Neutrino decay to electron and W-boson in a superstrong magnetic field in the Early Universe

A.M. Shitova
in collaboration with A.V. Kuznetsov and A.A. Okrugin

Yaroslavl P.G. Demidov State University

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Motivation

A problem of studying possible effects of an active environment on the neutrino dispersion properties is quite important.

A kind of external active medium: the strong magnetic field.

The natural scale for the field strength exists: the critical value $B_e = m_e^2/e \simeq 4.41 \times 10^{13}\,\mathrm{G}$; a quantizing field for an electron. Possible fields in magnetars: $B \sim 100\,B_e$.

Such extreme physical conditions make an active influence on the run of quantum processes, thus allowing or enhancing the transitions that are forbidden or strongly suppressed in a vacuum.

Motivation

Along with highly magnetized neutron stars (magnetars), the Early Universe could be considered as a natural laboratory for superstrong magnetic fields, i.e. quantizing fields for a W-boson.

Extreme conditions: super strong magnetic field.

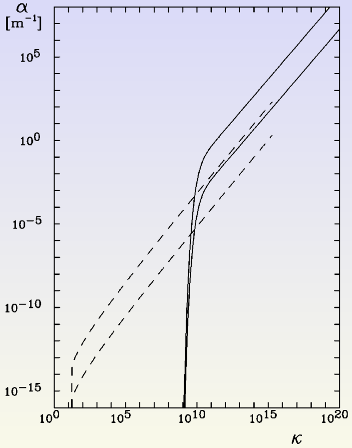
Another natural scale can serve as a natural boundary of applicability of Standard Model: $B_W = m_W^2/e \simeq 1.1 \cdot 10^{24}$ G.

The external field effects should be taken into account on the basis of exact solutions of the field theory equations for a charged particle in an external electromagnetic field, not on the basis of perturbation theory.

The process $\nu \to \nu e^- e^+$ vs the process $\nu_e \to e^- W^+$

Probably, the most interesting processes of such kind are the transitions of massless neutrinos, $\nu \to \nu e^- e^+$, $\nu \to e\,W$ in a strong field. Here are presented neutrino absorption coefficients for the processes $\nu_e \to e^- W^+$ (solid) and $\nu \to \nu e^- e^+$ (dashed) vs the dimensionless parameter $\kappa = eBp_\perp/m_e^3$ for $B = 10^{-1} B_e$ (upper) and $B = 10^{-3} B_e$ (lower)

A. Erdas, M. Lissia, *Phys. Rev. D, 2003*



The neutrino decay $\nu_e \to e^- W^+$ in an external field

Calculations of the width of the process $\nu_e \to e^- W^+$ in external magnetic fields:

- Borisov, Zhukovskiĭ, Kurilin, Ternov (1985)
- Erdas, Lissia (2003)
- Bhattacharya, Sahu (2009)
- Kuznetsov, Mikheev, Serghienko (2010)
- Dobrynina, Mikheev (2014)
- Satunin (2015)

The result by *Bhattacharya, Sahu (2009)* was incorrect.

The most possible reason: they used the W boson propagator expanded over the field tensor $F^{\mu\nu}$ to the linear terms, while the quadratic terms were also essential.

The neutrino self-energy operator in active media

The neutrino self-energy operator $\Sigma(p)$ is defined in terms of the invariant amplitude for the transition $\nu_e \to \nu_e$:

$$\mathcal{M}(\nu_e \to \nu_e) = - \left[\bar{\nu}_e(p) \, \Sigma(p) \, \nu_e(p)\right].$$

The operator $\Sigma(p)$ defines the neutrino dispersion properties.

The additional neutrino energy in an external active media is:

$$\Delta E = - \frac{1}{2\,E} \, \mathcal{M}(\nu_e \to \nu_e) \, .$$

The neutrino decay $\nu_e \to e^- W^+$ in magnetic field

The decay width is defined by the imaginary part of the additional neutrino energy

$$w(\nu_e \to e^- W^+) = -2\,\mathrm{Im}\,\Delta E = \frac{1}{E}\,\mathrm{Im}\,\mathcal{M}(\nu_e \to \nu_e)$$

The result for the hierarchy $p_\perp^2 \gg m_W^2 \gg eB \gg m_e^2$

Kuznetsov A. V., Mikheev N. V., Serghienko A. V., *Phys. Lett. B*, **690**:4 (2010), 386–389.

$$w(\nu \to e^- W^+) = \frac{G_F \, (eB)^{3/2} \; p_\perp}{\pi \sqrt{2\pi} \, E} \, \Phi(\eta) \, , \qquad \eta = \frac{4 \, eB \, p_\perp^2}{m_W^4}$$

$$\Phi(\eta) = \frac{1}{\eta} \int\limits_0^\infty \frac{\mathrm{d}y}{y^{1/2}} \, \frac{(\tanh y)^{1/2}}{(\sinh y)^2} \, \frac{(\sinh y)^2 - y \tanh y}{(y - \tanh y)^{3/2}} \, \exp\left[- \frac{y \tanh y}{\eta \, (y - \tanh y)} \right]$$

In the limiting cases:

$$\Phi(\eta \gg 1) \simeq \frac{1}{3} \sqrt{\pi(\eta - 0.3)}$$

and the error is less than 1 % for $\eta > 10$;

$$\Phi(\eta \ll 1) \simeq \left(1 - \frac{1}{2} \, \eta + \frac{3}{4} \, \eta^2 \right) \exp\left(- \frac{1}{\eta} \right)$$

and the error is less than 1 % for $\eta < 0.5$

Quantizing field for a W-boson

Superstrong magnetic field, $B \sim B_W = m_W^2/e \simeq 10^{24}\,\mathrm{G}$, should be quantizing field for a W-boson

There exists a question of stability of the electroweak vacuum at $B \to B_W$ (*Skalozub, 1978*; *Nielsen, Olesen, 1978*; *Ambjørn, Olesen, 1990*; *MacDowell, Törnkvist, 1992*; ... *Skalozub, 2014*).
As it was shown by *Skalozub (2014)*, the radiation corrections act to prevent the instability of the electroweak vacuum in strong fields.

The electron propagator expanded over the Landau levels

$$S(q) = \sum_{n=0}^{\infty} \frac{\mathrm{i}}{q_{\parallel}^2 - m_e^2 - 2n\beta} \left\{ \left[(q\gamma)_{\parallel} + m_e \right] \left[d_n(\alpha) - \frac{\mathrm{i}}{2} (\gamma\varphi\gamma)\, d'_n(\alpha) \right] - (q\gamma)_{\perp}\, 2n\, \frac{d_n(\alpha)}{\alpha} \right\}$$

where $\beta = eB$, $\alpha = q_{\perp}^2/\beta$. In the frame $\mathbf{B} = (0, 0, B)$, the 4-vectors with the subscripts $\perp$ and $\parallel$ belong to the Euclidean $\{1, 2\}$-subspace and the pseudo-Euclidean $\{0, 3\}$-subspace respectively: $q_{\perp} = (0, q_1, q_2, 0)$, $p_{\parallel} = (q_0, 0, 0, q_3)$. The functions are introduced:

$$d_n(\alpha) = (-1)^n \mathrm{e}^{-\alpha} [L_n(2\alpha) - L_{n-1}(2\alpha)]$$

$L_n(x)$ are the Laguerre polynomials $(L_{-1}(x) \equiv 0)$.

A. Chodos, K. Everding, D. A. Owen, *Phys. Rev. D.*, *1990*

The W-boson propagator expanded over the Landau levels

$$G_{\mu\nu}(q) = \sum_{n=0}^{\infty} \frac{-\mathrm{i}\,(-1)^n\, \mathrm{e}^{-\alpha}}{q_{\parallel}^2 - m_W^2 - \beta\,(2\,n-1)} \Bigg[-2\,(\tilde{\varphi}\,\tilde{\varphi})_{\mu\nu}\, L_{n-1}(2\alpha)$$

$$-\,(\varphi\,\varphi)_{\mu\nu} \Big(L_n(2\alpha) + L_{n-2}(2\alpha) \Big) + \mathrm{i}\,\varphi_{\mu\nu} \Big(L_n(2\alpha) - L_{n-2}(2\alpha) \Big) \Bigg]$$

where $\varphi_{\alpha\beta} = F_{\alpha\beta}/B$ is the dimensionless electromagnetic tensor, $\tilde{\varphi}_{\alpha\beta} = \frac{1}{2}\,\varepsilon_{\alpha\beta\mu\nu}\,\varphi^{\mu\nu}$ is the dual tensor.

A.V. Kuznetsov, A.A. Okrugin, A.M. Shitova, *Int. J. Mod. Phys. A*, **30**:24, 1550140 (2015).

The decay $\nu_e \to e^- W^+$ width

$$w(\nu_e \to e^- W^+) = \frac{G_{\mathrm{F}}\, m_W^2 \beta}{\sqrt{2}\,\pi\, E} \sum_{k=0}^{k_{max}} \sum_{n=0}^{n_{max}(k)} \mathrm{e}^{-\chi} \sqrt{D^{-1}(\chi)}$$

$$\times \Bigg\{ \left(\chi - \mu - k + n + \frac{1}{2}\right) \left[\frac{k!}{n!}\, \chi^{n-k} \left(L_k^{n-k}(\chi) \right)^2 \right.$$

$$\left. + \frac{(k-2)!}{(n-1)!}\, \chi^{n-k+1} \left(L_{k-2}^{n-k+1}(\chi) \right)^2 \right] - 4\,(-1)^{k+n} \chi\, L_{k-1}^{n-k+1}(\chi) L_{n-1}^{k-n}(\chi) \Bigg\}$$

$$\times\, \theta \left(\sqrt{\chi} - \sqrt{\mu + k - \frac{1}{2}} - \sqrt{n} \right),$$

The decay $\nu_e \to e^- W^+$ width

The notations are introduced ($\beta = eB$):

$$\chi = \frac{p_\perp^2}{2\beta}, \qquad \mu = \frac{m_W^2}{2\beta}$$

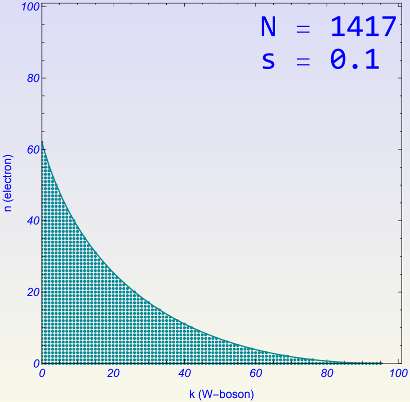
$$D(\chi) = \left(\chi - \mu - k + n + \frac{1}{2}\right)^2 - 4n\chi$$

$$n_{max}(k) = \mathrm{IntegerPart}\left[\left(\sqrt{\chi} - \sqrt{\mu + k - \frac{1}{2}}\right)^2\right]$$

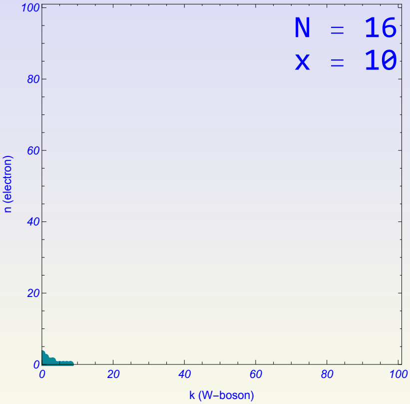
$$k_{max} = \mathrm{IntegerPart}\left[\chi - \mu + \frac{1}{2}\right]$$

At this stage, our analysis is incomplete, namely, the thermal effects are not taken into account.

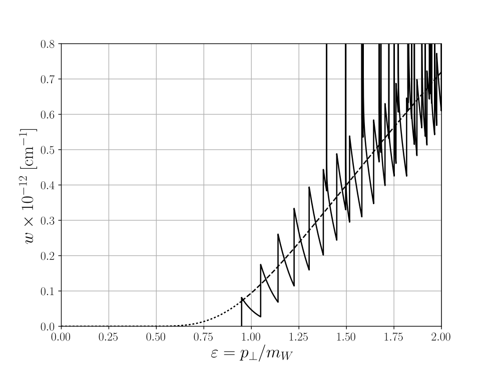
The evolution of the Landau levels as a function of the field's strength $s \equiv \beta/m_W^2$ $(\chi = 10^2)$



The evolution of the Landau levels as a function of $\chi \equiv \frac{p_\perp^2}{2\beta}$, $(s = 0.25)$

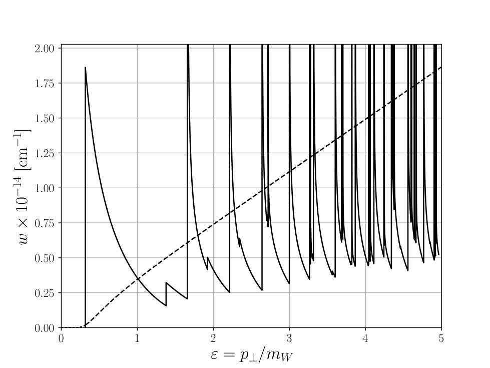


The decay $\nu_e \to e^- W^+$ width



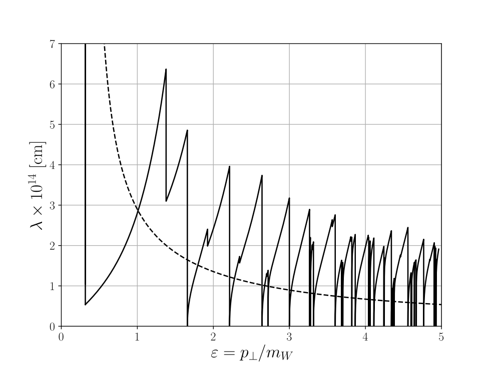
The decay $\nu_e \to e^- W^+$ width for $\beta = 0.1\, m_W^2$ (the "sawtooth" profile). Dashed line: approximate formula without considering the quantizing effect of the magnetic field.

The decay $\nu_e \to e^- W^+$ width



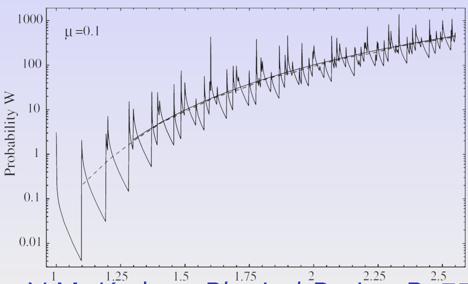
The decay $\nu_e \to e^- W^+$ width for $\beta = 0.9\, m_W^2$ (the "sawtooth" profile). Dashed line: approximate formula without considering the quantizing effect of the magnetic field.

Mean free path λ due to the $\nu_e \to e^- W^+$ process



Mean free path for $\beta = 0.9\, m_W^2$. Dashed line: approximate formula without considering the quantizing effect of the magnetic field.

The "sawtooth" profile is a known effect



V.N. Baier, V.M. Katkov, *Physical Review D*, **75**, 073009 (2007).

A peculiar "sawtooth" profile due to the square-root singularities (Klepikov, 1954) is known in the process $\gamma^* \to e^- e^+$ width in a strong field (Daugherty, Harding, 1983; Baier, Katkov, 2007).

The "sawtooth" profile is a known effect

Baier, Katkov, 2007:

The origin of the singularity is due to the properties of the space volume in the lowest order of perturbation theory (infinitesimally narrow level).

Taking account of the next order of perturbation theory should transform the square-root singularities to finite peaks. The decay width for the values $p_\perp$ corresponding to these peaks should be near two orders of magnitude greater than for another values.

The narrow dips in the mean free path dependence on $\varepsilon = p_\perp / m_W$ are also not zeros but finite.

Domain walls generatind the primordial magnetic field

In a non-equilibrium primordial electroweak phase transition, the low temperature phase starts to form, due to quantum fluctuations, simultaneously and independently in many parts of the system: a domain structure is formed $\Rightarrow$ domain walls.

However, such walls would introduce a large anisotropy into the relic blackbody radiation, and should be excluded (*Zel'dovich, Kobzarev and Okun, 1974*).

Nevertheless, ultrastrong magnetic fields from cosmological phase transitions were discussed (e.g. Vachaspati, 1991). VEV's of the Higgs field in regions separated by distances larger than the horizon should be uncorrelated, and the gradient of the VEV acts as a non-vanishing electromagnetic field ($B \sim 0.1 B_W$).

Domain walls generatind the primordial magnetic field

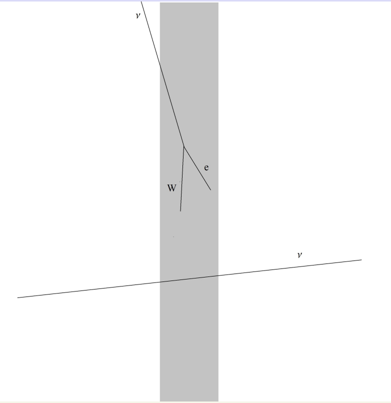
It was suggested (*Cea and Tedesco, 1999; 2000; 2003*) that the effective surface tension of the domain walls can be made vanishingly small due to a peculiar magnetic condensation induced by fermion zero modes localized on the wall. As a consequence, the domain wall acquires a non-zero magnetic field perpendicular to the wall, and it becomes almost invisible as far as the gravitational effects are concerned.

A magnetic field could be as strong as $B \sim B_W$

The process $\nu_e \to e^- W^+$ could go onto stage!

The processes $\nu_e \to e^- W^+$ inside a domain wall – possible consequences?

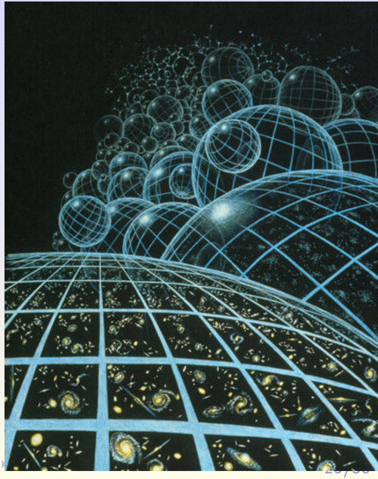
It would be important that the process width essentially depends on $p_\perp = E \sin\theta$, where θ is an angle between the neutrino momentum and the field direction. Neutrinos, moving almost perpendicular to the domain wall (i.e. almost parallel to the field direction) would skip it, while neutrinos moving almost parallel to the wall, would predominantly decay.



The processes $\nu_e \to e^- W^+$ inside a domain wall – possible consequences?

Suppose that the hypothesis of magnetic field generation in domain walls is correct, than neutrinos propagating almost parallel to the wall (in the way of the maximum magnetic field influence) with specific energies would generate a great amount of W-bosons in the thickness of the wall.

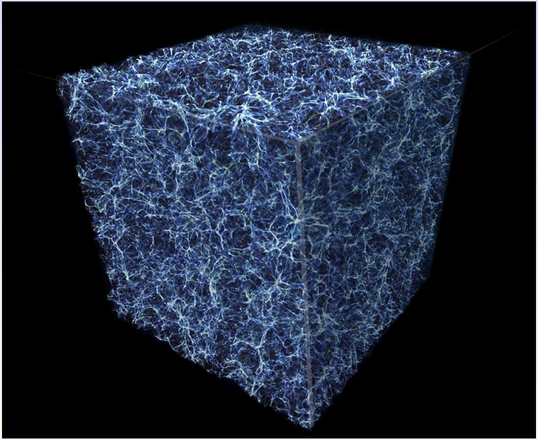
The subsequent decay of the W-boson by dominant quark channels could lead to some overabundance of hadron matter and antimatter inside domain walls to outside.



The processes $\nu_e \to e^- W^+$ inside a domain wall – possible consequences?

If the lepton-antilepton asymmetry, induced by the CP violation in the lepton sector, has arisen before the electroweak phase transition, leading to overabundance of neutrinos over antineutrinos in the Universe, the considered mechanism would provide an overabundance of W^+ and e^- over W^- and e^+ inside domain walls. The W^+-bosons finally transform by dominant quark channels to protons.

The subsequent formation of the baryon asymmetry would paint the final picture of the Universe.



Conclusions

- The processes of the neutrino decay $\nu_e \to e^- W^+$ was investigated in a superstrong magnetic field in the conditions of the Early Universe using the representation of the electron and W-boson propagators as the sum over the Landau levels.

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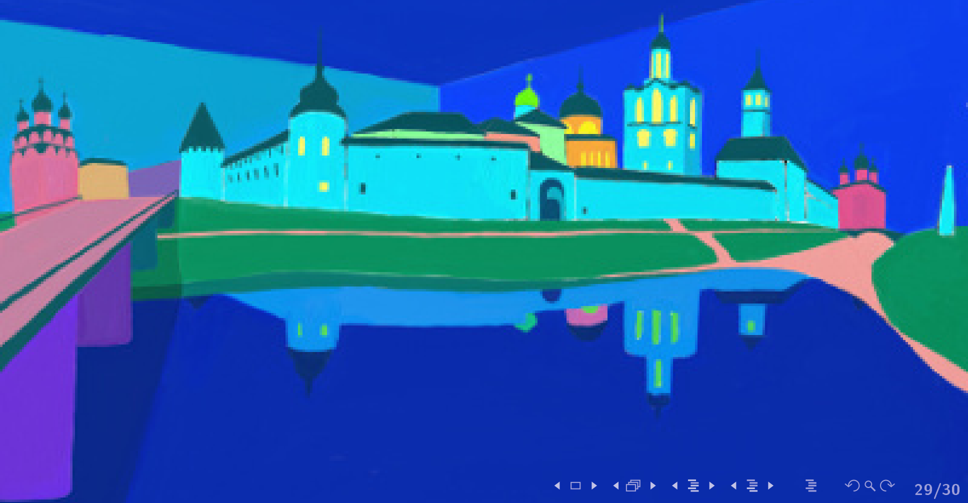
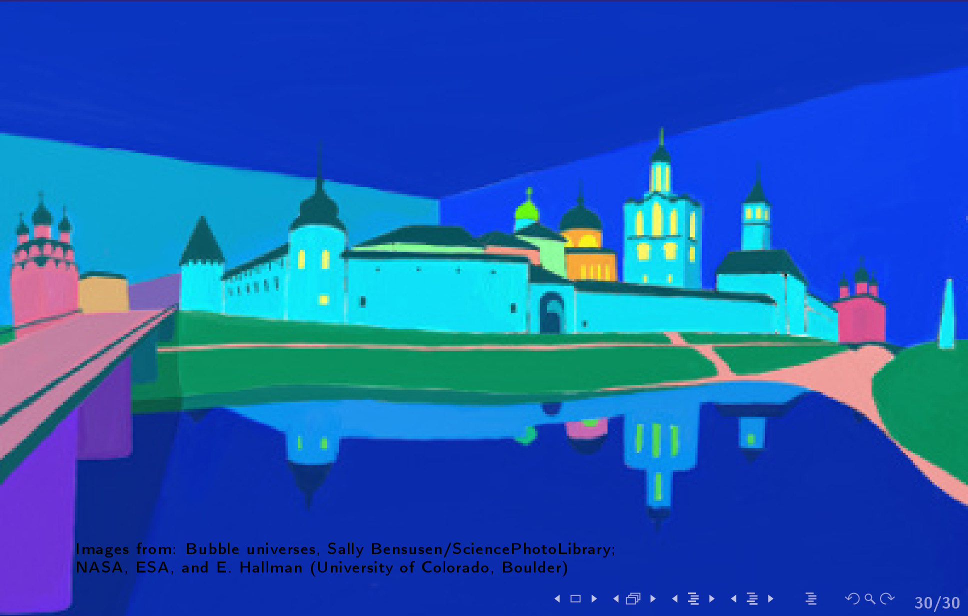
- It was shown, that the resonance peaks present in the decay width for certain values of $p_\perp$ correspond to the electron and the W-boson creation by neutrino at specific Landau levels.

Conclusions

- The processes of the neutrino decay $\nu_e \to e^- W^+$ was investigated in a superstrong magnetic field in the conditions of the Early Universe using the representation of the electron and W-boson propagators as the sum over the Landau levels.
- It was shown, that the resonance peaks present in the decay width for certain values of $p_\perp$ correspond to the electron and the W-boson creation by neutrino at specific Landau levels.
- If the hypothesis of magnetic field generation in domain walls is correct, than neutrinos propagating almost parallel to the wall (in the way of maximum magnetic field influence) with specific energies would generate a large number of W-bosons in the thickness of the wall influencing the picture of baryogenesis.

Thank you for your attention!





Images from: Bubble universes, Sally Bensusen/SciencePhotoLibrary; NASA, ESA, and E. Hallman (University of Colorado, Boulder)