PROCEEDINGS OF SCIENCE

Spin-Flavor oscillations of cosmic neutrino flux in intergalactic magnetic field

Ashutosh Kumar Alok,[a] **Neetu Raj Singh Chundawat**[a] **and Arindam Mandal**[a,*]

[a] *Indian Institute of Technology Jodhpur, Jodhpur 342037, India,*

E-mail: akalok@iitj.ac.in, chundawat.1@iitj.ac.in, mandal.3@iitj.ac.in

Neutrinos may possess tiny magnetic moments (μ_ν) via quantum corrections, by virtue of which they can undergo spin-flavor oscillations. This phenomenon can alter the flux of cosmic neutrinos. Considering the current limit on μ_ν , we show that the flux of cosmic neutrinos will reduce by half if they traverse a few Mpcs through the intergalactic magnetic field, in the range of μG to nG. Furthermore, if the current upper bound is improved by a few orders of magnitude, the effect of μ_ν can be safely neglected, even if the neutrinos travel through the size of the visible universe.

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1. Introduction

The nonzero mass of neutrinos gives rise to small but nonzero magnetic moment (μ_ν). In a magnetic field, the left-handed neutrinos can be converted to right-handed ones owing to μ_ν where these right-handed neutrinos escape without being detected. In the standard model, we expect μ_ν to be $10^{-20}\mu_{\rm B}$ [1]. Various new physics models predict several orders of magnitude higher value of μ_ν. The current experimental upper limit on magnetic moment is $\mu_\nu \sim 10^{-11}\mu_{\rm B}$ [2, 3]. If neutrinos possess a magnetic moment, then while passing through a magnetic field its spin may get flipped. This converts left-handed neutrinos to right-handed ones. In addition to the natural flavor oscillations, we have this phenomenon called spin-flavor oscillation (SFO). Neutrinos traversing through very large distances encounter the underlying intergalactic magnetic field, which can be of the order of μG or less [4]. Under the influence of such a magnetic field, active neutrinos may also turn into sterile neutrinos via SFO[5, 6]. We deduce the condition for averaging out, which halves the active neutrino flux. This phenomenon would affect the captured neutrino flux in the upcoming experimental setups. It turns out that if the upper limit on μ_ν improves by several orders of magnitude, the flux would remain unaffected even for the neutrinos traversing through a length scale of the visible universe [5].

2. Methodology

The Dirac equation governing the evolution of neutrinos in the presence of an external magnetic field $\boldsymbol{B}$ is given as [7],

$$(\gamma_\mu p^\mu - m_i - \mu_i \boldsymbol{\Sigma B})\nu_i^s(p) = 0,$$

where ν_i^s is the wave function of i-th mass eigenstate (with mass m_i) of neutrinos with $s\,(=\pm 1)$ being the eigenvalues of the spin operator

$$\hat{S}_i = \frac{m_i}{\sqrt{m_i^2 \boldsymbol{B}^2 + \boldsymbol{p}^2 \boldsymbol{B}_\perp^2}} \left[\boldsymbol{\Sigma B} - \frac{i}{m_i}\gamma_0\gamma_5 [\boldsymbol{\Sigma} \times \boldsymbol{p}]\boldsymbol{B} \right]$$

and μ_i is the magnetic moment of the same mass eigenstate. The SFO probabilities can be obtained from the stationary states of neutrinos in the magnetic field. The SFO probability can be written in a generic form as,

$$P_{\alpha\beta}^{hh'}(x) = |\langle \nu_\beta^{h'}(0)|\nu_\alpha^h(x)\rangle|^2\,,$$

For a neutrino flux traversing a very large distance, the probability is averaged out to,

$$P_{\alpha\beta}^{hh'}(x) = \delta_{\alpha\beta}\delta_{hh'} - 2\sum_{\{i,j,s,s'\}} \mathrm{Re}([A_{\alpha\beta}^{hh'}]_{i,j,s,s'})\,,$$

where $[A_{\alpha\beta}^{hh'}]_{i,j,s,s'} = U_{\beta i}^* U_{\alpha i} U_{\beta j} U_{\alpha j}^* (C_{is}^{h'h})(C_{is}^{h'h})^*$, $C_{is}^{h'h} = \langle \nu_i^{h'}|\hat{P}_i^s|\nu_i^h\rangle$ and U's are the PMNS matrix elements.

In the presence of omnipresent intergalactic magnetic field, the active neutrinos from a source at an astronomical distance can get converted into right-handed ones and vice versa. The active neutrino flux on Earth from a very distant source can be obtained as,

$$\Phi_\beta^\oplus = \sum_\alpha P_{\alpha\beta}^{LL}\Phi_\alpha^s,$$

where $\Phi^{\oplus}$ and Φ^{s} are the flux on Earth and at the source, respectively.

3. Results

We find that half of the active neutrinos become neutrinos while traversing large distances which leads to $\Phi_{\beta}^{\oplus SF} = \frac{\Phi_{\beta}^{\oplus F}}{2}$ for each of the flavor [5], where F denotes the usual flavor oscillations of neutrinos and SF represents the spin-flavor oscillation. However, this averaging is subjected to a large number of SFOs. The phase of SFO depends on both of the phases of vacuum oscillations ($\phi_\nu = \frac{\Delta m_{ij}^2}{2p} x$) and that due to the magnetic field $\phi_B = \mu(s - s')B_\perp x$. The probability is the sum of terms like $(\sin^2 \phi_\nu)(\sin^2 \phi_B)$, which forms a modulated waveform. Thus, the oscillation length corresponding to each of them is given by $l_\nu = \frac{\pi}{\omega_\nu}, \quad l_B = \frac{\pi}{\omega_B}$. Thus, the completion of a cycle will depend on which phase of the oscillations forms the envelope. Whichever of the two has a smaller frequency can be treated as the envelope of the modulated waveform. The oscillation lengths are shown in Fig. 1.

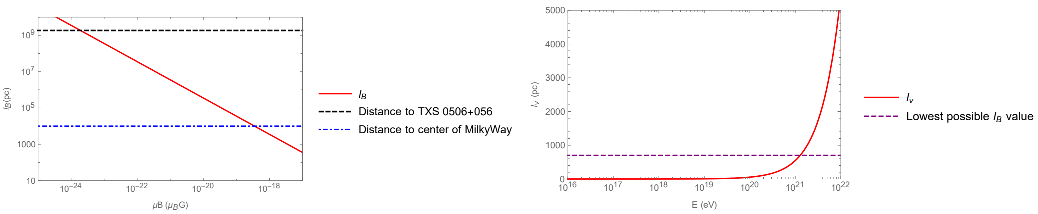

Figure 1: The plot on the left illustrates the variation of l_B with μB, whereas the one on the right shows the variation of vacuum oscillation length with energy.

The probability can be averaged out only if the number of SFOs, $n = \frac{x}{l_{\nu/B}} \gg 1$. We consider $n = 100$ (at least) as the condition to average out the probability i.e. the source must be situated at least at a distance $d_{\min} = 100\, l_B$. The parameter space of μ_ν and B for such averaging out to be possible for different distances are shown in the left plot Fig.2. For a neutrino flux sourced within the Milky Way, averaging out the SFO probabilities is only possible if $\mu B > 10^{-17}\, \mu_B$G (since $d_{\min} > 100\, l_B$). This is allowed only by a small region of parameter space, as shown in the right plot of Fig.2. As can be inferred from Fig.2, if the experimental upper limit on neutrino magnetic moment improves to $\mu_\nu \sim 10^{-13} \mu_B$, then the neutrino flux in the future experiments will be shielded from the SFO effect.

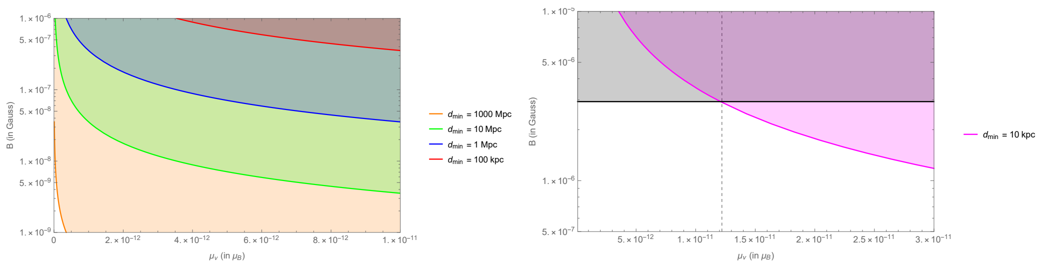

Figure 2: The plot on left shows the parameter space of the allowed values of μ_ν and B for different distances whereas the one on right depicts the same for the sources located within the Milky Way galaxy.

4. Conclusions

We find that the neutrinos under SFO in the intergalactic magnetic field maintain an unchanged flavor ratio, but their flux may reduce by half if they complete a substantial number of SFO cycles. Using the current limit on μ_ν and magnetic field ranging from μG to nG, we find that the condition for averaging out the probability is satisfied for the neutrino sources lying at a distance of several kpcs from the Earth. On the other hand, the condition for averaging out for the sources lying within the Milky Way is possible only for a small region of the allowed parameter space. We discover that if the current bound on μ_ν gets two orders of magnitude better, the condition for averaging out can only be met at larger distances. Also, the cosmic neutrino flux cannot be lowered, even if the neutrinos travel through the entire length of the visible universe.

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