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AMPLIFICATION OF ENERGY OF COSMIC RELIC ANTINEUTRINOS IN STRONGLY MAGNETIZED ASTROPHYSICAL OBJECTS

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We have calculated the energy loss in the scattering of relic antineutrinos by ultra relativistic electrons with the allowance for the transverse polarization of the spins of the electrons participating in the considered processes proceeding in strongly magnetized astrophysical objects. We have determined that when the cosmic electron-positron plasma bypasses a white dwarf, energy is transferred from the plasma electrons to the relic antineutrinos at the expense of the antistokes transitions and the energy of relic antineutrinos are amplified about 10^9 times and reaches $\sim 10^5$eV. This is a new mechanism of amplification of the energy of antineutrinos, in particular, relic antineutrinos.

Key words: neutrinos – acceleration of particles – white dwarfs – polarization – magnetic fields – cosmic rays

1. INTRODUCTION

The energy of cosmic rays is mainly in the range from $\sim 10^{-4}$eV to $\sim 10^{19}$eV and sometimes higher than $\sim 10^{19}$eV. The energy of $\sim 10^{-4}$eV corresponds to

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relict neutrinos and antineutrinos. The known values of the masses of elementary particles vary in the range from $\sim 10^{-1}$eV to $\sim 10^{11}$eV. According to the results obtained from the KATRIN experiment, the upper limit of the electron neutrino mass is estimated as $\sim 10^{-1}$eV. The mass of the Higgs boson detected in the ATLAS and CMS experiments performed at the Large Hadron Collider was determined to be approximately 125 GeV. The mass of the t-quark, which is heavier than the Higgs boson and is generally considered the heaviest particle among the elementary particles, is 173 GeV, that is, approximately, $\sim 10^{11}$eV. Therefore, the maximum kinetic energies of particles obtained from the decay of existing elementary particles known to science are much smaller than their rest energies. It is known that moving in galaxies and intergalactic space cosmic particles gain energy and accelerate due to various acceleration mechanisms (dynamic mechanism, hydrodynamic mechanism, electromagnetic mechanism, Fermi acceleration mechanism, acceleration due to a strong shock wave etc). For instance, PeV-energy $\left(\sim 10^{15}\text{eV}\right)$ antineutrinos was discovered among cosmic particles as a result of observing Glashow resonance [1] in the Ice Cube experiment performed in Antarctica [2]:

$$\tilde{\nu}_e + e^- \to W^-. \tag{1}$$

The energy of an electron antineutrino for this resonance reaction to occur in a system where the electron is at rest is to be

$$\omega_R = \frac{M_W^2}{2m_e} = 6.32\,\text{PeV}. \tag{2}$$

It is known that in an electromagnetic field charged particles are accelerated and their energies increase. However, electromagnetic field cannot accelerate neutral particles, in particular, neutrinos and antineutrinos. A natural question arises. What mechanisms are responsible for the amplification of the energies of neutrinos and antineutrinos? Finding an answer to this question is the main motivation of this research.

The object of the study is the antineutrino-electron scattering processes in a constant homogeneous magnetic field

$$\tilde{\nu}_i + e^- \to \tilde{\nu}_i' + e^{-\prime}, \tag{3}$$

where $\tilde{\nu}_i = \tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$ and $\tilde{\nu}_i' = \tilde{\nu}_e', \tilde{\nu}_\mu', \tilde{\nu}_\tau'$ are the antineutrinos of three flavours in the initial and final states, respectively.

Various aspects of the antineutrino-electron scattering in a magnetic field were studied in the papers [3–6]. The analyses of the papers [3–6] show that energy loss in the antineutrino-electron scattering in a magnetic field was not calculated with allowance for the transverse polarization of the spins of the electrons participating in the considered processes in the above-mentioned investigations. In the presented work, we calculate the energy loss in the scattering of relic antineutrinos by ultra relativistic electrons, taking into account the transverse polarization of the spins of the electrons participating in the processes (3).

The purpose of the presented investigation is to clarify the mechanism of energy transfer by calculating the energy losses in the scattering of relic antineutrinos by ultra relativistic electrons in an external constant homogenous magnetic field with allowance for the transverse polarization of the spins of the electrons participating in the processes (3) and to determine how the energy of relic antineutrinos changes.

2. THE PHYSICAL CONDITIONS AND ASSUMPTIONS

We consider the antineutrino-electron scattering in a constant homogenous magnetic field within the physical conditions and assumptions used in [7]. We assume that electrons in the initial and final states are ultra-relativistic

$$\varepsilon^2 \gg m_e^2, \quad \varepsilon'^2 \gg m_e^2 \tag{4}$$

and possess large transverse momenta

$$p_\perp = \quad (2eBn)^{1/2} \gg \quad m_e, \tag{5}$$

$$p'_\perp = \quad \left(2eBn'\right)^{1/2} \gg \quad m_e, \tag{6}$$

where $n\,(n')$ is the number of the Landau energy level belonging to the electron in the initial (final) state, B is the magnitude of the magnetic field vector $\mathbf{B}$ that is directed along the z-axis and assumed to be

$$B \ll B_0 = \frac{m_e^2}{e} \cong 4.414 \times 10^{13} G \tag{7}$$

We use the system of units $c = \hbar = k_B = 1$ and the pseudo-Euclidean metric with signature $(+ - --)$.

The assumptions (4)-(7) mean that the main contribution to the energy loss in this process comes from the electron states occupying high Landau levels $(n, n' \gg 1)$. In this case, the motion of the electrons in the initial and final states is semiclassical [8, 9]. We consider the case when the longitudinal momentum of the electron in the initial state is zero: $p_z = 0$.

Within the above considered physical conditions we can neglect the mass of an antineutrino and we can apply the massless antineutrino model. Let the incident low-energy antineutrino fly along the z-axis (along the magnetic field direction) and its energy is in the range

$$\omega_{\min} \ll \omega \ll m_e \tag{8}$$

where $\omega_{\min} = eB/p_{\perp}$.

The above-mentioned physical conditions and assumptions indicate that the energy loss in the processes (3) depends on the dynamical parameter

$$\chi = \frac{e}{m_e^2}\left[-\left(F_{\mu\nu}p^{\nu}\right)^2\right]^{1/2} = \frac{B}{B_0}\frac{p_{\perp}}{m_e} \tag{9}$$

and the kinematical parameter [9]

$$\kappa = \frac{2\omega\varepsilon}{m_e^2} = \frac{2kp}{m_e^2} \tag{10}$$

where $F_{\mu\nu} = \partial_{\mu}A_{v} - \partial_{\nu}A_{\mu}$ is the tensor of an external electromagnetic field of the magnetic type.

3. ENERGY LOSS BY THE ELECTRONS IN THE ANTINEUTRINO-ELECTRON SCATTERING

We obtain the following general formula for the energy lost by the electrons in the antineutrino electron scattering in an external constant homogenous magnetic field with allowance for the transverse polarization of the spins of the electrons participating in the considered processes

$$\frac{dE}{dt} = -\frac{G_F^2 m_e^2}{\pi^{3/2}V}\varepsilon\int_0^{\infty}\left[\tilde{A}\Phi_1(z) - \tilde{B}\left(\frac{\chi}{u}\right)^{2/3}\Phi'(z) - \tilde{C}\left(\frac{\chi}{u}\right)^{1/3}\Phi(z)\right]F\frac{u^2du}{(1+u)^5} \tag{11}$$

where

$$\tilde{A} = \frac{\kappa}{2u}\left[g_R^2(1+u)^2 + g_L^2 + 2g_Lg_R\zeta\zeta'(1+u)\right] - g_Lg_R\left(1+\zeta\zeta'\right)(1+u), \tag{12}$$

$$\tilde{B} = g_R^2(1+u)^2 + g_L^2 + 2g_Lg_R\zeta\zeta'(1+u), \tag{13}$$

$$\tilde{C} = g_R^2\zeta'(1+u)^2 - g_L^2\zeta + g_Lg_R\left(\zeta-\zeta'\right)(1+u), \tag{14}$$

$$F = f\left(1-f'\right) = \frac{1}{e^{\frac{\varepsilon-\mu}{T}}+1}\left(1-\frac{1}{e^{\frac{\varepsilon'-\mu}{T'}}+1}\right) \tag{15}$$

is the statistical factor, $f\,(f')$ is the Fermi-Dirac distribution function for the electrons in the initial (final) state, $\mu\,(\mu')$ and $T\,(T')$ are the chemical potential and the temperature of the electron gas before (after) the antineutrino-electron scattering, respectively. In (11-14) $\zeta\,(\zeta')$ is the projection of the spin of the electron in the initial (final) state onto the z-axis, $g_L = 0.5+\sin^2\theta_W$ and $g_R = \sin^2\theta_W$ for the $\tilde{\nu}_e e^- \to \tilde{\nu}_e' e^{-\prime}$ process, $g_L = -0.5+\sin^2\theta_W, g_R = \sin^2\theta_W \cong 0.23$ for the $\tilde{\nu}_\mu e^-$ $(\tilde{\nu}_\tau e^-)$scattering, θ_W is the Weinberg angle, G_F is the Fermi constant, V is the volume of the spatial domain where the process is formed,

$$u = \frac{\chi}{\chi'} - 1 = \frac{p_\perp}{p'_\perp} - 1 \simeq \frac{\omega'}{\varepsilon - \omega'}, \tag{16}$$

is the spectral variable, ω' is the energy of the scattered antineutrino, χ' is defined according to the formula (9) and belongs to the electron in the final state,

$$\Phi(z) = \frac{1}{2\sqrt{\pi}} \int_{-\infty}^{+\infty} dt \exp\left[i\left(zt + \frac{t^3}{3}\right)\right] \tag{17}$$

is the Airy function depending on the argument

$$z = \left(\frac{u}{\chi}\right)^{2/3}\left(1 - \frac{\kappa}{u}\right), \tag{18}$$

$$\Phi'(z) = d\Phi(z)/dz \quad \text{and} \quad \Phi_1(z) = \int_z^\infty \Phi(y)dy.$$

The analyses of the argument z of the Airy function shows that the influence of the external magnetic field on the antineutrino-electron scattering is determined by the parameter

$$\eta = \frac{\chi}{\kappa} = \frac{1}{2}\frac{B}{B_0}\frac{m_e}{\omega} \gtrsim 1. \tag{19}$$

The influence of the external magnetic field on the antineutrino-electron scattering is essential when $\eta \gtrsim 1$. The condition $\eta \gg 1$ corresponds to the strong field case and the condition $\eta \ll 1$ corresponds to the weak field case. When $\eta \sim 1$, the proceeding of the process depends on the ratio u/κ. As can be seen from expression (19), the influence of the external field on the considered process is significant when the magnetic field is strong enough (but $B \ll B_0$), and antineutrinos possess extremely low energy. Very low energy antineutrinos are relict antineutrinos.

When $\chi \gg \kappa$ (i.e., $\eta \gg 1$) we obtain the following asymptotic formula for the energy loss per unit time

$$\frac{dE}{dt} = -\frac{\Gamma(2/3)G_F^2 m_e^2}{27\pi}\frac{\varepsilon}{V}\left\{\left(2g_R^2 + \frac{5}{27}g_L^2 + \frac{8}{9}g_L g_R \zeta\zeta'\right)(3\chi)^{2/3} - \right.$$
$$\left. -\frac{5\Gamma(1/3)}{\Gamma(2/3)}\left[g_R^2\zeta' - \frac{1}{27}g_L^2\zeta + \frac{1}{9}g_L g_R\left(\zeta - \zeta'\right)\right](3\chi)^{1/3}\right\} F. \tag{20}$$

4. NUMERICAL ESTIMATIONS

Using the relations (8) and (19), taking into account the energy of relic antineutrinos ($\omega \cong 1.677\times\ 10^{-4}$eV) and the energy of the electrons in the cosmic plasma that is $\sim 10^2$GeV (e.g., $\varepsilon \cong 281.27$GeV) we obtain the following numerical value for the magnetic field strength $B \cong 8 \times 10^8 Qs$. This is the characteristic magnetic field strength of ordinary white dwarfs. It means that when the electrons of the energy $\sim 10^2$GeV of cosmic electron-positron plasma bypasses a white dwarf, the influence of a magnetic field of the white dwarf on a relic antineutrino-electron scattering becomes essential: $\eta = 2.757\times\ 10^4 \gg 1$. On the basis of the above-mentioned values of the physical quantities we obtain that $\varepsilon \cong T \gg \mu, \varepsilon' \cong T' \gg \mu, \varepsilon' \lesssim \varepsilon, F \cong 1.966 \times 10^{-1}$ and $\chi = 10 \gg 1$. The characteristic size of the domain of formation of the process under consideration is

$$l \sim \frac{m_e}{eB} = \lambda_c \frac{B_0}{B} = 2.13 \times 10^{-6}\text{sm} \tag{21}$$

where λ_c is the Compton wavelength of an electron. The corresponding volume is $V = (4\pi/3)l^3 \cong 4.05 \times 10^{-17}$ sm^3.

If we consider the process $\tilde{\nu}_e + e^- \to \tilde{\nu}_e' + e^{-\prime}$ and assume that the spin of the electron in the initial (final) state is oriented along (opposite to) the direction of the magnetic field vector $\mathbf{B}$, i.e. $\zeta = +1$ and $\zeta' = -1$, we obtain the following numerical estimation for the energy loss by the electrons

$$\frac{dE}{dt} = -1.458 \times 10^{-8} \frac{\text{eV}}{\text{s}}. \tag{22}$$

This is the energy taken or absorbed by the relic electron antineutrinos from the medium per unit time. The negative sign indicates that energy is transferred from the medium (cosmic plasma electrons) to the relic electron antineutrinos, not from the relic electron antineutrinos to the medium. This happens at the expense of the antistokes transitions. In this case the electrons in the final state make transition to relatively low Landau levels and the energy of relic electron antineutrinos increases significantly. The antistokes transitions take place when the condition $B \gg B_0 \left(\omega m_e/\varepsilon^2\right)$ is satisfied. The magnetic field strength existing in a white dwarf satisfies this condition. Really, in case of relic antineutrinos and $\varepsilon \cong 281.27$ GeV, we obtain the following estimation $B \gg 4.77 \times 10^{-8} Qs$. So, when the energy of the electrons of the cosmic plasma bypassing a white dwarf is $\sim 10^2$GeV, relic antineutrinos and a white dwarf satisfy the antistokes condition.

Energy transferred to relic electron antineutrinos from a unit volume of medium per unit time is

$$\frac{1}{V}\frac{dE}{dt} = -3.6 \times 10^8 \frac{eV}{sm^3 \times s}. \tag{23}$$

If we take the relic antineutrino concentration $n_\nu \cong 57\text{sm}^{-3}$ into account, we can calculate the energy carried by each relic antineutrino from the medium per unit time

$$\frac{\left(\frac{1dE}{Vdt}\right)}{n_{\tilde{\nu}}} \cong 6.32\frac{\text{MeV}}{\text{s}}. \tag{24}$$

If we take into account that the size of an ordinary white dwarf is about $0.8-2\%$ of the radius of the Sun $\left(R_\odot \cong 6.957\times10^8 \text{ m}\right)$ and relic antineutrinos pass this distance during $(1.85-4.63)\times10^{-2}$ s, the energy gained by the scattered relic electron antineutrino reaches $\omega'_{\tilde{\nu}_e} \sim 10^5\text{eV}$ that is 10^9 times more than the initial energy of a relic antineutrino $\left(\omega \cong 1.677\times10^{-4}\text{eV}\right)$.

5. CONCLUSION

We calculated the energy loss in the scattering of relic antineutrinos by ultra relativistic electrons, taking into account the transverse polarization of the spins of the electrons participating in the processes (3). We have determined that when the condition $B \gg B_0 \left(\omega m_e/\varepsilon^2\right)$ is satisfied for the scattering of relic antineutrinos by ultra relativistic electrons in a magnetic field, energy is transferred from the electrons to the relic antineutrinos at the expense of the antistokes transitions. We have also determined that when the cosmic electron-positron plasma bypasses a white dwarf, the energy of relic antineutrinos are amplified about 10^9 times and reaches $\sim 10^5\text{eV}$. Search for the antineutrinos of the energy $\sim 10^5\text{eV}$ coming from white dwarfs in the future experiments in neutrino observatories opens prosperity for understanding the mechanism of amplification of the energy of relic antineutrinos.

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