SCATTERING OF LOW-ENERGY ANTINEUTRINOS AT TRANSVERSELY POLARIZED ULTRA-RELATIVISTIC ELECTRONS IN MAGNETIZED STARS

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We investigate the scattering of sufficiently low-energy antineutrinos at transversely polarized ultra-relativistic electrons in an external magnetic field in the low-energetic approximation of the standard Weinberg-Salam model and consider the astrophysical application of the obtained results.

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1. INTRODUCTION

One of the most important problems of modern nuclear physics, particle physics, astrophysics and cosmology is exploration of interactions of neutrinos and antineutrinos with strongly magnetized medium.

Analyses of the investigations [1-3] on the antineutrino-electron scattering (AES)

$$\tilde{\nu}_i + e^- \rightarrow \tilde{\nu}_i{}' + e^{-\prime} \qquad (1)$$

in an external magnetic field (MF) show that in case of low-energy antineutrinos the field effects are essential [1]. The anti-Stokes scattering of low-energy antineutrinos and neutrinos on relativistic electrons in a MF with allowance of the transverse polarization of the electrons was investigated in [2] where the authors calculated the dependence of the cross-section on the invariant dynamic parameter χ. Detailed calculations and analyses show that some coefficients and signs in the expressions for the cross sections of the process (1) are incorrect in the work [3] (see at: [4]). In [2] the cross section for the scattering of antineutrinos at electrons in a constant homogenous magnetic field was calculated and the longitudinal polarization of electrons was taken into account. Apart from the work [3] in [2] the authors calculated the dependence of the cross section on the invariant kinematic parameter κ and dynamic parameter χ. In [2] it was shown that the influence of the external magnetic field on the AES is determined by the parameter

$$\eta = \frac{\chi}{\kappa}. \qquad (2)$$

In the presented paper we investigate the anti-Stokes scattering of sufficiently low energy antineutrinos ($\omega \ll m_e$) at transversely polarized ultra-relativistic electrons in an external constant homogenous MF with the strength $B \ll B_0$ in the low energetic approximation of the standard Weinberg-Salam model. The purpose of the presented work is to clarify the mechanism of transition of the energy from the electrons of the magnetized medium to low-energy antineutrinos.

2. MATRIX ELEMENT OF THE PROCESS

We choose the gauge of a four-potential of the external field as $A^\mu = (0, 0, xB, 0)$. In this gauge the MF is directed along the z-axis. We use the pseudo-Euclidean metric with signature $(+ - - -)$.

When the momentum transferred is relatively small, $|q^2| \ll m_W^2, m_Z^2$ (m_W is the $W^{\pm}$-boson mass, m_Z is the Z-boson mass), the low-energetic (the four-fermion) approximation of the standard Weinberg-Salam electroweak interaction theory can be used.

The matrix element of the considered processes (1) in a MF is written as follows

$$M = \frac{G}{\sqrt{2}} \int \mathrm{N}_\alpha(x) \Lambda^\alpha(x) d^4x \qquad (3)$$

where

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$$\mathrm{N}_{\alpha}(x) = \overline{\psi}_{\tilde{\nu}}(x)\gamma_{\alpha}(1+\gamma^5)\psi_{\tilde{\nu}'}(x) \qquad (4)$$

is the antineutrino current,

$$\Lambda^{\alpha}(x) = \overline{\psi}_{e'}(x)\gamma^{\alpha}(g_V + g_A\gamma^5)\psi_e(x) \qquad (5)$$

is the electron current, γ^{α} are the Dirac matrices, $\gamma^5 = -i\gamma^0\gamma^1\gamma^2\gamma^3$, $g_V = 0.5 + 2\sin^2\theta_W$ and $g_A = 0.5$ are for $\tilde{\nu}_e e^-$-scattering, $g_V = -0.5 + 2\sin^2\theta_W$ and $g_A = -0.5$ are for $\nu_\mu e^-(\nu_\tau e^-)$-scattering, $\sin^2\theta_W \cong 0.23$, θ_W is the Weinberg angle, $\psi_{\tilde{\nu}}(x) = (2\omega V)^{-1/2}v(k)exp(ikx)$ is the wave function of the incident antineutrino possessing the four-momentum k and the energy ω, $\overline{\psi}_{\tilde{\nu}}(x) = \psi^{+}_{\tilde{\nu}}(x)\gamma^0$, $\psi_{\tilde{\nu}'}(x) = (2\omega' V)^{-1/2}v'(k')exp(ik'x)$ is the wave function of the scattered antineutrino possessing the four-momentum k' and energy ω', V is the normalization volume, $v(k)$ and $v'(k')$ are the Dirac bispinors of the incident and scattered antineutrinos, respectively, $\psi_e(x)$ ($\psi_{e'}(x)$) is the solution of the Dirac equation in a constant homogeneous external MF for the electron [4] in the initial (final) state, $\overline{\psi}_{e'}(x) = \psi^{+}_{e'}(x)\gamma^0$.

When the electrons are polarized transversely, the spin coefficients, c_i $(i = 1,2,3,4)$ are given by [4]

$$\begin{pmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{pmatrix} = \frac{1}{2\sqrt{2}}\begin{pmatrix} B_3(A_3 + A_4) \\ B_4(A_4 - A_3) \\ B_3(A_3 - A_4) \\ B_4(A_4 + A_3) \end{pmatrix} \qquad (6)$$

where $A_3 = \sqrt{1 + (p_z/E)}$, $A_4 = \zeta\sqrt{1 - (p_z/E)}$, $B_3 = \sqrt{1 + \zeta(m_e/E_\perp)}$, $B_4 = \zeta\sqrt{1 - \zeta(m_e/E_\perp)}$, E - energy of the electron in the initial state, m_e is the electron mass, $E_\perp = \sqrt{E^2 - p_z^2} = m_e\sqrt{1 + 2fn}$, $f = B/B_0$, $B_0 = m_e^2c^3/e\hbar = 4.414 \times 10^{13}\ G$ is the Schwinger field strength, $e > 0$ is the elementary electric charge, $\zeta = \pm 1$ is the spin quantum number that determines the projection of the electron spin along (opposite to) the direction of the MF vector $\vec{B}$. The electrons in the final state are described and denoted with the primed quantities that are determined with the same expressions (6) and above indicated related formulae.

3. CROSS SECTION OF THE PROCESS

We consider that the electrons in the initial and final states are ultra-relativistic ($E^2 \gg m_e^2, {E'}^2 \gg m_e^2$) and they possess large transverse momentum ($p_\perp = (2eBn)^{1/2} = m_e(2fn)^{1/2} \gg 1$, $p'_\perp = (2eBn')^{1/2} = m_e(2fn')^{1/2} \gg 1$) in the MF that is not enough strong and satisfies the condition $f \ll 1$. The latter two assumptions mean that the electron states occupying high Landau levels $(n, n' \gg 1)$ mainly contribute to the total cross section for the process. We assume that the longitudinal momentum of the electrons in the initial state is zero: $p_z = 0$.

We consider a massless antineutrino model that is justified for ultra-relativistic antineutrinos ($\omega, \omega' \gg m_\nu$). We suppose that the incident antineutrinos fly along the MF direction

$$k^{\mu} = \omega(1, 0, 0, 1). \qquad (7)$$

and their energies are in the range

$$\omega_{min} \ll \omega \ll m_e. \qquad (8)$$

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

Standard calculations of the cross section of the process gives the following general formula

$$\sigma = \frac{G_F^2 m_e^2}{4\pi^{3/2}}\int_0^{\infty}\left[\tilde{A}\Phi_1(z) - \tilde{B}\left(\frac{\chi}{u}\right)^{2/3}\Phi'(z) - \tilde{C}\left(\frac{\chi}{u}\right)^{1/3}\Phi(z)\right]\frac{u\,du}{(1+u)^4} \qquad (9)$$

where

$$\tilde{A} = \frac{\kappa}{2u}\left[g_L^2 + g_R^2(1+u)^2 + 2g_Lg_R\zeta\zeta'(1+u)\right] - g_Lg_R(1+\zeta\zeta')(1+u), \qquad (10)$$

$$\tilde{B} = g_L^2 + g_R^2(1+u)^2 + 2g_Lg_R\zeta\zeta'(1+u), \qquad (11)$$

$$\tilde{C} = g_R^2\zeta'(1+u)^2 - g_L^2\zeta + g_Lg_R(\zeta - \zeta')(1+u), \qquad (12)$$

$$\chi = \frac{e}{m_e^3}\left[-\left(F_{\mu\nu}p^{\nu}\right)^2\right]^{1/2} = \frac{B}{B_0}\frac{p_\perp}{m_e} \qquad (13)$$

is the field parameter, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the tensor of the external field,

$$\kappa = \frac{2\omega E}{m_e^2} = \frac{2kp}{m_e^2} \qquad (14)$$

is the kinematical parameter, u is the invariant spectral variable

$$u = \frac{\chi}{\chi'} - 1 = \frac{p_\perp}{p'_\perp} - 1 \simeq \frac{\omega'}{E - \omega'}, \qquad (15)$$

the field parameter χ' belongs to the electrons in the final state,

$$\Phi(z) = \frac{1}{2\sqrt{\pi}} \int_{-\infty}^{+\infty} dt exp\left[i\left(zt + \frac{t^3}{3}\right)\right] \tag{16}$$

is the Airy function depending on the argument

$$z = \left(\frac{u}{\chi}\right)^{2/3}\left(1 - \frac{\kappa}{u}\right), \tag{17}$$

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

4. BEHAVIOR OF THE CROSS SECTION IN STRONG FIELD CASE

Let us consider the limiting case when $\chi \gg 1$ and $\chi \gg \kappa$. In this case the parameter $\eta \gg 1$. Using the explicit formula of the argument of the Airy function

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

we can write $|z| \ll 1$. If we take the fact $|z| \ll 1$ into account in the general formula of the cross section of the process, we obtain

$$\sigma = \frac{G_F^2 m_e^2}{9\pi}\left\{\frac{3}{2}\left[\kappa\left(\frac{1}{3}g_L^2 + g_R^2 + g_L g_R \zeta\zeta'\right) - g_L g_R(1 + \zeta\zeta')\right] + \right.$$

$$+\Gamma\left(\frac{2}{3}\right)\left(\frac{5}{27}g_L^2 + g_R^2 + \frac{2}{3}g_L g_R \zeta\zeta'\right)(3\chi)^{2/3} -$$

$$\left. -\Gamma\left(\frac{1}{3}\right)\left[2g_R^2\zeta' - \frac{4}{27}g_L^2\zeta + \frac{1}{3}g_L g_R(\zeta - \zeta')\right](3\chi)^{1/3}\right\}. \tag{19}$$

If we consider the anti-Stokes scattering of an antineutrino at an electron, the following condition

$$B \gg B_0 \frac{\omega m_e}{E^2} \tag{20}$$

is to be satisfied. In that case the behavior of the cross section is in the form

$$\sigma = \frac{G_F^2 m_e^2}{9\pi}\left\{\Gamma\left(\frac{2}{3}\right)\left(\frac{5}{27}g_L^2 + g_R^2 + \frac{2}{3}g_L g_R \zeta\zeta'\right)(3\chi)^{2/3} - \right.$$

$$\left. -\Gamma\left(\frac{1}{3}\right)\left[2g_R^2\zeta' - \frac{4}{27}g_L^2\zeta + \frac{1}{3}g_L g_R(\zeta - \zeta')\right](3\chi)^{1/3}\right\}. \tag{21}$$

5. DISCUSSION OF THE RESULTS

If we compare this result with the corresponding formula of the work [3], we see that the second term is absent in [3]. It is explained with that in the limiting case when $\chi \gg 1$, the second term can be neglected and the result of the work [3] is obtained from our result as a private case. It should be also noted that the sign in front of $2g_L g_R \zeta\zeta'/3$ in the first term that contains the multiplier $(3\chi)^{2/3}$ is positive. However, the sign in front of $2g_L g_R \zeta\zeta'/3$ in the term that contains the multiplier $(3\chi)^{2/3}$ is negative. Our detail calculations and analysis confirm that the sign in front of the term $2g_L g_R \zeta\zeta'/3$ in the work [3] is incorrect. Now let us consider the astrophysical application of the obtained results. For the neutron stars possessing the magnetic field $B \sim 10^{12}G$ with the internal temperature $T \sim 10^{11}K$ ($E \sim 10^7 eV$) and antineutrinos of the energy $\omega \lesssim 10^3 eV$, we obtain $1 \lesssim \chi \lesssim 10$, $\kappa \lesssim 1$. In this case $\eta \gtrsim 1$ and the field effect become essentially. It means that in the neutron stars possessing the magnetic field $B \sim 10^{12}G$ with the internal temperature $T \sim 10^{11}K$ the anti-Stokes scattering of antineutrinos of the energy $\omega \lesssim 10^3 eV$ at electrons contribute to cooling of the neutron stars significantly.

6. CONCLUSION

We obtained the analytical formula for the cross section of the scattering of low-energy antineutrinos at transversely polarized ultra-relativistic electrons in a constant homogenous magnetic field. We also obtained the analytical formula for the anti-Stokes scattering of antineutrinos at transversely polarized electrons. We applied the obtained results to the magnetized stars and showed that in the neutron stars possessing the magnetic field $B\sim10^{12}G$ with the internal temperature $T\sim10^{11}K$ the anti-Stokes scattering of antineutrinos of the energy $\omega\lesssim10^{3}eV$ at electrons contribute to cooling of the neutron stars significantly. This is a new mechanism of cooling of the neutron stars possessing the magnetic field $B\sim10^{12}G$ with the internal temperature $T\sim10^{11}$.

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