New effects in ν flavour, spin and spin flavour oscillations

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50 years of ν oscillation formulae
Gribov & Pontecorvo (1969)

new developments in ν spin and flavour scillations

(1) generation of ν spin (flavour) oscillations by interaction with transversal matter current $j_\perp$

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) inherent interplay of ν spin and flavour oscillations in B

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

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 $\Rightarrow$ 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

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 $B = |\mathbf{B}_\perp| e^{i\phi(t)}$

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

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

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

- Resonance amplification of oscillations in matter:

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

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

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 $j_\perp$

~~$(\mu_\nu B)_\perp$~~

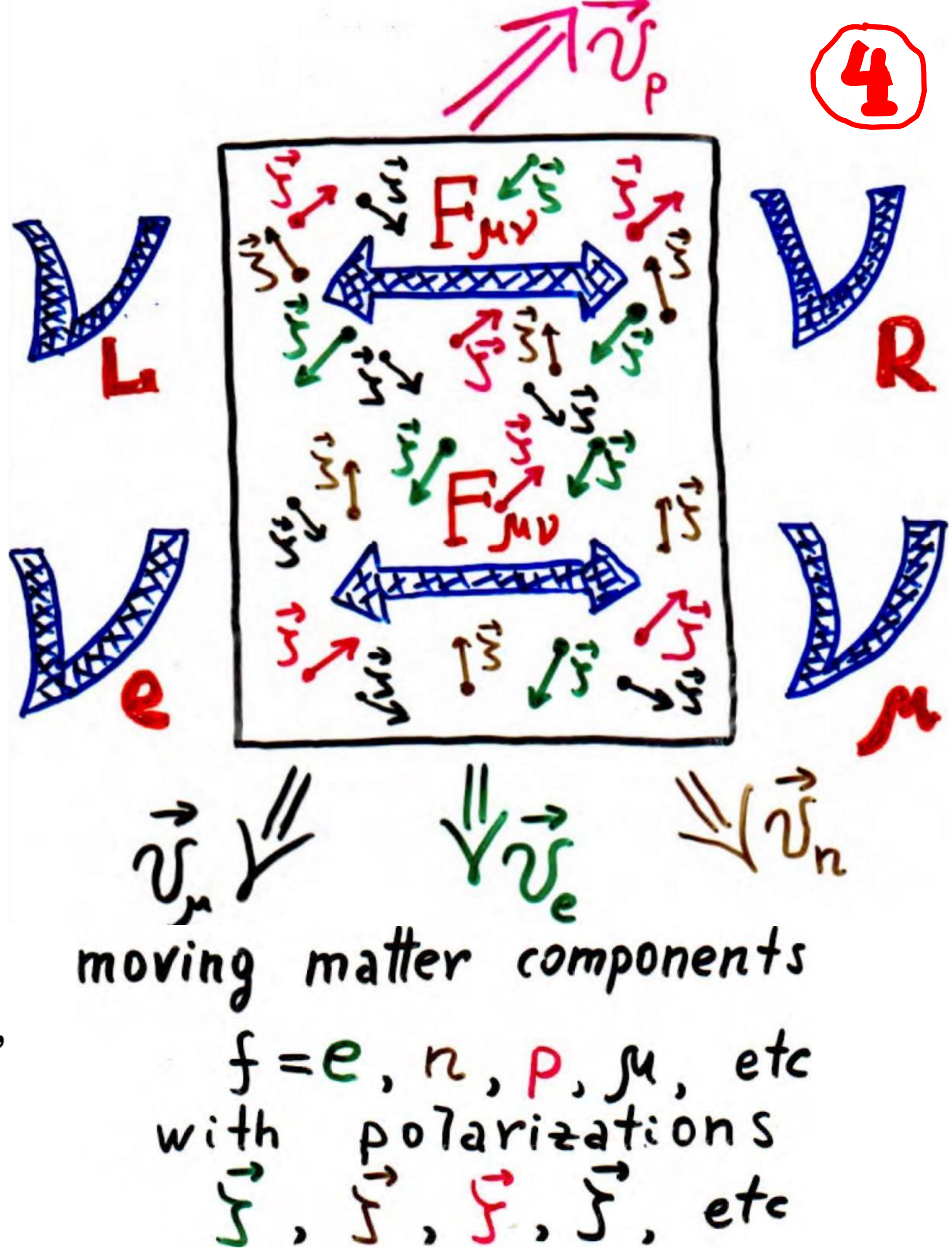
P. Pustoshny, A. Studenikin,
"Neutrino spin and spin-flavour oscillations in transversal matter currents with standard and non-standard interactions"
Phys. Rev. D98 (2018) no. 11, 113009

- 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



… 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

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

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

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

matter density

$\parallel$ $\perp$

ν spin procession in moving matter !!!

without any magnetic field !!!

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

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

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:

$$\dot{\vec{\zeta}}_\nu = 2g_a\left\{A^0[\vec{\zeta}_\nu \times \vec{\beta}] - \frac{m_\nu}{E_\nu}[\vec{\zeta}_\nu \times \vec{A}] - \frac{E_\nu}{E_\nu+m_\nu}(\vec{A}\vec{\beta})[\vec{\zeta}_\nu \times \vec{\beta}]\right\} \\ +2g_t\left\{[\vec{\zeta}_\nu \times \vec{b}] - \frac{E_\nu}{E_\nu+m_\nu}(\vec{\beta}\vec{b})[\vec{\zeta}_\nu \times \vec{\beta}] + [\vec{\zeta}_\nu \times [\vec{a} \times \vec{\beta}]]\right\} + \\ +2ig_t'\left\{[\vec{\zeta}_\nu \times \vec{c}] - \frac{E_\nu}{E_\nu+m_\nu}(\vec{\beta}\vec{c})[\vec{\zeta}_\nu \times \vec{\beta}] - [\vec{\zeta}_\nu \times [\vec{d} \times \vec{\beta}]]\right\}.$$

- ***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**

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

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

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Важнейшим новым эффектом, который следует из проведенного в разделе 4 настоящей статьи исследования спиновых осцилляций нейтрино, является возможность возникновения такого рода осцилляций (например, $\nu_{e_L} \leftrightarrow \nu_{e_R}$) за счет взаимодействия нейтрино с веществом при условии, что существует ненулевая поперечная компонента тока или поляризации вещества, т.е. $\vec{M}_{0_\perp} \neq 0$. До сих пор считалось, что спиновые осцилляции нейтрино могут возникать лишь в случае, если в системе покоя нейтрино существует ненулевое поперечное магнитное поле.

$B_\perp$

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

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 $j_\perp$

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

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

matter density

$\parallel$ $\perp$

where

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

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

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

- V. Cirigliano, G. M. Fuller, and A. Vlasenko, "A new spin on neutrino quantum kinetics" Phys. Lett. B747 (2015) 27
- J. Serreau and C. Volpe, "Neutrino-antineutrino correlations in dense anisotropic media", Phys .Rev. D90 (2014) 125040
- 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: $n = \dfrac{n_0}{\sqrt{1-v^2}}$ neutron number density in laboratory reference frame

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

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

$l = e,\ or\ \mu$

$i = 1,\ 2$

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

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

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

ν flavour and mass states

P. Pustoshny, A. Studenikin,

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

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

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

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

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

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

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

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

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

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

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

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

!

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

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

ν (2 flavours x 2 helicities) evolution equation

$$i\frac{d}{dt}\nu_f^s = \left(H_0 + \Delta H_0^{SM} + \Delta H_{j_{||}+j_{\perp}}^{SM} + \Delta H_{B_{||}+B_{\perp}}^{SM} + \Delta H_0^{NSI} + \Delta H_{j_{||}+j_{\perp}}^{NSI}\right)\nu_f^s$$

- H_0: vacuum
- ΔH_0^{SM}: matter at rest
- $\Delta H_{j_{||}+j_{\perp}}^{SM}$: moving matter
- $\Delta H_{B_{||}+B_{\perp}}^{SM}$: B
- ΔH_0^{NSI}: matter at rest
- $\Delta H_{j_{||}+j_{\perp}}^{NSI}$: moving matter

Standard Model (matter at rest, moving matter)

Non-Standard Interactions (matter at rest, moving matter)

Resonant amplification of ν oscillations:

- $\nu_e^L \Leftarrow (j_{\perp}) \Rightarrow \nu_e^R$ by longitudinal matter current $j_{||}$
- $\nu_e^L \Leftarrow (j_{\perp}) \Rightarrow \nu_e^R$ by longitudinal $B_{||}$
- $\nu_e^L \Leftarrow (j_{\perp}) \Rightarrow \nu_\mu^R$ by matter-at-rest effect
- $\nu_e^L \Leftarrow (j_{\perp}^{NSI}) \Rightarrow \nu_\mu^R$ by matter-at-rest effect

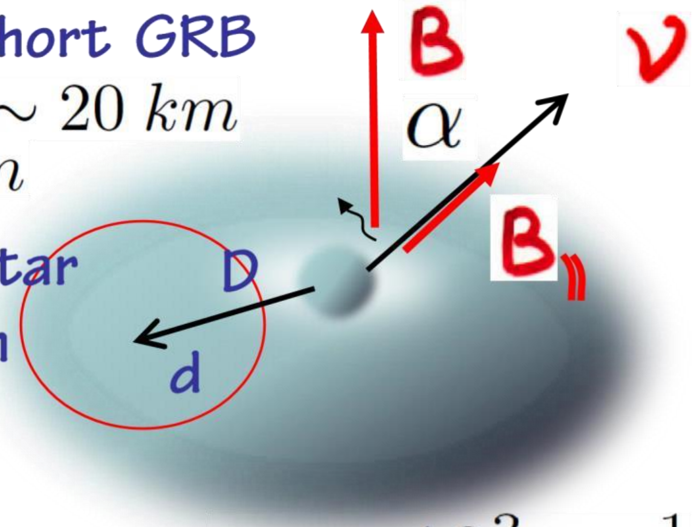
P. Pustoshny, A. Studenikin, Phys. Rev. D98 (2018) no. 11, 113009

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

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: $B_{\parallel} = B \sin\alpha \sim \frac{1}{2} B$

- Toroidal bulk of rotating dense matter with $\omega = 10^3\ s^{-1}$

- transversal velocity of matter

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

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

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

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

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

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

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

resonance condition

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

•

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:

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

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

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

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

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

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

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

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

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

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

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

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, A.Studenikin,

Eur. Phys .J. C79 (2019) 144,

arXiv: 1902.08195

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

$\hat{H}_i \nu_i^s = E\nu_i^s$ $\quad \hat{H}_i = \gamma_0 \boldsymbol{\gamma p} + \mu_i \gamma_0 \boldsymbol{\Sigma B} + m_i \gamma_0$ $\quad (s = \pm 1)$ $\quad \mu_{ij}(i \neq j) = 0$ •

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

"bra-ket" products

- $\hat{S}_i = \frac{1}{N}\left[\boldsymbol{\Sigma B} - \frac{i}{m_i}\gamma_0\gamma_5[\boldsymbol{\Sigma} \times \boldsymbol{p}]\boldsymbol{B}\right]$ $\quad \hat{S}_i \left|\nu_i^s\right\rangle = s\left|\nu_i^s\right\rangle, s = \pm 1$ $\quad \langle \nu_i^s | \nu_k^{s'} \rangle = \delta_{ik}\delta_{ss'}$ •

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

- ν energy spectrum

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

Probabilities of ν oscillations (flavour, spin and spin-flavour)

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

$\mu_\pm = \frac{1}{2}(\mu_1 \pm \mu_2)$ magnetic moments of ν mass states

flavour

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

spin

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

spin-flavour

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

... 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

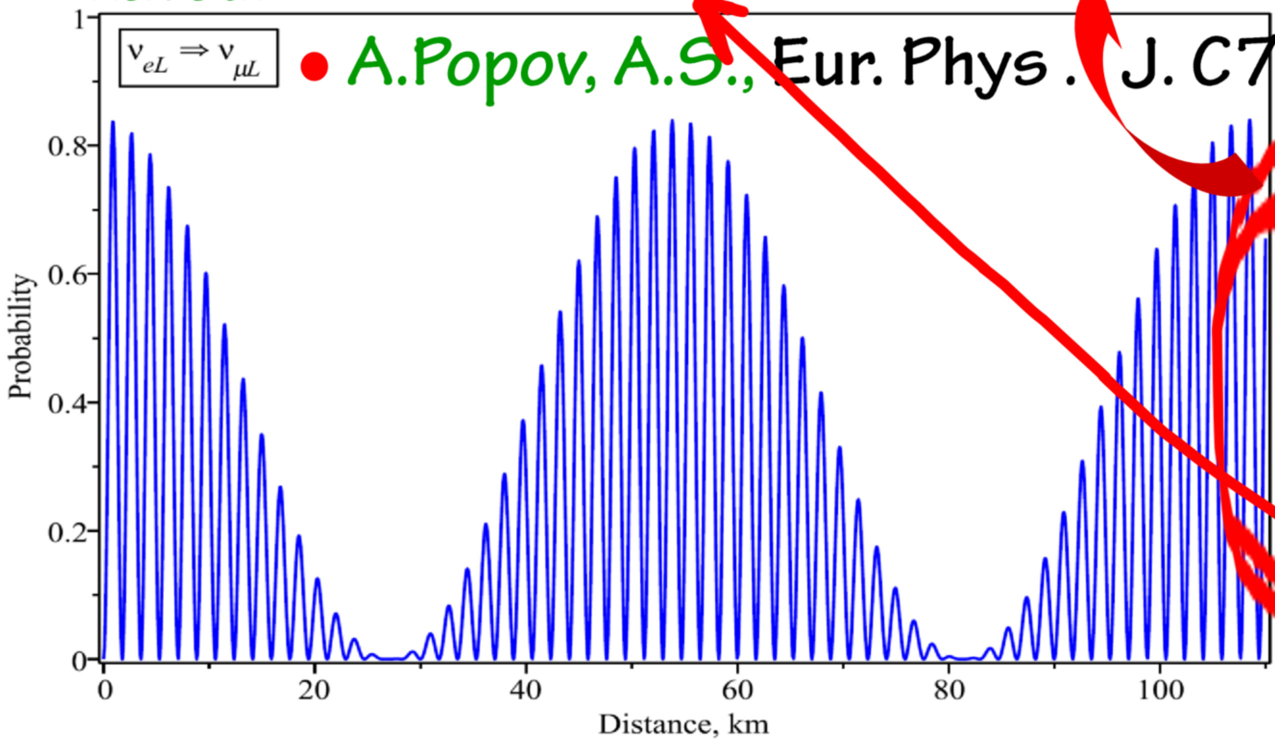
• For the case $\mu_1 = \mu_2$: probability of flavour oscillations

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

flavour

no spin oscillations

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



... amplitude of flavour oscillations on vacuum frequency $\omega_{vac} = \frac{\Delta m^2}{4p}$ is modulated by magnetic frequency $\omega_B = \mu B_\perp$

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 $\mu_1 = \mu_2 = 10^{-20} \mu_B$.

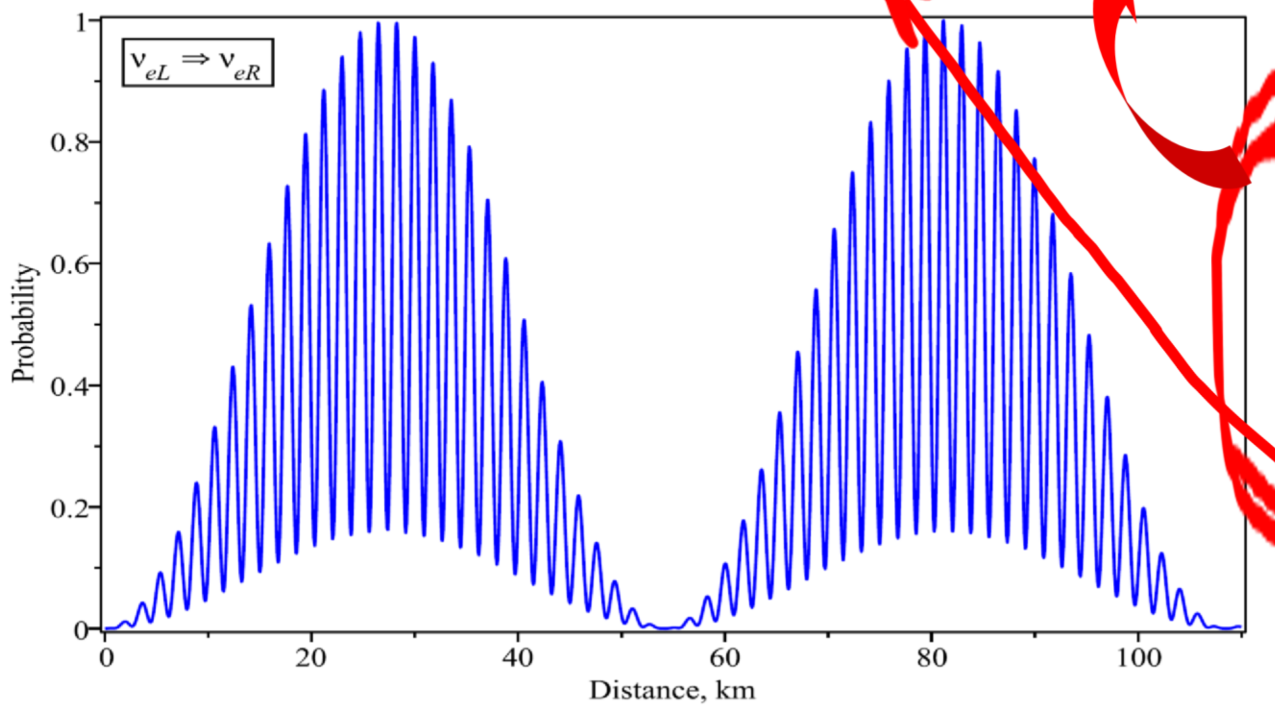
Chotorlishvili, Kouzakov, Kurashvili, Studenikin, Spin-flavor oscillations of ultrahigh-energy cosmic neutrinos in interstellar space: The role of neutrino magnetic moments, Phys. Rev. D96 (2017) 103017

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



... amplitude of spin oscillations on magnetic frequency $\omega_B = \mu B_\perp$ is modulated by vacuum frequency $\omega_{vac} = \frac{\Delta m^2}{4p}$

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 $\mu_1 = \mu_2 = 10^{-20}\mu_B$.

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Conclusions

③ 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 $j_\perp$

P. Pustoshny, A. Studenikin, Phys.Rev. D98 (2018) 113009

2 consistent treatment of ν spin, flavour and spin-flavour oscillations in B

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new effects in ν oscillations in analysis of supernovae ν fluxes (for JUNO ?)

Thank you