Creation of electron-positron pairs at excited Landau levels by a neutrino in a strong magnetic field

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July 28 - August 1, 2014

"Physics of Neutron Stars 2014", Saint-Petersburg

In collaboration with D. Rumyantsev and V. Savin

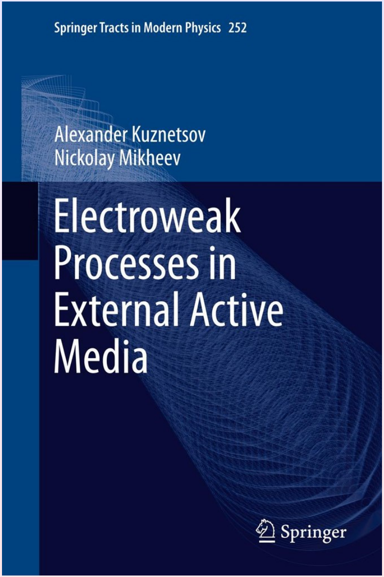
Paper submitted to Int. J. Mod. Phys. A (arXiv:1406.3904 [hep-ph])

Motivation

I. Zalamea & A. Beloborodov (2011) calculated the efficiency of the electron-positron plasma production by neutrino through the process $\nu \to \nu e^- e^+$ in the conditions of the Kerr black hole accretion disk. It is considered by experts as the most likely source of a short cosmological gamma-ray burst.
They used the result for the energy deposition rate in this process obtained in the crossed field limit by A.K. & N. Mikheev (1997).
However, in those physical conditions (B to 180 B_e, E_ν to 25 MeV) the approximation of a crossed field is poorly applicable,
as well as the approximation of a superstrong field when $e^- e^+$ are created in the ground Landau level.
The next Landau levels can be also excited.

Calculation technics

The calculation technics can be found e.g. in:



The four-vector of losses: $Q^\alpha = E \int (P - P')^\alpha \, \mathrm{d}W$

The energy deposition rate:

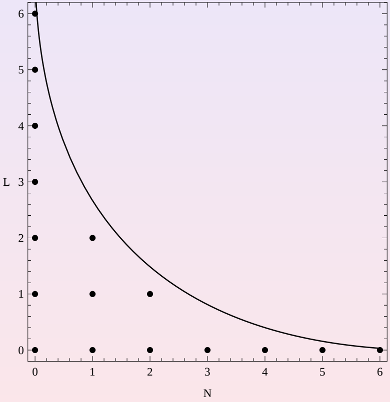
$$Q_0 = (C_V^2 + C_A^2)\, \sigma_0 \, m_e^4 \, E \, f\left(\frac{E}{m_e}, \frac{B}{B_e}\right), \qquad \sigma_0 = \frac{4\, G_\mathrm{F}^2 \, m_e^2}{\pi}$$

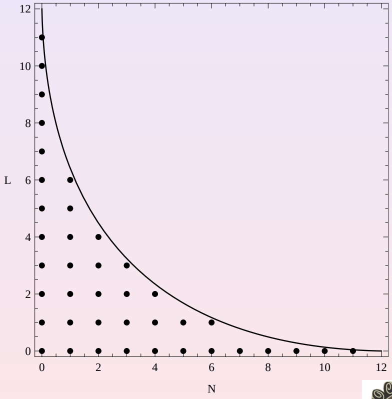
I. Zalamea & A. Beloborodov (2011) used the result obtained in the crossed field limit by A.K. & N. Mikheev (1997)

$$f^{(cr)}(y, \eta) \simeq \frac{7\, y^2 \, \eta^2}{1728\, \pi^2} \ln(y\, \eta)$$

The crossed field limit is poorly applicable in those physical conditions (B to 180 B_e, E_ν to 25 MeV).

Landau levels of $e^-_{(N)} e^+_{(L)}$ to be excited at $E = 25$ MeV, and at $B = 180\, B_e$ (left) and $100\, B_e$ (right)





Neutrino energy losses

The contribution of the channel $\nu \to \nu e^-_{(0)} e^+_{(0)}$, A. K. & N. Mikheev (1997)

$$f^{(00)}(y,\eta) = \frac{\eta\, y^4}{32\,\pi^2} \int\limits_0^1 \mathrm{d}\rho\, \rho (1-\rho^2)^2 \exp\left(-\frac{y^2(1+\rho^2)}{2\eta} \right) I_0\left(\frac{y^2}{\eta}\, \rho \right)$$

$I_0(x)$ is the modified Bessel function.

In a general case, for $\nu \to \nu e^-_{(n)} e^+_{(\ell)}$, the function $f^{(n\ell)}(y,\eta)$ is much more complicated.

Neutrino energy losses

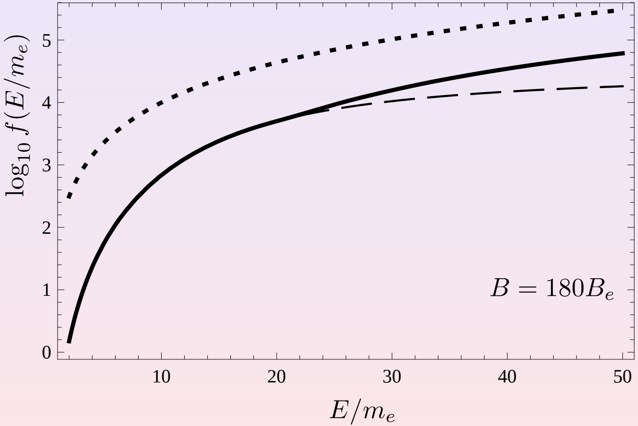
The contribution of the channels $\nu \to \nu e^-_{(n)} e^+_{(0)}$ and $\nu \to \nu e^-_{(0)} e^+_{(n)}$

$$f^{(n0+0n)}(y,\eta) = \frac{\eta\, y^4}{4\pi^2 (n-1)!} \left(\frac{y^2}{2\eta}\right)^{n-1} \int\limits_0^{\rho_m} \mathrm{d}\rho\, \rho \int\limits_0^{z_m} \frac{\mathrm{d}z(1-r)}{r(1-2r+\rho^2)^2}$$

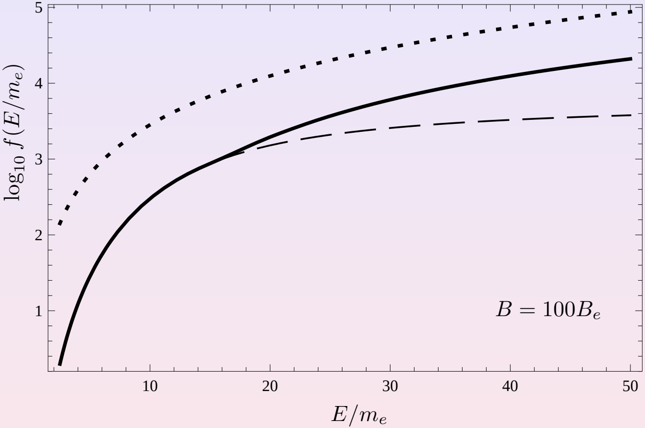
$$\times \left[(1-\rho^2)^2 + 4r^2 - 2r(1+\rho^2)\right] \int\limits_0^{2\pi} \frac{\mathrm{d}\phi}{2\pi}(r - \rho\cos\phi)$$

$$\times (1 - 2\rho\cos\phi + \rho^2)^{n-1} \exp\left(-\frac{y^2(1-2\rho\cos\phi+\rho^2)}{2\eta}\right)$$

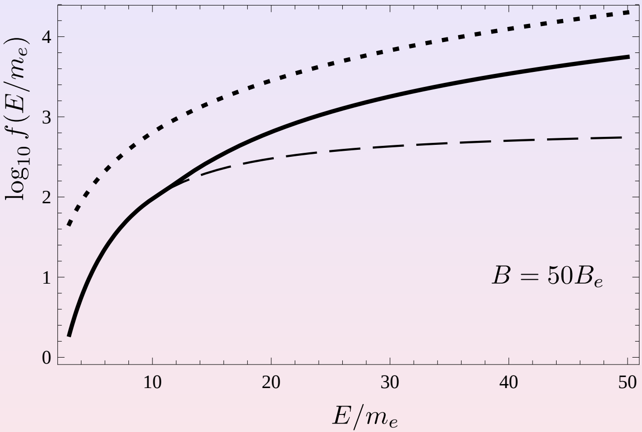
Crossed field limit (dotted), the ground (0,0) Landau level (dashed), the sum of all excited levels (solid)



Neutrino energy losses



Neutrino energy losses



Conclusions

- The process $\nu \to \nu e^- e^+$ is investigated in the magnetic field of an arbitrary strength, when $e^- e^+$ can be produced in the excited Landau levels.
- The neutrino energy losses due to this process are calculated. The results should be used for calculations of the efficiency of the $e^- e^+$ plasma production by neutrinos in the conditions of the Kerr black hole accretion disk. In these conditions, the crossed field limit gives the overstated result which is in orders of magnitude greater than the sum of the lower Landau levels.
- This study may be useful for further development of computational techniques to analyze quantum processes in an external active environment, particularly in conditions of moderately strong magnetic field, when the allowance for the contribution of only the ground Landau level is insufficient.

In memoriam

We dedicate our talk to the blessed memory of our colleague and friend Nickolay Vladimirovich Mikheev who passed away on June 19.