Analysis of particles’ masses effects in spin light of neutrino and related processes

A. Grigoriev
<u>A. Lokhov</u>
A. Studenikin

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$SL\nu$

- A. Grigoriev, A. Lokhov, A. Studenikin, A. Ternov

  "Spin light in neutrino transition between different mass states in matter"

  arXiv:1003.0630 [hep-ph]

New mechanism of electromagnetic radiation by neutrino in matter

$SL\nu$

$$\nu \to \nu + \gamma$$

$$\mu_\nu \neq 0!$$

$$m_\nu \neq 0$$

Recent review of neutrino electromagnetic properties

see: **C. Giunti, A. Studenikin, 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

Neutrino radiative decay in vacuum

$$\nu_i \to \nu_j + \gamma$$

$$\nu_i \downarrow m_i \qquad \nu_j \downarrow m_j$$

was also considered before:

S. Petcov, Nucl. Phys. 25 (1977) 641
G. Zatsepin, A. Smirnov, Nucl. Phys. 28 (1978) 6
A. De Rujula and S. L. Glashow, Phys. Rev. Lett. 45 (1980) 942
P. Pal, L. Wolfenstein, Phys.Rev.D 25 (1982) 766
C. Giunti, C.W. Kim, W.P. Lam, Phys.Rev.D 43 (1991) 164

$$\nu_i \to \nu_j + \gamma$$

$$m_i \neq m_j$$

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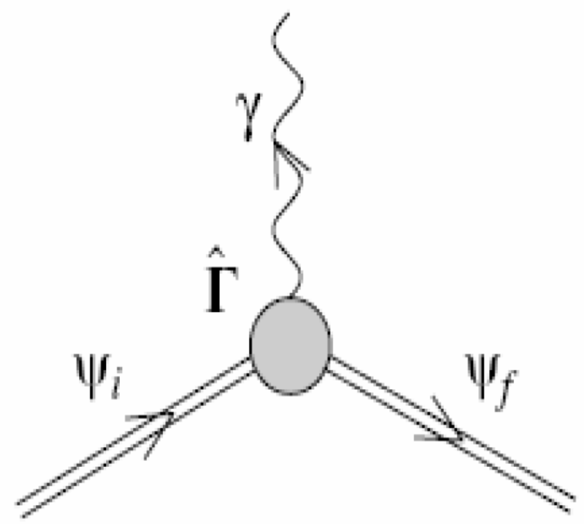
Neutrinos weak interaction with matter is taken into account: we use exact wave functions for the initial and final neutrinos in presence of matter



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

Modified Dirac Equation

$SL\nu$

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

$$f^{\mu} = \frac{G_F}{\sqrt{2}}\left(n_n, 0, 0, 0\right)$$

for unpolarized and matter at rest

neutrino energy spectrum

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

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

Modified Dirac Equation

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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

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

$$\delta = \arctan p_2/p_1$$

L is normalization length

$$\vec{p} = (p_1, p_2, p_3)$$

- neutrino momentum

A. Studenikin, A. Ternov Phys.Lett. B 60 (2005) 107

A. Studenikin, J.Phys. A:Math.Theor. 41 (2008) 16402

Photon Spectrum

$$\nu_i \rightarrow \nu_j + \gamma$$

$\nu_i \rightarrow m_i$, $\nu_j \rightarrow m_j$

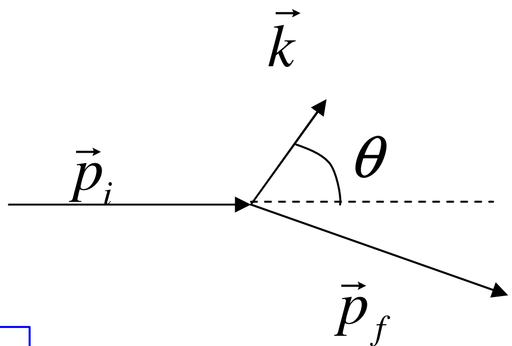
$SL\nu$

Initial and final neutrino energies:

$$E_{i,f} = \sqrt{(p_{i,f} - s_{i,f}\alpha m_{i,f})^2 + m_{i,f}^{\;2}} + \alpha m_{i,f}$$

Energy and momentum conservation laws:

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



Three main parameters:

$$\gamma = \frac{m_i}{p_i}; \quad \kappa = \frac{\alpha m_i}{p_i}; \quad \delta = \frac{\Delta m^2}{p_i^2} = \frac{m_i^2 - m_f^2}{p_i^2}$$

Useful designations:

$$K = \sqrt{(1 - s_i \cdot \kappa)^2 + \gamma^2} - x; \quad D = s_i \cdot \kappa - \delta;$$

$$x = \cos\theta$$

Photon Spectrum

$$\nu_i \rightarrow \nu_j + \gamma$$

$$\nu_i \downarrow m_i, \quad \nu_j \downarrow m_j$$

SLν

In the most interesting case: $s_i = -1, s_f = 1$

The *SLν* spectrum (within abovementioned notations):

$$\frac{\omega}{p_i} = \frac{-(KD + x\kappa^2) + \sqrt{(KD + x\kappa^2)^2 - (K^2 - \kappa^2)(D^2 - \kappa^2)}}{K^2 - \kappa^2}$$

Differential Probability of the Process

$$\frac{d\Gamma}{d\cos\theta} = \frac{(K - w + \cos\theta)(w \cdot K - \kappa - \delta) w^3 S}{\sqrt{(KD + \kappa^2 \cos\theta)^2 - (K^2 - \kappa^2)(D^2 - \kappa^2)}}$$

$$w = \frac{\omega}{p_i}$$

Total rate

$$\nu_i \rightarrow \nu_j + \gamma$$

m_i m_j

SLν

Parameters: $\dfrac{\alpha m_i}{p_i},\ \dfrac{m_i}{p_i},\ \dfrac{m_i^2 - m_f^2}{p_i^2}$

matter density parameter

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

$$\frac{1}{2\sqrt{2}}\tilde{G}_F n \sim 1\ eV$$

for

$$n = 10^{37}\ cm^{-3}$$

- **Ultrahigh density**

$$\Gamma = 4\mu^2\alpha^3 m_i^3 \left[1 + \frac{3}{2}\frac{m_i^2 - m_f^2}{\alpha m_i p_i} + \frac{p_i}{\alpha m_i}\right]$$

$$\frac{\alpha m_i}{p_i} \gg 1,\quad \frac{m_i}{p_i} \ll 1,\quad \frac{m_f}{p_i} \ll 1,\quad \frac{m_i^2 - m_f^2}{p_i^2} \ll 1$$

- **High density**

$$\Gamma = 4\mu^2\alpha^2 m_i^2 p_i \left(1 + \frac{\alpha m_i}{p_i} + \frac{m_i^2 - m_f^2}{\alpha m_i p_i} + \frac{3}{2}\frac{m_i^2 - m_f^2}{p_i^2}\right)$$

$$\frac{m_i}{p_i} \ll \alpha \ll \frac{p_i}{m_i}$$

- **Low density**

$$\Gamma = 1.87 \cdot \mu^2 p_i^3 \left(\frac{m_i^2 - m_f^2}{p_i^2}\right)^3$$

$$\frac{\alpha m_i}{p_i} \ll \frac{m_i^2}{p_i^2}$$

Total rate

$$\nu_i \rightarrow \nu_j + \gamma$$

$\nu_i \downarrow m_i$, $\nu_j \downarrow m_j$

$SL\nu$

- **Non-relativistic case (in vacuum)**

$$\Gamma \sim m_i^5$$

$$\frac{m_i}{p_i} \gg 1, \quad n \approx 0, \quad m_i \gg m_f$$

A. De Rujula and S. L. Glashow, Phys. Rev. Lett. 45 (1980) 942
G. Zatsepin, A. Smirnov, Nucl. Phys. 28 (1978) 6
S. Petcov, Nucl. Phys. 25 (1977) 641
P. Pal, L. Wolfenstein, Phys.Rev.D 25 (1982) 766
C. Giunti, C.W. Kim, W.P. Lam, Phys.Rev.D 43 (1991) 164

Conclusions

$SL\nu$

- The theory of spin light of neutrino in matter is now generalized for the case of neutrino transition between two different mass states (originally *SLν* was considered for the case of equal masses of neutrino in initial and final states)
- The rate of the process provided by the transition magnetic moment is of the same order as provided by the diagonal one
- The energy spectrum of *SLν* for the case of relativistic neutrino moving in dense matter span up to the range peculiar for gamma-rays
- In the case of ultra-relativistic neutrino energies and high densities of matter (astrophysical applications) the neutrino mass difference gives subdominant effect
- In the case of low neutrino energies and low densities of matter in the leading order our result is in agreement with

  A. De Rujula and S. L. Glashow; G. Zatsepin, A.Smirnov; S. Petcov; P. Pal, L. Wolfenstein
- The rate of *SLν* is determined by the value of neutrino effective magnetic (transition) moment

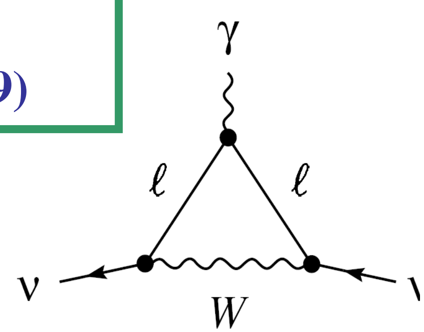
$SL\boldsymbol{\nu}$

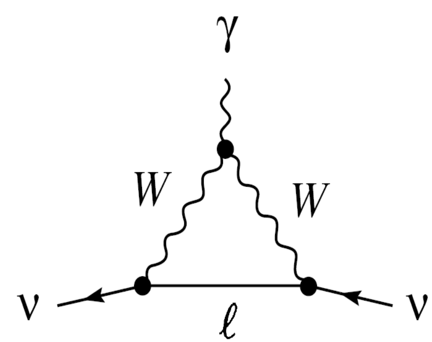
SLν

Neutrino magnetic moment

Recent review of neutrino electromagnetic properties see:

C. Giunti, A. Studenikin, Phys.Atom.Nucl. 72, 2151 (2009)





U_{ij} **- mixing matrix**

Theory SM with massive neutrino

$$\mu_{ij}^{D} = \frac{eG_F m_i}{8\sqrt{2}\pi^2}\left(1+\frac{m_j}{m_i}\right)\sum_{l=e,\mu,\tau} U_{1l}U_{2l}F(r_l)$$

$$\mu_{ii}^{D} \approx 3.2\times 10^{-19}\left(\frac{m_i}{1\ eV}\right)\mu_B$$

K. Fujikawa and R. E. Shrock, Phys. Rev. Lett. 45, 963 (1980)

Experiment

$$\mu_\nu \leq 3.2\times 10^{-11}\mu_B$$

GEMMA collaboration

A.G. Beda *et al.*, in *Particle Physics on the Eve of LHC*, Ed. by A. Studenikin (World Sci., Singapore, 2009), p. 112, arXiv:0906.1926

It is possible to have $\tau = \frac{1}{\Gamma_{SL\nu}}$ **<< age of the Universe ?**

For ultra-relativistic ν

with momentum $p \sim 10^{20} eV$

and magnetic moment $\mu \sim 10^{-10} \mu_B$

in very dense matter $n \sim 10^{40} cm^{-3}$

from $\Gamma_{SL\nu} = 4\mu^2 \alpha^2 m_\nu^2 p$

$p \gg m_{plasmon}$

recently also discussed by A.Kuznetsov, N.Mikheev, 2006

A.Lobanov, A.Studenikin, PLB 2003; PLB 2004
A.Grigoriev, A.Studenikin, PLB 2005
A.Grigoriev, A.Studenikin, A.Ternov, PLB 2005

$$\alpha m_\nu = \frac{1}{2\sqrt{2}} G_F n \left(1 + sin^2\theta_W\right)$$

it follows that

$$\tau = \frac{1}{\Gamma_{SL\nu}} = 1.5 \times 10^{-8} s$$

Exact Formula for S

$$S = (1+\beta_1\beta_2)\left(1-\frac{w-x-w\cdot x+w\cdot x^2}{\sqrt{1+w^2-2w\cdot x}}x\right)-(\beta_1+\beta_2)\left(x-\frac{w-x}{\sqrt{1+w^2-2w\cdot x}}\right);$$

$$\beta_1=\frac{1+\kappa}{\sqrt{(1+\kappa)^2+\gamma^2}},\quad \beta_2=\frac{\sqrt{1+w^2-2w\cdot x}-\kappa}{K'-w+x}.$$