Resonant electron-positron pairs production in magnetar polar cap

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The problem: If is it possible an effective mechanism of e^+e^- – plasma production in magnetar magnitosphere?

The standard mechanism is the following: the e^+e^- – plasma is produced in two stages (Beloborodov A. M., Thompson C. 2007)

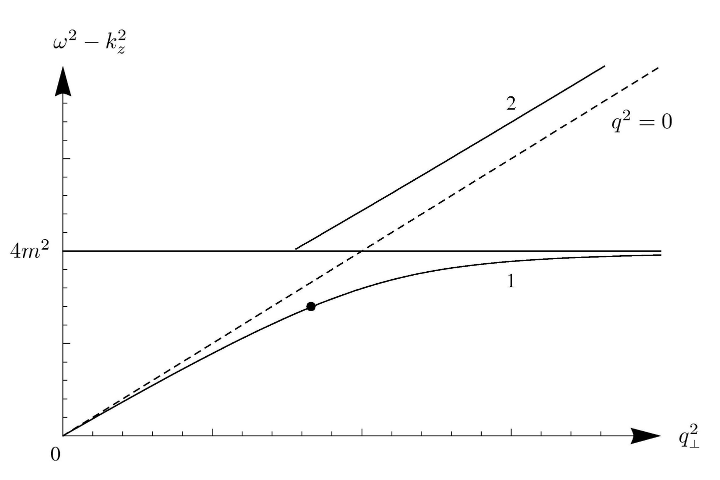
i)The hard X-ray production by Compton mechanism $\gamma e \to e\gamma$, $\omega > 2m$ (inverse Compton effect);

ii)The increase of the pitch angle, $\omega^2 \sin^2 \theta > 4m^2$ and e^+e^- pair production, $\gamma \to e^+e^-$ (Klepikov N.P. 1954)

The problem: the photon is trapped by magnetic field (see Fig. 1) (Shabad A.E. 1988)

The solution: the Compton like process $\gamma + e^- \to e^- + e^+e^-$!!!

Fig. 1. Photon dispersion curve in a strong magnetic field. The point on the dispersion curve indicates the position of a photon that is produced in the reaction $e\gamma \to e\gamma$. The dispersion curves 1 and 2 lie in the regions situated, respectively, below and above the threshold for the production of electron–positron pairs.



Formulation of the problem.

We consider the region near the magnetar polar cap, where $\vec{\mathcal{E}} \uparrow\downarrow \vec{B}$, $\vec{B} = B\vec{n}_z$ and $|\vec{\mathcal{E}}| \ll |\vec{B}|$.

The relativistic electron with energy ~ 10 GeV propagates along magnetic field direction (the electric field is collinear to the magnetic field) collides with soft gamma quantum, which is emitted from neutron star surface.

The parameters hierarchy

$$T^2 \ll m^2 \ll eB \ll E^2.$$

The initial electron occupies the lowest Landau level.

The processes of the first order $e \to e + all$ are kinematically forbidden in this case.

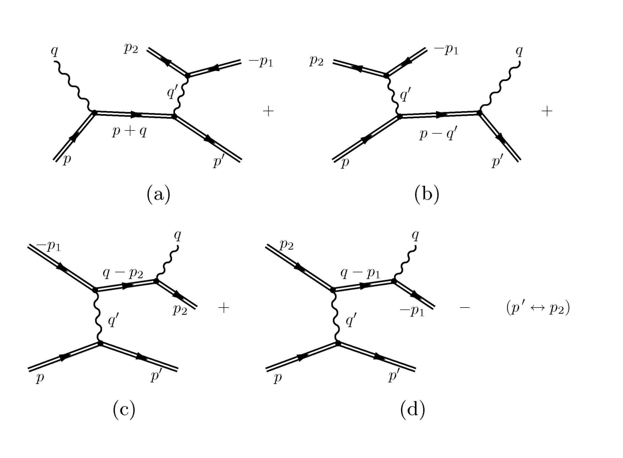
Some notations

$$\gamma + e^- \to e^- + e^+ + e^-$$
$$(q + p)_\mu = (p' + p_1 + p_2)_\mu \,, \quad \mu = 0, 2, 3 \,,$$

p^μ is the momentum of initial electron,
p'^μ is the momentum of final electron,
p_2^μ and p_1^μ are the momenta of the electron and positron of pair correspondingly,
q^μ is the momentum of initial photon,
q'^μ is the momentum of virtual photon.

$$(ab)_\perp = a_x b_x + a_y b_y, \; (ab)_\parallel = a_0 b_0 - a_z b_z, \; (a\varphi b) = a_y b_x - a_x b_y .$$

Feynman diagrams for the process $\gamma + e^- \to e^- + e^+ e^-$.



The s-channel diagram (a) with replacement $p' \leftrightarrow p_2$ provides a leading contribution to the resonance.

The electron absorption coefficient in the equilibrium photon gas with temperature T

$$W = \int \frac{\delta^3(\ldots)|\mathcal{M}|^2}{2^5(2\pi)^6 \omega E E' E_1 E_2} \, \frac{\mathrm{d}^3 q}{\mathrm{e}^{\omega/T} - 1} \mathrm{d}p'_y \mathrm{d}p'_z \mathrm{d}p_{1y} \mathrm{d}p_{1z} \mathrm{d}p_{2y} \mathrm{d}p_{2z} \,,$$

where

$$\mathcal{M} \simeq \sum_{n=0}^{\infty} \int\limits_{-\infty}^{\infty} \frac{\mathrm{d}q'_x \, [F(q, q', p, p', p_1, p_2) - (p' \leftrightarrow p_2)]}{[q'^2 - \mathcal{R} + \mathrm{i}\mathcal{I}][q_\parallel^2 + 2(pq)_\parallel - 2eBn + \mathrm{i}(E + \omega)\Gamma_n]} \,,$$

$$\delta^3(\ldots) = \delta_{0,2,3}(p + q - p' - p_1 - p_2),$$

$F(q, q', p, p', p_1, p_2)$ is the some function of 4-momenta of particles.

The resonances are possible!

- In the framework of our problem ($T \ll m$) the leading contribution in the width Γ_n is given by the conversion process $e_n \to e_0 + \gamma$ with $n = 1$ and we obtain

$$(E + \omega)\Gamma_1 \simeq \alpha e B (1 - \mathrm{e}^{-1}).$$

- The leading contribution to the imaginary part of polarization operator is given by first cyclotron resonance

$$\mathcal{I} \simeq -\frac{4m^2 \alpha e B \mathrm{e}^{-q_\perp'^2/2eB}}{\sqrt{q_\parallel'^2 (q_\parallel'^2 - 4m^2)}} \, .$$

Near the resonance

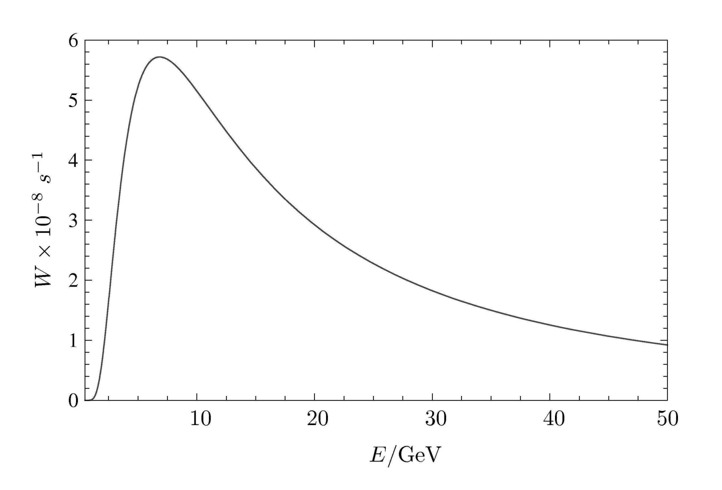
$$\frac{1}{(q_{\parallel}^2 + 2(pq)_{\parallel} - 2eB)^2 + (E+\omega)^2\Gamma_1^2} \simeq$$
$$\simeq \frac{\pi}{(E+\omega)\Gamma_1}\delta(q_{\parallel}^2 + 2(pq)_{\parallel} - 2eB)\,.$$

$$\frac{1}{(q'^2 - \mathcal{R})^2 + \mathcal{I}^2} \simeq \frac{\pi}{\mathcal{I}}\delta(q'^2 - \mathcal{R})\,.$$

After integration with delta-functions, we obtain

$$W \simeq \frac{\alpha}{2} T \frac{B}{B_e} \left(\frac{m}{E}\right)^2 \ln\left(1 - \mathrm{e}^{-\frac{eB}{2ET}}\right)^{-1}.$$

The absorption rate dependance on initial electron energy at $B = 100 B_e$ and $T = 1$ keV.



The efficiency of e^+e^- – pairs production

We obtain that the electron free path is $\ell \simeq 57$ cm. This value is very small in comparison with the electric gap width $(h \sim 100)$ m. On the other hand, the change of electron number in the stream can be expressed with optical thickness τ in the following way

$$N = N_0 \exp\left[-\tau\right] \simeq N_0 \exp\left[-\int\limits_0^h \mathrm{d}x W\right] \simeq 0.99 N_0 \,,$$

where N_0 is the initial electron number in the stream.

Conclusion

- We have considered the resonant Compton like process of electron-positron pair production near polar cap of magnetar magnetosphere.
- It has been shown, that the leading contribution in the process amplitude $\gamma + e^{\pm} \to e^{\pm} + e^{+}e^{-}$ occur from cyclotron resonances.
- It has been shown, that this mechanism can be efficient for the $e^{+}e^{-}$ plasma production in magnetar magnetosphere.