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Sterile neutrinos, dark matter, and resonant effects in ultra high energy regimes

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ABSTRACT

Interest in light dark matter candidates has recently increased in the literature; some of these works consider the role of additional neutrinos, either active or sterile. Furthermore, extragalactic neutrinos have been detected with energies higher than have ever been reported before. This opens a new window of opportunities to the study of neutrino properties that were unreachable up to now. We investigate how an interaction potential between neutrinos and dark matter might induce a resonant enhancement in the oscillation probability, an effect that may be tested with future neutrino data.

1. Introduction

It is well known that neutrinos propagating through a material medium experience an enhancement effect in the oscillation probability, the so-called MSW effect [1]. The standard MSW effect takes into account the interaction of active neutrinos with electrons and quarks.

However, the oscillation of standard flavor neutrinos into non-standard sterile neutrinos has been considered in previous works [2] as, e.g., an explanation for the reactor neutrino anomaly [3], for the LSND and MiniBooNE experimental results [4], in the context of primordial nucleosynthesis [5–10], and in supernovae [11]. In addition, sterile neutrinos appear in models attempting to explain the dark matter problem [12], either as the main component for the dark matter content or as an additional subleading component of a multiparticle dark matter model. Couplings between neutrino, either active or sterile, and dark matter have also been studied in many different contexts [13–24].

We propose that, if there is a mixing between active and sterile neutrinos, high-energy neutrinos interacting with dark matter may suffer a kind of MSW effect when they propagate in a dark matter medium. We show that if there is an interaction of neutrinos with dark matter, their corresponding potential might induce a resonant effect, in just the same way as active neutrinos are affected by the interaction with the electrons of a medium.

2. Dark matter and resonant effects

We begin our analysis by showing the neutrino evolution equation, which includes both ordinary and dark matter potentials. We study a simplified picture with one sterile neutrino, ν_s, and an active one, ν_α. For a neutrino energy, E, the evolution equation can be written as

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_\alpha\\ \nu_s\end{pmatrix} = \mathrm{M}_\alpha \begin{pmatrix}\nu_\alpha\\ \nu_s\end{pmatrix}, \tag{1}$$

with

$$\mathrm{M}_\alpha = \begin{pmatrix} -\frac{\Delta m^2_{i4}}{4E}\cos 2\theta_0 + V_{\nu_\alpha f} + V_{\nu_\alpha \chi} & \frac{\Delta m^2_{i4}}{4E}\sin 2\theta_0 \\ \frac{\Delta m^2_{i4}}{4E}\sin 2\theta_0 & \frac{\Delta m^2_{i4}}{4E}\cos 2\theta_0 + V_{\nu_s \chi} \end{pmatrix}, \tag{2}$$

where $\Delta m^2_{i4} = m^2_4 - m^2_i$, and the angle θ_0 is the vacuum mixing angle between the sterile and the active neutrino; $V_{\nu_\alpha f} = V^{CC}_{\nu_\alpha f} + V^{NC}_{\nu_\alpha f}$ accounts for the well-known interaction potential of the active neutrino with ordinary fermions; $V_{\nu_\alpha \chi}$ takes into account the potential due to a possible interaction between active neutrinos and dark matter. In this work, we also investigate the effect of the potential $V_{\nu_s \chi}$, coming from the interaction of sterile neutrinos with dark matter. This interaction naturally appears in

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different extensions of the Standard Model, where many dark particles, including sterile neutrinos, could populate the dark sector and interact among themselves [19,20,25]. The interaction potential $V_{\nu_s f}$ has already been studied [26] and is negligible compared to the other potentials in Eq. (2). Therefore, we do not include it in our calculations.

The resonance condition derived from Eq. (1) is then given by

$$\Delta m^2_{i4}\cos 2\theta_0 = 2E(V_{\nu_\alpha f} + V_{\nu_\alpha\chi} - V_{\nu_s\chi}). \quad (3)$$

We can write these potentials as follows:

$$V_{\nu_\alpha f} = \frac{1}{4}\frac{g^2}{m_W^2}(N_\alpha - N_n/2) = \sqrt{2}G_F(N_\alpha - N_n/2); \quad (4)$$

$$V_{\nu_\alpha\chi} \sim \frac{g_{\nu_\alpha} g_\chi}{m_I^2}N_\chi = G'_{\nu_\alpha}N_\chi = \varepsilon_{\nu_\alpha\chi}G_F N_\chi; \quad (5)$$

$$V_{\nu_s\chi} \sim \frac{g_{\nu_s} g_\chi}{m_I^2}N_\chi = G'_{\nu_s}N_\chi = \varepsilon_{\nu_s\chi}G_F N_\chi, \quad (6)$$

where N_α, N_n, and N_χ are, respectively, the number density of leptons, neutrons, and dark matter particles interacting with neutrinos. In Eq. (4), g is the Standard Model coupling constant and m_W is the W boson mass; while, g_{ν_α}, g_{ν_s}, and g_χ represent the coupling constants of the corresponding particle (active neutrino, sterile neutrino, and dark matter) with an intermediate gauge boson with mass m_I. The parameters $\varepsilon_{\nu_{\alpha,s}\chi}$ account for the coupling strength in terms of the Fermi constant G_F.

Using the above expressions for the potentials, the resonance condition is written as

$$\Delta m^2_{i4}\cos 2\theta_0 = 2EG_F[\sqrt{2}(N_\alpha - N_n/2) + (\varepsilon_{\nu_\alpha\chi} - \varepsilon_{\nu_s\chi})N_\chi]. \quad (7)$$

The standard contribution to this equation, $V_{\nu_\alpha f} = \sqrt{2}G_F(N_\alpha - N_n/2)$, is zero for the case of electron neutrinos, considering an astrophysical environment with $N_e \approx N_n/2$, and $V_{\nu_{\mu,\tau}f} = -\sqrt{2}G_F N_n/2$ for muon and tau neutrinos ($N_\mu \approx N_\tau \approx 0$). In practice, $V_{\nu_{\mu,\tau}f}$ will be negligible in comparison with the new contributions from $V_{\nu_\alpha\chi}$ and $V_{\nu_s\chi}$ and, therefore, our results will apply to any of the three active neutrino species. For the estimate of the dark matter number density, N_χ, we consider that the main contribution arise from a single heavy dark matter particle with mass m_χ and, therefore, the relevant density in our case will take the value $N_\chi = \rho_\chi/m_\chi$.[2] To estimate $\varepsilon_{\nu_{\alpha,s}\chi}$ we need to study in detail the coupling constants $g_{\nu_\alpha,\nu_s,\chi}$. Recently, the interest in models with an intermediate boson with a relatively light mass m_I has grown, especially in the context of the dark matter problem [14–18,21]. We show in Table 1 an incomplete list of values for $\varepsilon_{\nu_{\alpha,s}\chi}$ in these types of models. Notice that the coupling of active neutrinos with dark matter can be strongly constrained ($g_\chi g_\nu \sim 10^{-6}$ [16,17]) while for the sterile case the constraints are weaker, as should be expected.

3. An application

We now turn our attention to the search for physical processes that could be sensitive to the effects of the ν–χ interaction potential, trying to shed some light in the study of two hidden sectors: sterile neutrino and dark matter sectors.

Table 1
Coupling constants and mass estimates from different models.

Ref.	$\frac{(g_\chi)(g_\nu)}{(m_I/[\mathrm{MeV}])^2}$	$\varepsilon_{\nu_e\chi}$	$\varepsilon_{\nu_s\chi}$	$\frac{m_\chi}{[\mathrm{MeV}]}$
Aarssen et al. [14]	$\frac{(0.7)(10^{-6}-10^{-1})}{10^{-2}-1}$	0	10^5–10^{15}	10^6
Mirror [19,20]	$\frac{(1)(1)}{(30m_W)^2}$	0	10^{-3}	10^3
Fayet [16,17]	$< \frac{10^{-6}}{1}$	$< 10^5$	0	10
Mangano et al. [15]	$< \frac{10^{-3}}{1}$	$< 10^8$	0	10

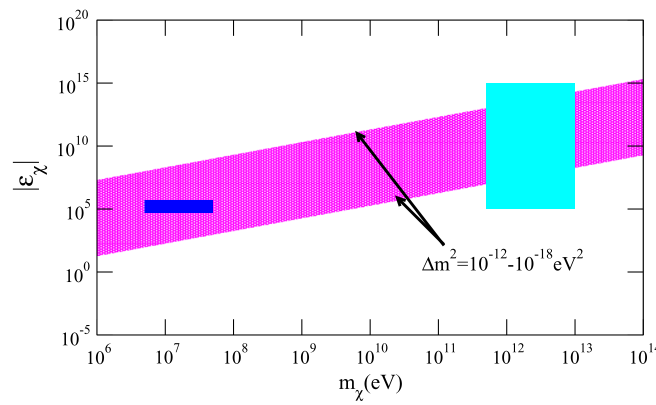

Fig. 1. Coupling strength $|\varepsilon_\chi|$ and dark matter mass m_χ corresponding to oscillation resonance for active neutrinos with energy $E = 10^{15}$ eV and Δm^2 in the range from 10^{-18} eV^2 up to 10^{-12} eV^2, propagating in the vicinity of our galaxy. In this plot we have considered the limit case of a vanishing mixing angle θ_0. As a matter of comparison, we plot different models considered in the literature. In the left dark blue box are those of Fayet [16,17] and in the right light blue box is Aarssen et al. [14]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In order to find the conditions in which an oscillation resonance can take place according to Eq. (7), we compute the values of Δm^2 (from now on we omit the subscript $i4$ from Δm^2_{i4}), $\varepsilon_\chi = (\varepsilon_{\nu_\alpha\chi} - \varepsilon_{\nu_s\chi})$, and m_χ that induce such an effect. We present our results in Fig. 1 for the parameter space $|\varepsilon_\chi|$ vs m_χ in a range of Δm^2 values, taking as a first approximation $\theta_0 \approx 0$. Notice that ε_χ changes sign depending on which coupling is stronger: whether it is $\varepsilon_{\nu_\alpha\chi}$ or $\varepsilon_{\nu_s\chi}$. Therefore, the resonance condition is valid only for neutrinos (if $\varepsilon_{\nu_\alpha\chi} > \varepsilon_{\nu_s\chi}$) or for antineutrinos (if $\varepsilon_{\nu_s\chi} > \varepsilon_{\nu_\alpha\chi}$).

We have conducted an analysis considering the dark matter around our galactic halo, where, on average, the electron density can be approximately $N_e = 3\times 10^{-16}$ eV^3 [27] and it is expected that $\rho_\chi = 0.3$ GeV cm^{-3} [28]. We compute our result for a fixed neutrino energy of $E = 10^{15}$ eV. In particular, we show a tilted band that corresponds to the range 10^{-18} eV$^2 < \Delta m^2 < 10^{-12}$ eV^2, that was previously studied in a similar context, although for pseudo-Dirac oscillations [29–34]. In the same Fig. 1, we also plot the space of parameters $|\varepsilon_\chi|$-m_χ obtained from the work of Aarssen et al. [14] (light blue box on the right). These authors discussed the possibility of an interaction between dark matter and neutrinos in order to address ΛCDM small-scale problems. We consider the couplings discussed in this article as a guidance for a sterile neutrino coupling with dark matter. Finally, for the interaction between active neutrinos and dark matter, we plot the space of parameters (dark blue box on the left) constrained in Refs. [16,17].

It is quite interesting that this Δm^2 range is consistent with an oscillation resonance for coupling constants and masses for dark matter candidates proposed in other articles, especially because it has already been noticed that a pseudo-Dirac oscillation could lead to an UHE neutrino flux deficit [29]. If the dark matter surrounding our galaxy induces such a resonance effect there could be an energy range where active neutrinos convert to sterile neutrinos.

[2] It is possible that in some models the heaviest dark particle is different from the particles interacting with the sterile neutrinos, however, we would expect the number density to be approximately equal; an example in this direction could be a mirror model where the interacting particle is a mirror electron and the heaviest dark matter particle is a mirror proton.

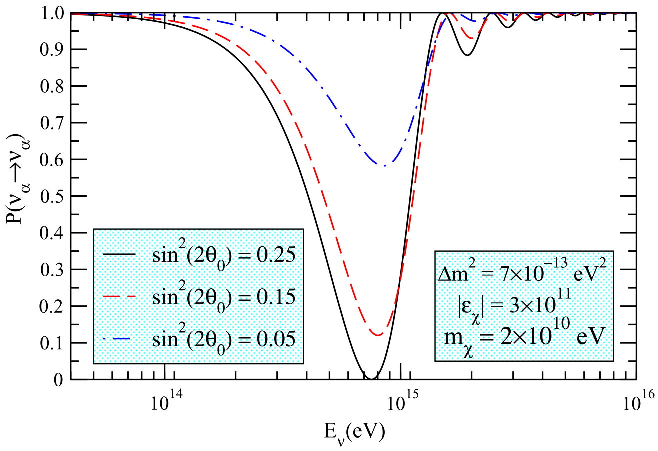

Fig. 2. Survival probability $P(\nu_\alpha \to \nu_\alpha)$ as a function of the neutrino energy E_ν, considering the galactic halo average dark matter density.

This would cause an important change in the neutrino flux spectrum, as long as the source is extragalactic.

Several constraints on the UHE neutrino flux, coming from Auger [35] and ANTARES [36] have been reported, and a bound on neutrinos from gamma ray bursts has also been presented by Icecube [37]. Recently, Icecube also reported the detection of neutrinos coming from extraterrestrial sources: The first report presented the detection of two electron neutrino events with energies around PeV [38], while a later report presented data on the detection of 26 neutrino events in the range of 30–300 TeV [39]. The detection of 37 events in three years of data collection was presented in [40]. Additional research is needed in order to develop a more complete understanding of this data [41].

With the accumulation of data from IceCube, Auger, and future telescopes as the KM3Net, we would have a better understanding of the galactic and extragalactic neutrino spectrum. In this context, we would like to study if the interaction potential between neutrino and dark matter that we propose might induce an oscillation resonance in the UHE regime. If the experiments collect sufficient data, it might be possible to observe the MSW mechanism for dark matter as a distortion in the UHE neutrino spectrum.

Additionally, instead of considering the limit of a vanishing mixing angle, we compute the survival probability for active neutrinos as:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2(2\theta_m)\sin^2\left(\pi \frac{L_0^{osc}}{L_m^{osc}}\right). \quad (8)$$

In this expression

$$\sin^2(2\theta_m) = \frac{\sin^2(2\theta_0)}{\cos^2(2\theta_0)\left(1 - \frac{(V_{\nu_\alpha\chi} - V_{\nu_s\chi})}{V_R}\right)^2 + \sin^2(2\theta_0)}, \quad (9)$$

where $V_R = \frac{\Delta m^2}{2E}\cos(2\theta_0)$. And the oscillation length in matter is given by

$$L_m^{osc} = \frac{L_0^{osc}}{\sqrt{\cos^2(2\theta_0)\left(1 - \frac{V_{\nu_\alpha\chi} - V_{\nu_s\chi}}{V_R}\right)^2 + \sin^2(2\theta_0)}}. \quad (10)$$

We have computed the survival probability, for different values of $\sin^2(2\theta_0)$, for the case in which the neutrino squared mass difference is given by $\Delta m^2 = 7 \times 10^{-13}$ eV^2, with a coupling $|\varepsilon_\chi| = 3 \times 10^{11}$, and a dark matter mass $m_\chi = 2 \times 10^{10}$ eV. We found the resonant energy around $E = 8 \times 10^{14}$ eV, as shown in Fig. 2. From this figure we see that a mixing of the order $\sin^2(2\theta_0) = 0.25$ could give a maximal conversion with a wide energy window. These values also make an effective oscillation length possible in conformity with the expected dark matter halo dimension [42], as the oscillation length in dark matter may be given by $L_m^{osc} = \frac{4\pi E}{\sin(2\theta_0)\Delta m^2} \sim 10^{18}$ km.

Although this suggests that the high energy spectrum of extragalactic neutrinos could be affected by the existence of sterile neutrino and its interaction with dark matter, a more detailed study must be conducted. For instance, in order to have an MSW resonance, other conditions must be fulfilled [2], like the adiabaticity condition. We start from the definition of the adiabaticity parameter [43]:

$$\gamma = \frac{(\Delta m_{\rm m}^2)^2}{2E\sin(2\theta_m)|dA_{cc}/dr|}, \quad (11)$$

where

$$\sin(2\theta_m) = \Delta m^2 \sin 2\theta_0/\Delta m_{\rm m}^2, \quad (12)$$

$$\Delta m_{\rm m}^2 = \sqrt{(\Delta m^2\cos 2\theta_0 - A_{cc})^2 + (\Delta m^2 \sin 2\theta_0)^2}, \quad (13)$$

and, in our case,

$$A_{cc} = 2E(V_{\nu_\alpha f} + V_{\nu_\alpha\chi} - V_{\nu_s\chi}) \simeq 2E\varepsilon_\chi G_F N_\chi. \quad (14)$$

It is possible to note that the adiabaticity condition can be expressed as

$$\gamma = \frac{((\Delta m^2\cos 2\theta_0 - 2E\varepsilon_\chi G_F N_\chi)^2 + (\Delta m^2 \sin 2\theta_0)^2)^{3/2}}{4E^2\Delta m^2 \sin 2\theta_0 \varepsilon_\chi G_F |dN_\chi/dr|} >> 1. \quad (15)$$

This condition is satisfied for the case of a constant density dark matter distribution. Another important condition to be fulfilled, in order to have significant conversion probability, is that the width d of dark matter [2], should be larger than a minimum width d_{min}. Following closely Ref. [2], in our analysis, this condition is given by

$$d = \int N_\chi(L)dL \geq d_{min} = \frac{1}{|\varepsilon_\chi|G_F \tan 2\theta_0}, \quad (16)$$

where L denotes the distance traveled by the neutrino in the dark matter medium. Taking into account the parameters considered for Fig. 2, that is $|\varepsilon_\chi| = 3 \times 10^{11}$ and $\sin^2(2\theta_0) = 0.25$, we obtain $d_{min} = 1.3 \times 10^{21}$ cm^{-2}, while, for a dark matter halo of 6×10^{18} km, $d = 9 \times 10^{21}$ cm^{-2}. This shows that the width of dark matter is approximately one order of magnitude bigger than the minimum width, making the conversion from active to sterile neutrinos possible.

Although it is promising that these resonance conditions [2] are satisfied for a constant distribution, it would be necessary to study the case of a more realistic dark matter profile. In order to obtain a first estimate, we consider a halo density of the form

$$\rho(r) = \frac{\rho_0}{(r/R)^\delta[1 + (r/R)^\alpha]^{(\beta-\delta)/\alpha}}, \quad (17)$$

where α, β, δ, and R (in kpc) depend on the specific model to be considered [44]. We have computed the adiabaticity parameter for the widely known profiles of Navarro, Frenk, White [45] ($\alpha = 1$, $\beta = 3$, $\delta = 1$ and $R = 20$ kpc), Kravtsov et al. [47] ($\alpha = 2$, $\beta = 3$, $\delta = 0.4$ and $R = 10$ kpc), Moore et al. [48] ($\alpha = 1.5$, $\beta = 3$, $\delta = 1.5$ and $R = 28$ kpc), and for the modified isothermal profile [46] ($\alpha = 2$, $\beta = 2$, $\delta = 0$ and $R = 3.5$ kpc). We found that the three resonance conditions are satisfied for all the profiles if we consider a dark matter mass of the order of 100 MeV, the same parameter for neutrino mass difference, $\Delta m^2 = 7 \times 10^{-13}$ eV^2, the coupling $|\varepsilon_\chi| = 3 \times 10^{11}$, and a neutrino energy $E = 10$ TeV. For these parameters, in the case of the Navarro, Frenk and White profile, the minimum value of the adiabaticity parameter is $\gamma \approx 13$ and the resonance is located around 18 kpc from the galactic center. The dark matter width is $d = 1.3 \times 10^{23}$ cm$^{-2} > d_{min}$. These results are encouraging and suggest that a wider region of parameters, satisfying the resonance conditions, could be found by conducting a detailed study for these profiles.

4. Conclusions

In summary, in this work we have studied the possibility that neutrinos might have a resonant effect in the presence of additional sterile neutrino states and dark matter. We have conducted an analysis of the necessary couplings of dark matter with either active or sterile neutrinos in order to have such an effect. Our results show that, if the phenomenological models discussed here happen in nature, they may induce a resonant oscillation of high energy active to sterile neutrinos. We have shown values of Δm^2_{i4} where there could be a resonant effect for an adequate range of neutrino couplings and dark matter mass. The mechanism discussed here could be tested with future ultra high energy neutrino data, for instance, from the IceCube experiment.

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