Hindawi Publishing Corporation
Advances in High Energy Physics
Volume 2012, Article ID 571874, 8 pages
doi:10.1155/2012/571874

Research Article

The Impact of Excited Neutrinos on $\nu\overline{\nu} \to \gamma\gamma$ Process

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Received 24 August 2012; Revised 24 October 2012; Accepted 25 October 2012

Academic Editor: Joseph Formaggio

We examine the effect of excited neutrinos on the annihilation of relic neutrinos with ultrahigh energy cosmic neutrinos for the $\nu\overline{\nu} \to \gamma\gamma$ process. The contributions of the excited neutrinos to the neutrino-photon decoupling temperature are calculated. We see that photon-neutrino decoupling temperature can be significantly reduced below the obtained value of the Standard Model with the impact of excited neutrinos.

1. Introduction

According to standard cosmology, neutrinos are probably one of the most abundant particles of the universe. The universe is filled with a sea of relic neutrinos that decoupled from the rest of the matter within the first few seconds after the Big Bang. It is excessively difficult to measure relic neutrinos since the interactions of their cross-sections with matter are tremendously suppressed. Besides, it is crucial to detect relic neutrinos in order to test the neutrino aspects of the Big Bang model of cosmology, but it would seem impossible with present methods. However, some indirect evidences of the relic sea may be observed. For example, Weiler [1] have shown that the UHE cosmic neutrinos may interact with relic neutrinos via the following reactions occurring on the Z resonance:

$$\nu_{\text{cosmic}} + \overline{\nu}_{\text{relic}} \longrightarrow Z \longrightarrow \text{nucleons} + \text{photons}. \tag{1.1}$$

In such an event, a UHE cosmic neutrino has energy $E_\nu \approx 10^{23}$ eV. Therefore, the interaction of relic neutrinos and UHE cosmic neutrinos would have significant cross-section.

The high energy photon-neutrino interactions are very important in astrophysics, high energy cosmic ray physics, and cosmology. From Yang's theorem [2, 3], the leading term of the cross-section for the $\nu\overline{\nu} \rightarrow \gamma\gamma$ process is very small due to the vector-axial vector nature of the weak coupling when the neutrinos are massless. It is shown that $\omega < m_e$, where m_e is the electron mass and ω is the photon energy in the center of the mass frame, where the cross-section for the $\nu\overline{\nu} \rightarrow \gamma\gamma$ process is in the order of $G_F^2 \alpha^2 w^6 / m_W^4$, and m_W is the W boson mass [4–6]. The dimension-8 effective Lagrangian for the photon-neutrino interaction in Standard Model (SM) is as follows [7]:

$$L_{\text{eff}}^{\text{SM}} = \frac{1}{32\pi} \frac{g^2 \alpha}{m_W^4} A \left[\overline{\psi}\gamma_\nu (1-\gamma_5)(\partial^\mu \psi) - (\partial^\mu \overline{\psi})\gamma_\nu (1-\gamma_5)\psi\right] F_{\mu\lambda} F^{\nu\lambda}, \tag{1.2}$$

where ψ is the neutrino field, g is the electroweak gauge coupling, $F_{\mu\nu}$ is the photon field tensor, α is the fine structure constant, and A is the following:

$$A = \left[\frac{4}{3} \ln\left(\frac{m_W^2}{m_e^2}\right) + 1\right]. \tag{1.3}$$

Equation (1.2) can be rewritten as the following format [7]:

$$L_{\text{eff}}^{\text{SM}} = \frac{1}{8\pi} \frac{g^2 \alpha}{m_W^4} A T_{\alpha\beta}^{(\nu)} T^{(\gamma)\alpha\beta}. \tag{1.4}$$

Here, $T_{\alpha\beta}^{(\nu)}$ and $T^{(\gamma)\alpha\beta}$ are the stress-energy tensors of the neutrinos and photons which are given as follows:

$$\begin{aligned} T_{\alpha\beta}^{(\nu)} &= \frac{1}{8}\left[\overline{\psi}\gamma_\alpha (1-\gamma_5)(\partial_\beta \psi) + \overline{\psi}\gamma_\beta (1-\gamma_5)(\partial_\alpha \psi) \right. \\ &\quad \left. - (\partial_\beta \overline{\psi})\gamma_\alpha (1-\gamma_5)\psi - (\partial_\alpha \overline{\psi})\gamma_\beta (1-\gamma_5)\psi\right], \\ T_{\alpha\beta}^{(\gamma)} &= F_{\alpha\lambda} F_\beta^\lambda - \frac{1}{4} g_{\alpha\beta} F_{\lambda\rho} F^{\lambda\rho}. \end{aligned} \tag{1.5}$$

For the SM, the photons and neutrinos decouple, that is, $\nu\overline{\nu} \rightarrow \gamma\gamma$ process at a temperature $T \sim 1.6\,\text{GeV}$ within one micro second after the Big Bang [6]. When decoupling temperature is reduced to the QCD phase transition ($\Lambda_{\text{QCD}} \sim 200\,\text{MeV}$), some remnants of the photons circular polarization can possibly be retained in the cosmic microwave background [7], which can be considered as an evidence for the relic neutrino background. For reducing the decoupling temperature, the cross-section for the $\nu\overline{\nu} \rightarrow \gamma\gamma$ process should be increased. This can be done via the models which are beyond the SM. For instance, contributions of large extra dimensions to these process have been calculated in [7]. They have shown that the inclusion of the extra dimension effects did not provide large enough high energy neutrinos to scatter from relic neutrinos in this process but concluded that the photon decoupling temperature can be significantly reduced. Also, in [8], it has been remarked that unparticle physics can lower decouple temperature below the Λ_{QCD}.

The SM has been successful in describing the physics of the electroweak interactions, and it is consistent with experiments. However, some questions are still left unanswered, such as, the number of fermion generation and fermion mass spectrum has not been exhibited by the SM. Attractive explanations are provided by models assuming composite quarks and leptons. The existence of excited states of the leptons and quarks is a natural consequence of these models, and their discovery would provide convincing evidence of a new scale of matter. In this model, charged and neutral leptons can be considered as a heavy lepton sharing leptonic quantum number with the corresponding SM lepton. They should be regarded as the composite structures which are made up of more fundamental constituents. Therefore, excited neutrinos can be considered to spin 1/2 bound states, including three spin 1/2 or spin 1/2 and spin 1 substructures. All composite models have an underlying substructure which is characterized by a scale Λ.

The interaction between spin 1/2 excited fermions, gauge bosons, and the SM fermions can be described by the $SU(2) \times U(1)$ invariant effective Lagrangian as follows [9–13]:

$$L = \frac{1}{2\Lambda}\overline{\ell}^{*}\sigma^{\mu\nu}\left(gf\frac{\vec{\tau}}{2}\vec{W}_{\mu\nu} + g'f'\frac{Y}{2}B_{\mu\nu}\right)\ell_L + \text{h.c.} \tag{1.6}$$

In these expressions, $\sigma^{\mu\nu} = i(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$ with γ^μ being the Dirac matrices, $\vec{W}_{\mu\nu}$ and $B_{\mu\nu}$ are the field strength tensors of the SU(2) and $U(1)$, $\vec{\tau}$ and Y are the generators of the corresponding gauge group, and g and g' are standard electroweak and strong gauge couplings. Λ is the scale of the new physics responsible for the existence of excited neutrinos, and f, f' scale the SU(2) and $U(1)$ couplings, respectively. The effective Lagrangian can be rewritten in the physical basis

$$L = \frac{g_e}{2\Lambda}(f - f')N_{\mu\nu}\sum_{\ell=\nu_e,e}\overline{\ell}^{*}\sigma^{\mu\nu}\ell_L + \frac{g_e}{2\Lambda}f\sum_{\ell,\ell'=\nu_e,e}\Theta_{\mu\nu}^{\overline{\ell}^{*},\ell}\overline{\ell}^{*}\sigma^{\mu\nu}\ell'_L + \text{h.c.} \tag{1.7}$$

First term in the previous equation is a purely diagonal term with $N_{\mu\nu} = \partial_\mu A_\nu - \tan\theta_W\partial_\mu Z_\nu$, and second term is a non-Abelien part which involves triple as well as quartic vertices with

$$\begin{aligned}
\Theta_{\mu\nu}^{\overline{\nu}_e^{*},\nu_e} &= \frac{2}{\sin 2\theta_W}\partial_\mu Z_\nu - i\frac{g_e}{\sin^2\theta_W}W_\mu^+W_\nu^-,\\
\Theta_{\mu\nu}^{\overline{e}^{*},e} &= -\left(2\partial_\mu A_\nu + 2\cot 2\theta_W\partial_\mu Z_\nu - i\frac{g_e}{\sin^2\theta_W}W_\mu^+W_\nu^-\right),\\
\Theta_{\mu\nu}^{\overline{\nu}_e^{*},e} &= \frac{\sqrt{2}}{\sin\theta_W}\left(\partial_\mu W_\nu^+ - ig_eW_\mu^+(A_\nu + \cot\theta_W Z_\nu)\right),\\
\Theta_{\mu\nu}^{\overline{e}^{*},\nu_e} &= \frac{\sqrt{2}}{\sin\theta_W}\left(\partial_\mu W_\nu^- + ig_eW_\mu^-(A_\nu + \cot\theta_W Z_\nu)\right).
\end{aligned} \tag{1.8}$$

The chiral $V\ell^*\ell$ ($V = \gamma, Z, W$) interaction term can be found as follows:

$$\Gamma_\mu^{V\overline{\ell^*}\ell} = \frac{g_e}{2\Lambda}q^\nu\sigma_{\mu\nu}(1 - \gamma_5)f_V, \tag{1.9}$$

where q is the momentum of the gauge boson, f_V is the electroweak coupling parameter, and f_γ is defined for photon by $f_\gamma = I_{3L}(f - f')$, where we have assumed that $f = -f'$.

Up to now, searches have not found any signal for excited neutrinos at the colliders. The current mass limits on excited neutrinos are $m_* > 190\,\text{GeV}$ at the LEP [14] and $m_* > 213\,\text{GeV}$ assuming $f_\gamma/\Lambda = 1/m_*$ at the HERA [15]. Excited neutrinos have been also studied for hadron colliders [16–18] and next linear colliders [18, 19]. In these studies, it has been obtained that excited neutrinos masses up to 2 TeV can be detected at the LHC.

In this paper, we examine the effect of the excited neutrinos on the interaction of the UHE cosmic and relic neutrinos for the $\nu\overline{\nu} \to \gamma\gamma$ process.

2. $\nu\overline{\nu} \to \gamma\gamma$ Process Including Excited Neutrinos

The SM contributions to $\nu\overline{\nu} \to \gamma\gamma$ process have been calculated in [4, 6] using (1.2). From this effective Lagrangian, the squared amplitude for the SM can be obtained in terms of Mandelstam invariants u and t as follows:

$$|M_{\text{SM}}|^2 = A_{\text{SM}}^2\left(u^3t + t^3u\right), \tag{2.1}$$

where $A_{\text{SM}} = 4(g^2\alpha A/32\pi M_W^4)$.

The new physics (NP) contribution comes from t and u channels of excited neutrino exchange. The analytical expressions for the polarization summed amplitudes square for NP, SM and NP interference terms are given as follows:

$$\begin{aligned}|M_{\text{NP}}|^2 &= A_{\text{NP}}^2\left(\frac{u^3t}{(u-m_*^2)^2} + \frac{t^3u}{(t-m_*^2)^2}\right),\\ |M_{\text{INT}}|^2 &= -2A_{\text{SM}}A_{\text{NP}}\left(\frac{u^3t}{(u-m_*^2)} + \frac{t^3u}{(t-m_*^2)}\right),\end{aligned} \tag{2.2}$$

where $A_{\text{NP}} = 2(f_\gamma g_e/\Lambda)^2$. Therefore, the whole squared amplitude can be calculated as follows:

$$|M|^2 = |M_{\text{SM}}|^2 + |M_{\text{INT}}|^2 + |M_{\text{NP}}|^2. \tag{2.3}$$

Because of low center of mass energy of the neutrinos, we have used an approximation, $m_*^2 >> |u|,\ |t|$. In the limit $m_*^2 >> |u|, |t|$, the amplitude turns into following formation:

$$\left(A_{\text{SM}}^2 + \frac{2A_{\text{NP}}A_{\text{SM}}}{m_*^2} + \left(\frac{A_{\text{NP}}}{m_*^2}\right)^2\right)\left(u^3t + t^3u\right). \tag{2.4}$$

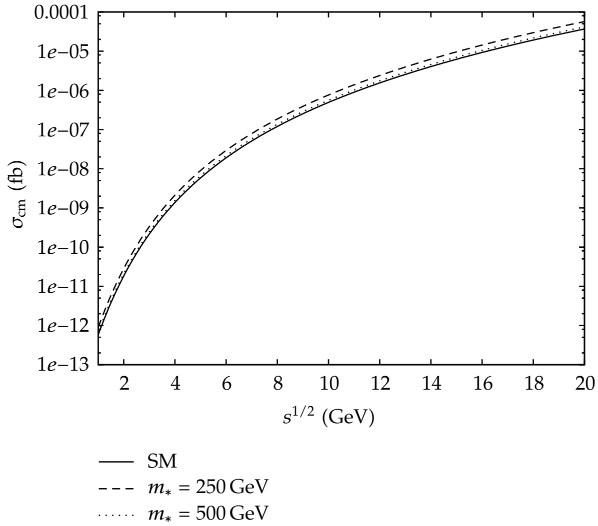

Figure 1: The SM and total cross-sections for the process $\nu\bar{\nu} \rightarrow \gamma\gamma$ via center of mass energy $s^{1/2}$ for the $\Lambda/f_\gamma = 250\,\text{GeV}$. m_* are taken to be 250 GeV and 500 GeV.

We have calculated the cross-section with/without approximation cross-section. We have seen that results are close for different m_* and f_γ/Λ. Therefore, the differential cross-section for $\nu\bar{\nu} \rightarrow \gamma\gamma$ process can be obtained by using

$$\frac{d\sigma}{dz} = \frac{1}{2!}\frac{1}{32\pi s}|M|^2. \tag{2.5}$$

Then, the total cross-section can be found from (2.5) as follows:

$$\sigma_{\nu\bar{\nu}\rightarrow\gamma\gamma} = \int_{-1}^{1} dz\frac{d\sigma}{dz} = \frac{A_{\rm SM}^2 s^3}{320\pi} + \frac{\left(2A_{\rm SM}A_{\rm NP}m_*^2 + A_{\rm NP}^2\right)s^3}{160\pi m_*^4}. \tag{2.6}$$

In Figure 1, we have plotted the total cross-sections as a function of the center of mass energy $\sqrt{s}$ for both the SM and total cross-sections when $\Lambda/f_\gamma = 250\,\text{GeV}$. These cross-sections are obtained for the two excited neutrinos, with masses of $m_* = 250\,\text{GeV}$ and $m_* = 500\,\text{GeV}$. Also, in Figure 2, we have showed the cross-sections for $m_* = 250\,\text{GeV}$ and three scales of the new physics $\Lambda/f_\gamma = 250\,\text{GeV}$, 500 GeV, and 1000 GeV. This figure shows similar behavior with Figure 1.

Extra contribution to the $\nu\bar{\nu} \rightarrow \gamma\gamma$ cross-section from excited neutrino exchange influences the decoupling temperature. The temperature at which this process ceases to take place can be found from the the reaction rate per unit volume,

$$\rho = \frac{1}{(2\pi)^6}\int\frac{d^3\vec{p}_1}{\exp(E_1/T)+1}\int\frac{d^3\vec{p}_2}{\exp(E_2/T)+1}\sigma|\vec{v}|. \tag{2.7}$$

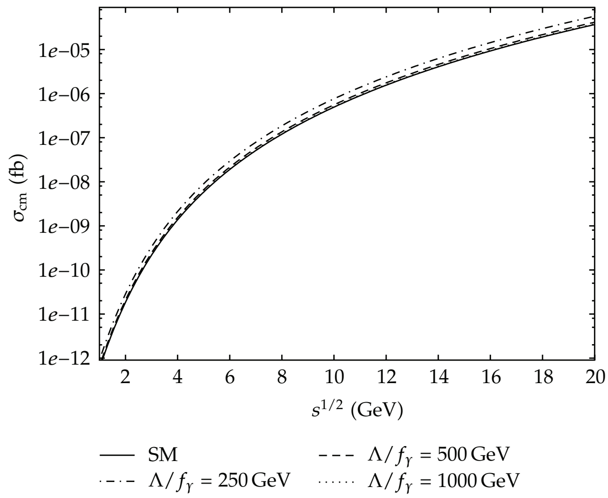

Figure 2: The SM and total cross-sections for the process $\nu\bar{\nu} \rightarrow \gamma\gamma$ via center of mass energy $s^{1/2}$ for the $m_* = 250$ GeV. Λ/f_γ are taken to be 250 GeV, 500 GeV, and 1000 GeV.

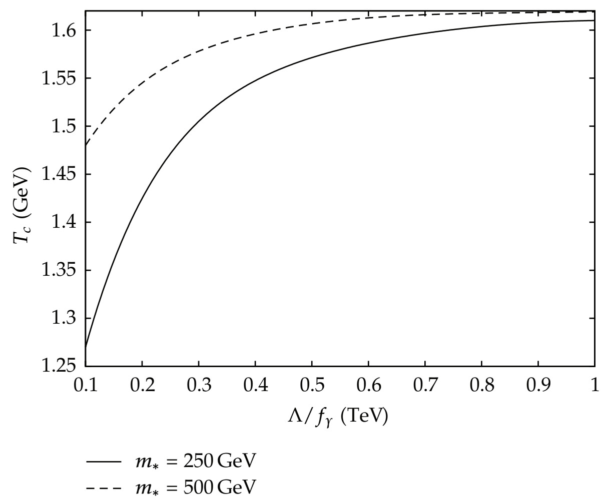

Figure 3: The decoupling temperature T_c as a function of Λ/f_γ when the m_* are equivalent to 250 GeV and 500 GeV.

The terms in (2.7) are as the following: $\vec{p_1}$ and $\vec{p_2}$ are the momentum of the neutrino and antineutrino; E_1 and E_2 are their energies; T is the temperature; $|\vec{v}|$ is the flux. The $\sigma|\vec{v}|$ can be given in terms of $\sigma_{\rm cm}$ in the center of mass frame by use of invariance of $\sigma|\vec{v}|E_1E_2$,

$$\sigma|\vec{v}| = \frac{\sigma_{\rm cm}s}{2E_1E_2},$$
$$\sigma|\vec{v}| = \frac{A_{\rm SM}^2 s^4}{640\pi E_1E_2} + \frac{\left(2A_{\rm SM}A_{\rm NP}m_*^2 + A_{\rm NP}^2\right)s^4}{320\pi E_1E_2m_*^4}, \tag{2.8}$$

where $s = 2E_1E_2(1 - \cos\theta_{12})$ and θ_{12} is the angle between $\vec{p_1}$ and $\vec{p_2}$. Equation (2.7) can be found

$$\rho = \left(\frac{A_{\rm SM}^2}{50\pi^5} + \frac{2A_{\rm SM}A_{\rm NP}m_*^2 + A_{\rm NP}^2}{25\pi^5 m_*^4}\right)T^{12}\int_0^\infty \frac{x^5 dx}{e^x+1}\int_0^\infty \frac{y^5 dy}{e^y+1}, \quad (2.9)$$

where $x = E_1/T$ and $y = E_2/T$. Then, the reaction rate per unit volume has been obtained,

$$\rho = \left(\frac{A_{\rm SM}^2}{50\pi^5} + \frac{2A_{\rm SM}A_{\rm NP}m_*^2 + A_{\rm NP}^2}{25\pi^5 m_*^4}\right)T^{12}\left[\frac{31}{32}\Gamma(6)\zeta(6)\right]^2, \quad (2.10)$$

where $\zeta(x)$ is the Riemann Zeta function. The interaction rate R is obtained by dividing ρ by the neutrino density $n_\nu = 3\zeta(3)T^3/4\pi^2$ at temperature T. Thus, we have found that

$$R = 2.32 \times 10^{29}\left(\frac{A_{\rm SM}^2}{50\pi^5} + \frac{2A_{\rm SM}A_{\rm NP}m_*^2 + A_{\rm NP}^2}{25\pi^5 m_*^4}\right)\left(\frac{T}{\rm GeV}\right)^9 {\rm sec}^{-1}. \quad (2.11)$$

Multiplying (2.11) by the age of the universe,

$$t = 1.48 \times 10^{-6}\left(\frac{T}{\rm GeV}\right)^{-2}{\rm sec}, \quad (2.12)$$

at least one interaction to occur is $Rt = 1$. The solution of the following equation gives the decoupling temperature:

$$3.43 \times 10^{23}\left(\frac{A_{\rm SM}^2}{50\pi^5} + \frac{2A_{\rm SM}A_{\rm NP}m_*^2 + A_{\rm NP}^2}{25\pi^5 m_*^4}\right)\left(\frac{T}{\rm GeV}\right)^7 = 1. \quad (2.13)$$

If $A_{\rm NP}$ and $A_{\rm SM}$ are replaced in the previous equation, then the following equation can be found:

$$\left(3.40 \times 10^{-2} + \left(\frac{f_\gamma}{\Lambda m_*}\right)^4\left(6.67 \times 10^7\Lambda^2 m_*^2 + 1.67 \times 10^{16}\right)\right)\left(\frac{T}{\rm GeV}\right)^7 = 1. \quad (2.14)$$

Figure 3 shows solution of this equation.

3. Conclusion

We have analyzed the contribution of excited neutrinos on the interaction of relic neutrinos with UHE cosmic neutrinos via the $\nu\overline{\nu} \to \gamma\gamma$ process. It is shown that excited neutrino contribution to total cross-section of the $\nu\overline{\nu} \to \gamma\gamma$ process is significant depending on the m_*, f_γ/Λ. We have seen that for the appropriate values of these parameters, the SM and total cross-sections can be distinguished from each other in the specific center of mass energy regions.

For decreasing decoupling temperature, the total cross-section of the $\nu\overline{\nu} \to \gamma\gamma$ should be increased. If the m_* or new physics parameter Λ/f_γ decrease, then the total cross-section increases. Therefore, T_c can be decreased significantly. For different values of m_*, T_c have been shown in Figure 3 as a function of the new physics parameter Λ/f_γ. As seen from this figure, our obtained values of the decoupling temperature can decrease the value of the SM decoupling temperature ($\approx 1.6\,\text{GeV}$).

As a result, excited neutrinos can allow lowering the decoupling temperature of the $\nu\overline{\nu} \to \gamma\gamma$ scattering. Therefore, they can provide significant contribution to search for relic neutrinos.

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