New neutrino spin oscillations in moving matter and magnetic fields

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Moscow State University

&

JINR

"Results and Perspectives in Particle Physics",
La Thuile, Italy
12/03/2019

- since 1995 - ν electromagnetic properties and interactions ⟹
- new developments in ν spin and flavour oscillations

① P. Pustoshny, A. Studenikin,
"Neutrino spin and spin-flavour oscillations in transversal matter currents with standard and non-standard interactions"

Phys. Rev. D98 (2018) no. 11, 113009

② A. Popov, A. Studenikin,
"Neutrino eigenstates and flavour, spin and spin-flavor oscillations in a constant magnetic field"

Eur. Phys .J. C 79 (2019) no.2, 144, arXiv: 1902.08195

- since 1995 in La Thuile

- since 1995 - oscillations in matter and B

Neutrino oscillations in the magnetic field of the sun, supernovae, and neutron stars

G. G. Likhachev and A. I. Studenikin

M. V. Lomonosov Moscow State University, 119899 Moscow, Russia
(Submitted 10 March 1995)
Zh. Éksp. Teor. Fiz. **108**, 769–782 (September 1995)

We examine the feasibility of oscillations of Dirac and Majorana neutrinos in a strong magnetic field (assuming a nonvanishing neutrino magnetic moment). We determine the critical magnetic field $\tilde{B}_{cr}(\Delta m^2_\nu, \theta, \ n_{\text{eff}}, \ E_\nu, \ \dot{\phi}(t))$ as a function of the neutrino mass difference, the vacuum mixing angle, the effective mass density, the neutrino energy, and the angle specifying the variation of the magnetic field in the plane transverse to the neutrino's motion. The conditions under which magnetic field-induced neutrino oscillations are significant are discussed. We study the possibility that such oscillations come about in supernova explosions, neutron stars, the sun, and the interstellar medium. We analyze the possible conversion of half the active neutrinos in a beam into sterile neutrinos when the beam emerges from the surface of a neutron star (cross-boundary effect), as well as when it crosses the interface between internal layers of a neutron star. © *1995 American Institute of Physics.*

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

Neutrino electromagnetic interactions: A window to new physics

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(published 16 June 2015)

. . . no word for a review. . .

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.

DOI: 10.1103/RevModPhys.87.531 PACS numbers: 14.60.St, 13.15.+g, 13.35.Hb, 14.60.Lm

CONTENTS

PHYSICAL REVIEW D **98,** 113010 (2018)

Editors' Suggestion

Neutrino charge radii from COHERENT elastic neutrino-nucleus scattering

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Coherent elastic neutrino-nucleus scattering is a powerful probe of neutrino properties, in particular of the neutrino charge radii. We present the bounds on the neutrino charge radii obtained from the analysis of the data of the COHERENT experiment. We show that the time information of the COHERENT data allows us to restrict the allowed ranges of the neutrino charge radii, especially that of ν_μ. We also obtained for the first time bounds on the neutrino transition charge radii, which are quantities beyond the standard model.

DOI: 10.1103/PhysRevD.98.113010

Ch – It – Ru collaboration

Physical Review D – Highlights 2018 – Editors' Suggestion

"Using data from the COHERENT experiment, the authors put bounds on electromagnetic ν charge radii, including the first bounds on the transition charge radii. These results show promising prospects for current and upcoming ν – nucleus experiments"

K. Kouzakov, A. Studenikin, "Electromagnetic properties of massive neutrinos in low-energy elastic neutrino-electron scattering"
Phys. Rev. D 95 (2017) 055013

participation in Les Rencontres de Physique de la Vallée d'Aoste for ¼ century

- not only increasing skills in particle physics
- increasing skills in skiing

… this part of activities was highlighted by awarding prestigious cup for slalom competition among conference participants that was organized on occasion of 30th jubilee of the conference (2016)

Les Rencontres de Physique de la Vallée d'Aoste
Slalom Cup 2016

Pavel Pustoshny, A. S.
"Neutrino spin and spin-flavour oscillations in transversal matter currents with standard and non-standard interactions",
Phys. Rev. D98 (2018) no. 11, 113009

Artem Popov, A. S..
"Neutrino eigenstates and flavour, spin and spin-flavour oscillations in a constant magnetic field",
Eur. Phys .J. C79 (2019) no.2, 144

Bruno Pontecorvo, «Inverse β processes and nonconcervation of leptonic charge», JINR Preprint P-95, Dubna, 1957 (3 pp.) :

62 years of mixing and oscillations

«Neutrinos in vacuum can transform themselves into antineutrino and vice versa. This means that neutrino and antineutrino are particle mixtures ... So, for example, a beam of neutral leptons from a reactor which at first consists mainly of antineutrinos will change its composition and at a certain distance R from the reactor will be composed of neutrino and antineutrino in equal quantities».

Бруно Понтекорво

Staff member at Faculty of Physics of Moscow State University, 1966 - 1986

if $m_\nu \neq 0$

then $\nu \leftrightarrow \bar{\nu}$ in vacuum

Бруно Понтекорво

Bruno Pontecorvo,
«Mesonium and anti-mesonium»,
Sov.Phys.JETP 6 (1957) 429
Zh.Eksp.Teor.Fiz. 33 (1957) 549-551:

if $m_\nu \neq 0$ then $\nu \leftrightarrow \bar{\nu}$ In vacuum

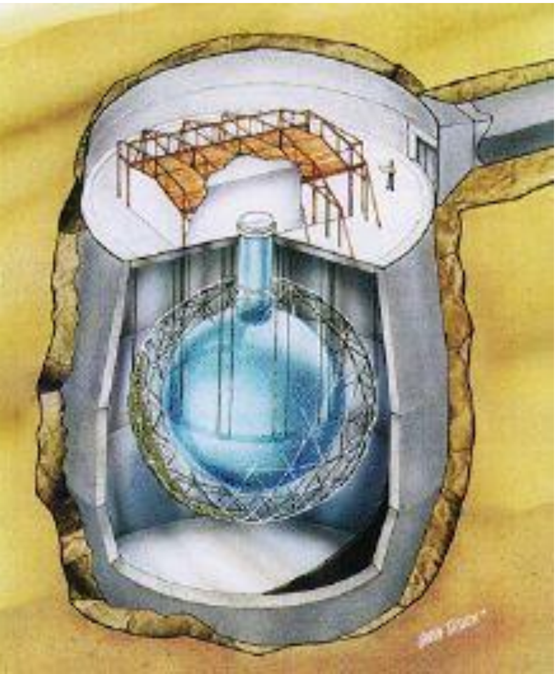
«It was assumed above that there exists a conservation law for the neutrino charge, according to which a neutrino cannot change into an antineutrino in any approximation. This law has not yet been established; evidently it has been merely shown that the neutrino and antineutrino are not identical particles.

If the two-component neutrino theory should turn out to be incorrect … and if the conservation law of neutrino charge would not apply, then in principle neutrino – antineutrino transitions could take place in vacuo»

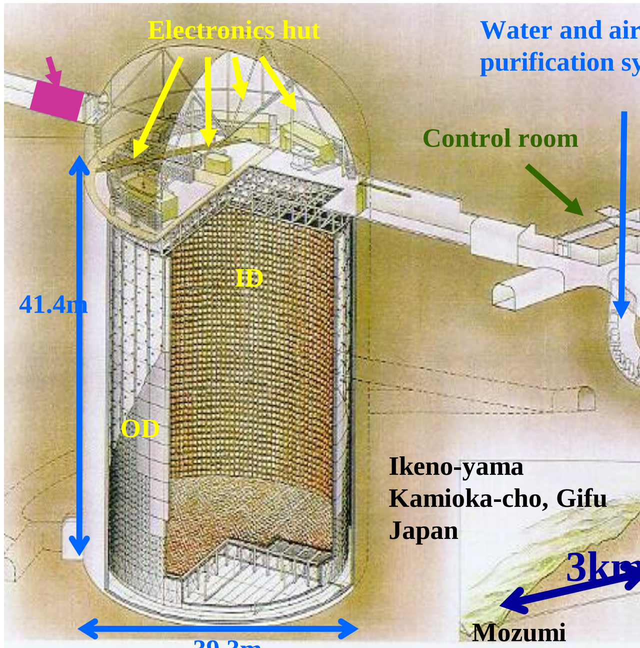
Arthur McDonald

The Nobel Prize in Physics 2015

Takaaki Kajita



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



Main steps in ν oscillations

62 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

* Neutrino oscillations in vacuum

B. Pontecorvo (1957)

(1) Flavour states, ν_e, ν_μ, are linear combinations of the mass states, ν_1, ν_2

Z. Maki
M. Nakagawa
S. Sakata
(1962)

$$\nu_e = \nu_1 \cos\theta_v + \nu_2 \sin\theta_v$$

$$\nu_\mu = -\nu_1 \cos\theta_v + \nu_2 \sin\theta_v ,$$

states
flavour physical

$$\nu^{(f)} = U \nu^{(p)} , \quad \nu^{(f)} = \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}, \quad \nu^{(p)} = \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$U = \begin{pmatrix} \cos\theta_v & \sin\theta_v \\ -\sin\theta_v & \cos\theta_v \end{pmatrix}$$

* Time evolution of ν beam

(vacuum mixing angle)

V. Gribov, B. Pontecorvo (1969)

S. Bilenky, B. Pontecorvo (1976)

Probability of finding ν_μ in an initial ν_e beam

$$* \quad P_{\nu_e \nu_\mu}(x) = |\langle \nu_\mu | \nu_e \rangle_t|^2 = \sin^2 2\theta_V \sin^2\left(\frac{\pi x}{L_v}\right),$$

$$L_v = \frac{4\pi E}{|m_1^2 - m_2^2|}, \quad (E \simeq |\vec{p}|),$$

② 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

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

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

ν evolution equation

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

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

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

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

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

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

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

- Resonance amplification of oscillations in matter:

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

Akhmedov, 1988
Lim, Marciano

… similar to MSW effect

In magnetic field

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

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

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

① ν

P. Pustoshny, A. Studenikin

Neutrino spin $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_e^R$ and

spin-flavour $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_\mu^R$

oscillations engendered

by transversal matter currents $j_\perp$

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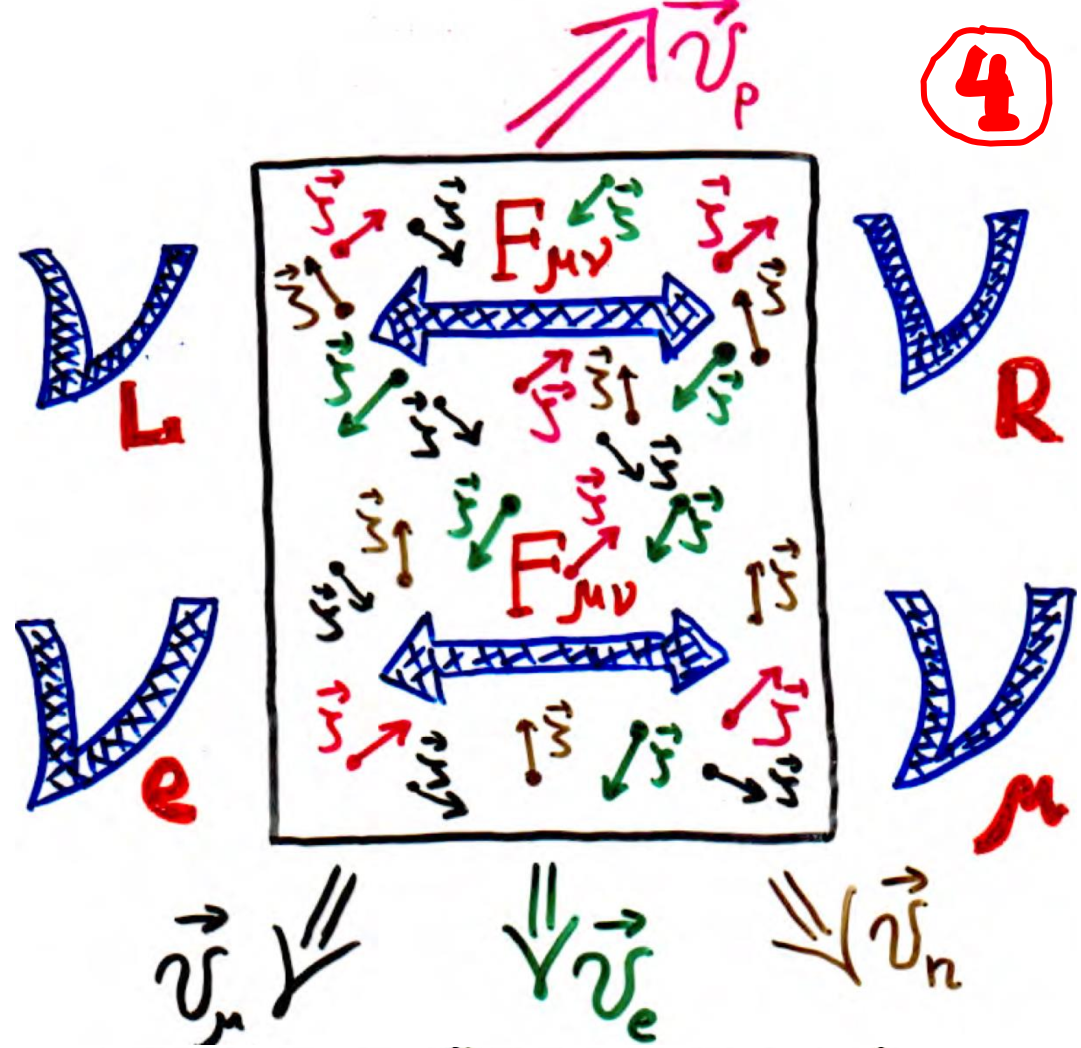
- neutrino spin and flavor oscillations in moving matter

A.Egorov, A.Lobanov, A.Studenikin, Phys.Lett.B 491 (2000) 137

A.Lobanov, A.Studenikin, Phys.Lett.B 515 (2001) 94

A.Lobanov, A.Grigoriev, A.Studenikin, Phys.Lett.B 535 (2002) 187



moving matter components

$f = e, n, p, \mu$, etc

with polarizations

$\vec{\xi}, \vec{\xi}, \vec{\xi}, \vec{\xi}$, etc

... once more...

For SM+SU(2)-singlet ν_R and matter $f=e$

Bargmann-Michel-Telegdi eq

$$\frac{d\vec{S}_\nu}{dt} = \frac{2\mu_\nu}{\gamma_\nu}\left[\vec{S}_\nu \times (\vec{B}_0 + \vec{M}_0)\right],$$

interaction of neutrino with an electromagnetic field

in rest frame of neutrino

$$\vec{B}_0 = \gamma_\nu\left(\vec{B}_\perp + \frac{1}{\gamma_\nu}\vec{B}_\parallel + \sqrt{1-\frac{1}{\gamma_\nu^2}}\left[\vec{E}_\perp \times \vec{n}\right]\right),$$

interaction of neutrino with matter

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

matter density

$\parallel$ $\perp$

$$\rho_e^{(1)} = \frac{G_F}{2\mu\sqrt{2}}(1 + 4\sin^8\theta_W),$$

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

$\Rightarrow$ ν spin procession in moving matter !!!

without any magnetic field !!!

Physics of Atomic Nuclei, Vol. 67, No. 5, 2004, pp. 993–1002. Translated from Yadernaya Fizika, Vol. 67, No. 5, 2004, pp. 1014–1024.
Original Russian Text Copyright © 2004 by Studenikin.

ELEMENTARY PARTICLES AND FIELDS
Theory

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

Neutrino in Electromagnetic Fields and Moving Media

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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.
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Consider spin / spin-flavour

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

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

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

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

A.Studenikin,
"Neutrinos in electromagnetic fields and moving media",
Phys. Atom. Nucl. 67 (2004)

- transversal current $j_\perp$

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

matter density

$\parallel$ $\perp$

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

where

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

Physics of Atomic Nuclei, Vol. 67, No. 5, 2004, pp. 993–1002. Translated from Yadernaya Fizika, Vol. 67, No. 5, 2004, pp. 1014–1024.
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Neutrino in Electromagnetic Fields and Moving Media

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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.

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

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

- J. Serreau and C. Volpe, "Neutrino-antineutrino correlations in dense anisotropic media", Phys .Rev. D90 (2014) 125040
- V. Cirigliano, 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 …

Neutrino spin (spin-flavour) oscillations in transversal matter currents
… quantum treatment …

- ν spin evolution effective Hamiltonian in moving matter ? transversal and longitudinal currents $\vec{j}_\perp + \vec{j}_\parallel$
- two flavor ν with two helicities: $\nu_f = (\nu_e^+, \nu_e^-, \nu_\mu^+, \nu_\mu^-)^T$

ν interaction with matter composed of neutrons: $n = \frac{n_0}{\sqrt{1-v^2}}$ neutron number density in laboratory reference frame

$\mathbf{v} = (v_1, v_2, v_3)$ velocity of matter

- $$L_{int} = -f^\mu \sum_l \bar{\nu}_l(x)\gamma_\mu \frac{1+\gamma_5}{2}\nu_l(x) = -f^\mu \sum_i \bar{\nu}_i(x)\gamma_\mu \frac{1+\gamma_5}{2}\nu_i(x)$$

$l = e, \text{ or } \mu$

$i = 1, 2$

$$f^\mu = -\frac{G_F}{2\sqrt{2}} j_n^\mu$$

- $$j_n^\mu = n(1, \mathbf{v})$$

$$\nu_e^\pm = \nu_1^\pm \cos\theta + \nu_2^\pm \sin\theta,$$

$$\nu_\mu^\pm = -\nu_1^\pm \sin\theta + \nu_2^\pm \cos\theta$$

ν flavour and mass states

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Two flavour ν with two helicities in moving matter

$$i\frac{d}{dt}\begin{pmatrix}\nu_e^+\\ \nu_e^-\\ \nu_\mu^+\\ \nu_\mu^-\end{pmatrix} = \left\{H_{vac}^{eff} + \Delta H^{eff}\right\}\begin{pmatrix}\nu_e^+\\ \nu_e^-\\ \nu_\mu^+\\ \nu_\mu^-\end{pmatrix}$$

$$\Delta H^{eff} = \Delta H^{eff}_{v=0} + \Delta H^{eff}_{\vec{j}_{\parallel}+\vec{j}_{\perp}}$$

$\vec{j}_{\perp} + \vec{j}_{\parallel}$

Contribution of matter currents

$$\Delta H^{eff} = \begin{pmatrix} \Delta_{ee}^{++} & \Delta_{ee}^{+-} & \Delta_{e\mu}^{++} & \Delta_{e\mu}^{+-} \\ \Delta_{ee}^{-+} & \Delta_{ee}^{--} & \Delta_{e\mu}^{-+} & \Delta_{e\mu}^{--} \\ \Delta_{\mu e}^{++} & \Delta_{\mu e}^{+-} & \Delta_{\mu\mu}^{++} & \Delta_{\mu\mu}^{+-} \\ \Delta_{\mu e}^{-+} & \Delta_{\mu e}^{--} & \Delta_{\mu\mu}^{-+} & \Delta_{\mu\mu}^{--} \end{pmatrix}$$

$$\Delta_{kl}^{ss'} = \langle \nu_k^s | \Delta H^{SM} | \nu_l^{s'} \rangle \quad k,l = e,\mu \qquad s,s' = \pm$$

$$\Delta H^{SM} = -\frac{G_F}{2\sqrt{2}}\frac{n}{\sqrt{1-v^2}}\left(1-\gamma_0\boldsymbol{\gamma}\mathbf{v}\right)\left(1+\gamma_5\right)$$

$$\nu_e^{\pm} = \nu_1^{\pm}\cos\theta + \nu_2^{\pm}\sin\theta, \qquad \nu_\mu^{\pm} = -\nu_1^{\pm}\sin\theta + \nu_2^{\pm}\cos\theta$$

$$\gamma_{\alpha\alpha'}{}^{-1} = \frac{1}{2}\left(\gamma_\alpha^{-1} + \gamma_{\alpha'}^{-1}\right) \qquad \widetilde{\gamma}_{\alpha\alpha'}^{-1} = \frac{1}{2}\left(\gamma_\alpha^{-1} - \gamma_{\alpha'}^{-1}\right)$$

$$\Delta_{\alpha\alpha'}^{ss'} = \frac{G_F}{2\sqrt{2}}\frac{n_0}{\sqrt{1-v^2}}\left\{u_\alpha^{s\,T}\left[\left(1-\sigma_3\right)\left(v_{\parallel}-1\right) + \left(\gamma_{\alpha\alpha'}{}^{-1}\sigma_1 + i\widetilde{\gamma}_{\alpha\alpha'}^{-1}\sigma_2\right)v_{\perp}\right]u_{\alpha'}^{s'}\right\} \alpha = 1,2$$

$$\Delta_{\alpha\alpha'}^{ss'} = \frac{G_F}{2\sqrt{2}}\frac{n_0}{\sqrt{1-v^2}}\left\{u_\alpha^{s\,T}\left[\begin{pmatrix}0 & 0\\ 0 & 2\end{pmatrix}\left(v_{\parallel}-1\right) + \begin{pmatrix}0 & \gamma_\alpha^{-1}\\ \gamma_{\alpha'}^{-1} & 0\end{pmatrix}v_{\perp}\right]u_{\alpha'}^{s'}\right\}$$

$$u^+ = \begin{pmatrix}1\\0\end{pmatrix}, \qquad u^- = \begin{pmatrix}0\\1\end{pmatrix}$$

two helicity states $s,s' = \pm$

$$\gamma_\alpha^{-1} = \frac{m_\alpha}{E_\alpha}$$

Studenikin, PoS (2017) NOW2016_070, arXiv:1610.06563
J.Phys.Conf.Ser. 888 (2017) 012221

- longitudinal currents $j_{\parallel}$ do not change ν helicity
- transversal currents $j_{\perp}$ do change ν helicity

Two flavour ν with two helicities $\nu_f = (\nu_e^+, \nu_e^-, \nu_\mu^+, \nu_\mu^-)^T$

in moving matter $\vec{j}_\perp + \vec{j}_\parallel$ and $\vec{B} = \vec{B}_\perp + \vec{B}_\parallel$

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ν evolution equation

$$i\frac{d}{dt}\nu_f = \Big(H_{vac} + \Delta H_{\boldsymbol{j}} + \Delta H_{\boldsymbol{B}}\Big)\nu_f$$

$$\nu_e^\pm = \nu_1^\pm \cos\theta + \nu_2^\pm \sin\theta, \qquad \nu_\mu^\pm = -\nu_1^\pm \sin\theta + \nu_2^\pm \cos\theta$$

$$\Delta H_{\boldsymbol{j}} = n\tilde{G}\begin{pmatrix} 0 & (\frac{\eta}{\gamma})_{ee}v_\perp & 0 & (\frac{\eta}{\gamma})_{e\mu}v_\perp \\ (\frac{\eta}{\gamma})_{ee}v_\perp & 2(1-v_\parallel) & (\frac{\eta}{\gamma})_{e\mu}v_\perp & 0 \\ 0 & (\frac{\eta}{\gamma})_{e\mu}v_\perp & 0 & (\frac{\eta}{\gamma})_{\mu\mu}v_\perp \\ (\frac{\eta}{\gamma})_{e\mu}v_\perp & 0 & (\frac{\eta}{\gamma})_{\mu\mu}v_\perp & 2(1-v_\parallel) \end{pmatrix}$$

$$\left(\frac{\eta}{\gamma}\right)_{ee} = \frac{\cos^2\theta}{\gamma_{11}} + \frac{\sin^2\theta}{\gamma_{22}}$$

$$\left(\frac{\eta}{\gamma}\right)_{\mu\mu} = \frac{\sin^2\theta}{\gamma_{11}} + \frac{\cos^2\theta}{\gamma_{22}}$$

$$\left(\frac{\eta}{\gamma}\right)_{e\mu} = \frac{\sin 2\theta}{\tilde{\gamma}_{21}}$$

$$\gamma_{\alpha\alpha'}{}^{-1} = \frac{1}{2}(\gamma_\alpha^{-1} + \gamma_{\alpha'}^{-1})$$

$$\tilde{\gamma}_{\alpha\alpha'}^{-1} = \frac{1}{2}(\gamma_\alpha^{-1} - \gamma_{\alpha'}^{-1})$$

$$\gamma_\alpha^{-1} = \frac{m_\alpha}{E_\alpha} \qquad \alpha = 1, 2$$

moving matter

$$\mathbf{v} = (v_1, v_2, v_3)$$

$$n = \frac{n_0}{\sqrt{1-v^2}}$$

$$f^\mu = -\frac{G_F}{2\sqrt{2}} j_n^\mu$$

$$j_n^\mu = n(1, \mathbf{v})$$

neutron number density in laboratory reference frame

Two flavour ν with two helicities $\nu_f = (\nu_e^+, \nu_e^-, \nu_\mu^+, \nu_\mu^-)^T$

in moving matter $\vec{j}_\perp + \vec{j}_\parallel$ and $\vec{B} = \vec{B}_\perp + \vec{B}_\parallel$

$$\nu_e^\pm = \nu_1^\pm \cos\theta + \nu_2^\pm \sin\theta, \qquad \nu_\mu^\pm = -\nu_1^\pm \sin\theta + \nu_2^\pm \cos\theta$$

ν evolution equation

$$i\frac{d}{dt}\nu_f = \Big(H_{vac} + \Delta H_j + \Delta H_B\Big)\nu_f$$

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no. 11, 113009

$$\Delta H_B = \begin{pmatrix} -(\frac{\mu}{\gamma})_{ee}B_{||} & \mu_{ee}B_\perp & -(\frac{\mu}{\gamma})_{e\mu}B_{||} & \mu_{e\mu}B_\perp \\ \mu_{ee}B_\perp & (\frac{\mu}{\gamma})_{ee}B_{||} & \mu_{e\mu}B_\perp & (\frac{\mu}{\gamma})_{e\mu}B_{||} \\ -(\frac{\mu}{\gamma})_{e\mu}B_{||} & \mu_{e\mu}B_\perp & -(\frac{\mu}{\gamma})_{\mu\mu}B_{||} & \mu_{\mu\mu}B_\perp \\ \mu_{e\mu}B_\perp & (\frac{\mu}{\gamma})_{e\mu}B_{||} & \mu_{\mu\mu}B_\perp & (\frac{\mu}{\gamma})_{\mu\mu}B_{||} \end{pmatrix}$$

$$\gamma_\alpha^{-1} = \frac{m_\alpha}{E_\alpha} \qquad \alpha = 1,2$$

$$\gamma_{\alpha\alpha'}^{-1} = \frac{1}{2}(\gamma_\alpha^{-1} + \gamma_{\alpha'}^{-1})$$

effective magnetic moments of ν_e and ν_μ

$$\mu_{ee} = \mu_{11}\cos^2\theta + \mu_{22}\sin^2\theta + \mu_{12}\sin 2\theta$$

$$\mu_{e\mu} = \mu_{12}\cos 2\theta + \frac{1}{2}(\mu_{22} - \mu_{11})\sin 2\theta$$

$$\mu_{\mu\mu} = \mu_{11}\sin^2\theta + \mu_{22}\cos^2\theta - \mu_{12}\sin 2\theta$$

$$\Big(\frac{\mu}{\gamma}\Big)_{ee} = \frac{\mu_{11}}{\gamma_{11}}\cos^2\theta + \frac{\mu_{22}}{\gamma_{22}}\sin^2\theta + \frac{\mu_{12}}{\gamma_{12}}\sin 2\theta$$

$$\Big(\frac{\mu}{\gamma}\Big)_{e\mu} = \frac{\mu_{12}}{\gamma_{12}}\cos 2\theta + \frac{1}{2}\Big(\frac{\mu_{22}}{\gamma_{22}} - \frac{\mu_{11}}{\gamma_{11}}\Big)\sin 2\theta$$

$$\Big(\frac{\mu}{\gamma}\Big)_{\mu\mu} = \frac{\mu_{11}}{\gamma_{11}}\sin^2\theta + \frac{\mu_{22}}{\gamma_{22}}\cos^2\theta - \frac{\mu_{12}}{\gamma_{12}}\sin 2\theta$$

ν spin oscillations in moving matter $\vec{j}_\perp + \vec{j}_{||}$ and $\vec{B} = \vec{B}_\perp + \vec{B}_{||}$

- $$\nu_e^L \Leftarrow (j_\perp, B_\perp) \Rightarrow \nu_e^R$$

ν evolution equation

$$\mu_{ee} = \mu_{11}\cos^2\theta + \mu_{22}\sin^2\theta + \mu_{12}\sin 2\theta$$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e^L \\ \nu_e^R\end{pmatrix} = \begin{pmatrix} (\frac{\mu}{\gamma})_{ee}B_{||} + \tilde{G}n(1-\boldsymbol{v\beta}) & \mu_{ee}B_\perp + (\frac{\eta}{\gamma})_{ee}\tilde{G}nv_\perp \\ \mu_{ee}B_\perp + (\frac{\eta}{\gamma})_{ee}\tilde{G}nv_\perp & -(\frac{\mu}{\gamma})_{ee}B_{||} - \tilde{G}n(1-\boldsymbol{v\beta}) \end{pmatrix}\begin{pmatrix}\nu_e^L \\ \nu_e^R\end{pmatrix}$$

$$\left(\frac{\mu}{\gamma}\right)_{ee} = \frac{\mu_{11}}{\gamma_{11}}\cos^2\theta + \frac{\mu_{22}}{\gamma_{22}}\sin^2\theta + \frac{\mu_{12}}{\gamma_{12}}\sin 2\theta$$

$$\left(\frac{\eta}{\gamma}\right)_{ee} = \frac{\cos^2\theta}{\gamma_{11}} + \frac{\sin^2\theta}{\gamma_{22}}$$

Probability of ν spin oscillations $\nu_e^L \Leftarrow (j_\perp, B_\perp) \Rightarrow \nu_e^R$

$$P_{\nu_e^L \to \nu_e^R}(x) = \sin^2 2\theta_{\text{eff}} \sin^2\frac{\pi x}{L_{\text{eff}}}$$

$$\sin^2 2\theta_{\text{eff}} = \frac{E_{\text{eff}}^2}{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2}, \quad L_{\text{eff}} = \frac{\pi}{\sqrt{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2}}$$

$j_{||}$

$$\Delta_{eff} = \left|\left(\frac{\mu}{\gamma}\right)_{ee}\boldsymbol{B}_{||} + \tilde{G}n(1-\boldsymbol{v\beta})\boldsymbol{\beta}\right|$$

$$E_{eff} = \left|\mu_{ee}\boldsymbol{B}_\perp + \left(\frac{\eta}{\gamma}\right)_{ee}\tilde{G}n\boldsymbol{v}_\perp\right|$$

$j_\perp$

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ν spin-flavour oscillations in moving matter $\vec{j}_\perp + \vec{j}_\parallel$

- $$\nu_e^L \Leftarrow (j_\perp, B_\perp) \Rightarrow \nu_\mu^R$$ and $\vec{B} = \vec{B}_\perp + \vec{B}_\parallel$

ν evolution equation

$$\mu_{ee} = \mu_{11}\cos^2\theta + \mu_{22}\sin^2\theta + \mu_{12}\sin 2\theta$$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e^L\\ \nu_e^R\end{pmatrix} = \begin{pmatrix} (\frac{\mu}{\gamma})_{ee}B_{||} + \tilde{G}n(1-\boldsymbol{v\beta}) & \mu_{ee}B_\perp + (\frac{\eta}{\gamma})_{ee}\tilde{G}nv_\perp \\ \mu_{ee}B_\perp + (\frac{\eta}{\gamma})_{ee}\tilde{G}nv_\perp & -(\frac{\mu}{\gamma})_{ee}B_{||} - \tilde{G}n(1-\boldsymbol{v\beta}) \end{pmatrix}\begin{pmatrix}\nu_e^L\\ \nu_e^R\end{pmatrix}$$

$$\left(\frac{\mu}{\gamma}\right)_{ee} = \frac{\mu_{11}}{\gamma_{11}}\cos^2\theta + \frac{\mu_{22}}{\gamma_{22}}\sin^2\theta + \frac{\mu_{12}}{\gamma_{12}}\sin 2\theta$$

$$\left(\frac{\eta}{\gamma}\right)_{ee} = \frac{\cos^2\theta}{\gamma_{11}} + \frac{\sin^2\theta}{\gamma_{22}}$$

Probability of ν spin oscillations $\nu_e^L \Leftarrow (j_\perp, B_\perp) \Rightarrow \nu_\mu^R$

$$P_{\nu_e^L\to\nu_\mu^R}(x) = \sin^2 2\theta_{\text{eff}}\sin^2\frac{\pi x}{L_{\text{eff}}}$$

$$\sin^2 2\theta_{\text{eff}} = \frac{E_{\text{eff}}^2}{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2}, \quad L_{\text{eff}} = \frac{\pi}{\sqrt{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2}}$$

$$\Delta_{eff} = \left|\Delta M - \frac{1}{2}\left(\frac{\mu_{11}}{\gamma_{11}} + \frac{\mu_{22}}{\gamma_{22}}\right)B_{||} - \tilde{G}n(1-\boldsymbol{v\beta})\right|$$

$$E_{eff} = \left|\mu_{e\mu}B_\perp + \left(\frac{\eta}{\gamma}\right)_{e\mu}\tilde{G}nv_\perp\right|$$

$$\Delta M = \frac{\Delta m^2\cos 2\theta}{4p_0^\nu}$$

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Resonance in ν spin oscillations

Probability of oscillations

$$P_{\nu^L \to \nu^R}(x) = \sin^2 2\theta_{\text{eff}} \sin^2 \frac{\pi x}{L_{\text{eff}}}$$

where $$\sin^2 2\theta_{\text{eff}} = \frac{E_{\text{eff}}^2}{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2}, \quad L_{\text{eff}} = \frac{\pi}{\sqrt{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2}}$$

resonance $$\sin^2 2\theta_{\text{eff}} = \frac{E_{\text{eff}}^2}{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2} \rightarrow 1$$

when $\Delta_{eff} \rightarrow 0$

Probabilities of oscillations in $\vec{j}_{\perp} + \vec{j}_{\parallel}$ and $\vec{B} = \vec{B}_{\perp} + \vec{B}_{\parallel}$

$$P_{\nu^L \to \nu^R}(x) = \sin^2 2\theta_{\text{eff}} \sin^2 \frac{\pi x}{L_{\text{eff}}}$$

$$\sin^2 2\theta_{\text{eff}} = \frac{E_{\text{eff}}^2}{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2}, \quad L_{\text{eff}} = \frac{\pi}{\sqrt{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2}}$$

- **Spin oscillations**

$$\nu_e^L \Leftarrow (j_\perp, B_\perp) \Rightarrow \nu_e^R$$

$$E_{eff} = \left| \mu_{ee} \boldsymbol{B}_\perp + \left(\frac{\eta}{\gamma}\right)_{ee} \widetilde{G} n \boldsymbol{v}_\perp \right|$$

$$\Delta_{eff} = \left| \left(\frac{\mu}{\gamma}\right)_{ee} \boldsymbol{B}_{||} + \widetilde{G} n (1 - \boldsymbol{v}\boldsymbol{\beta}) \boldsymbol{\beta} \right|$$

- **Spin-flavor oscillations**

$$\nu_e^L \Leftarrow (j_\perp, B_\perp) \Rightarrow \nu_\mu^R$$

$$E_{eff} = \left| \mu_{e\mu} B_\perp + \left(\frac{\eta}{\gamma}\right)_{e\mu} \widetilde{G} n v_\perp \right|$$

$$\Delta_{eff} = \left| \Delta M - \frac{1}{2}\left(\frac{\mu_{11}}{\gamma_{11}} + \frac{\mu_{22}}{\gamma_{22}}\right) B_{||} - \widetilde{G} n (1 - \boldsymbol{v}\boldsymbol{\beta}) \right|$$

$$\Delta M = \frac{\Delta m^2 \cos 2\theta}{4 p_0^\nu}$$

- **Resonance in oscillations**

$$\sin^2 2\theta_{\text{eff}} = \frac{E_{\text{eff}}^2}{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2} \longrightarrow 1$$

$$\Delta_{eff} \longrightarrow 0$$

$\Longrightarrow$

- **Criterion – oscillations are important:**

$$\sin^2 2\theta_{\text{eff}} = \frac{E_{\text{eff}}^2}{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2} \geq \frac{1}{2}$$

$$E_{eff} \geq \Delta_{eff}$$

Resonance amplification of spin oscillations in $j_\perp$ by longitudinal matter current $j_{||}$

$$\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_e^R$$

$\vec{B} = \vec{B}_\perp + \vec{B}_{||} \rightarrow 0$

Criterion – oscillations are important:

$$\sin^2 2\theta_{\rm eff} = \frac{E_{\rm eff}^2}{E_{\rm eff}^2 + \Delta_{\rm eff}^2} \geq \frac{1}{2}$$

$$E_{eff} = \left| \left(\frac{\eta}{\gamma}\right)_{ee} \tilde{G} n v_\perp \right|$$

$$\Delta_{eff} = \left| \tilde{G} n (1 - \boldsymbol{v}\boldsymbol{\beta})\boldsymbol{\beta} \right|$$

$$E_{eff} \geq \Delta_{eff}$$

$$\left(\frac{\eta}{\gamma}\right)_{ee} v_\perp \geq (1 - \boldsymbol{v}\boldsymbol{\beta})$$

In case $\Delta m = m_2 - m_1 \ll m_1, m_2$ $\rightarrow$ $\frac{1}{\gamma_\nu} = \frac{1}{\gamma_{11}} \sim \frac{1}{\gamma_{22}}$ then

$$\frac{v_\perp}{\gamma_\nu} \geq (1 - \boldsymbol{v}\boldsymbol{\beta})$$

Assuming

$m_1, m_2 \sim 0.1\, eV$ $\gamma_\nu \sim 10^7$ and if $\gamma_\nu \gg \gamma_n$ (ν 's are more relativistic then n)

$p_0^\nu \sim 10\ MeV$

$$\frac{1}{\gamma_\nu} \geq \frac{1}{\gamma_n^2}$$

… can be valid for ultrarelativistic background matter with

$\gamma_n \geq {\gamma_\nu}^{1/2} \sim 3 \times 10^3$

… the oscillation length

$$L_{eff} = \frac{\pi}{\left(\frac{\eta}{\gamma}\right)_{ee} \tilde{G} n v_\perp}$$

in this case is (for $n \sim 10^{37}\ cm^3$)

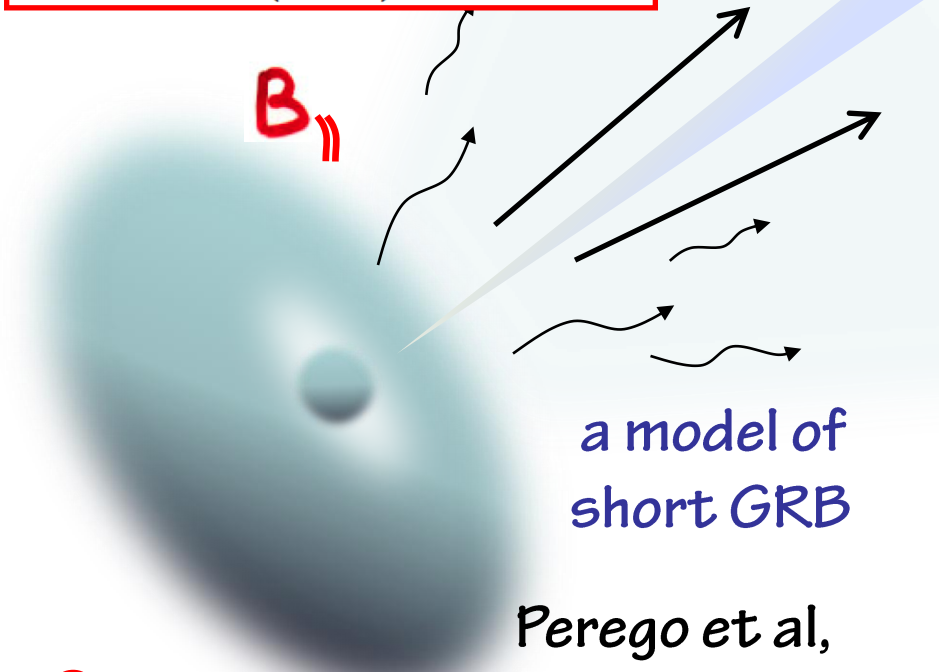
$$L_{eff} \sim 50\ km$$

$$\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_e^R$$

Resonance amplification of spin oscillations in $j_\perp$ by longitudinal magnetic field $B_{||}$

$$E_{eff} = \left| \mu_{ee} \boldsymbol{B}_\perp + \left(\frac{\eta}{\gamma}\right)_{ee} \widetilde{G} n \boldsymbol{v}_\perp \right|$$

$$\Delta_{eff} = \left| \left(\frac{\mu}{\gamma}\right)_{ee} \boldsymbol{B}_{||} + \widetilde{G} n (1 - \boldsymbol{v}\boldsymbol{\beta}) \boldsymbol{\beta} \right|$$



a model of short GRB

- Resonance $E_{eff} \geq \Delta_{eff}$

$\Delta_{eff} \longrightarrow \mathbf{0}$

was considered due to $(1 - \boldsymbol{v}\boldsymbol{\beta}) \longrightarrow \mathbf{0}$

(when $B_{||} = 0$)

Perego et al, Mon.Not.Roy.Astron.Soc. 443 (2014) 3134

Grigoriev, Lokhov, Studenikin, Ternov, JCAP 1711 (2017) 024

- Now consider resonance due to

$B_{||} \neq 0$: $\Delta_{eff} \longrightarrow \mathbf{0}$

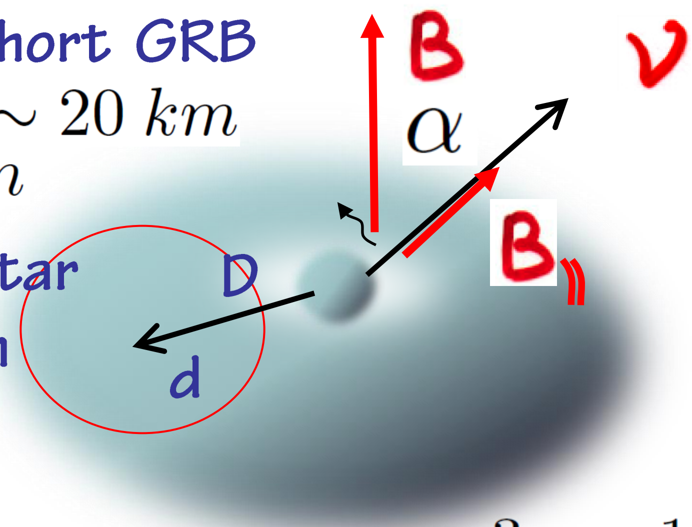
$\left(\frac{\mu}{\gamma}\right)_{ee} \boldsymbol{B}_{||}$ "eats" $\widetilde{G} n (1 - \boldsymbol{v}\boldsymbol{\beta}) \boldsymbol{\beta}$ (when $\boldsymbol{B}_{||}\boldsymbol{\beta} = -1$)

$$\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_e^R$$

a model of short GRB

$D \sim 20\ km$

$d \sim 20\ km$



- Consider ν escaping central neutron star with inclination angle α from accretion disk: $B_{||} = B \sin\alpha \sim \frac{1}{2}B$
- Toroidal bulk of rotating dense matter with $\omega = 10^3\ s^{-1}$
- transversal velocity of matter

Perego et al, Mon.Not.Roy.Astron.Soc. 443 (2014) 3134

$v_\perp = \omega D = 0.067$ and $\gamma_n = 1.002$

$$E_{eff} = \left(\frac{\eta}{\gamma}\right)_{ee} \widetilde{G} n v_\perp = \frac{\cos^2\theta}{\gamma_{11}} \widetilde{G} n v_\perp \approx \widetilde{G} n_0 \frac{\gamma_n}{\gamma_\nu} v_\perp$$

$$\Delta_{eff} = \left| \left(\frac{\mu}{\gamma}\right)_{ee} \boldsymbol{B}_{||} + \eta_{ee} \widetilde{G} n \boldsymbol{\beta} \right| \approx \left| \frac{\mu_{11}}{\gamma_\nu} B_{||} - \widetilde{G} n_0 \gamma_n \right|$$

$$\boldsymbol{B}_{||}\boldsymbol{\beta} = -1$$

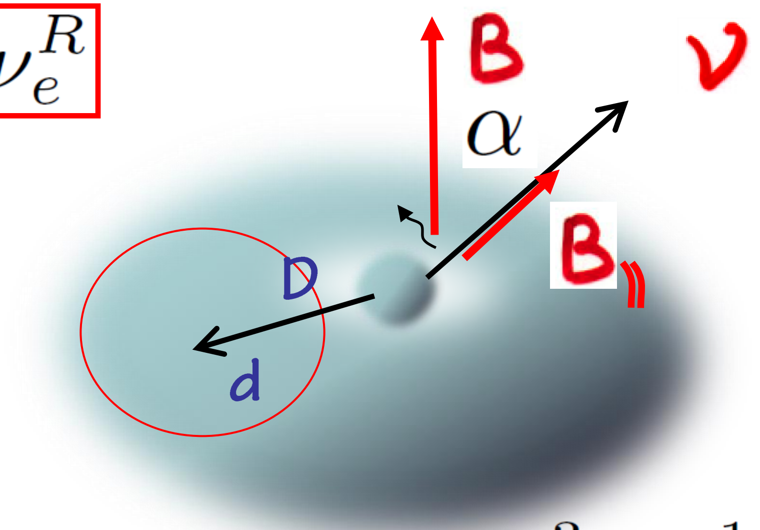
$$E_{eff} \geq \Delta_{eff}$$

resonance condition

$$\left| \frac{\mu_{11} B_{||}}{\widetilde{G} n_0 \gamma_n} - \gamma_\nu \right| \leq 1$$

$$\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_e^R$$

resonance in magnetic field



$$\left| \frac{\mu_{11} B_{||}}{\tilde{G} n_0 \gamma_n} - \gamma_\nu \right| \le 1$$

$$B_{||} = B_{||}^{cr} \sim \gamma_n \gamma_\nu \frac{\tilde{G} n_0}{\mu_{11}}$$

$$\omega = 10^3 \; s^{-1}$$

- **if** $\mu_{11} \sim 3 \times 10^{-11} \mu_B$ $\quad \gamma_\nu = 2 \times 10^7$

  $n_0 \sim 10^{23} \; cm^{-3}$ $\Rightarrow$ $B_{||}^{cr} \sim 8 \times 10^{-3} B_0$

  $B_0 = \frac{m_e^2}{e_0} = 4.41 \times 10^{13} \; Gauss$

- **if** $n_0 \sim 10^{36} \; cm^{-3}$ $\Rightarrow$ $B_{||}^{cr} \sim 10^{24} \; Gauss$

- **however,** $L_{eff} = \frac{\pi}{(\frac{\eta}{\gamma})_{ee} \tilde{G} n v_\perp}$ $\Rightarrow$ $L_{eff} \sim 300 \; km$

Resonance amplification of spin-flavor oscillations (in the absence of $j_{\parallel}$)

$$\nu_e^L \Leftarrow (j_\perp, B_\perp) \Rightarrow \nu_\mu^R$$

$\vec{B} = \vec{B}_\perp + \vec{B}_\parallel \rightarrow 0$

Criterion – oscillations are important:

$$\sin^2 2\theta_{\text{eff}} = \frac{E_{\text{eff}}^2}{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2} \geq \frac{1}{2}$$

$$E_{eff} = \left| \mu_{e\mu} B_\perp + \left(\frac{\eta}{\gamma}\right)_{e\mu} \tilde{G} n v_\perp \right| \geq \left| \Delta M - \frac{1}{2}\left(\frac{\mu_{11}}{\gamma_{11}} + \frac{\mu_{22}}{\gamma_{22}}\right) B_\parallel - \tilde{G} n (1 - \boldsymbol{v\beta}) \right|$$

neglecting $\vec{B} = \vec{B}_\perp + \vec{B}_\parallel \rightarrow 0$:

$$L_{eff} = \frac{\pi}{\left(\frac{\eta}{\gamma}\right)_{e\mu} \tilde{G} n v_\perp} \qquad \left(\frac{\eta}{\gamma}\right)_{e\mu} \approx \frac{\sin 2\theta}{\gamma_\nu}$$

$$\left| \left(\frac{\eta}{\gamma}\right)_{e\mu} \tilde{G} n v_\perp \right| \geq \left| \Delta M - \tilde{G} n (1 - \boldsymbol{v\beta}) \right| \Longrightarrow \tilde{G} n \sim \Delta M$$

$$\tilde{G} = \frac{G_F}{2\sqrt{2}} = 0.4 \times 10^{-23} \ eV^{-2}$$

- $\Delta m^2 = 7.37 \times 10^{-5} \ eV^2$
  $\sin^2 \theta = 0.297$
  $p_0^\nu = 10^6 \ eV$

$$\Longrightarrow \Delta M = 0.75 \times 10^{-11} eV$$

$$n_0 \sim \frac{\Delta M}{\tilde{G}} = 10^{12} \ eV^3 \approx 10^{26} \ cm^{-3}$$

$$L_{eff} = \frac{\pi}{(\frac{\eta}{\gamma})_{e\mu} \tilde{G} n v_\perp} \approx 5 \times 10^{11} \ km$$

- $L_{eff} \approx 10 \ km$ (within short GRB) if $n_0 \approx 5 \times 10^{36} \ cm^{-3}$

PHYSICAL REVIEW D **98,** 113009 (2018)

Neutrino spin and spin-flavor oscillations in transversal matter currents with standard and nonstandard interactions

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VII. NEUTRINO SPIN-FLAVOR OSCILLATIONS $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_\mu^R$ ENGENDERED BY NONSTANDARD INTERACTIONS

... Account for flavour-changing ν NSI soften demand on density of transversal matter current for resonance appearance ...

②

ν

Neutrino eigenstates and flavour, spin and spin-flavour oscillations in a constant magnetic field

$$\nu_e^L \leftrightarrow \nu_\mu^L \qquad \nu_e^L \leftrightarrow \nu_e^R \qquad \nu_e^L \leftrightarrow \nu_\mu^R$$

A.Popov and A.Studenikin,

Eur. Phys .J. C79 (2019) 144, arXiv: 1902.08195

New developments in ν spin (flavour) oscillations in B

A. Dmitriev, R. Fabbricatore, A. Studenikin,
"Neutrino electromagnetic properties: new approach to oscillations in magnetic fields",
arXiv:1506.053115

A. Studenikin,
"Status and perspectives of neutrino magnetic moments",
arXiv:1603.00337

R. Fabbricatore, A. Grigoriev, A. Studenikin,
"Neutrino spin-flavour oscillations derived from the mass basis",
arXiv:1604.01245

Consider two flavour ν with two helicities as superposition of **helicity mass states** $\nu_i^{L(R)}$

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

however, $\nu_i^{L(R)}$ are not stationary states in magnetic field $\mathbf{B} = (B_\perp, 0, B_\parallel)$

$$\nu_i^L(t) = c_i^+ \nu_i^+(t) + c_i^- \nu_i^-(t),$$
$$\nu_i^R(t) = d_i^+ \nu_i^+(t) + d_i^- \nu_i^-(t)$$

$\Leftarrow$ $\nu_i^{-(+)}$ stationary states in B

- Dirac equation $(\gamma_\mu p^\mu - m_i - \mu_i \boldsymbol{\Sigma B})\nu_i^s(p) = 0$ in a constant B

$$\hat{H}_i \nu_i^s = E \nu_i^s \qquad \hat{H}_i = \gamma_0 \boldsymbol{\gamma p} + \mu_i \gamma_0 \boldsymbol{\Sigma B} + m_i \gamma_0 \quad (s = \pm 1)$$

$\mu_{ij}(i \neq j) = 0$ •

ν spin operator that commutes with $\hat{H}_i$:

"bra-ket" products

- $$\hat{S}_i = \frac{1}{N}\left[\boldsymbol{\Sigma B} - \frac{i}{m_i}\gamma_0\gamma_5[\boldsymbol{\Sigma} \times \boldsymbol{p}]\boldsymbol{B}\right]$$

$$\hat{S}_i \left|\nu_i^s\right\rangle = s \left|\nu_i^s\right\rangle, \ s = \pm 1$$

$$\langle \nu_i^s | \nu_k^{s'} \rangle = \delta_{ik}\delta_{ss'} \quad \bullet$$

$$\frac{1}{N} = \frac{m_i}{\sqrt{m_i^2 \boldsymbol{B}^2 + \boldsymbol{p}^2 B_\perp^2}}$$

- ν energy spectrum

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

It is useful to introduce spin projection operators • $\hat{P}_i^{\pm} = \frac{1 \pm \hat{S}_i}{2}$ $\Longrightarrow$ $\langle \nu_k^{s'} | \hat{P}_i^s | \nu_i^s \rangle = \delta_{ik}\delta_{ss'}$

Helicity states in terms of stationary states:

$$\nu_i^L(t) = c_i^+ \nu_i^+(t) + c_i^- \nu_i^-(t), \quad |c_i^{\pm}|^2 = \langle \nu_i^L | \hat{P}_i^{\pm} | \nu_i^L \rangle \quad (d_i^{\pm})^* c_i^{\pm} = \langle \nu_i^R | P_i^{\pm} | \nu_i^L \rangle$$

$$\nu_i^R(t) = d_i^+ \nu_i^+(t) + d_i^- \nu_i^-(t) \quad |d_i^{\pm}|^2 = \langle \nu_i^R | \hat{P}_i^{\pm} | \nu_i^R \rangle$$

c, d are time independent

Initial ν are produced mostly as lefthanded helicity states

spinor structure of ν initial and final states: $\nu_i^{L(R)} \approx \nu_i^{ch^-(ch^+)}$

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

$$|c_i^{\pm}|^2 = \frac{1}{2}\left(1 \pm \frac{m_i B_{\parallel}}{\sqrt{m_i^2 B^2 + p^2 B_{\perp}^2}}\right)$$

$$|d_i^{\pm}|^2 = \frac{1}{2}\left(1 \mp \frac{m_i B_{\parallel}}{\sqrt{m_i^2 B^2 + p^2 B_{\perp}^2}}\right)$$

$$(d_i^{\pm})^* c_i^{\pm} = \mp \frac{1}{2} \frac{p(B_1 - iB_2)}{\sqrt{m_i^2 B^2 + p^2 B_{\perp}^2}}$$

Accounting for ν stationary states propagation law $\nu_i^s(t) = e^{-iE_i^s t} \nu_i^s(0)$

space-time evolution of ν flavour state

$B_{\perp} = 0$ $\quad |c_i^+|^2 = |d_i^-|^2 = 1$

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

$$\nu_i^s \equiv \nu_i^s(0)$$

Probabilities of ν oscillations

$\nu_e^L \leftrightarrow \nu_\mu^L$ $\quad P_{\nu_e^L\to\nu_\mu^L}(t) = \left|\langle\nu_\mu^L|\nu_e^L(t)\rangle\right|^2$ $\quad \mu_\pm = \frac{1}{2}(\mu_1 \pm \mu_2)$ magnetic moments of ν mass states

$$P_{\nu_e^L\to\nu_\mu^L}(t) = \sin^2 2\theta\Big\{\cos(\mu_1 B_\perp t)\cos(\mu_2 B_\perp t)\sin^2\frac{\Delta m^2}{4p}t + \\ +\sin^2(\mu_+ B_\perp t)\sin^2(\mu_- B_\perp t)\Big\}$$

flavour

$$P_{\nu_e^L\to\nu_e^R} = \Big\{\sin(\mu_+ B_\perp t)\cos(\mu_- B_\perp t) + \cos 2\theta \sin(\mu_- B_\perp t)\cos(\mu_+ B_\perp t)\Big\}^2 \\ -\sin^2 2\theta \sin(\mu_1 B_\perp t)\sin(\mu_2 B_\perp t)\sin^2\frac{\Delta m^2}{4p}t.$$

spin

$$P_{\nu_e^L\to\nu_\mu^R}(t) = \sin^2 2\theta\Big\{\sin^2\mu_- B_\perp t\cos^2(\mu_+ B_\perp t) + \\ +\sin(\mu_1 B_\perp t)\sin(\mu_2 B_\perp t)\sin^2\frac{\Delta m^2}{4p}t\Big\}$$

spin-flavour

… interplay of oscillations on vacuum $\omega_{vac} = \frac{\Delta m^2}{4p}$ and on magnetic $\omega_B = \mu B_\perp$ frequencies

A.Popov, A.S., Eur. Phys .J. C79 (2019) 144

- For the case $\mu_1 = \mu_2$: probability of flavour oscillations

$$P_{\nu_e^L \to \nu_\mu^L} = \left(1 - \sin^2(\mu B_\perp t)\right) \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4p} t = \left(1 - P^{cust}_{\nu_e^L \to \nu_e^R}\right) P^{cust}_{\nu_e^L \to \nu_\mu^L}$$

flavour

no spin oscillations

- A.Popov, A.S., Eur. Phys .J. C79 (2019) 144

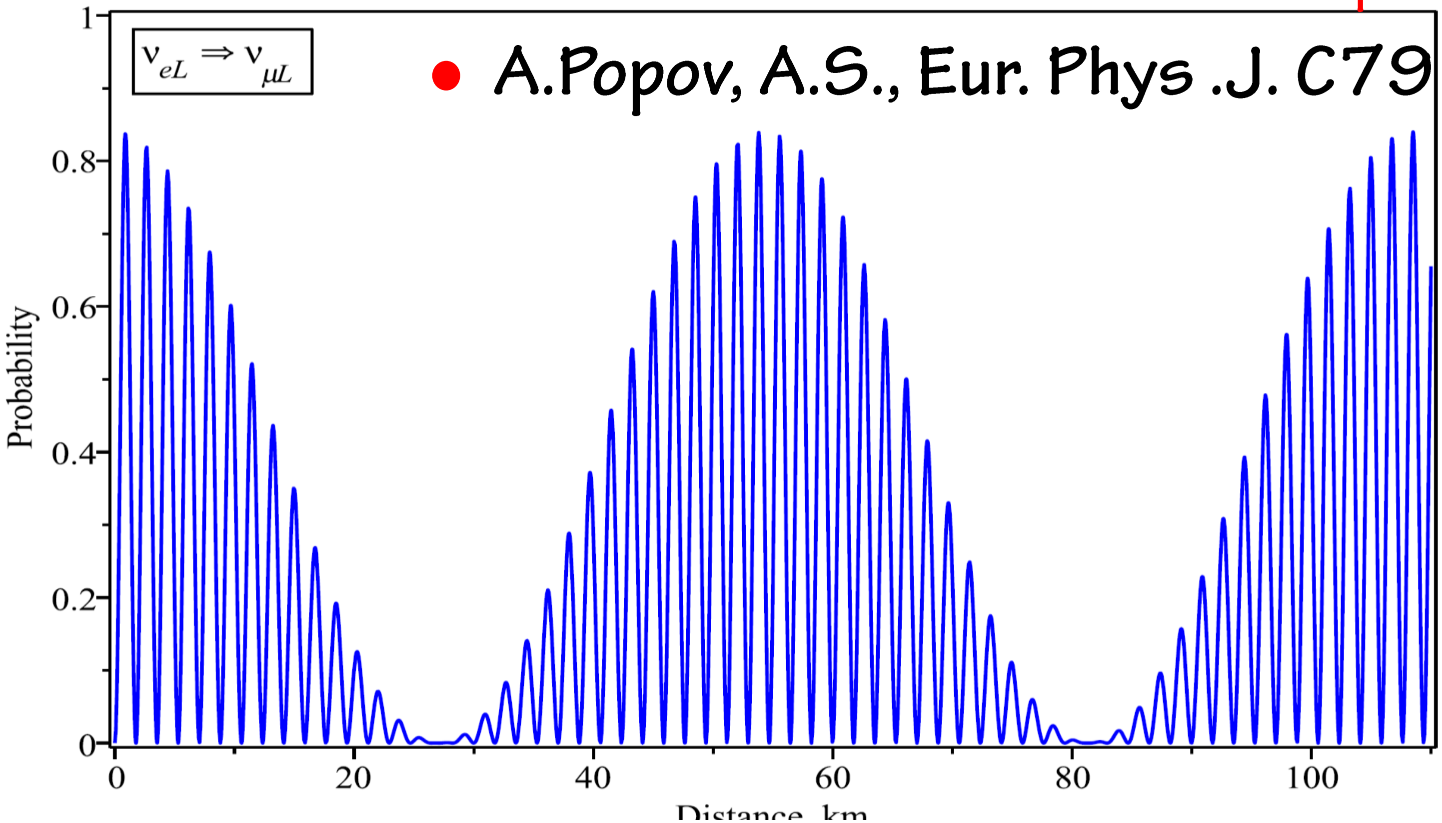

Fig. 1 The probability of the neutrino flavour oscillations $\nu_e^L \to \nu_\mu^L$ in the transversal magnetic field $B_\perp = 10^{16}\ G$ for the neutrino energy $p = 1\ MeV$, $\Delta m^2 = 7 \times 10^{-5}\ eV^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-20} \mu_B$.

Chotorlishvili, Kouzakov, Kurashvili, Studenikin, Spin-flavor oscillations of ultrahigh-energy cosmic neutrinos in interstellar space: The role of neutrino magnetic moments, Phys. Rev. D96 (2017) 103017

For the case $\mu_1 = \mu_2$: probability of spin oscillations

no flavour oscillations

$$P_{\nu_e^L \to \nu_e^R} = \left[1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4p}t\right)\right] \sin^2(\mu B_\perp t) = \left(1 - P^{cust}_{\nu_e^L \to \nu_\mu^L}\right) P^{cust}_{\nu_e^L \to \nu_e^R}$$

spin

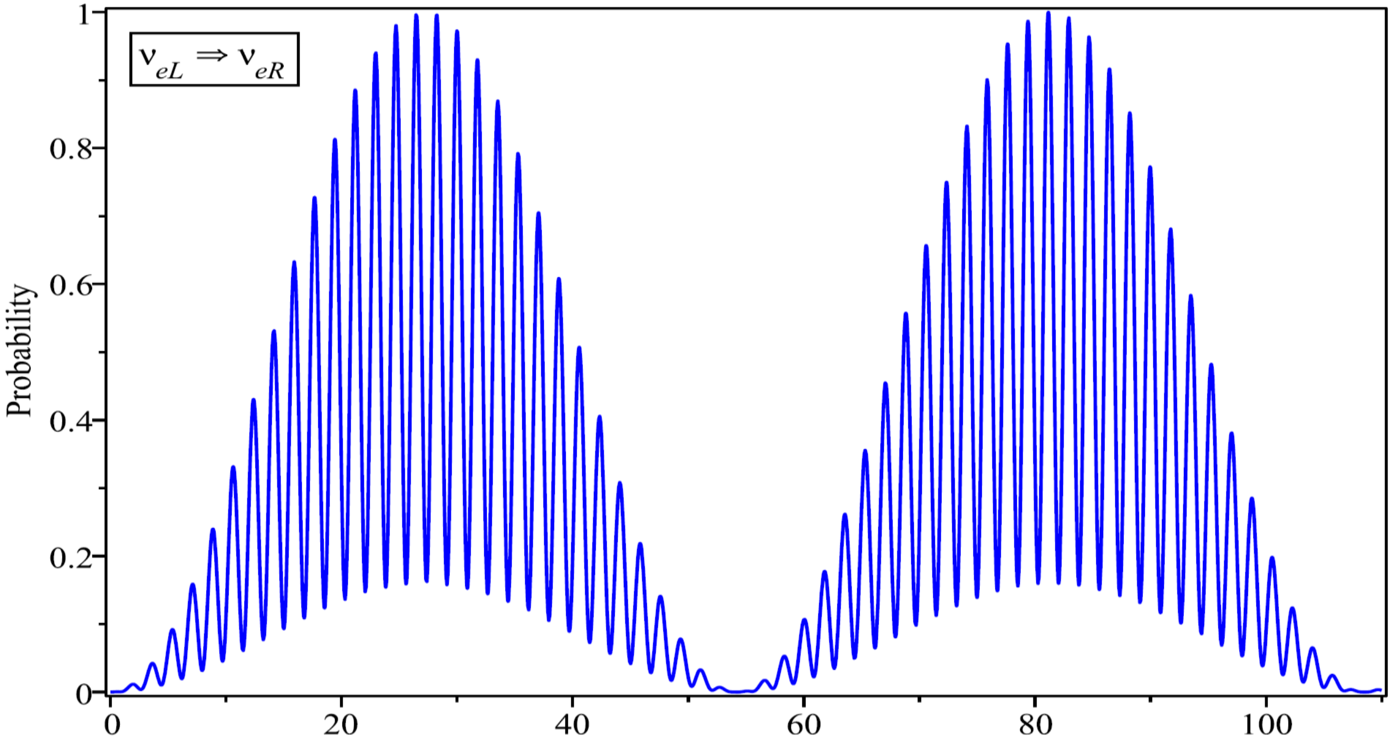

Fig. 2 The probability of the neutrino spin oscillations $\nu_e^L \to \nu_e^R$ in the transversal magnetic field $B_\perp = 10^{16}\ G$ for the neutrino energy $p = 1\ MeV$, $\Delta m^2 = 7 \times 10^{-5}\ eV^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-20}\mu_B$.

- For the case $\mu_1 = \mu_2$: probability of spin-flavour oscillations

$$P_{\nu_e^L \to \nu_\mu^R} = \sin^2(\mu B_\perp t) \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4p} t = P^{cust}_{\nu_e^L \to \nu_e^R} P^{cust}_{\nu_e^L \to \nu_\mu^L}$$

spin-flavour

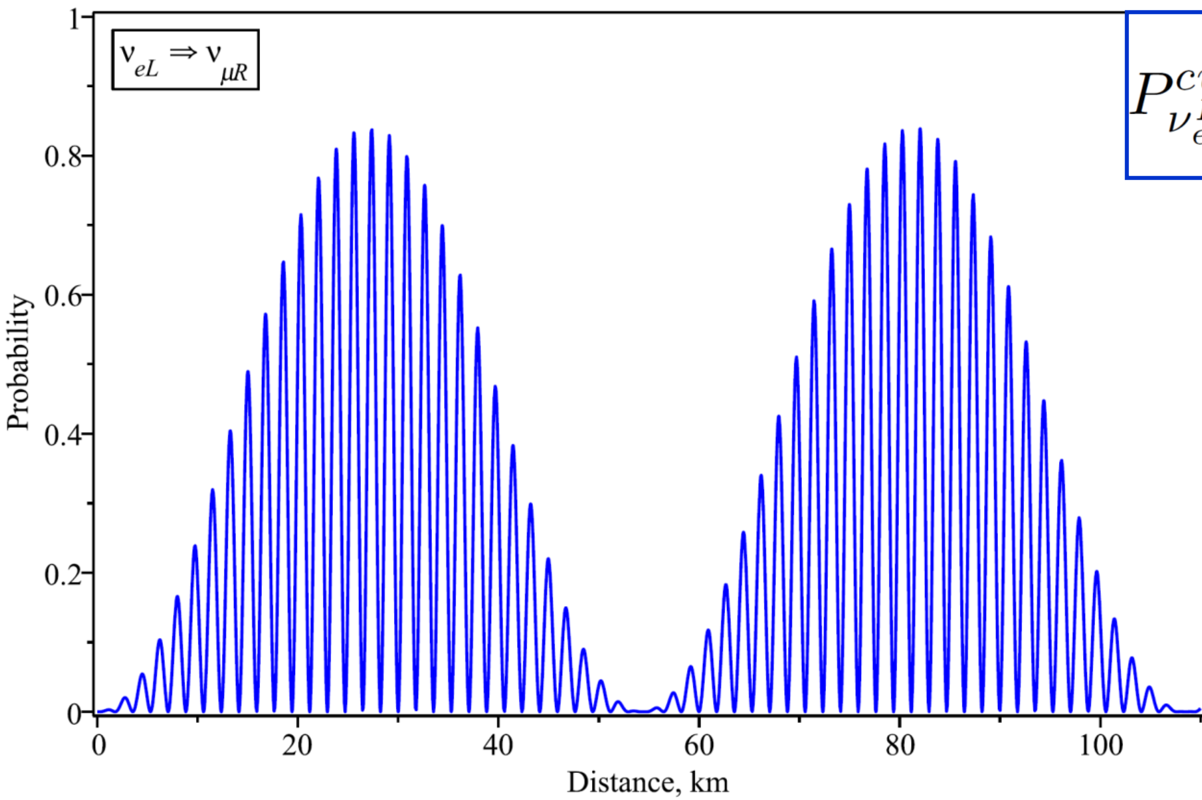

Fig. 3 The probability of the neutrino spin flavour oscillations $\nu_e^L \to \nu_\mu^R$ in the transversal magnetic field $B_\perp = 10^{16}\ G$ for the neutrino energy $p = 1\ MeV$, $\Delta m^2 = 7 \times 10^{-5}\ eV^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-20} \mu_B$.

$$P^{cust}_{\nu_e^L \to \nu_\mu^L} = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4p} t$$

$$P^{cust}_{\nu_e^L \to \nu_e^R} = \sin^2(\mu B_\perp t)$$

... interplay of oscillations on vacuum $\omega_{vac} = \frac{\Delta m^2}{4p}$ and on magnetic $\omega_B = \mu B_\perp$ frequencies

... in literature:

- $P_{\nu_e^L \nu_\mu^R} = \sin^2(\mu_{e\mu} B_\perp t) = 0$

$\mu_{e\mu} = \frac{1}{2}(\mu_2 - \mu_1) \sin 2\theta$

$\mu_1 = \mu_2, \quad \mu_{ij} = 0, \ i \neq j$

- For completeness: ν survival $\nu_e^L \leftrightarrow \nu_e^L$ probability

$$P_{\nu_e^L \to \nu_e^L}(t) = \left\{ \cos\left(\mu_+ B_\perp t\right) \cos\left(\mu_- B_\perp t\right) - \cos 2\theta \sin\left(\mu_+ B_\perp t\right) \sin\left(\mu_- B_\perp t\right) \right\}^2$$

$$- \sin^2 2\theta \cos(\mu_1 B_\perp t) \cos(\mu_2 B_\perp t) \sin^2 \frac{\Delta m^2}{4p} t$$

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

Conclusions

Conclusions

- ν electromagnetic interactions (new effects)
- two new aspects of ν spin, spin-flavour and flavour oscillations

1. generation of ν spin and spin-flavour oscillations by ν interaction with transversal matter current $j_{\perp}$
2. consistent treatment of ν spin, flavour and spin-flavour oscillations in B

P. Pustoshny, A. Studenikin, Phys. Rev. D98 (2018) no. 11, 113009

A. Popov, A. Studenikin, Eur. Phys .J. C 79 (2019) no.2, 144

③ μ_ν interactions could have important effects in astrophysical and cosmological environments

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

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

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

new effects in ν oscillations in analysis of supernovae ν fluxes

Back up slides

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ν exhibits unexpected properties (puzzles)

W. Pauli, 1930

- neutral "neutron" $\Rightarrow$ ν — Enrico Fermi, 1933

- probably $\mu_\nu \neq 0$!? — Luigi Radicati & Bruno Touschek, 1957

Pauli himself wrote to Baade:

"Today I did something a physicist should never do. I predicted something which will never be observed experimentally..."

Осцилляции нейтрино

флейворные

$\nu_e \leftrightarrow \nu_\mu$

спиновые

$\nu_L \leftrightarrow \nu_R$

flavour oscillations spin

$$P_{\nu_e \nu_\mu}(x) = \sin^2 2\theta \cdot \sin^2 \frac{\Delta m^2}{4E} x$$

$$\Delta m^2 = m_2^2 - m_1^2$$

$$P_{\nu_L \nu_R} = \sin^2 \beta \cdot \sin^2 \Omega x$$

$$\Omega = \left((\mu B)^2 + \left(\frac{\Delta_{LR}}{4E} \right)^2 \right)^{1/2}$$

$$\sin^2 \beta = \frac{(\mu B)^2}{(\mu B)^2 + (\Delta_{LR}/4E)^2}$$

resonance amplification of ν oscillation probabilities amplitudes

*

P. Pustoshny, A. S.
Phys. Rev. D98 (2018) no. 11, 113009

E. Akhmedov
C.-S. Lim, W. Marciano
(1988)

{Neutrino spin $\nu_L \overset{B_\perp}{\longleftrightarrow} \nu_R$ oscillations

(mixing due to $\frac{\Delta m_\nu^2}{2E_\nu} \sin 2\theta_{vac} \rightarrow 2\mu B_\perp$)

$$P(\nu_L \leftrightarrow \nu_R) = \sin^2 2\theta_{eff} \sin^2 \frac{\pi x}{L_{eff}},$$

$$\sin^2 2\theta_{eff} = \frac{(2\mu B_\perp)^2}{(2\mu B_\perp)^2 + \Omega^2},$$

$$* \quad \Omega = \frac{\Delta m_\nu^2}{2E_\nu} A(\theta_{vac}) - \sqrt{2} G_F n_{eff},$$

particle number density

$$L_{eff} = \frac{2\pi}{\sqrt{\Omega^2 + (2\mu B_\perp)^2}}$$

$\Omega^2 \rightarrow 0$: resonance in $\nu_L \leftrightarrow \nu_R$ neutrino spin oscillations

$\Downarrow$

Spin and spin-flavour oscillations for $\nu_\odot$ and ν_{SN}

Bruno Pontecorvo,
«Mesonium and anti-mesonium»,
Sov.Phys.JETP 6 (1957) 429
Zh.Eksp.Teor.Fiz. 33 (1957) 549-551:

if
$m_\nu \neq 0$
then
$\nu \leftrightarrow \bar{\nu}$
In vacuum

«It was assumed above that there exists a conservation law for the neutrino charge, according to which a neutrino cannot change into an antineutrino in any approximation. This law has not yet been established; evidently it has been merely shown that the neutrino and antineutrino are not identical particles.

If the two-component neutrino theory should turn out to be incorrect … and if the conservation law of neutrino charge would not apply, then in principle neutrino – antineutrino transitions could take place in vacuo»

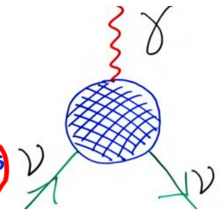
Electromagnetic Properties of ν

(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

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

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

②

$$\mu_{jj}^D = \frac{3e_0 G_F m_j}{8\sqrt{2}\pi^2} \approx 3.2\times 10^{-19}\mu_B \left(\frac{m_j}{1\ \text{eV}}\right)$$

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

$\mu_\nu^{eff} < 2.8 \times 10^{-11}\mu_B$ (2.9 / 2.8 / ~0.1)

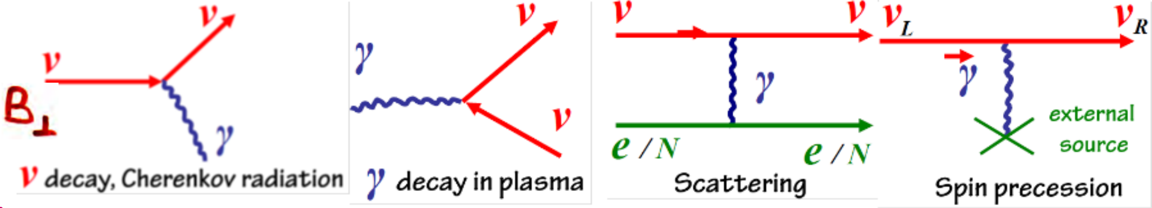
- 2.9 — GEMMA Coll. 2012
- 2.8 — Borexino Coll. 2017
- ~0.1 — Astrophysics, Raffelt ea 1988, Arcoa Dias ea 2015

$q_{\nu_e} <$
- $\sim 10^{-12}$ — reactor ν scattering: AS '14, Chen ea '14
- $\sim 10^{-19}$ — AS '14 (astrophysics)
- $\sim 10^{-21}$ — neutrality of matter

e_0

Effects of ν magnetic moment:

- spin precession and oscillations in $B_\perp$



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

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

Kouzakov & AS, **PRD 96 (2017)**

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

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

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

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

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

Popov & AS, Eur. Phys .J. C 79 (2019) no.2, 144

probability of spin oscillations depends on Δm^2

$$P_{\nu_e^L \to \nu_e^R} = \left\{ \sin(\mu_+ B_\perp t)\cos(\mu_- B_\perp t) + \cos 2\theta \sin(\mu_- B_\perp t)\cos(\mu_+ B_\perp t) \right\}^2 - \sin^2 2\theta \sin(\mu_1 B_\perp t)\sin(\mu_2 B_\perp t)\sin^2 \frac{\Delta m^2}{4p} t$$

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

Pustoshny & AS, Phys. Rev. D98 (2018) 113009

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

new mechanism of EM radiation by ν

JCAP 1711 (2017) no. 11, 024

"SL ν in astrophysical environments"