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$\nu\bar{\nu}$-Pair and Axion Productions in Strong Magnetic Field in Relativistic Quantum Approach and Cooling of Magnetars

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Abstract. We study the $\nu\bar{\nu}$-pair and axion production from electron and proton, which occurs only under the strong magnetic field. We perform the exact relativistic quantum calculation including the Landau levels and the anomalous magnetic moment. Cooling by $\nu\bar{\nu}$-pair and axion emission are shown to be much larger than neutrino cooling by the Urca processes. Thus, these processes by the strong magnetic field is expected to contribute very largely to the cooling process of the magnetar.

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. Indeed, the magnetars emit high energy photons [3], and their surface temperatures are $T \approx 0.28 - 0.72$ keV, which is larger than those of normal neutron star $T \approx 0.01 - 0.15$ keV with the similar age [4]. Thus, the associate strong magnetic fields may have significant roles in these phenomena, and phenomena related with the magnetars must give a lot of information about the roles of the magnetic field.

Many people have paid attention into neutron star cooling processes, which must give us important information of neutron stars structure [5]. 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. Particle emission by synchrotron radiation is a cooling process peculiar to strong magnetic field systems. In particular, the $\nu\bar{\nu}$-pair and axion productions have been studied by many people through the processes via $e^-(p) \rightarrow e^-(p) + \nu\bar{\nu}(a)$.

However, the calculations have been performed within the semi-classical approach,which is available when a magnetic field is as weak as the Landau level being negligible, for $\nu\bar{\nu}$-pair production [6, 7] and the axion production [8]. In Refs. [9, 10], we have introduced Landau levels and have calculated pion production from proton synchrotron radiation in the strong magnetic fields. The number of the produced pions is much larger in the quantum calculation than in the semi-classical calculations. In that work we have found that quantum calculations give much large production rates than semi-classical calculations.

In this work, then, we apply our quantum theoretical approach to the $\nu\bar{\nu}$-pair and axion productions in the strong magnetic field and calculate them 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.

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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:

$$\left[\alpha_z p_z - i\alpha_x \partial_x + \alpha_y (p_y - \zeta eBx) + (M - U_s)\beta + U_0 \frac{\kappa B}{M} \Sigma_z\right] \psi(x, p_z, s) = E\psi(x, p_z, s), \tag{1}$$

where α and β are Dirac matrices, M is the proton (electron) mass, κ is the anomalous magnetic moment, e is the particle charge, $\zeta = \pm 1$ is the sign of the particle charge. U_s and U_0 are the scalar field and time component of the vector field, respectively.

In our model charged particles are protons and electrons. The mean-fields are taken to be zero for electrons, while for protons they are given by relativistic mean-field (RMF) theory [11]. The single particle energy is then written as

$$E(n, p_z, s) = \sqrt{p_z^2 + \left(\sqrt{2eBn + M^{*2}} - \frac{se\kappa B}{M}\right)^2} + U_0 \tag{2}$$

with $M^* = M - U_s$ and n being the Landau number.

The interaction parts for the neutrino and the axion in the Lagrangian density is written as

$$\mathcal{L}_W = G_F \bar{\psi}_\nu \gamma_\mu (1 - \gamma_5) \psi_\nu \sum_\alpha \bar{\psi}_\alpha \gamma_\mu (c_V - c_A \gamma_5) \psi_\alpha - i \sum_\alpha g_{a\alpha f} \bar{\psi}_\alpha \gamma^\mu \gamma_5 \psi_\alpha \phi_a, \tag{3}$$

where ψ_ν is the neutrino field, ϕ_a is the axion field, ψ_α is the field of the particle α which indicates the proton and electron, and G_F, c_V and c_A are the coupling constants for the weak interaction [12].

By using the above wave function and the interaction, we calculate the width of protons and electrons for $\nu\bar{\nu}$-pairs and axion. Actually we perform the calculation in the neutron-star matter composed of 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. [13].

RESULTS

Before showing calculation results, we give a comment on the calculation in very low temperature region, $T <$ 10 keV.

With $\sqrt{eB} \ll E_F^* = E_F - U_0$, where E_F is the Fermi energy, we can expand the transition energy between two Landau levels as

$$\begin{aligned} \Delta E &= E(n_i, p_z, s_i) - E(n_f, p_z - \Delta p_z, s_f) \\ &= \sqrt{2eBn_i + p_z^2 + M^{*2}} - \sqrt{2eB(n_i - \Delta n_{if}) + (p_z - \Delta p_z)^2 + M^{*2}} - \frac{eB\kappa}{M}\Delta s_{if} \\ &\approx \frac{eB}{\sqrt{2n_i eB + M^{*2}}}\Delta n_{if} + \frac{p_z \Delta p_z}{\sqrt{2n_i eB + M^{*2}}} - \frac{eB\kappa}{M}\Delta s_{if}, \end{aligned} \tag{4}$$

where $\Delta n_{if} = n_i - n_f$, $\Delta s_{if} = (s_i - s_f)/2$, and $n_{i,f} \gg \Delta n_{if}$ is assumed.

Because a particle production is not allowed without the magnetic field because of the energy momentum conservation, the relation $\sqrt{eB}\Delta n_{if} \gg |\Delta p_z|$ is satisfied, and a contribution from the second term in Eq. (6) is very small. In the low temperature region, the initial and final states are near the Fermi surface, so that the energy interval of the dominant transition is given by

$$\Delta E \approx \frac{eB}{E_F^*}\Delta n_{if} - \frac{eB\kappa}{M}\Delta s_{if}. \tag{5}$$

The luminosities are proportional to the Fermi distribution of the initial state and the Pauli-blocking factor of the final state, $f(E_i)[1 - f(E_f)]$. In the low temperature expansion, it is assumed that energies of the initial and final states

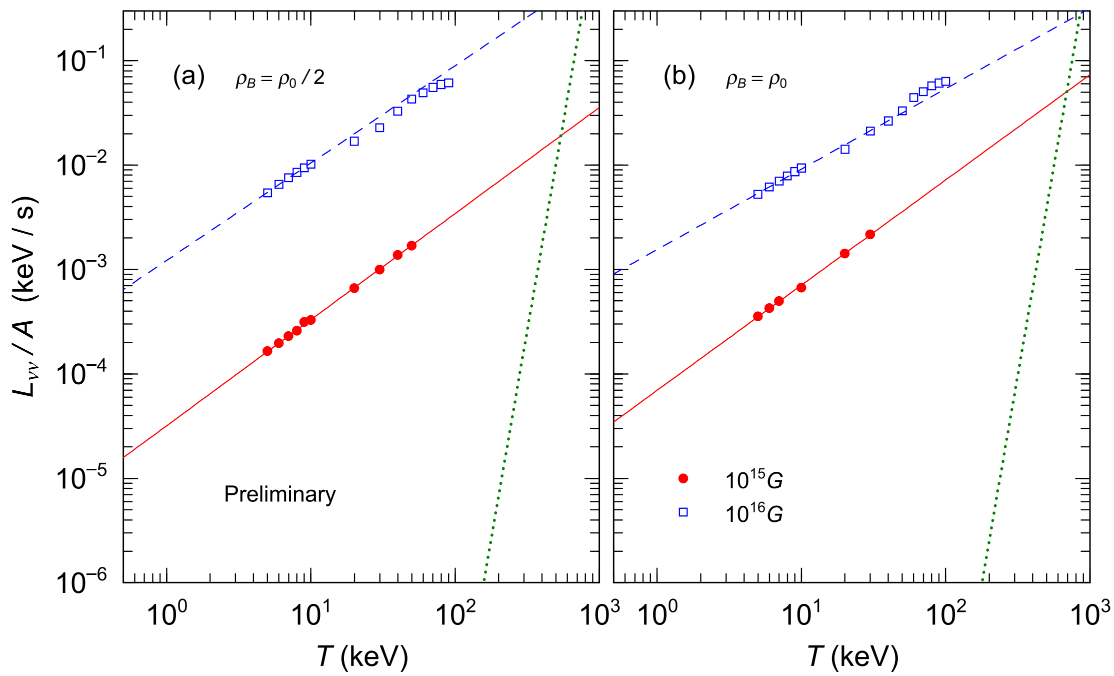

FIGURE 1. $\nu\bar{\nu}$-pair emission luminosity per nucleon at the baryon density $\rho_B = \rho_0/2$ (a) and $\rho_B = \rho_0$ (b). The solid circles and the open squares represent results when $B = 10^{15}$G and $B = 10^{16}$G, respectively. The dotted lines indicates the results with the modified Urca process.

populate the region with $\Delta E \lesssim T$. When $B = 10^{15}$ G, however, $\sqrt{eB} = 2.4$ MeV and $T \lesssim \Delta E$, so that the low temperature expansion is not available. We need to calculate the luminosity exactly.

In Fig. 1, we show the calculation results of the $\nu\bar{\nu}$-pair emission luminosity per nucleon $L_{\nu\bar{\nu}}/A$ at the baryon density $\rho_B = \rho_0/2$ (a) and $\rho_B = \rho_0$ (b), where ρ_0 is normal nuclear matter density. The solid circles and open squares represent the calculation results when $B = 10^{15}$G and $B = 2 \times 10^{15}$G, respectively. For comparison, we give the neutrino luminosity per volume in the modified Urca (MU) process [14] with the dotted line.

As mentioned before, we need to calculate the luminosities exactly without using the low temperature expansion but we are not able to calculate them in a realistic temperature region, $T \lesssim 1$ keV. It is well known that the low temperature expansion leads to a power law temperature dependence of the emission luminosity. Then, we need to extrapolate them up to the realistic temperature by using the fitting function $L_{\nu\bar{\nu}}/A = cT^a$ with a and c being the fitting parameters. The solid and dot lines represent the results of the fitting function when $B = 10^{15}$G and $B = 10^{16}$G, respectively. The values of fitting parameter a are exhibited in Table 1

TABLE 1. Estimated total luminosity of $\nu\bar{\nu}$-pair per volume $L_{\nu\bar{\nu}}/V$ at $T = 0.7$ keV.

ρ_B	$\frac{1}{2}\rho_0$		ρ_0	
B	10^{15}G	10^{16}G	10^{15}G	10^{16}G
a	1.08	0.93	1.01	0.77
$L_{\nu\bar{\nu}}/A$ (keV/s) at $T = 0.7$ keV	2.2×10^{-5}	8.7×10^{-4}	4.8×10^{-5}	1.2×10^{-3}
MU	1.0×10^{-25}		5.6×10^{-26}	

In order to examine our results, furthermore, we show the results at $T = 700$eV in Table 1. Thus, we can know that $\nu\bar{\nu}$ luminosities are much larger than the ν luminosity from the MU process.

Here, we give a comment on the contributions from protons and electrons. In actual calculations proton contributions do not change any results. At $T = 0.7$ keV and $\rho_B = 0.1\rho_0$, for example, the luminosity are 9.0×10^{-5} keV/s for electron and 2.6×10^{-15} keV/s for proton, while the luminosity is 9.9×10^{10} erg/cm^3/s in the MU process. In the $\nu\bar{\nu}$-production process, the electron contribution is dominant though the proton contribution is negligibly small. Then, we can consider only the electron contributions.

In addition, the semi-classical approach in Ref. [7] 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.

Next. we discuss the axion production. In this work we choose the axion-nucleon coupling to be $g_{aNN} = 6 \times 10^{-12}$ and the axion-electron coupling to be $g_{aee} = 9\times10^{-15}$, which are 10^{-2} below the maximum value deduced in Ref. [15]. These parameters are chosen to impose the condition that the axion emission be negligible compared to the neutrino emission in normal neutron stars.

In Fig. 2 we show the temperature dependence of the axion luminosity per nucleon L_a/A at $B = 10^{15}$G for baryon densities of $\rho_B = 0.1\rho_0$ (a), $\rho_B = 0.5\rho_0$ (b), $\rho_B = \rho_0$ (c) and $\rho_B = 2\rho_0$ (d). The solid and long-dashed lines represent the contributions from protons and those of electrons, respectively. For comparison, we also exhibit the neutrino luminosities from the modified Urca (MU) process [14] (dotted lines).

First, we see that the axion luminosity varies slowly when $T \gtrsim 10$ keV, while it changes rapidly in the low temperature region.

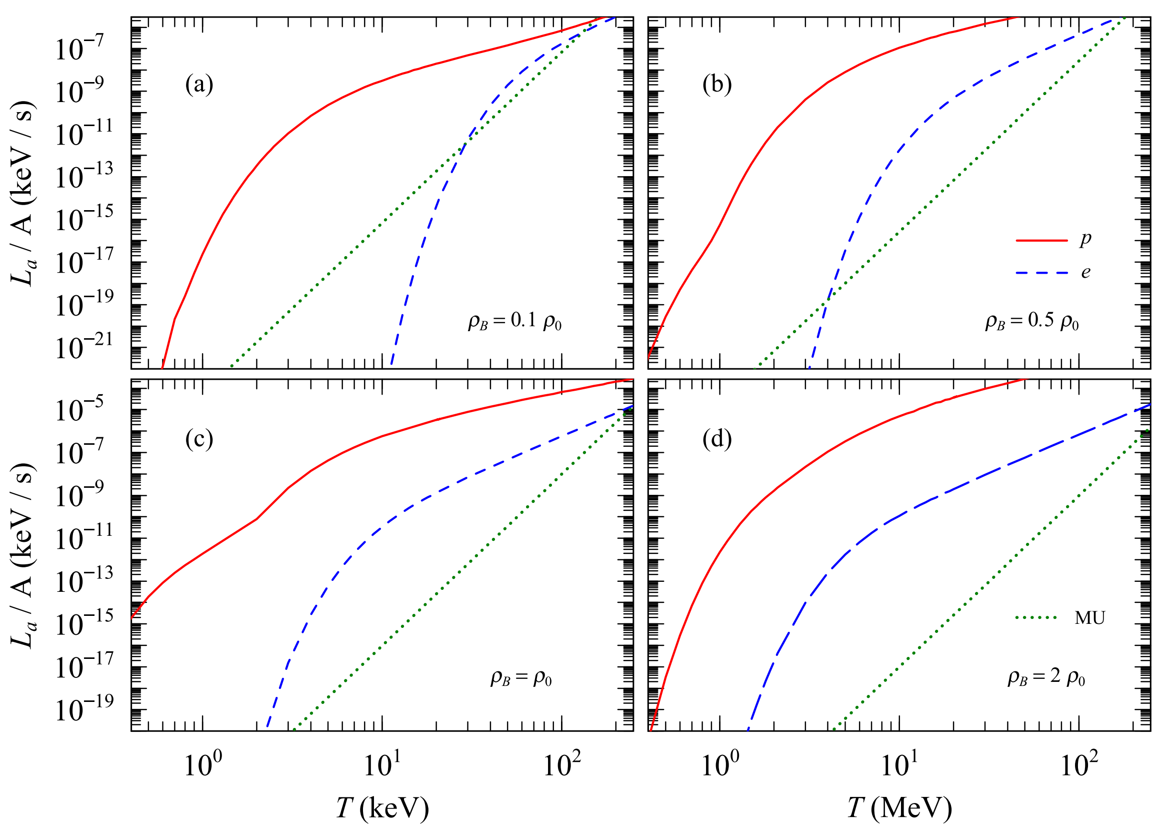

FIGURE 2. Axion luminosity versus temperature at baryon densities $\rho_B = 0.1\rho_0$ (a) $\rho_B = 0.5\rho_0$ (b), $\rho_B = \rho_0$ (c) and $\rho_B = 2\rho_0$ (d) for $B = 10^{15}$G. The solid and dashed lines represent the results for protons and for electrons, respectively. The dotted lines indicate the neutrino luminosities from the MU process, respectively.

In the semi-classical approach [8], the axion luminosity from an electron was shown to be proportional to T^a with $a = 13/3 \approx 4.3$. In our results the electron contributions can be fitted with $a = 3.6 - 3.8$ in the high temperature region; these values are similar to those obtained in the semi-classical approach. However, one should also consider realistic low magnetar temperatures $T \lesssim 1$ keV. In this case, the temperature dependence of the luminosity is more complicated. In particular, to satisfy the power law, one requires that the particle energies be continuous. In a strong magnetic field, however, the transverse momentum is discontinuous.

The energy of emitted particles at the largest decay strength is proportional to the mass of the produced particle [10]. The axion mass is negligibly small, and the largest contribution comes from $\Delta n_{if} = n_i - n_f = 1$, so that the energy of an emitted axion is estimated to be

$$\Delta E \approx \frac{eB}{E_F^*} - \frac{eB\kappa}{M}\Delta s_{if}. \tag{6}$$

When $B = 10^{15}$G, $eB/E_F^* = 6.6$ keV at $\rho_B = 0.1\rho_0$ and $eB/E_F^* = 9.4$ keV at $\rho_B = \rho_0$ for protons, while $eB/E_F^* = 6.7$ keV at $\rho_B = \rho_0$ for electrons. As can be seen in Fig. 2, indeed, the change of the axion luminosities becomes more abrupt for $T \lesssim eB/E_F^*$.

Furthermore, the energy step is much smaller for protons than that for electrons because the proton mass is much larger than the electron mass, and the proton axion luminosity becomes the dominant source. The relation in the luminosity between the proton and the electron for the axion production is opposite to that for the $\nu\bar{\nu}$-pair production. The invariant mass of the $\nu\bar{\nu}$-pair is not fixed. As the mass of a source particle decreases, the invariant mass becomes larger in the particle transition, and the production probability increases.

SUMMARY

In this work we have studied $\nu\bar{\nu}$ and axion production from neutron-star matter with the strong magnetic fields, $B = 10^{15}$G and 10^{16} G in the relativistic quantum approach. We calculated their luminosities due to the transitions of protons and electrons between two different Landau levels without invoking any classical approximation.

In our calculation for the $\nu\bar{\nu}$-pair production the power of the temperature turned out to be very small, $a \approx 1.0$, while $a = 8$ for the MU process, and $a = 6$ for the direct Urca process [16]. These smaller powers of the temperature make the total luminosities much larger than that of the usual cooling processes such as the MU and DU processes.

The present results for the $\nu\bar{\nu}$-air production are still preliminary, while the results for the axion production is fixed. We may improve the numerical calculations carefully. Therefore, we have not been able to give a conclusion, yet. However, it can be convinced that the quantum approach is very important in the strong magnetic field.

Full quantum calculations provide a higher yield for particle production than the semi-classical and/or the perturbative calculations for pions [10], $\nu\bar{\nu}$-pair and axions. Hence, it would be worthwhile to investigate the heating processes of magnetars [17] by calculating particle production from other mechanisms such as photons from synchrotron radiation in the quantum approach.

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