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Tau Neutrino as Dark Matter

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Abstract

A stable ν_τ with mass $m_\nu \simeq$ 1–35 MeV and magnetic moment $\mu \simeq 10^{-6}$ Bohr magnetons is a viable cold dark matter candidate. Such a large value of μ, which is responsible for depleting the ν_τ relic abundance, is consistent with present laboratory data, astrophysical observations, and cosmological information.

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The nature of the dark matter remains a subject of speculation. Because of indications of its non-baryonic nature, many as yet undiscovered particles have been proposed as its constituent. On the other hand, the only weakly interacting neutral particle that certainly exists, the neutrino, is not regarded as a very likely candidate for the dark matter. It is well known [1] that a neutrino with mass 100 eV $\lesssim m_\nu \lesssim$ 1 GeV would have a present energy density (ρ_ν) larger than the critical density, thus leading to a too young Universe. Light neutrinos ($m_\nu \lesssim$ 100 eV), although they are acceptable experimentally and provide the required value of ρ_ν, are highly disfavored as dark matter candidates. In fact, they lead to the hot dark matter scenario, unsuccessful in predicting the large–scale structure of the Universe, and also they cannot explain the observed [2] halos in dwarf spheroidal galaxies because of phase-space constraints [3].

In this paper I show that, if the τ neutrino has a large magnetic moment, it can be identified as a cold dark matter particle constituting the galactic halo†.

Let us consider a stable ν_τ with mass between 1 MeV and the present experimental bound of 35 MeV. The stability can be achieved by imposing some additional symmetries, *e.g.* individual lepton number conservation. If ν_τ has a non-zero magnetic moment, it can annihilate in the early Universe via electromagnetic processes, in addition to its ordinary weak interactions. The dominant electromagnetic channel is $\bar{\nu_\tau}\nu_\tau \to e^+e^-$, since the rate for $\bar{\nu_\tau}\nu_\tau \to \gamma\gamma$ is suppressed by two extra powers of the magnetic moment. The cross section for $\bar{\nu_\tau}\nu_\tau \to e^+e^-$ via photon exchange in the s–channel is:

$$\sigma(\bar{\nu_\tau}\nu_\tau \to e^+e^-) = \frac{\alpha\mu^2}{6}\sqrt{\frac{1-4m_e^2/s}{1-4m_\nu^2/s}}\left(1+8\frac{m_\nu^2}{s}\right)\left(1+2\frac{m_e^2}{s}\right) \quad , \tag{2}$$

where m_e, m_ν are the electron and neutrino mass, μ is the ν_τ magnetic moment and $\sqrt{s}$ is the total energy in the center of mass frame. In the non-relativistic limit, eq.(1) becomes

$$< \sigma(\bar{\nu_\tau}\nu_\tau \to e^+e^-)v_{rel} >= \alpha\mu^2\sqrt{1-y}\left(1+\frac{y}{2}-\frac{1-\frac{y}{2}-\frac{13}{8}y^2}{1-y}x\right) \equiv a(1+bx) \quad , \tag{3}$$

where $y \equiv m_e^2/m_\nu^2$, v_{rel} is the annihilating neutrinos' relative velocity, and I have used the thermal average $v_{rel}^2 = 6T/m_\nu \equiv 6x$. For $\mu_0 \gtrsim 2\cdot 10^{-9}m_\nu/10$ MeV, where μ_0 is the ν_τ

†The idea of introducing new neutrino interactions to modify the standard value of ρ_ν is not new. Other authors [4] have suggested the existence of very light or massless scalar particles to open new channels for primordial neutrino annihilation.

magnetic moment in units of Bohr magnetons ($\mu^2 \equiv \mu_0^2 \alpha\pi/m_e^2$), the rate (2) dominates the rates for the weak annihilation processes $\bar{\nu_\tau}\nu_\tau \to e^+e^-, \bar{\nu_e}\nu_e, \bar{\nu_\mu}\nu_\mu$, mediated by Z^0 exchange.

The standard relic abundance calculation [1] gives a neutrino freeze-out temperature T_f:

$$\frac{m_\nu}{T_f} \equiv x_f^{-1} \simeq A - \frac{1}{2}\ln A + \ln(1+\frac{b}{A}) \quad , \tag{4}$$

$$A = \ln\left(0.076\frac{m_{Pl} m_\nu a}{g_*^{1/2}}\right) \quad , \tag{5}$$

where g_* counts the total number of effectively massless degrees of freedom at freeze-out contributing to the radiation energy density, $g_* \equiv 30\ \rho(T_f)\ /(\pi^2 T_f^4)$. Assuming vanishing ν_τ cosmic asymmetry, the present τ neutrino and antineutrino contribution to Ω, the energy density in units of the critical density, is:

$$\Omega h^2 = 1.7 \cdot 10^{-16}\ \frac{g_*^{1/2}}{g_{*S}} \frac{\mathrm{MeV}^{-2}}{x_f\ a(1+\frac{b}{2}x_f)} \quad , \tag{6}$$

where h is the Hubble constant in units of 100 km sec^{-1} Mpc^{-1}, and g_{*S} counts the number of effectively massless degrees of freedom at freeze-out contributing to the entropy density, $g_{*S} \equiv 45\ s(T_f)\ /(2\pi^2 T_f^3)$[‡]. Replacing eq.(2) into eqs.(3–5), I obtain:

$$x_f^{-1} \simeq 12.5 + \ln\frac{m_\nu}{3\ \mathrm{MeV}} + 2\ln\frac{\mu_0}{10^{-6}} \qquad \text{for}\ \ m_\nu \lesssim 7\ \mathrm{MeV} \tag{7}$$

$$x_f^{-1} \simeq 13.8 + \ln\frac{m_\nu}{20\ \mathrm{MeV}} + 2\ln\frac{\mu_0}{10^{-6}} \qquad \text{for}\ \ m_\nu \gtrsim 7\ \mathrm{MeV} \tag{8}$$

$$\text{and} \qquad \Omega h^2 \simeq 1.2 - 1.8\left(\frac{\mu_0}{10^{-6}}\right)^{-2} \quad . \tag{9}$$

Therefore a ν_τ magnetic moment $\mu_0 \simeq 10^{-6}$ can deplete the present neutrino relic abundance and explain the dark matter in the form of ν_τ with mass in the range 1–35 MeV.

Such a large magnetic moment has been experimentally ruled out for neutrinos of the first two generations, since $\bar{\nu_e}e$ and $\nu_\mu e$ scattering data impose the bounds $\mu_0 < 1.5 \cdot 10^{-10}$

[‡]For $T_f > m_e$, photons, electrons, and massless neutrinos contribute to $g_* = g_{*S} = 9$. For $T_f < m_e$, the reheating of photons with respect to massless neutrinos should be taken into account. Depending on whether the ν_τ is relativistic or non-relativistic at the freeze-out temperature of massless neutrinos ($\simeq 1$ MeV), the ratio between $\nu_{e,\mu}$ and γ temperatures is respectively $(2/9)^{1/3}$ or $(4/11)^{1/3}$. Therefore, in the case $T_f < m_e$, the effective degrees of freedom vary continuously with m_ν from $g_* = 2.47$, $g_{*S} = 2.78$ (for $m_e \lesssim m_\nu \lesssim 1$ MeV) to $g_* = 2.91$, $g_{*S} = 3.27$ (for $m_\nu \gtrsim 5$ MeV).

for ν_e and $\mu_0 < 1.2 \cdot 10^{-9}$ for ν_μ [5]. No such limits apply to the τ neutrino however, since no experiment has made use of ν_τ beams. In order to derive bounds on μ_0, one can consider collider experiments.

A test of the ν_τ magnetic moment comes from neutrino counting experiments via single-photon events in e^+e^- collisions: a non-vanishing μ enhances the ν_τ expected cross section. For $\sqrt{s} << M_Z$, the dominant contribution due to a ν_τ magnetic moment interaction comes from the diagrams of fig.1 and yields the differential cross section:

$$\frac{d\sigma}{dxdy}(e^+e^- \to \bar{\nu}_\tau \nu_\tau \gamma) = \frac{\alpha^2\mu^2}{3\pi} \frac{(1-\frac{x}{2})^2 + (\frac{xy}{2})^2}{x(1-y^2)} \quad . \tag{10}$$

Here I have neglected fermion masses, and $x \equiv 2E_\gamma/\sqrt{s}$, $y \equiv \cos\theta$, where E_γ and θ are the photon energy and polar angle.

It is worthwhile to notice that, unlike the case of massless *charged* particles in QED, the cross section (9) is not divergent as the massless neutrinos become collinear[§]. On the other hand, eq.(9) presents the familiar divergences for zero energy photons or for photons emitted along the beam line.

Imposing the cuts on the photon energy $E_\gamma < 10$ GeV, on the polar angle $|\theta| < 20^\circ$, and on the transverse photon momentum $p_T > 0.8$ GeV, the ASP collaboration [6] has reported the limit $\sigma(e^+e^- \to \bar{\nu}\nu\gamma) < 0.072$ pb from experiments at PEP ($\sqrt{s} = 29$ GeV). By integrating eq.(9) with the above cuts, I obtain:

$$\mu_0 < 8 \cdot 10^{-6} \qquad \text{at} \qquad 90\%\text{C.L.} \tag{11}$$

The bound in eq.(10) holds under the assumption that the magnetic moment coupling remains pointlike at $\sqrt{s}$. If the interaction contains a form factor and becomes softer as the energy increases, the limit (10) will be correspondingly less restrictive.

A large neutrino magnetic moment can produce anomalous single photon events at LEP through the process $Z^0 \to \bar{\nu}_\tau \nu_\tau \gamma$ (see fig.2). The differential Z^0 partial width, for point-like

[§]The neutrino current in the diagrams of fig.1 is proportional to $p^\mu - q^\mu$, where p and q are the neutrino and antineutrino momenta. As the neutrinos become collinear, $p^\mu - q^\mu$ becomes proportional to k^μ, the momentum of the virtual photon. Due to gauge invariance, the divergence in the photon propagator is cancelled and the matrix element remains finite.

magnetic moment interactions, is:

$$\frac{d\Gamma}{dx}(Z^0 \to \bar{\nu_\tau}\nu_\tau\gamma) = \frac{\alpha\mu^2 M_Z^3}{96\pi^2 \sin^2\theta_W \cos^2\theta_W} x(1 - x + \frac{x^2}{12}) \quad , \tag{12}$$

where $x \equiv 2E_\gamma/M_Z$, and the neutrino mass has been neglected. As before, no divergence occurs as the photon and the neutrino become collinear. Eq.(11) yields a Z^0 branching ratio:

$$BR(Z^0 \to \bar{\nu_\tau}\nu_\tau\gamma) = 2 \cdot 10^{-7} \left(\frac{\mu_0}{10^{-6}}\right)^2 \quad . \tag{13}$$

Given the very clear experimental signal, LEP can improve the bound (10), yielding a result closer to the cosmologically interesting value $\mu_0 \simeq 10^{-6}$.

Strong limits on the ν magnetic moment have been derived by computing cooling rates of stars and stellar collapses [7–8]. These limits do not apply to the ν_τ's considered here, which are typically too heavy to be relevant in most astrophysical conditions. Even in situations where very large temperatures are involved, as in supernova explosions, and ν_τ's can be pair produced, the strong magnetic interaction traps the neutrinos, inhibiting their emission. Let us consider the case of SN1987A, and estimate the ν_τ luminosity. The ν_τ mean free path inside the protoneutron star of density ρ is [8]:

$$l \simeq 4 \cdot 10^{-2}\text{cm}\frac{10^{14}\text{g cm}^{-3}}{\rho}\left(\frac{10^{-6}}{\mu_0}\right)^2 \quad . \tag{14}$$

As the distance from the core (R) increases, ρ descreases and l gets larger. Neutrinos are trapped inside a region where $l(R) \lesssim R$ and radiated from the surface according to the Stefan–Boltzmann law. This gives an emission in ν_τ which is suppressed by more than five orders of magnitude with respect to ordinary neutrinos.

Let us now check that a τ neutrino with $\mu_0 \simeq 10^{-6}$ and mass 1–35 MeV does not upset the successful predictions of big-bang nucleosynthesis. The presence of non-standard contributions to the energy density at the time of primordial nucleosynthesis can increase the synthesized abundances, leading to overproduction of ^{4}He. Before freeze-out, for $T > T_f \simeq m_\nu/13$, the ν_τ's are in thermal equilibrium. The magnetic moment interaction, allowing the transition between left- and right-handed neutrinos, doubles the effective ν_τ degrees of freedom contributing to the energy density with respect to the case of a massless neutrino. Nevertheless, at the time of nucleosynthesis, the ν_τ energy density is smaller than the corresponding value for a massless neutrino, because of the Boltzmann suppression for $T < m_\nu$. For $T < T_f$, the ν_τ's have the typical energy density of cold dark matter relic particles, $\rho \simeq \rho_c(T/T_0)^3$, T_0 being the present neutrino temperature and ρ_c the critical density. For instance, at $T = 0.1$ MeV, decoupled τ neutrinos have an energy density of only 10^{-4} times the contribution from a massless neutrino. Therefore, in this scenario, the ^{4}He abundance can even be reduced compared to the standard prediction with three massless neutrinos.

The primordial ν_τ annihilations produce e^+e^- pairs with energy $E_e = m_\nu$. The electrons and positrons will rapidly thermalize by Compton scattering, because of the large number of background photons, and generate secondary high-energy photons. These photons will lose energy by producing e^+e^- pairs off thermal background photons or by Compton scattering. To a lesser extent, they can be degraded by photodissociation of nuclei, thus jeopardizing the successes of nucleosynthesis.

The maximum energy of a secondary photon created by inverse Compton scattering of an electron with energy $E_e = m_\nu$ is:

$$E_{max}(T) = m_\nu \left(1 + \frac{m_e^2}{4m_\nu E_\gamma^B}\right)^{-1} \quad , \tag{15}$$

where E_γ^B is the typical thermal energy of a background photon, $E_\gamma^B \simeq 3T$. At any given temperature T, there is a critical photon energy $E_{crit}(T)$ above which the e^+e^- pair production is so efficient that the probability for photodissociation becomes vanishingly small [9],

$$E_{crit}(T) \simeq 0.04 - 0.08 \; \frac{m_e^2}{T} \quad . \tag{16}$$

Therefore the highest energy (E_γ) available to photons which can potentially photodissociate nuclei is given by the minimum of eqs.(14) and (15), $E_\gamma \simeq 0.5 - 0.6 \; m_\nu$. Only nuclei with low binding energies ($E_b < 0.5 - 0.6 \; m_\nu$) are vulnerable to photons coming from ν_τ annihilations. Notice that these photons are produced at temperatures below ν_τ freeze-out, when however occasional annihilations can still occur.

Since ^{4}He photofission ($E_b \simeq 20$ MeV), which generally provides the most stringent limits on high energy photon production, is typically not accessible, one has to consider reactions with lower threshold energy: ^{7}Li(γ,T)^{4}He (E_b=2.5 MeV), ^{3}He destruction (E_b=5.5 MeV), and D(γ, n)p (E_b=2.2 MeV). Ref. [10] has studied limits on late annihilations of relic particles from ^{7}Li destruction. From their eqs.(29–30), it can be inferred that photons from ν_τ annihilation can only deplete the ^{7}Li abundance with respect to standard nucleosynthesis results by less than 10%; such a depletion is therefore compatible with observations.

If τ neutrinos form the halo of our galaxy, they have a local number density of about 300 (10 MeV/m_ν)cm^{-3}. Unfortunately, probing their existence is beyond the reach of the presently operating experimental dark matter searches. Actually, the maximum energy transfer that neutrinos can deposit on a target particle of mass M is $E_{max} = 2 \cdot 10^{-6} M(1 + M/m_\nu)^{-2}$, which is too small to be detected for either nuclei or electron targets.

Recently, it has been suggested [11] that the cosmic neutrino background could be measured by observing Bremsstrahlung photons emitted in the coherent ν scattering off free cold electrons. In the case of the ν_τ here discussed, the large local neutrino density and the strong magnetic moment interaction at low energy guarantee a copious rate of Bremsstrahlung photons. If detectors sensitive to soft photons are developed in the future, the hypothesis of ν_τ dark matter could be experimentally tested.

So far I have not made any reference to the kind of interaction giving rise to the effective ν_τ magnetic moment coupling. The standard model accounts for

$$\mu_0 = \frac{3G_F m_e m_\nu}{4\sqrt{2}\pi^2} = 3 \cdot 10^{-12} \left(\frac{m_\nu}{10 \text{ MeV}}\right) \quad , \tag{17}$$

much too small to be the value advocated in this paper. Nevertheless, large values of μ_0 can arise in extensions of the standard model.

It is amusing to note a potential connection with the solar neutrino problem. If the depletion of neutrinos from the Sun is due to an electron neutrino magnetic moment $\mu_0 \simeq 10^{-10} - 10^{-12}$ [12], it seems reasonable to argue that the ν_τ also has a magnetic moment, maybe several orders of magnitude larger, if, as assumed here, $m_{\nu_\tau} >> m_{\nu_e}$.

In conclusion, I have proposed that a stable ν_τ with mass 1–35 MeV and magnetic moment $\mu_0 \simeq 10^{-6}$ could be the constituent of the dark matter responsible for the observed galactic halos.

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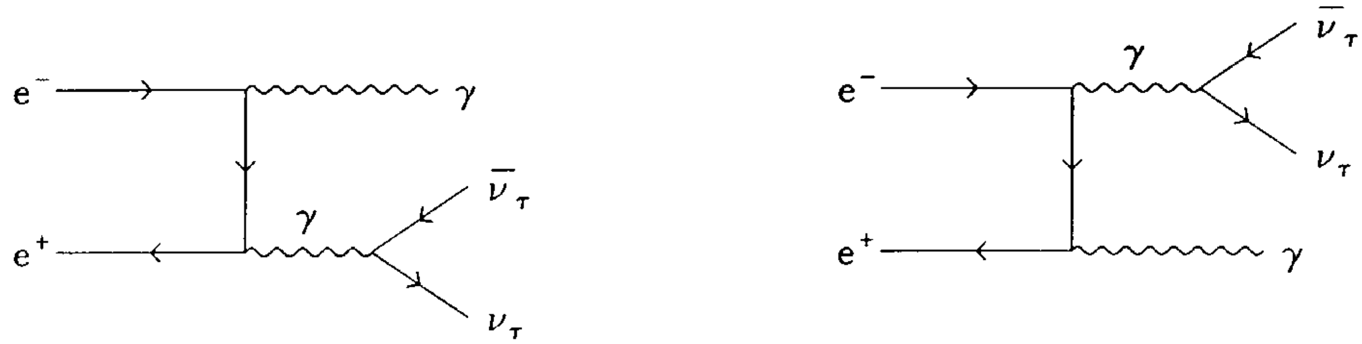
Figure Captions

Fig.1 - Dominant Feynman diagrams for the process $e^+e^- \to \bar{\nu}_\tau \nu_\tau \gamma$ at $\sqrt{s} << M_Z$.

Fig.2 - Feynman diagrams for the decay $Z^0 \to \bar{\nu}_\tau \nu_\tau \gamma$.



e⁻
e⁺
γ
γ
$\bar{\nu}_\tau$
ν_τ
e⁻
e⁺
γ
γ
$\bar{\nu}_\tau$
ν_τ

Fig.1

Z^0
$\bar{\nu}_\tau$
γ
ν_τ
Z^0
$\bar{\nu}_\tau$
γ
ν_τ

Fig.2