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Asymmetric Neutrino Emissions and Magnetic Structures of Magnetars in Relativistic Quantum Approach

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We study a cooling process of magnetars through the $\nu\bar{\nu}$-pair emission from electron and proton, which occurs only under the strong magnetic field, in the exact quantum calculation. Our results show that the luminosity is proportional to $T^{0.95} - T^{1.7}$ when the magnetic fields are $B = 10^{15} - 10^{16}$G. The powers of the temperature are much smaller than those in the direct Urca and moderate Urca processes. Thus, the $\nu\bar{\nu}$-pair emission processes by the strong magnetic field is expected to contribute very largely to the cooling process of the magnetar.

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1. Introduction

Magnetic fields in neutron stars play important roles in the interpretation of many observed phenomena. Magnetars, which are associated with a super strong magnetic field, [1, 2] have properties different from normal neutron stars. Thus, phenomena related with the magnetars give a lot of information about the roles of the magnetic field.

The characteristic spin down ages ($P/2\dot{P}$) of the magnetars appear to be systematically overestimated compared to ages of the associated supernova remnants [3]. Soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) correspond to magnetars [4]. Namely the magnetar emits large energy photons. Furthermore, surface temperature of the magnetars are $T \approx 300-900$eV, which is larger than those of normal neutron star $T \approx 10-150$eV [5]. Thus, the associate strong magnetic fields may have significant roles in these phenomena. There must be a mechanism to convert the magnetic energy into thermal and radiant energies.

We have been studying neutrino reactions in strongly magnetized neutron-star matters in the relativistic mean field theory. In that work we found the asymmetry of neutrino emissions from the magnetized proto-neutron-stars (PNSs), and showed that this asymmetry largely contributes to the pulsar-kick [6] and the spin-deceleration of the PNSs [7]. In the above calculations, however, we considered only spin currents in a perturbative way.

In Ref. [8], we have introduced Landau levels in our framework and have calculated pion production though proton synchrotron radiation under strong magnetic field . In that work we have found that quantum calculations give much large production rates than semi-classical calculations.

On the other hand, many people have paid attention into cooling processes of neutron stars because it must give important information of structure of neutron stars [9]. The neutron stars are cooled by the neutrino emission, and the magnetic field is expected to affect the emission mechanism largely because the strong magnetic field can supply energy and momentum into the process.

In the strong magnetic field the $\nu\bar{\nu}$-pair synchrotron radiation is allowed via $e^-(p) \to e^-(p) + \nu + \bar{\nu}$. Its calculations have been performed within the semi-classical approach [10, 11].

In the strong magnetic field, however, the $\nu\bar{\nu}$-par can be produced by the transition between the different Landau levels for the charged particles such as electrons and protons.

In this work, we apply our quantum theoretical approach to the $\nu\bar{\nu}$-pair productions in the strong magnetic field and calculate it through the transition between the different Landau levels for electrons and protons. Only this quantum approach can exactly describe the momentum transfer from the magnetic field.

2. Formalism

Here, we briefly explain our formalism. We assume a uniform magnetic field along the z-direction, $\boldsymbol{B} = (0,0,B)$, and take the electro-magnetic vector potential A^μ to be $A = (0,0,xB,0)$ at the position $\boldsymbol{r} \equiv (x,y,z)$. The relativistic proton (electron) wave function ψ is obtained from the following Dirac equation:

$$\left[\alpha_z p_z - i\alpha_x \partial_x + \alpha_y (p_y - eB_x) + M\beta - \frac{\kappa}{M} B\Sigma_z\right] \psi(x, p_z, s) = E\,\psi(x, p_z, s), \tag{2.1}$$

where M_N is the proton (electron) mass, κ is the AMM, e is the particle charge, and E is the single particle energy written as with

$$E(n,p_z,s) = \sqrt{p_z^2 + (\sqrt{2|e|Bn + M^2} - s\kappa B/M)^2}. \tag{2.2}$$

The weak interaction part of the Lagrangian density is written as

$$\mathscr{L}_W = G_F \overline{\psi}_\nu \gamma_\mu (1-\gamma_5)\psi_\nu \sum_\alpha \overline{\psi}_\alpha \gamma_\mu (c_V - c_A\gamma_5)\psi_\alpha, \tag{2.3}$$

where ψ_ν is the neutrino field, ψ_α is the field of the particle α which indicates the proton and electron, and the c_V and c_A are the weak vector and axial coupling constants dependent on each channel.

Now we consider the decay width of protons and electrons to neutrino and anti-neutrino pair. We define $n_{i(f)}$, $p_{i(f)z}$ and $s_{i(f)}$ as the Landau level, the z-component of momentum and the spin of the initial (final) particle. In addition the momenta of the emitted neutrino and anti-neutrino are written as k_1 and k_2, respectively. Then, we can obtain the differential decay width as

$$\begin{aligned} d\Gamma(n_i,n_f,s_i,s_f) = {} & \frac{G_F}{2}\frac{dp_{fz}}{(2\pi)^3}\frac{dk_1^3}{(2\pi)^3}\frac{dk_2^3}{(2\pi)^3}\frac{1}{E_iE_f|\boldsymbol{k}_1||\boldsymbol{k}_2|}\frac{1}{2}N_{\mu\nu}L^{\mu\nu} \\ & \times(2\pi)^2\delta(E_i - E_f - |\boldsymbol{k}_1| - |\boldsymbol{k}_2|)\delta(p_{iz} - p_{fz} - k_{1z} - k_{2z}) \end{aligned} \tag{2.4}$$

with $q = k_1 + k_2$, $q_T = \sqrt{q_x^2 + q_y^2}$ and

$$L_{\mu\nu} = \frac{1}{2}\left\{k_{1\mu}k_{2\nu} + k_{2\mu}k_{1\nu} - g_{\mu\nu}(k_1\cdot k_2) + i\varepsilon_{\mu\nu\lambda\kappa}k_1^\lambda k_2^\kappa\right\}, \tag{2.5}$$

$$\begin{aligned} N_{\mu\nu} = {} & \frac{1}{4}\mathrm{Tr}\int dx_1 dx_2 \tilde{F}_f\left(x_1 - \frac{q_T}{2\sqrt{|e|B}}\right)\rho_M^{(+)}(n_f,s_f,p_{fz})\tilde{F}_f\left(x_2 + \frac{q_T}{2\sqrt{|e|B}}\right)\gamma_\mu(c_V - c_A\gamma_5) \\ & \times\tilde{F}_i\left(x_2 - \frac{q_T}{2\sqrt{|e|B}}\right)\rho_M^{(+)}(n_i,s_i,p_{iz})\tilde{F}_i\left(x_1 + \frac{q_T}{2\sqrt{|e|B}}\right)\gamma_\nu(c_V - c_A\gamma_5), \end{aligned} \tag{2.6}$$

where

$$\begin{aligned} \rho_M = {} & \frac{\left[E\gamma_0 + \sqrt{2|e|Bn}\gamma^2 - p_z\gamma^3 + M + (\kappa B/M)\Sigma_z\right]}{4E} \\ & \times\left[1 + \frac{s\left(\kappa B/M + p_z\gamma_5\gamma^0 - E\gamma_5\gamma^3\right)}{\sqrt{2|e|Bn + M^2}}\right], \end{aligned} \tag{2.7}$$

$$\tilde{F} = f_{n-\frac{1}{2}(s-\frac{e}{|e|})}(x)\frac{1+\Sigma_z}{2} + f_{n-\frac{1}{2}(s+\frac{e}{|e|})}(x)\frac{1-\Sigma_z}{2} \tag{2.8}$$

with f_n being the harmonic oscillator wave function with the principle quantum number n.

Actually we perform the calculation in the neutron-star matter composing proton, neutron and electron. The equation of state is obtained at the zero temperature in the relativistic mean-field theory using the parameter-set in Ref. [7]. As shown later, the proton contribution is negligibly small, and then only the electron (proton) fraction affects the $\nu\bar{\nu}$-emission.

3. Results

The $\nu\bar{\nu}$-pair luminosity per volume, L/V, is calculated as

$$L_{\nu\bar{\nu}}/V = \sum_{s_i,s_f} \int \frac{d\boldsymbol{p}_i}{(2\pi)^3} n(E_i)[1-n(E_f)](|\boldsymbol{k}_1|+|\boldsymbol{k}_2|)\Gamma. \tag{3.1}$$

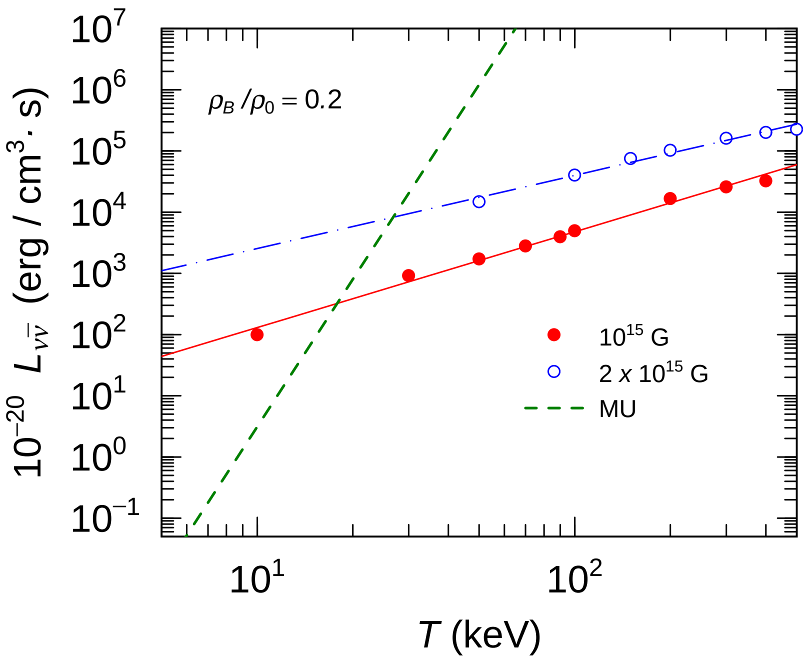

Figure 1: $\nu\bar{\nu}$-pair emission luminosity per volume at the baryon density $\rho_B = 0.2\rho_0$. The solid circles and the open circles represent results when $B = 10^{15}$G and $B = 2\times10^{15}$G, respectively. The dashed lines indicates the results with the modified Urca process.

In Fig. 1, we show the calculation results at the baryon density $\rho_B = 2\rho_0$, where ρ_0 is normal nuclear matter density. The solid circles and open circles represent the calculation results when $B = 10^{15}$G and $B = 2\times10^{15}$G, respectively. For comparison, we give the neutrino luminosity per volume in the modified Urca (MU) process [13] with the dashed line.

Since $\sqrt{eB} = 2.4$MeV when $B = 10^{15}$G, the transition energy is a few MeV, which is much larger than the realistic temperature of magnetars $T \approx 300-900$eV. Then, we need to extrapolate them up to a realistic temperature by using the fitting function $L_{\nu\bar{\nu}}/V = cT^a$ with a and c being the fitting parameters. The solid and dot-dashed lines represent results of the fitting function when $B = 10^{15}$G and when $B = 2\times10^{15}$G, respectively.

In Fig. 2 we show the results at the baryon density $\rho_B = \rho_0$ (left panel) and $\rho_B = 2\rho_0$ (right panel).

The solid and dot-dashed lines represent results of the fitting function $L_{\nu\bar{\nu}}/V = cT^a$; $L_{\nu\bar{\nu}}/V = 3.54T^{1.6}$ when $B = 10^{15}$G and $L_{\nu\bar{\nu}}/V = 121T^{1.2}$ when $B = 2\times10^{15}$G.

For comparison, we give the neutrino luminosity per volume in the modified Urca (MU) process and direct Urca (DU) process [14] with the dashed and dotted lines, respectively. Note that the DU process occurs in $\rho_B \gtrsim 2\rho_0$.

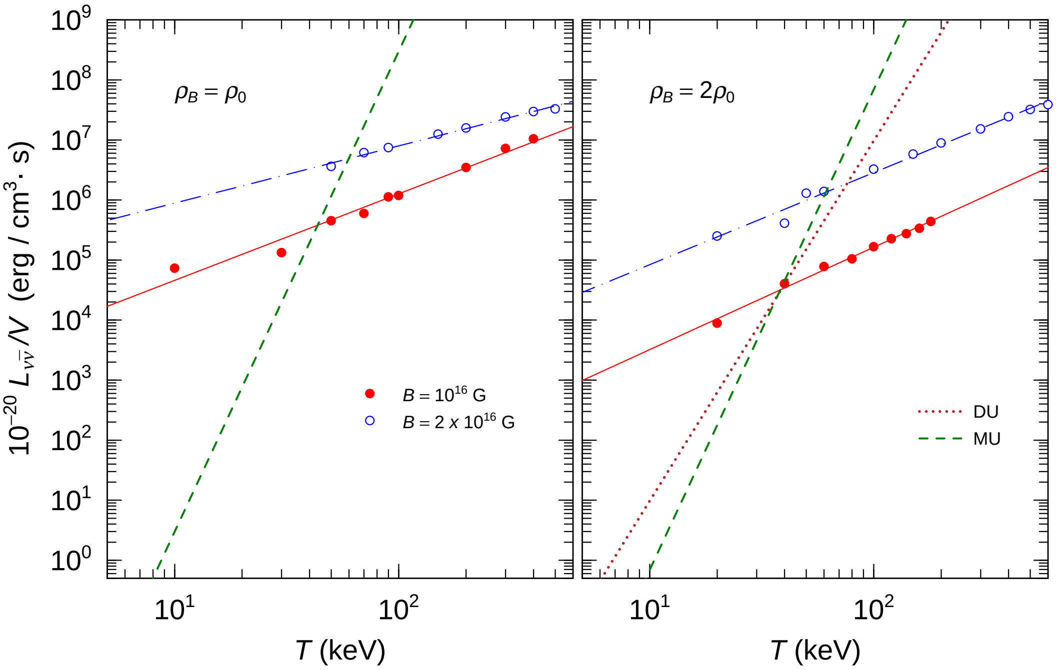

Figure 2: $\nu\bar{\nu}$-pair emission luminosity per volume at the baryon density $\rho_B = \rho_0$ (left panel) and $\rho_B = 2\rho_0$ (right panel). The solid circles and open circles represent results when $B = 10^{16}$G and $B = 2 \times 10^{16}$G, respectively. The dashed and dotted lines indicates the results with the MU and DU processes, respectively.

In order to examine our results, we show the results at $T = 700$eV in the Table 1.

In this table we give a contribution from proton when $B = 10^{15}$G and $\rho_B = 0.2\rho_0$. We see that the proton contribution is much smaller than that from electron. In the transition between two fixed Landau levels, a smaller mass particle makes larger energy transfer and gives larger luminosity. Thus, the electron contribution is much larger than the proton one, so that we consider only the electron contribution.

ρ_B	$0.2\rho_0$		ρ_0		$2\rho_0$	
B	10^{15}G	2×10^{15}G	10^{16}G	2×10^{16}G	10^{16}G	2×10^{16}G
a	1.6	1.2	1.4	0.95	1.71	1.53
Electron	1.8×10^{20}	9.6×10^{21}	1.8×10^{22}	4.7×10^{24}	3.0×10^{21}	1.3×10^{23}
Proton	1.2×10^{13}					
MU	9.9×10^{10}		9.5×10^{10}		2.2×10^{10}	
DU					7.3×10^{13}	

Table 1: Estimated total luminosity of $\nu\bar{\nu}$-pair per volume $L_{\nu\bar{\nu}}/V$ at $T = 700$eV from electron and proton.

Furthermore, we see that our results are much larger than those of DU and MU processes. When we fit the total luminosity per volume with the fitting function, $L_{\nu\bar{\nu}}/V = cT^a$, the DU and MU processes give $a = 6$ and $a = 8$, respectively, while our results indicate $a \approx 0.95 - 1.7$. The small values of the power, a, lead to much larger luminosities than those in the usual Urca processes at the realistic temperature.

In the low temperature expansion the power of the temperature is determined by the numbers of the fermions in the initial and final states besides the neutrino and the anti-neutrino. Only one electron contributes to the calculation in the $\nu\bar{\nu}$-pair emissions in our approach, so that the power is much smaller than that of the DU and MU processes. As mention before, furthermore, the energy transfer is much larger than that of the temperature, and it makes the power of the temperature, a, smaller.

In addition, the semi-classical approach in Ref. [11] gives $L_{\nu\bar{\nu}} \propto T^5$, their results are much smaller than ours. In the strong magnetic field the quantum calculation is very important, and we need to introduce the Landau levels for particle productions.

4. Summary

We study $\nu\bar{\nu}$-pair emission in the strong magnetic field by calculating the transition between different Landau levels. Our calculation can be performed above about $T \sim 10^4 - 10^5$eV, so that we extrapolate the results of the total luminosity per volume, $L_{\nu\bar{\nu}}$ to several hundred eV by using the fitting function $L_{\nu\bar{\nu}}/V = cT^a$.

In our calculation the power of the temperature turned out to be very small, $a \approx 0.95 - 1.7$, and then the total luminosity is much larger than that of the usual cooling processes such as the MU and DU processes. Our results are still preliminary, and we need to examine the extrapolation. Then, we cannot give any conclusion, yet. However, we can mention that the quantum calculation is very important in the strong magnetic field.

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