Neutrino Oscillations and Quantum Decoherence

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Neutrino quantum decoherence is the process of the violation of the coherent superposition of neutrino states engendered by the neutrino interaction with external environment. In [1–3] we proposed and considered the new mechanism of the neutrino quantum decoherence engendered by neutrino decay to a lighter neutrino and an arbitrary massless particle. In this paper we consider that there are two possible independent neutrino decays: (1) neutrino decay to a lighter state and a massless particle and (2) neutrino decay to a lighter state and another massless particle. Photons, dark photons, axions, etc. can be considered as an example of these massless particles.

The evolution of the entire system of both neutrinos and external environment (reservoir consisted of two types of massless particles) can be represented as follows

$$\rho(t) = U(t)\,\rho_0\,U^{\dagger}(t), \tag{1}$$

where $\rho(t)$ and $U(t)$ is the density matrix and evolution operator of the entire system, ρ_0 is the density matrix of the system at the initial moment of time. According to the approach proposed in [1–3] we use an expression for the expansion of the evolution operator of the entire system up to the second order in powers of the coupling constant

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Y. Tayalati, M. Gouighri (eds.), *The First African Conference on High Energy Physics*, Springer Proceedings in Physics 425,
https://doi.org/10.1007/978-3-031-88933-2_34

$$U\left(t,t_0\right)=1+(-i)\int_{t_0}^{t}dt_1 H_I\left(t_1\right)+(-i)^2\int_{t_0}^{t}dt_1\int_{t_0}^{t_1}dt_2 H_I\left(t_1\right)H_I\left(t_2\right)+\ldots \tag{2}$$

where $H_I\left(t\right)$ is the Hamiltonian of the interaction of the neutrino with external reservoir. To get an expression for the neutrino density matrix, we take the trace of the external environment states of freedom $\rho_\nu\left(t\right)=\mathrm{Tr}_{\mathrm{A}}\rho\left(t\right)$. Finally, for the neutrino density matrix we get

$$\begin{aligned}\rho\left(t\right)=\rho_0+i\int_{t_0}^{t}\left[H_I,\rho\right]dt+&\\ &+\frac{1}{2}\left(\int_{t_0}^{t}\int_{t_0}^{t}dt_1dt_2H_I\left(t_2\right)\rho H_I\left(t_1\right)+\int_{t_0}^{t}\int_{t_0}^{t}dt_1dt_2H_I\left(t_1\right)\rho H_I\left(t_2\right)-\right.\\ &-\int_{t_0}^{t}dt_1\int_{t_0}^{t}dt_2\ \underset{\rightarrow}{T}\left\{H_I\left(t_1\right)H_I\left(t_2\right)\right\}\rho\\ &\left.-\rho\int_{t_0}^{t}dt_1\int_{t_0}^{t}dt_2\ \underset{\leftarrow}{T}\left\{H_I\left(t_1\right)H_I\left(t_2\right)\right\}\right).\end{aligned} \tag{3}$$

The neutrino interaction with an external environment is described by two independent interaction Hamiltonians

$$H_I\left(t_2\right)=H_1(t_2)+H_2(t_2). \tag{4}$$

Following the approach [1–3] we get the expression for the neutrino evolution

$$\frac{d\rho_\nu(t)}{dt}=-i\left[H_1(x)+H_2(x),\rho_\nu(t)\right]+D\left[\rho_\nu(t)\right], \tag{5}$$

where the term $D\left[\rho_\nu(t)\right]$ is responsible for neutrino decoherence engendered by neutrino decays. The neutrino decoherence parameter Γ that describes the amplitude of the effect turned out to be a sum of the two independent neutrino decoherence parameters Γ_1 and Γ_2 engendered by the first channel of the neutrino decay and the second channel correspondingly, i.e. $\Gamma=\Gamma_1+\Gamma_2$. In other words there is no interference terms in neutrino quantum decoherence when considering two independent channels of the neutrino decay.

Acknowledgments One of the authors (A.S.) is thankful to the organizers of the First African Conference on High Energy Physics for the hospitality. This study was supported by the Russian Science Foundation (project No. 22-22-00384).

This study also Supported by the Scientific Program of the National Center for Physics and Mathematics, Section No. 8 (Stage 2023-2025).

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