Possible Effects of the Existence of the 4th Generation Neutrino

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Abstract

The 4th generation of fermions predicted by the phenomenology of heterotic string models can possess new strictly conserved charge, which leads, in particular, to the hypothesis of the existence of the 4th generation massive stable neutrino. The compatibility of this hypothesis with the results of underground experiment DAMA searching for weakly interactive particles of dark matter and with the EGRET measurements of galactic gamma–background at energies above 1 GeV fixes the possible mass of the 4th neutrino at the value about 50 GeV. The possibility to test the hypothesis in accelerator experiments is considered. Positron signal from the annihilation of relic massive neutrinos in the galactic halo is calculated and is shown to be accessible for planned cosmic ray experiments.

The superstring theory \cite{1} is considered in the last decade as the approach to the finite unified "theory of everything", in which, in an ideal case, all parameters of the theory are

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deduced from the first principles. However there is a wide variety of possible realisations of the superstring theory reproducing in low energy limit the Standard Model. Therefore the analysis of superstring phenomenology plays an important role allowing to specify possible parameters of the hidden sector of the theory. The existence of no less than 4 fermion generations, phenomenology of broken $E_6$ symmetry (the one which includes the symmetry of the Standard Model), $N = 1$ supergravity, and (broken?) $E_8'$ symmetry of shadow particles and their interactions are important consequences of the superstring theory [2], describing possible effects of the hidden sector in the simplest variants of the model of heterotic string. Identification of the 4th generation fermions with the states possessing new strictly conserved charge leads to the stability of lightest leptons and quarks of the 4th generation. In the present work we consider some consequences of the hypotheses that the lightest lepton of the 4th generation is a stable massive neutrino and we show, using in particular results of our previous works [3, 4, 5, 6], that the modern experimental data can be compatible with this hypothesis, as well as we describe the possibilities for its further experimental proof.

The results of measurement of $Z$ boson width exclude the possibility for the existence of the 4th generation neutrino with a mass $m < m_Z/2 \approx 45$ GeV. Therefore the heavy neutrino mass $m$ should be greater than $m_Z/2$. Due to radiative corrections such heavy neutrinos could affect masses of intermediate bosons. However the effect at least of one new generation can be compensated by the increase of top quark mass within the experimental accuracy [7].

In the present article we do not specify the physical nature of the 4th generation charge but we take into account that due to conservation of this charge the mass of heavy neutrino should be Dirac one but not Majorana mass. Strict conservation of this charge leads to the stability of the 4th generation neutrino.

Let us assume that the 4th generation quarks and leptons possess the same $SU(3)_c \otimes SU(2)_L \otimes U(1)$ gauge charges as corresponding quarks and leptons of standard generations. In this case within the framework of the Big Bang theory, assuming a thermodynamical equilibrium of plasma at $T > m$, it is possible to calculate the present number density of relic neutrinos of the 4th generation [4] taking into account annihilation reactions

$$\nu + \bar{\nu} \rightarrow f + \bar{f}, \quad W^+ + W^-,$$

where $f$ denotes a light fermion.

At the stage of the formation of the Galaxy contracting due to its energy dissipation baryonic matter provides an effective mechanism for the condensation of collisionless gas of relic massive neutrinos. As a consequence an average cosmological density $\rho_\nu(0)$ of the massive neutrinos in the Galaxy increases following the baryonic density $\rho_b(t)$ by the law [3, 4]:

$$\rho_\nu(0) = \rho_b(t) \left( \frac{T}{m_\nu} \right)^4,$$
\[
\frac{\rho_\nu(t)}{\rho_\nu(0)} \sim \left[ \frac{\rho_b(t)}{\rho_b(0)} \right]^{\frac{3}{4}}
\]

According to Eq. (1) massive neutrinos are distributed mainly outside the visible region of the Galaxy but still their central density increases up to seven orders of magnitude with respect to the average cosmological density. Such increase in neutrino density in the galactic halo could lead to an observable effect of neutrino interaction with a matter in underground detectors. As we have shown earlier the results of the underground experiment DAMA could be compatible with the existence of heavy neutrino with \( m = 50 \text{ GeV} \). The range of neutrino masses \( 60 \text{ GeV} < m < 290 \text{ GeV} \) is excluded by underground experiments if the increase of neutrino density is of the order \( 10^7 \). On the other hand, the clumping of heavy neutrinos in the galactic halo leads to an increase in the rate of the neutrino annihilation, resulting in a copious production of cosmic rays due to reactions

\[
\nu + \bar{\nu} \rightarrow e^+ + e^-
\]

or

\[
\nu + \bar{\nu} \rightarrow q + \bar{q}.
\]

Generally, photons are produced in hadron decays due to hadronization of quarks and antiquarks in reaction Eq. (3). To calculate the photon flux from annihilation of heavy neutrinos in the Galaxy we used the Monte Carlo approach described in [6]. The results of numerical simulations of the photon flux (see Fig 4) for \( m = 50 \text{ GeV} \) predict the gamma–background of the Galaxy below the observed by EGRET at \( E_\gamma > 1 \text{ GeV} \). However the inverse Compton effect for the energetic electrons and positrons (produced in reaction Eq. (2)) on optical photons of the Galaxy increases the photon flux by (80–40)% in the energy range \( 1 \text{ GeV} < E_\gamma < 15 \text{ GeV} \) respectively, leading to a qualitative agreement with EGRET data in the energy range under consideration. Note that the EGRET observations of gamma–background at \( E_\gamma > 50 \text{ GeV} \) indicate on the existence of additional mechanisms for a generation of high energy gamma radiation. These mechanisms could contribute as well at \( E_\gamma < 50 \text{ GeV} \).

High precision measurements of gamma–background in forthcoming experiments AGILE, AMS, GLAST can give an important information on peculiar features of gamma-spectrum and, in particular, to test a sharp decrease of gamma-spectrum at \( E_\gamma \approx 50 \text{ GeV} \) which could be a signature of heavy neutrino annihilation with \( m = 50 \text{ GeV} \).

The hypothesis of the existence of the 4th generation neutrino with the mass about 50 GeV can be checked for example in the experiment L3 on the electron–positron collider.
at CERN, studying one–photon events in the reaction \( e^+ + e^- \to \nu + \bar{\nu} + \gamma \) above \( Z^- \) resonance. In this case the 4th generation neutrinos could be observed due to the threshold behavior of the cross section \([11]\) (see Fig.2).

The existence of 50 GeV neutrino leads also to an interesting hadronless signature for Higgs meson production at accelerators

\[ e^+e^- \to Z \ H \to l^+l^-\nu\bar{\nu} \]

and this mode would be the dominant one.

Note that if there is no new physics up to Grand Unification scale the strong constraint on the 4th generation neutrino mass \( m < 220 \text{ GeV} \) \([7]\) follows from the stability of electroweak vacuum and from the absence of Landau pole in Higgs potential. This also stimulates the search for heavy neutrinos in the modern accelerator experiments.

Experimental measurement of positron and antiproton components of cosmic rays, planned in the near future, in particular, in the experiment \( AMS \) \([12]\), can provide the test for the existence of primordial stable 50 GeV neutrino and antineutrino in the Galaxy by the effect of their annihilation. The Monte Carlo simulations, described in \([6]\), show (see Figs.3,4) that the positron flux from the annihilation reaction Eq.(2) can be above the expected flux of cosmic rays. The search for effects of the reaction Eq.(2) will allow to distinguish the physical nature of the signal (not excluded by the results of \( DAMA \) experiment) in underground detectors. The interpretation of such signal by the hypothesis of a neutralino \( \chi \) (the lightest supersymmetric particle) can not be accompanied by a significant high energy positron signal from the annihilation of neutralinos in the galactic halo. The reaction

\[ \chi + \chi \to e^+ + e^- \]  

is forbidden in the s-wave due to angular momentum conservation. This is a consequence of Majorana nature of the neutralino. It requires that the annihilation should be in the p-wave, what severely suppresses the neutralino annihilation into light fermions. Indeed, non relativistic neutralinos in the galactic halo have relative velocities \( v/c \lesssim 10^{-3} \), and therefore the cross section of the reaction Eq.(4) (which is proportional to \((v/c)^2\)) is suppressed.

It is important to note that the methods of testing of the hypothesis of the 4th generation neutrino at accelerators and in experiments with cosmic rays are complementary to each other. Indeed, if the dimensionless constant \( \alpha_{EW} \) of heavy neutrino interaction with \( Z \) bosons is suppressed one has to expect the corresponding suppression of heavy neutrino production at accelerators. However the number density of relic heavy neutrino in the Galaxy is proportional to their number density at freeze-out, which is inversely proportional to the rate of annihilation \( r \sim (\sigma v)^{-1} \). The fluxes of particles from the annihilation in the reactions Eqs.(2),(3) are proportional to \( F \sim n_\nu n_\bar{\nu} \sim r^2(\sigma v) \sim (\sigma v)^{-2} \sim \alpha_{EW}^{-2} \).
therefore fluxes increase with the decrease of $\alpha_{EW}$. In the opposite case the increase of the constant $\alpha_{EW}$ reduces the astrophysical effects of the 4th generation neutrino but simplifies its search at accelerators.

Note that the condition for 50 GeV neutrino lifetime to exceed the modern age of the Universe implies very stringent conservation of the lepton charge of the 4th generation. In particular, effective operators of dimension 5 leading to a neutrino decay with the probability $W \sim m^3/m_{Pl}^2$ and corresponding to the life time $\tau << t_{Univ}$, have to be excluded in the final theory of the stable 4th generation neutrino.

Since primordial stable 50 GeV neutrinos maintain less than $10^{-3}$ of the critical density they can not play the dynamical role of the modern nonbaryonic dark matter. Thus the selfconsistent scenario of their cosmological evolution should account for some other forms of nonbaryonic dark matter, dominating in the modern Universe and forming the halo of our Galaxy. In the presence of other forms of dark matter the increase of heavy neutrino density in the Galaxy can be an order of the magnitude smaller than the one considered here, since the effective clumping starts only after the dissipation in the baryonic matter makes its density larger than the total density of all the forms of dark matter. On the other hand, one can expect the increase of neutrino density within the small scale inhomogeneities of the dominating dark matter, what leads to the increase of their annihilation rate. It makes the analysis of realistic scenarios for the 4th generation neutrino cosmology the interesting subject of our further studies.

The development of the hypothesis of the 4th generation neutrino assumes the investigation of specific properties and possible searches for the existence of the 4th generation stable quark and stable hadrons, containing this quark. It would be also interesting to study the embedding of the 4th generation into the model of horizontal unification, developed earlier [14]. Such possibility extends the model beyond the framework of simplest models of heterotic string in which the rank of symmetry group does not allow to include the gauge symmetry of generations [15]. We can expect that the combination of indirect experimental, cosmological and astroparticle tests will strongly reduce the allowed set of variants for such models.

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Figure 1: The comparison of the simulation of the $\gamma$-quanta flux from the annihilation of the with $m = 50$ GeV heavy neutrinos in the reactions (2), (3) with \textit{EGRET} data [9]. The factor of the neutrino particle density enhancement in the Galaxy in comparison with the cosmological one has been chosen equal to $n_G/n = 1.25 \cdot 10^7$. 

Figure 1. $\gamma$ quanta

$m_\nu = 50$ GeV
Figure 2: The total cross section of the process $e^+e^- \rightarrow \nu \bar{\nu} \gamma$ for the photon energy $\omega > 1.5 \text{ GeV}$ and the photon angles $30^\circ < \theta < 150^\circ$.
Figure 3: The simulated positron flux from the annihilation of the $m = 50 \text{ GeV}$ heavy neutrinos. The references on the experimental data are given in [6]. The factor of the neutrino particle density enhancement in the Galaxy in comparison with the cosmological one has been chosen equal to $n_G/n = 1.25 \cdot 10^7$. 
Figure 4: The simulated antiproton flux from the annihilation of the $m = 50 \text{ GeV}$ heavy neutrinos. The references on the experimental data are given in [6]. The factor of the neutrino particle density enhancement in the Galaxy in comparison with the cosmological one has been chosen equal to $n_G/n = 1.25 \cdot 10^7$. 