UHE neutrinos encountering decaying and non-decaying magnetic fields of compact stars

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The phenomena of neutrino spin flavour precession in the presence of an extraneous magnetic field is a repercussion of neutrino magnetic moment which is consociated with the physics beyond the standard model of electroweak interactions. Ultra high energy neutrinos are spawned from a number of sources in the universe including the highly energetic astrophysical objects such as active galactic nuclei, blazar or supermassive black holes. When such high energy neutrinos pass through any compact stellar objects like neutron stars or white dwarfs, their flux can significantly reduce due to the exorbitant magnetic field provided by these compact objects. For Dirac neutrinos, such phenomena occur due to the conversion of neutrinos to their sterile counterparts. In this work, we consider a neutron star possessing a spatially varying magnetic field which may or may not decay with time. We find that, for the non-decaying magnetic field, the flux of high energy Dirac neutrinos becomes nearly half after passing through the neutron star. The flux is further enfeebled by $\sim 10\%$ in the presence of muons inside the neutron star. For decaying magnetic field, the flux reduction is abated by $\sim 5\%$ as compared to the temporally static magnetic field. In the case of a white dwarf, the depletion of flux is lesser as compared to the neutron stars.

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I. INTRODUCTION

The aberrant and largish potential of ultra high energy (UHE) neutrinos of cosmic origin to probe the structure of the universe at the leviathan scales has effectively propelled them to the omphalos of high energy physics. The fact that neutrinos interact only via weak interactions, it can perambulate colossal scales without interacting with the ambient environment which includes compact objects as well as interstellar or intergalactic medium. This may enable identification of sources of distant UHE cosmic ray sources as these neutrinos are usually generated due to interaction of cosmic rays with the cosmic microwave or infrared backgrounds. In fact, one such identification has already been accomplished [1]. In case neutrino interactions do occur, the nature of interactions can be revealed if this results in the change of flux or flavor ratios as compared to that of the vacuum oscillations. Therefore UHE neutrinos relishes unmatched potential in unsnaring remotest demesnes of our Universe.

To capitalize on this elephantine potentiality, a profusion of experimental facilities are either under construction or planned [2]. These can be categorized in terms of sensitivities to energies of cosmic neutrinos. For TeV-PeV energy range, neutrinos have high opacity [3–8]. In defiance of this, a smatter of neutrinos can still sally up to thousands of km inside the Earth before interacting [9–11]. These neutrinos can be ensnared by photonic detectors instilled in pharaonic volume of ice or submerged in grandiose water body. In the impending future, the northern sky will be mapped by the IceCube [12, 13] whereas KM3NeT [14], Baikal-GVD [15], P-ONE [16] will monitor the southern sky. The experiments such as IceCube-Gen2 [17], RET-N [18], TAMBO [19] and Trinity [20, 21] are sensitive to neutrinos in the range of (1 - 100) PeV. If neutrino energy lies in the range of EeV, the interaction length becomes achingly diminutive [22–25]. In such a case, the experimental set up should be accoutred to dredge up neutrinos interacting in the atmosphere, rock, ice or water outside of the detector volume [26–28]. The experimental facilities such as Pierre Auger Observatory [29, 31], ANITA I-IV [32], ARIANNA [33], ARA [34, 35] or are under construction RNO-G [36, 37] and PUEO [38] are bestowed with such proficiencies.

The high energy neutrinos can beseeam as an important tool to quest physics beyond the standard model (SM) of electroweak interactions. In this context, one of the less skirred aspects of neutrinos is its electromagnetic properties. In particular, if a neutrino possesses a finite magnetic moment due to quantum loop corrections [39, 40] then it may have several important hegemonies for physics of high energy cosmic neutrinos. The neutrinos would then be jaundiced by any external magnetic field, particularly a strong magnetic field. For cosmic neutrinos, even a relatively small intergalactic
magnetic field of the order of $\mu G$ can have sober-sided ramifications. Using the current upper bound on the magnetic moment of neutrinos, it was shown that the flux of the cosmic neutrons can be depleted by half if they peregrinate sufficiently large distances in the intergalactic field \[41\].

Such neutrinos can also stumble onto compact objects such as neutron stars or white dwarf stars which have large magnetic fields. The presence of such fields within compact stars would effectuate spin flip oscillations rendering depletion in the neutrino flux. In this work, we examine this aspect. We assume that high energy muon neutrinos are emitted from a point neutrino source and after travelling some distance, it encounters a compact star with a large internal magnetic field. The compact star is assumed to be located sufficiently closer to the source that the initial flux ratio remains unchanged. It would be interesting to see whether such interactions have any observational implications or not.

The plan of our work is as follows. In section \[II\] we describe the dynamics of neutrino spin flip oscillations. In section \[III\] we present a brief overview of neutron star and then exhibit our results for UHE neutrinos traversing through it. In the next section, we provide results for white dwarf star. Finally, in section \[V\] we furnish conclusions of our work.

II. NEUTRINO SPIN FLIP OSCILLATIONS

The phenomenon of neutrino oscillations are experimentally well-entrenched \[42–48\]. Such oscillations are possible only if the neutrino flavour state is a linear superposition of the non-degenerate mass eigenstates. It is illustrious that a massless and chiral neutrinos cannot have a non-zero magnetic dipole moment. However, a massive Dirac neutrino, in general, may have a magnetic moment which emerges at the one-loop level. In the standard electroweak theory, the Dirac neutrino magnetic moment $\mu_\nu$ at the leading order in $m_\ell^2/m_W^2$ is given as \[49\]

$$
\mu_{\nu}^{SM} = \frac{3eG_F m_\nu}{8\sqrt{2}\pi^2},
$$

(1)

where $e$ is positive, $G_F$ is Fermi constant and $m_\nu$ ($m_\ell$) is neutrino (lepton) mass. The mass of $W$ boson is denoted by $m_W$. It is ostensible that at the leading order in $m_\ell^2/m_W^2$, $\mu_\nu$ is independent of $m_\ell$ and the PMNS matrix. Numerically

$$
\mu_{\nu}^{SM} \approx \frac{3.2 \times 10^{-19} m_\ell}{1 eV} \mu_B.
$$

(2)

It is apparent that the neutrino magnetic moment is directly proportional to its mass. Therefore in order to have plenteously large value of $\mu_\nu$ so that it can have some observational implications,
one should have sufficiently large neutrino mass. However, we have tight constraints on the mass of neutrinos \cite{50}. Therefore, it might appear that the neutrino magnetic moment cannot be enhanced enough up to a level to have any observational impact. However, many new physics models are up to this demurral to effectuate a nonzero magnetic moment without affecting the neutrino mass. For e.g., models with scalar leptoquark \cite{51, 52}, vector leptoquarks in the TeV mass range with couplings both to the left and right-handed neutrinos \cite{53}, charged scalars \cite{54}, R-parity breaking SUSY \cite{55, 56}, an additional approximate horizontal symmetry $SU(2)_H$ with the SM gauge group \cite{57}, non standard interaction (NSI) \cite{39, 58–60} can generate a non-zero neutrino magnetic moment that may lie within the experimental reach.

On the experimental front, various reactor and accelerator experiments have provided bounds on the neutrino magnetic moment. The reactor experiments include the GEMMA experiment at the Kalinin Nuclear Power Plant, Russia \cite{61} and the TEXONO experiment at the Kuo-Sheng Reactor Neutrino Laboratory, Taiwan \cite{62} and ROVNO experiment at Rovno nuclear power plant, Ukraine \cite{63}. The accelerator experimental set ups entail LAPMF \cite{64} and LSND \cite{65}. The bounds from these reactor and accelerator neutrinos are in the range $(10^{-11} - 10^{-10}) \mu_B$. Recently, the XENON1T experiment provided upper bound on $\mu_{\nu e}$ as $(1.65 - 3.42) \times 10^{-11} \mu_B$ \cite{57}.

The limits on $\mu_{\nu}$ can also be obtained from astrophysics and cosmology through the evolution of stars \cite{66}, plasmon decay in the stellar environment \cite{67}, supernova events \cite{68} and $^4He$ nucleosynthesis \cite{69}. In fact, the most stringent limits on the neutrino magnetic moment comes from the red giant branch (RGB) of globular cluster which is $\mu_{\nu} < 4.5 \times 10^{-12} \mu_B$ \cite{70}. This value is about one order of magnitude smaller than that obtained from several terrestrial experiments.

Since neutrinos are deprived of electric charge, they can partake in electromagnetic interactions only by coupling with photons through quantum corrections. The Hamiltonian for the neutrino-photon interaction is given by \cite{39}

$$\mathcal{H}_{EM} = \bar{\nu}(x) \Lambda^\mu \nu(x) A_\mu \sim J^{EM}_\mu A_\mu, \quad (3)$$

where $A_\mu$ is the electromagnetic field and $\Lambda_\mu$ represents the vertex function subsuming the electromagnetic properties of neutrino which is a $4 \times 4$ matrix in the spinor space and contains all the form factors corresponding to the four electromagnetic properties, given by (a) electric moment, (b) magnetic moment, (c) neutrino charge and (d) anapole moment. In Dirac picture, the form factor corresponding to electric moment vanishes due to the assumption of $CP$ invariance and the hermiticity of the electromagnetic current, $J^{EM}_\mu$. The hermiticity of the current, $J^{EM}_\mu$ also restricts the form factors corresponding to the magnetic moment, neutrino charge and anapole moment to
be real.

The magnetic moment spawns the neutrino spin to precess in the contiguity of an external magnetic field which ushers to the mixing between the left handed and right handed neutrino current. In the two flavour framework, the Hamiltonian for the neutrino state evolution is expressed as a $4 \times 4$ Hermitian matrix. In our work we consider only Dirac neutrinos, for which the basis vector is $(\nu_e L, \nu_\mu L, \nu_e R, \nu_\mu R)$ and the Hamiltonian in this case manifests as

$$H_D = \begin{pmatrix}
-\frac{\Delta m^2}{4E_\nu} \cos 2\theta + V_e & \frac{\Delta m^2}{4E_\nu} \sin 2\theta & \mu_{ee} B_\perp & \mu_{e\mu} B_\perp \\
\frac{\Delta m^2}{4E_\nu} \sin 2\theta & \frac{\Delta m^2}{4E_\nu} \cos 2\theta + V_\mu & \mu_{\mu e} B_\perp & \mu_{\mu\mu} B_\perp \\
\mu_{ee}^* B_\perp & \mu_{\mu e}^* B_\perp & -\frac{\Delta m^2}{4E_\nu} \cos 2\theta & \frac{\Delta m^2}{4E_\nu} \sin 2\theta \\
\mu_{e\mu}^* B_\perp & \mu_{\mu\mu}^* B_\perp & \frac{\Delta m^2}{4E_\nu} \sin 2\theta & \frac{\Delta m^2}{4E_\nu} \cos 2\theta
\end{pmatrix}.$$  \tag{4}

A spin rotation from negative helicity state towards positive state will reduce the resultant effective weak neutral and charged-current scattering cross sections for neutrino which emerge, in the relativistic case, predominantly from the negative helicity state for neutrinos.

In equation (4), $B_\perp$ denote transverse magnetic field, while $\mu$ is the neutrino magnetic moment. Here, $\Delta m^2 = m_2^2 - m_1^2$. $V_e$ and $V_\mu$ are the potentials experienced by $\nu_e$ and $\nu_\mu$, respectively which are dependent on the matter composition of the medium through which the neutrino travels. If the matter is consisted of only nucleons and electron ($npe$), the matter potentials take the form of, $V_e = \sqrt{2}G_F(n_e - n_n/2)$ and $V_\mu = -\sqrt{2}G_F n_n/2$, while if muons are added with it ($npe\mu$), $V_\mu$ is altered to be, $V_\mu = -\sqrt{2}G_F(n_\mu - n_n/2)$ due to the occurrence of $\nu_\mu$ charged current (CC) interaction in matter in addition to that of the electrons also. Here, $n_e$, $n_n$ and $n_\mu$ are the number densities of electron, neutron and muon respectively.

## III. COSMIC NEUTRINOS PASSING THROUGH NEUTRON STAR

Neutron stars (NS) are unique compact stars engendered when the core nuclear fuel of a main sequence star of intermediate mass ($M \geq 8M_\odot$) is completely exhausted with the formation of the most stable iron nuclei. At this stage, the hydrodynamic equilibrium in the stellar structure is sustained by the degeneracy pressure of excess neutrons, against the inward gravitational collapse, which are the byproducts of photodisintegration and the following process of neutron drip from the iron nuclei. With further infalling matter from the outer layer towards the center, the density of the system may even exceed nuclear saturation density and the system detonates with type-II supernova (SN) explosion. As a consequence, NSs are born. The typical mass and radius of a NS are of the order of $\sim 2M_\odot$ and $\sim 10$ km respectively, with its central density being a few times
of the nuclear saturation density. The exact estimation of these quantities are obtained from its matter configuration and the equation of state (EOS). The simplest NS models consist of matter containing neutrons, protons and electrons ($npe$). However, muons start to appear in the matter when the chemical potential of the electrons exceeds the rest mass of muons ($105.6$ MeV) \[\text{MeV}\] 74. NSs also possess extremely high magnetic fields, also known as magnetars, which can even reach as high values as $10^{18}$ G at its center \[\text{G}\] 75. The central and surface values of magnetic fields may differ by one or two orders of magnitude.

NSs are the natural sources of neutrinos having energy in the $\sim$MeV ($10^6$ eV) range which are initially trapped for a few seconds during the birth of the star. Later during the different stages of its thermal evolution, neutrinos also continue to be emitted from the star as they are the most efficient heat carriers and help to reduce the temperature of the star. These $\nu_e$ neutrinos can also undergo spin flip precession, see for e.g., 77, 78. However, in this work we are not considering the neutrinos which are generated inside the NS. Rather, we consider UHE neutrinos generated from existing sources nearby the NS 76, such as active galactic nuclei (AGN) 79, 80 or a blazar 81, 82. These objects are able to produce mainly $\nu_{\mu L}$ with energies which can transcend the $\sim$EeV ($10^{19}$ eV) range. We contemplate these UHE neutrinos peregrinating through the NS which are expected to be affected by the star’s magnetic field and hence exhibit the reduction in their flux due to the SFP phenomena.

In our analysis, we consider a massive NS dovetailed of normal matter and having mass $2.3 M_\odot$ and radius 11.8 km, i.e., we consider the composition of $npe$ and $npe\mu$ with large magnetic field at its core $10^{18}$ G. The matter configuration of the star is described by a nonlinear Walecka model containing $\sigma$, $\omega$ and $\rho$-mesons 83, 84, and is governed by the GM1 equation of state (EOS) 85. The neutrinos are assumed to be Dirac in nature and have a finite magnetic moment of $\sim 10^{-11} \mu_B$.

In this analysis, we consider the simplification of zero vacuum mixing ($\theta_{12} = 0$) which yields the Hamiltonian to have a form of $2 \times 2$ matrix, given by 71

$$ H = \begin{pmatrix} -\Delta m_{12}^2/4E + \Delta V/2 & \mu_eB \\ \mu_eB & \Delta m_{12}^2/4E - \Delta V/2 \end{pmatrix}. \tag{5} $$

Here $\Delta V = \sqrt{2} G_F \rho Y_e^\text{eff} / m_N$ with $\rho$ being the matter density. $Y_e$ and $m_n$ denote the effective electron fraction and nucleonic mass, respectively. Further, $Y_e^\text{eff} = (3Y_e - 1)/2$ for Dirac basis. Following eqn. 5, the neutrino spin flavour evolution equation in the presence of an external magnetic field is expressed as 71

1 For convenience, from now on, we write $\nu_\mu$ for $\nu_{\mu L}$. 
\[
\frac{d^2 \nu_{\mu L}}{dr^2} - \left( \frac{\mu B}{\mu B} + i \zeta \right) \frac{d\nu_{\mu L}}{dr} + \left[ \phi^2 + i \frac{d\phi}{dr} \right] \left[ (\mu B)^2 - i \phi \frac{\mu B}{\mu B} + \phi \zeta \right] \nu_{\mu L} = 0, \quad (6)
\]

where

\[
\phi = -\frac{\Delta m^2}{4E} + \frac{1}{\sqrt{2}} G_F n_e,
\]
\[
\zeta = \frac{1}{\sqrt{2}} G_F n_n, \quad \nu_{\mu L} \rightarrow \nu_{\mu R}. \quad (7)
\]

The transition probability of left handed electron neutrino can be obtained after solving (6) along with (7).

A. Non-decaying magnetic field

We consider the following universal profile of the internal magnetic field of the NS

\[
B(x) = B_c(1 - 1.6x^2 - x^4 + 4.2x^6 - 2.4x^8), \quad (8)
\]

where \(x = r/R\), with \(r\) is the radial distance from the center of the star and \(R\) is the radius of the star. \(B_c\) is the magnetic field at the center which is assumed to be \(B_c = 10^{18} \text{ G}\). The profile is independent of any free parameter which works at its advantage. The magnetic field at the surface of the star is obtained to be \(\sim 10^{17} \text{ G}\), following the profile given in eqn. (8).

![Variation of survival probability $P(\nu_\mu \to \nu_\mu)$ with the radial distance inside the star for two different energy sets of incoming $\nu_\mu$. The star contains nuclear matter with npe configuration.](image_url)
Fig. 1 demystifies the survival probability of the incoming $\nu_\mu$ beam. In the left and right panels of the figure, we consider the neutrino energies to be $E = 10^{15}$ eV and $E = 10^{19}$ eV, respectively. We contemplate the magnetar as a sphere in which the neutrino beam enters at the point $r = -R$ and leaves the star from the point $r = R$. As stated before, $R$ is the radius of the star with value 11.8 km. We assume that the incoming UHE neutrinos travel along the diameter of the star as being the largest traversed distance, the effect of SFP will be maximal. It can be observed from the figure that the survival probability of $\nu_\mu$ at its point of emission from the star at $r = R$ is $\sim 0.5$ which implies that almost half of the incoming neutrinos are converted into their sterile counterparts. The result does not vary significantly with increase in incoming neutrino energy, as observed comparing left and right panels of the figure. The survival probability of $\nu_\mu$ is obviously unity at the point of entry to the star, $r = -R$, as we have considered zero vacuum mixing and hence the neutrino beam incident on the magnetar only consists of $\nu_\mu$.

![Graph](image-url)

**FIG. 2.** Same as fig. 1, comparing $npe\mu$ and $npe$ matter.

In fig. 2 we portray the plot for $\nu_\mu$ survival probability after crossing the NS for two kinds of matter composition, $npe$ and $npe\mu$. In the left and right panels of the plot, the incoming energy of $\nu_\mu$ beam is considered to be $10^{15}$ eV and $10^{19}$ eV, respectively. The plots clearly show that starting from the point of incidence ($r = -R$) till the center of the star, the survival probability is nearly similar for the two kinds of matter configuration. However, the difference starts to be pronounced once it crosses the stellar center and becomes greater near the surface region. It is to be noted that in the presence of muon in NS matter, at the point of emission ($r = R$), the survival probability of $\nu_\mu$ is further lowered to a value of $\sim 0.45$ from $\sim 0.5$ which is the muon neutrino survival probability for only $npe$ matter at $r = R$. This implies that the presence of muon
| Conditions  | $P(\nu_\mu \to \nu_\mu)$ at $r = R$ | % decrease in flux at $r = R$ |
|------------|-----------------------------------|--------------------------|
|            | $10^{15}$ eV | $10^{19}$ eV |
| Without muon | 0.5 | 0.5 | 50% |
| With muon   | 0.45 | 0.45 | 55% |

TABLE I. Survival probability and the $\nu_\mu$ flux reduction at the point of emission from the star, i.e., at $r = R$, $R = 11.8$ km.

affects the SFP phenomena to a greater extent and thus aids to generate a larger flux of sterile neutrino. The flux of incoming $\nu_\mu$ is diminished by 50% after they drift through the npe matter of NS whereas the reduction is enhanced to 55% in the presence of muons. The result does not exhibit any significant variation for the case of lower and higher energies as observed from assimilating the two panels of the figure. The results are summarized in table I.

B. Decaying magnetic field

In NS, the magnetic field starts to deplete over time which may undergo via three mechanisms: (a) Ohmic decay, in case of which the magnetic field diffuses with respect to the charged particles, (b) ambipolar diffusion, which is a dissipative effect where the diffusion of electrons and protons in opposite directions in a neutron background takes place and (c) Hall drift. In our analysis, we consider the dissipation of magnetic field by the process of ambipolar diffusion which is the most important mechanism occurring inside the core of the magnetar and affects the magnetic field most significantly at the lower core temperature ($\sim 10^8$ K). To incorporate the effect of magnetic field dissipation in the magnetar, we consider only the occurrence of ambipolar diffusion for the transport of magnetic flux and follow the formalism mentioned in the ref. [89, 91], according to which the expression for time varying magnetic field in npe matter, is given by

$$B(r, t) = \frac{B_0(r)}{1 + t/\tau}.$$  \hspace{1cm} (9)

Here $B_0$ is the constant magnetic field without taking the decaying effect into account and is obtained from eqn. (8). Further, $\tau$ is the characteristic decay time for the magnetic field due to the occurrence of ambipolar diffusion and can be expressed as,

$$\tau \approx 25 L_3^2 B_{17}^{-2} T_9^2 (\rho/\rho_0)^{2/3} \text{ yrs},$$  \hspace{1cm} (10)
where $L_5 = L/10^5$ cm, $L$ being the distance over which the variation of magnetic field is considered, $B_{17} = B/10^{17}$ G and $T_9 = T/10^9$ K. $\rho_0$ is the saturation nuclear density which is dependent on the choice of EOS of NS matter. For GM1 EOS, $\rho_0 = 0.153 \text{ fm}^{-3}$ [92].

The surface temperature of our model star varies within a range of $\sim 10^7 - 10^4$ K over a temporal span of $10^6$ years, starting after the birth of the NS and the corresponding surface magnetic field varies from $\sim 10^{18}$ G to $10^4$ G which are depicted in the left and right panels of fig. 3 respectively. For a massive NS like our model star, the initial thermal relaxation period of the stellar thermal evolution lasts upto $\sim 100$ years, during which the surface magnetic field also shows drastic reduction in its value from $\sim 10^{14}$ G to $10^{11}$ G, as observed from fig. 3.

![FIG. 3. Variation of surface temperature (left panel) and magnetic field (right panel) with time of a magnetar of mass $2.3 M_\odot$ and radius 11.8 km.]

Fig. 4 illustrates the muon neutrino survival probability for the case of a decaying magnetic field of a NS for $npe$ matter. For comparison, the plot for a non-decaying field is also shown. We consider a time span of $10^3$ years in which the magnetic field of the magnetar is reduced at least by five orders of magnitude. Further, it should be mentioned that at $t \approx 10^3$ years, the core temperature is $\sim 10^8$ K which implies that the ambipolar diffusion could be the most significant process for the dissipation of the magnetic field in the magnetar. It can be observed from the figure that at $t = 10^3$ years, around the central region of the star ($R \approx 0$), the decaying magnetic field enhances the survival probability whereas at the point of $\nu_\mu$ emission from the NS i.e. at $r = R$, the decaying magnetic field induces slightly higher survival probability ($\sim 0.53$) as compared to that of no decay ($\sim 0.5$). Thus the decaying magnetic field favours $\sim 5\%$ enhancement in the $\nu_\mu$ flux as compared to the temporally static magnetic field. The results remain almost the same at
FIG. 4. Variation of survival probability \( P(\nu_\mu \rightarrow \nu_\mu) \) with radial distance for decaying magnetic field in npe matter of NS.

| Quantities                  | Without decay | With decay |
|-----------------------------|--------------|------------|
| \( P(\nu_\mu \rightarrow \nu_\mu) \) at \( r = R \) | 0.5          | 0.53       |
| % reduction in \( \nu_\mu \) flux at \( r = R \) | 50%          | 47%        |

TABLE II. Survival probability and the % reduction of the incoming \( \nu_\mu \) flux, at the point of emission from the star at \( r = R \), \( R = 11.8 \) km.

\( t = 10^5 \) years, as can be seen from the figure. Thus, it can be concluded that there can only be a marginal alteration in the outgoing neutrino flux from the NS for a decaying magnetic field as compared to the static field. Further, these conclusions are almost independent of the age of the NS. The results are further illustrated in table II.

IV. COSMIC NEUTRINOS PASSING THROUGH WHITE DWARF

White dwarfs (WD) are another branch of compact stars the formation of which originated from the progenitor stars having lower mass \( (1M_\odot \leq M \leq 8M_\odot) \). When there is sufficient nuclear fusion in the core of such a low mass main sequence star which generates helium or some successive heavier nuclei, the outer layer of the star expands to form a red giant (RG). Due to rapid expansion and cooling of the outer layer it becomes unstable and is expelled as a planetary nebulae. The remnant forms WD in which the inward gravitational pull is balanced by the electron degeneracy pressure \( 93 \). The maximum mass of a WD is about \( 1.475 M_\odot \) which is the Chandrashekhar limit,
having its central density \( \sim 10^6 \) gm cm\(^{-3}\). The core of a low mass WD usually consists of helium, while heavier ones may contain carbon or oxygen. WDs are smaller compared to NSs and are less massive. Considering non-relativistic degenerate electron gas, the mass radius relation \((M - R)\) and the central density are expressed as \([94]\)

\[
R = (10,500 \text{ km}) \left( \frac{0.6M_{\odot}}{M} \right)^{1/3} (2Y_e)^{5/3},
\]

\[
\rho_{central} = 1.46 \times 10^6 \text{ gm cm}^{-3} \left( \frac{M}{0.6M_{\odot}} \right)^2 (2Y_e)^{-5}, \tag{11}
\]

where \(0.6M_{\odot}\) is the canonical mass of a WD. \(Y_e\) is the electron number density per baryon, \(Y_e = n_e/(n_p + n_n)\) with \(n_e\), \(n_p\) and \(n_n\) being the number density of electron, proton and neutron, respectively. WDs usually consist of \(npe\) matter. Muons cannot be present inside WDs, as the Fermi energy of muons is very small inside the star. Isolated WDs may contain large internal magnetic fields, although the surface value of the magnetic field may be vanishing. In a recent work, the upper bound of the WD magnetic field is estimated to be as \([94]\)

\[
B_{max} = 8.8 \times 10^{11} G \left( \frac{M}{0.6M_{\odot}} \right)^{1/3} \tag{12}
\]

WDs are also capable of producing MeV neutrinos at their core. However, similar to the previous analysis in case of NS, we proceed with UHE Dirac neutrinos coming from a local source which pass through the WD. Due to large magnetic field of WD, it is expected that a fraction of the incoming UHE is converted to their sterile counterpart.

For our analysis, we consider an isolated WD of mass 0.6 \(M_{\odot}\) and radius 10,500 km having constant internal magnetic field of \(8.8 \times 10^{11} \) G with \(npe\) matter configuration having \(Y_e = 0.5\). We assume that the local UHE neutrino source gives away \(\nu_\mu\) beam which crosses the white dwarf along its diameter, entering at the point \(r = -10,500 \) km considering at its center at \(r = 0\) and exiting from \(r = 10,500 \) km. We determine the survival probability of \(\nu_\mu\) after they pass through the star at the point of emission, \(r = 10,500 \) km.

In fig. 5 we represent \(\nu_\mu\) survival probability varying with the radial distance inside the WD star. Similar to fig. 1 in the case of WD, we also present our results considering the energy values of \(10^{15}\) eV and \(10^{19}\) eV in the left and right panels of the plots, respectively. It is observed that the survival probability follows an oscillatory pattern throughout the star and retains a value of \(0.75\) at the exit point from the star at \(r = 10,500 \) km implying a reduction of incoming \(\nu_\mu\) flux by 25\%. The result does not vary significantly in case of lower and higher energy values. Compared to NS, UHE Dirac \(\nu_\mu\)s are affected to a lesser extent by the SFP phenomena inside the WD which can be
accredited to a smaller value of magnetic field. Thus, in the case of a WD, the conversion of Dirac neutrinos into the sterile form occurs in a lower amount as compared to the NS. This difference can be determined from the proper estimation of the flux by a suitable terrestrial neutrino detector with high efficiency.

Unlike NS, the decay of magnetic fields in a magnetic WD is not realistic as the decay time is very large $\sim (2 - 6) \times 10^{11}$ yrs. Therefore, we curtail our analysis to the estimation of flux reduction of UHE neutrinos passing through WD stars containing $npe$ matter and constant magnetic field without delving into the concept of field decay.

V. CONCLUSION

We appraise the reduction of flux of ultra high energy Dirac neutrinos passing through two of the most compact stellar objects in the universe, neutron star and white draft, after being generated from a point source residing close enough to the compact star. As a model star, we consider a neutron star with mass $2.3 \, M_\odot$ and radius $11.8$ km having a mammoth central magnetic field of $10^{18}$ G. Using the current experimental bound on the magnetic moment of neutrinos and assuming GM1 parametrization, we evaluate the survival probability of the incoming UHE $\nu_\mu$ beam at the point of emission for $npe$ as well as $npe\mu$ matter. We observe the following:

- For a non-decaying magnetic field, the flux of a $\nu_\mu$ beam can be reduced to half at the emission point for $npe$ matter.
• For muons in the neutron star matter, the survival probability of $\nu_\mu$ decreases from 0.50 to 0.45.

• These results remain unaltered in the $\nu_\mu$ energy range of $(10^{15} - 10^{19})$ eV.

• For a decaying magnetic field in $npe$ matter of neutron star, the survival probability of $\nu_\mu$ increases by $\sim 5\%$ as compared to the temporally static field. Although the decaying and non-decaying scenarios show a significant difference in the values of neutrino survival probability around the central region of the neutron star, this may not have any observational implications.

We then consider a white dwarf star consisting of only $npe$ matter and having mass $0.6M_\odot$ and radius 10,500 km with a constant magnetic field of $8.8 \times 10^{11}$ G. This leads to $\nu_\mu$ survival probability of $\sim 0.8$ at the point of emission after they traverse along its diameter. Like neutron stars, the conclusions are almost the same in the energy range of $(10^{15} - 10^{19})$ eV. We do not consider the case of magnetic field evolution in white dwarf due to its unusually large decaying time scale.

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