



Axion production from Landau quantization in the strong magnetic field of magnetars

Tomoyuki Maruyama^{a,b,*}, A. Baha Balantekin^{c,b}, Myung-Ki Cheoun^{f,b},
Toshitaka Kajino^{e,b,d}, Grant J. Mathews^{g,b}

^a College of Bioresource Sciences, Nihon University, Fujisawa 252-8510, Japan

^b National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

^c Department of Physics, University of Wisconsin, Madison, WI 53706, USA

^d Department of Astronomy, Graduate School of Science, University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan

^e Beihang University, School of Physics and Nuclear Energy Engineering, Int. Research Center for Big-Bang Cosmology and Element Genesis, Beijing 100191, China

^f Department of Physics, Soongsil University, Seoul, 156-743, Republic of Korea

^g Center of Astrophysics, Department of Physics, University of Notre Dame, Notre Dame, IN 46556, USA

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ABSTRACT

We utilize an exact quantum calculation to explore axion emission from electrons and protons in the presence of the strong magnetic field of magnetars. The axion is emitted via transitions between the Landau levels generated by the strong magnetic field. The luminosity of axions emitted by protons is shown to be much larger than that of electrons and becomes stronger with increasing matter density. Cooling by axion emission is shown to be much larger than neutrino cooling by the Urca processes. Consequently, axion emission in the crust may significantly contribute to the cooling of magnetars. In the high-density core, however, it may cause heating of the magnetar.

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The axion is a hypothetical pseudoscalar particle. It is a pseudo-Goldstone boson associated with the Peccei–Quinn symmetry [1] and has been introduced as a solution to the strong CP-violation problem [2]. The physics related to the axion has been discussed in many papers, e.g. [3–6].

In particular, axion phenomenology in astrophysical environments has been extensively explored in Refs. [7–9]. Axions are candidates for the cold dark matter of the universe because they have non-zero mass and their interactions with normal matter should be small. In view of the lack of detections in recent WIMP searches, the study of axion production or detection is well motivated and axions become a compelling candidate for cold dark matter [10,11]. Axion dark matter can couple to two photons that can subsequently be observed [12]. However, various astronomical phenomena and laboratory experimental data [4,11,13] have only placed upper limits on the axion mass and decay constants. Specifically, for hadronic axions the mass and couplings are expected to be proportional to each other.

* Corresponding author.

E-mail address: maruyama.tomoyuki@nihon-u.ac.jp (T. Maruyama).

Axions produced in a hot astrophysical plasma can transport energy out of stars or even reheat the interior plasma if they have a small mean free path. The strength of the axion coupling with normal matter and radiation is bounded by the condition that stellar evolution lifetimes and/or energy loss rates should not conflict with observation. Such arguments can also be applied to the physics of supernova explosions, where the dominant energy loss processes are thought to be the emission of neutrinos and anti-neutrinos along with axions via the mechanism of nucleon bremsstrahlung [14–16].

Axions may be efficiently produced in the interiors of stars and act as an additional sink of energy. Therefore, they can alter the energetics of some processes, for example, type-II supernova explosions. Several authors have noted that the emission of axions (a) via the nucleon (N) bremsstrahlung process $N + N \rightarrow N + N + a$ may drain too much energy from type-II supernovae, making them inconsistent with the observed kinetic energy of such events [15–18].

In Refs. [19,20] the thermal evolution of a cooling neutron star was studied by including axion emission in addition to neutrino energy losses. An upper limit on the axion mass of $m_a < 0.06\text{--}0.3$ eV was deduced. Axion cooling is an interesting possi-

bility for the cooling mechanism of the neutron stars [20–24]. In their pioneering study, Umeda et al. [19] considered the axion radiation produced via the bremsstrahlung in NN collisions in bulk nuclear matter. Axion emission from a meson condensate [25] was also studied.

Cosmological constraints may also provide upper and lower limits on the mass of the axion [26]. Nevertheless, there still remains a large region of the parameter space to be searched. One of the most well developed and sensitive experiments is the Sikivie haloscope [27]. This approach exploits the inverse Primakoff effect whereby a magnetic field provides a source of virtual photons in order to induce axion-to-photon conversion via a two-photon coupling. The generated real photon frequency is then determined by the axion mass. This signal can be resonantly enhanced by a cavity structure and resolved above the thermal noise of the measurement system. It has been proposed [27,28] that the expected power due to axion-to-photon conversion can be detected in a haloscope with an axial DC magnetic field.

The present status of the mass and coupling constant are well summarized and tabulated in Ref. [29]. Upper limits exist for the coupling constant, $g_{a\gamma\gamma}$, appearing in the Lagrangian,

$$\mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} \phi_A, \quad (1)$$

where ϕ_A is the axion field and $F_{\mu\nu}$ is the electro-magnetic field strength tensor. Currently, from Helioscopes, $|g_{a\gamma\gamma}| < 6.6 \times 10^{-11} \text{ GeV}^{-1}$ (95% CL) for a mass range of, $10^{-10} \text{ eV} < m_a < 1 \text{ eV}$. In addition, the analysis of gamma-rays from SN1987A [30] has led to the constraint that $|g_{a\gamma\gamma}| \lesssim 5.3 \times 10^{-12} \text{ GeV}^{-1}$ and $m_a < 4.4 \times 10^{-10} \text{ eV}$.

Axion couplings for fermions, g_{aNN} and g_{aee} , in the Lagrangian

$$\mathcal{L}_{aff} = -ig_{aff} \bar{\Psi} \gamma_5 \Psi \phi_A \quad (2)$$

are constrained to be $\alpha_{aee} = g_{aee}^2/4\pi < 1.5 \times 10^{-26}$ and $g_{aNN} = (3.8 \pm 3) \times 10^{-10}$ based upon many experiments and observations [29].

On the other hand, magnetic fields in neutron stars are much stronger than those in laboratory experiments. Thus, axion emission may play a vital role in the interpretation of many observed phenomena. In particular, magnetars, which are associated with super-strong magnetic fields, [31,32] have many exotic features that distinguish them from normal the neutron stars. Hence, they can provide information about the physical processes associated with strong magnetic fields.

It has been noted [33] that the characteristic magnetar spin down periods ($\dot{P}/P$) (where P is the spin period) appear to be systematically overestimated compared to the ages of the associated supernova remnants. Soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are believed to be to magnetars [34]. Magnetars emit energetic photons. Furthermore, the surface temperature of the magnetars ($T \approx 280\text{--}720 \text{ eV}$) is larger than that of normal neutron star which typically have a surface temperature of $T \approx 10\text{--}150 \text{ eV}$ for similar ages [35]. Thus, the associated strong magnetic fields appears to be a mechanism to convert the magnetic energy into thermal and radiant energies.

In this work we calculate the axion emission due to electrons and protons in the Landau quantization of the strong magnetic field. This mechanism is different from the previously considered bremsstrahlung or Primakoff mechanisms for axion production. Such axion emission from electrons has been previously calculated classically and quantum mechanically [36,37]. However, the emission from protons was not taken into account. Here we show that the axion luminosity expected from the protons inside a magnetar is much larger than that due to electrons. Indeed, it is high enough

to be considered in the neutron star cooling (or reheating) process. In particular, contributions from the anomalous magnetic moment (AMM) of the protons becomes significant, as has been discussed in the case of pion production by the magnetic field [38,39].

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

$$\left[\gamma_\mu \cdot (i\partial^\mu - \zeta e A^\mu - U_0 \delta_\mu^0) - M + U_s - \frac{e\kappa}{2M} \sigma_{\mu\nu} (\partial^\mu A^\nu - \partial^\nu A^\mu) \right] \psi_a(x) = 0, \quad (3)$$

where κ is the AMM, e is the elementary charge and $\zeta = \pm 1$ is the sign of the particle charge. U_s and U_0 are the scalar field and the time component of the vector field, respectively, as is usual in the relativistic mean field (RMF) theory [40].

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 the RMF theory. The single particle energy is then written as

$$E(n, p_z, s) = \sqrt{p_z^2 + (\sqrt{2eBn + M^{*2}} - s\kappa B/M)^2} + U_0 \quad (4)$$

with $M^* = M - U_s$, where n is the Landau number, p_z is a z -component of momentum, and $s = \pm 1$ is the spin. The U_0 plays the role of shifting the single particle energy and does not contribute to the result of the calculation. Hence, we can omit the U_0 in what follows.

We obtain the differential decay width of the proton from the pseudo-vector coupling for the axion-proton (electron) interaction,

$$\frac{d^3\Gamma}{d\mathbf{q}^3} = \frac{g_a^2}{8\pi^2 e_a} \sum_{n_f, s_f} \frac{\delta(E_f + e_a - E_i)}{4E_i E_f} W_{if} f(E_i) [1 - f(E_f)], \quad (5)$$

with

$$W_{if} = \text{Tr} \left\{ \rho_M(n_i, s_i, p_z) \mathcal{O}_A \rho_M(n_f, s_f, p_z - q_z) \mathcal{O}_A^\dagger \right\}, \quad (6)$$

where e_a is the energy of the emitted axion, $\mathbf{q} \equiv (q_x, q_y, q_z)$ is the axion momentum, g_a is the pseudo-scalar axion coupling constant, and

$$\begin{aligned} \rho_M = & \left[E\gamma_0 + \sqrt{2eBn}\gamma^2 - p_z\gamma^3 + M^* + (eB\kappa/M)\Sigma_z \right] \\ & \times \left[1 + \frac{s}{\sqrt{2eBn + M^{*2}}} (eB\kappa/M + p_z\gamma_5\gamma_0 + E\gamma_5\gamma_3) \right], \end{aligned} \quad (7)$$

while

$$\mathcal{O}_A = \gamma_5 \left[\mathcal{M}(n_i, n_f) \frac{1 + \zeta \Sigma_z}{2} + \mathcal{M}(n_i - 1, n_f - 1) \frac{1 - \zeta \Sigma_z}{2} \right]. \quad (8)$$

In the above equation, the harmonic oscillator (HO) overlap function $\mathcal{M}(n_1, n_2)$ is defined as [38,39]

$$\mathcal{M}(n_1, n_2) = \int_{-\infty}^{\infty} dx h_{n_1} \left(x - \frac{q_T}{2\sqrt{eB}} \right) h_{n_2} \left(x + \frac{q_T}{2\sqrt{eB}} \right), \quad (9)$$

where $q_T = \sqrt{q_x^2 + q_y^2}$, and $h_n(x)$ is the HO wave function with quantum number n .

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