gamma^i_{kl}}\, |k\rangle\langle l|, \end{aligned} \tag{6}$$

where Γ^d_{kn} is the neutrino decay rate ($\nu_k \to \nu_n + a$) and Γ^i_{kn} is the emission rate ($\nu_k + a \to \nu_n$), where a stands for a massless particle of the external environment. Note, that Γ^d and Γ^i are the rates in the presence of the external environment at a finite temperature, i. e. $\Gamma^d = [1 + N(E)]\,\Gamma^d_{vac}$ where Γ^d_{vac} is the neutrino decay rate in a vacuum and $N(E)$ is the Bose-Einstein distribution function

$$N(E) = \frac{1}{e^{\beta E} - 1}, \tag{7}$$

where $\beta = 1/T$ is the temperature of the external environment. Note, that in the vacuum (when the temperature of the external environment $T = 0$) the Lindblad operators are zero, $B_k = 0$.

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) generalize 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 and emission rates $\Gamma^{d(i)}$. 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 ($SL\nu$), studied in different astrophysical environments, (see [16] and references therein) or to neutrino decay engendered by the induced magnetic moment [17].

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], and also to neutrino decay to dark photons [21–23].

4 Acknowledgements

The work is done within the program of the Interdisciplinary Scientific and Educational School of Moscow University "Fundamental and Applied Space Research" and is supported by the Russian Science Foundation under grant No.22-22-00384. The work of KS is also supported by the RFBR under grant No. 20-32-90107 and by the "BASIS" Foundation No. 20-2-2-3-1. The work of MV is also supported by the "BASIS" Foundation No. 20-2-1-25-1.

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