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A reduction in the UHE neutrino flux due to neutrino spin precession

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ABSTRACT

Motivated by the stringent flux limits for UHE neutrinos coming from gamma ray bursts or active galactic nuclei, we explore the possibility that the active neutrinos generated in such astrophysical objects could oscillate to sterile right handed states due to a neutrino magnetic moment μ_ν. We find that a value as small as $\mu_\nu \approx 10^{-15}\mu_B$ could produce such a transition thanks to the intense magnetic fields that are expected in these objects.

In recent years the observation of very distant astrophysical sources, such as Active Galactic Nuclei (AGN) and Gamma Ray Bursts (GRB), has improved notoriously. Now we have a better knowledge of these objects, despite the fact that there is still a lot of puzzles to be unraveled. It is a general belief that GRBs and AGNs provide a mechanism for the acceleration of the most energetic cosmic rays that have been detected so far. One of the reasons for this belief are the strong magnetic fields inside these objects, that may accelerate protons and heavier nuclei up to the highest energy range of the spectrum of the cosmic radiation [1,2]. Currently, cosmic rays with energies as high as 10^{20} eV have been detected at different experiments on Earth. However, there is a limit for protons with energies above 10^{20} eV to travel distances larger than 100 Mpc [3] and, therefore, there is no physical chance to obtain direct information about the most distant sources from ultra-high energy protons, as has been confirmed by HiRes [4] and the Pierre Auger Observatory [5].

In principle, this limitation do not apply to neutrinos and it would be expected that, at energies around 10^{18} eV it would be possible to observe neutrinos coming from extragalactic sources and obtain, at least in principle, direct information from their original source. This has been one of the main motivations of the IceCube experiment [6]. Recent reports from several experiments, however, show negative results in the search for extragalactic neutrinos, giving upper limits for a diffuse or for point source neutrino fluxes [7–10]. Although it could be possible that in future, with more statistics, a positive detection and a determination of the UHE neutrino flux could be established, we think that it is a good time to search for possible alternative explanations to the absence or reduction in the flux of neutrinos. There have been efforts to understand effects on the neutrino flux and other cosmological observables, such as the CMB power spectrum, by considering an interaction of the neutrino with a Dark Matter candidate. However, most of these attempts lead to small effects [11–16]. The main problem to explain a suppression in the neutrino flux due to this kind of interaction is that the neutrino-Dark Matter expected cross section is too small to play an important role, except for the case of an ultra-light scalar field ($m_\phi \sim 10^{-23}$–10^{-33} eV) where the small cross section is compensated by the large amount of DM particles [17].

Here we focus on a different approach that may be simpler and physically appealing: the case of a spin flip of the neutrino due to a nonzero neutrino magnetic moment. In the Standard Model (SM), the neutrino magnetic moment is expected to be extremely small [18–20]:

$$\mu_\nu = \frac{3G_F m_e m_\nu}{4\sqrt{2}\pi^2} = 3.2 \times 10^{-19}\left(\frac{m_\nu}{[\text{eV}]}\mu_B\right). \tag{1}$$

However, motivated by the solar neutrino problem, it was noticed that a relatively large neutrino magnetic moment could play a role in neutrino conversion inside the Sun. The most successful

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mechanism in this direction was the well-known Resonant Spin Flavor Precession (RSFP) [21] where an oscillation $\nu_e \to \bar{\nu}_{\mu,\tau}$ may occur. Despite RSFP was not able to be a solution of the solar neutrino problem [22] it motivated several theoretical efforts to construct models beyond the SM that could explain a large value of the neutrino magnetic moment [23–25]. This same mechanism had also been applied in the past to the case of UHE cosmic rays [26,27], mainly motivated by the possibility to detect tau neutrinos appearing from oscillation during the neutrino propagation in cosmological distances [28]. Tau neutrinos could be identified by very unique signatures such as double bang events [29,30] and Earth skimming [31]. At present, thanks to a remarkable experimental effort, there are limits to the neutrino magnetic moment as strong as $\mu_\nu \leqslant 10^{-11}\mu_B$ coming from laboratory measurement [32,33] or from a combined analysis [34], and $\mu_\nu \leqslant 10^{-12}\mu_B$ from astrophysical observations [35] or from solar data [36].

Given the nonobservation until now of UHE neutrinos, our main goal in the study of spin flip neutrino conversion due to a neutrino magnetic moment will be the transition from an active electron neutrino (presumably produced in an extragalactic object such as an AGN or a GRB) into a right handed sterile neutrino. Such a conversion may take place in different scenarios. We can consider in the first place the case of a conversion due to a diagonal magnetic moment that converts the active electron neutrino into a right handed sterile electron neutrino. This case had been considered as a possible explanation of the solar neutrino problem long time ago [37] and the conversion probability in this case is given by

$$P(\nu_{e_L} \to \nu_{e_R}; r) = \sin^2\left(\int_0^r \mu_\nu B_\perp(r')\,dr'\right). \tag{2}$$

As has been noticed before [38,39] there is a possibility in this picture that a neutrino flux can be fully converted into sterile neutrinos if the condition[1]

$$\mu_\nu B_\perp r \approx \frac{\pi}{2} \tag{3}$$

is satisfied.

Considering the vast range of both magnetic field intensities and sizes of the astrophysical objects it would be not a surprise that, for a reasonable value of the neutrino magnetic moment, there will be astrophysical objects that could induce a spin conversion, while for an unsuitable combination of this values the effect will not be valid (otherwise this will be a fine tuning).

Therefore, if future experimental results continue reporting no observation of neutrinos for certain objects, or for certain neutrino flavors, this could be a clue for a Dirac magnetic moment. On the other hand the future experimental results should give, at the same time, positive neutrino signals for astrophysical objects that do not fulfill the requirements of Eq. (3).

We show in Fig. 1 the regions in the B–r plane that satisfy the above condition for a diagonal neutrino magnetic moment of $10^{-12}\mu_B$, $10^{-14}\mu_B$, and $10^{-15}\mu_B$. Inspired by the Hillas Plot [1], we also show in the same figure the astrophysical objects that lie in such regions. For a given neutrino magnetic moment, the astrophysical objects lying in the corresponding curve may induce a neutrino transition into a sterile state. In this picture, a relatively small neutrino magnetic moment, e.g., of the order of $\mu_\nu = 10^{-15}\mu_B$, could produce an efficient conversion into sterile states in the case of GRB, an interesting feature considering the recent limit for the neutrino flux coming from such objects [7]. Note that a higher neutrino magnetic moment around $10^{-14}\mu_B$, could induce the same effect for an AGN; in this case, there could be a very efficient mechanism for the suppression of neutrinos coming from the AGN, since the condition of Eq. (3) would be satisfied, while the flux for a GRB would only be suppressed by a factor one half due to the high value of μ_ν; as mentioned above, in this case a future positive signal of GRB neutrinos combined with a negative result for AGN could be a hint for a nonzero neutrino magnetic moment of the order of $10^{-14}\mu_B$. Note also that, at least in first approximation, the weak magnetic field in the galactic halo and intergalactic medium may also produce a spin conversion given the long distance traveled by the neutrino flux.

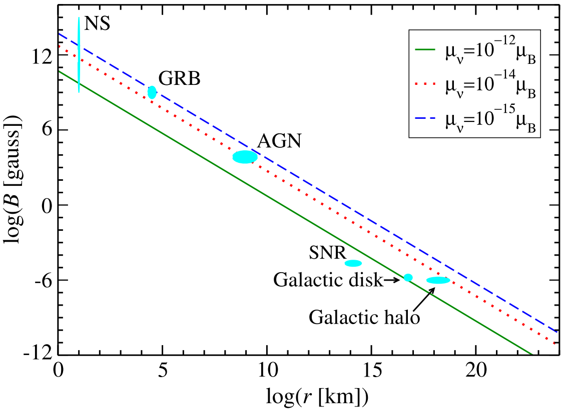

Fig. 1. Relation of magnetic field B and size r of astrophysical sources for an efficient neutrino spin transition $\nu_{e_L} \to \nu_{e_R}$. The curves show different values of the neutrino magnetic moment. The acronyms refer NS for Neutron Stars, GRB for Gamma Ray Bursts, AGN for Active Galactic Nuclei, and SNR for Supernova Remnants.

Table 1
Comparison of the expected electron density versus the product of a $10^{-14}\mu_B$ neutrino magnetic moment times the magnetic field of the astrophysical source.

Source	V_e (eV)	μB (eV)
GRBs [43]	2×10^{-34}	10^{-13}
AGNs [44]	10^{-27}	6×10^{-20}
SNRs [45]	10^{-37}	10^{-28}
Galactic Disk [46]	5×10^{-39}	5×10^{-29}

We believe that, given the fact that there has been no observation of neutrinos coming from AGNs or GRBs, it would be important to consider this mechanism in more detail. Besides the detailed comparison with the experimental results, it would also be important to consider matter effects [40,41], that might diminish the mechanism. For constant density matter the conversion probability in this case will be given by [38,40–42]

$$P = \frac{(2\mu_\nu B_\perp)^2}{V_e^2 + (2\mu_\nu B_\perp)^2}\sin^2\left(\frac{1}{2}\sqrt{V_e^2 + (2\mu_\nu B_\perp)^2}\,r\right). \tag{4}$$

With $V_e = \sqrt{2}G_F(N_e - N_n/2)$, G_F the Fermi constant, and $N_{e,n}$ the electron and neutron densities. It is possible to see from this formula that a high value of the potential V_e would suppress the spin conversion. This is not the case for an AGN or a GRB. We show in Table 1 the approximate expected values of the potential, considering only the N_e contribution, and compare them with the product of the neutrino magnetic moment and the expected magnetic field strength at the source. One can see that the potential is always negligible.

Another important mechanism to consider would be a *spin flavor* precession into a different sterile neutrino flavor. In this last case we consider the evolution equation

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[1] For a constant magnetic field.

$$i\begin{pmatrix}\dot{\nu}_{e_L}\\ \dot{\nu}_{x_R}\end{pmatrix}=\begin{pmatrix}V_e-\delta & \mu_\nu B_+\\ \mu_\nu B_- & \delta\end{pmatrix}\begin{pmatrix}\nu_{e_L}\\ \nu_{x_R}\end{pmatrix}, \qquad (5)$$

where μ_ν denotes now a neutrino transition magnetic moment [47], $B_\pm = B_x \pm iB_y$ and $\delta = (\Delta m^2/4E_\nu)\cos 2\theta$ with Δm^2 the neutrino mass difference parameter, θ the corresponding neutrino mixing angle and E_ν the neutrino energy. Finally, x may denote a μ or τ neutrino or even a new sterile state, in which case we are not constrained to the squared mass differences of the active neutrino states and, therefore, we could have more room to consider a sterile neutrino even in the range of keV. However, it is important to note that in this case the conversion probability will depend also on the mass square difference [21,38]:

$$P_{\nu_{eL}\to\nu_{xR}} = \frac{(2\mu_\nu B_\perp)^2}{(2\delta - V_e)^2 + (2\mu_\nu B_\perp)^2} \times \sin^2\left(\frac{1}{2}\sqrt{(2\delta - V_e)^2 + (2\mu_\nu B_\perp)^2}\,r\right). \qquad (6)$$

From this expression, and comparing for the case of GRBs ($E_\nu \approx 10^{15}$ eV) or AGNs ($E_\nu \approx 10^{18}$ eV), it is possible to see that even in the case of the standard neutrino mass differences ($\Delta m^2_{13} = 7.6 \times 10^{-5}$ eV^2 and $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2 [48]) the value of δ gets closer to the product $\mu_\nu B_\perp$ and, consequently, it is in the limit to suppress the conversion mechanism, while a conversion into a heavier sterile neutrino, such as a keV neutrino, will be certainly suppressed. Finally, considering a random magnetic field, instead of the regular case that we have discussed, is of no help in this case since it has been shown that in this case the conversion probability into a sterile state is at most of one half [49].

In the present day there are several experiments, like IceCube and the Auger Observatory, expecting to detect extragalactic neutrinos. Until now, neutrinos with energy above 10^{15} eV, coming from extragalactic sources, have not been detected. Based on the nonobservation of extragalactic neutrinos, AGN [44,50–54] and GRB [55–58] models that predict high observable neutrino fluxes could be excluded, but with the mechanism of neutrino flavor conversion that we have discussed, this apparent contradiction may not exist. The neutrinos could be generated in the sources but converted into sterile neutrinos due to the strong magnetic fields that prevails in those environments.

In this work we have stressed the possibility of an efficient transition of the neutrinos into a right handed sterile neutrinos due to a nonzero magnetic moment and due to the presence of strong magnetic fields both in GRBs as well as in AGNs. We consider this is an interesting mechanism that could be studied in more detail as more experimental results appear. If the current tendency of getting strong limits on the UHE neutrino flux continues, this could be a hint for a nonzero neutrino magnetic moment effect, while a positive observation could put a stronger limit on μ_ν. Moreover, in this picture it would be natural that different objects could produce different reduction rates, providing a way to test the mechanism if future experimental results could detect neutrinos from different sources.

Note added

After the first version of this work, other articles have discussed different mechanisms that could also lead to a neutrino flux suppression [59,60]. Besides, they also discussed the recent claim of a possible detection of electron neutrinos by IceCube (while no muon neutrinos have been yet detected) [61]. We would like to note that, if these were the case, the mechanism discussed here could also work, for instance, with a vanishing neutrino magnetic moment for electron neutrinos and, for ν_μ case, a magnetic moment value of the order discussed above.

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