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Propagation and oscillations of cosmic neutrinos in a stochastic magnetic field

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Introduction

One of the important fields of neutrino astrophysics is a search for ultrahigh-energy (UHE) cosmic neutrinos (even above PeV–EeV energies). These neutrinos are believed to be produced by reactions of UHE cosmic rays composed of protons and nuclei and are expected to provide information about cosmic accelerators and the high-energy, distant universe. The neutrino massiveness supports the assumption that neutrinos have nonzero electromagnetic characteristics [1]: even though neutrinos are generally believed to be electrically neutral particles they can still have nonzero magnetic moments. This means that the propagation of the UHE cosmic neutrinos can be influenced by the presence of magnetic fields due to the effect of spin oscillations [2]. In this work we focus on the effects of neutrino magnetic moments interactions with the stochastic component of an interstellar magnetic field. Specifically, we examine the differences in the neutrino flavor and spin oscillation patterns in the absence and in the presence of the stochastic magnetic-field component, respectively.

Neutrino evolution in a stochastic magnetic field

In the scope of our interest are two neutrino helicity basis states $|\nu_1^{\pm}\rangle$, $|\nu_2^{\pm}\rangle$ with masses m_1 and m_2. The effective Hamiltonian of the problem is given by (see Ref. [2])

$$\hat{H} = \begin{pmatrix} -\omega_\nu - \frac{\mu_1}{\gamma}B_\parallel & \mu_1 B_\perp & -\frac{\mu_{12}}{\gamma}B_\parallel & \mu_{12}B_\perp \\ \mu_1 B_\perp & -\omega_\nu + \frac{\mu_1}{\gamma}B_\parallel & \mu_{12}B_\perp & \frac{\mu_{12}}{\gamma}B_\parallel \\ -\frac{\mu_{21}}{\gamma}B_\parallel & \mu_{21}B_\perp & \omega_\nu - \frac{\mu_2}{\gamma}B_\parallel & \mu_2 B_\perp \\ \mu_{21}B_\perp & \frac{\mu_{21}}{\gamma}B_\parallel & \mu_2 B_\perp & \omega_\nu + \frac{\mu_2}{\gamma}B_\parallel \end{pmatrix}, \qquad \omega_\nu = \frac{\Delta m^2}{4E_\nu}, \tag{1}$$

where $\Delta m^2 = m_2^2 - m_1^2$, E_ν is the neutrino energy, $B_\parallel$ and $B_\perp$ are the parallel and transverse magnetic-field components with respect to the neutrino velocity, and $\mu_{1(2)}$ ($\mu_{12(21)}$) are the diagonal (transition) neutrino magnetic moments. We neglect the neutrino interaction with the longitudinal magnetic-field component, setting $(\mu/\gamma)B_\parallel = 0$. The latter is justified by large γ values for UHE neutrinos.

We consider the case when the galactic and extragalactic magnetic fields are composed of the large-scale regular component $\vec{B}$ that enters Eq. (1) and a small-scale stochastic component $\vec{h}$. The stochastic magnetic field $\vec{h}$ is a result of interstellar fluctuations, galactic winds, cosmic turbulence and primordial magnetic field fluctuations. It is characterized by the correlation function $\langle h_\alpha(t)h_\beta(0)\rangle = \frac{w^2}{2\mu_\nu^2}\delta(t)$, where μ_ν is a putative neutrino magnetic moment and $w^2 = 2\eta(\mu_\nu B)^2 L_0$ is the dissipation parameter, with L_0 being the correlation length.

The density matrix of the system obeys the Lindblad master equation in the form [3–5]:

$$\frac{d\hat{\varrho}}{dt} = -i\left[\hat{H}, \hat{\varrho}\right] - \frac{w^2}{4\mu_\nu^2}\left(\hat{\varrho}\hat{\mathcal{M}}^2 + \hat{\mathcal{M}}^2\hat{\varrho} - 2\hat{\mathcal{M}}\hat{\varrho}\hat{\mathcal{M}}\right), \tag{2}$$

where $\hat{\mathcal{M}}$ is the neutrino magnetic moment matrix given by

$$\hat{\mathcal{M}} = \begin{pmatrix} 0 & \mu_1 & 0 & \mu_{12} \\ \mu_1 & 0 & \mu_{12} & 0 \\ 0 & \mu_{21} & 0 & \mu_2 \\ \mu_{21} & 0 & \mu_2 & 0 \end{pmatrix}. \tag{3}$$

In the case of Dirac neutrinos the matrix $\hat{\mathcal{M}}$ is real and $\mu_{12} = \mu_{21}$, whereas for the Majorana neutrinos it is imaginary with $\mu_1 = \mu_2 = 0$ and $\mu_{12} = -\mu_{21} = -\mu_{12}^*$.

In this study, the transition magnetic moments of Dirac neutrinos are zeroed, i.e., $\mu_{12} = \mu_{21} = 0$. If the initial neutrino state is $\nu(0) = \nu_\mu^L$, the solution of the Lindblad master equation (2) yields the flavor-change probability $P^D_{\nu_\mu^L \to \nu_e^L}$ for the Dirac neutrino as

$$\boxed{\begin{aligned} P^D_{\nu_\mu^L \to \nu_e^L} =& \frac{1}{4}\sin^2 2\theta \left\{1 + \frac{1}{2}\exp\left(-w^2\frac{\mu_1^2}{\mu_\nu^2}t\right)\cos\left(2\mu_1 B_\perp t\right) + \frac{1}{2}\exp\left(-w^2\frac{\mu_2^2}{\mu_\nu^2}t\right)\cos\left(2\mu_2 B_\perp t\right)\right. \\ & \left. - \cos\left(2\omega_\nu t\right)\left[\exp\left(-w^2\frac{\mu_-^2}{\mu_\nu^2}t\right)\cos\left(2\mu_- B_\perp t\right) + \exp\left(-w^2\frac{\mu_+^2}{\mu_\nu^2}t\right)\cos\left(2\mu_+ B_\perp t\right)\right]\right\}, \end{aligned}} \tag{4}$$

where $\mu_\pm = (\mu_1 \pm \mu_2)/2$.

The spin-flip probability $P^D_{\nu_\mu^L \to \nu^R}$ is determined by the expression:

$$\boxed{P^D_{\nu_\mu^L \to \nu^R} = \frac{1}{2}\left[1 - \sin^2\theta\exp\left(-w^2\frac{\mu_1^2}{\mu_\nu^2}t\right)\cos\left(2\mu_1 B_\perp t\right) - \cos^2\theta\exp\left(-w^2\frac{\mu_2^2}{\mu_\nu^2}t\right)\cos\left(2\mu_2 B_\perp t\right)\right].} \tag{5}$$

Unlike the probability of neutrino flavor oscillations (4), it does not depend on the neutrino energy E_ν.

We also obtained a solution for the Majorana neutrino case, but it is too cumbersome and will be presented elsewhere.

Flavor and spin oscillations of UHE cosmic neutrinos

We present the results for the probabilities of flavor and spin oscillations of UHE Dirac neutrinos in an interstellar magnetic field at three different energies: $E_\nu = 10^{18}$ eV, $E_\nu = 10^{20}$ eV and $E_\nu = 10^{22}$ eV. The deterministic magnetic field strength is set to the value $B = 2.93\,\mu$G [3]. The stochastic magnetic-field component is characterized by $\eta \sim 1$ and $L_0 \sim 50$ pc [6]. The putative magnetic moment value is chosen to be $\mu_\nu = 10^{-12}\mu_B$ that falls within the upper astrophysical limits (see Ref. [7] and references therein). The squared mass difference is taken from solar neutrino measurements, $\Delta m^2 = \Delta m^2_{sol} = 7.53 \times 10^{-5}$ eV^2 [7]. All numerical calculations were performed in the case when the initial state of the neutrino is $\nu(0) = \nu_\mu^L$.

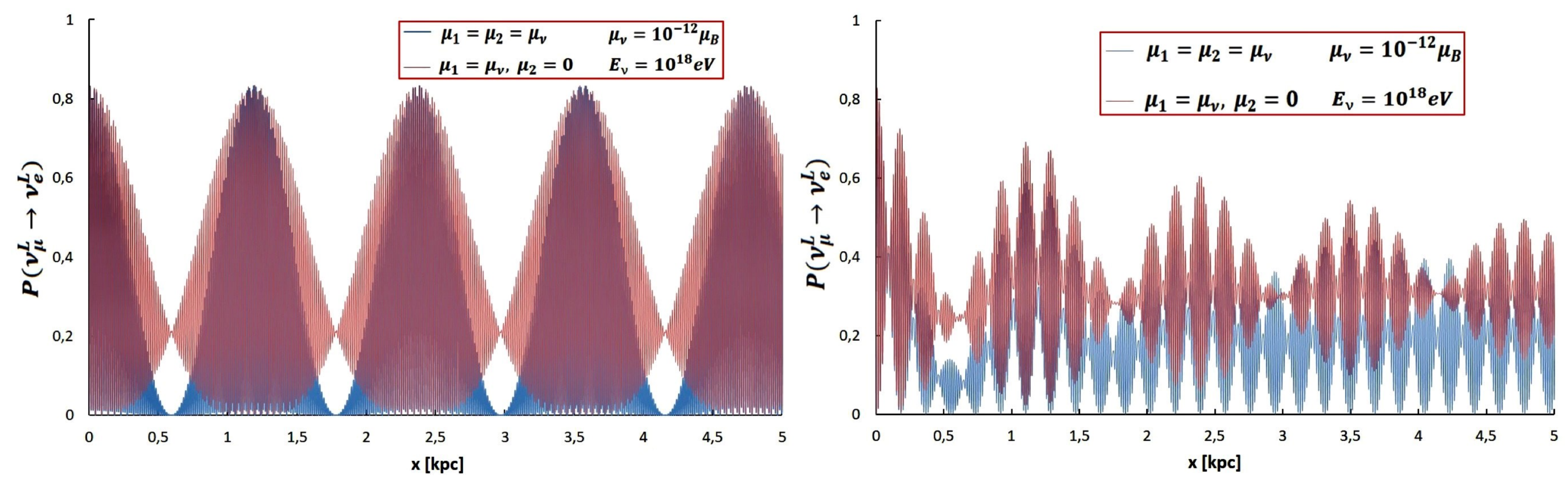

Figure 1: The neutrino flavor-change probability both in the absence (left panel) and in the presence (right panel) of the stochastic magnetic-field component as a function of the distance x traveled by an 1-EeV neutrino interacting with an interstellar magnetic field.

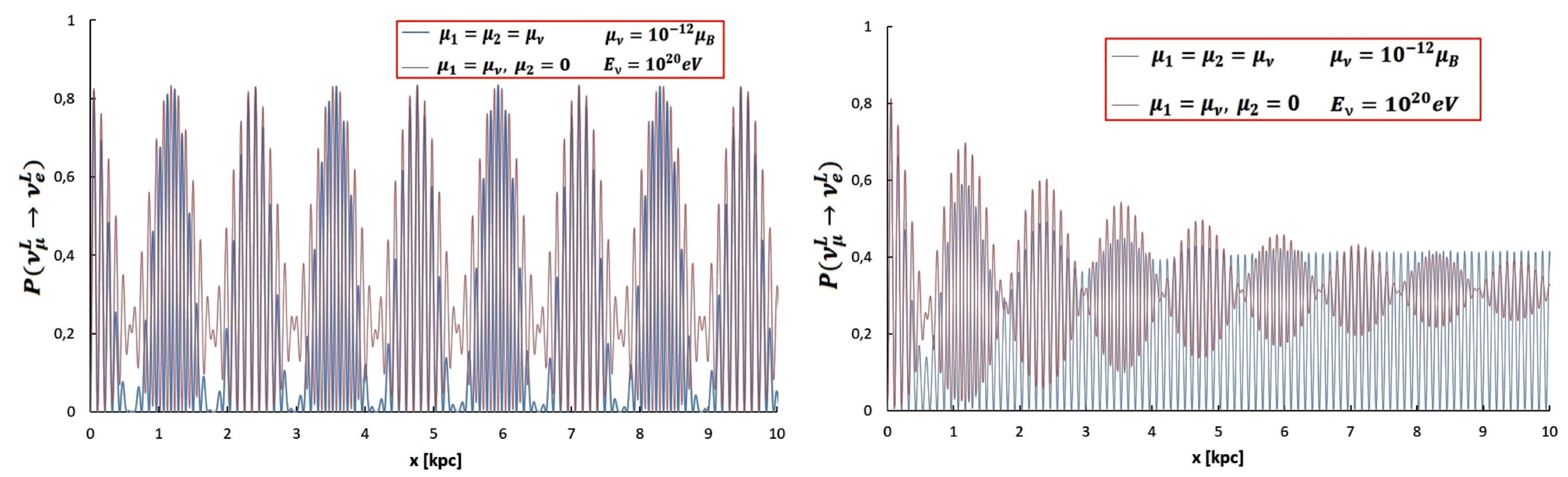

Figure 2: The same as in Fig. 1, but when $E_\nu = 100\,$EeV.

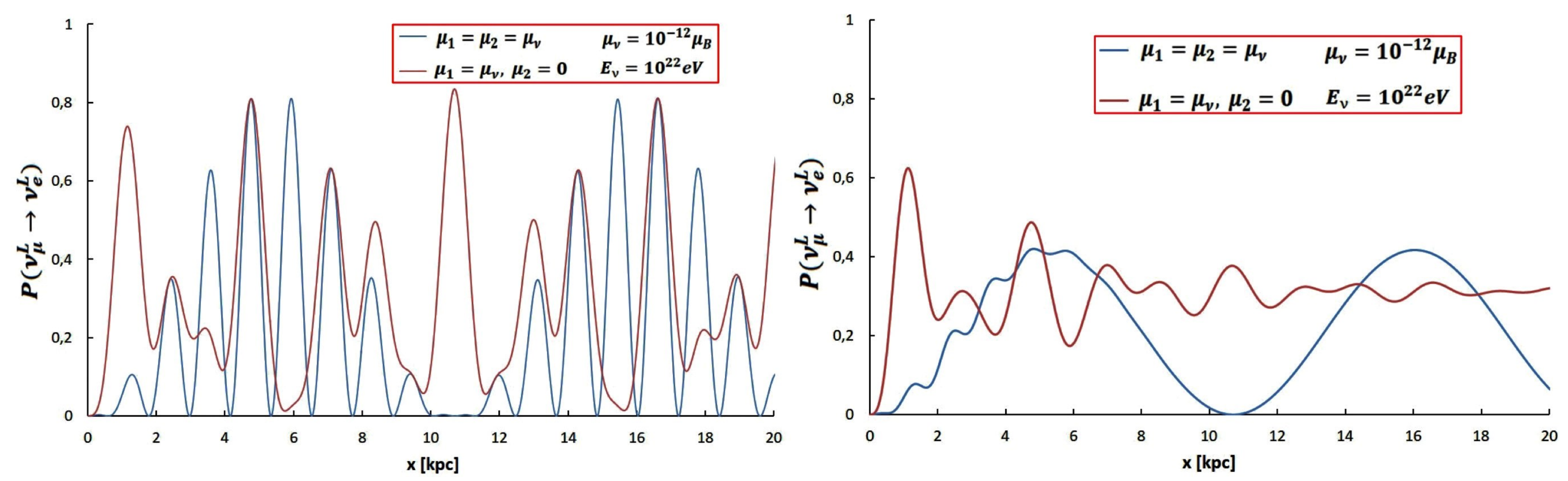

Figure 3: The same as in Fig. 1, but when $E_\nu = 10\,$ZeV.

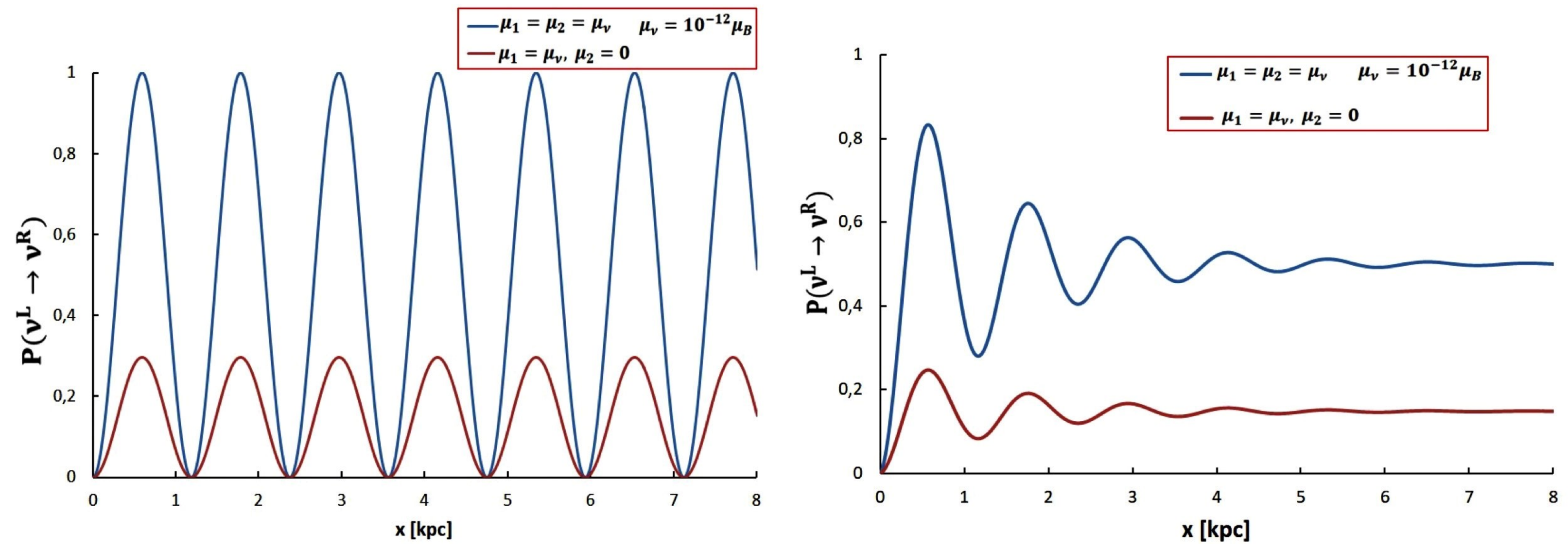

Figure 4: The neutrino spin-flip probability both in the absence (left panel) and in the presence (right panel) of the stochastic magnetic-field component as a function of the distance x traveled by an UHE cosmic neutrino interacting with an interstellar magnetic field.

Summary

- The Lindblad master equation is solved for both Dirac and Majorana neutrinos with a nonzero magnetic moment propagating in an interstellar magnetic field.
- The probabilities of flavor neutrino and spin oscillations are derived.
- The numerical results for these probabilities were presented at neutrino energies below, around and above the Greisen-Zatsepin-Kuzmin limit ($E_\nu = 10^{18}$ eV, $E_\nu = 10^{20}$ eV and $E_\nu = 10^{22}$ eV, respectively). The marked effect of the stochastic component of an interstellar magnetic field on the neutrino oscillations is outlined.

Acknowledgements

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