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Plasma influence on neutrino electromagnetic properties

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New mechanism of electromagnetic radiation by neutrino in matter

$SL\nu$

$$\boxed{\nu \rightarrow \nu + \gamma}$$

$$\mu_\nu \neq 0! \qquad m_\nu \neq 0$$

Recent review of neutrino electromagnetic properties see: C. Giunti, A. Studenikin, arXiv:0812.3646, Phys.Atom.Nucl. 72, 2151 (2009)

$$m_i = m_f$$

Spin Light of Neutrino in matter (gamma-rays for relativistic neutrinos $\omega \sim 1/3\, E_\nu$)

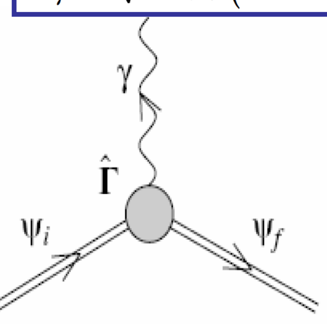
A.Lobanov, A.Studenikin, **Phys.Lett.B**; **564** (2003) 27; **601** (2004) 171
A.Studenikin, A.Ternov, **Phys.Lett.B 608** (2005) 107
A.Grigoriev, A.Studenikin, A.Ternov, **Phys.Lett.B 622** (2005) 199

Recently a new mechanism of electromagnetic radiation by neutrino in matter has been proposed. It was called the Spin Light of neutrino in matter ($SL\nu$) [2,3]. It is based on the common supposition that neutrino possesses non-zero mass and thus non-zero magnetic moment [1]. Its principle is the following: initial and final neutrinos interact with the particles of the medium and in average this interaction results in changing of energies of neutrino states in matter (the energy change also depends on the helicity of the corresponding neutrino). Though the effect is quantum by its nature it has a simple quasiclassical interpretation.[7] That is the radiation produced by the precession of neutrino magnetic moment in matter. It has been shown that this mechanism of electromagnetic radiation is efficient in the case when an ultrarelativistic neutrino propagates in high density matter. And that could be important for astrophysical applications.

$$\boxed{\nu_i \rightarrow \nu_j + \gamma} \qquad \boxed{\omega = \sqrt{k^2 + m_\gamma^2}} \qquad SL\nu$$

$$\boxed{m_\gamma = \sqrt{2\alpha_{em}}\left(3\sqrt{\pi}n\right)^{1/3}}$$

Neutrinos weak interaction with matter is taking into account: we use exact wave functions for the initial and final neutrinos in presence of matter



- γ is coupled to *neutrinos* by the magnetic moment μ_ν
- high density of matter $n \sim 10^{37} \div 10^{40}\ cm^{-3}$ (neutron stars)
- relativistic neutrinos

I would like to present the further development of the theory of spin light of neutrino in matter. Now our investigation considers the spin light of relativistic neutrino propagating in dense plasma which is the most interesting case for possible astrophysical applications. Here is the diagram of the process. The broad lines stand for the initial and final neutrino states exactly accounting for the presence of matter.
For our study we take this simple expression for the photon dispersion in plasma. And the plasmon mass in cold dense plasma could be taken as m_γ shown above.
The photon (or plasmon) is coupled to the neutrinos by the magnetic moment of neutrino.

Modified Dirac Equation

$SL\nu$

$$\boxed{\left\{ i\gamma_\mu \partial^\mu - \frac{1}{2}\gamma_\mu(1+\gamma^5)f^\mu - m \right\}\Psi(x) = 0.}$$

$$f^\mu = \frac{G_F}{\sqrt{2}}(n_n, 0, 0, 0) \quad \text{for unpolarized and matter at rest}$$

neutrino energy spectrum

$$\boxed{E_\varepsilon = \varepsilon\sqrt{(p - s\alpha m)^2 + m^2} + \alpha m}$$

p — neutrino momentum

matter density parameter

$$\alpha = \frac{1}{2\sqrt{2}} G_F \frac{n_n}{m}$$

s is neutrino helicity

$\varepsilon = \pm 1$ defines positive and negative energy solutions

n_n is neutron number density

A. Studenikin, A. Ternov Phys.Lett. B 60 (2005) 107
A. Studenikin, J.Phys. A:Math.Theor. 41 (2008) 16402

The wave functions of neutrino in matter are obtained as the exact solutions of the Modified Dirac Equation.[4,5,6] This equation can be obtained by varying of the Standard Model Lagrangian averaged over the matter parameters. Here generally "f" accounts for the polarization and the movement of the medium. But in case of unpolarized and non-moving matter "f" has a simple signature depending on the density of the medium. Let us also consider the matter composed of neutrons.
Than here is the neutrino energy spectrum. Note that it depends on the helicity of neutrino and alpha is the matter density parameter.

Modified Dirac Equation

$SL\nu$

Exact Solutions:

$$\Psi_{\varepsilon,\vec{p},s}(\vec{r},t) = \frac{e^{-i(E_\varepsilon - \vec{p}\vec{r})}}{2L^{3/2}} \begin{pmatrix} \sqrt{1+\frac{m}{E_\varepsilon - \alpha m}}\sqrt{1+s\frac{p_3}{p}} \\ s\sqrt{1+\frac{m}{E_\varepsilon - \alpha m}}\sqrt{1-s\frac{p_3}{p}}\cdot e^{i\delta} \\ s\varepsilon\sqrt{1-\frac{m}{E_\varepsilon - \alpha m}}\sqrt{1+s\frac{p_3}{p}} \\ \varepsilon\sqrt{1-\frac{m}{E_\varepsilon - \alpha m}}\sqrt{1-s\frac{p_3}{p}}\cdot e^{i\delta} \end{pmatrix}$$

matter density parameter

$$\boxed{\alpha = \frac{1}{2\sqrt{2}} G_F \frac{n_n}{m}}$$

$$\boxed{\delta = \arctan p_2/p_1} \quad L \text{ is normalization length}$$

$$\boxed{\vec{p} = (p_1, p_2, p_3)} \quad \text{- neutrino momentum}$$

A. Studenikin, A. Ternov Phys.Lett. B 60 (2005) 107
A. Studenikin, J.Phys. A:Math.Theor. 41 (2008) 16402

And here the abovementioned exact solution of the Modified Dirac Equation is presented. This wave function of neutrino propagating in matter depends on the matter density as a parameter and we can also see the dependence on the neutrino helicity. "p" with indexes 1, 2, 3 simply stands for different components of the neutrino momentum.

Kinematics

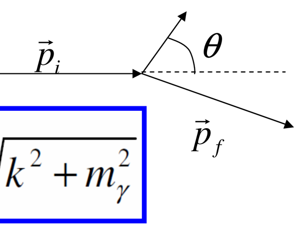
$$\boxed{\nu_i \rightarrow \nu_j + \gamma} \qquad SL\nu$$

Initial and final neutrino energies:

$$\boxed{E_{i,f} = \sqrt{(p_{i,f} - s_{i,f}\tilde{n})^2 + m^2} + \tilde{n}} \qquad \boxed{\tilde{n} = \alpha m}$$

Energy and momentum conservation laws:

$$\boxed{E_i = E_f + \omega} \qquad \boxed{\vec{p}_i = \vec{p}_f + \vec{k}}$$



$$\boxed{\sqrt{(p_i - s_i\tilde{n})^2 + m^2} = \sqrt{(p_f - s_f\tilde{n})^2 + m^2} + \sqrt{k^2 + m_\gamma^2}}$$

$$\boxed{s_i = -1} \quad \boxed{s_f = +1}$$

Threshold condition

$$\boxed{\tilde{n}p_i > \frac{m_\gamma^2}{4}}$$

A.Lobanov, A.Studenikin, PLB 2003; PLB 2004
A.Grigoriev, A.Studenikin, PLB 2005
A.Grigoriev, A.Studenikin, A.Ternov, PLB 2005
A.Kuznetsov, N.Mikheev, 2006

The neutrino spectrum from the Modified Dirac Equation provides us with the exact energies of neutrino in initial and final states. Now, possessing those energies we can resolve the energy-momentum conservation law relative to the momentum of the photon. The kinematical scheme of the process is presented here. We will consider the initial neutrino with the helicity -1 and the final neutrino with the helicity +1. The main result here is the presence of the threshold. The process is kinematically open if the corresponding condition is satisfied. The threshold of the process has been discussed in the previous studies of the Spin light, and the estimation of the threshold condition has been made in [8].

Total rate and power of the Spin Light

$SL\nu$

- **$SL\nu$ without plasma influence**

$$\boxed{\Gamma = 4\mu^2\tilde{n}^2(\tilde{n} + p)} \qquad \boxed{m_\gamma \rightarrow 0}$$

$$\boxed{I = \frac{4}{3}\mu^2\tilde{n}^2(3\tilde{n}^2 + 4p\tilde{n} + p^2)}$$

- **Far from the threshold**

$$\boxed{\Gamma = 4\mu^2 p\tilde{n}^2(1 + 6\lambda + 4\lambda\ln\lambda)} \qquad \boxed{\lambda = \frac{m_\gamma^2}{4\tilde{n}p}} \qquad \lambda \ll 1$$

$$\boxed{I = \frac{4}{3}\mu^2 p^2\tilde{n}^2\left(1 - 6\lambda - 57\lambda\frac{\tilde{n}}{p} - 12\lambda\frac{\tilde{n}}{p}\ln\lambda\right)}$$

- **Approaching the threshold**

$$\boxed{\Gamma \sim (1-\lambda)} \qquad \boxed{\lambda \rightarrow 1}$$

$$\boxed{I \sim (1-\lambda)}$$

The next step will be the calculation of the total rate and the power of the process. As the exact expressions are large it is more convenient to explore several ranges of parameters.
First of all we consider the spin light of neutrino without plasma influence. In the limit of zero plasmon mass we obtain the original formulas for the Spin Light.
Taking the plasma influence into account we can consider two more cases: the system far from the threshold and near it. The parameter λ here defines the distance from the threshold. Near the threshold the rate and the power have the same asymptotic forms. And far from the threshold the plasmon mass becomes a minor parameter.

Conclusions

$SL\nu$

- **The theory of spin light of neutrino ($SL\nu$) in matter is now generalized for the case of neutrino propagating in cold dense plasma (originally $SL\nu$ was considered for the case of massless photon)**
- **The influence of plasmon mass becomes significant when the parameter λ is comparable with 1; this corresponds to the system near the threshold**
- **As soon as the system is far from the threshold one can use either $SL\nu$ radiation rate and total power without accounting for the plasmon mass**
- **In the case of relativistic neutrino energies (astrophysical applications) the plasmon mass gives subdominant effect. It is though possible to use rather compact generalizations of the original formulas where the plasmon mass is accounted for as a minor adjustment**

For further details see: A. Grigoriev, A. Lokhov, A. Studenikin, A. Ternov: Proceedings of the La Thuile 2011 - Les Rencontres de Physique de La Vallée d'Aoste, Results and Perspectives in particle physics

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