CONTRIBUTION OF MEDIUM FACTORS TO ELASTIC RELIC NEUTRINO-ELECTRON SCATTERING IN CLOSE VICINITY TO MAGNETIZED ASTROPHYSICAL OBJECTS

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The presented work is devoted to the estimation of the contribution of medium factors (chemical potential and temperature) to the elastic relic neutrino-electron scattering in close vicinity to magnetized astrophysical objects like neutron stars and white dwarfs. It is determined that the contribution of medium factors to the elastic relic neutrino-electron scattering in close vicinity to magnetized astrophysical objects depends on the ratio of the energy of the electron in the final state and the temperature of the non-degenerate final-state electron gas. It is clarified that the influence of the medium to the elastic relic neutrino-electron scattering is determined by the temperature of the non-degenerate final-state electron gas.

Keywords: relic neutrinos; magnetic field; cosmic electrons; chemical potential, Fermi-Dirac distribution
DOI:10.70784/azip.1.2024439

1. INTRODUCTION

Despite great observational and theoretical successes in the exploration of cosmic rays [1-18], the problem associated with the acceleration of cosmic neutrinos to high and even ultra-high energies, which is one of the most important problems existing in high-energy particle astrophysics and cosmology, has not been resolved yet and the acceleration mechanism of cosmic neutrinos remains a major puzzle of modern astrophysics and cosmology.

In their propagation, cosmic neutrinos pass through various magnetic fields (MFs) existing in cosmic space [19] and simultaneously interact with high-energy cosmic electrons and positrons (see, eg., PAMELA [20], AMS-02 [21, 22], and the Fermi Large Area Telescope [23]). Due to their low mass, high energy cosmic electrons and positrons undergo strong energy loss. In other words, they tend to lose their energies. It is not excluded that in their propagation in space cosmic neutrinos can scatter by high-energy electrons or positrons. Hereafter, we will consider the elastic scattering of cosmic neutrinos by high-energy cosmic electrons. Among the cosmic neutrinos, relic neutrinos are distinguished by their two peculiarities: 1) their flux ($\Phi \sim 10^{13} - 10^{14}\ cm^{-2} \cdot s^{-1}$) [24] is the highest one among all the neutrino and antineutrino fluxes coming from the known natural neutrino and antineutrino sources; 2) the relic neutrino (antineutrino) energy is the least one ($\omega \cong 1.68 \times 10^{-4}\ eV$) among the energies of all neutrinos (antineutrinos) coming from the known natural neutrino (antineutrino) sources. The first peculiarity of relic neutrinos leads to increasing the rate of the scattering of relic neutrinos by high-energy cosmic electrons. The second peculiarity opens a gate for their acceleration. Relic neutrinos have an energy which is significantly lower than the energy of cosmic electrons. Therefore, when relic neutrinos scatter by cosmic electrons, energy transfer from high-energy cosmic electrons to relic neutrinos is more plausible and realistic than energy transfer from relic neutrinos to high-energy cosmic electrons. This unique opportunity should lead to the amplification of the energies of relic neutrinos and therefore, it opens a gate to the solution of the problem of acceleration of relic neutrinos. The magnetic fields existing in astrophysical media affect the relic neutrino-cosmic electron scattering by deforming the energy spectrum of the electrons in both the initial and final states, polarizing

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the spins of the electrons and changing the phase space of the electrons.

We investigate the elastic scattering of relic neutrinos by high-energy cosmic electrons

$$\nu_i + e^- \to \nu_i' + e^{-\prime} \qquad (1)$$

in close vicinity to magnetized astrophysical objects where $\nu_i(\nu_i')$ are the three flavours of a neutrino $\nu_i = \nu_e, \nu_\mu, \nu_\tau$ $(\nu_i' = \nu_e', \nu_\mu', \nu_\tau')$ in the initial (final) state.

The elastic neutrino-electron scattering processes in an external MF and some aspects of these processes were studied by numerous authors [25-38]. However, the analyses of the papers [25-38] show that the differential probability of the elastic relic neutrino-electron scattering in a MF with allowance for the medium factors (chemical potential and temperature) existing in the close vicinity to strongly magnetized astrophysical objects have not been investigated.

The purpose of this investigation is to estimate the contribution of the medium factors (chemical potential and temperature) to the differential probability of the elastic relic neutrino-electron scattering in close vicinity to magnetized astrophysical objects like neutron stars and white dwarfs.

2. INITIAL PHYSICAL CONDITIONS AND ASSUMPTIONS

We use the system of units $c = \hbar = k_B = 1$ and the pseudo-Euclidean metric with the signature $(+ - - -)$. We assume that the electrons in the initial and final states are ultra-relativistic

$$\varepsilon^2 \gg m_e^2, \qquad (2)$$

$$\varepsilon'^2 \gg m_e^2 \qquad (3)$$

and possess large transverse momenta

$$p_\perp = (2eBn)^{1/2} \gg m_e, \qquad (4)$$

$$p_\perp' = (2eBn')^{1/2} \gg m_e \qquad (5)$$

where ε (ε') and n (n') are the energy and the number of the Landau energy level of the electron in the initial (final) state, respectively, B is the magnitude of the MF vector B that is directed along the z-axis and assumed to be

$$B \ll B_0, \qquad (6)$$

where $B_0 = m_e^2/e \cong 4.41 \times 10^{13} G$ is the Schwinger field strength. MFs of the strengths (6) exist in the vicinity of neutron stars and white dwarfs.

The assumptions (3)-(6) mean that the main contribution to the differential probability of the processes (1) comes from the electron states occupying very high Landau levels $(n,\ n' \gg 1)$. In this case, the motion of the electrons in both the initial and final states is semiclassical [39, 40]. We consider the case when the longitudinal momentum of the electron in the initial state is zero: $p_z = 0$. Here, we assume that a relic neutrino possesses an extremely small mass and we neglect the neutrino mass. Therefore, in the presented work, we have dealings with the massless neutrino model [41, 42] according to that there are only a left-handed polarized neutrino and a right-handed polarized neutrino. In other words, the relic neutrinos participating in the considered processes (1) are left-handed polarized neutrinos.

Let the incident relic neutrino fly along the z-axis (the MF direction), i.e.,

$$k^\mu = (\omega, 0, 0, \omega) \qquad (7)$$

and its energy ω is in the range

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

where k^μ is the incident neutrino four-momentum and $\omega_{min} = eB/p_\perp$.

Since we are interested in significant increasing the energy of the scattered neutrino, we assume that the energy ω' of the neutrino in the final state (the scattered neutrino) satisfies the condition $\omega' \gg \omega$. From the comparison of the conditions (2) and (8) we obtain that $\varepsilon \gg \omega$.

3. DIFFERENTIAL PROBABILITY

The differential probability per unit time is calculated according to the general formula [43]

$$dw = 2\pi \int \prod_i dn_i f_i \prod_f dn_f \left(1 - f_f\right) |A|^2 \delta_E \qquad (9)$$

where $|A|^2$ is the squared amplitude per unit time, f_i (f_f) is the distribution function of the particles in the initial (final) state, dn_i (dn_f) is the number of the initial (final) states in an element of the phase space, δ_E is the Dirac delta function depending on the energy of the particles taking part in the given process. If we choose the gauge of four-potential as $A^\mu = (0, 0, xB, 0)$, the number of electrons in the initial and final states are given by

$$dn_i = \frac{L_y}{2\pi} dp_y \frac{L_z}{2\pi} dp_z, \qquad (10)$$

$$dn_f = \frac{L_y}{2\pi} dp_y' \frac{L_z}{2\pi} dp_z'. \qquad (11)$$

where $p_y(p_y')$ and $p_z(p_z')$ are the y-component and z-component of the momentum of the electron in the initial (final) state, respectively. For the neutrinos in the initial and final states, the number of states is determined by the following expressions

$$dn_i = \frac{Vd\mathbf{k}}{(2\pi)^3}, \tag{12}$$

$$dn_f = \frac{Vd\mathbf{k}'}{(2\pi)^3}, \tag{13}$$

respectively, where k(k′) is the momentum vector of the neutrino in the initial (final) state.

We have already indicated that the longitudinal momentum of the electron in the initial state is zero: $p_z = 0$. At the same time the initial neutrino state (the incident neutrino is left-handed polarized) is fixed. Since the initial electron and neutrino states are fixed, we will not perform averaging over initial neutrino and electron states when we calculate the differential probability of the processes (1). Therefore, the Fermi-Dirac distribution functions of the gas consisting of the incident relic neutrinos and gas consisting of the initial state electrons will not be included in the formula for the differential probability. So, the differential probability of the processes (1) per unit time is given by the formula

$$dw = 2\pi \sum_{n'} |A|^2 \delta_\varepsilon (1 - f_e') \frac{L_y dp_y'}{2\pi} \frac{L_z dp_z'}{2\pi} \left(1 - f_{\nu_i}'\right) \frac{Vd\vec{k}'}{(2\pi)^3} \tag{14}$$

where $\delta_\varepsilon = \delta(\varepsilon' + \omega' - \varepsilon - \omega)$, $\delta_y = \delta\left(p_y - p_y' - q_y\right)$, $\delta_z = \delta(p_z - p_z' - q_z)$, $q_y = k_y' - k_y$, $q_z = k_z' - k_z$, L_y (L_z) is the normalizing length along the y- axis (z-axis), G_F is the Fermi constant,

$$f_e' = \left[exp\left(\frac{E' - \mu_e'}{T_e'}\right) + 1\right]^{-1} \tag{15}$$

is the Fermi-Dirac distribution function for the electrons in the final state,

$$f_{\nu_i}' = \left[exp\left(\frac{\omega' - \mu_{\nu_i}'}{T_{\nu_i}'}\right) + 1\right]^{-1} \tag{16}$$

is the Fermi-Dirac distribution function for the neutrinos in the final state, μ_e' (μ_{ν_i}') and T_e' (T_{ν_i}') are the chemical potential and the temperature of the electron (neutrino) gas after the elastic relic neutrino-electron scattering, respectively.

4. CONTRIBUTION OF STATISTICAL FACTOR TO PROBABILITY OF PROCESSES IN STRONG FIELD LIMITING CASE

Let us analyze the statistical factor

$$F_f = (1 - f_e')(1 - f_\nu') \tag{17}$$

that is included to the differential probability (14) of the processes (1). In the elastic scattering of relic neutrinos by ultra-relativistic electrons, energy is transferred, namely, from the electrons to the relic neutrinos because the energy of the incident relic neutrinos ($\omega \sim 10^{-4}\ eV$) is much less than the energy of the ultra-relativistic electrons in the initial state: $\omega \ll m_e \ll \varepsilon$. This happens at the expense of the anti-Stokes transitions. In the limiting case $\chi \gg 1$, the condition for the anti-Stokes transition is given by the inequality $\omega \ll \varepsilon$ where $\chi = (\varepsilon/m_e)(B/B_0)$ is the field parameter. It means that in the strong field limiting case ($\chi \gg 1$), the ultra-relativistic electrons in the initial state with the energy $\varepsilon \gg m_e$ $(n \gg 1)$ undergo the transition to the final state with the energy $\varepsilon' \gg m_e$ $(n' \gg 1)$ provided that $\varepsilon' < \varepsilon$ $(n' < n)$. Since the electrons make transitions from high Landau levels to relatively low Landau levels, the energy of the electron in the final state and the temperature of the gas consisting of the electrons in the final state after scattering decrease: $\varepsilon' < \varepsilon$ and $T_e' < T_e$. According to [44], the chemical potential of the gas consisting of the final state electrons in a MF with the strength $B \ll B_0$ decreases with decreasing the temperature of the indicated gas: $\mu_e' < \mu_e$. Since we consider the ultra-relativistic electrons (especially, the cosmic plasma electrons with the energy $\varepsilon, \varepsilon' \sim 10^2\ GeV \sim 10^{15}\ K$) not exceeding the unitarity limit $\sqrt{s} \simeq 600\, GeV$ for the elastic neutrino-electron scattering [41], we can accept $\varepsilon \gg \mu_e$, $\varepsilon' \gg \mu_e'$. We consider the non-degenerate electron gas for which $\mu_e \ll T_e$ and $\mu_e' \ll T_e'$. The energy lost by the electrons is transferred to the relic neutrinos. Therefore, the energy of the relic neutrinos in the final state (ω') and the temperature of the gas consisting of the relic neutrinos in the final state $(T_{\tilde{\nu}_i}')$ increase: $\omega' > \omega$, $T_{\tilde{\nu}_i}' > T_{\tilde{\nu}_i}$. Relic neutrinos are neutral particles and do not directly undergo the influence of an external MF. Therefore, the relic neutrino gas behaves itself as a free $(B = 0)$ Fermi-gas. When the temperature of the free final state Fermi gas (in this work, the relic neutrino gas) in the final state increases, its chemical potential decreases: $\left|\mu_{\tilde{\nu}_i}'\right| < \left|\mu_{\tilde{\nu}_i}\right|$. For relic neutrinos the parameter $\xi_{\tilde{\nu}_i} = \mu_{\tilde{\nu}_i}/T_{\tilde{\nu}_i}$ varies in the range $-0.04 \le \xi_{\tilde{\nu}_e} \simeq \xi_{\tilde{\nu}_\mu} \simeq \xi_{\tilde{\nu}_\tau} \le 0.04$ where $\mu_{\tilde{\nu}_i} = \mu_{\tilde{\nu}_e}, \mu_{\tilde{\nu}_\mu}, \mu_{\tilde{\nu}_\tau}$ and $T_{\tilde{\nu}_i} = T_{\tilde{\nu}_e}, T_{\tilde{\nu}_\mu}, T_{\tilde{\nu}_\tau}$ [42]. It means that $\left|\mu_{\tilde{\nu}_i}\right| = \left|\xi_{\tilde{\nu}_i} T_{\tilde{\nu}_i}\right| \le 0.04 T_{\tilde{\nu}_i} \ll T_{\tilde{\nu}_i}$. So, we obtain the following relation for the relic neutrinos in the final state:

$$\omega' \simeq T_{\tilde{\nu}_i}' > T_{\tilde{\nu}_i} \gg \left|\mu_{\tilde{\nu}_i}\right| > \left|\mu_{\tilde{\nu}_i}'\right| \tag{18}$$

or in a simpler form

$$\omega' \simeq T_{\tilde{\nu}_i}' \gg \left|\mu_{\tilde{\nu}_i}'\right|. \tag{19}$$

Taking into account the relations $\varepsilon' \gg \mu_e'$ and $\omega' \simeq T_{\tilde{\nu}_i}' \gg \left|\mu_{\tilde{\nu}_i}'\right|$ in the expression of the statistical factor F_f we obtain

$$F_f = \begin{cases} \left(\frac{e}{e+1}\right)^2 \simeq 0.53, & \varepsilon' \simeq T'_e\ , \\ \frac{e}{e+1} \simeq 0.73, & \varepsilon' \gg T'_e\ . \end{cases} \quad (20)$$

Thus, the contribution of medium factors to the differential probability of the processes (1) is more pronounced in the case $\varepsilon' \gg T'_e$ than in the case $\varepsilon' \simeq T'_e$:

$$\frac{F_f(\varepsilon' \gg T'_e \varepsilon' \gg T'_e)}{F_f(\varepsilon' \simeq T'_e)} \simeq 1.4. \quad (21)$$

5. CONCLUSION

We have investigated the elastic scattering of relic neutrinos by high-energy cosmic electrons $\nu_i e^- \to \nu'_i e^{-\prime}$ in close vicinity to magnetized astrophysical objects like neutron stars and white dwarfs. We have determined that the contribution of medium factors (chemical potential and temperature) to the elastic relic neutrino-electron scattering in close vicinity to magnetized astrophysical objects depends on the ratio of the energy of the electron in the final state and the temperature of the non-degenerate final-state electron gas. The contribution of medium factors (chemical potential and temperature) to the elastic relic neutrino-electron scattering in close vicinity to magnetized astrophysical objects is more pronounced in the case $\varepsilon' \gg T'_e$ than in the case $\varepsilon' \simeq T'_e$. We have clarified that the influence of the medium to the elastic relic neutrino-electron scattering is determined by the temperature of the non-degenerate final-state electron gas.

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Received: 25.11.2024