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ELECTRON-POSITRON PAIRS ABSORPTION BY NEUTRINOS IN SUPERSTRONGLY MAGNETIZED HOT STELLAR MEDIUM

R.E.Gasimova

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We have calculated the energy absorption per unit time per unit volume by the neutrinos in superstrongly magnetized hot stellar medium provided that the electrons occupying the ground Landau level and the positrons occupying the first Landau level are absorbed by the neutrinos moving along the stellar magnetic field direction. We have shown that the spectral and angular distribution of the energy absorption is not sensitive to the neutrino flavour, it is anisotropic on the scattering angle (the polar angle of the final neutrino momentum) and asymmetric with respect to the positron spin polarization. The arising spin asymmetry is significant for an ordinary neutron star medium ($H \cong H_0 \sim 10^{13} G$) and it is $A \cong 57.74\%$. The obtained results enable us to explain the arising anisotropies and asymmetries connected with the cooling of neutron stars.

Keywords: neutrino, electron-positron pair, superstrong magnetic field, low Landau levels, spin asymmetry, neutron star, magnetar

Introduction

Young neutron stars possess very strong external magnetic fields of the strengths $H \sim 10^{12} - 10^{13} G$ [1-2]. Superstrong magnetic fields with the strengths $H \geq H_0 = m_e^2 / e = 4.41 \times 10^{13} G$ are met in strongly magnetized astrophysical objects and processes [1-10], where H_0 is the Schwinger field strength (we use the system of units $\hbar = c = k_B = 1$, where k_B is the Boltzmann constant). Generation of the superstrong magnetic fields of the strengths $H \sim 10^{15} G$ is possible in collapsing and rotating stellar cores [1-3]. The strengths of the magnetic fields of the anomalous X-ray pulsars and soft gamma ray repeaters, the so-called magnetars, can reach the magnitude of $H \sim 10^{15} G$ [4, 5]. Neutron stars may possess the magnetic fields of the strengths $H \sim 10^{15} G$ long after their birth in supernovae [6] and at least the magnetic fields of the indicated strengths can be generated during the formation of some protoneutron stars. In [7] it is suggested that the magnetic fields of the strengths $H \sim 10^{16} G$ may be produced near the surface of a protoneutron star. The sources of

cosmological gamma-ray bursts may have even higher ($H \sim 10^{16} - 10^{17} G$) magnetic field strengths [8]. By equating the magnetic energy of a protoneutron star to its gravitational binding energy, the upper limit of the magnetic field strengths ($H \sim 10^{18} G$) for new-born neutron stars can be estimated [9]. 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 stronger than the field strength $H \sim 10^{18} G$. Possible existence of the superstrong magnetic fields with the strengths higher than $\sim 10^{20} G$ and production of such fields in cosmic objects and phenomena are not excluded [10].

Investigation of various interaction processes of high energy particles in superstrong magnetic fields has great importance for both particle physics and astrophysics. The effective mechanism of transportation of internal energy of strongly magnetized hot stars to surroundings is not realized by photons, but it realized by neutrinos and antineutrinos. One of the main processes taking a great importance in cooling

of strongly magnetized hot stars can be the processes of the absorption of the electron-positron pairs by neutrinos in a superstrong magnetic field. These processes are described by the reaction

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

where ν_i are the neutrino flavours: $\nu_i = \nu_e, \nu_\mu, \nu_\tau$. When we have dealings with ν_e , both the neutral and charged currents contribute to the processes (1). However, when we have dealings with ν_μ or ν_τ , the neutral currents only contribute to the processes (1). The processes describing by the reaction (1) in a strongly magnetized thermal plasma were investigated in [11, 12]. In [11] relatively simple expressions for the probability and mean losses of the neutrino energy and momentum were obtained. In [12] the rates of the indicated processes were calculated on the basis of the technique of finite temperature field theory. In the superstrong magnetic fields the electrons and positrons participating in the processes (1) are mainly occupy the low Landau levels. In such magnetic fields the energy gained by electrons and the energy of the interaction between the electron spin and the magnetic field is in order of the electron rest mass and even higher than its rest mass. Thus, for the processes (1) proceeding in superstrong magnetic fields the field and spin (polarization) effects should be taken into account. However, in [11, 12] the spins of the electrons and positrons and the polar and azimuthal angles of the momenta of the initial and final neutrinos have not been taken into account.

The purpose of this work is to investigate the energy absorption per unit time per unit volume by the neutrinos in superstrongly magnetized hot medium with allowance for the temperature and the chemical potentials of the electron-positron gas and neutrino gas provided that the electrons and positrons occupying the low Landau levels are transversely polarized and the polar and azimuthal angles of the momenta of the final neutrinos are arbitrary, to ob-

tain the formula enabling us to calculate the energy absorption, to clarify the role of the spin (polarization) effects and to determine the astrophysical applications of the obtained results.

We investigate the considered processes for the small momentum transferred, i.e. for the case when $|q_z|^2 \ll m_Z^2$ and $|q_w|^2 \ll m_W^2$, where m_Z is the Z -boson mass and m_W is the W -boson mass. It is true the experimental confirmation of neutrino oscillations is evident for the existence of the small mass of neutrinos. The estimations indicate the upper boundary of the neutrino mass $m_\nu < 2 \text{ eV}$ [13]. However, the value of the neutrino mass is much smaller than the electron mass and the Z -boson (W -boson) mass and the characteristic energy of neutrinos (antineutrinos) considered here is much greater than the neutrino mass. Therefore, the massless neutrino approximation is justified for the considered problem. Contribution of the electromagnetic interaction of the possible anomalous magnetic moment of a neutrino with the magnetic field can be neglected for the observable strengths of the known magnetized stars. Here we use the pseudo-euclidean metrics with the signature $(+---)$.

1. Spectral and angular distribution of energy absorption transported from unit volume of the medium per unit time. Using the Feynman rules for weak processes [14] and the method of exact solution of the relativistic wave equations (here we use the Dirac equation) in a constant uniform magnetic field [15] we obtain the following formula for the spectral and angular distribution of the energy absorption transported from the unit volume of the medium per unit time with allowance for the temperature and the chemical potential of the electron gas and a neutrino gas when the electrons and positrons occupying any low Landau levels are transversely polarized

$$Q = \frac{d\left(\frac{dE}{dt}\right)}{d\omega'd\Omega'} = \frac{G_F^2}{(2\pi)^4 V} eH \times$$

$$\times \sum_{n=0}^{\infty} \sum_{n'=0}^{\infty} \sum_i \frac{E_i E'_i}{|E'_i p_{zi} - E_i p'_{zi}|} \frac{\omega'}{\omega} (\omega' - \omega) R f_{e^-} f_{e^+} (1 - f_{\nu'}), \quad (2)$$

where G_F is the Fermi constant, H is the strength of the magnetic field which is assumed to be directed along the z -axis, f_{e^-} and f_{e^+} are the Fermi-Dirac distribution functions of the electron gas and positron gas, respectively, $f_{\nu'}$ is the Fermi-Dirac distribution function of the final neutrino gas, ω and ω' are the energies of the initial and final neutrinos, respectively, R is the quantity obtained from the absolute value of the squared amplitude (or squared matrix element) of the considered processes, E_i and E'_i are energies of the electron and positron, respectively, and they are the roots of the equation $\omega' = \omega + E + E'$ that expresses the energy conservation law ($E = \sqrt{m_e^2 + 2eHn + p_z^2}$ and $E' = \sqrt{m_e^2 + 2eHn' + p_z'^2}$), p_{zi} and p'_{zi} are the third components of the electron and positron, respectively, and they are the roots of the equation $k'_z = k_z + p_z + p'_z$ that expresses the conservation law of the third component of momentum. The formula (2) is right for the arbitrary strength H of the magnetic field.

2. Spectral and angular distribution of energy absorption when electrons and positrons occupy low Landau levels. When the magnetic field is superstrong $H \geq H_0$, electrons and positrons occupy the ground Landau level or the first Landau level. The calculations show that when both the electrons and the positrons occupy the ground Landau level, i.e. when $n = 0, p_z = 0, \zeta = -1$ and $n' = 0, p'_z = 0, \zeta' = +1$, the following results are obtained for R

$$R(n = 0, n' = 0) = 0. \quad (3)$$

and for the energy absorption

$$Q(n = 0, n' = 0) = 0, \quad (4)$$

where $\zeta(\zeta')$ is the spin quantum number for the electron (positron). When the spin of the

electron (positron) is oriented along the magnetic field direction, $\zeta = +1(\zeta' = +1)$ and when the spin of the electron (positron) is oriented opposite to the magnetic field direction, $\zeta = -1(\zeta' = -1)$.

The result (4) means that the electrons and the positrons occupying the ground Landau level do not contribute to the electron-positron pair absorption by the neutrinos in a superstrong magnetic field. The same result is obtained when the electrons occupy the first Landau level ($n = 1$) and the positrons occupy the ground Landau level ($n' = 0, p'_z = 0, \zeta' = +1$)

$$R(n = 1, n' = 0) = 0, \quad (5)$$

$$Q(n = 1, n' = 0) = 0. \quad (6)$$

When the initial neutrinos move along the magnetic field direction (therefore the initial neutrino polar angle is $\vartheta = 0$) provided that the electrons occupy the ground Landau level and the positrons occupy the first Landau level, we obtain for the quantity R the expression

$$R(n = 0, n' = 1, \vartheta = 0) = \frac{\omega \omega'^3}{eH} g_R^2 (1 + \cos \vartheta') \sin^2 \vartheta' \times \\ \times \left(1 + \frac{\omega' \cos \vartheta' - \omega}{E'} \right) \left(1 - \zeta' \frac{m_e}{E'_\perp} \right) \exp \left(- \frac{\omega'^2 \sin^2 \vartheta'}{2eH} \right), \quad (7)$$

where $g_R = \sin^2 \vartheta_w \cong 0.23$, ϑ_w is the Weinberg angle, ϑ' is the scattering angle (in the considered case the polar angle of the final neutrino momentum is equal to the scattering angle) and

$$E'_\perp = \sqrt{E'^2 - p_z'^2} = \sqrt{m_e^2 + 2eHn'}. \quad (8)$$

Taking into account the expression for R in the formula (2) and performing the straightforward calculations we obtain the spectral and angular distribution of the energy absorption transported from the unit volume of the medium per unit time provided that the initial neu-

trinos move along the magnetic field direction, the electrons occupy the ground Landau level and the positrons occupy the first Landau level

$$Q = \frac{G_F^2 g_R^2}{(2\pi)^4 V} \omega'^4 (\omega' - \omega) \left(\frac{E'}{\omega' \cos \vartheta' - \omega} + 1 \right) \left(1 - \zeta' \frac{m_e}{E'_\perp} \right) \times \\ \times f_{e^-} f_{e^+} (1 - f_{\nu'}) (1 + \cos \vartheta') \sin^2 \vartheta' \exp \left(- \frac{\omega'^2 \sin^2 \vartheta'}{2eH} \right) \quad (9)$$

where

$$\omega' = \omega + m_e + \sqrt{m_e^2 + 2eH} \quad (10)$$

is the final neutrino energy.

Using the expressions (7) and (9) we derive that when $\vartheta' = 0$ and $\vartheta' = \pi$, the process does not take place. In general, the presence of the angle ϑ' in the expression (9) means that the spectral and angular distribution of the energy absorption transported from the unit volume of the medium per unit time depends on the scattering angle (the polar angle of the final neutrino momentum) and it is anisotropic. The presence of the multiplier g_R^2 in the formula (9) enables us to come to the conclusion that when the initial neutrinos move along the magnetic field direction, the spectral and angular distribution of the energy absorption is not sensitive to the neutrino flavour.

3. Spin asymmetry in the spectral and angular distribution of the energy absorption and numerical estimations. The obtained formula shows that the spectral and angular distribution of the energy absorption transported from the unit volume of the medium per unit time is sensitive to the positron spin projection. The calculations show that the spectral and angular distribution of the energy absorption is not symmetric in two different spin polarization cases of the positrons participating in the processes

$$Q(\zeta' = -1) \neq Q(\zeta' = +1). \quad (10)$$

The arising spin asymmetry in the spectral and angular distribution of the energy absorption can be determined as follows

$$A = \frac{Q(\zeta' = -1) - Q(\zeta' = +1)}{Q(\zeta' = -1) + Q(\zeta' = +1)}. \quad (11)$$

If we take into account the formula (9) in the definition (11), we obtain the simple expression for the spin asymmetry

$$A = \frac{m}{\sqrt{m_e^2 + 2eH}}. \quad (12)$$

The following result is obtained from the formula (12): the spin asymmetry is determined by the magnetic field strength and the greater is the magnetic field strength the smaller is the spin asymmetry. For the ordinary neutron star medium ($H \cong H_0 \sim 10^{13} \text{ G}$) the spin asymmetry is $A \cong 57.74\%$. If we consider the magnetar medium ($H \cong 40H_0 \sim 10^{15} \text{ G}$), we obtain $A \cong 11.11\%$. For supernova explosions ($H \cong 10^4 H_0 \sim 10^{17} \text{ G}$) the spin asymmetry is $A \cong 0.71\%$. So, for sufficiently super strong magnetic fields ($H \gg H_0$) the spin asymmetry tends to zero. Thus, the spin asymmetry in the spectral and angular distribution of the energy absorption is significant for an ordinary neutron star medium ($H \cong H_0 \sim 10^{13} \text{ G}$). The contribution of the positrons with the spin orientation opposite to the magnetic field direction is about 3.73 times more than that one of the positrons with the spin orientation along the magnetic field direction. It means that when the initial neutrinos moving along the magnetic field direction absorb the electrons occupying the ground Landau level and the positrons occupying the first Landau level, the positrons with the spin oriented opposite to the magnetic field direction contribute to the cooling process of ordinary neutron stars 3.73 times more than the positrons with the spin oriented along the magnetic field direction.

Conclusions

We have investigated the electron-positron pairs absorption by neutrinos in a strongly magnetized hot stellar medium. We have calculated the energy absorption per unit time per unit volume by the neutrinos in strongly magnetized hot medium with allowance for the temperature and the chemical potentials of the electron-positron gas and neutrino gas provided that the electrons occupying the ground Landau level and the positrons occupying the first Landau level are absorbed by the neutrinos moving along the magnetic field direction. We have shown that the spectral and angular distribution of the energy absorption transported from the unit volume of the medium per unit time depends on the scattering angle (in the considered case the polar angle of the final neutrino momentum is equal to the neutrino scattering angle) and it is anisotropic. The analyses show that when the initial neutrinos move along the magnetic field direction, the spectral and angular distribution of the energy absorption is not sensitive to the neutrino flavour. The calculations show that the spectral and angular distribution of the energy absorption is asymmetric with respect to the positron spin polarization. We have shown that the spin asymmetry is determined by the magnetic field strength and the greater is the magnetic field strength the smaller is the spin asymmetry. The spin asymmetry in the spectral and angular distribution of the energy absorption is significant for an ordinary neutron star medium ($H \cong H_0 \sim 10^{13} G$) and it is $A \cong 57.74\%$. When the initial neutrinos moving along the magnetic field direction absorb

the electrons occupying the ground Landau level and the positrons occupying the first Landau level, the positrons with the spin oriented opposite to the magnetic field direction contribute to the cooling process of ordinary neutron stars 3.73 times more than the positrons with the spin oriented along the magnetic field direction.

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*Shamakhy Astrophysical Observatory of ANAS
Baku State University
Qafqaz University
gasimovar@yahoo.co.uk*

İFRATGÜCLÜ MAQNİTLƏŞMİŞ QIZMAR ULDUZ MÜHİTİNDƏ NEYTRİNOLAR TƏRƏFİNDƏN ELEKTRON-POZİTRON CÜTLƏRİNİN UDULMASI

R.E.Qasimova

Biz, əsas Landau səviyyəsində yerləşən elektronların və birinci Landau səviyyəsində yerləşən pozitronların ulduz maqnit sahəsi boyunca hərəkət edən neytrinolar tərəfindən udulması şərti daxilində ifratgüclü maqnitləşmiş qızmar ulduz mühitində neytrinolar tərəfindən vahid zamanda vahid həcmə düşən enerji udulmasını hesablamışıq. Biz göstərmişik ki, enerji udulmasının spektral və bucaq paylanması neytrino növünə həssas olmayıb, səpilmə bucağına (son haldakı neytrinin impulsunun polyar bucağına) görə anizotrop və pozitronun spininin polyarlaşmasına nəzərən asimmetrikdir. Ortaya çıxan spin asimmetriyası adi neytron ulduzu mühiti ($H \cong H_0 \sim 10^{13} G$) üçün əhəmiyyətli dərəcədədir və $A \cong 57,74\%$ təşkil edir. Alınmış nəticələr neytron ulduzlarının soyuması ilə bağlı ortaya çıxan anizotropiyaları və asimmetriyaları izah etməyə imkan verir.

Açar sözlər: neytrino, elektron-pozitron cütü, ifratgüclü maqnit sahəsi, aşağı Landau səviyyələri, spin asimmetriyası, neytron ulduzu, maqnitar

ПОГЛОЩЕНИЕ ЭЛЕКТРОН-ПОЗИТРОННЫХ ПАР НЕЙТРИНО В СВЕРХСИЛЬНОЙ ЗАМАГНИЧЕННОЙ ЗВЕЗДНОЙ СРЕДЕ

Р.Э.Гасимова

Мы вычислили энергию, поглощенную нейтрино за единицу времени в единицу объема в сверхсильно замагниченной горячей звездной среде, при условии, что электроны, занимающие основной уровень Ландау и позитроны, занимающие первый уровень Ландау, поглощаются нейтрино, движущимся вдоль направления звездного магнитного поля. Мы показали, что спектральное и угловое распределение поглощения энергии не является чувствительным к аромату нейтрино и оно анизотропно по углу рассеяния (по полярному углу импульса конечного нейтрино) и асимметрично по поляризации спина позитрона. Возникающая спиновая асимметрия является существенным для среды обычной нейтронной звезды и составляет $A \cong 57.74\%$. Полученные результаты позволяют объяснить возникающие анизотропии и асимметрии, связанные с охлаждением нейтронных звезд.

Ключевые слова: нейтрино, электрон-позитронная пара, сверхсильное магнитное поле, низкие уровни Ландау, спиновая асимметрия, нейтронная звезда, магнитар