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OF VERY HEAVY NEUTRINOS IN THE GLACTIC HALO
BY 1 KM³ NEUTRINO DETECTOR**

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ON THE POSSIBILITY OF DETECTING THE ANNIHILATION OF VERY HEAVY NEUTRINOS IN THE GALACTIC HALO BY 1 KM³ NEUTRINO DETECTOR

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ABSTRACT

We consider the possibility of detecting in a hypothetical 1 km^3 neutrino telescope high energy neutrinos resulting from the annihilation of very heavy neutrinos of fourth generation in the Galactic halo. It is shown that such a large telescope could in principle detect this negligible component which, if it does exist, gives even a tiny contribution of the order 10^{-2} to the dark matter of the Universe.

It is generally agreed that significant high energy neutrino astronomy can not be done without construction of a neutrino detector with an effective detecting volume of at least 1 km^3 [1]. The principle science goals for a 1 km^3 neutrino detector are the observation of very high energy neutrinos from active galactic nuclei and the search for the astrophysical effects of hypothetical particles existing in the Universe at different stages of cosmological evolution. The early Universe can manifest itself in fluxes of high energy neutrinos (preserved at the present time in the Universe) from decays of hypothetical unstable particles [2]. In the present Universe there could be decays and annihilation of weakly interacting cold dark matter particles (with masses generally in the GeV to TeV range) in the Galaxy. The most popular candidates for cold dark matter are neutralino - the lightest supersymmetric particle and axion - very light pseudoscalar particle. However, very heavy neutrinos of fourth generation could also contribute in part to the Galactic halo. In the present paper we consider the possibility to detect in a hypothetical 1 km^3 telescope high energy neutrinos resulting from the annihilation of very heavy neutrinos (if they exist) in the Galactic halo.

Since measurements of the width of the Z-boson peak at the LEP collider [3] rule out the possibility for fourth generation neutrinos having a mass smaller than 45 GeV, in the following we assume that the standard electroweak model is extended to include an additional fermion family: a heavy neutrinos ν of mass $m > 45 \text{ GeV}$ and a heavy charged lepton L , of mass M_L . In order to ensure the stability of the heavy neutrino we assume that $m < M_L$ and that the heavy neutrino is a Dirac particle. Also in the following we neglect the possible mixing of the heavy neutrino with other generations.

In the early Universe at high temperatures ($T \gg m$) heavy neutrinos should be in thermal equilibrium with the other kinds of particles and their number density should be compatible with that of photons. As the temperature in the Universe decreases the heavy neutrinos become non-relativistic at $T \approx m$ and their abundance falls off rapidly according to an exponential law. In the further expansion of the Universe, as the temperature drops below the freeze-out temperature T_f , the weak

interaction processes become too slow to keep neutrinos in equilibrium with the other particles and heavy neutrinos decouple. In this way very heavy neutrinos are cosmologically acceptable since their number density decreases drastically, so avoiding the conflict with the average density of matter in the Universe. A standard calculation [4] of the residual relic number density of heavy neutrinos gives [5]:

$$n \approx 4 \times 10^{-18} g_*^{-1/2} \frac{M_p}{m} (\sigma M_p^2)^{-1} [40 + \ln(\sigma M_p^2) + \ln(\frac{m}{M_p}) + \ln(\frac{g_s}{g_*^{1/2}})] n_\gamma, \quad (1)$$

where g_* is the number of effective degrees of freedom. g_s is the number of particle spin states, M_p is the proton mass, v is the relative neutrino velocity, σ is the total cross section of neutrino annihilation at freeze-out.

The analysis of the annihilation reactions of heavy neutrinos shows [5] that in the region of neutrino masses $m < 100$ GeV the dominant annihilation process is the neutrino annihilation into a light fermion pair through Z-boson exchange : $\nu\bar{\nu} \rightarrow Z \rightarrow f\bar{f}$. However, in the region of neutrino mass $m > 100$ GeV. the neutrino annihilation into W^+W^- pair through Z-boson exchange ($\nu\bar{\nu} \rightarrow Z \rightarrow W^+W^-$) starts dominating the total cross section [5,6]. If $m > 2M_W$. where M_W is the W-boson mass. then this annihilation cross section is given approximately by $\sigma\beta \approx 6.8[(m/M_W)^2 + 4]$, (pb), which gives according to eq.(1) the following relic number density of heavy neutrinos [5]:

$$n \approx 2 \times 10^{-9} (\frac{M_W}{m}) [(\frac{m}{M_W})^2 + 4]^{-1}, cm^{-3}. \quad (2)$$

We note that in deriving eq.(2) the annihilation cross section was evaluated at the total energy $S \approx 4m^2 + 6mT_f$, where the freeze-out temperature $T_f \approx m/30$, corresponding to non-relativistic neutrinos at freeze-out.

Of course such a small value for the cosmological number density of heavy neutrinos would not lead to significant astrophysical consequences. However the non uniform distribution of heavy 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 [7,8] the condensation of heavy neutrinos in the Galaxy should speed up their annihilation resulting in the copious generation of cosmic rays.

According to [7] the contracting baryon matter induces the condensation of heavy neutrinos and leads to the significant increase in the neutrino density in the Galaxy, roughly estimated [5,7] as

$$n_G \approx n \rho_G / \rho, \quad (3)$$

where $\rho_G \approx 5 \times 10^{-24} \text{g/cm}^3$ is the average density of the matter in the Galaxy, ρ is the cosmological density of baryons in the Universe. In order to obtain an upper bound on neutrino fluxes we take $\rho \approx 2 \times 10^{-31} \text{g/cm}^3$, which is allowed by the observed abundances of light elements [9].

The condensation of heavy neutrinos in the Galaxy leads to the increase in the rate of the neutrino annihilation resulting in a copious production of cosmic rays. The output of light neutrinos (ν_e, ν_μ, ν_τ) from the annihilation of heavy neutrinos in the Galaxy can be evaluated by exploiting the following formula for the flux

$$F = \frac{dn}{dt} \left(\frac{V}{4\pi R^2} \right) \frac{3}{8\pi} (cm^{-2} sr^{-1} s^{-1}), \quad (4)$$

where

$$dn/dt = n_G^2 \sigma_G v \quad (5)$$

is the rate of neutrino annihilation in the Galaxy, σ_G is the cross section of the neutrino annihilation in the Galaxy, V is the volume of the Galaxy, $R \approx 10 \text{ kps}$ is the typical distance.

Substituting formulae (3),(5) into eq.(4) gives us the general expression for the flux of one specie (ν or $\bar{\nu}$) of light neutrinos

$$F \approx 1.6 \times 10^{10} n^2 (\sigma_{G\beta} / pb), \quad (6)$$

where the annihilation cross section for the process $\nu\bar{\nu} \rightarrow \nu_f \bar{\nu}_f$ ($f=e, \mu, \tau$) can be written as

$$\sigma_{G\beta} \approx 5.7 \frac{SM_W^2}{[(S - M_Z^2)^2 + \Gamma^2 M_Z^2]} (pb), \quad (7)$$

with M_Z and Γ being the mass and the width of the Z-boson.

Let us note that we are considering the direct production of light neutrinos in the annihilation reaction of heavy neutrinos. Because heavy neutrinos are non-relativistic in the Galaxy, light neutrinos are produced in this reaction practically monochromatic with $E \approx m$ and the width of the energy distribution is very narrow of the order $\Delta E \sim mv/c$, where $v = 300$ km/s is the velocity of heavy neutrinos in the Galaxy. Of course light neutrinos can be also produced in the secondary processes from the decay of W-bosons, μ -, τ - leptons and quarks, but these processes contribute generally to the soft part of the spectrum and we shall neglect them.

The results of numerical calculations of the flux for $\nu_\mu + \bar{\nu}_\mu$ (the flux will be exactly the same for $\nu_e + \bar{\nu}_e$, $\nu_\tau + \bar{\nu}_\tau$) on the basis of the exact expressions of refs.[5,6] for the cross sections are shown in fig.1. The same figure shows also the calculated atmospheric neutrino flux [10] integrated over $\Delta E = 1$ GeV from background processes such as decays of π -, K- mesons (which appear due to p - p and p - nucleus collisions). As one can see from fig.1 the annihilation flux of ν_μ is significantly less than the background one. This is exactly the case for ν_e . However, for ν_τ the situation is completely different. Until now nobody calculated a tau neutrino contribution to the atmospheric neutrino flux. It is however clear that this contribution is completely negligible at least up to the PeV energy range. Indeed, the only effective mechanism of tau neutrino production in the atmosphere is D_s -, B - meson decays, but the cross sections of heavy quark production are too small even in the PeV range and practically zero below 1 TeV. In some way the situation with tau

neutrinos is similar to the one with neutrinos coming from decays of charmed particles, and, as it was shown [11], the neutrino flux from such decays is completely negligible below the TeV range.

Let us now evaluate the number of events in the detector with volume of 1 km^3 of water due to tau neutrinos ($\nu_\tau + \bar{\nu}_\tau$). The cross section of a ν - nucleon interaction is given by $\sigma(\nu_\tau N \rightarrow \tau^- + \dots) \approx 2\sigma(\bar{\nu}_\tau N \rightarrow \tau^+ + \dots) \approx 0.44 G^2 M_p E / \pi$. Since in our case $E \approx m$, we obtain the following number of events in the detector

$$N \approx 0.74 \left(\frac{m}{M_W} \right) \left(\frac{F}{10^{-10}} \right) \left(\frac{t}{1 \text{ yr}} \right). \quad (8)$$

The number of tau neutrino events per year for 1 km^3 detector of water as a function of heavy neutrino mass is shown in fig.2. As it is seen, in the mass range 50 - 200 GeV we can expect up to 1 - 50 events with tau neutrinos. It was shown in ref.[5] that the 60 - 115 GeV range is ruled out by considering the electronic component of cosmic rays. However, outside this range, at least in principle, neutrino astronomy can give new bounds on the masses of very heavy neutrinos. In our consideration it was assumed that the Universe is symmetric with respect to leptons and anti leptons. The same result holds for a small charge asymmetry in the Universe. However, if for example in the early Universe the lepton number density significantly exceeds the anti lepton number density then it leads to a strong exponential suppression of the anti lepton component at the instant of decoupling. In this case at present it would be possible to expect a significant heavy neutrino contribution to the cosmological density of the order 1 due to a negligible annihilation rate because of the absence of heavy antineutrinos. If this would be the case the heavy neutrinos could contribute significantly to the dynamics of the Universe without any important observable effects in cosmic ray spectra (the annihilation rate in the Galaxy is also negligible) and even in very large neutrino detectors. However, such possibility is ruled out by underground direct searches [12] for cold dark matter.

Uncertainties in deriving expression (8) are large due to line broadening and rough estimation of the increase in neutrino density (3), but it is important for us to show that the construction of large 1 km^3 detector can lead to the investigation of processes totally invisible at the present experimental level such as detection of a component (of a multicomponent dark matter of the Universe) which gives even a negligible contribution of the order 10^{-2} to the dark matter of the Universe. The construction of such a detector would allow one to extend the study of neutrino astronomy to tau neutrinos [13], in particular to very large energies in PeV region. In this case it would be possible to expect tau neutrino events with a non trivial signature due to the production of a τ - lepton in the detector and the following decay of the τ - lepton at large distance from the point of the tau neutrino interaction. Of course the realistic proposals for a 1 km^3 detector can be possible only after obtaining information from small high - energy neutrino detectors which are under construction now and are beginning to operate.

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Figure captions

- Fig.1 The full-line curve is the flux of cosmic neutrinos ($\nu_\mu + \bar{\nu}_\mu$) from the neutrino annihilation in the Galaxy as a function of heavy neutrino mass. The broken curve is the background atmospheric neutrino flux.
- Fig.2 The total number of the tau neutrino and tau antineutrino events per year for 1 km³ detector as a function of heavy neutrino mass.

Fig. 1

Fig. 2