Diffuse Ionization in the Milky Way and Sterile Neutrinos

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Abstract

We propose the radiative decay of sterile neutrinos which fill a fraction of the halo dark matter with a mass of 27.4 eV and lifetime of $\sim 10^{22}$ sec. as a way to explain the observed diffuse ionization in the Milky Way galaxy. Since the sterile neutrino number density in the present universe can be adjusted by arranging its dynamics appropriately, the resulting hot dark matter contribution to $\Omega_m$ can be small as required by many scenarios of structure formation. On the other hand a 27.4 eV neutrino could easily be the partial halo dark matter. One realization of this idea could be in the context of a mirror universe theory where the gauge and matter content of the standard model are completely duplicated in the mirror sector (except for an asymmetry in the weak scale); the three mirror neutrinos can mix with the known neutrinos via some strongly suppressed mechanism such as the gravitational or heavy right handed neutrino mediated forces. Two of the mirror neutrinos (say $\nu'_\mu$ and $\nu'_\tau$) could play the role of the above sterile neutrino.
The interstellar medium of the Milky Way galaxy is known to contain ionized hydrogen gas with properties which seem to defy common astrophysical explanations\(^1\). Similar problems also seem to exist for other galaxies studied. One solution that proposes to use a decaying dark matter neutrino was suggested by Sciama\(^1\). According to this idea, if the relic tau neutrinos which are supposed to pervade the cosmic background with a density of \(\approx 113\, \text{(cm)}^{-3}\) have a mass of 27.4 eV and decay to one of the other two lighter neutrinos plus a photon with a lifetime of about \(2 \times 10^{23}\) sec. then they could provide enough ionizing photons on galaxy scale heights of nearly a kiloparsec to solve this problem. The reason for this is that the decay photon has an energy of 13.7 eV and so would be able to ionize hydrogen—the lifetime is chosen to ensure that the resulting photon flux would produce the observed electron density. With these parameters the tau neutrino could be the dark matter needed to account for the flat rotation curve of the galaxy. Despite the attractiveness of this suggestion, the fact that a 27.4 eV neutrino must provide 100% of the dark matter of the universe runs into trouble with the standard scenarios for structure formation. Also the fact that this scenario implies that the \(\Omega_m = 1\) may be in conflict with high z type Ia supernova data\(^2\) as well as data from clusters\(^3\), which suggest that \(\Omega_m\) may be considerably less than unity. Although one could use cosmic strings to get out of the first difficulty, it is tempting to look for alternative proposals that may keep the basic ingredients of the idea and yet not force us into a 100% HDM-full universe.

In order to set the stage for our suggestion, let us note that the reason why an active neutrino of mass 27.4 eV constitutes nearly 100% of the dark matter in the universe is that its normal weak interaction allows it to remain in equilibrium until the universe is a second old. After it decouples, the annihilation of \(e^+e^-\) to photons increases the temperature of the universe slightly leaving the neutrinos unaffected.
Thus at the present epoch their number density becomes somewhat lower than that of the photons yielding about 113 neutrinos of each type per cm$^3$. For the Hubble parameter $h$ of about 0.5, this leads to $\Omega_\nu = 1$. On the other hand if we had a sterile neutrino of mass 27.4 eV, its present number density will be controlled by its interactions with the standard model particles which by virtue of its being sterile are much weaker. This makes it decouple earlier from the cosmic soup (say at $T \geq 200$ MeV), thus making its number density much smaller (since the number of degrees of freedom contributing to the energy density of the universe changes drastically below the QCD phase transition temperature which happens to be around 200 MeV). Their contributions to $\Omega$ is therefore much smaller. These relic sterile neutrinos will be uniformly distributed throughout the universe and will eventually concentrate into the halos of galaxies after they form constituting a fraction of the halo dark matter (which could be about 10% or so). If its lifetime to photonic decay is proportionally reduced, then it could explain the problem of diffuse ionization in our Galaxy while at the same time avoiding being the dominant dark matter constituent. In this letter we elaborate on this proposal, seek gauge theories where this proposal can be realized and suggest some tests.

I. The sterile neutrino mass and lifetime implied by the solution to the diffuse ionization problem

To introduce the requirements for the sterile neutrino to solve the diffuse ionization problem, let us recapitulate some of the basic issues involved\[1]. The major problem that needs a solution is the observed diffuse ionization in the Milky Way, specifically its scale height of nearly 670 pc and its rather uniform distribution in different directions. Suggestions involving the cosmic rays have been ruled out by observations\[4] and any local sources for hydrogen ionizing radiation must overcome
the problem of opacity due to neutral hydrogen HI, that makes it difficult to un-
derstand the magnitude of the scale height. On the other hand if an all pervading
medium of relic neutrinos decay to photon with an energy of 13.7 eV, it easily evade
all these problems.

The key formula for our purpose is the one that dictates the equilibrium be-
tween the process of hydrogen ionization by the photons from neutrino decay and
recombination of free electron with proton to form neutral hydrogen back. If $\alpha$ is
assumed to denote the recombination rate of $e^- + p \to H$, the equilibrium condition
is given by:

$$\frac{n_\nu}{\tau_\nu} = \alpha n_e^2$$  \hspace{1cm} (1)

For the relevant electron temperature of $10^4$ K, the value of $\alpha \simeq 2.6 \times 10^{-13}$ cm$^3$
sec$^{-1}$. Taking $n_e \sim 0.033$ cm$^{-3}$ known from observations, we find that $\frac{n_\nu}{\tau_\nu} \sim 2 \times 10^{-16}$

cm$^{-3}$ sec$^{-1}$. If we now assume that the neutrino lifetime is $2 \times 10^{23}$ sec. this is then
consistent with the various constraints from supernova 1987A observations[6]. This
requires the halo density of neutrinos to be about $4 \times 10^7$ cm$^{-3}$. As has been shown
by Sciama, within a simple approximation of isothermal and isotropic distribution of
halo dark matter[3] of neutrinos, the above number density emerges quite naturally.
A simple way to see this is to note that the halo density is known from fits to the
galaxy rotation curves to be about $\rho \sim 0.3$ GeV cm$^{-3}$. The formula $\rho \sim n_\nu m_\nu$ then
yields the above number for the halo density of tau neutrinos.

This discussion can be translated to the case of sterile neutrinos, for whom the
relic density will be given by:

$$\frac{n_\nu'}{n_\gamma} \simeq \frac{g_e(T_0)}{g_e(200\text{MeV})}$$  \hspace{1cm} (2)

where $g^*(T)$ is the number of degrees of freedom of the particle species in equilibrium
with electrons at the temperature, T. If we assume that the QCD phase transition
temperature is below 200 MeV, then we get $g_*(200\text{MeV}) = \frac{261}{4}$ and $g_*(T_0) = 2$ where $T_0$ is the present temperature of the universe. This gives, $n_{\nu'} \simeq 12$. This leads to $\Omega_{\nu'} \simeq 0.08$. Thus the sterile neutrinos do not constitute a significant part of the dark matter "menu". If we further assume that $\Omega_m \simeq 0.4$ and $\Omega_B \simeq 0.08$ and the same ratio is maintained for all the particle species in the dark halo, the halo density of sterile neutrinos will be $\simeq 2 \times 10^6 \text{cm}^{-3}$. Eq. (1) then dictates that we must have a radiative lifetime of the sterile neutrino of $10^{22}$ sec. for it to be able to explain the diffuse ionization problem.

Before getting into the particle physics models let us first note how such a radiative decay lifetime can be achieved for the sterile neutrino. Recall that in order for the sterile neutrino to be useful in resolving the neutrino puzzles as we will eventually assume, the active and the sterile neutrinos must mix with each other. But for this mixing not to effect the big bang nucleosynthesis constraints\[9\], the masses and mixings must satisfy the constraint\[10\]:

$$\Delta m_{\nu_a \nu'}^2 (\sin^4 2\theta) \leq 2 \times 10^{-6} \text{eV}^2 \tag{3}$$

Since in our case, $\Delta m^2 \simeq 10^3 \text{eV}^2$, we get, $\sin 2\theta \leq 0.7 \times 10^{-2}$. Now suppose that there is a transition magnetic moment involving the $\nu_\mu - \nu_\tau$ ($\mu_{23}$). Then, the radiative decay of the sterile neutrino can occur via its mixing with either the $\nu_\mu$ or $\nu_\tau$. This will lead to a decay rate

$$\Gamma_{\nu' \rightarrow \nu_\mu + \gamma} \simeq \frac{\theta^2 \mu_{23}^2 m_{\nu'}^3}{8\pi} \tag{4}$$

Using the afore mentioned values for the parameters in the above expression, we get a lifetime for the sterile neutrino $\tau_{\nu'} \simeq 10^{22}$ sec. for the choice of $\mu_{23} \simeq 10^{-12} \mu_B$ for

\[1\]Note however, a recent argument by Foot and Volkas\[11\] according to which the bounds on sterile-active neutrino mixing could be considerably weaker for certain parameter ranges due to lepton asymmetry generated before the big bang nucleosynthesis epoch. This would help us in expanding the allowed parameter space of our proposal.
\[ \theta \simeq 0.01. \] Thus we get the desired radiative lifetime to solve the diffuse ionization problem. Since we have quite reasonable values for all the necessary parameters involved in our mechanism, we feel that this is a viable solution to the problem at hand.

A point that needs to be noted here is that the supernova bound for the radiative lifetime for the eV neutrinos need not apply to our case since we are considering a sterile neutrino and not an active one. Its production in the supernova will be different from the active neutrino case.

This brings us to raise the two key particle physics issues that we must address: is it possible to have a viable model for a sterile neutrino whose mass of 27.4 eV is not unnatural and how does it fit into the full neutrino picture that accommodates the observations or indications of neutrino oscillations in solar, atmospheric as well as the LSND data. We address these questions in the next section.

**II. The Complete Scenario for Neutrino Puzzles:**

There are various scenarios for neutrino masses that can be constructed to fit a radiatively decaying 27.4 eV sterile neutrino. For simplicity of presentation, we focus on a variation of the following six neutrino picture that emerges in the context of the mirror universe model for particle physics and assume the following pattern for the neutrino masses:

\[ m_{\nu'^{e}} - m_{\nu^{e}} \approx 10^{-5} \text{eV}^2; \quad m_{\nu^{\mu}} \simeq m_{\nu^{\tau}} \approx \sqrt{\Delta m^2_{\text{LSND}}} \sim .2 \text{ eV} - 3 \text{ eV} \] and \[ m_{\nu'^{\mu}} \approx m_{\nu'^{\tau}} \approx 27.4 \text{ eV}. \] Except perhaps for a possible mirror symmetry, there is no reason for the \( \nu'^{\mu} \) and \( \nu'^{\tau} \) to have same mass and when needed we can revert to a scheme with only one of \( \nu'^{\mu, \tau} \) having a mass of 27.4 eV and the other much lighter. Note that the primed neutrinos do not couple to the standard model gauge group and are therefore the sterile neutrinos.

In this picture, the solar neutrino puzzle is solved via \( \nu_e - \nu'^{e} \) oscillation whereas, the atmospheric neutrino oscillation is between the \( \nu_{\mu} - \nu_{\tau} \) as suggested in Ref. [13].
The 27.4 eV $\nu'_{\mu,\tau}$ will play the role in solving the diffuse ionization problem. Next, we present a gauge model where the radiative decay with the required lifetime can emerge. The basic idea is that we must generate a reasonable transition magnetic moment between the active $\nu_\mu$ and $\nu_\tau$. For this we can choose a version of MSSM with R-parity violating interactions as in Ref. [7]. Whereas we have chosen this particular model for the purpose of illustration, one could use any other model that generates a large neutrino magnetic moment while at the same time keeping the mass small [8].

Let us consider the gauge group of the model to be $G \otimes G'$ where $G$ and $G'$ are identical groups with $G$ operating on the visible sector fields which contain the standard model particles and $G'$ operating on the mirror sector fields which have an identical spectrum as the visible sector. We choose $G \equiv G' = SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$. (All groups in the mirror sector will be denoted by a primed symbol). The spectrum of matter and Higgs fields for each sector is same as in the MSSM. The mirror sector fields will be denoted by a prime on the above fields. The basic idea of the class of models we will be interested in is that they will generate a transition magnetic moment $\mu_{23} \sim 10^{-12}\mu_B$ while at the same time keeping all neutrino masses $\leq 1$ eV.

For the superpotential, we choose,

$$W = h_u Q H_u u^c + h_d Q H_d d^c + LH_d e^c + MH_u H_d$$
$$+ f (L_\mu L_\tau \mu^c + L_\tau L_\mu \tau^c) + f_1 L_\mu L_\tau e^c + L_\mu H_d e^c$$
$$h_\mu (L_\mu H_d \mu^c + L_\tau H_d \tau^c) \quad (5)$$

Note that this superpotential has an $SU(2)_H$ symmetry between the $L_\mu$ and $L_\tau$ (as between $(\mu^c, \tau^c)$). We break this symmetry softly in the supersymmetry breaking sector by the slepton mass terms being different. As in Ref. [7], this model gives rise
to a large transition magnetic moment for the $\mu$ and $\tau$ neutrinos without simultaneously giving them large masses. The value of $\mu_{23}$ is given by

$$\mu_{23} \simeq \frac{f f_1 e}{8\pi^2} m_\tau \sin 2\phi \left( \frac{1}{M^2} \ln \frac{M^2}{m_\tau^2} \right) \simeq f f_1 5 \times 10^{-8} \mu_B$$

(6)

where $\phi$ denotes a mixing angle in the Higgs sector and $M$ a typical Higgs mass for which we have chosen a value of 100 GeV. Thus to get the desired value for the magnetic moment, we need $f f_1 \simeq 2 \times 10^{-5}$. Note that in the absence of symmetry breaking the muon and the tau have the same mass. But it is well known that supersymmetry breaking terms can be used to generate this splitting if they are appropriately chosen. We do not go into this discussion since this is identical to what is in Ref. [7]. One needs a certain degree of fine tuning to achieve the desired values. However, since our goal is to give plausible arguments for the kind of parameters we use in our proposal, we refrain from getting into the full naturalness discussion.

Turning now to the discussion of the muon and tau neutrino masses, we see that in this model, the dominant contribution comes from the radiative one loop diagram and leads to an off diagonal mass matrix in the lowest order. Again in the symmetry limit, they vanish. Their magnitude can be calculated to be:

$$m_{\nu_\mu - \nu_\tau} \simeq \frac{f f_1}{16\pi^2} m_\tau F(M^2, M'^2, \delta, \delta')$$

(7)

where $M, M', \delta, \delta'$ are parameters characterising the supersymmetry breaking sector of the second and the third generation. It is not impossible to arrange these parameters to get this mixing mass to be in the few eV range, since all one needs to do is to have $F \approx 0.1$. The key point here is that in the limit of the exact $SU(2)_H$ symmetry, $F = 0$ whereas $\mu_{23} \neq 0$. This property enables us to maintain a degree of naturalness in generating the small neutrino masses. Note that this mass matrix gives rise to a maximal mixing pattern for the $\nu_\mu - \nu_\tau$ sector as required by the atmospheric neutrino data. The mass splitting between them must come from alter-
native sources. One way for example is to put in a doubly charged field $\Delta \oplus \bar{\Delta}$ which is an $SU(2)_L$ singlet with a coupling in the superpotential $\Delta e^c e^c$ and a symmetry violating term in the soft breaking term of type $\tilde{m}_\mu \tilde{\mu}^c \mu^c \Delta$. This generates a neutrino mass of type $\nu_\mu \nu_\mu$ at the two loop level. Its value can be estimated to be of order

$$m_{\nu_\mu} \approx \frac{f^2}{(16\pi^2)^2} \frac{m_\mu^2}{M}$$

(8)

so that the above diagonal term is of order 0.03 eV which is in the right range for the atmospheric neutrino data.

This model leads to a one loop contribution to the $\nu_e$ mass given by

$$m_{\nu_e} \approx \frac{f^2}{16\pi^2 m_\tau} \ln\frac{m_\tau^2}{m_\tau^2}$$

(9)

which is easily in the eV range if we require that $f \sim 10^{-4}$. Thus the understanding of the solar neutrino problem would require very fine tuned vacuum oscillation between the $\nu_e - \nu'_e$. This would require that the soft slepton masses must be asymmetric between the normal and the mirror sector so that $m_{\nu_e} \approx m_{\nu'_e}$.

The mirror sector of the model in the limit of exact gauge symmetry and supersymmetry is assumed to be a complete duplicate of the visible sector. After electroweak symmetry breaking, we will choose the symmetry breaking vev $v'_{wk}$ to be much larger (about a factor of 30) than the $v_{wk}$. Similarly the slepton masses which result from supersymmetry breaking will also be required to be different in the two sectors. The mixing between the normal and mirror sector arise via the higher dimensional operators such as $L_\mu H_u L_{\mu'} H'_u / M_{Pl}$ etc as in Ref.[12] and as demonstrated there, one can have eV range masses for the $\nu_\mu, \tau$ and 30 eV mass for the $\nu'_\tau$, enabling our mechanism to operate.

Coming to the $\nu_e$ sector, similar arguments also imply a mixing mass of order $10^{-3}$ eV and if $m_{\nu_e} \approx 0.1$ eV, this gives $\sin^2 2\theta_{\nu_e - \nu'_e} \approx 10^{-2}$ which is in the right range for the MSW solar neutrino oscillation via the small angle oscillation.
We thus see that it is possible to construct plausible particle physics models for our proposal.

It is worth pointing out that the large transition magnetic moment between $\nu_\mu$ and $\nu_{\tau}$ which is an essential ingredient of our proposal has other applications. It has been suggested[14] that it can provide a mechanism to revive the stalled shock in supernovae. Another application is its usefulness in understanding pulsar velocities using resonant spin flavor transition[15] in the neutrino sphere of supernovae[7].

In conclusion, we have presented a modified version of the original tau neutrino radiative decay model for understanding the diffuse ionization in the Milky Way and other galaxies. The model avoids difficulties with structure formation. One particle physics realization of the idea is presented in the context of the already proposed mirror universe idea for neutrino puzzles.

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