On the resonant production of axions in a magnetar magnitosphere

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June 11, 2010

International Seminar *"Quarks-2010"*, Kolomna, Russia

Based on the paper N. Mikheev, D. Rumuyantsev and Y. Shkol'nikova
Pis'ma in JETP 2009 Vol.90. p.668.

Outline

Introduction

Axion is one of most probable candidate for Cold Dark Matter
The Peccei-Quinn symmetry violation scale

$$f_a \gtrsim 10^8 \text{ GeV (PDG 2008)}$$

The experimental detection of the axion is a complicated problem

The efficient axion production is possible in the extreme conditions of magnetars $B \sim 10^{14} - 10^{15}$ G $\gg B_e$,

$$B_e = m^2/e \simeq 4.41 \times 10^{13} \text{ G}.$$

Introduction

The electron number density in the region of closed field lines is estimated as (*Lyutikov et. al. Astrophys. J. 2002*)

$$n \simeq 5 \cdot 10^5 \left(\frac{10\,\mathrm{rad/s}}{\Omega} \right) \left(\frac{10\,\mathrm{km}}{R_{NS}} \right) n_{GJ} \gg n_{GJ},$$

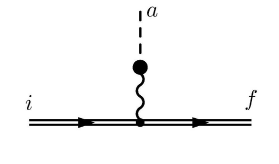
where

$$n_{GJ} \simeq 3 \cdot 10^{13}\,\mathrm{cm}^{-3} \left(\frac{B}{100 B_e} \right) \left(\frac{10\,\mathrm{s}}{P} \right)$$

is the Goldreich-Julian charge number density.

General reaction

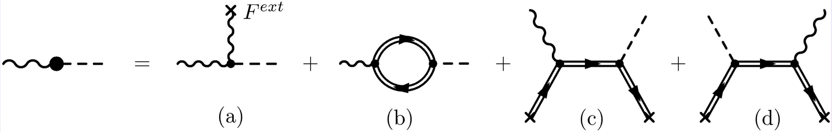
We have consider the production of axions in the general reaction $i \to f + a$. The initial (i) and final (f) states can involve the electromagnetic multipole components of the medium.



It is easy to see that the process under consideration can be resonant owing to the presence of a virtual photon.

A similar situation for the region close to resonance was recently considered (*V.V. Skobelev JETP 2007. Vol.132. p.1121*)

The effective γa interaction constant



$$\bar{g}_{a\gamma} = g_{a\gamma} + \Delta g^{B}_{a\gamma} + \Delta g^{pl}_{a\gamma}$$

L. A. Vassilevskaya et al., Yad. Fiz. 62, 1662 (1999) N. V. Mikheev and E. N. Narynskaya, Mod. Phys. Lett. A 21, 433 (2006)

$g_{a\gamma}$ и $\Delta g^{pl}_{a\gamma}$ are not take into account in the paper *V.V. Skobelev*

The effective Lagrangian and amplitude of the process $i \to f + a$

The effective Lagrangian γa interaction

$$\begin{aligned} \mathcal{L}_{a\gamma}(x) &= g_{a\gamma}\tilde{F}^{\mu\nu}[\partial_\nu A_\mu(x)]a(x) + \\ &+ \frac{g_{af}}{2m_f}[\bar{\psi}_f(x)\gamma^\mu\gamma_5\psi_f(x)]\partial_\mu a(x) + \\ &+ Q_f[\bar{\psi}_f(x)\gamma^\mu\psi_f(x)]A_\mu(x) \end{aligned}$$

The axion-photon and axion-fermion couplings

$g_{a\gamma} = \alpha\xi/2\pi f_a, \quad g_{af} = C_f m_f/f_a, \quad \xi, C_f \sim 1$

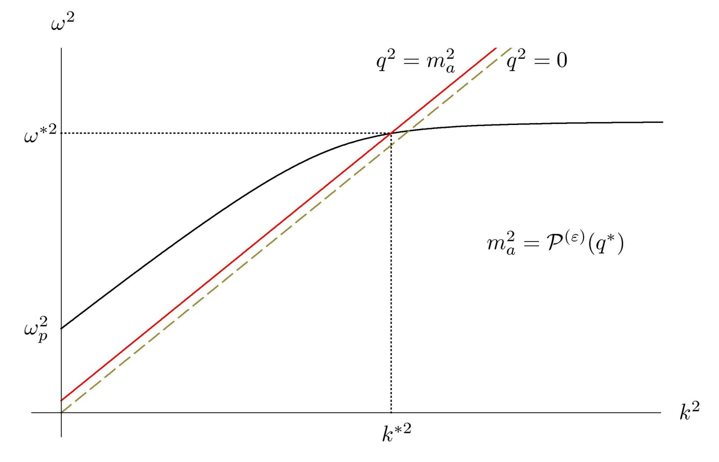
Amplitude

$$\mathcal{M}^a_{i\to f} = -\frac{\mathcal{M}^\gamma_{if}\mathcal{M}_{\gamma\to a}}{q'^2 - \mathcal{P}^{(\varepsilon)}(q')}, \quad \mathcal{M}_{\gamma\to a} = i\bar{g}_{a\gamma}(\varepsilon\tilde{F}q')$$

$\tilde{F}^{\mu\nu}$ is the dual tensor of the external field

Photon and axion dispersion properties

Resonance condition $\omega_p^2 = \frac{4\pi\alpha n}{m} \geq m_a^2$



Polarization operator

The photon is unstable in active medium

$$\mathcal{P}^{(\varepsilon)} = \Re - i\Im$$

The $\Im$ is due to the processes of the absorption and emission of photons in the plasma

$$\Im = \omega' \left(e^{\omega'/T} - 1 \right) \Gamma_{cr} ,$$

$$\Gamma_{cr} = \sum_{i,f} \int |\mathcal{M}^{\gamma}_{if}|^2 d\Phi_{if} ,$$

(Weldon, Phys Rev D 1983)

$d\Phi_{if}$ is the phase volume element of the states i and f for the process $i \to f + \gamma$. Summation is performed over all of the possible initial and final states.

Axion emissivity

Taking into account the above consideration, the axion emissivity, due to the reactions involving the particles of the plasma, can be represented in the form

$$Q = \int \frac{d\Phi' \, |\mathcal{M}_{\gamma \to a}|^2}{e^{\omega'/T} - 1} \, \frac{\Im}{(q'^2 - \Re)^2 + \Im^2} \, .$$

$d\Phi' = \frac{d^3 k'}{(2\pi)^3 2\omega'}$ is the phase volume element of axion.

Near the resonance, the last factor of the integrand can be interpolated by the δ function

$$\frac{\Im}{(q'^2 - \Re)^2 + \Im^2} \simeq \pi \, \delta(q'^2 - \Re) \, .$$

Resonant axion emissivity

The axion emissivity in the resonance region, owing to the reactions involving the particles of the medium, is certainly expressed in terms of $Q_{\gamma \to a}$

$$Q \simeq Q_{\gamma \to a} = \frac{\bar{g}_{a\gamma}^2 (eB)^2}{32\pi^2 \alpha} \int_{-1}^{1} \frac{dx}{e^{\omega/T} - 1} \left. \frac{Z_\varepsilon k (\varepsilon \tilde{\varphi} q)^2}{\left| 1 - \frac{d\omega^2}{dk^2} \right|} \right|_{k=k^*} .$$

Here $x = \cos\theta$,

$k^* = k^*(\theta)$ is a root of the equation

$\omega^2(\vec{k}) = m_a^2 + k^2$,

$\tilde{\varphi}_{\alpha\beta} = \tilde{F}_{\alpha\beta}/B$,

$Z_\varepsilon^{-1} = 1 - \frac{\partial \Re}{\partial \omega^2}$ corresponds to the renormalization of the photon wavefunction.

Particular cases

- Weakly magnetized dense plasma, $m_a^2 \ll eB \ll T^2, \mu^2$

$$Q = \frac{\bar{g}_{a\gamma}^2 (eB)^2}{48\pi^2\alpha} \frac{(k^*)^3}{e^{k^*/T} - 1}, \quad \omega^2(\vec{k}^*) = m_a^2 + k^{*2}$$

(*Mikheev et al. Phys. Rev.* **D** *V.58. P.055008. 1998*)

- Strongly magnetized plasma $eB \gg m^2,\ \mu^2 \gg T^2$, $\bar{g}_{a\gamma} = g_{a\gamma}$
  - When the axion mass is the smallest parameter of the problem, $\omega_p,\ T \gg m_a \sim 10^{-5}$ eV

$$Q \simeq \frac{g_{a\gamma}^2 (eB)^2}{16\pi^2\alpha} \omega_p^3 \frac{(1+\eta)^{3/2}}{\eta^{5/2}} \left(\exp\left[\frac{\omega_p}{T} \sqrt{1 + \frac{1}{\eta}} \right] - 1 \right)^{-1} .$$

  - $\omega_p \gg T \sim m_a$

$$Q \simeq \frac{g_{a\gamma}^2 (eB)^2}{16\pi^2\alpha} T m_a^2 \, e^{-\omega_p/T} .$$

Number of axions

In addition to emissivity, it is also of interest to estimate the number of axions produced in the magnetar magnetosphere in unit volume per unit time through the above resonant mechanism

$$\frac{dN}{dtdV} = \frac{g_{a\gamma}^2 (eB)^2}{32\pi^2\alpha} \int_{-1}^{1} \frac{dx}{e^{\omega/T} - 1} \left. \frac{kZ_\varepsilon (\varepsilon\tilde{\varphi}q)^2}{\omega \left| 1 - \frac{d\omega^2}{dk^2} \right|} \right|_{k=k^*} .$$

Number of axions

Strong field limit $eB \gg m^2,\ \mu^2 \gg T^2$

- $\omega_p,\ T \gg m_a$

$$\frac{dN}{dtdV} \simeq \frac{g_{a\gamma}^2 (eB)^2}{16\pi^2\alpha}\, \omega_p^2 \frac{1+\eta}{\eta^2} \left(\exp\left[\frac{\omega_p}{T} \sqrt{1 + \frac{1}{\eta}} \right] - 1 \right)^{-1},$$

- $\omega_p \gg T \sim m_a$

$$\frac{dN}{dtdV} \simeq \frac{g_{a\gamma}^2 (eB)^2}{16\pi^2\alpha} \frac{T m_a^2}{\omega_p} e^{-\omega_p/T}.$$

Number of axions

In particular, for the number of axions produced by the CMB radiation

$T \sim m_a \sim 10^{-3}\,\text{eV},\ B = 100 B_e$

The resonant scattering is possible $n_{min} \sim 10^{15}\,\text{cm}^{-3}$

$$\frac{dN}{dVdt} \sim 10^{10} \quad \frac{1}{\text{cm}^3\ \text{s}}$$

For magnetar magnetosphere we obtain $V \sim 10^{19}\,\text{cm}^3$,

$$\frac{dN}{dt} \sim 10^{29} \quad \frac{1}{\text{s}}$$

In the most optimistic variant, estimating the number of magnetars in the Galaxy as $N_{mag} \sim 10^6$, they produce $N_{tot} \sim 10^{51}$ axions in $t \sim 10^9$ yr. Therefore, the number density of axions in the Galaxy should be

$$n_a \sim 10^{-21} \quad \text{cm}^{-3} \ll n_b \sim 10^{-7} \quad \text{cm}^{-3}$$

Conclusion

- We have considered the resonant photoproduction of axions in the general reaction $i \to f + a$. It has been shown that the calculation of axion emissivity owing to this process is reduced to the calculation of the emissivity of the photon $\to$ axion transition.
- The number of axions produced by the equilibrium cosmic microwave background radiation in the magnetar magnetosphere has been determined.
- It has been shown that this mechanism is inefficient for the production of axion even at the plasma density $n \sim 10^{15}\,\mathrm{cm}^{-3}$.