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SIGNATURE OF RELIC HEAVY STABLE NEUTRINOS IN UNDERGROUND EXPERIMENTS

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Considering heavy stable neutrinos of 4-th generation we calculate the relic density of such neutrinos in the Universe. Taking into account the condensation of heavy neutrinos in the Galaxy and applying the results of calculations to experimental data from underground experiments on search for WIMP's in elastic neutral current scattering on nuclei we found an exclusion region of neutrino mass 60 GeV $< m <$ 290 GeV. The bounds obtained from present underground experiments while confirming the previous bounds derived from analysis of cosmic ray spectra are more reliable ones. We discuss also the first indication of elastic scattering induced by WIMP in DAMA experiment finding a very narrow window of neutrino mass 45 GeV $< m <$ 50 GeV compatible with the possible signal rate in the detector.

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There are strong theoretical arguments and experimental evidences favoring the average density of the matter in the Universe, which might be significantly greater than allowable 15% [1] of critical density possibly provided by baryons. The nature of this dark matter is one of the most important questions facing both cosmology and particle physics. Amongst the variety of dark matter candidates the theoretically favorite candidates are light neutrinos, axions and neutralinos. However in some models heavy neutrinos can play an important role in cosmology as a cold dark matter contributing a part of closure density.

In the present article we calculate the heavy neutrino density in the Galaxy and apply the results of calculations to experimental data from underground experiments on the direct search for WIMP – nucleus elastic scattering in order to obtain bounds on the mass of neutrino of 4-th generation.

In order to be specific we consider the standard electroweak model, including, however, one additional family of fermions. The heavy neutrino ν and heavy charged lepton L form a standard $SU(2)_L$ doublet. In order to ensure the stability of the heavy neutrino, we assume that its mass $m < M_L$ and that the heavy neutrino is a Dirac particle.

It is known that modern laboratory experimental results are not inconsistent with the existence of heavy Dirac neutrinos with mass $m < M_Z/2$, where M_Z is the mass of the Z boson. In the early Universe at high temperatures such heavy neutrinos should be in thermal equilibrium with other species of particles. As the temperature in the Universe drops, heavy neutrinos become nonrelativistic (at $T = m$) and their abundance falls off rapidly according to exponential law. In the further expansion of the Universe, as the temperature decreases below the freeze-out value T_f, the weak interaction processes become too slow to keep neutrinos in equilibrium with other particles. As a consequence, the number density of heavy neutrinos fails to follow the equilibrium concentration reaching at present

$$n = \frac{6 \cdot 10^3}{\sqrt{g_*}} \left(\frac{m_p}{M_{PL}}\right) \left(\frac{m_p}{m}\right) \left(\frac{\rho_c}{10^{-29} h^2 \mathrm{g} \cdot \mathrm{cm}^{-3}}\right) \left[\int_0^{x_f} dx m_p^2 (\sigma v)\right]^{-1} \mathrm{cm}^{-3} \,, \tag{1}$$

where $\rho_c = 1.879 \cdot 10^{-29} h^2 \mathrm{g} \cdot \ \mathrm{cm}^{-3}$ is the critical density of the Universe; h is the normalized Hubble constant; $M_{PL} = 1.221 \cdot 10^{19}$ GeV is the Planck mass; m_p is the proton mass; $x = T/m$; $x_f = T_f/m$; σ is the annihilation cross section; v is the relative velocity of the neutrino-antineutrino pair in its center-of-mass frame; g^* is the effective number of relativistic degrees of freedom at $T = T_f$ (bosons contribute 1 to g^* and fermions 7/8). The freeze-out temperature T_f can be computed iteratively from

$$x_f^{-1} = \ln \frac{0.0955 M_{PL} \sigma v m \sqrt{x_f}}{\sqrt{g^*}} \tag{2}$$

and generally $T_f \approx m/30$.

In general case the following processes could lead to the annihilation of heavy neutrinos in the Universe: $\nu\bar{\nu} \to f\bar{f}$, W^+W^-, ZZ, ZH, HH, however the dominant processes are $\nu\bar{\nu} \to f\bar{f}$ below the threshold for W^+W^- production and $\nu\bar{\nu} \to W^+W^-$ above the threshold [2].

Fig. 1 shows the dependence of cosmological density $\rho_\nu = 2mn$ of heavy neutrinos as a function of neutrino mass. In the region $m \sim M_Z/2$, the neutrino density is extremely small as a result of the huge value of the annihilation cross section at the Z boson pole. When the neutrino mass increases the cross section for neutrino annihilation drops and this leads to an increase of the neutrino density, which reaches its maximum value at

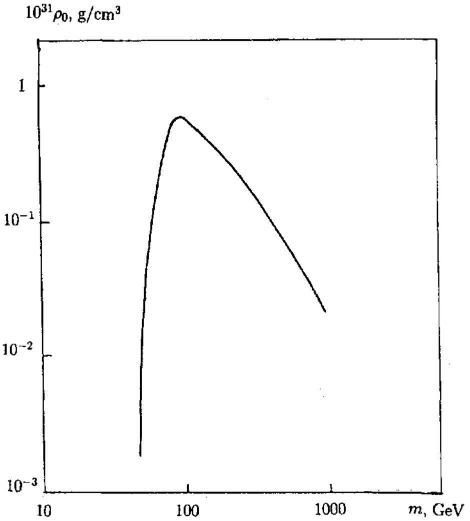

Fig.1. Cosmological density of heavy neutrinos as a function of neutrino mass

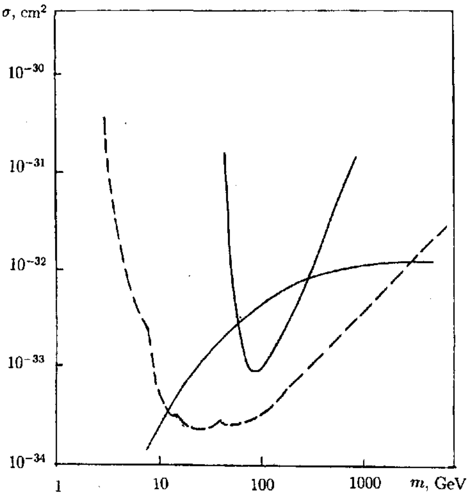

Fig.2. Mass exclusion plot for interaction of dark matter particles with Ge. Dashed line represents the boundary [7] corresponding to the case when neutrinos constitute all dark matter (ρ = 0.3 GeV$\cdot$ cm^{-3}). Solid line corresponds to "real" neutrino density in the Galaxy. The curve near the bottom of the plot shows the predicted cross section for a Dirac neutrino

$m \approx 100$ GeV. At $m > M_W$ the annihilation channel into W^+W^- opens and gradually becomes the dominant one, and since its cross section grows like m^2 [2,3] the present neutrino density drops again.

As it is seen from Fig.1 neutrino density is small in comparison with critical density. However in the Galaxy neutrino density can be increased by some orders of magnitude due to neutrino condensation. It was shown [3,4] that at the stage of galaxy formation the motion of heavy neutrinos in the nonstatic gravitational field of ordinary matter, which contracts as a result of energy dissipation via radiation, provides an effective mechanism of energy dissipation for neutrinos. As a consequence, the contracting ordinary matter induces the collapse of the neutrino gas and leads to the following significant increase in the neutrino density in the central part of the Galaxy:

$$n_{0G} \approx n\left(\frac{\rho_{0G}}{\rho_U}\right)^{3/4}, \tag{3}$$

where $\rho_{0G} \approx 10^{-20}\mathrm{g}\cdot\mathrm{cm}^{-3}$ is the central density of the matter in the Galaxy and $\rho_U \approx$ $\approx 4\cdot 10^{-31}\mathrm{g}\cdot\mathrm{cm}^{-3}$ is the density of matter in the Universe (here we take an upper limit [1] on the density of matter in order to evaluate neutrino density from below). It is often assumed that the density of dark matter halo in the Galaxy decreases with the distance from the center according to the law

$$\rho(r) = \frac{\rho_0}{1+(\rho/a)^2}, \tag{4}$$

where a (2 kpc $< a <$ 20 kpc) is the core radius of the halo. Assuming that neutrino density also follow the distribution (4), taking into the minimal value for the core radius $a = 2$ kpc and substituting into Eq.(4) the distance $r_{Sun} \approx 8.5$ kpc from the sun to the center of the Galaxy we find that the density in the solar neighborhood is reduced by the factor ≈ 19 in comparison with the central neutrino density (3). Therefore taking into account (3), (4) we obtain that the density of heavy neutrinos in the solar neighborhood has to satisfy the condition

$$n_{Sun} \geq 3.3 \cdot 10^6 n \ . \tag{5}$$

Let us apply the results obtained above to the experimental data on the direct search for WIMP's by WIMP-nucleus elastic scattering. Neutrinos scatter from nuclei by Z boson exchange and therefore the axial coupling, which only produces small spin-dependent effects, can be neglected. In the nonrelativistic limit the neutrino cross section due to coherent scattering on nuclei is given by [5]

$$\sigma_{elastic} \approx \frac{m^2 M^2}{2\pi (m+M)^2} G_F^2 \bar{Y}^2 \bar{N}^2 \ , \tag{6}$$

where $\bar{N} = N - (1 - \sin^2\theta_w)\ Z; N, Z$ are numbers of neutrons and protons, respectively; M is the mass of target nucleus, G_F is the Fermi constant, Y is an average hypercharge ($\bar{Y} \sim 1$). The nuclear degrees of freedom can be taken into account by a nuclear form factor [6].

Fig.2 shows an exclusion plot in a cross section of coherent neutrino elastic interaction with Ge obtained in underground experiments [7] versus heavy neutrino mass. The theoretical cross section corresponding to heavy neutrino elastic interaction taking into account the loss of coherence at high masses also is shown in Fig.2. However this exclusion plot was obtained under the assumption that the heavy neutrinos constitute all of dark matter with the density $\rho = 0.3$ GeV$\cdot$ cm^{-3}, which is $5.3 \cdot 10^{-25}$ g$\cdot$ cm^{-3}. In order to substitute ρ by ρ_{Sun} and modify the exclusion plot to the "real" case we have to divide the values corresponding to the bound of the exclusion plot by the ratio

$$\xi = \rho_{Sun}/\rho \ . \tag{7}$$

The new bound corresponding to the "real" neutrino density in the Galaxy is shown also in Fig.2 by dashed line. As we can see, in this case the existence of very heavy neutrinos is forbidden in the mass region

$$60\,\text{GeV} \geq m \geq 290\,\text{GeV} \ . \tag{8}$$

We note that (8) represents the minimal region excluded by Ge underground experiments because this result has been obtained by using for the astrophysical and cosmological parameters a conservative set of values. Changing in parameters chosen above leads only to the extension of the excluded region (8).

Previously less restrictive limits on mass of heavy neutrinos were obtained [3] from the analysis of the spectrum of electrons in cosmic rays. However that consideration contained uncertainties related in particular with poor knowledge of life time of cosmic rays in the Galaxy. Meanwhile bound (8) is based practically on the only assumption (but well physically motivated) concerning the condensation of heavy neutrinos in the Galaxy.

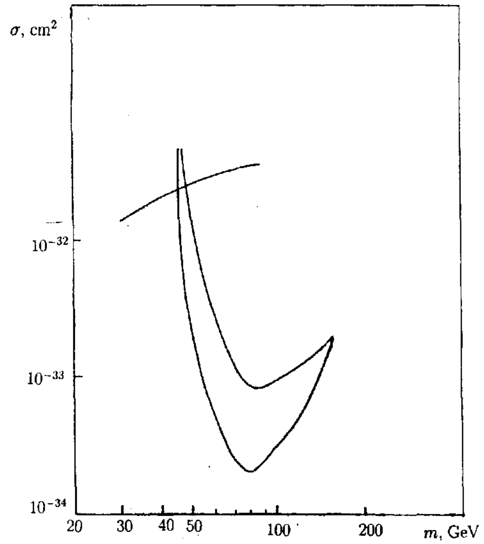

Fig.3. Region which corresponds qualitatively to the region of possible dark matter signal [8] at $m > 45$ GeV. Line intercepting the region shows the predicted cross section for a Dirac neutrino

Let us note that if Higgs meson exists the bound (8) does not exclude the possibility for heavy neutrinos to have mass in the region $|M_H - m| \leq \Gamma_H$, where Γ_H is the width of Higgs meson, because in this case the s-channel annihilation $\nu\bar{\nu} \to H \to \ldots$ could reduce significantly the neutrino density in the Galaxy [3].

Recently preliminary results on underground WIMP's search using the annual modulation signature with large mass NaI(Tl) detectors were published [8]. The overall analysis has shown that there is an indication on the single crystal response (however as it was mentioned by the authors [8] only very large exposure would possibly allow to reach a firm conclusion).

In Fig.3 we have shown qualitatively the region corresponding to the possible signal [8] taking into account the "real" neutrino density in the Galaxy according to Eq.(7). It was noted in [8] that the region of the signal is well embedded [6] in the minimal supersymmetric standard model estimates for neutralino. However as we see from Fig.3 this case can corresponds also to the elastic scattering by nucleus of NaI of relic neutrinos with mass between 45 GeV and 50 GeV. This region is consistent with the present laboratory bound $m > 45$ GeV.

The confirmation of this event can be obtained in experiments with cosmic rays, by AMS spectrometer, which is in preparation for the operation on Alfa station. As it was mentioned in [3,9,10] the detection of an anomalous output of monochromatic positrons with energy above 45 GeV would be a clear signature of the annihilation of Dirac neutrinos in the galactic halo because the direct annihilation of Majorana fermions into electron-positron pair in the Galaxy is severely suppressed. On the other hand the detection of the irregularity in the continuum spectrum of positrons could be an indication on the annihilation of neutralinos.

Our approach is easily testable because we assumed only the simplest extended Standard Model with 4-th generation without any ad hoc and fine tuning parameters.

We also note that the search for heavy neutrinos at accelerators [11] in the reaction $e^+e^- \to \nu\bar{\nu}\gamma$ could give a possibility of analyzing the mass region $m \sim M_Z/2$, which is difficult for an astrophysical investigation because of small value of neutrino density but can be important in relation with an event possibly observed in DAMA experiment [8]. If heavy neutrinos exist there could be also an interesting hadronless signature for Higgs meson bremsstrahlung production at accelerators $e^+e^- \to ZH \to Z\nu\bar{\nu} \to 1^+1^-\nu\bar{\nu}$ and this mode could be the dominant one.

In conclusion we emphasize that it seems that only complex investigations including underground experiments, accelerator searches, and astrophysical investigations can clarify the physical nature of dark matter.

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