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COLD DARK MATTER CANDIDATE?

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IS STABLE TAU - NEUTRINO REALLY AN ALLOWABLE COLD DARK MATTER CANDIDATE?

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Abstract

Considering the annihilation of massive tau-neutrinos in the Galactic halo we show that it is difficult to obtain the concordance between the observed (directly or indirectly) and predicted fluxes of cosmic electrons and positrons in the case of a stable tau-neutrino with mass $m \approx 1 - 24$ MeV and magnetic moment $\mu \sim 10^{-6} \mu_B$. These results exclude the possibility for such tau-neutrino to be the cold dark matter particle component.

The concordance that exists between the predicted and observed abundances of light elements such as D, He, Li in the framework of the standard cosmology leads to the accurate determination of the baryon density [1],

$$\rho_b = 1.7 \times 10^{-31} \text{ g} \cdot \text{cm}^{-3} - 4.1 \times 10^{-31} \text{ g} \cdot \text{cm}^{-3}. \quad (1)$$

Because the critical density,

$$\rho_c = 3H_0^2 / (8\pi \cdot G) = 1.88h^2 \times 10^{-29} \text{ g} \cdot \text{cm}^{-3}, \quad (2)$$

depends on the Hubble constant H_0 ($h \equiv H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1}$) the present ratio of the baryon density ρ_b of the Universe to its critical density ρ_c also depends on H_0 ,

$$\Omega_b \equiv \rho_b / \rho_c \approx 0.009h^{-2} - 0.022h^{-2}. \quad (3)$$

For a wide range for the Hubble constant, $h = 0.4-1$, baryons contribute between 1% and 15% of critical density of the Universe.

This fact has important implications. First, since the contribution of luminous matter,

$$\Omega_{lum} \approx 0.003h^{-1}, \quad (4)$$

is much less than 1% of closure density, most baryons in the Universe should be dark at the present either in form of hot gas in clusters of galaxies or in other form as dark stars, neutron stars, black holes et cetera.

Second, there are strong theoretical arguments (e.g. structure formation, inflation) and experimental evidences favouring the average density of the matter which might be significantly greater than allowable 15% of critical density possibly provided by baryons. If this is the case, then most of the matter in the Universe must be nonbaryonic. The nature of this dark matter is one of the most important questions facing both cosmology and particle physics. The variety of dark matter candidates is somehow confusing and one must try to select the most realistic dark matter particles allowed by all known observational bounds.

Usually we distinguish two classes of nonbaryonic dark matter on the basis of their clustering properties, hot dark matter being rapidly moving particles at galaxy formation and cold dark matter whose particles being slow at that epoch. Recent investigations are in favour of mixed scenario for the dark matter. A combination of 70% cold and 30% hot dark matter produces a favourable spectrum of density perturbations and leads to a better consistency between the inflationary predictions and some dynamical estimates. The only reasonable candidate for hot dark matter is a neutrino of mass several to several dozen eV. The most popular candidate for cold dark matter is a neutralino - the lightest supersymmetric particle. However there is also a very interesting hypothesis of Giudice [2] that tau-neutrinos with mass between 1 MeV and the present experimental

bound 24 MeV [3] and a magnetic moment near the present experimental limit $\mu(\nu_\tau) \approx 10^{-6}\mu_B$ [4] could play a relevant role in cosmology as a cold dark matter particle constituting totally the galactic halo. This would supply a nice solution to the problem of structure formation.

Let us consider a stable ν_τ with mass m between 1-24 MeV and a non-zero magnetic moment. For $\beta > 2 \times 10^{-9} m / (10 \text{ MeV})$, where β is the ν_τ magnetic moment in units of Bohr magnetons ($\beta^2 \equiv (\mu m_e)^2 / (\alpha \pi)$), the weak neutrino annihilation through Z-boson exchange is suppressed in comparison with the electromagnetic channel

$$\nu_\tau \bar{\nu}_\tau \rightarrow \gamma \rightarrow e^+ e^-. \quad (5)$$

The cross section for the process (5) is given by [2]

$$\sigma = \frac{1}{6} \alpha \mu^2 \sqrt{\frac{1 - 4m_e^2/s}{1 - 4m^2/s}} \left(1 + \frac{8m^2}{s}\right) \left(1 + \frac{2m_e^2}{s}\right), \quad (6)$$

where $\sqrt{s}$ is the total energy. The standard calculations [5] give a tau-neutrino freeze-out temperature

$$T_f \approx m / \left[13 + 2 \ln(\beta / 10^{-6})\right], \quad (7)$$

and therefore at the instant of decoupling tau-neutrinos are non-relativistic. In the non-relativistic limit eq.(6) takes very simple form $\sigma v \approx \alpha \mu^2$, where v is the relative neutrino velocity, and the present relic (homogeneous cosmological) number density of such massive tau-neutrinos is defined approximately by the equation

$$n \approx 0.006 (10^{-6} / \beta)^2 (MeV / m), cm^{-3}. \quad (8)$$

It is assumed in deriving of eq.(8) that the neutrino magnetic moment β is of the order 10^{-6} . In this case the fraction of critical density contributed by tau-neutrinos is

$$\Omega_\nu \equiv \rho_\nu / \rho_c = 2mn / \rho_c \approx 1.2 (10^{-6} / \beta)^2 h^{-2}. \quad (9)$$

As we see from eq.(9) the existence of tau-neutrinos with the properties mentioned above is cosmologically acceptable[2] due to annihilation of massive ν_τ in reaction (5) which leads to the decreasing of neutrino number density to the cosmologically acceptable value.

However the nonuniform distribution of massive tau-neutrinos in the Universe and the local increase of the neutrino density in the formation of the galactic halo lead to processes which might have relevant consequences in astrophysical observations. As it

was shown [6,7] the condensation of neutrinos in the Galaxy should speed up their annihilation resulting in the generation of cosmic rays. Therefore the comparison of the predicted cosmic ray flux due to such annihilation with the observed flux allows one to obtain some severe restrictions on neutrino properties.

According to [6] the contracting baryon matter induces the collapse of the neutrino gas and leads to the significant increase in the neutrino density in the Galaxy. At the first stage of galaxy formation, when the density of baryon matter is small, the latter increases due to the effects of dissipation, without any sizeable effect on the neutrino density. However, when the baryon density becomes comparable with the neutrino density the last one starts to increase its density contrast following the baryon density and reaching the present value in the Galaxy [6]

$$n_{\nu g} \approx n(\rho_b)_g / (\rho_b)_{in} \quad (10)$$

where $(\rho_b)_g \approx 5 \times 10^{-24} \text{ g/cm}^3$ is the average density of the extended galactic halo and $(\rho_b)_{in}$ is the average "initial" baryon density in the Galaxy, starting from which the cosmological neutrino density (at that time comparable with $(\rho_b)_{in}$) increases and therefore $(\rho_b)_{in} \approx \rho_\nu \approx 2 \times 10^{-29} \text{ g/cm}^3$.

Let us note that the same order of the increase for neutrino density contrast can be expected by the two-fluid clustering model [8], in the expanding Universe or even at the long wave limit ($k \rightarrow 0$) in the standard one-fluid clustering where $\delta\rho/\rho \sim (t/t_i)^{2/3} \sim (\rho_\nu/\rho_{BBR}) \sim 10^5$.

The flux of cosmic electrons (positrons) from the neutrino annihilation (5) in the Galaxy is given by the following formula:

$$J = T_e \frac{dn}{dt} \frac{c\delta}{8\pi}, (cm^{-2}s^{-1}sr^{-1}) \quad (11)$$

where $dn/dt = n_{\nu g}^2 \sigma_g v$ is the rate of neutrino annihilation in the Galaxy per unit volume, σ_g is the cross section of the neutrino annihilation in the Galaxy, $T_e \approx 10^8$ years is the life-time of cosmic electrons (at MeV energies) in the Galaxy, c is the velocity of light, δ is the number of electrons which are produced in one act of the neutrino annihilation. Substituting formulae (6),(8),(10) into eq.(11) we find the flux of cosmic electrons (positrons)

$$J_e \approx 6 \times 10^4 (10^{-6} / \beta)^2 (MeV / m)^2. \quad (12)$$

The electron (positron) line from tau-neutrino annihilations in the Galaxy is expected to be very narrow (its width is of the order $\sim mv/c \sim 10^{-3}m$) at $E \sim m$. For electron energies between 1 MeV and 24 MeV the experimental differential electron flux [9] (integrated over such ΔE that $\Delta E/E \sim 0.1$) is $J_{\text{exp}} \approx 10^{-3} \text{MeV/m}$ and this value is much less (by many order of magnitude) than the possible electron flux (12) from the tau-neutrino annihilation. So the existence of tau-neutrinos with the mass between 1-24 MeV and the magnetic moment $\beta \sim 10^{-6}$ would lead to a very large flux of cosmic electrons from tau-neutrino annihilation in the Galaxy and to a contradiction with the observed spectrum of cosmic electrons. Of course it would be possible to obtain the consistency between the flux (12) and the experimental flux for larger values of the magnetic moment $\beta \gg 10^{-6}$ but such values are in contradiction with the modern laboratory bounds on neutrino magnetic moment [4].

We should note that uncertainties in our calculations are large, even one or two orders of magnitude due to electron line broadening, uncertainties in the life-time of cosmic rays and the law of condensation (10), modulations of the electron flux with the Sun activity. It seems nevertheless unlikely that all these effects could eliminate the difference between the observed flux and the predicted one by about 6 orders of magnitude. In our consideration we assumed that the neutrino number density in the Galaxy is increased by about 10^5 in comparison with the cosmological density but even the increase by few hundreds does not leave much room for tau-neutrino with the properties mentioned above.

Electron fluxes while being a firm measure they probe mainly the nearby surrounding in our solar system and might just reflect a local galactic signal which could be inhomogeneous or even suppressed one with respect to larger electron fluxes all over the Galaxy. Therefore it would be useful to infer in an independent way the possible traces of galactic electron fluxes. There are indeed two main processes responsible for the energy losses of electrons in the Galaxy: the inverse compton scattering (ICS) onto the cosmic BBR and the synchrotron radiation (SR) by the relativistic electrons onto random galactic magnetic fields. Unfortunately ICS of MeV electrons induce a tiny undetectable influence in the dominant infra red background. The same ICS produce also a decrease in the photon number density and a deviation in the BBR spectra (a Sunyaev-Zeldovich like-effect), which is below present sensitivity: its Comptonization factor is $y < 10^{-7}$.

However the synchrotron radiation "pollute" with efficiency the lowest region of radio waves band leading to detectable radio fluxes. Indeed we may easily deduce the total energy radiated in ICS by each electron into radio waves:

$$P = \frac{4}{3} \sigma_T \frac{B^2}{8\pi} c \gamma^2 \approx 4 \times 10^{-26} \left(\frac{E}{\text{MeV}} \right)^2 \left(\frac{B}{B_0} \right)^2 \text{erg} \cdot \text{sec}^{-1}, \quad (13)$$

where σ_T is the Thomson cross section, $B_0 = 3 \times 10^{-6} \text{G}$ is the average magnetic field in the Galaxy, γ is the electron Lorentz factor. The corresponding critical frequency of SR is

$$\omega_c = \frac{3}{2} \frac{Be}{mc} \gamma^3 \approx 6 \times 10^5 \left(\frac{m}{10 \text{MeV}} \right)^3 \left(\frac{B}{B_0} \right) \text{sec}^{-1}. \quad (14)$$

While the life time of MeV electrons exceed 10^{16} sec ($3 \times 10^8 \text{yr}$) most of their born synchrotron photons (whose $\omega_c > 10^4 \text{Hz}$) will escape from galactic halo ($\sim 100 \text{ kpc}$) in a corresponding time $\tau \sim 10^{13} \text{sec}$. For a firmer lower bound we use the latter lowest time to obtain the minimal energy density in radio waves by SR: $\rho_{\gamma R} \approx 8 \times 10^{-19} \text{erg cm}^{-3}$. The result is independent on neutrino mass. The consequent predicted differential flux at MHz frequency (with a characteristic dipole anisotropy due to the galactic halo) is $(\Delta\Phi/\Delta\nu)_{\text{theor}} \approx 2.4 \times 10^{-14} \text{erg Hz}^{-1} \text{sec}^{-1} \text{cm}^{-2} \text{sr}^{-1}$, which is above three order of magnitude of the experimental flux $(\Delta\Phi/\Delta\nu)_{\text{exp}} \approx 3 \times 10^{-17} \text{erg Hz}^{-1} \text{sec}^{-1} \text{cm}^{-2} \text{sr}^{-1}$ [10].

One may note that the radio arguments apply better to neutrinos with the mass $> 10 \text{ MeV}$ because of eq.(14). However it is possible to verify also the presence of the fluxes of non relativistic positrons (electrons). Indeed the positron annihilation line has the prominent signature. We can see that most all 1 MeV - 24 MeV positrons born by tau-neutrino annihilation will be captured with in the galactic halo by the magnetic field and annihilate by relic free electrons. Because the annihilation cross section increases as the inverse of the positron velocity most of these annihilations will occur at non relativistic stage from positronium system producing practically monochromatic line with $E_\gamma = m_e$. Therefore we should expect a clear energy input by this positron annihilation into the sensitive gamma line with the gamma flux comparable with the electron (positron) flux (12): $J_\gamma \sim J_e$. We can compare this strong signal with the present experimental one at $E_\gamma \approx 1 \text{ MeV}$: $(J_\gamma)_{\text{exp}} \approx 10^{-2} \text{sec}^{-1} \text{cm}^{-2} \text{sr}^{-1}$. For tau-neutrinos in the mass range between 1 MeV - 24 MeV the predicted flux is nearly from 7 order to 4 order of magnitude above the experimental one. So the investigation of positron annihilation line confirms previous results and excludes the existence of Giudice's tau-neutrino.

Finally we may estimate the higher energy components of gamma rays due to the relativistic annihilation in the positron collisions with static relic electrons. They will

produce a continuous spectrum of photons at few MeV with an intensity once again at least four power of magnitude above the experimental ones.

Therefore it seems to us that there are no allowable free window for parameters of stable tau-neutrino self consistent with know astrophysical and cosmological data to be the cold dark matter particle constituting totally the critical density of the Universe.

In conclusion we should emphasize the importance of search for the monochromatic annihilation lines in spectra of cosmic electrons and positrons. If found they would be a strong indication on the annihilation in the Galaxy of hypothetical heavy particles of a definite nature (for example Dirac neutrino) and of definite masses [11,12]. We also note that our approach is valid in the case of a multicomponent dark matter and may also be used for species that give even a negligible contribution to the total energy of the Universe. Our treatment can be easily extended to any other "weakly" interacting stable neutral particles, and, what is more important, the weaker is their interaction the larger is their relic number density (see eq.(8)) and more stringent constraints could be obtained on the parameters of these particles from astrophysical experiments.

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