Electromagnetic neutrino properties: present status and future prospects

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Outline

① (short) review of ν electromagnetic properties

② experimental constraints on μ_ν and q_ν

③ ν electromagnetic interactions (new effects)

④ two new aspects of ν spin (flavour) oscillations

- consistent treatment of ν flavour (spin) oscillations in B
- generation of ν spin (flavour) oscillations by ν interaction with transversal matter current $j_\perp$

new oscillations !

Studenikin (2004, 2016, 2017)
Popov, Pustoshny, AS (2017, 2018)

...2018 anniversaries in ν oscillation story

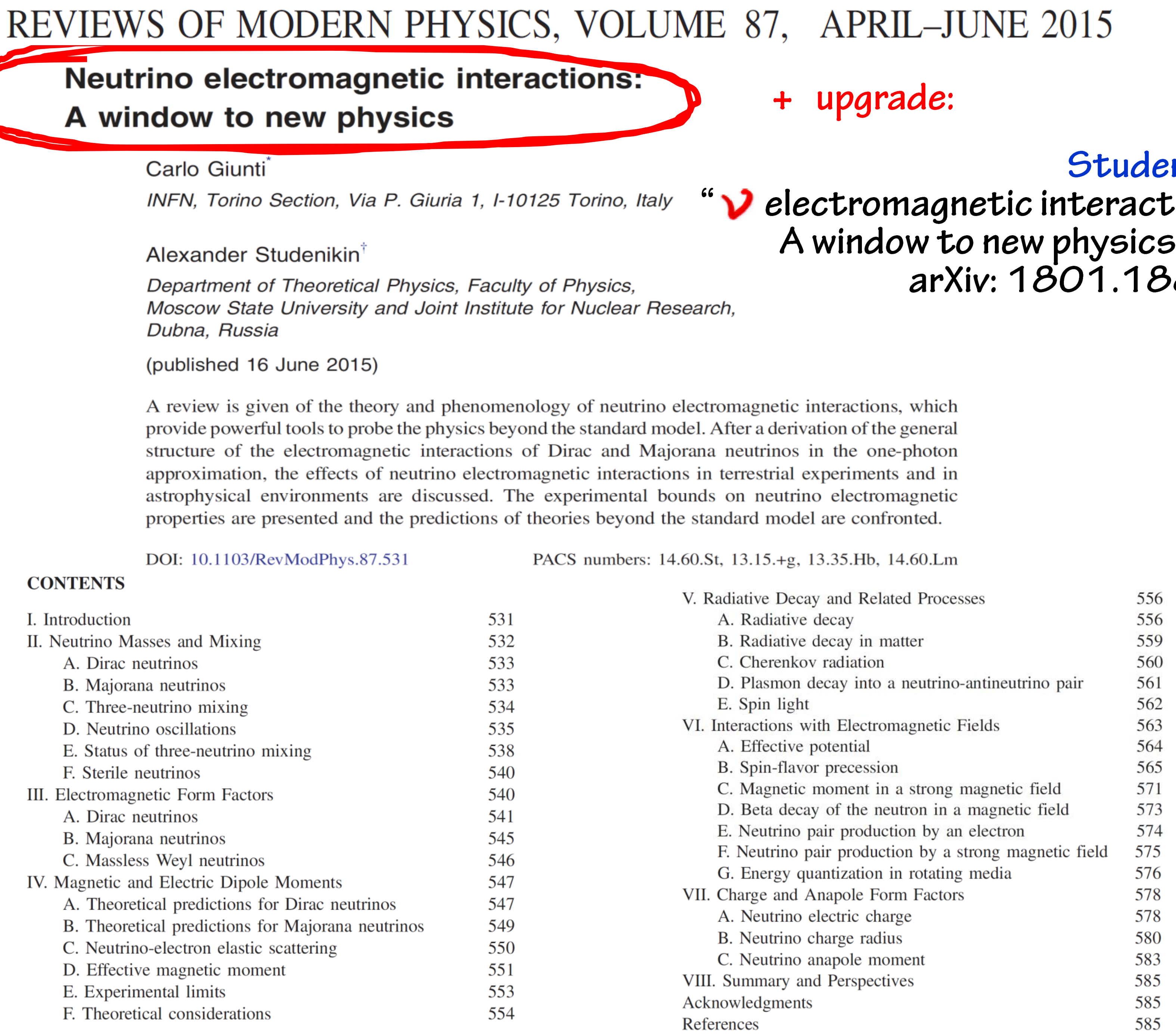
1968 - Davis et al - $\nu_{\odot}$

1968 - Gribov & Pontecorvo - $\nu_e \leftrightarrow \nu_\mu$ (theory)

1988 - Resonance Spin-Flavour ν Precession in matter (Akhmedov + Lim & Marciano)

1998 - Super-Kamiokande –

ν oscillations in ν_{atm} flux



REVIEWS OF MODERN PHYSICS, VOLUME 87, APRIL–JUNE 2015

Neutrino electromagnetic interactions: A window to new physics

\+ upgrade:

Studenikin,
“ν electromagnetic interactions:
A window to new physics – II”,
arXiv: 1801.18887

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A review is given of the theory and phenomenology of neutrino electromagnetic interactions, which provide powerful tools to probe the physics beyond the standard model. After a derivation of the general structure of the electromagnetic interactions of Dirac and Majorana neutrinos in the one-photon approximation, the effects of neutrino electromagnetic interactions in terrestrial experiments and in astrophysical environments are discussed. The experimental bounds on neutrino electromagnetic properties are presented and the predictions of theories beyond the standard model are confronted.

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CONTENTS

[1] C.Guinti and A.Studenikin, Neutrino electromagnetic interactions: a window to new physics, Rev. Mod. Phys. 87 (2015) 531-591

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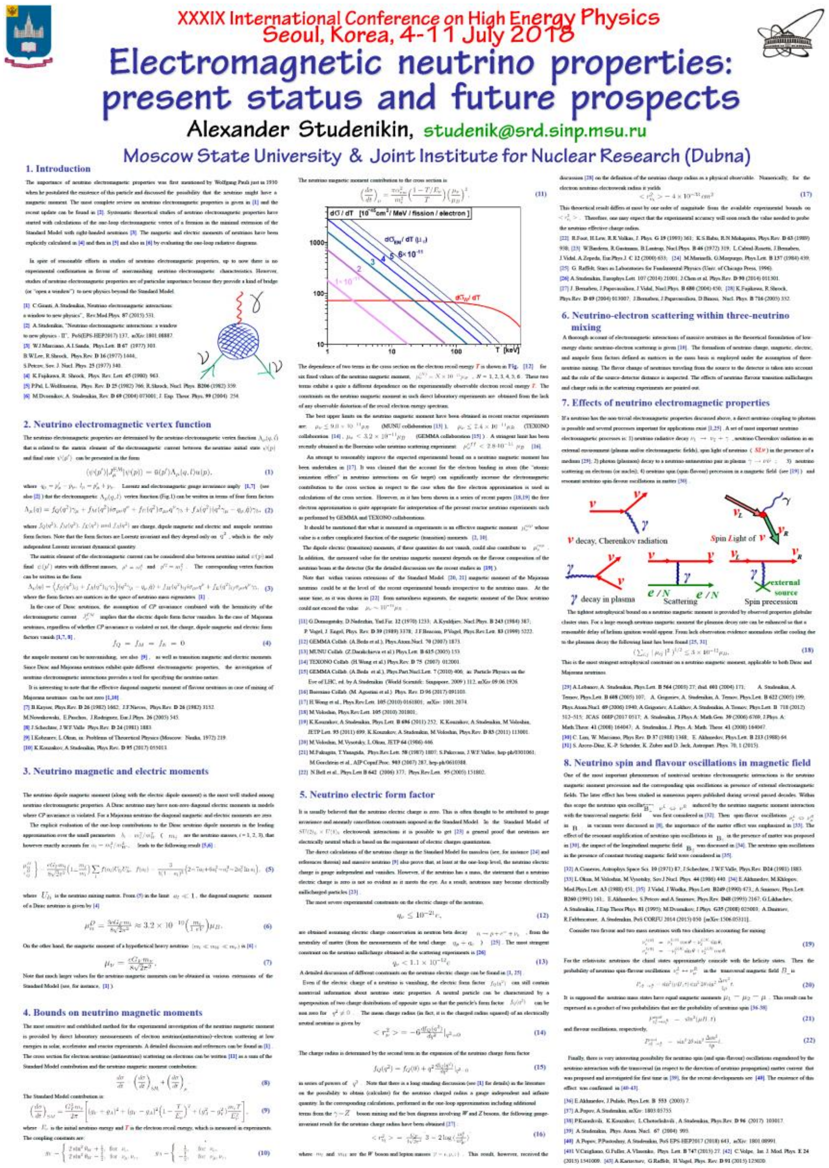
A. Studenikin, T_40 poster # 650 P. Pustoshny, AS, T_13 poster # 697



XXXIX International Conference on High Energy Physics
Seoul, Korea, 4-11 July 2018

Electromagnetic neutrino properties: present status and future prospects

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1. Introduction

2. Neutrino electromagnetic vertex function

3. Neutrino magnetic and electric moments

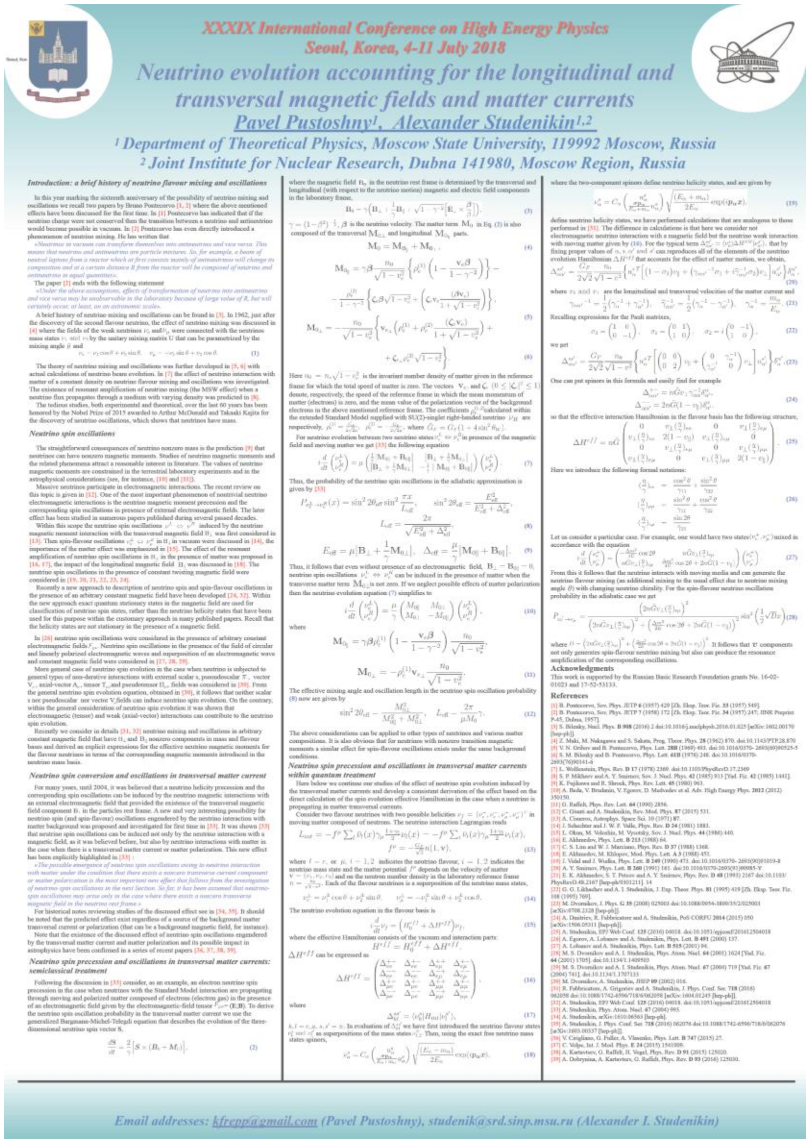
4. Bounds on neutrino magnetic moments

5. Neutrino electric form factor

6. Neutrino-electron scattering within three-neutrino mixing

7. Effects of neutrino electromagnetic properties

8. Neutrino spin and flavour oscillations in magnetic field



XXXIX International Conference on High Energy Physics
Seoul, Korea, 4-11 July 2018

Neutrino evolution accounting for the longitudinal and transversal magnetic fields and matter currents

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Introduction: a brief history of neutrino flavour mixing and oscillations

Neutrino spin oscillations

Neutrino spin conversion and oscillations in transversal matter current

Neutrino spin precession and oscillations in transversal matter currents: semiclassical treatment

Neutrino spin precession and oscillations in transversal matter currents within quantum treatment

Acknowledgements

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A. Popov, AS, T_16 poster # 754

K. Kouzakov, AS, T_11 poster # 686

XXXIX International Conference on High Energy Physics Seoul, Korea, 4-11 July 2018

Oscillations and exact eigenstates of neutrinos in a magnetic field

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Introduction

Massive neutrinos have nontrivial electromagnetic properties (see [2] for a review, the update can be found in [3]). And for many years since [4], it is known that at least the magnetic moment is not zero ($\mu_i \neq 0$ are magnetic moments of the mass states of neutrino). The best terrestrial upper bounds on the level of $\mu_\nu < 2.9 \div 2.8 \times 10^{-11}\mu_B$ on neutrino magnetic moments is obtained by the GEMMA reactor neutrino experiment [5] and recently by the Borexino collaboration [6] from solar neutrino fluxes. An order of magnitude more strict astrophysical bound on the neutrino magnetic moment is provided by the observed properties of globular cluster stars [7, 8, 9].

The neutrino magnetic moment precession in the transversal magnetic field $\mathbf{B}_\perp$ was first considered in [10], then spin-flavor precession in vacuum was discussed in [11], the importance of the matter effect was emphasized in [12]. The effect of resonant amplification of neutrino spin oscillations in $\mathbf{B}_\perp$ in the presence of matter was proposed in [13, 14], the magnetic field critical strength the presence of which makes spin oscillations significant was introduced [15], the impact of the longitudinal magnetic field $\mathbf{B}_\parallel$ was discussed in [16] and just recently in [17]. In a series of papers [18, 19, 20, 21] the solution of the solar neutrino problem was discussed on the basis of neutrino oscillations with subdominant effect from the neutrino transition magnetic moments conversion in the solar magnetic field (the spin-flavour precession).

Following to the general idea first implemented in [22, 23], we further develop a new approach to description of the relativistic neutrino flavour $\nu_e^L \leftrightarrow \nu_\mu^L$, spin $\nu_e^L \leftrightarrow \nu_e^R$ and spin-flavour $\nu_e^L \leftrightarrow \nu_\mu^R$ oscillations in the presence of an arbitrary constant magnetic field. Our approach is based on the use of the exact stationary states in the magnetic field for classification of neutrino spin states, contrary to the customary approach when the neutrino helicity states are used for this purpose.

Massive neutrino in a magnetic field

Consider two flavour neutrinos with two chiralities accounting for mixing

$$\nu_e^{L(R)} = \nu_1^{L(R)}\cos\theta + \nu_2^{L(R)}\sin\theta, \nu_\mu^{L(R)} = -\nu_1^{L(R)}\sin\theta + \nu_2^{L(R)}\cos\theta,$$

where $\nu_i^{L(R)}$ are the chiral neutrino mass states, $i = 1,2$. For the relativistic neutrinos the chiral states approximately coincide with the helicity states $\nu_i^{L(R)} \approx \nu_i^{h^-(h^+)}$. Note that the helicity mass states $\nu_i^{h^-(h^+)}$ are not stationary states in the presence of a magnetic field. In our further evaluations we shall expand $\nu_i^{h^-(h^+)}$ over the neutrino stationary states $\nu_i^{-(+)}$ in the presence of a magnetic field.

The wave function ν_i^s ($s = \pm1$) of a massive neutrino that propagates along $\mathbf{n}_z$ direction in the presence of a constant and homogeneous arbitrary orientated magnetic field can be found as the solution of the Dirac equation

$$(\gamma p - m_i - \mu_i \Sigma \mathbf{B})\nu_i^s(p) = 0, \tag{1}$$

where μ_i is the neutrino magnetic moment and the magnetic field is given by $\mathbf{B} = (B_\perp, 0, B_\parallel)$. In the discussed two-neutrino case the possibility for nonzero neutrino transition moment μ_{ij} ($i \neq j$) is not considered and two equations for two neutrinos states ν_i^s are decoupled. The equation (1) can be re-written in the equivalent form

$$\hat{H}_i \nu_i^s = E \nu_i^s, \tag{2}$$

where the Hamiltonian is

$$\hat{H}_i = m_i\gamma_0 + \gamma_0\gamma p + \mu_i\gamma_0\Sigma \boldsymbol{B}. \tag{3}$$

The spin operator that commutes with the Hamiltonian (3) can be chosen in the form [24]

$$\hat{S}_i = \frac{m_i}{\sqrt{m_i^2\boldsymbol{B}^2 + \boldsymbol{p}^2B_\perp^2}}\left[\Sigma\boldsymbol{B} - \frac{i}{m_i}\gamma_0\gamma_5[\Sigma \times \boldsymbol{p}]\boldsymbol{B}\right]. \tag{4}$$

For the neutrino energy spectrum one obtains

$$E_i^s = \sqrt{m_i^2 + p^2 + \mu_i^2\mathbf{B}^2 + 2\mu_i s\sqrt{m_i^2\mathbf{B}^2 + p^2B_\perp^2}}, \tag{5}$$

where $s = \pm1$ correspond to two different eigenvalues of the Hamiltonian (3) and $p = |\boldsymbol{p}|$. Hence, we specify the neutrino spin states as the stationary states for the Hamiltonian in the presence of the magnetic field, contrary to the customary approach to the description of neutrino oscillations when the helicity states are used.

The spin operator $\hat{S}_i$ commutes with the Hamiltonian $\hat{H}_i$, and for the neutrino stationary states we have

$$\hat{S}_i\left|\nu_i^s\right\rangle = s\left|\nu_i^s\right\rangle, s = \pm1, \tag{6}$$

and

$$\langle \nu_i^s | \nu_k^{s'} \rangle = \delta_{ik}\delta_{ss'}. \tag{7}$$

Following this line, the corresponding projector operators can be introduced

$$\hat{P}_i^{\pm} = \frac{1 \pm \hat{S}_i}{2}. \tag{8}$$

It is clear that projectors act on the stationary states as follows

$$\langle \nu_k^{s'} | \hat{P}_i^s | \nu_i^s \rangle = \delta_{ik}\delta_{ss'}. \tag{9}$$

Now in order to solve the problem of the neutrino flavour $\nu_e^L \leftrightarrow \nu_\mu^L$, spin $\nu_e^L \leftrightarrow \nu_e^R$ and spin-flavour $\nu_e^L \leftrightarrow \nu_\mu^R$ oscillations in the magnetic field we expand the neutrino chiral states over the neutrino stationary states

$$\nu_i^L(t) = c_i^+\nu_i^+(t) + c_i^-\nu_i^-(t), \tag{10}$$

$$\nu_i^R(t) = d_i^+\nu_i^+(t) + d_i^-\nu_i^-(t), \tag{11}$$

where $c_i^\pm$ and $d_i^\pm$ are independent on time.

The quadratic combinations of the coefficients $c_i^{+(-)}$ and $d_i^{+(-)}$ are given by matrix elements of the projector operators (8)

$$|c_i^\pm|^2 = \langle \nu_i^L | \hat{P}_i^\pm | \nu_i^L \rangle, \tag{12}$$

$$|d_i^\pm|^2 = \langle \nu_i^R | \hat{P}_i^\pm | \nu_i^R \rangle, \tag{13}$$

$$(d_i^\pm)^* c_i^\pm = \langle \nu_i^R | P_i^\pm | \nu_i^L \rangle. \tag{14}$$

Since $|c_i^\pm|^2$, $|d_i^\pm|^2$ and $(d_i^\pm)^*c_i^\pm$ are time independent, they can be determined from the initial conditions. Now let's take into account the fact that only chiral states can participate in weak interaction and, consequently, in processes of neutrino creation and detection. It means, that the spinor structure of the neutrino initial and final states is determined by

$$\nu^L = \frac{1}{\sqrt{2}L^{\frac{3}{2}}}\begin{pmatrix}0\\-1\\0\\1\end{pmatrix}, \quad \nu^R = \frac{1}{\sqrt{2}L^{\frac{3}{2}}}\begin{pmatrix}1\\0\\1\\0\end{pmatrix}, \tag{15}$$

where L is the normalization length. Thus, for the quadratic combinations of the coefficients we get

$$|c_i^\pm|^2 = \langle \nu^L | \hat{P}_i^\pm | \nu^L \rangle = \frac{1}{2}\left(1 \pm \frac{m_iB_\parallel}{\sqrt{m_i^2B^2 + p^2B_\perp^2}}\right), \tag{16}$$

$$|d_i^\pm|^2 = \langle \nu^R | \hat{P}_i^\pm | \nu^R \rangle = \frac{1}{2}\left(1 \mp \frac{m_iB_\parallel}{\sqrt{m_i^2B^2 + p^2B_\perp^2}}\right), \tag{17}$$

$$(d_i^+)^*c_i^+ = \langle \nu^R | P_i^+ | \nu^L \rangle = -\frac{1}{2}\frac{p(B_1 - iB_2)}{\sqrt{m_i^2B^2 + p^2B_\perp^2}}, \tag{18}$$

$$(d_i^-)^*c_i^- = \langle \nu^R | P_i^- | \nu^L \rangle = \frac{1}{2}\frac{p(B_1 - iB_2)}{\sqrt{m_i^2B^2 + p^2B_\perp^2}}. \tag{19}$$

In the case $B_\perp = 0$ the helicity states are stationary and $(d_i^+)^*c_i^+ = (d_i^-)^*c_i^- = |c_i^-|^2 = |d_i^+|^2 = 0$, $|c_i^+|^2 = |d_i^-|^2 = 1$.

Using eqs. (10), (11) and accounting for the fact that stationary states' propagation law has the form $\nu_i^s(t) = e^{-iE_i^st}\nu_i^s(0)$, we get that the evolution in time (space) of the relativistic neutrino flavour state ν_e^L is given by

$$\nu_e^L(t) = \left(c_1^+e^{-iE_1^+t}\nu_1^+ + c_1^-e^{-iE_1^-t}\nu_1^-\right)\cos\theta + \left(c_2^+e^{-iE_2^+t}\nu_2^+ + c_2^-e^{-iE_2^-t}\nu_2^-\right)\sin\theta, \tag{20}$$

where $\nu_i^s \equiv \nu_i^s(0)$. In exactly the same way we can write out the decomposition of the wave function of a muon neutrino. The probability of the flavour neutrino oscillations $\nu_e^L \leftrightarrow \nu_\mu^L$ is just

$$P_{\nu_e^L \to \nu_\mu^L}(t) = \left|\langle \nu_\mu^L | \nu_e^L(t) \rangle\right|^2.$$

The probability of oscillations $\nu_e^L \leftrightarrow \nu_\mu^L$ is simplified if one accounts for the relativistic neutrino energies ($p \gg m$) and also for realistic values of the neutrino magnetic moments and strengths of magnetic fields ($p \gg \mu B$). In this case we have

$$E_i^s \approx p + \frac{m_i^2}{2p} + \frac{\mu_i^2B^2}{2p} + \mu_i sB_\perp. \tag{21}$$

It is reasonably to suppose that $\mu B << m$, then the contribution $\frac{\mu_i^2B^2}{2p}$ can be neglected in (21). In the considered case we also have

$$|c_i^s|^2|c_k^{s'}|^2 \approx \frac{1}{4}. \tag{22}$$

Finally, for the probability of flavour oscillations $\nu_e^L \leftrightarrow \nu_\mu^L$ we get

$$P_{\nu_e^L \to \nu_\mu^L}(t) = \sin^2 2\theta\Big\{\cos(\mu_1B_\perp t)\cos(\mu_2B_\perp t)\sin^2\frac{\Delta m^2}{4p}t + \sin^2(\mu_+B_\perp t)\sin^2(\mu_-B_\perp t)\Big\}, \tag{23}$$

where $\mu_\pm = \frac{1}{2}(\mu_1 \pm \mu_2)$.

From the obtained expression (23) a new phenomenon in the neutrino flavour oscillation in a magnetic field can be seen. It follows that the neutrino flavour oscillations in general can be modified by the neutrino magnetic moment interactions with the transversal magnetic field $B_\perp$. In the case of zeroth magnetic moment and/or vanishing magnetic field eq.(23) reduces to the well known probability of the flavour neutrino oscillations in vacuum.

In quite similar evaluations we also obtain probabilities of neutrino spin $\nu_e^L \leftrightarrow \nu_e^R$ and spin-flavour $\nu_e^L \leftrightarrow \nu_\mu^R$ oscillations. In particular, for of neutrino spin $\nu_e^L \leftrightarrow \nu_e^R$ oscillations we get

$$P_{\nu_e^L \to \nu_e^R} = \Big\{\sin(\mu_+B_\perp t)\cos(\mu_-B_\perp t) + \cos 2\theta\sin(\mu_-B_\perp t)\cos(\mu_+B_\perp t)\Big\}^2 - \sin^2 2\theta\sin(\mu_1B_\perp t)\sin(\mu_2B_\perp t)\sin^2\frac{\Delta m^2}{4p}t. \tag{24}$$

For the probability of the neutrino spin-flavour oscillations $\nu_e^L \leftrightarrow \nu_\mu^R$ we get

$$P_{\nu_e^L \to \nu_\mu^R}(t) = \sin^2 2\theta\Big\{\sin^2\mu_-B_\perp t\cos^2(\mu_+B_\perp t) + \sin(\mu_1B_\perp t)\sin(\mu_2B_\perp t)\sin^2\frac{\Delta m^2}{4p}t\Big\}. \tag{25}$$

For completeness, we also calculate within our approach the neutrino survival probability $\nu_e^L \leftrightarrow \nu_e^L$ and get

$$P_{\nu_e^L \to \nu_e^L}(t) = \Big\{\cos(\mu_+B_\perp t)\cos(\mu_-B_\perp t) - \cos 2\theta\sin(\mu_+B_\perp t)\sin(\mu_-B_\perp t)\Big\}^2 - \sin^2 2\theta\cos(\mu_1B_\perp t)\cos(\mu_2B_\perp t)\sin^2\frac{\Delta m^2}{4p}t. \tag{26}$$

It is just straightforward that the sum of the obtained four probabilities (23), (24), (25) and (26) is

$$P_{\nu_e^L \to \nu_\mu^L} + P_{\nu_e^L \to \nu_e^R} + P_{\nu_e^L \to \nu_\mu^R} + P_{\nu_e^L \to \nu_e^L} = 1. \tag{27}$$

Figure 1: The probability of the neutrino flavour oscillations $\nu_e^L \to \nu_\mu^L$ in the transversal magnetic field $B_\perp = 10^8\ G$ for the neutrino energy $p = 1\ MeV$, $\Delta m^2 = 7 \times 10^{-5}\ eV^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-12}\mu_B$.

Figure 2: The probability of the neutrino spin oscillations $\nu_e^L \to \nu_e^R$ in the transversal magnetic field $B_\perp = 10^8\ G$ for the neutrino energy $p = 1\ MeV$, $\Delta m^2 = 7 \times 10^{-5}\ eV^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-12}\mu_B$.

Figure 3: The probability of the neutrino spin flavour oscillations $\nu_e^L \to \nu_\mu^R$ in the transversal magnetic field $B_\perp = 10^8\ G$ for the neutrino energy $p = 1\ MeV$, $\Delta m^2 = 7 \times 10^{-5}\ eV^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-12}\mu_B$.

Finally, the obtained closed expressions (23), (24), (25) and (26) show that the neutrino oscillation $P_{\nu_e^L \to \nu_\mu^L}(t)$, $P_{\nu_e^L \to \nu_e^R}(t)$, $P_{\nu_e^L \to \nu_\mu^R}(t)$ and also survival $P_{\nu_e^L \to \nu_e^L}(t)$ probabilities exhibits quiet complicated interplay of the harmonic functions that are dependent on six different frequencies. On this basis we predict modifications of the neutrino oscillation patterns that might provide new important phenomenological consequences in case of neutrinos propagation in extreme astrophysical environments where magnetic fields are present.

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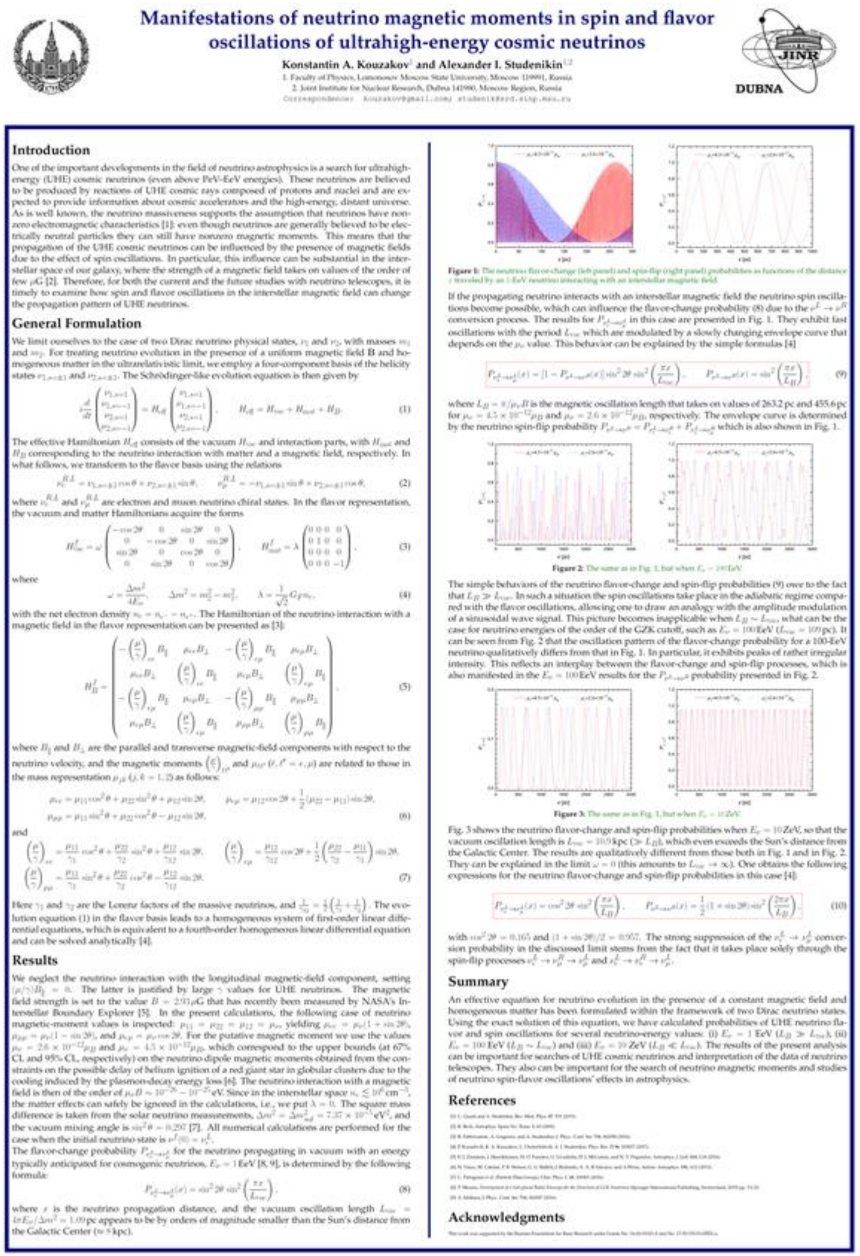

Manifestations of neutrino magnetic moments in spin and flavor oscillations of ultrahigh-energy cosmic neutrinos

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Introduction

One of the important developments in the field of neutrino astrophysics is a search for ultrahigh-energy (UHE) cosmic neutrinos (even above PeV-EeV energies). These neutrinos are believed to be produced by reactions of UHE cosmic rays composed of protons and nuclei and are expected to provide information about cosmic accelerators and the high-energy, distant universe. As is well known, the neutrino massiveness supports the assumption that neutrinos have nonzero electromagnetic characteristics [1]: even though neutrinos are generally believed to be electrically neutral particles they can still have nonzero magnetic moments. This means that the propagation of the UHE cosmic neutrinos can be influenced by the presence of magnetic fields due to the effect of spin oscillations. In particular, this influence can be substantial in the interstellar space of our galaxy, where the strength of a magnetic field takes on values of the order of few μG [2]. Therefore, for both the current and the future studies with neutrino telescopes, it is timely to examine how spin and flavor oscillations in the interstellar magnetic field can change the propagation pattern of UHE neutrinos.

General Formulation

We limit ourselves to the case of two Dirac neutrino physical states, ν_1 and ν_2, with masses m_1 and m_2. For treating neutrino evolution in the presence of a uniform magnetic field **B** and homogeneous matter in the ultrarelativistic limit, we employ a four-component basis of the helicity states $\nu_{1,s=\pm1}$ and $\nu_{2,s=\pm1}$. The Schrödinger-like evolution equation is then given by

$$i\frac{d}{dt}\begin{pmatrix}\nu_{1,s=1}\\\nu_{1,s=-1}\\\nu_{2,s=1}\\\nu_{2,s=-1}\end{pmatrix} = H_{\rm eff}\begin{pmatrix}\nu_{1,s=1}\\\nu_{1,s=-1}\\\nu_{2,s=1}\\\nu_{2,s=-1}\end{pmatrix}, \qquad H_{\rm eff} = H_{\rm vac} + H_{\rm mat} + H_{B}. \tag{1}$$

The effective Hamiltonian $H_{\rm eff}$ consists of the vacuum $H_{\rm vac}$ and interaction parts, with $H_{\rm mat}$ and H_B corresponding to the neutrino interaction with matter and a magnetic field, respectively. In what follows, we transform to the flavor basis using the relations

$$\nu_e^{R,L} = \nu_{1,s=\pm1}\cos\theta + \nu_{2,s=\pm1}\sin\theta, \qquad \nu_\mu^{R,L} = -\nu_{1,s=\pm1}\sin\theta + \nu_{2,s=\pm1}\cos\theta, \tag{2}$$

where $\nu_e^{R,L}$ and $\nu_\mu^{R,L}$ are electron and muon neutrino chiral states. In the flavor representation, the vacuum and matter Hamiltonians acquire the forms

$$H_{\rm vac}^f = \omega\begin{pmatrix}-\cos2\theta & 0 & \sin2\theta & 0\\0 & -\cos2\theta & 0 & \sin2\theta\\\sin2\theta & 0 & \cos2\theta & 0\\0 & \sin2\theta & 0 & \cos2\theta\end{pmatrix}, \qquad H_{\rm mat}^f = \lambda\begin{pmatrix}0&0&0&0\\0&1&0&0\\0&0&0&0\\0&0&0&-1\end{pmatrix}, \tag{3}$$

where

$$\omega = \frac{\Delta m^2}{4E_\nu}, \qquad \Delta m^2 = m_2^2 - m_1^2, \qquad \lambda = \frac{1}{\sqrt{2}}G_F n_e, \tag{4}$$

with the net electron density $n_e = n_{e^-} - n_{e^+}$. The Hamiltonian of the neutrino interaction with a magnetic field in the flavor representation can be presented as [3]:

$$H_B^f = \begin{pmatrix}-\left(\frac{\mu}{\gamma}\right)_{ee}B_\parallel & \mu_{ee}B_\perp & -\left(\frac{\mu}{\gamma}\right)_{e\mu}B_\parallel & \mu_{e\mu}B_\perp\\ \mu_{ee}B_\perp & \left(\frac{\mu}{\gamma}\right)_{ee}B_\parallel & \mu_{e\mu}B_\perp & \left(\frac{\mu}{\gamma}\right)_{e\mu}B_\parallel\\ -\left(\frac{\mu}{\gamma}\right)_{e\mu}B_\parallel & \mu_{e\mu}B_\perp & -\left(\frac{\mu}{\gamma}\right)_{\mu\mu}B_\parallel & \mu_{\mu\mu}B_\perp\\ \mu_{e\mu}B_\perp & \left(\frac{\mu}{\gamma}\right)_{e\mu}B_\parallel & \mu_{\mu\mu}B_\perp & \left(\frac{\mu}{\gamma}\right)_{\mu\mu}B_\parallel\end{pmatrix}, \tag{5}$$

where $B_\parallel$ and $B_\perp$ are the parallel and transverse magnetic-field components with respect to the neutrino velocity, and the magnetic moments $\left(\frac{\mu}{\gamma}\right)_{\ell\ell'}$ and $\mu_{\ell\ell'}$ ($\ell, \ell' = e, \mu$) are related to those in the mass representation μ_{jk} ($j, k = 1, 2$) as follows:

$$\mu_{ee} = \mu_{11}\cos^2\theta + \mu_{22}\sin^2\theta + \mu_{12}\sin2\theta, \qquad \mu_{e\mu} = \mu_{12}\cos2\theta + \frac{1}{2}(\mu_{22} - \mu_{11})\sin2\theta,$$
$$\mu_{\mu\mu} = \mu_{11}\sin^2\theta + \mu_{22}\cos^2\theta - \mu_{12}\sin2\theta, \tag{6}$$

and

$$\left(\frac{\mu}{\gamma}\right)_{ee} = \frac{\mu_{11}}{\gamma_1}\cos^2\theta + \frac{\mu_{22}}{\gamma_2}\sin^2\theta + \frac{\mu_{12}}{\gamma_{12}}\sin2\theta, \qquad \left(\frac{\mu}{\gamma}\right)_{e\mu} = \frac{\mu_{12}}{\gamma_{12}}\cos2\theta + \frac{1}{2}\left(\frac{\mu_{22}}{\gamma_2} - \frac{\mu_{11}}{\gamma_1}\right)\sin2\theta,$$
$$\left(\frac{\mu}{\gamma}\right)_{\mu\mu} = \frac{\mu_{11}}{\gamma_1}\sin^2\theta + \frac{\mu_{22}}{\gamma_2}\cos^2\theta - \frac{\mu_{12}}{\gamma_{12}}\sin2\theta. \tag{7}$$

Here γ_1 and γ_2 are the Lorentz factors of the massive neutrinos, and $\frac{1}{\gamma_{12}} = \frac{1}{2}\left(\frac{1}{\gamma_1} + \frac{1}{\gamma_2}\right)$. The evolution equation (1) in the flavor basis leads to a homogeneous system of first-order linear differential equations, which is equivalent to a fourth-order homogeneous linear differential equation and can be solved analytically [4].

Results

We neglect the neutrino interaction with the longitudinal magnetic-field component, setting $(\mu/\gamma)B_\parallel = 0$. The latter is justified by large γ values for UHE neutrinos. The magnetic field strength is set to the value $B = 2.93\,\mu$G that has recently been measured by NASA's Interstellar Boundary Explorer [5]. In the present calculations, the following case of neutrino magnetic-moment values is inspected: $\mu_{11} = \mu_{22} = \mu_{12} = \mu_\nu$, yielding $\mu_{ee} = \mu_\nu(1 + \sin2\theta)$, $\mu_{\mu\mu} = \mu_\nu(1 - \sin2\theta)$, and $\mu_{e\mu} = \mu_\nu\cos2\theta$. For the putative magnetic moment we use the values $\mu_\nu = 2.6 \times 10^{-12}\mu_B$ and $\mu_\nu = 4.5 \times 10^{-12}\mu_B$, which correspond to the upper bounds (at 67% CL and 95% CL, respectively) on the neutrino dipole magnetic moments obtained from the constraints on the possible delay of helium ignition of a red giant star in globular clusters due to the cooling induced by the plasmon-decay energy loss [6]. The neutrino interaction with a magnetic field is then of the order of $\mu_\nu B \sim 10^{-26} - 10^{-25}$ eV. Since in the interstellar space $n_e \lesssim 10^6\ \text{cm}^{-3}$, the matter effects can safely be ignored in the calculations, i.e., we put $\lambda = 0$. The square mass difference is taken from the solar neutrino measurements, $\Delta m^2 = \Delta m^2_{\rm sol} = 7.37 \times 10^{-5}\ \text{eV}^2$, and the vacuum mixing angle is $\sin^2\theta = 0.297$ [7]. All numerical calculations are performed for the case when the initial neutrino state is $\nu^f(0) = \nu_e^L$.

The flavor-change probability $P_{\nu_e^L \to \nu_\mu^L}$ for the neutrino propagating in vacuum with an energy typically anticipated for cosmogenic neutrinos, $E_\nu = 1$ EeV [8, 9], is determined by the following formula:

$$P_{\nu_e^L \to \nu_\mu^L}(x) = \sin^2 2\theta\sin^2\left(\frac{\pi x}{L_{\rm vac}}\right), \tag{8}$$

where x is the neutrino propagation distance, and the vacuum oscillation length $L_{\rm vac} = 4\pi E_\nu/\Delta m^2 = 1.09$ pc appears to be by orders of magnitude smaller than the Sun's distance from the Galactic Center (≈ 8 kpc).

Figure 1: The neutrino flavor-change (left panel) and spin-flip (right panel) probabilities as functions of the distance x traveled by an 1-EeV neutrino interacting with an interstellar magnetic field.

If the propagating neutrino interacts with an interstellar magnetic field the neutrino spin oscillations become possible, which can influence the flavor-change probability (8) due to the $\nu^L \to \nu^R$ conversion process. The results for $P_{\nu_e^L \to \nu_\mu^L}$ in this case are presented in Fig. 1. They exhibit fast oscillations with the period $L_{\rm vac}$ which are modulated by a slowly changing envelope curve that depends on the μ_ν value. This behavior can be explained by the simple formulas [4]

$$\boxed{P_{\nu_e^L \to \nu_\mu^L}(x) = [1 - P_{\nu^L \to \nu^R}(x)]\sin^2 2\theta\sin^2\left(\frac{\pi x}{L_{\rm vac}}\right), \qquad P_{\nu^L \to \nu^R}(x) = \sin^2\left(\frac{\pi x}{L_B}\right)} \tag{9}$$

where $L_B = \pi/\mu_\nu B$ is the magnetic oscillation length that takes on values of 263.2 pc and 455.6 pc for $\mu_\nu = 4.5 \times 10^{-12}\mu_B$ and $\mu_\nu = 2.6 \times 10^{-12}\mu_B$, respectively. The envelope curve is determined by the neutrino spin-flip probability $P_{\nu^L \to \nu^R} = P_{\nu_e^L \to \nu_e^R} + P_{\nu_e^L \to \nu_\mu^R}$ which is also shown in Fig. 1.

Figure 2: The same as in Fig. 1, but when $E_\nu = 100$ EeV

The simple behaviors of the neutrino flavor-change and spin-flip probabilities (9) owe to the fact that $L_B \gg L_{\rm vac}$. In such a situation the spin oscillations take place in the adiabatic regime compared with the flavor oscillations, allowing one to draw an analogy with the amplitude modulation of a sinusoidal wave signal. This picture becomes inapplicable when $L_B \sim L_{\rm vac}$, what can be the case for neutrino energies of the order of the GZK cutoff, such as $E_\nu = 100$ EeV ($L_{\rm vac} = 109$ pc). It can be seen from Fig. 2 that the oscillation pattern of the flavor-change probability for a 100-EeV neutrino qualitatively differs from that in Fig. 1. In particular, it exhibits peaks of rather irregular intensity. This reflects an interplay between the flavor-change and spin-flip processes, which is also manifested in the $E_\nu = 100$ EeV results for the $P_{\nu^L \to \nu^R}$ probability presented in Fig. 2.

Figure 3: The same as in Fig. 1, but when $E_\nu = 10$ ZeV

Fig. 3 shows the neutrino flavor-change and spin-flip probabilities when $E_\nu = 10$ ZeV, so that the vacuum oscillation length is $L_{\rm vac} = 10.9$ kpc ($\gg L_B$), which even exceeds the Sun's distance from the Galactic Center. The results are qualitatively different from those both in Fig. 1 and in Fig. 2. They can be explained in the limit $\omega = 0$ (this amounts to $L_{\rm vac} \to \infty$). One obtains the following expressions for the neutrino flavor-change and spin-flip probabilities in this case [4]:

$$\boxed{P_{\nu_e^L \to \nu_\mu^L}(x) = \cos^2 2\theta\sin^2\left(\frac{\pi x}{L_B}\right), \qquad P_{\nu^L \to \nu^R}(x) = \frac{1}{2}(1 + \sin2\theta)\sin^2\left(\frac{2\pi x}{L_B}\right)} \tag{10}$$

with $\cos^2 2\theta = 0.165$ and $(1 + \sin2\theta)/2 = 0.957$. The strong suppression of the $\nu_e^L \to \nu_\mu^L$ conversion probability in the discussed limit stems from the fact that it takes place solely through the spin-flip processes $\nu_e^L \to \nu_\mu^R \to \nu_\mu^L$ and $\nu_e^L \to \nu_e^R \to \nu_\mu^L$.

Summary

An effective equation for neutrino evolution in the presence of a constant magnetic field and homogeneous matter has been formulated within the framework of two Dirac neutrino states. Using the exact solution of this equation, we have calculated probabilities of UHE neutrino flavor and spin oscillations for several neutrino-energy values: (i) $E_\nu = 1$ EeV ($L_B \gg L_{\rm vac}$), (ii) $E_\nu = 100$ EeV ($L_B \sim L_{\rm vac}$) and (iii) $E_\nu = 10$ ZeV ($L_B \ll L_{\rm vac}$). The results of the present analysis can be important for searches of UHE cosmic neutrinos and interpretation of the data of neutrino telescopes. They also can be important for the search of neutrino magnetic moments and studies of neutrino spin-flavor oscillations' effects in astrophysics.

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Acknowledgments

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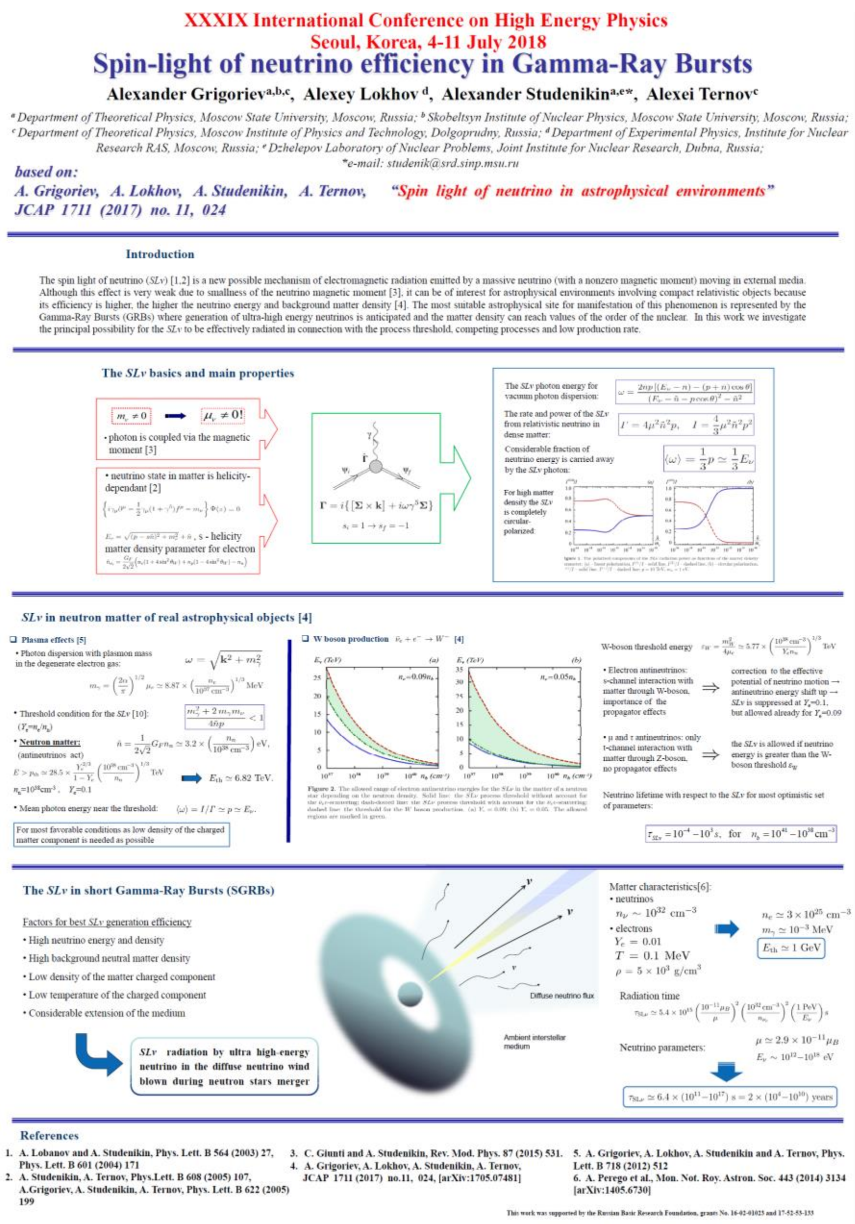
AS, A.Ternov T_17 # 775

K.Stankevich, AS
T_9 poster # 662



XXXIX International Conference on High Energy Physics
Seoul, Korea, 4-11 July 2018

Spin-light of neutrino efficiency in Gamma-Ray Bursts

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based on:
A. Grigoriev, A. Lokhov, A. Studenikin, A. Ternov, "Spin light of neutrino in astrophysical environments"
JCAP 1711 (2017) no. 11, 024

Introduction

The spin light of neutrino ($SL\nu$) [1,2] is a new possible mechanism of electromagnetic radiation emitted by a massive neutrino (with a nonzero magnetic moment) moving in external media. Although this effect is very weak due to smallness of the neutrino magnetic moment [3], it can be of interest for astrophysical environments involving compact relativistic objects because its efficiency is higher, the higher the neutrino energy and background matter density [4]. The most suitable astrophysical site for manifestation of this phenomenon is represented by the Gamma-Ray Bursts (GRBs) where generation of ultra-high energy neutrinos is anticipated and the matter density can reach values of the order of the nuclear. In this work we investigate the principal possibility for the $SL\nu$ to be effectively radiated in connection with the process threshold, competing processes and low production rate.

The $SL\nu$ basics and main properties

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

- photon is coupled via the magnetic moment [3]

- neutrino state in matter is helicity-dependant [2]

$E_\nu = \sqrt{(p - s\tilde{n})^2 + m_\nu^2} + \tilde{n}$, s - helicity

matter density parameter for electron

$$\Gamma = i\{[\mathbf{\Sigma} \times \mathbf{k}] + i\omega\gamma^5\mathbf{\Sigma}\}$$

$$s_i = 1 \rightarrow s_f = -1$$

The $SL\nu$ photon energy for vacuum photon dispersion:
$$\omega = \frac{2\tilde{n}p\,[(E_\nu - \tilde{n}) - (p + \tilde{n})\cos\theta]}{(E_\nu - \tilde{n} - p\cos\theta)^2 - \tilde{n}^2}$$

The rate and power of the $SL\nu$ from relativistic neutrino in dense matter:
$$\Gamma = 4\mu^2\tilde{n}^2 p, \quad I = \frac{4}{3}\mu^2\tilde{n}^2 p^2$$

Considerable fraction of neutrino energy is carried away by the $SL\nu$ photon:
$$\langle\omega\rangle = \frac{1}{3}p \simeq \frac{1}{3}E_\nu$$

For high matter density the $SL\nu$ is completely circular-polarized:

$SL\nu$ in neutron matter of real astrophysical objects [4]

❑ **Plasma effects [5]**

- Photon dispersion with plasmon mass in the degenerate electron gas: $\omega = \sqrt{\mathbf{k}^2 + m_\gamma^2}$
- Threshold condition for the $SL\nu$ [10]: $\boxed{\frac{m_\gamma^2 + 2m_\gamma m_\nu}{4\tilde{n}p} < 1}$ $(Y_e = n_e/n_n)$
- **Neutron matter:** (antineutrinos act) $\tilde{n} = \frac{1}{2\sqrt{2}}G_F n_n \simeq 3.2 \times \left(\frac{n_n}{10^{38}\,\text{cm}^{-3}}\right)\text{eV}$,

$n_n = 10^{38}\,\text{cm}^{-3}$, $Y_e = 0.1$ $\Longrightarrow E_{th} \simeq 6.82$ TeV.

- Mean photon energy near the threshold: $\langle\omega\rangle = I/\Gamma \simeq p \simeq E_\nu$.

For most favorable conditions as low density of the charged matter component is needed as possible

❑ **W boson production** $\bar{\nu}_e + e^- \rightarrow W^-$ **[4]**

W-boson threshold energy

- Electron antineutrinos: s-channel interaction with matter through W-boson, importance of the propagator effects ⇒ correction to the effective potential of neutrino motion → antineutrino energy shift up → $SL\nu$ is suppressed at $Y_e = 0.1$, but allowed already for $Y_e = 0.09$
- μ and τ antineutrinos: only t-channel interaction with matter through Z-boson, no propagator effects ⇒ the $SL\nu$ is allowed if neutrino energy is greater than the W-boson threshold ε_W

Neutrino lifetime with respect to the $SL\nu$ for most optimistic set of parameters:

$$\boxed{\tau_{SL\nu} = 10^{-4} - 10^{3}\,s, \text{ for } n_n = 10^{41} - 10^{38}\,\text{cm}^{-3}}$$

The $SL\nu$ in short Gamma-Ray Bursts (SGRBs)

Factors for best $SL\nu$ generation efficiency

- High neutrino energy and density
- High background neutral matter density
- Low density of the matter charged component
- Low temperature of the charged component
- Considerable extension of the medium

$SL\nu$ radiation by ultra high-energy neutrino in the diffuse neutrino wind blown during neutron stars merger

Diffuse neutrino flux

Ambient interstellar medium

Matter characteristics[6]:
- neutrinos
$n_\nu \sim 10^{32}\ \text{cm}^{-3}$
- electrons
$Y_e = 0.01$
$T = 0.1\ \text{MeV}$
$\rho = 5 \times 10^3\ \text{g/cm}^3$

$\Longrightarrow$ $n_e \simeq 3 \times 10^{25}\ \text{cm}^{-3}$, $m_\gamma \simeq 10^{-3}$ MeV, $\boxed{E_{th} \simeq 1\ \text{GeV}}$

Radiation time

Neutrino parameters: $\mu \simeq 2.9 \times 10^{-11}\mu_B$, $E_\nu \sim 10^{12} - 10^{18}$ eV

$$\boxed{\tau_{SL\nu} \simeq 6.4 \times (10^{11} - 10^{17})\ s = 2 \times (10^4 - 10^{10})\ \text{years}}$$

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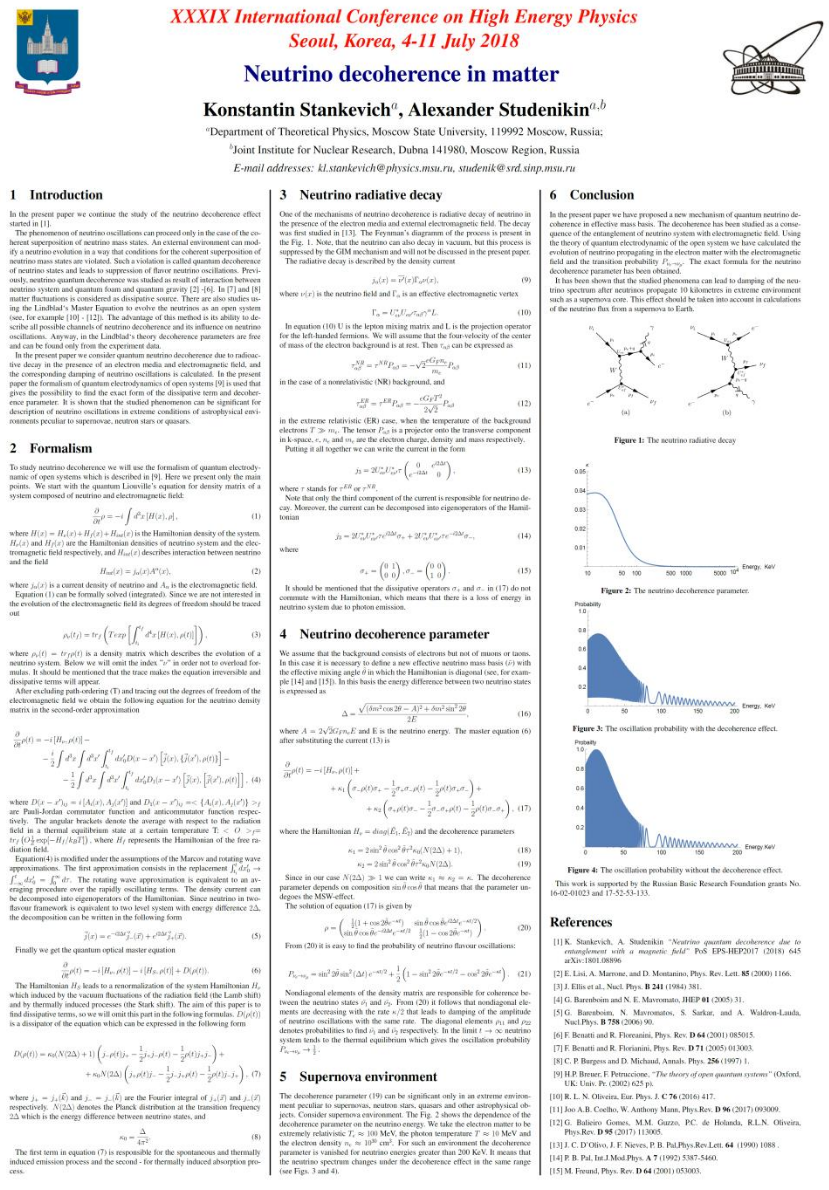

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Seoul, Korea, 4-11 July 2018

Neutrino decoherence in matter

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1 Introduction

In the present paper we continue the study of the neutrino decoherence effect started in [1].

The phenomenon of neutrino oscillations can proceed only in the case of the coherent superposition of neutrino mass states. An external environment can modify a neutrino evolution in a way that conditions for the coherent superposition of neutrino mass states are violated. Such a violation is called quantum decoherence of neutrino states and leads to suppression of flavor neutrino oscillations. Previously, neutrino quantum decoherence was studied as result of interaction between neutrino system and quantum foam and quantum gravity [2] -[6]. In [7] and [8] matter fluctuations is considered as dissipative source. There are also studies using the Lindblad's Master Equation to evolve the neutrinos as an open system (see, for example [10] - [12]). The advantage of this method is its ability to describe all possible channels of neutrino decoherence and its influence on neutrino oscillations. Anyway, in the Lindblad's theory decoherence parameters are free and can be found only from the experiment data.

In the present paper we consider quantum neutrino decoherence due to radioactive decay in the presence of an electron media and electromagnetic field, and the corresponding damping of neutrino oscillations is calculated. In the present paper the formalism of quantum electrodynamics of open systems [9] is used that gives the possibility to find the exact form of the dissipative term and decoherence parameter. It is shown that the studied phenomenon can be significant for description of neutrino oscillations in extreme conditions of astrophysical environments peculiar to supernovae, neutron stars or quasars.

2 Formalism

To study neutrino decoherence we will use the formalism of quantum electrodynamic of open systems which is described in [9]. Here we present only the main points. We start with the quantum Liouville's equation for density matrix of a system composed of neutrino and electromagnetic field:

3 Neutrino radiative decay

One of the mechanisms of neutrino decoherence is radiative decay of neutrino in the presence of the electron media and external electromagnetic field. The decay was first studied in [13]. The Feynman's diagramm of the process is present in the Fig. 1. Note, that the neutrino can also decay in vacuum, but this process is suppressed by the GIM mechanism and will not be discussed in the present paper.

The radiative decay is described by the density current

4 Neutrino decoherence parameter

... tween the neutrino states $\tilde{\nu}_1$ and $\tilde{\nu}_2$. From (20) it follows that nondiagonal elements are decreasing with the rate $\kappa/2$ that leads to damping of the amplitude of neutrino oscillations with the same rate. The diagonal elements ρ_{11} and ρ_{22} denotes probabilities to find $\tilde{\nu}_1$ and $\tilde{\nu}_2$ respectively. In the limit $t \rightarrow \infty$ neutrino system tends to the thermal equilibrium which gives the oscillation probability $P_{\nu_e \rightarrow \nu_e} \rightarrow \frac{1}{2}$.

5 Supernova environment

The decoherence parameter (19) can be significant only in an extreme environment peculiar to supernovas, neutron stars, quasars and other astrophysical objects. Consider supernova environment. The Fig. 2 shows the dependence of the decoherence parameter on the neutrino energy. We take the electron matter to be extremely relativistic $T_e \approx 100$ MeV, the photon temperature $T \approx 10$ MeV and the electron density $n_e \approx 10^{30}$ cm^3. For such an environment the decoherence parameter is vanished for neutrino energies greater than 200 KeV. It means that the neutrino spectrum changes under the decoherence effect in the same range (see Figs. 3 and 4).

6 Conclusion

In the present paper we have proposed a new mechanism of quantum neutrino decoherence in effective mass basis. The decoherence has been studied as a consequence of the entanglement of neutrino system with electromagnetic field. Using the theory of quantum electrodynamic of the open system we have calculated the evolution of neutrino propagating in the electron matter with the electromagnetic field and the transition probability $P_{\nu_e \rightarrow \nu_\mu}$. The exact formula for the neutrino decoherence parameter has been obtained.

It has been shown that the studied phenomena can lead to damping of the neutrino spectrum after neutrinos propagate 10 kilometres in extreme environment such as a supernova core. This effect should be taken into account in calculations of the neutrino flux from a supernova to Earth.

Figure 1: The neutrino radiative decay

Figure 2: The neutrino decoherence parameter.

Figure 3: The oscillation probability with the decoherence effect.

Figure 4: The oscillation probability without the decoherence effect.

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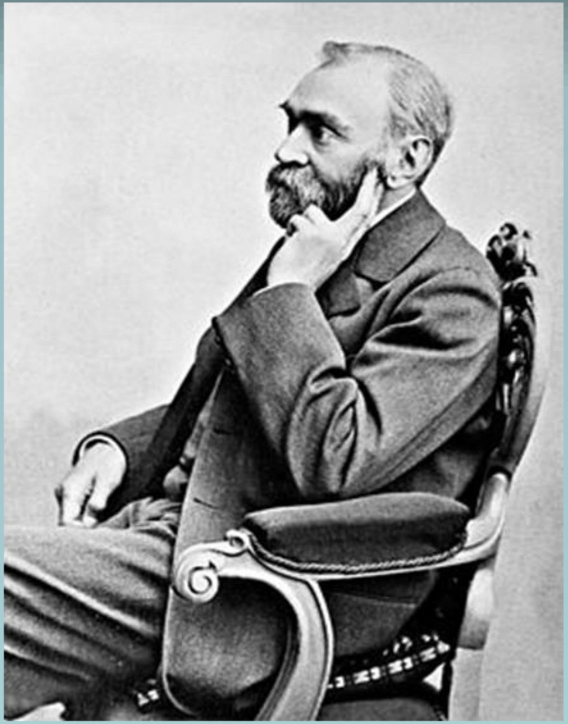
ν electromagnetic properties ?

… in spite of …

- results of terrestrial lab experiments on μ_ν (and ν EM properties in general)
- as well as data from astrophysics and cosmology

are in agreement with "ZERO" ν EM properties

Nobel Prizes



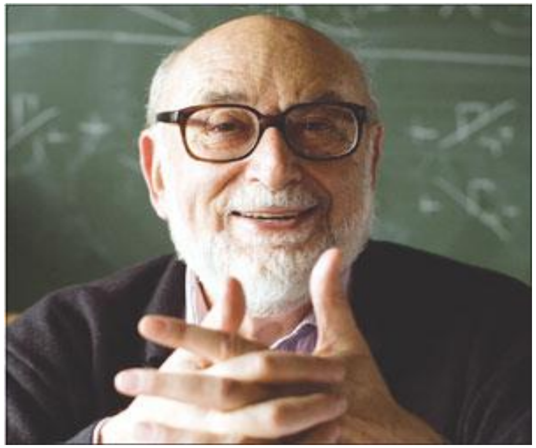
1833 – 1896

2013

&

2015

Robert Brout



François Englert

Peter Higgs

NP 2013

- Observation of Higgs boson confirms the symmetry breaking mechanism by Brout-Englert-Higgs (BEH)
- provides final glorious triumph of Standard Model

… new division in particle physics with special name **BEH Physics**

Arthur McDonald

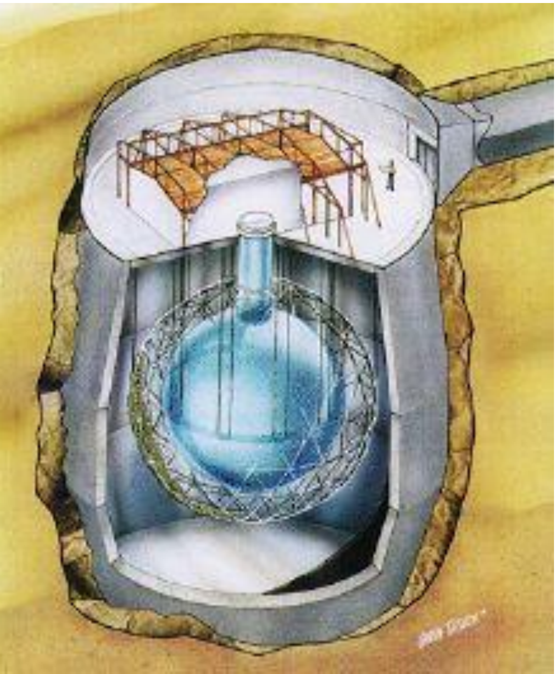
Sudbury Neutrino Observatory

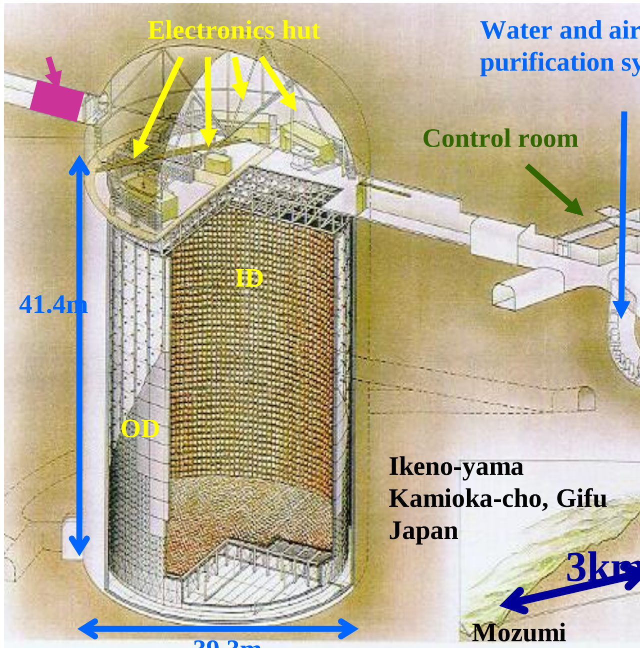
The Nobel Prize in Physics 2015

Takaaki Kajita

Super-Kamiokande Experiment

« for the discovery of neutrino oscillations, which shows that neutrinos have mass »





$m_\nu \neq 0$ … a tool for studying physics Beyond Extended Standard Model…

Theory (Standard Model with ν_R)

$$\mu_\nu = \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu \sim \boxed{3\cdot 10^{-19}} \mu_B \left(\frac{m_\nu}{1\,eV}\right), \quad \mu_B = \frac{e}{2m_e}$$

Lee Shrock, 1977; Fujikawa Shrock, 1980

magnetic moment

$$\boxed{a_e = \frac{\alpha_{QED}}{2\pi} \sim 10^{-3}}$$

… much greater values are desired

for astrophysical or cosmology

visualization of μ_ν

new physics

… hopes for physics BESM …

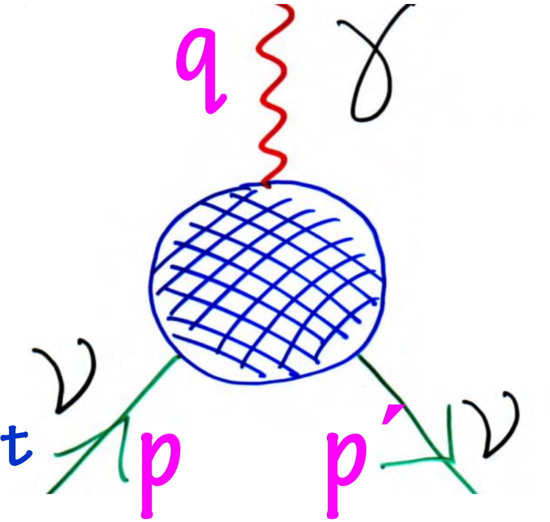
①

ν electromagnetic properties

(flash on theory)

$m_\nu \neq 0$

ν electromagnetic vertex function



$$< \psi(p')|J_\mu^{EM}|\psi(p) >= \bar{u}(p')\Lambda_\mu(q,l)u(p)$$

Matrix element of electromagnetic current is a Lorentz vector

$\Lambda_\mu(q,l)$ should be constructed using ●

matrices $\hat{1}, \quad \gamma_5, \quad \gamma_\mu, \quad \gamma_5\gamma_\mu, \quad \sigma_{\mu\nu},$

tensors $g_{\mu\nu}, \quad \epsilon_{\mu\nu\sigma\gamma}$

vectors q_μ and l_μ

$$\boxed{q_\mu = p'_\mu - p_\mu, \ l_\mu = p'_\mu + p_\mu}$$

● Lorentz covariance (1) and electromagnetic gauge invariance (2) ⟹

Matrix element of electromagnetic current between neutrino states

$$\langle \nu(p')|J_\mu^{EM}|\nu(p)\rangle = \bar{u}(p')\Lambda_\mu(q)u(p),$$

where vertex function generally contains 4 form factors

$$\Lambda_\mu(q) = f_Q(q^2)\gamma_\mu + f_M(q^2)i\sigma_{\mu\nu}q^\nu - f_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + f_A(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5$$

1. electric

dipole

2. magnetic

3. electric

4. anapole

- Hermiticity and discrete symmetries of EM current J_μ^{EM} put constraints on form factors

Dirac ν

1) CP invariance + Hermiticity ⟹ $f_E = 0$,

2) at zero momentum transfer only electric Charge $f_Q(0)$ and magnetic moment $f_M(0)$ contribute to $H_{int} \sim J_\mu^{EM} A^\mu$

3) Hermiticity itself ⟹ three form factors are real: $Im f_Q = Im f_M = Im f_A = 0$

Majorana ν

1) from CPT invariance (regardless CP or ~~CP~~).

$$f_Q = f_M = f_E = 0$$

…as early as 1939, W.Pauli…

- EM properties ⟹ a way to distinguish Dirac and Majorana ν

In general case matrix element of $J_\mu^{\rm EM}$ can be considered between different initial $\psi_i(p)$ and final $\psi_j(p')$ states of different masses

$p^2 = m_i^2,\ \ p'^2 = m_j^2$:

$$\boxed{< \psi_j(p')|J_\mu^{EM}|\psi_i(p) >= \bar{u}_j(p')\Lambda_\mu(q)u_i(p)}$$

… beyond SM…

and

$$\boxed{\begin{aligned}\Lambda_\mu(q) = \Big(f_Q(q^2)_{ij} + f_A(q^2)_{ij}\gamma_5\Big)(q^2\gamma_\mu - q_\mu \not{q}) &+ \\ f_M(q^2)_{ij} i\sigma_{\mu\nu}q^\nu &+ f_E(q^2)_{ij}\sigma_{\mu\nu}q^\nu\gamma_5\end{aligned}}$$

form factors are matrices in ν mass eigenstates space.

Dirac ν

(off-diagonal case $i \neq j$)

Majorana ν

1) Hermiticity itself does not apply restrictions on form factors,

2) CP invariance + Hermiticity

⇓

$f_Q(q^2),\ f_M(q^2),\ f_E(q^2),\ f_A(q^2)$

are relatively real (no relative phases).

1) CP invariance + hermiticity

$$\boxed{\mu_{ij}^M = 2\mu_{ij}^D \ \ and \ \ \epsilon_{ij}^M = 0}$$

or

$$\boxed{\mu_{ij}^M = 0 \ \ and \ \ \epsilon_{ij}^M = 2\epsilon_{ij}^D}$$

… quite different EM properties …

Dipole **magnetic** $\boxed{f_M(q^2)}$ and **electric** $\boxed{f_E(q^2)}$

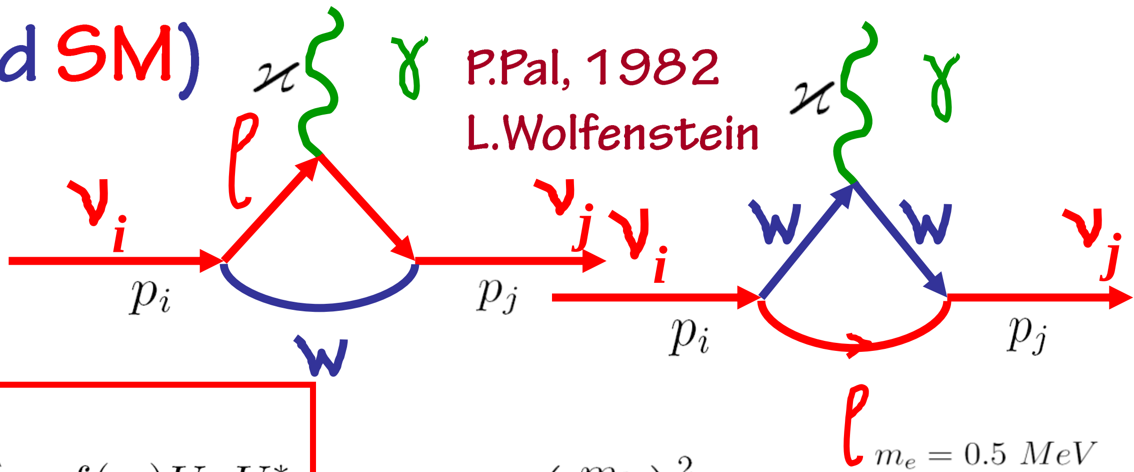
are most well studied and theoretically understood among **form factors**

…because in the limit $\boxed{q^2 \to 0}$ they have nonvanishing values

$$\boxed{\mu_\nu = f_M(0)}$$ ⇐ ν magnetic moment ●

$$\boxed{\epsilon_\nu = f_E(0)}$$ ⇐ ν electric moment ???

3.5 Neutrino (beyond SM) dipole moments (+ transition moments)



P.Pal, 1982
L.Wolfenstein

- **Dirac neutrino**

$$\left.\begin{matrix}\mu_{ij}\\ \epsilon_{ij}\end{matrix}\right\} = \frac{eG_F m_i}{8\sqrt{2}\pi^2}\left(1 \pm \frac{m_j}{m_i}\right)\sum_{l=\,e,\,\mu,\,\tau} f(r_l)U_{lj}U^*_{li}$$

$$r_l = \left(\frac{m_l}{m_W}\right)^2$$

$m_e = 0.5\ MeV$
$m_\mu = 105.7\ MeV$
$m_\tau = 1.78\ GeV$
$m_W = 80.2\ GeV$

- $m_i, m_j \ll m_l, m_W$

$$f(r_l) \approx \frac{3}{2}\left(1 - \frac{1}{2}r_l\right), \quad r_l \ll 1$$

transition moments vanish because unitarity of U implies that its rows or columns represent orthogonal vectors

- transition moments are suppressed, Glashow-Iliopoulos-Maiani cancellation,
- for diagonal moments there is no GIM cancellation

- **Majorana neutrino** only for $i \neq j$

$$\mu^M_{ij} = 2\mu^D_{ij} \quad and \quad \epsilon^M_{ij} = 0$$

or

$$\mu^M_{ij} = 0 \quad and \quad \epsilon^M_{ij} = 2\epsilon^D_{ij}$$

… depending on relative CP phase of ν_i and ν_j

②

✓ magnetic moment in experiments

(most easily understood and accessible for experimental studies are dipole moments)

Studies of ν-e scattering - most sensitive method for experimental investigation of μ_ν

Cross-section:

- $$\frac{d\sigma}{dT}(\nu + e \to \nu + e) = \left(\frac{d\sigma}{dT}\right)_{\rm SM} + \left(\frac{d\sigma}{dT}\right)_{\mu_\nu}$$

where the Standard Model contribution

- $$\left(\frac{d\sigma}{dT}\right)_{\rm SM} = \frac{G_{\rm F}^2 m_e}{2\pi}\left[(g_V + g_A)^2 + (g_V - g_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 + (g_A^2 - g_V^2)\frac{m_e T}{E_\nu^2}\right],$$

$\boldsymbol{T}$ is the electron recoil energy and

- $$\left(\frac{d\sigma}{dT}\right)_{\mu_\nu} = \frac{\pi\alpha_{em}^2}{m_e^2}\left[\frac{1 - T/E_\nu}{T}\right]\mu_\nu^2$$

$$\mu_\nu^2(\nu_l, L, E_\nu) = \sum_j \left|\sum_i U_{li} e^{-iE_i L} \mu_{ji}\right|^2$$

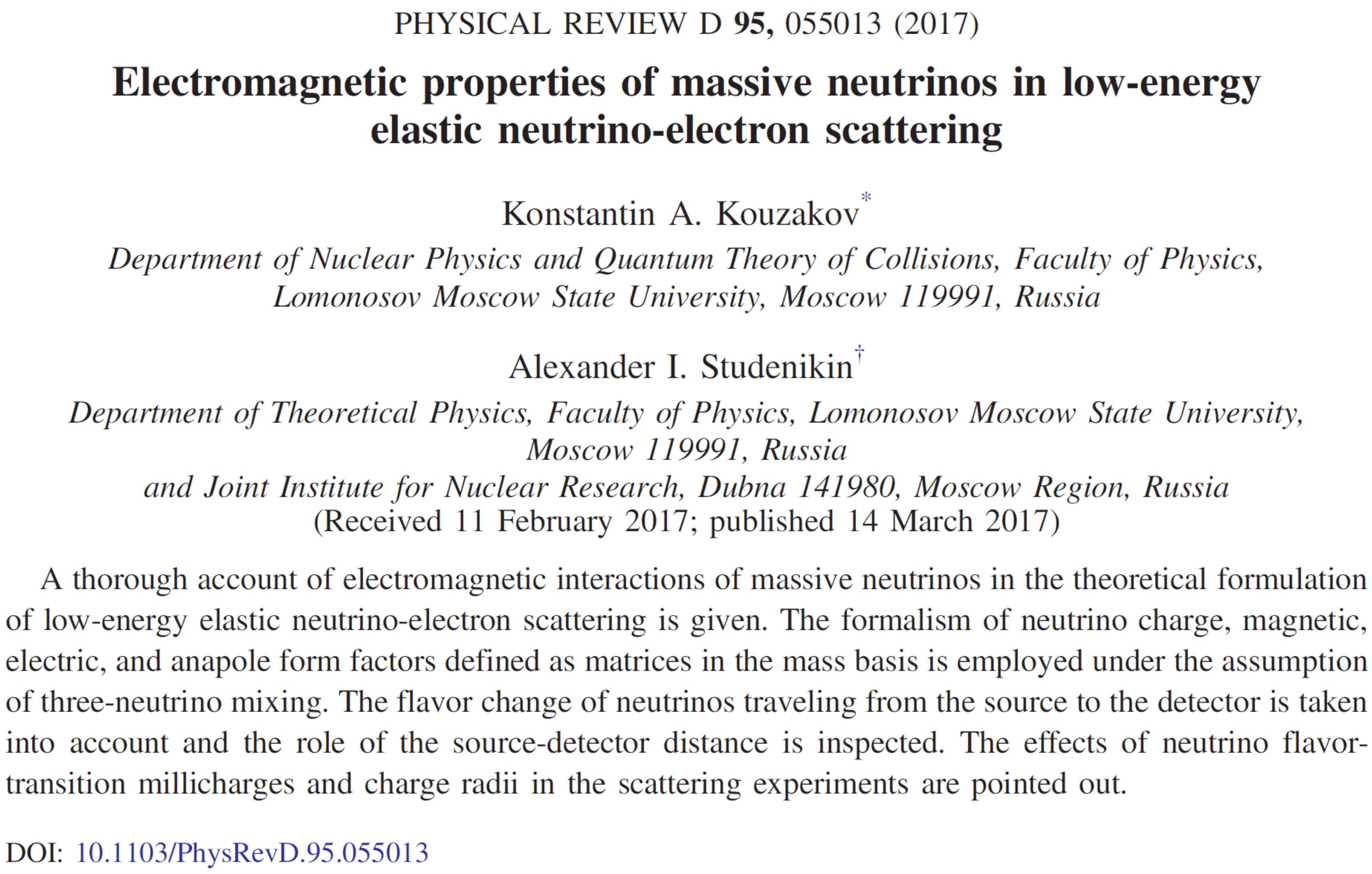
$$\mu_{ij} \to |\mu_{ij} - \epsilon_{ij}|$$

$$g_V = \begin{cases} 2\sin^2\theta_W + \frac{1}{2} & \text{for} \quad \nu_e\,, \\ 2\sin^2\theta_W - \frac{1}{2} & \text{for} \quad \nu_\mu, \nu_\tau\,, \end{cases} \qquad g_A = \begin{cases} \frac{1}{2} & \text{for} \quad \nu_e\,, \\ -\frac{1}{2} & \text{for} \quad \nu_\mu, \nu_\tau \end{cases}$$

for anti-neutrinos $g_A \to -g_A$

- to incorporate charge radius: $g_V \to g_V + \boxed{\frac{2}{3} M_W^2 \langle r^2 \rangle \sin^2\theta_W}$???

… comprehensive analysis of ν-e scattering …



PHYSICAL REVIEW D **95,** 055013 (2017)

Electromagnetic properties of massive neutrinos in low-energy elastic neutrino-electron scattering

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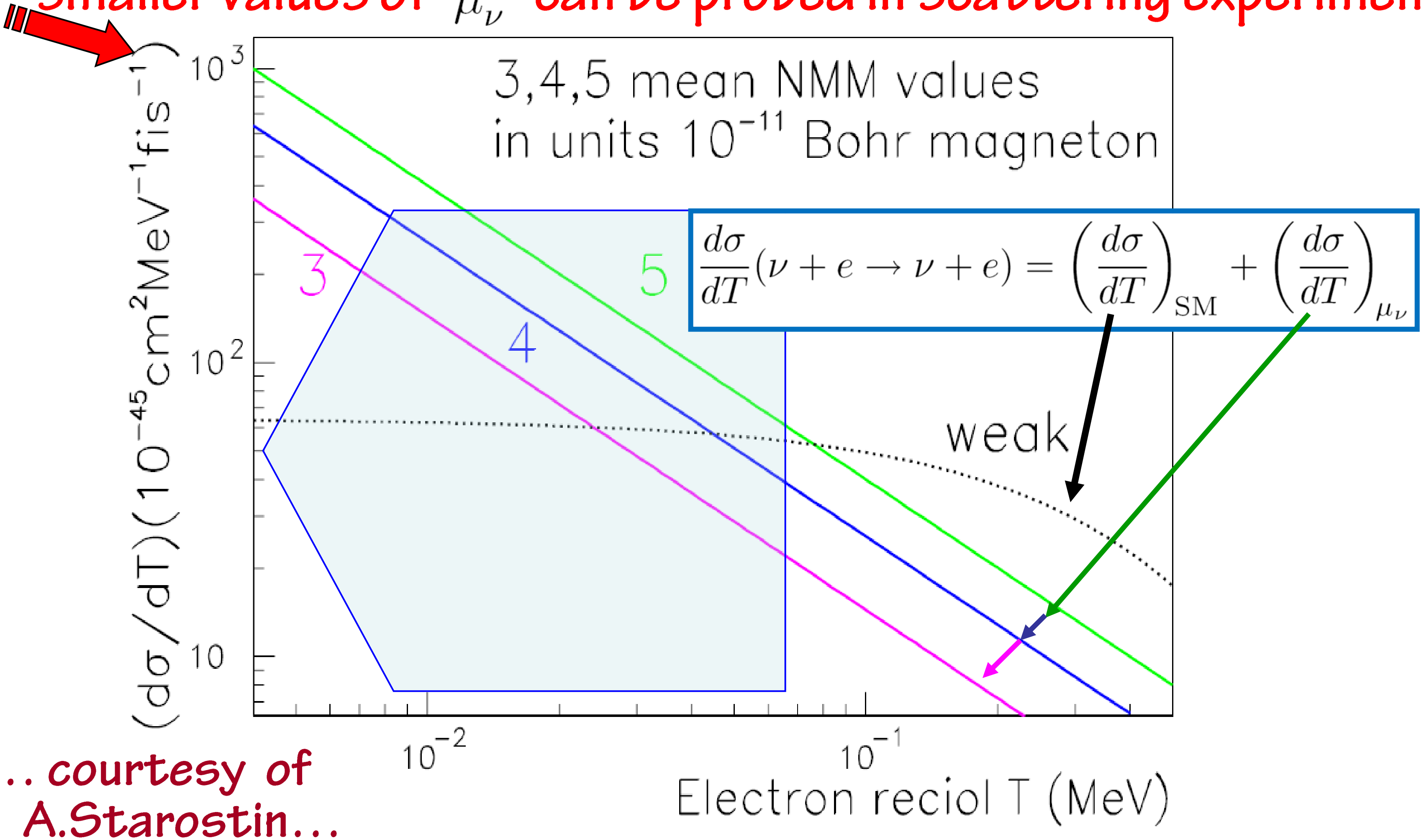
A thorough account of electromagnetic interactions of massive neutrinos in the theoretical formulation of low-energy elastic neutrino-electron scattering is given. The formalism of neutrino charge, magnetic, electric, and anapole form factors defined as matrices in the mass basis is employed under the assumption of three-neutrino mixing. The flavor change of neutrinos traveling from the source to the detector is taken into account and the role of the source-detector distance is inspected. The effects of neutrino flavor-transition millicharges and charge radii in the scattering experiments are pointed out.

DOI: 10.1103/PhysRevD.95.055013

… all experimental constraints on charge radius should be redone

Magnetic moment contribution dominates at low electron recoil energies when $\left(\frac{d\sigma}{dT}\right)_{\mu_\nu} > \left(\frac{d\sigma}{dT}\right)_{SM}$ **and** $\frac{T}{m_e} < \frac{\pi^2\alpha_{em}}{G_F^2 m_e^4}\mu_\nu^2$

… the lower the smallest measurable electron recoil energy is, smaller values of μ_ν^2 can be probed in scattering experiments …



$$\frac{d\sigma}{dT}(\nu + e \to \nu + e) = \left(\frac{d\sigma}{dT}\right)_{\rm SM} + \left(\frac{d\sigma}{dT}\right)_{\mu_\nu}$$ ●

… courtesy of A.Starostin…

GEMMA (2005-2012)
Germanium Experiment for Measurement of Magnetic Moment of Antineutrino

JINR (Dubna) + ITEP (Moscow) at Kalinin Nuclear Power Plant

World best experimental limit

- $$\boxed{\mu_\nu < 2.9 \times 10^{-11} \mu_B}$$

June 2012

A. Beda et al, in: Special Issue on "Neutrino Physics", Advances in High Energy Physics (2012) 2012,
editors: J. Bernabeu, G. Fogli, A. McDonald, K. Nishikawa

… quite realistic prospects of the near future … 2018-2019 ?

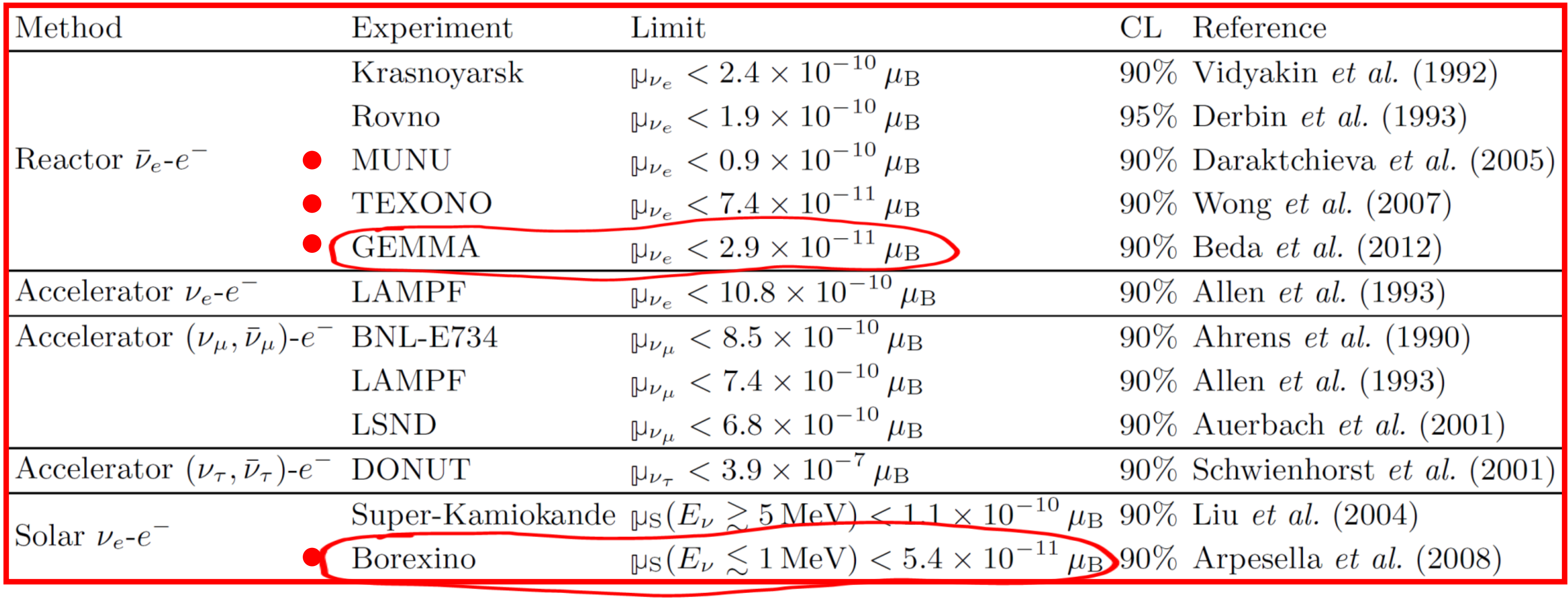
- $$\boxed{\mu_\nu^a \sim \ 0.7 \times 10^{-12} \ \mu_B}$$

unprecedentedly low threshold

$$\boxed{T \sim 200 \ \ eV}$$

②

Experimental limits for different effective μ_ν



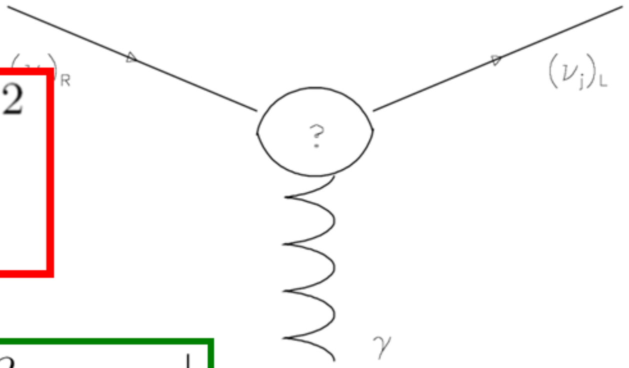
Method		Experiment	Limit	CL	Reference
Reactor $\bar{\nu}_e$-e^-		Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}\ \mu_B$	90%	Vidyakin *et al.* (1992)
		Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}\ \mu_B$	95%	Derbin *et al.* (1993)
	●	MUNU	$\mu_{\nu_e} < 0.9 \times 10^{-10}\ \mu_B$	90%	Daraktchieva *et al.* (2005)
	●	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}\ \mu_B$	90%	Wong *et al.* (2007)
	●	GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}\ \mu_B$	90%	Beda *et al.* (2012)
Accelerator ν_e-e^-		LAMPF	$\mu_{\nu_e} < 10.8 \times 10^{-10}\ \mu_B$	90%	Allen *et al.* (1993)
Accelerator $(\nu_\mu, \bar{\nu}_\mu)$-e^-		BNL-E734	$\mu_{\nu_\mu} < 8.5 \times 10^{-10}\ \mu_B$	90%	Ahrens *et al.* (1990)
		LAMPF	$\mu_{\nu_\mu} < 7.4 \times 10^{-10}\ \mu_B$	90%	Allen *et al.* (1993)
		LSND	$\mu_{\nu_\mu} < 6.8 \times 10^{-10}\ \mu_B$	90%	Auerbach *et al.* (2001)
Accelerator $(\nu_\tau, \bar{\nu}_\tau)$-$e^-$		DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}\ \mu_B$	90%	Schwienhorst *et al.* (2001)
Solar ν_e-e^-		Super-Kamiokande	$\mu_S(E_\nu \gtrsim 5\,\text{MeV}) < 1.1 \times 10^{-10}\ \mu_B$	90%	Liu *et al.* (2004)
	●	Borexino	$\mu_S(E_\nu \lesssim 1\,\text{MeV}) < 5.4 \times 10^{-11}\ \mu_B$	90%	Arpesella *et al.* (2008)

new 2017 PRD : $\mu_\nu^{eff} < 2.8 \cdot 10^{-11}\ \mu_B$ at 90% c.l.

C. Giunti, A. Studenikin, "Electromagnetic interactions of neutrinos: a window to new physics", Rev. Mod. Phys. 87 (2015) 531

Effective ν magnetic moment in experiments

(for neutrino produced as ν_l with energy E_ν
and after traveling a distance L)



$$\mu_\nu^2(\nu_l, L, E_\nu) = \sum_j \left| \sum_i U_{li} e^{-iE_iL} \mu_{ji} \right|^2$$

where **neutrino mixing matrix**

$$\mu_{ij} \equiv |\beta_{ij} - \varepsilon_{ij}|$$

magnetic and **electric** moments

- Observable μ_ν is an effective parameter that depends on neutrino flavour composition at the detector.

- Implications of μ_ν limits from different experiments (reactor , solar ^{8}B and ^{7}Be) are different.

Bounds on millicharge q_ν from μ_ν (GEMMA Coll. data)

②

two not seen contributions:

$$\boxed{\left(\frac{d\sigma}{dT}\right)_{\mu_\nu^a} \approx \pi\alpha^2 \frac{1}{m_e^2 T}\left(\frac{\mu_\nu^a}{\mu_B}\right)^2}$$

$$\boxed{\left(\frac{d\sigma}{dT}\right)_{q_\nu} \approx 2\pi\alpha \frac{1}{m_e T^2} q_\nu^2}$$

ν-e cross-section

$$\boxed{\left(\frac{d\sigma}{dT}\right)_{\nu-e} = \left(\frac{d\sigma}{dT}\right)_{SM} + \left(\frac{d\sigma}{dT}\right)_{\mu_\nu} + \left(\frac{d\sigma}{dT}\right)_{q_\nu}}$$

Bounds on q_ν from

… unobservable effects of New Physics

$$R = \frac{\left(\frac{d\sigma}{dT}\right)_{q_\nu}}{\left(\frac{d\sigma}{dT}\right)_{\mu_\nu^a}} = \frac{2m_e}{T}\frac{\left(\frac{q_\nu}{e_0}\right)^2}{\left(\frac{\mu_\nu^a}{\mu_B}\right)^2} \ll 1$$

Studenikin,
Eurphys. Lett.
107 (2014)
21001

● Particle Data Group, 2016 ●

Expected new constraints from GEMMA:

now $\mu_\nu^a < 2.9 \times 10^{-11} \mu_B$ ($T \sim 2.8\ keV$)

Constraints on q_ν

$$\boxed{| q_\nu | < 1.5 \times 10^{-12} e_0}$$ ●

2018/19 (expected)

… unprecedentedly low threshold …

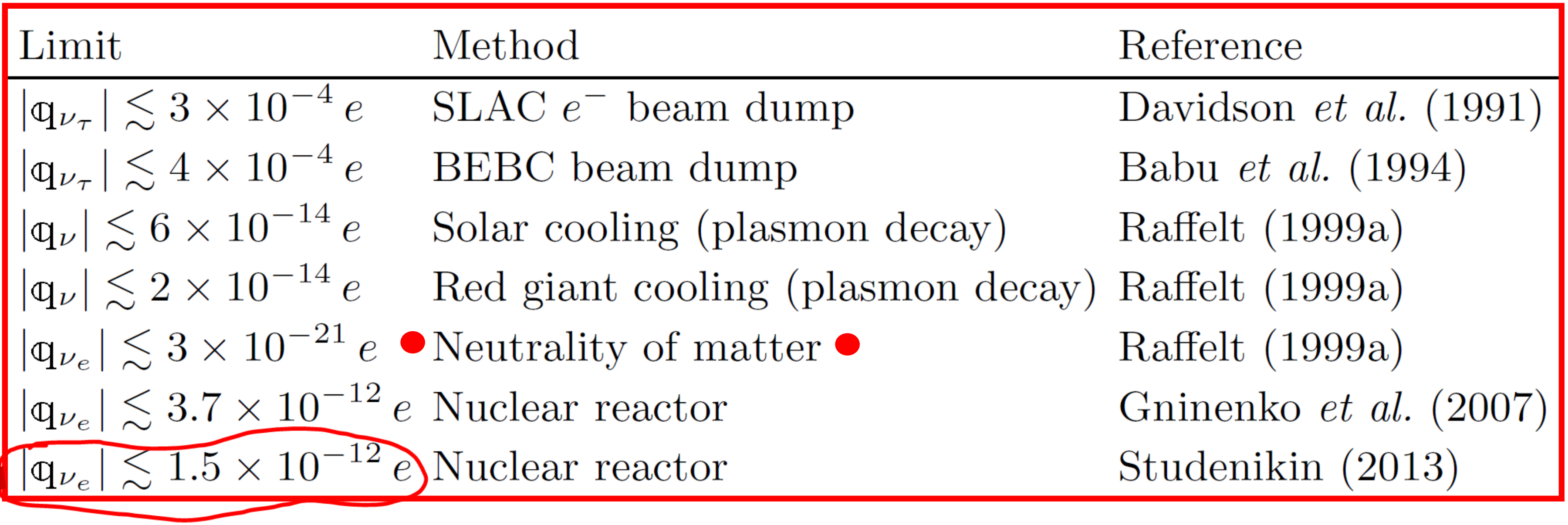
$$\boxed{\mu_\nu^a \sim\ 0.7 \times 10^{-12}\ \mu_B} \quad (\boxed{T \sim 200\ \ eV})$$

$$\boxed{|q_\nu| < 1.1 \times 10^{-13} e_0}$$

②

Experimental limits for different effective q_ν

C. Giunti, A. Studenikin, “Electromagnetic interactions of neutrinos: a window to new physics”, Rev. Mod. Phys. 87 (2015) 531

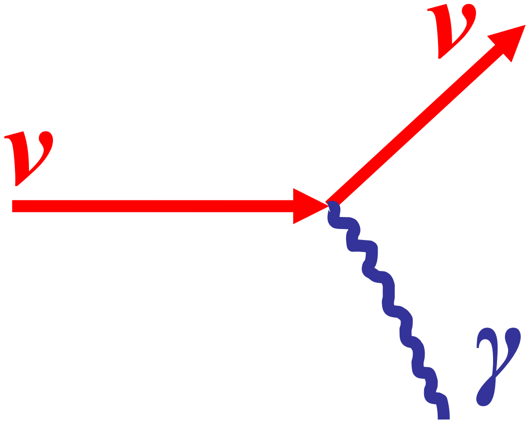


Limit	Method	Reference
$\lvert q_{\nu_\tau} \rvert \lesssim 3 \times 10^{-4}\, e$	SLAC e^- beam dump	Davidson *et al.* (1991)
$\lvert q_{\nu_\tau} \rvert \lesssim 4 \times 10^{-4}\, e$	BEBC beam dump	Babu *et al.* (1994)
$\lvert q_{\nu} \rvert \lesssim 6 \times 10^{-14}\, e$	Solar cooling (plasmon decay)	Raffelt (1999a)
$\lvert q_{\nu} \rvert \lesssim 2 \times 10^{-14}\, e$	Red giant cooling (plasmon decay)	Raffelt (1999a)
$\lvert q_{\nu_e} \rvert \lesssim 3 \times 10^{-21}\, e$	● Neutrality of matter ●	Raffelt (1999a)
$\lvert q_{\nu_e} \rvert \lesssim 3.7 \times 10^{-12}\, e$	Nuclear reactor	Gninenko *et al.* (2007)
$\lvert q_{\nu_e} \rvert \lesssim 1.5 \times 10^{-12}\, e$	Nuclear reactor	Studenikin (2013)

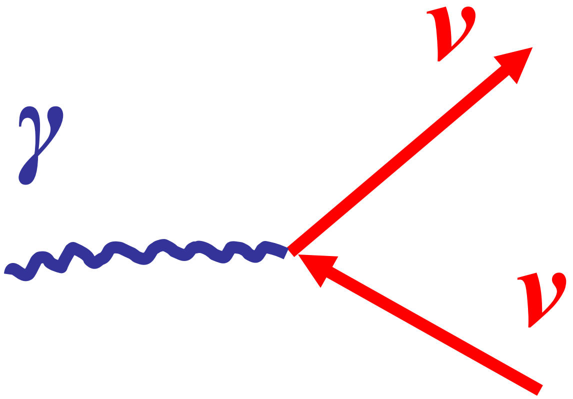
A. Studenikin: “New bounds on neutrino electric millicharge from limits on neutrino magnetic moment”, Eur.Phys.Lett. 107 (2014) 2100

C.Patrignani et al (Particle Data Group), “The Review of Particle Physics 2016” Chinese Physics C 40 (2016) 100001

③ ν electromagnetic interactions

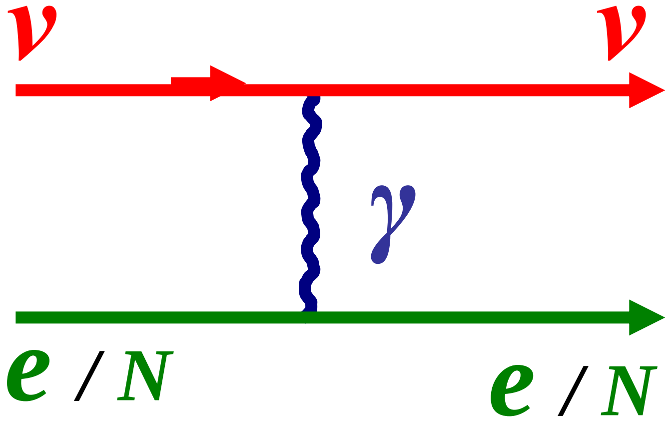


ν decay, Cherenkov radiation

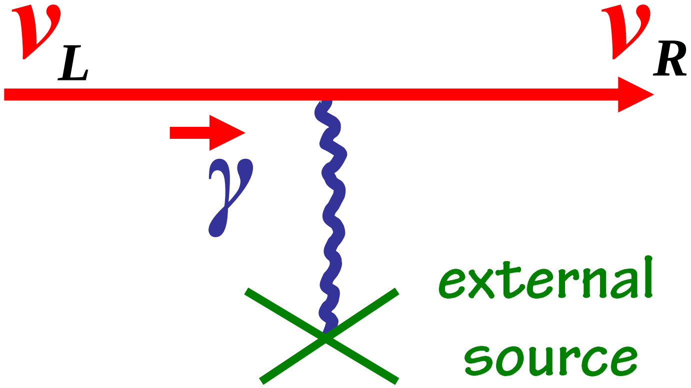


γ decay in plasma

!!!



Scattering

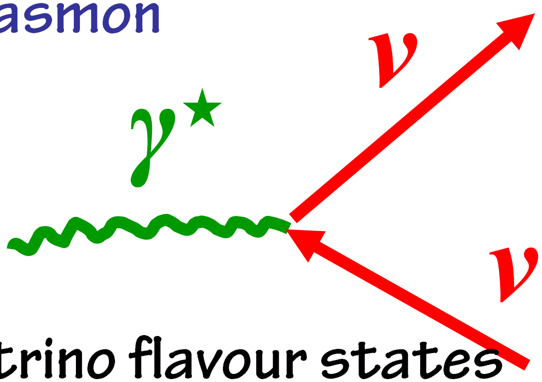


Spin precession

② Astrophysical bound on μ_ν

G.Raffelt, PRL 1990

comes from cooling of red gaint stars by plasmon decay $\gamma^\star \longrightarrow \nu\nu$



$$\boxed{L_{int} = \frac{1}{2}\sum_{a,b}\left(\mu_{a,b}\bar{\psi}_a\sigma_{\mu\nu}\psi_b + \epsilon_{a,b}\bar{\psi}_a\sigma_{\mu\nu}\gamma_5\psi_b\right)}$$

neutrino flavour states

$$\epsilon_\alpha k^\alpha = 0$$

Matrix element

$$|M|^2 = M_{\alpha\beta}p^\alpha p^\beta, \quad M_{\alpha\beta} = 4\mu^2(2k_\alpha k_\beta - 2k^2\epsilon^*_\alpha\epsilon_\beta - k^2 g_{\alpha,\beta}),$$

Decay rate

$$\boxed{\Gamma_{\gamma\to\nu\bar{\nu}} = \frac{\mu^2}{24\pi}\frac{(\omega^2-k^2)^2}{\omega}}$$

= 0 in vacuum $\omega = k$

In the classical limit $\gamma^\star$ - like a massive particle with $\omega^2 - k^2 = \omega_{pl}^2$

Energy-loss rate per unit volume

$$\boxed{Q_\mu = g\int\frac{d^3k}{(2\pi)^3}\omega f_{BE}\Gamma_{\gamma\to\nu\bar{\nu}}}$$

$$\mu^2 \to \sum_{a,b}\left(|\mu_{a,b}|^2 + |\epsilon_{a,b}|^2\right)$$

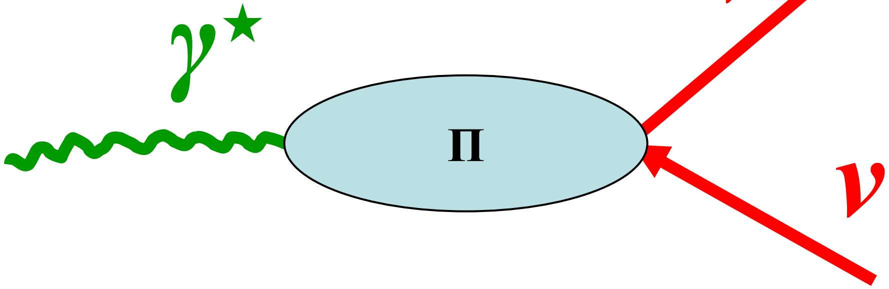
distribution function of plasmons

Astrophysical bound on μ_ν

$$Q_\mu = g \int \frac{d^3k}{(2\pi)^3}\,\omega f_{BE}\Gamma_{\gamma\to\nu\bar{\nu}}$$

Energy-loss rate
per unit volume

Magnetic moment plasmon decay
enhances the Standard Model photo-neutrino
cooling by photon polarization tensor



more fast star cooling

In order not to delay helium ignition (≤5% in Q)

... best
astrophysical
limit on
ν magnetic moment...

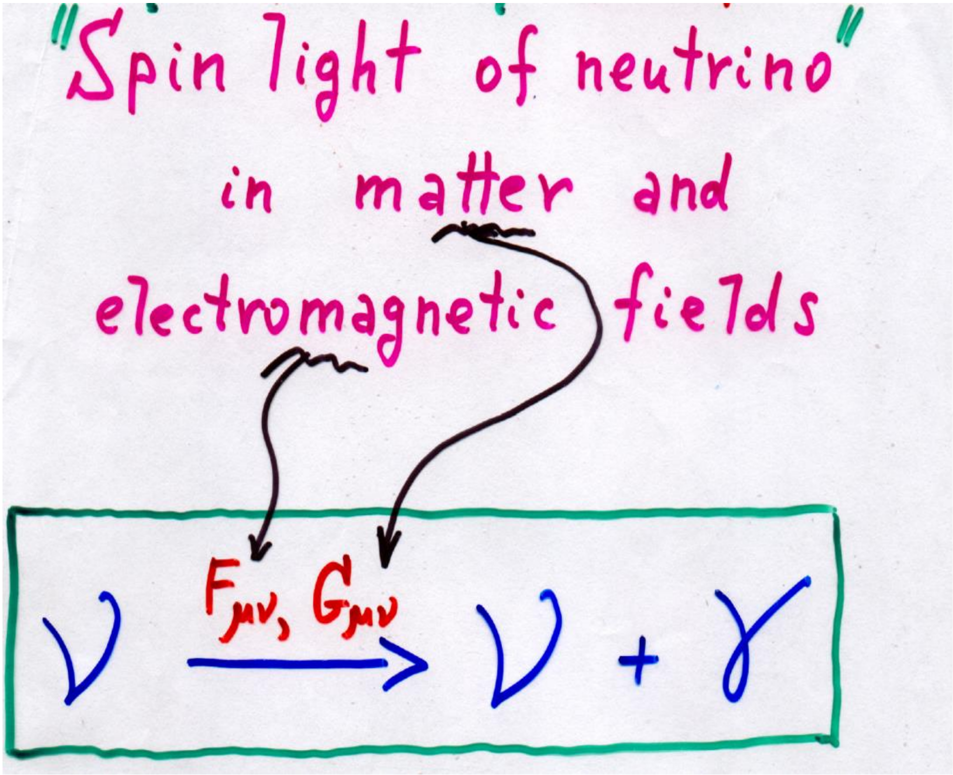
$$\mu \leq 3\times 10^{-12}\mu_B$$

$$\mu^2 \to \sum_{a,b}\left(|\mu_{a,b}|^2 + |\epsilon_{a,b}|^2\right)$$

G.Raffelt, PRL 1990

• New mechanism of electromagnetic radiation

$SL\nu$



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An IOP and SISSA journal

Spin light of neutrino in astrophysical environments

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A.Grigoriev, A.Lokhov, A.Studenikin, A.Ternov, Spin light of neutrino in astrophysical environments, J. Cosm. Astropart. Phys. 11 (2017) 024

● Grigoriev, Lokhov, AS, Ternov, T-17 poster # 775

SLν in neutron matter of real astrophysical objects [4]

☐ **Plasma effects [5]**

- Photon dispersion with plasmon mass in the degenerate electron gas:

$$\boxed{\omega = \sqrt{\mathbf{k}^2 + m_\gamma^2}}$$

$$\boxed{m_\gamma = \left(\frac{2\alpha}{\pi}\right)^{1/2} \mu_e \simeq 8.87 \times \left(\frac{n_e}{10^{37}\,\mathrm{cm}^{-3}}\right)^{1/3} \mathrm{MeV}}$$

- Threshold condition for the *SLν* [10]: ($Y_e = n_e/n_n$)

$$\boxed{\frac{m_\gamma^2 + 2\,m_\gamma m_\nu}{4\tilde{n}p} < 1}$$

- **Neutron matter:** (antineutrinos act)

$$\tilde{n} = \frac{1}{2\sqrt{2}} G_F n_n \simeq 3.2 \times \left(\frac{n_n}{10^{38}\,\mathrm{cm}^{-3}}\right) \mathrm{eV},$$

$$E > p_{\mathrm{th}} \simeq 28.5 \times \frac{Y_e^{2/3}}{1 - Y_e} \left(\frac{10^{38}\,\mathrm{cm}^{-3}}{n_n}\right)^{1/3} \mathrm{TeV} \quad E_{\mathrm{th}} \simeq 6.82\ \mathrm{TeV}.$$

$n_n = 10^{38}\mathrm{cm}^{-3}$, $Y_e = 0.1$

- Mean photon energy near the threshold: $\langle\omega\rangle = I/\Gamma \simeq p \simeq E_\nu$.

For most favorable conditions as low density of the charged matter component is needed as possible

☐ **W boson production** $\bar{\nu}_e + e^- \to W^-$ [4]

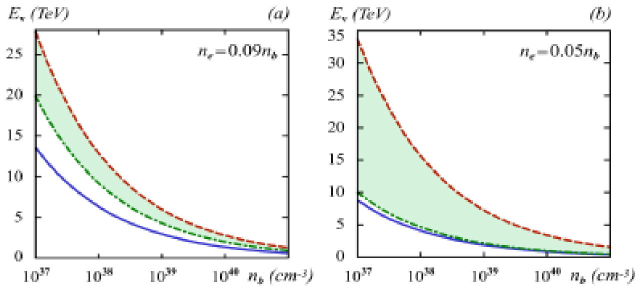


Figure 2. The allowed range of electron antineutrino energies for the *SLν* in the matter of a neutron star depending on the neutron density. Solid line: the *SLν* process threshold without account for the $\bar{\nu}_e e$-scattering; dash-dotted line: the *SLν* process threshold with account for the $\bar{\nu}_e e$-scattering; dashed line: the threshold for the *W* boson production. (a) $Y_e = 0.09$; (b) $Y_e = 0.05$. The allowed regions are marked in green.

W-boson threshold energy $\varepsilon_W = \frac{m_W^2}{4\mu_e} \simeq 5.77 \times \left(\frac{10^{38}\,\mathrm{cm}^{-3}}{Y_e n_n}\right)^{1/3} \mathrm{TeV}$

- Electron antineutrinos: s-channel interaction with matter through W-boson, importance of the propagator effects $\Rightarrow$ correction to the effective potential of neutrino motion → antineutrino energy shift up → *SLν* is suppressed at Y_e=0.1, but allowed already for Y_e=0.09

- μ and τ antineutrinos: only t-channel interaction with matter through Z-boson, no propagator effects $\Rightarrow$ the *SLν* is allowed if neutrino energy is greater than the W-boson threshold ε_W

Neutrino lifetime with respect to the *SLν* for most optimistic set of parameters:

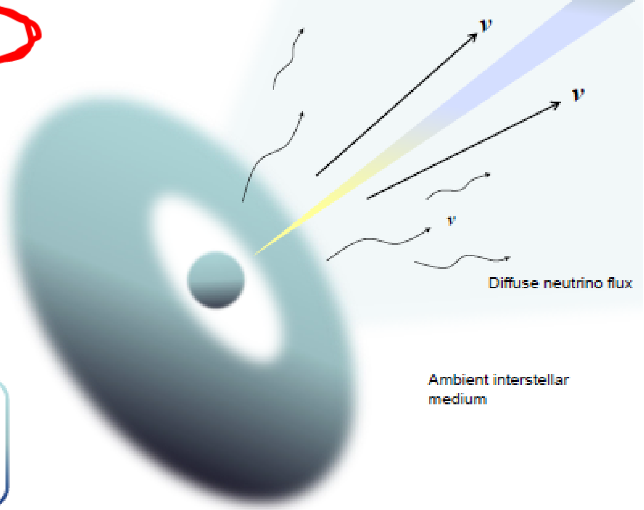
$$\boxed{\tau_{SL\nu} = 10^{-4} - 10^{3}\,s, \quad \text{for} \quad n_b = 10^{41} - 10^{38}\,\mathrm{cm}^{-3}}$$

The *SLν* in short Gamma-Ray Bursts (SGRBs)

Factors for best *SLν* generation efficiency

- High neutrino energy and density
- High background neutral matter density
- Low density of the matter charged component
- Low temperature of the charged component
- Considerable extension of the medium

SLν radiation by ultra high-energy neutrino in the diffuse neutrino wind blown during neutron stars merger



Matter characteristics[6]:

- neutrinos

$$n_\nu \sim 10^{32}\ \mathrm{cm}^{-3}$$

- electrons

$$Y_e = 0.01$$
$$T = 0.1\ \mathrm{MeV}$$
$$\rho = 5 \times 10^3\ \mathrm{g/cm}^3$$

$$n_e \simeq 3 \times 10^{25}\ \mathrm{cm}^{-3}$$
$$m_\gamma \simeq 10^{-3}\ \mathrm{MeV}$$
$$\boxed{E_{\mathrm{th}} \simeq 1\ \mathrm{GeV}}$$

Radiation time

$$\tau_{\mathrm{SL}\nu} \simeq 5.4 \times 10^{15} \left(\frac{10^{-11}\mu_B}{\mu}\right)^2 \left(\frac{10^{32}\,\mathrm{cm}^{-3}}{n_{\nu_e}}\right)^2 \left(\frac{1\,\mathrm{PeV}}{E_\nu}\right) \mathrm{s}$$

Neutrino parameters:

$$\mu \simeq 2.9 \times 10^{-11}\mu_B$$
$$E_\nu \sim 10^{12} - 10^{18}\ \mathrm{eV}$$

$$\boxed{\tau_{\mathrm{SL}\nu} \simeq 6.4 \times (10^{11} - 10^{17})\ \mathrm{s} = 2 \times (10^{4} - 10^{10})\ \mathrm{years}}$$

- ... astrophysical bound on millicharge q_ν from ②

ν energy quantization in rotating magnetized media

Grigoriev, Savochkin, Studenikin, Russ. Phys. J. 50 (2007) 845
Studenikin, J. Phys. A: Math. Theor. 41 (2008) 164047
Balantsev, Popov, Studenikin, J. Phys. A: Math. Theor. 44 (2011) 255301
Balantsev, Studenikin, Tokarev, Phys. Part. Nucl. 43 (2012) 727
Phys. Atom. Nucl. 76 (2013) 489
Studenikin, Tokarev, Nucl. Phys. B 884 (2014) 396

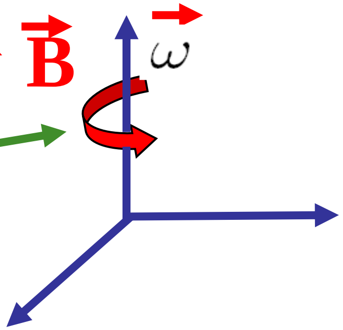
Millicharged ν in rotating magnetized matter

Balatsev, Tokarev, Studenikin,
Phys.Part.Nucl., 2012,
Phys.Atom.Nucl., Nucl.Phys. B, 2013,
Studenikin, Tokarev, Nucl.Phys.B (2014) ●

Modified Dirac equation for ν wave function

$$\boxed{\Big(\gamma_\mu(p^\mu + q_0 A^\mu) - \frac{1}{2}\gamma_\mu(c_l+\gamma_5)f^\mu - \frac{i}{2}\mu\sigma_{\mu\nu}F^{\mu\nu} - m\Big)\,\Psi(x) = 0}$$

external magnetic field



$$\boxed{V_m = \tfrac{1}{2}\gamma_\mu(c_l+\gamma_5)f^\mu} \qquad c_l = 1$$

matter potential

rotating matter

$$\boxed{f^\mu = -Gn_n(1, -\epsilon y\omega, \epsilon x\omega, 0)}$$

rotation
angular
frequency

ν energy is quantized in rotating matter

A.Studenikin, I.Tokarev,
Nucl.Phys.B (2014)

$$G = \frac{G_F}{\sqrt{2}}$$

$$\boxed{p_0 = \sqrt{p_3^2 + 2N|2Gn_n\omega - \epsilon q_\nu B| + m^2} - Gn_n - q\phi}$$

$$\boxed{N = 0, 1, 2, \ldots}$$

integer number

matter rotation
frequency

scalar potential
of electric field

ν energy is quantized in rotating matter
like electron energy in magnetic field
(Landau energy levels):

$$\boxed{p_0^{(e)} = \sqrt{m_e^2 + p_3^2 + 2\gamma N}, \quad \gamma = eB, \quad N = 0, 1, 2, \ldots}$$

• ν Star Turning mechanism (νST)

A. Studenikin, I. Tokarev, Nucl. Phys. B 884 (2014) 396

Escaping millicharged νs move on curved orbits inside magnetized rotating star and feedback of effective Lorentz force should effect initial star rotation

- New astrophysical constraint on ν millicharge

$$\boxed{\frac{|\triangle\omega|}{\omega_0} = 7.6\varepsilon \times 10^{18} \left(\frac{P_0}{10\ \mathrm{s}}\right) \left(\frac{N_\nu}{10^{58}}\right) \left(\frac{1.4M_\odot}{M_S}\right) \left(\frac{B}{10^{14}G}\right)}$$

- $|\triangle\omega| < \omega_0$! ...to avoid contradiction of νST impact with observational data on pulsars ...

$$\boxed{q_0 < 1.3 \times 10^{-19} e_0}$$

- ... best astrophysical bound ...

$m_\nu \neq 0$

ν electromagnetic properties

magnetic moment μ_ν

Main steps in ν oscillations

61 years !

early history of ν oscillations

① $\nu_e \overset{vac}{\longleftrightarrow} \bar{\nu}_e$, B. Pontecorvo, 1957

② $\nu_e \overset{vac}{\longleftrightarrow} \nu_\mu$, Z. Maki, M. Nakagava, S. Sakata, 1962

③ $\nu_e \overset{matter,\ \rho = const}{\longleftrightarrow} \nu_\mu$, L. Wolfenstein, 1978

④ $\nu_e \overset{matter,\ \rho \neq const}{\longleftrightarrow} \nu_\mu$, S. Mikheev, A. Smirnov, 1985

- resonances in ν flavour oscillations => **MSW-effect**, solution for $\nu_\odot$-problem

⑤ $\nu_{e_L} \overset{B_\perp}{\longleftrightarrow} \nu_{e_R}$, A. Cisneros, 1971
M. Voloshin, M. Vysotsky, L. Okun, 1986, $\nu_\odot$

⑥ $\nu_{e_L} \overset{B_\perp}{\longleftrightarrow} \nu_{e_R}, \nu_{\mu_R}$, E. Akhmedov, 1988
C.-S. Lim & W. Marciano, 1988

- resonances in ν spin (spin-flavour) oscillations in matter

30 years !

Bruno Pontecorvo

1913-1993

only in $B_\perp$ and matter at rest

④ ν spin and spin-flavour oscillations in $B_\perp$

Consider two different neutrinos: $\nu_{e_L}, \quad \nu_{\mu_R}, \quad m_L \neq m_R$

with magnetic moment interaction

$$\boxed{L \sim \bar{\nu}\sigma_{\lambda\rho}F^{\lambda\rho}\nu\,' = \bar{\nu}_L\sigma_{\lambda\rho}F^{\lambda\rho}\nu_R\,' + \bar{\nu}_R\sigma_{\lambda\rho}F^{\lambda\rho}\nu_L\,'}\,.$$

Twisting magnetic field $B = |\mathbf{B}_\perp| e^{i\phi(t)}$ or solar ν etc ...

ν evolution equation

$$\boxed{i\frac{d}{dt}\begin{pmatrix}\nu_L\\ \nu_R\end{pmatrix} = H\begin{pmatrix}\nu_L\\ \nu_R\end{pmatrix}}$$

$$\boxed{H = \begin{pmatrix} E_L & \mu_{e\mu}Be^{-i\phi} \\ \mu_{e\mu}Be^{+i\phi} & E_R \end{pmatrix} = \ldots \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \tilde{H}}$$

$$\boxed{\tilde{H} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \frac{V_{\nu_e}}{2} & \mu_{e\mu}Be^{-i\phi} \\ \mu_{e\mu}Be^{+i\phi} & \frac{\Delta m^2}{4E} - \frac{V_{\nu_e}}{2} \end{pmatrix}}$$

Probability of $\nu_{e_L} \Longleftrightarrow \nu_{\mu_R}$ oscillations in $\boxed{B = |\mathbf{B}_\perp| e^{i\phi(t)}}$

- $$\boxed{P_{\nu_L \nu_R} = \sin^2\beta \, \sin^2 \Omega z, \quad \sin^2\beta = \frac{(\mu_{e\mu}B)^2}{(\mu_{e\mu}B)^2 + \left(\frac{\Delta_{LR}}{4E}\right)^2}}$$

$$\boxed{\Delta_{LR} = \frac{\Delta m^2}{2}(\cos 2\theta + 1) - 2EV_{\nu_e} + 2E\dot{\phi}}$$

$$\boxed{\Omega^2 = (\mu_{e\mu}B)^2 + \left(\frac{\Delta_{LR}}{4E}\right)^2}$$

- Resonance amplification of oscillations in matter:

$$\boxed{\Delta_{LR} \to 0} \quad \Longrightarrow \quad \boxed{\sin^2\beta \to 1}$$

Akhmedov, 1988
Lim, Marciano

… similar to
MSW effect

In magnetic field

$$\nu_{e_L} \quad \nu_{\mu_R}$$

$$i\frac{d}{dz}\nu_{e_L} = -\frac{\Delta_{LR}}{4E}\nu_{e_L} + \mu_{e\mu}B\nu_{\mu_R}$$

$$i\frac{d}{dz}\nu_{\mu_L} = \frac{\Delta_{LR}}{4E}\nu_{\mu_L} + \mu_{e\mu}B\nu_{e_R}$$

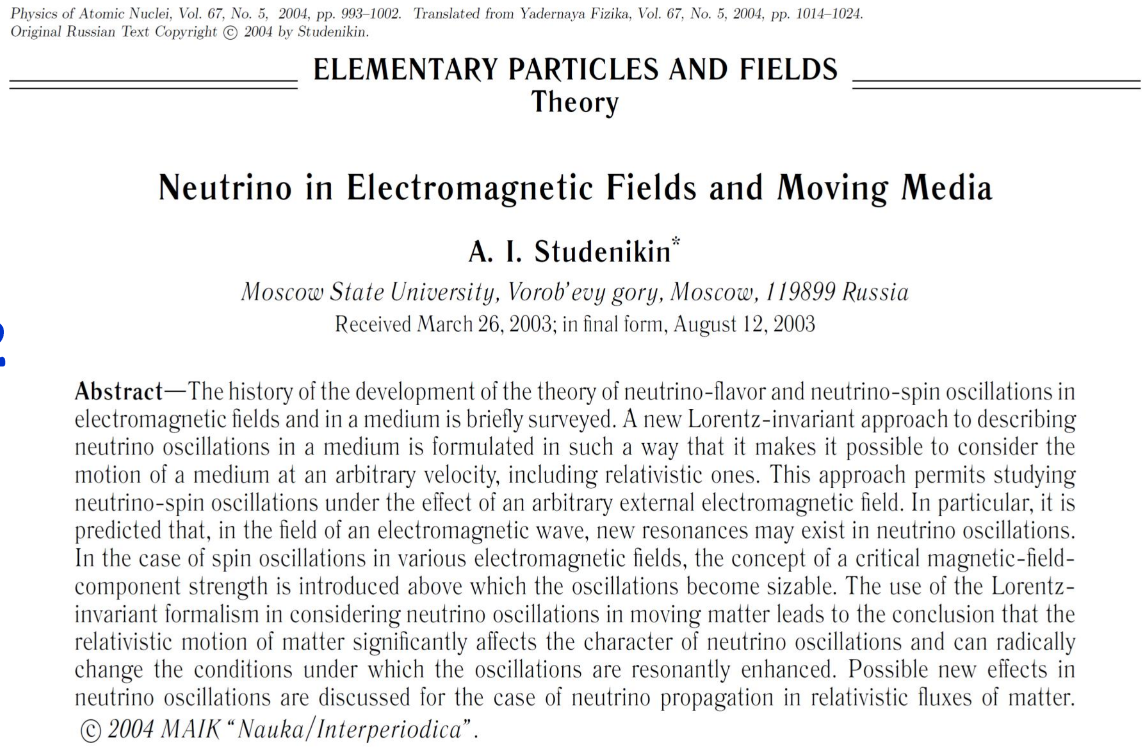
- P. Pustoshny, AS, T_13 poster # 697

. . . new phenomena in ν oscillations

- ν spin and spin-flavour oscillations in transversal matter currents

Studenikin (2004)

- Phys.Atom.Nucl. 67 (2004) 993-1002



Physics of Atomic Nuclei, Vol. 67, No. 5, 2004, pp. 993–1002. Translated from Yadernaya Fizika, Vol. 67, No. 5, 2004, pp. 1014–1024.

ELEMENTARY PARTICLES AND FIELDS
Theory

Neutrino in Electromagnetic Fields and Moving Media

A. I. Studenikin*

Moscow State University, Vorob'evy gory, Moscow, 119899 Russia

Received March 26, 2003; in final form, August 12, 2003

Abstract—The history of the development of the theory of neutrino-flavor and neutrino-spin oscillations in electromagnetic fields and in a medium is briefly surveyed. A new Lorentz-invariant approach to describing neutrino oscillations in a medium is formulated in such a way that it makes it possible to consider the motion of a medium at an arbitrary velocity, including relativistic ones. This approach permits studying neutrino-spin oscillations under the effect of an arbitrary external electromagnetic field. In particular, it is predicted that, in the field of an electromagnetic wave, new resonances may exist in neutrino oscillations. In the case of spin oscillations in various electromagnetic fields, the concept of a critical magnetic-field-component strength is introduced above which the oscillations become sizable. The use of the Lorentz-invariant formalism in considering neutrino oscillations in moving matter leads to the conclusion that the relativistic motion of matter significantly affects the character of neutrino oscillations and can radically change the conditions under which the oscillations are resonantly enhanced. Possible new effects in neutrino oscillations are discussed for the case of neutrino propagation in relativistic fluxes of matter.

- Electromagnetic properties of neutrinos: three new phenomena in neutrino spin oscillations, Europhys. J. Web of Conf. 125 (2016) 04018

- From neutrino electromagnetic interactions to spin oscillations in transversal matter currents, PoS NOW2016 (2017) 070

- Neutrino spin and spin-flavour oscillations in transversally moving or polarized matter, J. Phys. Conf. Ser. 888 (2017) 012221

ν spin evolution in presence of general external fields

M.Dvornikov, A.Studenikin,
JHEP 09 (2002) 016

General types non-derivative interaction with external fields

$$\boxed{\begin{aligned}-\mathcal{L} = g_s s(x)\bar{\nu}\nu + g_p \pi(x)\bar{\nu}\gamma^5\nu + g_v V^\mu(x)\bar{\nu}\gamma_\mu\nu + g_a A^\mu(x)\bar{\nu}\gamma_\mu\gamma^5\nu + \\ + \frac{g_t}{2}T^{\mu\nu}\bar{\nu}\sigma_{\mu\nu}\nu + \frac{g'_t}{2}\Pi^{\mu\nu}\bar{\nu}\sigma_{\mu\nu}\gamma_5\nu,\end{aligned}}$$

scalar, pseudoscalar, vector, axial-vector, tensor and pseudotensor fields:

$$s, \pi, V^\mu = (V^0, \vec{V}), A^\mu = (A^0, \vec{A}),$$
$$T_{\mu\nu} = (\vec{a}, \vec{b}), \Pi_{\mu\nu} = (\vec{c}, \vec{d})$$

Relativistic equation (quasiclassical) for ν spin vector:

$$\begin{aligned}\dot{\vec{\zeta}}_\nu = 2g_a \Big\{A^0[\vec{\zeta}_\nu \times \vec{\beta}] - \frac{m_\nu}{E_\nu}[\vec{\zeta}_\nu \times \vec{A}] - \frac{E_\nu}{E_\nu + m_\nu}(\vec{A}\vec{\beta})[\vec{\zeta}_\nu \times \vec{\beta}]\Big\} \\ +2g_t \Big\{[\vec{\zeta}_\nu \times \vec{b}] - \frac{E_\nu}{E_\nu + m_\nu}(\vec{\beta}\vec{b})[\vec{\zeta}_\nu \times \vec{\beta}] + [\vec{\zeta}_\nu \times [\vec{a} \times \vec{\beta}]]\Big\} + \\ +2ig'_t \Big\{[\vec{\zeta}_\nu \times \vec{c}] - \frac{E_\nu}{E_\nu + m_\nu}(\vec{\beta}\vec{c})[\vec{\zeta}_\nu \times \vec{\beta}] - [\vec{\zeta}_\nu \times [\vec{d} \times \vec{\beta}]]\Big\}.\end{aligned}$$

- *Neither* ***s*** *nor* ***π*** *nor* ***V*** *contributes to spin evolution*

- **Electromagnetic interaction**

$$T_{\mu\nu} = F_{\mu\nu} = (\vec{E}, \vec{B})$$

- **SM weak interaction**

$$G_{\mu\nu} = (-\vec{P}, \vec{M})$$

$$\vec{M} = \gamma(A^0\vec{\beta} - \vec{A})$$
$$\vec{P} = -\gamma[\vec{\beta} \times \vec{A}],$$

Phys.Atom.Nucl. 67 (2004) 993-1002

Physics of Atomic Nuclei, Vol. 67, No. 5, 2004, pp. 993–1002. Translated from Yadernaya Fizika, Vol. 67, No. 5, 2004, pp. 1014–1024.
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ELEMENTARY PARTICLES AND FIELDS
Theory

Neutrino in Electromagnetic Fields and Moving Media

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STUDENIKIN PHYSICS OF ATOMIC NUCLEI Vol. 67 No. 5 2004

Consider

$$\boxed{\nu_{e_L} \to \nu_{e_R}, \qquad \nu_{e_L} \to \nu_{\mu_R}}$$

$$\boxed{P(\nu_i \to \nu_j) = \sin^2(2\theta_{\text{eff}}) \sin^2 \frac{\pi x}{L_{\text{eff}}}, \qquad i \neq j}$$

$$\boxed{L_{\text{eff}} = \frac{2\pi}{\sqrt{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2}}}$$

$$\sin^2 2\theta_{\text{eff}} = \frac{E_{\text{eff}}^2}{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2}, \quad \Delta_{\text{eff}}^2 = \frac{\mu}{\gamma_\nu}\left|\mathbf{M}_{0\parallel} + \mathbf{B}_{0\parallel}\right|. \qquad E_{\text{eff}} = \mu\left|\mathbf{B}_\perp + \frac{1}{\gamma_\nu}\mathbf{M}_{0\perp}\right|$$

- A.Studenikin, "Status and perspectives of neutrino magnetic moments"
  J.Phys.Conf.Ser. 718 (2016) 062076

$$\left\{\vec{M}_0 = \gamma_\nu \rho n_e \left(\underline{\underline{\vec{\beta}_\nu}}\left(1 - \underline{\underline{\vec{\beta}_\nu}}\,\underline{\underline{\vec{v}_e}}\right) - \frac{1}{\gamma_\nu}\underline{\underline{\vec{v}_{e_\perp}}}\right),\right.$$

transversal matter current

matter density

∥

⊥

interaction of neutrino with matter

$$\gamma_\nu = \frac{E_\nu}{m_\nu},$$

where $$\boxed{\rho = \frac{G_F}{2\mu_\nu\sqrt{2}}(1 + 4\sin^2\theta_W)}$$

Physics of Atomic Nuclei, Vol. 67, No. 5, 2004, pp. 993–1002. Translated from Yadernaya Fizika, Vol. 67, No. 5, 2004, pp. 1014–1024.

ELEMENTARY PARTICLES AND FIELDS

Theory

Phys.Atom.Nucl. 67 (2004) 993-1002, hep-ph/04070100

Neutrino in Electromagnetic Fields and Moving Media

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Moscow State University, Vorob'evy gory, Moscow, 119899 Russia

Received March 26, 2003; in final form, August 12, 2003

The possible emergence of neutrino-spin oscillations (for example, $\nu_{eL} \leftrightarrow \nu_{eR}$) owing to neutrino interaction with matter under the condition that there exists a nonzero transverse current component or matter polarization (that is, $\mathbf{M}_{0\perp} \neq 0$) is the most important new effect that follows from the investigation of neutrino-spin oscillations in Section 4. So far, it has been assumed that neutrino-spin oscillations may arise only in the case where there exists a nonzero transverse magnetic field in the neutrino rest frame.

- P. Pustoshny, AS, T_13 poster # 697

... quantum treatment new phenomena in ν oscillations

- ν spin and spin-flavour oscillations in transversal matter currents

Studenikin (2004)

$\boxed{\nu_{e_L} \to \nu_{e_R}, \quad \nu_{e_L} \to \nu_{\mu_R}}$

… the effect of ν helicity conversions and oscillations induced by transversal matter currents has been recently confirmed:

- J. Serreau and C. Volpe, "Neutrino-antineutrino correlations in dense anisotropic media", Phys .Rev. D90 (2014) 125040
- V. Ciriglianoa, G. M. Fuller, and A. Vlasenko, "A new spin on neutrino quantum kinetics" Phys. Lett. B747 (2015) 27
- A. Kartavtsev, G. Raffelt, and H. Vogel, "Neutrino propagation in media: flavor-, helicity-, and pair correlations", Phys. Rev. D91 (2015) 125020
- A. Dobrynina, A. Kartavtsev, and G. Raffelt, "Helicity oscillations of Dirac and Majorana neutrinos", Phys. Rev. D93 (2016) 125030

Conclusions

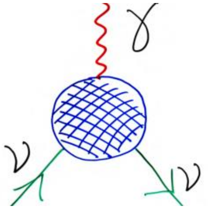
Electromagnetic Properties of ν

(effects of magnetic moments)

MSU **Alexander Studenikin** JINR

C.Giunti, A.Studenikin,
" ν electromagnetic interactions: A window to new physics", Rev.Mod.Phys, 2015

Studenikin,
" ν electromagnetic interactions: A window to new physics - II",
arXiv: 1801.18887



① νEP theory - ν vertex function

matrices in ν mass eigenstates space

$$\boxed{\Lambda_\mu^{if}(q) = f_Q^{if}(q^2)\gamma_\mu + f_M^{if}(q^2)i\sigma_{\mu\nu}q^\nu + f_E^{if}(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + f_A^{if}(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5,}$$

electric charge
magnetic moment
electric moment
anapole moment

form factors $f_X^{if}(q^2)$ at $q^2 = 0$ static EP of ν ⇒

⇐

Dirac	ν	Majorana	
q_{if}		$q_{if} = 0$	CPT + charge concervation
μ_{if}	$\neq 0$	$\mu_{if}\ (i \neq f)$	
ε_{if}		$\varepsilon_{if}\ (i \neq f)$	
a_{if}		a_{if}	

Hermiticity and discrete symmetries of EM current

$\boxed{\langle\nu(p')|J_\mu^{EM}|\nu(p)\rangle = \bar{u}(p')\Lambda_\mu(q)u(p)}$ put constraints on form factors

②

$$\boxed{\mu_{jj}^D = \frac{3e_0G_Fm_j}{8\sqrt{2}\pi^2} \approx 3.2\times 10^{-19}\mu_B\left(\frac{m_j}{1\ \mathrm{eV}}\right)}$$

Fujikawa & Shrock, 1980

- much greater values are Beyond Minimally Extended SM
- transition moments $\mu_{i\neq f}$, $\varepsilon_{i\neq f}$ are GIM suppressed

③ νEP ⇓ experimental bounds

$$\mu_\nu^{eff} < \begin{matrix} 2.9 \\ 2.8 \\ \sim 0.1 \end{matrix} \times 10^{-11}\mu_B$$

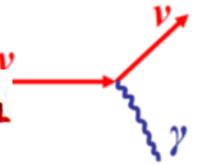
GEMMA Coll. 2012
Borexino Coll. 2017
Astrophysics, Raffelt ea 1988
Arcoa Dias ea 2015

$$q_{\nu_e} <\sim \left.\begin{matrix} \sim 10^{-12} \\ \sim 10^{-19} \\ \sim 10^{-21} \end{matrix}\right] e_0$$

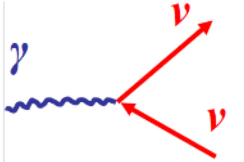
reactor ν scattering
AS '14, Chen ea '14
AS '14 (astrophysics)
neutrality of matter

Effects of ν magnetic moment:

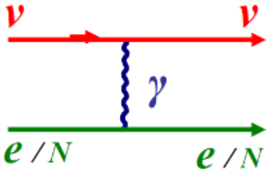
- spin precession and oscillations in $B_\perp$



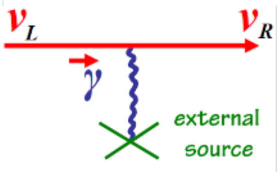
ν decay, Cherenkov radiation



γ decay in plasma



Scattering



Spin precession

Cisneros, Okun, Voloshin, Vysotsky, Valle, Raffelt, Schechter, Petkov, Akhmedov, Lim, Marciano, Smirnov, Pulido, Dvornikov, Grigoriev, Lobanov, Lokhov, Kouzakov, Ternov, Studenikin et al

New effects reported at ICHEP 2018

① Electromagnetic interactions and oscillations of ultrahigh-energy cosmic ν in interstellar space

Kouzakov & AS, poster # 686

PRD 96 (2017)

$$L_B = \pi/\mu_\nu B$$

$$P_{\nu^L\to\nu^R}(x) = \sin^2\left(\frac{\pi x}{L_B}\right)$$

$$P_{\nu_e^L\to\nu_\mu^L}(x) = [1 - P_{\nu^L\to\nu^R}(x)]\sin^2 2\theta\ \sin^2\left(\frac{\pi x}{L_{\rm vac}}\right)$$

amplitude of flavour oscillations is modulated by $\mu_\nu B$ frequency

② ν flavour, spin and spin-flavour oscillations and consistent account for a constant magnetic field

Popov & AS, poster # 754 **arXiv: 1803.05766**

probability of spin oscillations depends on Δm^2

$$P_{\nu_e^L\to\nu_e^R} = \left\{\sin(\mu_+B_\perp t)\cos(\mu_-B_\perp t)+\cos 2\theta\sin(\mu_-B_\perp t)\cos(\mu_+B_\perp t)\right\}^2 - \sin^2 2\theta\sin(\mu_1B_\perp t)\sin(\mu_2B_\perp t)\sin^2\frac{\Delta m^2}{4p}t$$

③ ν spin and spin-flavour oscillations engendered by transversal matter current

Pustoshny & AS, poster # 697 **arXiv: 1801.08911**

Studenikin 2004, 2017

- transversal matter currents $j_\perp$ do change ν helicity !

④ Spin-light of ν in Gamma-Ray Bursts

Grigoriev, Lokhov, Studenikin, Ternov, poster # 775

new mechanism of EM radiation by ν

JCAP 1711 (2017) no. 11, 024

“SL ν in astrophysical environments”

μ_ν interactions could have important effects in astrophysical and cosmological environments

future high-precision observations of supernova ν fluxes (for instance, in JUNO experiment) may reveal effect of collective spin-flavour oscillations due to Majorana

$$\mu_\nu \sim 10^{-21}\mu_B$$

- A. de Gouvea, S. Shalgar,
  Cosmol. Astropart. Phys. 04 (2013) 018

ν electromagnetic properties: future prospects

- new constraints on μ_ν (and q_ν) from GEMMA and Borexino

- charge radius in ν - e elastic scattering can't be considered as a shift $g_V \to g_V + \boxed{\frac{2}{3} M_W^2 \langle r^2 \rangle \sin^2 \theta_W}$, there are also contributions from flavor-transition charge radii –
new analysis (re-analysis) of data is needed

- need for inclusion of ν em interactions in analysis of supernovae ν fluxes

Thank you

Astrophysics bounds on μ_ν

$$\boxed{\mu_\nu(\text{astro}) < 10^{-10}\text{–}10^{-12}\ \mu_B}$$

Mostly derived from consequences of helicity-state change in astrophysical medium:

- **available degrees of freedom in BBN,**
- **stellar cooling via plasmon decay,**
- **cooling of SN1987a**

Red Giant lumin.
$\mu_\nu \leq 3 \cdot 10^{-12} \mu_B$
G. Raffelt, D. Dearborn,
J. Silk, 1989.

Bounds depend on

- **modeling of astrophysical systems,**
- **on assumptions on the neutrino properties.**

Generic assumption:

- **absence of other nonstandard interactions except for μ_ν**

A global treatment would be desirable, incorporating oscillation and matter effects as well as the complications due to interference and competitions among various channels

Data Set

- I phase – 5184 h ON, 1853 h OFF

$$\boxed{\mu_\nu < 5.8*10^{-11}\mu_B}$$

- II phase – 6798 h ON, 1021 h OFF
- I+II – 11982 h ON, 2874 h OFF

$$\boxed{\mu_\nu < 3.2*10^{-11}\mu_B}$$

- III phase – 6152 h ON, 1613 h OFF
- I+II+III – 18134 h ON, 4487 h OFF

$$\boxed{\mu_\nu < 2.9*10^{-11}\mu_B}$$

Beda A.G. et al. **// Advances in High Energy Physics. 2012. V. 2012, Article ID 350150.**
Beda A.G. et al. **// Physics of Particles and Nuclei Letters, 2013, V. 10, №2, pp. 139–143.**

GEMMA background conditions

- γ-rays were measured with Ge detector. The main sources are: ^{137}Cs , ^{60}Co, ^{134}Cs.
- Neutron background was measured with ^{3}He counters, i.e., thermal neutrons were counted. Their flux at the facility site turned out to be <u>30 times lower</u> than in the outside laboratory room.
- Charged component of the cosmic radiation (muons) was measured to be <u>5 times lower</u> than outside.

Experimental sensitivity

$$\mu_\nu \propto \frac{1}{\sqrt{N_\nu}}\left(\frac{B}{mt}\right)^{\frac{1}{4}}$$

N_ν : number of signal events expected
B : background level in the ROI
m : target (=detector) mass
t : measurement time

$N_\nu \sim \varphi_\nu\ (\sim Power / r^2)$
$\sim (T_{max} - T_{min} / T_{max} * T_{min})^{1/2}$

GEMMA I

$\varphi_\nu \sim 2.7 \times 10^{13}\ \nu / cm^2 / s$
$t \sim 4$ years
$B \sim 2.5\ keV^{-1}\ kg^{-1}\ day^{-1}$
$m \sim 1.5$ kg
$T_{th} \sim 2.8$ keV

$$\mu_\nu \le 2.9 \times 10^{-11}\ \mu_B$$

... courtesy of D.Medvedev...

Sensitivity of future experiments

B = 0.2 1/keV/kg/day (background level in ROI)

Mass, kg	Threshold, keV	Sensitivity, $10^{-12}\mu_B$
4.5	0.4	5.8
10	0.4	4.7
20	0.4	4.0
4.5	0.3	5.6
10	0.3	4.6
20	0.3	3.9

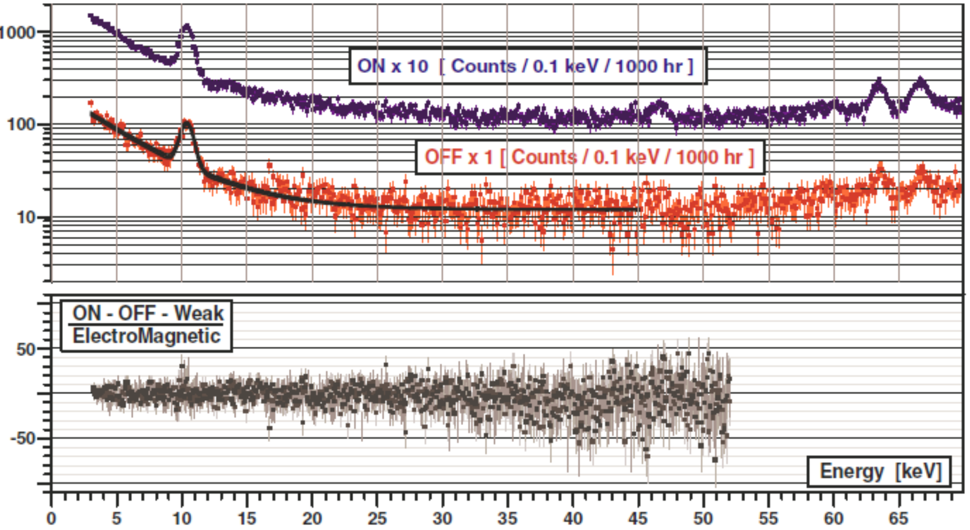
... courtesy of D.Medvedev...

… the obtained constraint on neutrino millicharge q_ν

- rough order-of-magnitude estimation,
- exact values should be evaluated using the
- corresponding statistical procedures

this is because limits on neutrino μ_ν are derived from GEMMA experiment data taken over an extended energy range 2.8 keV --- 55 keV, rather than at a single electron energy-bin at threshold

A.Studenikin : "New bounds on neutrino electric millicharge from limits on neutrino magnetic moment",
Eur.Phys.Lett. 107 (2014) 2100, arXiv:1302.1168



Difference between reactor on and off electron recoil energy spectra (with account for weak interaction contribution) normalized by theoretical electromagnetic spectra

A. Beda et al, Adv. High Energy Phys. 2012(2012) 350150

- Limit evaluated using statistical procedures is of the same order as previously discussed

- $$\boxed{|\, q_\nu \,| < 2.7 \times 10^{-12} e_0 \ (90\% \ \text{C.L.})}$$

A.Studenikin : "New bounds on neutrino electric millicharge from limits on neutrino magnetic moment", Eur.Phys.Lett. 107 (2014) 2100, arXiv:1302.1168

- V.Brudanin, D.Medvedev, A.Starostin, A.Studenikin : "New bounds on neutrino electric millicharge from GEMMA experiment on neutrino magnetic moment", arXiv: 1411.2279

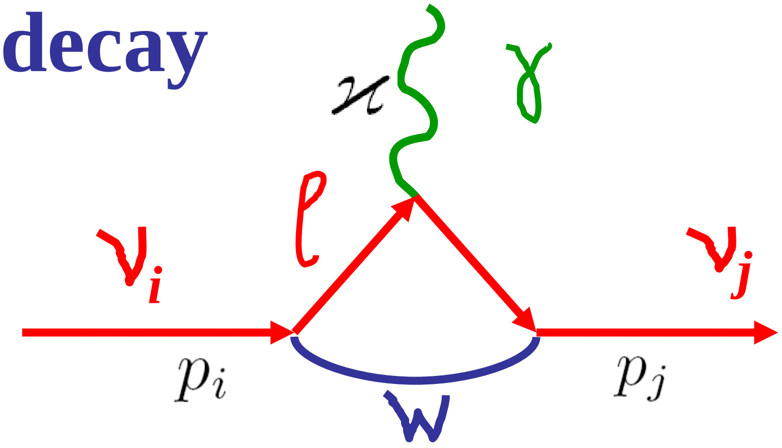
Radiative decay

3.7 Neutrino radiative decay

$\nu_i \longrightarrow \nu_j + \gamma$

$m_i > m_j$

$$\boxed{L_{int} = \frac{1}{2}\bar{\psi}_i \sigma_{\alpha\beta}(\sigma_{ij} + \epsilon_{ij}\gamma_5)\psi_j F^{\alpha\beta} + h.c.}$$



Radiative decay rate

Petkov 1977; Zatsepin, Smirnov 1978;
Bilenky, Petkov 1987; Pal, Wolfenstein 1982

$$\boxed{\Gamma_{\nu_i \to \nu_j + \gamma} = \frac{\mu_{eff}^2}{8\pi}\left(\frac{m_i^2 - m_j^2}{m_i^2}\right)^3} \approx 5\left(\frac{\mu_{eff}}{\mu_B}\right)^2\left(\frac{m_i^2 - m_j^2}{m_i^2}\right)^3\left(\frac{m_i}{1\ eV}\right)^3 s^{-1}$$

$$\boxed{\mu_{eff}^2 = \mid \mu_{ij} \mid^2 + \mid \epsilon_{ij} \mid^2}$$

- Radiative decay has been constrained from absence of decay photons:

1) reactor $\bar{\nu}_e$ and solar ν_e fluxes,

2) SN 1987A ν burst (all flavours),

3) spectral distortion of CMBR

Raffelt 1999

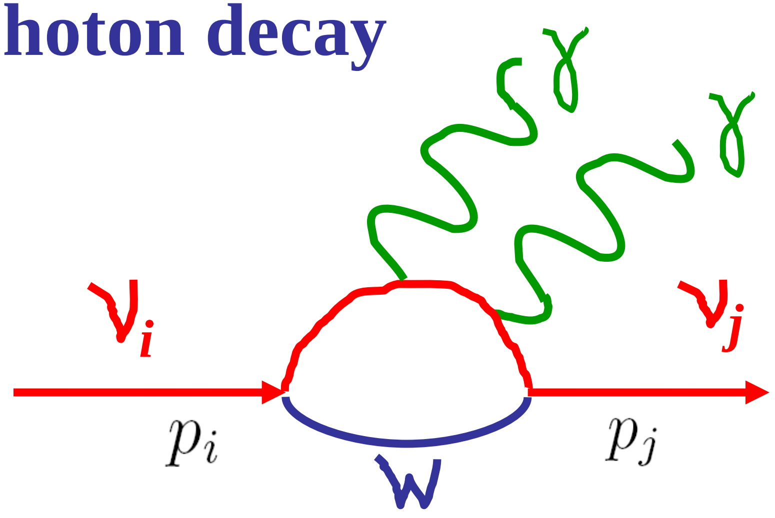
Kolb, Turner 1990;
Ressell, Turner 1990

3.8

Neutrino radiative two-photon decay

$$\nu_i \longrightarrow \nu_j + \gamma + \gamma$$

$$m_i > m_j$$



fine structure constant

$$\boxed{\Gamma_{\nu_i\to\nu_j+\gamma+\gamma} \sim \frac{\alpha_{QED}}{4\pi}\Gamma_{\nu_i\to\nu_j+\gamma}}$$

$\times$

… there is no GIM cancellation…

Nieves, 1983; Ghosh, 1984

… can be of interest for certain range of ν masses…

- ν quantum states in dense magnetized matter

… new effect of …

Spin Light of ν in matter

$\boxed{SL\nu}$

⇒

ν energy quantization in rotating matter

… phenomenological consequences in astrophysics (pulsars)

ν in matter treated within

«method of exact solutions»

(Dirac equation with matter potential for ν)

2015
the YEAR of LIGHT . . .
(United Nations)

③ I. Balantsev, A. Studenikin

"From electromagnetic neutrinos to new electromagnetic radiation mechanism in neutrino fluxes" Int. J. Mod. Phys. A 30 (2015) 1530044

$$\boxed{SL\nu} \Rightarrow SLe_{\nu}$$

$SL\nu$

Spin light of electron in dense neutrino fluxes SLe_{ν}

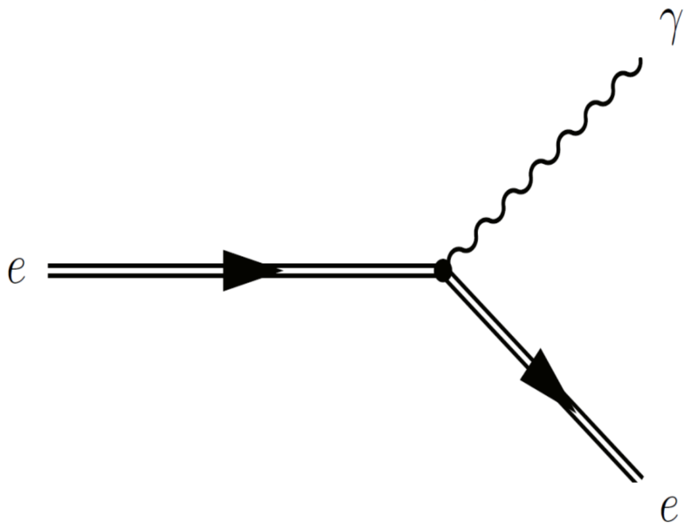
I.Balantsev, A.Studenikin, I

Int.J.Mod.Phys. A 30 (2015) 17, 1530044,
arXiv: 1405.6598, arXiv: 1502.05346

- Electrons in background matter potential (ultra-relativistic ν flux)

$$f^{\mu} = G(n,0,0,n)$$

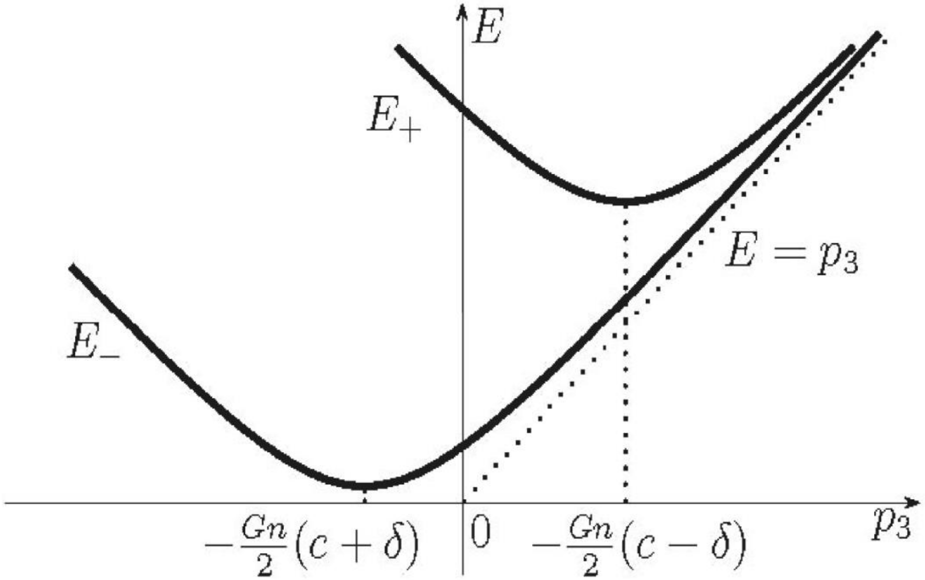
$$n = \frac{n_e + n_\mu + n_\tau}{3}$$



$$\boxed{\left(\gamma_\mu p^\mu + \gamma_\mu \frac{c + \delta_e \gamma^5}{2} f^\mu - m\right)\Psi(x) = 0}$$

$$c = \delta_e - 12\sin^2\theta_W$$

$$\delta_e = \frac{n_\mu + n_\tau - n_e}{n}$$



Energy spectrum of electrons in relativistic ν flux

Fig. 1. The dependence of the electron energies in two different spin states, $E_+(\boldsymbol{p})$ and $E_-(\boldsymbol{p})$, on the momentum component p_3.

$$\boldsymbol{p} = (\boldsymbol{p}_\perp, p_3)$$

$$\boxed{E_s^\varepsilon(\boldsymbol{p}) = \varepsilon\sqrt{m^2 + \boldsymbol{p}_\perp^2 + \Big(p_3 + A\Big)^2} - A} \quad A = \frac{Gn}{2}(c - s\delta), \ \delta = |\delta_e|$$

Wave function of electrons

$$\psi_i(\boldsymbol{r}, t) = \mathrm{e}^{i(-E_+t + \boldsymbol{pr})}\tilde{\psi}_i, \qquad \psi_f(\boldsymbol{r}, t) = \mathrm{e}^{i(-E_-t + \boldsymbol{pr})}\tilde{\psi}_f$$

$$\tilde{\psi}_i = \frac{1}{L^{\frac{3}{2}}C_+}\begin{pmatrix} 0 \\ m \\ p_\perp \mathrm{e}^{-i\phi} \\ E_+ - p_3 \end{pmatrix}, \quad \tilde{\psi}_f = \frac{1}{L^{\frac{3}{2}}C_-}\begin{pmatrix} E_- - p_3 \\ -p_\perp e^{i\phi} \\ m \\ 0 \end{pmatrix} \quad C_\pm = \sqrt{m^2 + p_\perp^2 + (E_\pm - p_3)^2}$$

SLe_{ν} in case of relativistic electrons in dense ν fluxes at supernovae environment

C. Frohlich, P. Hauser, M. Liebendorfer, G. Martinez-Pinedo, F.-K. Thielemann *et al.*, Composition of the innermost supernova ejecta, *Astrophys.J.* **637**, 415 (2006).

H.-T. Janka, K. Langanke, A. Marek, G. Martinez-Pinedo and B. Mueller, Theory of core-collapse supernovae, *Phys.Rept.* **442**, 38 (2007).

each second a reasonable part of ν flux energy can be transformed to gamma-rays

I.Balantsev, A.Studenikin,
Int.J.Mod.Phys. A 30 (2015) 17, 1530044

- new mechanism of electromagnetic radiation in the Year of Light