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SPIN ASYMMETRIES IN PROCESSES OF ELECTRON-POSITRON PAIRS PRODUCTION BY NEUTRINOS IN SUPERSTRONGLY MAGNETIZED STARS

R.E.Gasimova^{1,2}, V.A.Huseynov², B.T.Hajiyeva³
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We have calculated the energy transferred by the neutrinos to the unit volume of the superstrongly magnetized stellar medium per unit time at the expense of the processes $\nu_i \rightarrow \nu_i e^- e^+$ with allowance for the longitudinal and transverse polarizations of the spins of the produced positrons and electrons. We have also determined the spin asymmetries arising in these processes and shown the astrophysical applications of the obtained results for supernova explosions.

Keywords: neutrino, electron-positron pairs, longitudinal polarization, transverse polarization, supernovae, superstrong magnetic fields, ground Landau level, first Landau level

Introduction

The processes of production of electron-positron pairs by neutrinos are described by the reactions

$$\nu_i \rightarrow \nu_i + e^- + e^+. \quad (1)$$

In the reaction (1) ν_i denotes the three flavours of neutrinos: an electron neutrino ν_e , a muon neutrino ν_μ and a tauon neutrino ν_τ . In free case when an external field is absent, the processes described by the reaction (1) are excluded by the 4-momentum conservation law. However, when the external magnetic field is present, the processes (1) occur. Superstrong magnetic fields ($B \geq B_0 = m_e^2/e = 4.41 \times 10^{13} \text{ G}$ where B is the magnitude of the magnetic field induction vector and B_0 is the Schwinger value of B) essentially change the energy spectra charged particles participating in the processes. The superstrong magnetic fields are met in astrophysical objects (eg, in magnetars and other neutron stars) and phenomena (eg, in supernova explosions). The magnetic fields of the order $B \sim 10^{13} \text{ G}$ are met on the surfaces of neutron stars [1]. The magnetic fields of the order

$B \sim 10^{15} \text{ G}$ exist in magnetars [2, 3]. The magnetic fields of the order $B \sim 10^{15} - 10^{17} \text{ G}$ are produced at the infall stage of the gravitational collapse of a stellar core [4, 5]. The upper limit of B for new-born neutron star is estimated as $B \sim 10^{18} \text{ G}$ [6]. It is not excluded that the primordial magnetic field of the collapsing stellar core could be essentially amplified at the expense of the huge compression of the stellar matter of very high conductivity and it can be higher than $B \sim 10^{18} \text{ G}$.

The processes $\nu_\mu \rightarrow \nu_\mu e^- e^+$, $\nu_\tau \rightarrow \nu_\tau e^- e^+$ proceeding only via the neutral currents and the process $\nu_e \rightarrow \nu_e e^- e^+$ proceeding via both the neutral and charged currents have been investigated in [7-14]. The analysis of the above discussed works shows that the energy losses which are characteristic for the processes (1) have not been investigated yet in superstrong stellar magnetic fields with allowance for the transverse and longitudinal polarizations of the spins of the produced electrons and positrons and medium factors.

The purpose of this work is to calculate the energy losses which are characteristic for the processes (1) in an external constant and uniform superstrong stellar magnetic field, to

determine the spin asymmetries arising in these processes and to show the astrophysical applications of the obtained results. Here we consider both the cases of the longitudinal and transverse polarizations of the spins of the electrons and positrons produced at the expense of the processes (1).

1. General formula for energy loss when the spins of the produced electrons and positrons are longitudinally polarized

The energy transferred by neutrinos to the unit volume of the medium per unit time at the expense of the electron-positron pairs production is calculated on the following general formula

$$\frac{dE}{dt} = \frac{G_F^2}{(2\pi)^4} \frac{m_e^2}{V} f \int \frac{\omega'}{\omega} (\omega - \omega') R \delta(\omega' + E + E' - \omega) \times \\ \times (1 - f_{\nu'}) (1 - f_{e^-}) (1 - f_{e^+}) dp_z d\omega' d\Omega, \quad (2)$$

where G_F is the Fermi constant of weak interactions, R is the quantity derived from the squared absolute value of the matrix element that corresponds to the processes (1) in the low-energetic approximation of the Weinberg-Salam theory, ω is the incident neutrino energy, ω' is the scattered neutrino energy, E is the positron energy, E' is the electron energy, f_{e^-} , f_{e^+} , $f_{\nu'}$ are the Fermi-Dirac distribution functions of the electrons, positrons and scattered neutrinos, respectively. Here we use the system of units where $\hbar = c = k_B = 1$ and the pseudo-Euclidean metric with the signature $(+---)$, where k_B is the Boltzmann constant. The parametre f included in the formula (2) is the relativistic-invariant parametre and is determined as follows:

$$f = \frac{B}{B_0} = \frac{e_0}{m_e^2} \left(\frac{1}{2} |F_{\mu\nu} F^{\mu\nu}| \right)^{1/2}, \quad (3)$$

where $e_0 > 0$ is the elementary charge, m_e is the electron (positron) mass, $F_{\mu\nu}$ is the tensor

of an external electromagnetic field of a magnetic type: $F_{\mu\nu} F^{\mu\nu} > 0$, $F^{\mu\nu} \tilde{F}_{\mu\nu} = 0$ ($\tilde{F}_{\mu\nu} = (1/2)\epsilon_{\mu\nu\alpha\beta} F^{\alpha\beta}$ is the dual tensor).

Let us consider the case of production of the electrons on the ground Landau level ($n=0$) and the positrons on the first Landau level ($n=1$) provided that the spins of the electrons and positrons are longitudinally polarized. Let us also assume that the incident neutrinos move in perpendicular direction ($\vartheta = \pi/2$) with respect to the z -axis that is oriented along the magnetic field and the scattered neutrinos move in the direction opposite to the magnetic field ($\vartheta' = \pi$). It should be noted that within these geometrical conditions the occurrence of the processes (1) does not contradict to the conservation laws of energy and z -component of momentum. In this case provided that $E \gg T_e \gg m_e, \mu_e$ and $\omega', \mu_{\nu'} \gg T_{\nu'}$ we obtain the following formula for energy loss, i. e. for the energy transferred by the neutrinos to the unit volume of the medium per unit time at the expense of the processes $\nu_i \rightarrow \nu_i e^- e^+$:

$$\frac{dE}{dt} = \frac{\sqrt{2} G_F^2}{4\pi^3} \frac{m_e^3}{V} f^{3/2} \int \omega' (\omega - \omega') \{ g_L^2 (1 + \sigma\zeta) (1 - \nu\zeta) x + \\ + [g_L^2 + g_R^2 + 2g_L g_R \delta + (g_L^2 - g_R^2) \sigma\zeta] (1 + \nu\zeta) - \\ - 2[g_L^2 (1 + \sigma\zeta) + g_L g_R \delta] \gamma\zeta \sqrt{x} \} e^{-x} d\omega', \quad (4)$$

where ξ is the positron spin quantum number that determines the projection of the spin onto the generalized momentum: when the positron spin is oriented along the momentum vector direction, $\xi = +1$ and when the positron spin is oriented opposite to the momentum vector direction, $\xi = -1$; $g_L = 0.5 + \sin^2 \theta_W$ and $g_R = \sin^2 \theta_W \cong 0.23$ for the process $\nu_e \rightarrow \nu_e e^- e^+$ and $g_L = -0.5 + \sin^2 \theta_W$ and $g_R = \sin^2 \theta_W$ for the processes $\nu_\mu \rightarrow \nu_\mu e^- e^+$ and $\nu_\tau \rightarrow \nu_\tau e^- e^+$, θ_W is the Weinberg angle, $E = \sqrt{m_e^2 + 2m_e^2 f + \omega'^2}$

$$\begin{aligned}\delta &= m_e/E, \quad \sigma = \sqrt{1-\delta^2}, \\ \nu &= p_z/\sqrt{E^2-m_e^2} = \omega'/\sqrt{2m_e^2 f + \omega'^2}, \\ \gamma &= \sqrt{1-\nu^2}, \quad x = (\omega/\sqrt{2m_e})^2 f^{-1}.\end{aligned}$$

In the considered geometry for momenta of the incident and scattered neutrinos, i.e. when $\vartheta = \pi/2$ and $\vartheta' = \pi$, we have the following formulae for calculation of the scattered neutrino energy ω' and the positron energy E , respectively:

$$\omega' = \frac{\omega(\omega - 2m_e) - 2m_e^2 f}{2(\omega - m_e)}, \quad (5)$$

$$E = \frac{\omega(\omega - 2m_e) + 2(f+1)m_e^2}{2(\omega - m_e)}. \quad (6)$$

When $B \gg B_0$, i.e. $f \gg 1$, we have $E \gg m_e$. In this case if we assume $2m_e^2 f \gg \omega'^2$, we obtain $\delta \cong 0$, $\sigma \cong 1$, $\nu \cong 0$, $\gamma \cong 1$ and the following formula for the energy transferred by the neutrinos to the unit volume of the medium per unit time at the expense of the processes $\nu_i \rightarrow \nu_i e^- e^+$:

$$\begin{aligned}\frac{dE}{dt} &= \frac{\sqrt{2}G_F^2 m_e^3}{24\pi^3 V} \omega_{\max}'^2 (3\omega - 2\omega_{\max}') f^{3/2} \times \\ &\times \left[g_L^2 (\sqrt{x} - 1)^2 (1 + \zeta) + g_R^2 (1 - \zeta) \right] e^{-x}, \quad (7)\end{aligned}$$

where

$$\omega_{\max}' = \frac{\omega(\omega - 2m_e)}{4(\omega - m_e)}. \quad (8)$$

2. General formula for energy loss when the spins of the produced electrons and positrons are transversely polarized

And now let us consider the case of production of the electrons on the ground Landau level ($n' = 0$) and the positrons on the first Landau level ($n = 1$) provided that the

spins of the electrons and positrons are transversely polarized. We consider the same geometry for momenta of the incident and scattered neutrinos, i.e. $\vartheta = \pi/2$ and $\vartheta' = \pi$. In this case provided that $E \gg T_e \gg m_e, \mu_e$ and $\omega', \mu_{\nu'} \gg T_{\nu'}$ we obtain the following formula for the energy transferred by the neutrinos to the unit volume of the medium per unit time at the expense of the processes $\nu_i \rightarrow \nu_i e^- e^+$:

$$\begin{aligned}\frac{dE}{dt} &= \frac{\sqrt{2}G_F^2 m_e^3}{4\pi^3 V} f^{2/3} \int \omega'(\omega - \omega') \left\{ g_L \left(1 - \frac{\omega'}{E} \right)^{1/2} \sqrt{x} - \right. \\ &\left. - \left[g_L \left(1 + \frac{\omega'}{E} \right)^{1/2} + g_R \zeta \left(1 - \frac{\omega'}{E} \right)^{1/2} \right]^2 \right\} e^{-x} d\omega', \quad (9)\end{aligned}$$

where ξ is the positron spin quantum number that determines the projection of the spin onto the magnetic field induction vector $\vec{B}$: when the positron spin is oriented along the magnetic field direction, $\xi = +1$ and when the positron spin is oriented opposite to the magnetic field direction, $\xi = -1$. For astrophysical applications let us consider the supernova explosions. Let us assume that $\omega \cong 75 \text{ MeV}$ and $B = 10^4 B_0$ that are characteristic for supernova explosions. In this case we obtain $\omega' \cong 2.33 \text{ MeV}$, $E \cong 72.16 \text{ MeV}$ and $(\omega'/E) \ll 1$. When $(\omega'/E) \ll 1$, we obtain the following expression for the energy transferred by the neutrinos to the unit volume of the medium per unit time:

$$\begin{aligned}\frac{dE}{dt} &= \frac{\sqrt{2}G_F^2 m_e^3}{24\pi^3 V} \omega_{\max}'^2 (3\omega - 2\omega_{\max}') f^{3/2} \times \\ &\times \left[g_L (\sqrt{x} - 1) - g_R \zeta \right]^2 e^{-x}. \quad (10)\end{aligned}$$

3. Spin asymmetries

The presense of the terms proportional to ζ in the expressions (7) and (10) indicates that energy losses in the processes $\nu_i \rightarrow \nu_i e^- e^+$ are sensitive to the polarizations of the spins of the

produced positrons. In case of longitudinal polarization the dependence of energy loss on the polarizations of the spins of the produced positrons indicates that energy loss is not symmetric (or equal) when the spins of the positrons are oriented along their momenta and opposite to their momenta. In case of transverse polarization the dependence of energy losses on the polarizations of the spins of the produced positrons indicates that energy loss is not symmetric (or equal) when the spins of the positrons are oriented along the magnetic field direction and opposite to the magnetic field direction. In both cases the spin asymmetries arise in energy losses. In case of the longitudinal polarization of the spins of the positrons we determine the spin asymmetry according to the following formula:

$$A = \frac{\left(\frac{dE}{dt}\right)_L - \left(\frac{dE}{dt}\right)_R}{\left(\frac{dE}{dt}\right)_L + \left(\frac{dE}{dt}\right)_R} \quad (11)$$

where

$$\left(\frac{dE}{dt}\right)_L = \frac{dE}{dt}(\zeta = -1), \quad (12)$$

$$\left(\frac{dE}{dt}\right)_R = \frac{dE}{dt}(\zeta = +1). \quad (13)$$

If we take the expression (7) into account in the expressions (11)-(13), we obtain the following formula for the spin asymmetry

$$A = \frac{g_R^2 - g_L^2(\sqrt{x} - 1)^2}{g_R^2 + g_L^2(\sqrt{x} - 1)^2}. \quad (14)$$

Let us perform the numerical estimations. If we take $\omega \cong 75 \text{ MeV}$ and $B = 10^4 B_0$, we have $x \cong 1.08$. In this case we obtain $A \cong 96.8\%$ for the process $\nu_e \rightarrow \nu_e e^- e^+$ and $A \cong 99.6\%$ for the processes $\nu_\mu \rightarrow \nu_\mu e^- e^+$ and $\nu_\tau \rightarrow \nu_\tau e^- e^+$. The numerical estimations show

that the processes $\nu_i \rightarrow \nu_i e^- e^+$ with production of the positrons having the spins oriented opposite to the momentum vector contribute to the cooling process of supernovae much more than the processes $\nu_i \rightarrow \nu_i e^- e^+$ with production of the positrons having the spins oriented along the momentum vector.

In case of the transverse polarization of the spins of the positrons we determine the spin asymmetry according to the following formula:

$$A = \frac{\left(\frac{dE}{dt}\right)_- - \left(\frac{dE}{dt}\right)_+}{\left(\frac{dE}{dt}\right)_- + \left(\frac{dE}{dt}\right)_+} \quad (15)$$

where

$$\left(\frac{dE}{dt}\right)_- = \frac{dE}{dt}(\zeta = -1), \quad (16)$$

$$\left(\frac{dE}{dt}\right)_+ = \frac{dE}{dt}(\zeta = +1). \quad (17)$$

If we take the expression (10) into account in the expressions (15)-(17), we obtain the following formula for the spin asymmetry

$$A = \frac{2g_L g_R (\sqrt{x} - 1)}{g_R^2 + g_L^2 (\sqrt{x} - 1)^2}. \quad (18)$$

When $\omega \cong 75 \text{ MeV}$ and $B = 10^4 B_0$, we obtain $A \cong 25\%$ for the process $\nu_e \rightarrow \nu_e e^- e^+$ and $A \cong -9.4\%$ for the processes $\nu_\mu \rightarrow \nu_\mu e^- e^+$, $\nu_\tau \rightarrow \nu_\tau e^- e^+$. The asymmetry $A \cong 25\%$ indicates that the process $\nu_e \rightarrow \nu_e e^- e^+$ with production of the positrons having the spins oriented opposite to the magnetic field direction contributes to the cooling process of supernovae more than the processes $\nu_e \rightarrow \nu_e e^- e^+$ with production of the positrons having the spins oriented along the magnetic field direction. The asymmetry $A \cong -9.4\%$ indicates that the pro-

cesses $\nu_\mu \rightarrow \nu_\mu e^- e^+$, $\nu_\tau \rightarrow \nu_\tau e^- e^+$ with production of the positrons having the spins oriented along the magnetic field direction contribute to the cooling process of supernovae more than the processes $\nu_\mu \rightarrow \nu_\mu e^- e^+$, $\nu_\tau \rightarrow \nu_\tau e^- e^+$ with production of the positrons having the spins oriented opposite to the magnetic field direction.

The formula (14), (18) and the performed numerical estimations show that in both longitudinal and transverse polarization cases the spin asymmetries are sensitive to the neutrino flavour.

Conclusions

We have calculated the energy transferred by the neutrinos to the unit volume of the medium per unit time at the expense of the processes $\nu_i \rightarrow \nu_i e^- e^+$ in cases of the longitudinal and transverse polarizations of the spins of the produced positrons and electrons. We have determined that the energy losses happen asymmetrically depending on the polarization of the spins of the produced positrons. It means that the cooling of the supernovae happens asymmetrically depending on the polarization of the spins of the produced positrons. We have performed the numerical estimations for the spin asymmetries for the neutrinos with energy $\omega \cong 75 \text{ MeV}$ in supernova condition ($B = 10^4 B_0$). In case of the longitudinal polarization of the spins of the produced positrons we obtain $A \cong 96.8\%$ for the process $\nu_e \rightarrow \nu_e e^- e^+$ and $A \cong 99.6\%$ for the processes $\nu_\mu \rightarrow \nu_\mu e^- e^+$ and $\nu_\tau \rightarrow \nu_\tau e^- e^+$. It means that in case of the longitudinal polarization the processes $\nu_i \rightarrow \nu_i e^- e^+$ with production of the positrons having the spins oriented opposite to the momentum vector contribute to the cooling process of supernovae much more than the processes $\nu_i \rightarrow \nu_i e^- e^+$ with production of the positrons having the spins oriented along the momentum vector. In case of the transverse polarization of the spins of the produced positrons we obtain $A \cong 25\%$ for the process $\nu_e \rightarrow \nu_e e^- e^+$ and

$A \cong -9.4\%$ for the processes $\nu_\mu \rightarrow \nu_\mu e^- e^+$ and $\nu_\tau \rightarrow \nu_\tau e^- e^+$. It indicates that in case of the transverse polarization the process $\nu_e \rightarrow \nu_e e^- e^+$ with production of the positrons having the spins oriented opposite to the magnetic field direction contributes to the cooling process of supernova more than the process $\nu_e \rightarrow \nu_e e^- e^+$ with production of the positrons having the spins oriented along the magnetic field direction. In case of the transverse polarization the processes $\nu_\mu \rightarrow \nu_\mu e^- e^+$, $\nu_\tau \rightarrow \nu_\tau e^- e^+$ with production of the positrons having the spins oriented along the magnetic field direction contribute to the cooling process of supernova more than the processes $\nu_\mu \rightarrow \nu_\mu e^- e^+$, $\nu_\tau \rightarrow \nu_\tau e^- e^+$ with production of the positrons having the spins oriented opposite to the magnetic field direction. We have also shown that the spin asymmetries arising in the energy losses occurring at the expense of the processes $\nu_i \rightarrow \nu_i e^- e^+$ are sensitive to the neutrino flavour.

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¹*Shamakhy Astrophysical Observatory of ANAS*

²*Baku State University*

³*Nakhchivan State University*

gasimovar@yahoo.co.uk

İFRATGÜCLÜ MAQNİTLƏŞMİŞ ULDUZLARDA NEYTRİNOLAR TƏRƏFİNDƏN ELEKTRON-POZİTRON CÜTLƏRİNİN YARANMASI PROSESLƏRİNDƏ SPİN ASİMMETRİYALARI

R.E.Qasimova, V.A.Hüseynov, B.T.Hacıyeva

Biz, pozitronların və elektronların spinlərinin uzununa və eninə polyarlaşmaları nəzərə alınmaqla $\nu_i \rightarrow \nu_i e^- e^+$ prosesləri hesabına neytrinolar tərəfindən ifratgüclü maqnitləşmiş ulduz mühitinin vahid həcminə vahid zamanda ötürülən enerjini hesablamışıq. Biz, həm də bu proseslərdə ortaya çıxan spin asimmetriyalarını müəyyən etmişik və alınmış nəticələrin ifratyenilərin partlayışına astrofiziki tətbiqlərini göstərmişik.

Açar sözlər: neytrino, elektron-pozitron cütləri, uzununa polyarlaşma, eninə polyarlaşma, ifratyenilər, ifratgüclü maqnit sahələri, əsas Landau səviyyəsi, birinci Landau səviyyəsi

СПИНОВЫЕ АСИММЕТРИИ В ПРОЦЕССАХ ОБРАЗОВАНИЯ ЭЛЕКТРОН-ПОЗИТРОННЫХ ПАР НЕЙТРИНО В СВЕРХСИЛЬНО ЗАМАГНИЧЕННЫХ ЗВЕЗДАХ

Р.Э.Гасимова, В.А.Гусейнов, Б.Т.Гаджиева

Мы вычислили энергию, передаваемую со стороны нейтрино в единичный объем сверхсильно замагниченной звездной среды в единицу времени за счет процессов $\nu_i \rightarrow \nu_i e^- e^+$ с учетом продольной и поперечной поляризаций спинов позитронов и электронов. Мы также определили спиновые асимметрии, возникающие в этих процессах и показали приложения полученных результатов для взрывов сверхновых.

Ключевые слова: нейтрино, электрон-позитронные пары, продольная поляризация, поперечная поляризация, сверхновые, сверхсильные магнитные поля, основной уровень Ландау, первый уровень Ландау