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Neutrino and Antineutrino pair-Emission in Strong Magnetic Field in Relativistic Quantum Approach

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Abstract. We study the $\nu\bar{\nu}$-pair emission from electrons and protons in a relativistic quantum approach. In this work we calculate the luminosity of the $\nu\bar{\nu}$-pairs emitted from neutron-star-matter with a strong magnetic field, and find that this luminosity is much larger than that in the modified Urca process. The $\nu\bar{\nu}$-pair emission processes in strong magnetic fields significantly contribute to the cooling of the magnetars.

1 Introduction

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

Many authors have paid attention into cooling processes of neutron stars (NS) because it gives important information on neutron star structure [3]. Neutron stars are cooled by neutrino emission, and a magnetic field is expected to affect the emission mechanism largely because a strong magnetic field can supply energy and momentum into cooling processes.

In this work we study two kinds of the processes, the $\nu\bar{\nu}$-pair synchrotron radiation $p(e^-) \rightarrow p(e^-) + \nu + \bar{\nu}$ by calculating it through the transition between the different Landau levels for protons and electrons [4].

2 Formalism

In this work we assume the neutron-star matter composing of proton, neutron and electron, a uniform magnetic field along the z-direction, $\boldsymbol{B} = (0, 0, B)$. We 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:

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

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

$$E(n, p_z, s) = \sqrt{p_z^2 + (\sqrt{2|e|Bn + M^2} - s\kappa B/M)^2} + U_0 \tag{2}$$

with n being the Landau level number. In the above equations, U_s and U_0 are the scalar and vector mean-fields which are given by the relativistic mean-field approach with the parameter-set PM1 [5].

The detailed expressions to calculate the neutrino emissivity are written in Ref. [4]. Energy intervals between two states with different Landau numbers are much larger than the temperature, so that we cannot use the Sommerfeld expansion at the low temperature limit.

3 Results

In Fig. 1a, we show the density dependence of the luminosities in the $\nu\bar{\nu}$-pair emission by using the parameter-set, PM1-SF1 for the mean-fields. For comparison, we give the $\bar{\nu}$-luminosities from the modified Urca (MU) process [6].

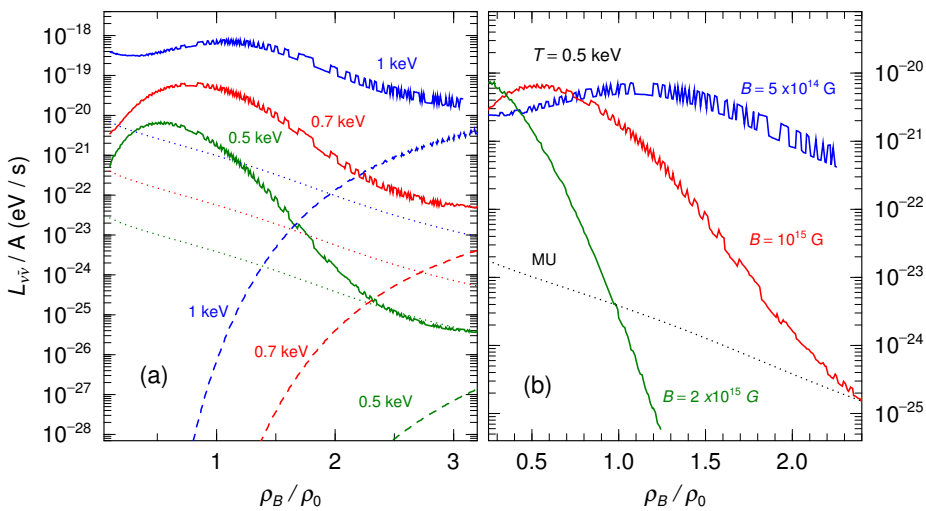

Figure 1. (a) Density dependence of the $\nu\bar{\nu}$-pair emission luminosity per nucleon. In the left panel (a) The solid and dashed lines represent the contributions from protons and electrons for $B = 10^{15}$G at $T = 0.5$, 0.7 and 1 keV (from bottom to top). The dotted lines indicate the neutrino luminosities from the MU process. In the right panel (b) solid lines show them for $B = 5 \times 10^{14}$ G, 10^{15} G and 2×10^{15} G at $T = 0.5$ keV. The dotted lines indicate the neutrino luminosity from the MU process.

We see that in the strong magnetic field, the neutrino luminosities become larger than those from the MU process particularly in low density regions. The calculation results include fluctuations. The density dependence of the factor $f(E_i)[1 - f(E_f)]$ does not smoothly vary for strong magnetic fields because the energy intervals between the initial and final states are larger than the temperature.

In Fig. 1b we show the density dependence of the $\nu\bar{\nu}$-luminosities at $B = 5 \times 10^{14}$ G, $B = 10^{15}$ G and $B = 2 \times 10^{15}$ G. We see that as the magnetic field strength decreases, the luminosity increases in the density region, $\rho_B/\rho_0 \gtrsim 1$. The $\nu\bar{\nu}$-pairs are produced via the transition of the proton and electron between different Landau levels. As the magnetic field

strength increases, the momentum transfer from the magnetic field becomes larger, and the energy interval between the initial and final states is also larger. The former effect enhances the emission rate, but the latter effect suppresses it. In the present calculations the latter effect dominates in the higher density region.

4 Summary

We have used a relativistic quantum approach to study neutrino and anti-neutrino emission in the $\nu\bar{\nu}$-pair production and DU processes from NS matter with strong magnetic fields. We see that the magnetic field has a role to enhance the neutrino emission in the both processes largely.

The $\nu\bar{\nu}$-pair emission process has a much larger effect than that of the MU process in strong magnetic fields. We can conclude that the $\nu\bar{\nu}$-pair emission process is dominant in the low density region, $\rho_B \lesssim \rho_0$, for a cooling process of magnetars whose magnetic field strength is $10^{14} - 10^{15}$ G. Therefore, our results suggest that one needs to introduce the $\nu\bar{\nu}$-pair emission process when calculating the cooling rate of magnetars.

The present results demonstrate that the magnetic field very largely contributes to the neutrino emission processes, and that the quantum calculations are necessary to describe the momentum transfer from the magnetic field exactly. In the high density region, $\rho_B \gtrsim 3\rho_0$, the direct Urca (DU) process must appear, and its contribution is much larger than those of the $\nu\bar{\nu}$-pair emission and MU processes. The strong magnetic field must also contribute to the neutrino emission from the DU process [7]

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