Neutrino photoproduction on the electron in dense magnetized medium

Denis Shlenev

Yaroslavl State University, Russia

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In collaboration with Dmitriy Rumyantsev and Alexander Kuznetsov

Introduction

$e\gamma \to e\nu\bar{\nu}$ (V. Skobelev 2000, D. Rumyantsev and M. Chistyakov 2008, A. Borisov et al 2012)

Where? The outer crust of magnetar, $B \sim 10^{14} - 10^{16}$ G.,

$B \gg B_e$, $B_e = m^2/e \simeq 4.41 \times 10^{13}$ G,

$T \sim 10^8 - 10^9$ K, $T \ll m$, $\rho_6 = 10^6 \text{g/cm}^3$, $\rho_6 \le \rho \le 10^3 \rho_6$

N. Mikheev, D. Rumyantsev, M. Chistyakov 2014 - photon dispersion properties were taken into account in non-resonant case.

Boundary between inner and outer crust of magnetar

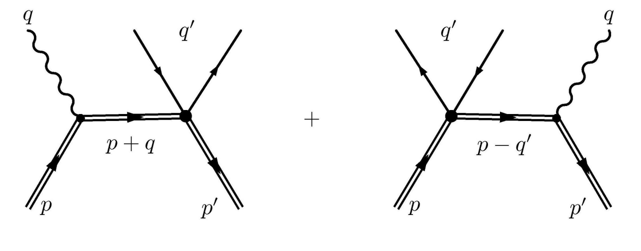
$\rho \gtrsim \rho_9 = 10^9 \text{g/cm}^3$

Higher Landau levels of virtual electron are excited.

Resonance on virtual electron becomes possible.

Introduction

Feynman diagrams for the process $\gamma e \to e \nu \bar{\nu}$.



Some notations

p^{μ} (p'^{μ}) are the momenta of initial (final) electrons,
q^{μ} and q'^{μ} are the momenta of initial photon and neutrino pair,
$(ab)_{\perp} = a_x b_x + a_y b_y$, $(ab)_{\parallel} = a_0 b_0 - a_z b_z$, $(a\varphi b) = a_y b_x - a_x b_y$.
$\varphi_{\alpha\beta} = F_{\alpha\beta}/B$ and $\tilde{\varphi}_{\alpha\beta} = \frac{1}{2}\varepsilon_{\alpha\beta\mu\nu}\varphi_{\mu\nu}$ are the dimensionless field tensor and dual field tensor correspondingly.

Neutrino emissivity

A general expression for the neutrino emissivity (the loss of energy from a unit volume per unit time due to the neutrino escape) can be defined as follows:

$$Q = \frac{1}{V} \int \prod_i \mathrm{d}\Gamma_i f_i \prod_f \mathrm{d}\Gamma_f (1 \pm f_f) \, q_0' \, \frac{|S_{if}|^2}{\tau},$$

where $\mathrm{d}\Gamma_i$ ($\mathrm{d}\Gamma_f$) are the number of states of initial (final) particles; f_i (f_f) are the corresponding distribution functions, the sign $+$ ($-$) corresponds to final bosons (fermions); q_0' is the neutrino pair energy; V is the plasma volume, τ is the interaction time, S_{if} is the S-matrix element.

Neutrino emissivity

When calculating S-matrix element we will consider the case of relatively low momentum transfers $|q'^2| \ll m_W^2$. Under this condition, the electroweak interaction can be considered in the local limit by using the effective Lagrangian

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \left[\bar{\Psi}\gamma_\alpha(C_V + C_A\gamma_5)\Psi\right] j_\alpha + e(\bar{\Psi}\gamma_\alpha\Psi)A_\alpha \,,$$

where $C_V = \pm 1/2 + 2\sin^2\theta_W$, $C_A = \pm 1/2$, $j_\alpha = \bar{\nu}\gamma_\alpha(1+\gamma_5)\nu$ – is the neutrino current.

"$+$" – ν_e,

"$-$" – ν_μ and ν_τ

Resonance in the process $\gamma e \longrightarrow e\nu\bar{\nu}$

$$\mathcal{S}^{s's}_{e\gamma\to e\nu\bar{\nu}} = \frac{\mathrm{i}(2\pi)^3\delta^{(3)}_{0,y,z}(P - p' - q')}{\sqrt{2q_0 V 2q'_0 V 2E_\ell L_y L_z 2E'_{\ell'} L_y L_z}} \mathcal{M}^{s's}_{e\gamma\to e\nu\bar{\nu}} \,,$$

s, s' - polarization state of initial and final electrons
s'' - polarization state of virtual electron

$$\mathcal{M}^{s's}_{e\gamma\to e\nu\bar{\nu}} \simeq \sum_{n=0}^{\infty} \sum_{s''} \int \mathrm{d}X_1 \mathrm{d}Y_1 \frac{(...)}{P_\parallel^2 - M_n^2 + \mathrm{i}\,\mathcal{I}^{s''}_{\Sigma}(P)} + \dots$$

$$P_\alpha = (p+q)_\alpha, \quad \alpha = 0, 2, 3.$$

$$\mathcal{I}^{s''}_{\Sigma}(P) = -\tfrac{1}{2} P_0 \Gamma^{s''}_n, \text{ (Jukovskiy, 1994)}$$

$\Gamma^{s''}_n$ - full width of the change of the electron state.

We can present $\Gamma_n^{s''}$ in the following way (Weldon, 1983).

$$\Gamma_n^{s''} = \Gamma_n^{(abs)\, s''} + \Gamma_n^{(cr)\, s''} \simeq \Gamma^{(cr)\, s''}_{e_n \to e_{\ell'}\gamma} \left[1 + \mathrm{e}^{(E_n'' - \mu)/T}\right]$$

Total width of electron creation in state n,s''

$$\Gamma_n^{(cr)\, s''} = \sum_{n=0}^{\infty} \sum_{s''} \frac{1}{2E_n''} \int \frac{d^3 k}{2q_0 (2\pi)^3} f_\gamma(q_0) \frac{d^2 p}{2E_\ell} f_e(E_\ell) \times$$

$$\times (2\pi)^3 \delta^{(3)}(P - p'') |M_{e_\ell \gamma \to e_n}|^2$$

Resonance in the process $\gamma e \longrightarrow e\nu\bar{\nu}$

In the case of narrow resonance peak:

$$\frac{1}{(P_{\parallel}^2 - m_e^2 - 2eBn)^2 + (\frac{1}{2}P_0\Gamma_n^{s''})^2} \simeq \frac{2\pi}{P_0\Gamma_n^{s''}}\delta(P_{\parallel}^2 - m_e^2 - 2eBn)$$

$$\delta(P_{\parallel}^2 - m_e^2 - 2eBn) = \frac{1}{2E_n''}\delta(P_0 - E_n''),$$

where $E_n'' = \sqrt{p_z''^2 + m_e^2 - 2eBn}$.
The amplitude squared, averaged over polarizations of initial photon, is factorized

$$|\mathcal{M}_{\gamma e \to e\nu\bar{\nu}}|^2 \simeq \sum_{n=1}^{\infty} \frac{2\pi}{P_0\Gamma_n^{s''}}\,\delta(P_{\parallel}^2 - m_e^2 - 2eBn)\,|\mathcal{M}_{e_\ell\gamma\to e_n}|^2\,|\mathcal{M}_{e_n\to e_{\ell'}\nu\bar{\nu}}|^2\,.$$

Resonance in the process $\gamma e \longrightarrow e\nu\bar{\nu}$

The neutrino emissivity due to the process $\gamma e_\ell \longrightarrow e_{\ell'}\nu\bar{\nu}$ can be written as

$$Q_{\gamma e_\ell \to e_{\ell'}\nu\bar{\nu}} = \sum_{n=1}^{\infty} \sum_{\ell'=0}^{n-1} Q_{e_n \to e_{\ell'}\nu\bar{\nu}} \,,$$

where $Q_{e_n \to e_{\ell'}\nu\bar{\nu}}$ is the neutrino emissivity due to the process $e_n \longrightarrow e_\ell \nu\bar{\nu}$.

$$Q_{e_n \to e_{\ell'}\nu\bar{\nu}} = \frac{1}{L_x} \int \frac{\mathrm{d}^2 p''}{(2\pi)^2\, 2E''_n}\, f_e(E''_n)\, \frac{\mathrm{d}^2 p'}{(2\pi)^2\, 2E'_{\ell'}} \, \left[1 - f_e(E'_{\ell'})\right]$$

$$\times \frac{\mathrm{d}^3 p_1}{(2\pi)^3\, 2\varepsilon_1} \frac{\mathrm{d}^3 p_2}{(2\pi)^3\, 2\varepsilon_2}\, q'_0\, (2\pi)^3\, \delta^3(p'' - p' - q') |\mathcal{M}_{e_n \to e_{\ell'}\nu\bar{\nu}}|^2$$

– neutrino emissivity due to the process $e_n \longrightarrow e_{\ell'}\nu\bar{\nu}$ (D. G. Yakovlev et al. Phys. Rep. 2001).

Conclusion

- We have considered the neutrino photoproduction on an electron, $e\gamma \to e\nu\bar{\nu}$, in dense magnetized medium in resonant case.
- It has been shown that in the case of resonance on the virtual electron, the neutrino emissivity due to the process $\gamma e_0 \to e_0\nu\bar{\nu}$ can be expressed in terms of the neutrino emissivity due to the process $e_n \to e_0\nu\bar{\nu}$.

Thank you!!!

Appendix: electron wavefunctions in external magnetic field

$\Psi^{s'}_{p',\ell'}(Y)$ and $\Psi^{s}_{p,\ell}(X)$ – eigenfunctions of covariant operator $\hat{\mu}_z$ (Sokolov, Ternov 1974).

$$\hat{\mu}_z = m_f \Sigma_z - \mathrm{i}\gamma_0\gamma_5[\vec{\Sigma} \times \vec{P}]_z$$

where $\vec{P} = -\mathrm{i}\vec{\nabla} + e_f\vec{A}$, $\vec{\Sigma} = \gamma_0\gamma_5\vec{\gamma}$, $A^\lambda = (0, 0, xB, 0)$.

$$\hat{\mu}_z \, \Psi^{s}_{p,\ell}(X) = s\, M_\ell \, \Psi^{s}_{p,\ell}(X)\,, \quad s = \pm 1$$

$$\Psi^{s}_{p,\ell}(X) = \frac{e^{-\mathrm{i}(E_\ell X_0 - p_y X_2 - p_z X_3)} \; U^s_\ell(\xi)}{\sqrt{4E_\ell M_\ell (E_\ell + M_\ell)(M_\ell + m_f) L_y L_z}}$$

$$V = L_x L_y L_z,$$

$$E_\ell = \sqrt{M_\ell^2 + p_z^2}\,, \quad M_\ell = \sqrt{m_f^2 + 2\beta\ell}\,, \quad \beta = eB$$