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Outline(1)

(short) review of ${oldsymbol {\mathcal V}}$ electromagnetic properties



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Neutrino electromagnetic interactions: A window to new physics

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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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The European Physical Society Conference on High Energy Physics, 10-17 July 2019, Ghent, Belgium Constraints on neutrino millicharge and charge radius from neutrino-atom scattering

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Introduction

n the standard model neutrinos are massless left-handed fermions which very weakly interact In the satisfield model neutrino are masses intertubuted terminos which very weakly interact in matter via exchange of the V_{i} and V_{i} becomes. The development of our knowledge about the satisfield of the system of the standard model (BSM). In this respect, the study of neurambing electromagnetic inductions of the satisfield som uneres and/or to min a new proposes. The effects or neurine section agreed properties and be searched in astrophysical environments, where neutrinos from various so curces. In he latter case, a very sensitive method is provided by the direct measurement of low-energy elas-ic neutrino scattering on atomic electrons and nuclei in a detector. A general strategy of such periments consists in determining deviations of the scattering cross section differential with spect to the energy transfer from the value predicted by the standard model of the electroweak tetraction. In this contribution, we present our bounds on the neutrino millicharge [7] and harge radii [9] that have been derived from the data of the GEMMA [3] and COHERENT [4] attering experiments, respectively, and included in the Particle Data Group's Review of Partic

Electromagnetic properties of massive neutrinos

Here we briefly outline the general form of the electromagnetic interactions of Dirac and Ma-orana neutrinos. There are at least three massive neutrino fields ν_i with respective masses m_i (i = (j = 0.000), j = 0.000, j

$$\mathcal{H}_{em}^{(\nu)} = j_{\mu}^{(\nu)}A^{\mu} = \sum_{i=1}^{3} \overline{\nu}_{f}\Lambda_{\mu}^{fi}\nu_{i}A^{\mu},$$

where we take into account possible transitions between different massive neutrinos. The physial effect of $\mathcal{H}_{em}^{(\nu)}$ is described by the effective electromagnetic vertex, which in momentum-space presentation depends only on the four-momentum $q = p_i - p_f$ transferred to the photon and n be expressed as follows:

$$\Lambda_{\mu}(q) = \left(\gamma_{\mu} - q_{\mu}q/q^2\right) \left[f_Q(q^2) + f_A(q^2)q^2\gamma_5\right] - i\sigma_{\mu\nu}q^{\nu}\left[f_M(q^2) + if_E(q^2)\gamma_5\right].$$

Here $\Lambda_{\mu}(q)$ is a 3×3 matrix in the space of massive neutrinos expressed in terms of the four Heritian 3×3 matrices of form factors

$$q = f_Q^{\dagger}, \quad f_M = f_M^{\dagger}, \quad f_E = f_E^{\dagger}, \quad f_A = f_A^{\dagger},$$

where Q, M, E, A refer respectively to the real charge, magnetic, electric, and anapole neutrino form factors. The Lorentz-invariant form of the vertex function (2) is also consistent with electroagnetic gauge invariance that implies four-current conservation. For the coupling with a real photon in vacuum ($q^2 = 0$) one has

$$f_O^{f_i}(0) = e_{f_i}, \quad f_M^{f_i}(0) = \mu_{f_i}, \quad f_E^{f_i}(0) = \epsilon_{f_i}, \quad f_A^{f_i}(0) = a_{f_i},$$

where e_{fi} , μ_{fi} , e_{fi} and a_{fi} are, respectively, the neutrino charge, magnetic moment, electric mo-nent and anapole moment of diagonal (f = i) and transition $(f \neq i)$ types. Even if the electric harge of a neutrino is zero, the electric form factor $f_{\Omega}(q^2)$ can still contain nontrivial information hange of a neutrino electrost table properties. A neutral particle can be characterized by a superposition f two charge distributions of opposite signs, so that the particle form factor $f_Q(q^2)$ can be nonzero for $q^2 \neq 0$. The mean charge radius (in fact, it is the squared charge radius) of an electrically eutral neutrino is given by $(-2) = 1 df_O(q^2)$

$$\langle r_{\nu}^{2} \rangle = \frac{1}{6} \frac{q_{eq}(q_{eq})}{dq^{2}}\Big|_{q^{2}=0},$$

which is determined by the second term in the power-series expansion of the neutrino charge

Elastic neutrino-electron scattering

Here we consider the process $\nu + e^- \rightarrow e^- + \nu$ where an ultrarelativistic neutrino with energy F_{-} There we consider the process $p + e^{-\gamma} e^{-\gamma} e^{-\gamma}$ where an untarelativistic neutrino with energy c_p lastically socializes on an atomic electron in a detector at energy transfer *T*. The simplest mode of the electron system in the detector is a free-electron model, where it is assumed that electrons are free and at rest. In the scattering experiments the observables are the kinetic energy T_r of the coil electron and/or its solid angle Ω_e . From the energy-momentum conservation one gets

$$= T$$
, $\cos \theta_e = \left(1 + \frac{m_e}{E_\nu}\right) \sqrt{\frac{T}{T + 2m_e}}$,

where θ_c is the angle of the recoil electron with respect to the neutrino beam. The cross section, which is differential with respect to the electron kinetic energy T_c , can be presented in the form of a sum of helicity-conserving (e.q. Q) and helicity-flipping (Q) components [6]:

$$\frac{d\sigma}{dT_e} = \frac{d\sigma_{(w,Q)}}{dT_e} + \frac{d\sigma_{(\mu)}}{dT_e}, \label{eq:dsigma_state}$$

here $d\sigma_{(w,Q)}/dT_e$ is the electroweak cross section modified by the effect of the neutrino millicharge, charge radius and anapole moment, and $d\sigma_{(\mu)}/dT_e$ is the magnetic cross section due to the neutrino dipole magnetic and electric moments. At small T_e values the contributions to the recoil-electron spectrum due to the weak, milliarge, and magnetic scattering channels exhibit qualitatively different T_e dependencies, namely

$$\mathcal{N}_{e^-}^{(w;Q)}(T_e) \propto \begin{cases} \text{const} \\ \frac{2\pi \alpha^2}{m_e T_e^2} \left(\frac{e_{\nu}}{e_0}\right)^2 (e_{\nu} \neq 0), & \text{and} & \mathcal{N}_{e^-}^{(\mu)}(T_e) \propto \frac{\pi \alpha^2}{m_e^2 T_e} \left(\frac{\mu_{\nu}}{\mu_B}\right)^2, \end{cases}$$

where α is the fine structure constant, e_{ν} and μ_{ν} are the neutrino (effective) millicharge and magrelic moment, and e_0 and μ_B are an elementary electric charge and a Bohr magneton, respectively. For the ratio R of the millicharge and magnetic-moment contributions to the recoil-electron v spectrum one thus has $\mathcal{R} = \frac{\mathcal{N}_{e^-}^{(Q)}(T_e)}{\mathcal{N}_{e^-}^{(\mu)}(T_e)} = \frac{2m_e}{T_e} \frac{(e_\nu/e_0)^2}{(\mu_\nu/\mu_B)^2}$

In case there are no observable deviations from the weak contribution to the electron spectr It is possible to get the upper bound for the neutrino millicharge demanding that a possible effect due to e_{ν} does not exceed one due to the neutrino (anomalous) magnetic moment μ_{ν} . This implies that R < 1 and from the relation 0, using the GEMMA data [3], namely the detector energy threshold ~ 2.8 keV and the μ_{ν} bound $\mu_{\nu} < 2.9 \times 10^{-11} \mu_B$, one obtains the following upper limit on the neutrino millicharge [7]: $|e_{\nu}| < 1.5 \times 10^{-12} e_0.$

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The e_v range that expected to be probed in a few years with the GEMMA-II experiment (an ef fective threshold of 1.5 keV and the μ_{ν} sensitivity at the level of $1 \times 10^{-11} \mu_B$) is $|e_{\nu}| < 3.7 \times 10^{-13} e^{-13} e^{-13}$

Coherent elastic neutrino-nucleus scattering

Here we consider the process $\nu_l + a(Z, N) \rightarrow a(Z, N) + \nu_{R \rightarrow loc}$ where an utrarelativistic neutrin First we contact with photoset $f(r_0(x), r_1) \rightarrow u(x_1, r_1) \rightarrow v_{d_{d_1}(x_1)} \rightarrow v_{d_{d_2}(x_1)}$ which are an unitarity statementations, in a detector at energy-momentum transfer q = (T, q). For a spin-zero nucleus and $T_q \ll E_p$, where $T_a = T$ is the nuclear recoil kinetic energy, the differential cross section due to the weak and charge-radius scattering channels is given by [6, 9]

$$\frac{d\sigma_{(w,r_{\nu})}}{dT_{a}} \simeq \frac{G_{F}^{2}M_{a}}{\pi} \left(1 - \frac{M_{a}T_{a}}{2E_{\nu}^{2}}\right) \left\{ \left[\left(g_{V}^{p} - \delta_{\ell\ell}\right)F_{Z}(|\vec{q}|^{2}) + g_{V}^{2}F_{N}(|\vec{q}|^{2})\right]^{2} + F_{Z}^{2}(|\vec{q}|^{2})\sum_{P,d} |\delta_{\ell\ell}|^{2} \right\}, (1)$$

where M_a is the nuclear mass, $g_V^p = 1/2 - 2\sin^2\theta_W$ and $g_V^n = -1/2$ (the neglected radiative corrections are too small to affect the results). $F_{Z,N}(q_V^0)$, such that $F_Z(0) = Z$ and $F_N(0) = N$, are the nuclear form factors, which are the Fourier transforms of the corresponding nucleon density distribution in the nucleus and describe the loss of coherence for $|\vec{a}|_R \ge 1$, where R is the nucleus radius. The effect of the neutrino charge radii is accounted for through

$$\delta_{\ell\ell'} = \frac{2}{3} m_W^2 \sin^2 \theta_W \langle r_{\nu_{\ell\ell'}}^2 \rangle$$
, with $\langle r_{\nu_{\ell\ell'}}^2 \rangle = \sum_{i=1} U_{\ell i}^* U_{\ell' j} \langle r_{\nu_{\ell'}}^2 \rangle$

where U is the neutrino mixing matrix. The diagonal $(\ell = \ell')$ charge radii are already predicte in the standard model [8]:

 $\langle r_{\mu_c}^2 \rangle_{SM} = -0.83 \times 10^{-32} \text{ cm}^2$, $\langle r_{\mu_c}^2 \rangle_{SM} = -0.48 \times 10^{-32} \text{ cm}^2$, $\langle r_{\mu_c}^2 \rangle_{SM} = -0.30 \times 10^{-32} \text{ cm}^2$. (11)

waver, the transition $(\ell \neq \ell')$ charge radii are essentially the BSM quantities. Fig. 1 shows the results of our fit [9] of the time-dependent COHERENT data [4]. In the analy sis, we used the Helm parametrization of the nuclear form factors $F_{Z,N}(|\vec{q}|^2)$ and the rms radii o the proton distribution $R_p(^{133}Cs) = 4.804$ fm and $R_p(^{127}I) = 4.749$ fm that have been determine with high accuracy with muonic atom spectroscopy [10].



Figure 1: 90% CL allowed regions in the $\langle r_{\mu_i}^2 \rangle - \langle r_{\mu_j}^2 \rangle$ plane obtained from the fit of the time-dependent COHERE energy spectrum without (left panel) and with (right panel) the transition charge radii. The red and blue point are to solve CL answer regions at the $(n_{ij}) = \langle n_{ij} \rangle$ base obtained using the transition charge radii. The relation of the transition charge radii. The relation of the relativistic mean field R_{ij} (10) and R_{ij} (11) and R_{ij} (1 R_{10}^{10} (We take at a starting 11). R_{12}^{-1} R_{10}^{100} Ca) and $R_{2}^{(100)}$ are allowed to vary in suitable intervals, with the lower bounds given by the co-adim experimental R_{12} values (see above) and the upper bound of 6 fm.

In addition to the customary, diagonal charge radii, from the COHERENT data we have obtain for the first time limits on the neutrino transition charge radii [9]

 $(|\langle r_{\mu_{\mu}}^2 \rangle|, |\langle r_{\mu_{\mu}}^2 \rangle|, |\langle r_{\nu_{\mu}}^2 \rangle|,) < (22, 38, 27) \times 10^{-32} \text{ cm}^2$

at 90% CL₂ marginalizing over reliable allowed intervals of the rms radii $R_n(^{123}Cs)$ and $R_n(^{127}Tin)$. This is an interesting information on the BSM physics which can generate the neutrino transitio charge radii [12].

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M. Cadeddu, C. Giunti, K. Kouzakov, **poster** Y.F. Li, A. Studenikin, Y. Zhang **# 34**

"Constraints on neutrino millicharge and charge radius from neutrino-atom scattering"



poster K. Stankevich, A. Studenikin "The effect of neutrino quantum decoherence"







in moving matter and B electromagnetic interactions (new effects) two interesting new phenomena in spin (flavour) oscillations

50 years of $\mathcal V$ oscillation formulae Gribov & Pontecorvo (1969)

new developments in v spin and flavour oscillations generation of \mathbf{v} spin (flavour) oscillations by interaction with transversal matter current

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

inherent interplay of ${oldsymbol {\mathcal V}}$ spin and flavour oscillations in ${f B}$

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

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Neutrino spin and spin-flavor oscillations in matter currents and magnetic fields

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V. Shakhov, Bachelor Dissertation "Neutrino oscillations in arbitrarily directed magnetic fields and matter currents", MSU, 2019 Neutrino spin $\nu_e^L \iff (j_{\perp}) \implies \nu_e^R$ and spinflavor $\nu_e^L \leftarrow (j_\perp) \Rightarrow \nu_u^R$ oscillations engen-

dered by transversal matter currents: Quantum

treatment

∆Heff can be expressed as [3]

 $\tilde{G} = \frac{G_{Z}}{3\sqrt{4}}, n = \frac{n_{L}}{\sqrt{1-n^{2}}}$ and

 H_B^{f} -

The history of neutrino spin oscillations in] transversal matter currents and/or transversally polarized matter

For many space, until 2004, it was below that a settime below precedues and the interpreting space structures are built and the matchine structure interaction measurements and the structure structure interaction measurements and the structure structure interaction of the structure structure structure structure interaction of the structure structure interaction of the structure struct For many source until 2004, it was believed that a postering believity procession and th

scillations may arise only in the case where the

ar magnetic field in the nontrino entifytame.¹⁵ Or historical notes reviewing studies of the discussed effect see in [2, 3, 4]. It should noted that the predicted effect exists regardless of a source of the background mat-transversal current or polarization (that can be a background magnetic field, for in-tead). e.). te that the existence of the discussed effect of neutrino spin oscillation

Note that the existance of the discussed effect of neutrino quasa excitations expandent for the probability of the probability

Neutrino spin oscillations $\nu_e^L \leftarrow (j_\perp) \Rightarrow \nu_e^R$ engendered by transversal matter currents: Semiclassical treatment

llowing the discussion in [1] consider, as an example, an electron neutrino spin pre-ssion in the case when neutrinos with the Standard Model interaction are propagating ough moving and polarized matter composed of electrons electrons may in the pre-ce of an electromagnetic field given by the electromagnetic-field tensor $F_{\mu\nu} = ({\bf E}, {\bf B})$. To derive the neutrino spin oscillation probability in the transversal matter or use the generalized Bargmann-Michel-Telegdi equation that describes the evo he three-dimensional neutrino spin vector **S**,

$\frac{dB}{dt} = \frac{z}{\gamma} \mathbf{S} \times (\mathbf{B}_0 + \mathbf{M}_0) ,$		(1
netic field B ₀ in the neutrino rest frame is determined by dinal (with respect to the neutrino motion) magnetic and the laboratory frame.	the tran- electric	fick

where the may sal and longit

 $B_0 = \gamma \left(B_{\perp} + \frac{1}{\gamma} B_{\parallel} + \sqrt{1 - \gamma^{-2}} \left[E_{\perp} \times \frac{\beta}{\beta} \right] \right)$

 $\gamma=\left(1-\beta^{2}\right)^{\frac{-1}{2}},$ β is the neutrino velocity. The matter term M_{0} in Eq. (1) is also

$\mathbf{M}_0 = \mathbf{M}_{0_2} + \mathbf{M}_{0_1}$	3)
$\begin{split} \mathbf{M}_{\mathbf{n}_{\mathbf{j}}} &= \gamma \beta \frac{u_{\mathbf{s}}}{\sqrt{1-u_{\mathbf{j}}^{2}}} \left\{ \rho_{\mathbf{s}}^{(1)} \left(1 - \frac{u_{\mathbf{s}}\theta}{1-\gamma^{-2}}\right) \right\} - \\ &- \frac{\mu_{\mathbf{s}}^{(0)}}{1-\gamma^{-2}} \left\{ \zeta_{\mathbf{s}} \theta \sqrt{1-u_{\mathbf{s}}^{2}} + \left(\zeta_{\mathbf{s}} \mathbf{v}_{\mathbf{s}} \frac{(\theta u_{\mathbf{s}})}{1+\sqrt{1-u_{\mathbf{j}}^{2}}} \right) \right\}, \end{split}$	4)
$M_{k_{\pm}} = -\frac{m}{\sqrt{1-q_{\pm}^2}} v_{e_{\pm}} \left(\rho_{e}^{(1)} + \rho_{e}^{(2)} \frac{c_{0}(q_{\pm})}{1+\sqrt{1-q_{\pm}^2}} \right) + c_{\pm} \rho_{e}^{(2)} \sqrt{1-v_{\pm}^2}.$ (6)	5)
Here $u_0 = v_0 \sqrt{1-c_0^2}$ is the invariant number density of matter given in the variant point with the board apped of matter in zero. The variant $V_{a,b}$ is $U_{a,b}$ is a final strain of the strain point of matter invariant. The variant $V_{a,b}$ is $U_{a,b}$ is a matter ordering the variant $V_{a,b}$ is a strain of the variant $V_{a,b}$ is a strain $V_{a,b}$ is a	ef- nd he a- he t)- se
$i \frac{d}{dt} \begin{pmatrix} \nu_c^L \\ \nu_c^L \end{pmatrix} = \mu \begin{pmatrix} \frac{1}{2} \mathbf{M}_{01} + \mathbf{B}_{01} & \mathbf{B}_{\perp} + \frac{1}{2} \mathbf{M}_{01} \\ \mathbf{B}_{\perp} + \frac{1}{2} \mathbf{M}_{01} & -\frac{1}{2} \mathbf{M}_{01} + \mathbf{B}_{02} \end{pmatrix} \begin{pmatrix} \nu_c^L \\ \nu_c^L \end{pmatrix}$. (6)	6)
Thus, the probability of the neutrino spin oscillations in the adiabatic approximation given by $P_{1,1}(x_{1}) = a \log x_{1} + a \log x_{1} + a \log x_{1} $	is

 $L_{\rm eff} = \frac{\pi}{\sqrt{E_{\rm eff}^2 + \Delta_{\rm eff}^2}}, \label{eq:Leff}$ $E_{\text{eff}} = \mu [\mathbf{B}_{\perp} + \frac{1}{2}\mathbf{M}_{1\perp}] \quad \Delta_{\text{eff}} = \frac{\mu}{2}[\mathbf{M}_{01} + \mathbf{B}_{02}].$ lows [1] that even in the absence of the transversal m

field the

Consider two states of neutrino $(v_{n_1}^{\beta_1}, v_{\mu}^{\beta_2})$. The corresponding oscillations are governed with evolution evolution $i\frac{d}{dt}\begin{pmatrix} v_1^1\\ v_2^V \end{pmatrix} = \begin{pmatrix} -\Delta M + \begin{pmatrix} \xi \\ y \\ z \end{pmatrix}_{\mathbb{R}} B_{1} + \hat{O}n(1-z\beta) & -\mu_{\alpha}B_{\alpha}e^{i\theta} + \begin{pmatrix} \xi \\ y \\ z \end{pmatrix}_{\alpha}\hat{O}nv_{\alpha} \\ -\mu_{\alpha}B_{1}e^{-i\theta} + \begin{pmatrix} \xi \\ y \\ z \end{pmatrix}_{\alpha}\hat{O}nv_{\alpha} & \Delta M - \begin{pmatrix} \xi \\ y \\ z \end{pmatrix}_{\alpha}B_{1} - \hat{O}n(1-z\beta) \begin{pmatrix} v_{\alpha}^{2} \\ v_{\alpha}^{2} \end{pmatrix}$ (24) Here below we continue our studies of the effect of neutrino spin evo True recove we continue our indicis of the effect of neutrino spin evolution induced by the transversal matter currents and develop a convisiont derivation of the effect based on the direct calculation of the spin evolution effective Hamiltonian in the case when a neutron is propagating in matter transversal currents. Consider two fascour neutrinos with two possible belicities up $-\left(e_{i}^{a},e_{j}^{-},i_{k}^{a},e_{j}^{-}\right)$ moving matter composed of neutrons. The neutrino interaction Lagrangian reads For the oscillation $v_s^L \Leftrightarrow (j_{\perp}, B_{\perp}) \Rightarrow v_s^R$ probability we get (7) with $L_{int} = -f^{\mu} \sum \bar{\nu}_i(x) \gamma_{\mu} \frac{1 + \gamma_5}{2} \nu_1(x) = -f^{\mu} \sum \bar{\nu}_i(x) \gamma_{\mu} \frac{1 + \gamma_5}{2} \nu_i(x),$ (9) $E_{\text{ref}} = \sqrt{\left(\mu_{op}B_{\perp}\cos\phi - \left(\frac{\eta}{\gamma}\right)_{ze}\hat{G}nv_{\perp}\right)^2 + (\mu_{op}B_{\perp}\sin\phi)^2}$ where $f^{\mu} = -\frac{\partial \mu}{\partial N} n(\mathbf{i}, \mathbf{v})$, $l = e, \mu$ indicates the neutrino flavour, i = 1, 2 indicate the neutrino mass site and the matter potential P^{μ} depends on the velocity of matter $\Delta_{\text{eff}} = \left| \Delta M - \frac{1}{2} \left(\frac{\mu_{11}}{\gamma_{11}} + \frac{\mu_{22}}{\gamma_{20}} \right) B_{\parallel} - \tilde{G}n(1 - v_{\parallel}) \right|, \quad \Delta M = \frac{\Delta m^2 \cos 2\theta}{4g\xi}.$ where $p^{-} = -\frac{1}{\sqrt{2}} m(t, \Psi)$, $t = c_{+}\mu$ indicates the neutrino mission, t = 1, 2 indicating the neutrino mass state and the matter potential P^{0} depends on the velocity of matti- $\Psi = (v_{1}, v_{2}, v_{3})$ and on the neutron number density in the laboratory reference fram $n = \frac{1}{\sqrt{1-\mu_{1}}}$. Each of the flavour neutrinos is a superposition of the neutrino mass states $\nu_s^{\pm} = \nu_1^{\pm} \cos \theta + \nu_2^{\pm} \sin \theta$, $\nu_s^{\pm} = -\nu_1^{\pm} \sin \theta + \nu_2^{\pm} \cos \theta$. 0.00 reolution equation in the flavour basis is Resonance amplification of neutrino spin-flavor oscilla $i\frac{d}{ds}\nu_f = \left(H_0^{eff} + \Delta H^{eff}\right)\nu_f,$ (11) tions $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_\mu^R$ by longitudinal matter current $H^{eff} = H^{eff}_{c} + \Delta H^{eff}_{c}$ lition $E_{eff} \ge \Delta_{eff}$. $\Delta H^{eff} = \begin{pmatrix} \Delta_{ae}^{ae} & \Delta_{ae}^{ae} & \Delta_{ae}^{ae} & \Delta_{ae}^{ae} \\ \Delta_{ae}^{ae} & \Delta_{ae}^{ae} & \Delta_{ae}^{ae} & \Delta_{ae}^{ae} \\ \Delta_{\mu e}^{ae} & \Delta_{\mu e}^{ae} & \Delta_{\mu e}^{ae} & \Delta_{\mu e}^{ae} \\ \Delta_{\mu e}^{ae} & \Delta_{\mu e}^{ae} & \Delta_{\mu e}^{ae} & \Delta_{\mu e}^{ae} \end{pmatrix}$ (13) $\left| \left(\frac{\eta}{\eta} \right) | \hat{G}nv_{\perp} \right| \ge |\Delta M - \hat{G}n(1 - v_{\parallel})|.$ $\Delta_{ni}^{ni'} = \left(\nu_{n}^{i} |H_{ni}| \nu_{n}^{i'}\right)$ (14) $k, l = e, u, s, s' = \pm$. In evaluation of $\Delta^{tt'}$ we have first introduced the neutrino flavor states ν_{a}^{a} and ν_{a}^{a} as superpositions of the mass states ν_{a}^{a} . Then, using the exact fro $\frac{\hat{G}nv_{\perp}}{\hat{m}}\sin 2\theta + \hat{G}n \approx \hat{G}n$ $v_0^s = C_0 \left(\frac{v_0^s}{\frac{E_0^s + m_0}{E_0 + m_0}} \eta_0^s \right) \sqrt{\frac{(E_0 + m_0)}{2E_0}} \exp\left(ip_0 x\right)$ where it will restrict a set of parametery basis here [11, 12]. Noticino concerning the viscal accessor tax with inclusions given by an angle of from the plane of the access on delta propagates through the toroidal ball of over the set on tends with the split archively or about $\sim D^{-1}$, "manufactors in the accession ball of the accession D^{-1} and the distance of the set of the set of the set of the accession σ about the set of moment minore define pentring belicity states, and are $u_{n}^{+} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad u_{n}^{-} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$ for the typical term $\Delta_{\alpha\alpha'}^{\alpha'} = \langle \nu_{\alpha}^{a} | \Delta H^{\beta M} | \nu_{\alpha'}^{a'} \rangle$, that by fixing proper values of α, s, s $\Delta_{\mathbf{s}\mathbf{s}'}^{\mathbf{s}'} = \tilde{G}n \left\{ \mathbf{u}_{\mathbf{s}}^{\mathbf{s}''} \begin{bmatrix} \begin{pmatrix} 0 & 0 \\ 0 & 2 \end{pmatrix} \mathbf{v}_{1} + \begin{pmatrix} 0 & \gamma_{\mathbf{s}}^{-1} \\ \gamma_{\mathbf{s}'}^{-1} & 0 \end{pmatrix} \mathbf{v}_{\perp} \end{bmatrix} \mathbf{u}_{\mathbf{s}'}^{\mathbf{s}'} \right\} \delta_{\mathbf{s}'}^{\mathbf{s}'}$ dinal and transversal velocities of the matter $\gamma_{aa'}^{-1} = \frac{1}{2} \left(\gamma_a^{-1} + \gamma_{a'}^{-1} \right), \quad \tilde{\gamma}_{aa'}^{-1} = \frac{1}{2} \left(\gamma_a^{-1} - \gamma_{a'}^{-1} \right), \quad \gamma_a^{-1} = \frac{m_a}{E}.$ (18) om the criterion $\bar{G}_N \ge \Delta M$ we get the quite reasonable con Tective interaction Hamiltonian in the flavour basis has the following struc $n_0 \ge \frac{\Delta M}{C} = 10^{12} \text{eV}^3 \approx 10^{26} \text{cm}^{-3}$. $H^{eff} = n \mathcal{G} \begin{pmatrix} 0 & \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} & 0 & \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} \\ \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} & 2\left(1 - v_{1} \right) & \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} & 0 \\ 0 & \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} & 0 & \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} \\ \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} & 0 & \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} & 2\left(1 - v_{1} \right) \end{pmatrix}.$ The corresponding oscillation length is approximately $L_{\rm eff} = \frac{\pi}{\left(\frac{g}{\gamma}\right)_{\rm cr} \bar{G} m v_{\perp}} \approx 5 \times 10^{10} \rm km. \label{eq:Leff}$ 0.09 The oscillation length can be within the scale of short gamma-ray bursts Here we introduce the following formal notations: $\left(\frac{\eta}{\gamma}\right)_{\mu\mu} = \frac{\cos^2\theta}{\gamma_{11}} + \frac{\sin^2\theta}{\gamma_{22}}, \quad \left(\frac{\eta}{\gamma}\right)_{\mu\mu} = \frac{\sin^2\theta}{\gamma_{11}} + \frac{\cos^2\theta}{\gamma_{22}}, \quad \left(\frac{\eta}{\gamma}\right)_{\mu\mu} = \frac{\sin 2\theta}{\gamma_{21}}.$ (20) Let pr 10km The flavor neutrino evolution Hamiltonian in the magnetic field H_{H}^{L} can be calculat in the same way. One just should start from the neutrino electromagnetic interacti-Lagrangian $L_{EH} = \frac{1}{\mu_{\mu\nu}} \omega_{\mu\nu} \omega_{\mu\nu} F^{\mu\nu} + h.c.$ if the matter density equals $n_0 \approx 5 \times 10^{36} cm^{-3}$. Conclusions $\left(-\left(\frac{s}{\gamma}\right)_{ac}B_{\parallel} - \mu_{ac}B_{\perp}e^{-i\phi} - \left(\frac{s}{\gamma}\right)_{ac}B_{\parallel} - \mu_{ac}B_{\perp}e^{-i\phi}$ $\begin{array}{c} (\gamma)_{\mu} \rightarrow_{i} - \rho_{\mu\nu}\sigma_{i\nu} = -(\gamma)_{\mu\nu}\sigma_{i} - \frac{\rho_{\mu\nu}\sigma_{i\nu}}{\rho_{i}} = \rho_{\mu\mu}\sigma_{i\nu}e^{i\nu} \\ -\rho_{\mu\mu}B_{\mu}e^{i\nu} = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\nu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ -\rho_{\mu\mu}B_{\mu}e^{i\nu} = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ +\rho_{\mu\mu}B_{\mu}e^{i\nu} = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{1} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{1} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{1} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} \\ = \begin{pmatrix} q \\$ where ϕ is the angle between transversal components of magnetic field B_1 and mat References $\left(\frac{\mu}{\gamma}\right)_{-1} = \frac{\mu_{11}}{\gamma_{11}}\cos^2\theta + \frac{\mu_{22}}{\gamma_{22}}\sin^2\theta + \frac{\mu_{12}}{\gamma_{12}}\sin 2\theta,$ $\left(\frac{\mu}{\gamma}\right)_{zz} = \frac{\mu_{11}}{\gamma_{12}} \cos 2\theta + \frac{1}{2} \left(\frac{\mu_{22}}{\gamma_{22}} - \frac{\mu_{11}}{\gamma_{13}}\right) \sin 2\theta,$ Ad NOV 2014 (2015) the petite (1915) 3 Pallet, A. Manello, Phys. Lett. B 207 ($\left(\frac{\mu}{\gamma}\right)_{uv} = \frac{\mu_{11}}{\gamma_{11}}\sin^2\theta + \frac{\mu_{22}}{\gamma_{22}}\cos^2\theta - \frac{\mu_{12}}{\gamma_{12}}\sin 2\theta,$ L. B. Wagel, Phys. Rev. D 98 (2015) 1250

[9] P. Pashalay and J. Makesian, Neuko Sons, Phys. Rev. B 98 (2018), 113005

Arre we examine the case when the annihilade of oscillations sin² 28,4 in (7) is not small nd we use the criterion based on the demand that $\sin^2 2\theta_{eff} \ge \frac{1}{2}$ which is provided by he condition $E_{eff} \ge \Delta_{eff}$. Consider the case when the effect of the magnetic field is negligible, thus we get

(27)

In the further evaluations we use the approximation $\begin{pmatrix} 1 \\ 2 \end{pmatrix}_{\gamma\mu} \approx \frac{i \theta_1 M}{\gamma_0}$, where $\gamma_0 = \gamma_{11} \sim \gamma_{22}$ is the neutrino effective gamma-factor. In the case $\eta_1 = 0$ we get

Probability of neutrino spin-flavor oscillations

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

inally, the criterion $\sin^2 2\theta_{eff} \ge \frac{1}{2}$ is fulfilled when the following condition is valid:

also about $D \sim 20$ km. The transversal velocity of matter can be estimated accord $w_c \rightarrow D = 0.05$ what corresponds to $w_m = 1.002$. The mass squared difference and mixing angle are taken from the solar sentimes summerms, $\Delta m^2 = 7.37 \times 10^{-4} V_{\rm e}^{-1}$ miss $\theta = 0.202$ (co.29 = 0.00). Con-mentino with energy $g_{\rm e}^{--1}$ for e^{4} and moving matter characterized by $\gamma_m = 1.022$. we get $\Delta M = 0.75$ m ¹¹ VeV. Accomming for the estimation $G = \frac{25}{30} = 0.4 \times 10^{-3}$

(29) (30) The performed studies [9, 10] of neutrino spin $v_{c}^{0} \leftrightarrow \langle j_{c} \rangle \Rightarrow v_{c}^{0}$ and spin-flavor $v_{c}^{0} \leftrightarrow \langle j_{c} \rangle \rightarrow v_{c}^{0}$ oscillations engendered by the transversal matter currents in the presence of arbitrary magnetic fields allow one to consider possibilities of applications of these very interesting new effects in different strephysical settings.



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

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

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

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

$$\begin{split} \sin^2\theta \cos^2\theta \big| |c_1^+|^2 e^{-iE_1^+t} + |c_2^-|^2 e^{-iE_2^-t} \\ - |c_1^+|^2 e^{-iE_1^+t} - |c_1^-|^2 e^{-iE_1^-t} \big|^2. \end{split}$$

 $E_{i}^{s} \approx p + \frac{m_{i}^{2}}{2p} + \frac{\mu_{i}^{2}B^{2}}{2p} + \mu_{0}sB_{\perp}.$

 $\|c\|^2 \|c\|^2 \approx \frac{1}{2}$

 $P_{s_{\pm}^2 \rightarrow w_{\pm}^4}(x) = \sin^2 2\theta \left\{ \cos(\mu_1 B_{\perp} x) \cos(\mu_2 B_{\perp} x) \sin^2 \frac{\Delta m^2}{4\pi} x \right\}$

 $\nu_{t}^{L}(t) = \left(c_{1}^{+}e^{-tE_{1}^{+}t}\nu_{1}^{+}\right)$

 $+ \left(c_2^+ e^{-dE_2^+ l} \nu_l^+ + \right)$

Introduction

Mattice matrixs have noticitid elementsprints preperiors (see [1]) for x_1 -ves, or, he update can be used in [1]). And for matrix parts and (4, 3), we have the other of the same that of the soft of the same the same the soft of the same In the case $B_{\perp} = 0$ the helicity states $\sum_{i=1}^{n-1} |a_i|^2 = 0, |a_i^+|^2 = |d_i^-|^2 = 1.$ nirary to the customary approach when the neutrino helicity states are used for Neutrino states in a magnetic field ider two flavour neutrinos with two helicities accounting for mixing $\nu_e^{L(R)} = \nu_1^{L(R)} \cos \theta + \nu_2^{L(R)} \sin \theta,$ $\nu_\pi^{L(R)} = -\nu_1^{L(R)} \sin \theta + \nu_2^{L(R)} \cos \theta,$ where $\nu_{i}^{s} \equiv \nu_{i}^{s}(0)$. In exactly the same of the wave function of a muon neutri Neutrino flavour oscil where $v_i^{U(k)}$ are the helicity neutrino mass states, i = 1, 2. Recall that for the rel-trivistic neutrinos the helicity states approximately coincide with the chiral states $(\delta^{(0)} = u_i \delta^{(0)-k})$. The detailed discussion on neutrino helicity and distributy can be found in [2]. Real relativistic neutrinos produced in a weak process are almost or homotop in the neutrino in the state of the states of the sta field The probability of the neutrino flavour ft-handed helicity states. Note that the helicity mass states $\nu_1^{L(d)}$ are not stationary states in the p Note that the helicity mass states $\nu_{i}^{(A)}$ mass not stationary states in the poor a magnetic field. In our further evaluations we shall expand $\nu_{i}^{(A)}$ on notation statisticary states $\nu_{i}^{(A)}$ in the presence of a magnetic field. The wave function x_{i}^{a} (x_{i}^{a}) the presence of a magnetic field. The wave function x_{i}^{a} (x_{i}^{a}) $= \pm 1$) of a massive neutrino that propagates magnetic field can be found as the solution of the Dirac equation blicit form of the neutrino stationary states wave functions to calculate the oscil-ation probability. The dependence of the neutrino oscillation probability on the magnetic field is due to the matrix elements of the projectors (14)-(16) and the $(\gamma_A p^\mu - m_i - \mu_i \Sigma B) v_i^\mu(p) = 0,$ $\chi_{(M^{-1})} \rightarrow \pi_{(M^{-1})}(M^{-1}) \rightarrow (M^{-1})$ (2) where μ_i is the neutrino magnetic moment and the magnetic field is given by $B = (B_i, 0, B_j)$. In the discussed two-neutrino case the possibility for a nonzero-neutrino transmission moment μ_{ij} ($x \neq j$) is not considered and two equations for two neutrinos states x_i^* are decoupled. The equation (2) can be re-written in the equivalent form magnetic nets is one to the matrix elements of the projectors (14)-(16) and the energy spectrum (7) field dependence. The probability of oscillations $\nu_{a}^{2} \leftrightarrow \nu_{a}^{2}$ is simplified if one accounts for the relativistic neutrino energies ($\mu \gg \nu_{a}$) and also for realistic values of the neutrino magnetic moments and strengths of magnetic fields ($\mu \gg \mu B$). In this case we have $\hat{H}_{\mu\nu}^{\mu} = E_{\mu\nu}^{\mu}$ $\hat{H}_i = \gamma_0 \gamma p + \mu_i \gamma_0 \Sigma B + m_i \gamma_0.$ It is reasonably to suppose that $\mu B << m$, then the contribution $\frac{\mu_L^2 B^2}{2p}$ can be eglected in (23). In the considered case we also have ator that commutes with the Hamiltonian (4) can be chosen in t $\hat{S}_{i} = \frac{1}{N} \left[\Sigma B - \frac{i}{m_{i}} \gamma_{0} \gamma_{0} [\Sigma \times p] B \right],$ Finally, for the probability of flavour oscillations $\nu_a^L \leftrightarrow \nu_a^L$ we get $\frac{1}{N} = \frac{m_i}{\sqrt{m_i^2 B^2 + p^2 B_{\perp}^2}}.$ $E_{i}^{a} = \sqrt{m_{i}^{2} + p^{2} + \mu_{i}^{2}B^{2} + 2\mu_{i}s\sqrt{m_{i}^{2}B^{2} + p^{2}B_{\perp}^{2}}},$ Neutrino evolution in a magnetic field The spin operator \hat{S}_i commutes with the Hamiltonian $\hat{H}_{i:}$ and for the neutrinoid \hat{S}_i $\hat{S}_t |\nu_t^s\rangle = s |\nu_t^s\rangle$, $s = \pm 1$, $(w^{\dagger}|w^{\dagger}) = \delta_{ik}\delta_{ik}$ esponding projector op- $\hat{P}_{t}^{\pm} = \frac{1 \pm \hat{S}_{t}}{2}.$ It is clear that projectors act on the stationary states as follows $\langle \nu_k^{s'} | \hat{P}_i^s | \nu_i^s \rangle = \delta_{ik} \delta_{ss'}.$ Now in order to solve the problem of the neutrino flavour $\nu_n^L \leftrightarrow \nu_{\mu^n}^L$ spin $\nu_n^L \leftrightarrow \nu_n^R$ and spin-flavour $\nu_n^L \leftrightarrow \nu_n^R$ oscillations in the magnetic field we ex-pand the neutrino helicity states over the neutrino stationary states

 $\nu_t^L(t) = c_t^+ \nu_t^+(t) + c_t^- \nu_t^-(t),$ $\nu_t^R(t) = d_t^+ \nu_t^+(t) + d_t^- \nu_t^-(t),$

 $\begin{array}{l} |c_i^{\pm}|^2 \,=\, (\nu_i^L | \dot{P}_i^{\pm} | \nu_i^L) \\ |d_i^{\pm}|^2 \,=\, (\nu_i^R | \dot{P}_i^{\pm} | \nu_i^R) \\ (d_i^{\pm})^* c_i^{\pm} \,=\, (\nu_i^R | P_i^{\pm} | \nu_i^L) \end{array}$

Since $|c_1^+|^2$, $|d_1^+|^2$ and $(d_1^+)^*c_1^+$ are time independent, they can be determined from the initial conditions. Now let's take into account the fact that only chiral state

an participate in weak interaction and, consequently, in processes of neutrin reation and detection. It means, that the spinor structure of the neutrino initia

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

(14) (15) (16)

where cit and dit are independent on time.



$= \sqrt{m_i^2 B^2 + p^2 B^2}$			8V28* \$1 eV7	
$bd_1^{m-1} = \frac{1}{2} \left(1 + \frac{m_1 B_1}{\sqrt{m_1^2 B^2 + p^2 B_1^2}} \right),$ (C) $(b_1^{m-1})^{-1} = \frac{1}{2} - \frac{m_1 B_1}{\sqrt{m_1^2 B^2 + p^2 B_2^2}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1 B_1}{2 - \frac{m_1^2 B_1^2 + p^2 B_2^2}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1^2 B_1}{2 - \frac{m_1^2 B_1^2}{\sqrt{m_1^2 B^2 + p^2 B_2^2}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1^2 B_1}{2 - \frac{m_1^2 B_1}{\sqrt{m_1^2 B^2 + p^2 B_2^2}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1^2 B_1}{2 - \frac{m_1^2 B_1}{\sqrt{m_1^2 B^2 + p^2 B_2^2}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1^2 B_1}{2 - \frac{m_1^2 B_1}{\sqrt{m_1^2 B^2 + p^2 B_2^2}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1^2 B_1}{2 - \frac{m_1^2 B_1}{\sqrt{m_1^2 B^2 + p^2 B_2^2}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1^2 B_1}{2 - \frac{m_1^2 B_1}{\sqrt{m_1^2 B^2 + p^2 B_2^2}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1^2 B_1}{2 - \frac{m_1^2 B_1}{\sqrt{m_1^2 B^2 + p^2 B_2^2}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1^2 B_1}{2 - \frac{m_1^2 B_1}{\sqrt{m_1^2 B^2 + p^2 B_2^2}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1^2 B_1}{2 - \frac{m_1^2 B_1}{\sqrt{m_1^2 B^2 + p^2 B_2^2}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1^2 B_1}{2 - \frac{m_1^2 B_1}{\sqrt{m_1^2 B^2 + p^2 B_2^2}}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1^2 B_1}{2 - \frac{m_1^2 B_1}{\sqrt{m_1^2 B^2 + p^2 B_2^2}}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1^2 B_1}{2 - \frac{m_1^2 B_1}{\sqrt{m_1^2 B^2 + p^2 B_2^2}}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1^2 B_1}{2 - \frac{m_1^2 B_1}{\sqrt{m_1^2 B^2 + p^2 B_2^2}}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1^2 B_1}{2 - \frac{m_1^2 B_1}{\sqrt{m_1^2 B^2 + p^2 B_2^2}}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1^2 B_1}{2 - \frac{m_1^2 B_1}{\sqrt{m_1^2 B^2 + p^2 B_2^2}}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1^2 B_1}{2 - \frac{m_1^2 B_1}{\sqrt{m_1^2 B^2 + p^2 B_2^2}}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1^2 B_1}{\sqrt{m_1^2 B^2 + p^2 B_2^2}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1^2 B_1}{\sqrt{m_1^2 B^2 + p^2 B_2^2}},$ (G) $(b_1^{m-1})^{-1} = \frac{m_1^2 B_1}{\sqrt{m_1^2 B^2 + p^2 B_2^2}},$ (G) (H) (H) (H) (H) (H) (H) (H) (H	9) 50) = ne	for neutrino masses of the (25) of the neutrino flavous for this particular choice fit is clearly seen that the $\lambda_{tac} = \frac{\Delta w_{t}}{4\rho}$ is modulated responding oscillation leng the typical dimensions of amplitude modulation still $\frac{1}{\sqrt{w_{t}-w_{tc}}}$	order $m \sim 0.1 \text{ eV}$. In Fig. 1 we oscillations $s_1^{\mu} \rightarrow s_2^{\mu}$ in the trans of parameters and the neutrino of amplitude of oscillations at the by the magnetic field frequency of this $L = 1/\mu B \sim 50$ km. This magnetars, but the discussed eff exists being slightly washed out.	show the probability versal magnetic field mergy $p = 1 MeV$ $t v accum frequencyt_B = \mu B_{\perp}. The cor-value indeed accedeslet of the oscillation$
$\begin{split} &= \left(c_1^{*}e^{-i\theta_1^{*}}u_2^{*}+c_1^{*}e^{-i\theta_2^{*}}u_2^{*}\right)\cos\theta \\ &+ \left(c_2^{*}e^{-i\theta_2^{*}}u_2^{*}+c_2^{*}e^{-i\theta_2^{*}}u_2^{*}\right)\sin\theta, G \\ &= \operatorname{cust} h \ \text{some varias}, G \\ &= \operatorname{cust} h \ \text$	n) on ic	63 64 64 62		

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DHHHMM.

Consider the mass square difference $\Delta m^2 = 7 \times 10^{-5} eV^2$ and the magnetic moments $\mu_1 = \mu_2 = \mu \sim 10^{-20} \mu_S$ that corresponds the Standard Model prediction

 $\mu_{ii}^D = \frac{3\epsilon G_F m_i}{8\sqrt{2}\pi^2} \approx 3.2 \times 10^{-29} \left(\frac{m_i}{1 \text{ eV}}\right) \mu_B,$

Figure 1: The probability of the neutrino flavour oscillations transversal magnetic field $B_{\perp} = 10^{16} G$ for the neutrino ene = 10⁻⁻⁻ G for the neutrino energy p = 1 MeVnetic moments $\mu_1 = \mu_2 = 10^{-20} \mu_B$. $\Delta m^2 - 7 \times 10^{-5} eV^2$ and



Figure 2: The probability of the neutrino spin oscillations $\nu_e^L \rightarrow \nu_e^R$ in the transversal magnetic field $B_\perp = 10^{46}~G$ for the neutrino energy p = 1~MeV $\Delta m^2 = 7 \times 10^{-5}~eV^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-28}\mu_B$.



Figure 3: The probability of the neutrino spin flavour oscillations $\nu_e^L \rightarrow \nu_g^R$ 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 $\mu_1 = \mu_2 = 10^{-26} \mu_B$.

Finally, the obtained closed expressions (25), (25), (27) and (20) show that the contron oscillation $P_{d-q}(x)$, $P_{d-q}(x)$, $P_{d-q}(x)$, and also service $P_{d-q}(x)$; probabilies scabiling using complexitation implying probability functions that are dependent on six different frequencies. On this have separa-tic modifications of the neutrino scaling partners that angling proofs are important phenomenological convergences in case of second procession are present.

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A. Pustoshny, V. Shakhov, A. Studenikin "Neutrino spin and spin-flavour oscillations in transversal matter currents with standard and non-standard interactions" poster # 25

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

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

 $\mu_{ss} = \mu_{ss} \sin^2 \theta + \mu_{ss} \cos^2 \theta - \mu_{ss} \sin 2\theta$

A. Popov, A. Studenikin "Neutrino eigenstates and flavour, spin and spin-flavour oscillations in a constant magnetic field" poster #34

 $P_{ab \rightarrow ab} + P_{ab \rightarrow ab} + P_{ab \rightarrow ab} + P_{ab \rightarrow ab} = 1.$

As an illustration of the interplay of neutrino oscillations on different for ties, it is interesting to find a particular realistic set of parameters (the ne mas square difference, energy and magnetic moment, as well as the stren magnetic field) which also allows one to hope for significant planomenol

consequences. Arguing so, consider an accumple the nutritical phenomenological consequences. Arguing so, consider an accumple the nutrition flavour wolf-lations $\nu_n^L \rightarrow \nu_n^L$ in the transversal magnetic field B_1 . Obviously, the stronger the magnetic field, the greater the influence it will have on the probability of the neutrino flavour oscillations. The strongest magnetic field are exected to avaid on

flavour oscillations. The strongest magnetic field are expected to exist in rs, where the strength of the field can be of the value up to $B_{\perp} = 10^{26} G$



V electromagnetic properties

(flash on theory) $m_{3} \neq 0$





EM properties \implies a way to distinguish Dirac and Majorana \checkmark

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









are most well studied and theoretically understood among form factors





V magnetic moment in experiments

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



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

$$\mu_{\nu} < 2.9 \times 10^{-11} \mu_B$$
 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 ... 2019 ?

•
$$\mu_{\nu}^{a} \sim 0.7 \times 10^{-12} \mu_{B}$$

unprecedentedly low threshold



Effective v magnetic moment in experiments



Implications of μ limits from different experiments (reactor, solar $^{8}\mathrm{B}$ and $^{7}\mathrm{Be}$) are different.



Limiting the effective magnetic moment of solar neutrinos with the Borexino detector

Livia Ludhova on behalf of the Borexino collaboration

IKP-2 FZ Jülich, RWTH Aachen, and JARA Institute, Germany

Phys. Rev. D 96 (2017) 091103





Data selection:

Fiducial volume: R < 3.021 m, |z| < 1.67 m Muon, ²¹⁴Bi-²¹⁴Po, and noise suppression Free fit parameters: solar-v (pp, ⁷Be) and backgrounds (⁸⁵Kr,²¹⁰Po, ²¹⁰Bi, ¹¹C, external bgr.), response parameters (light yield, ²¹⁰Po position and width, ¹¹C edge (2 x 511 keV), 2 energy resolution parameters) Constrained parameters: ¹⁴C, pile up Fixed parameters: pep-, CNO-, ⁸B-v rates Systematics: treatment of pile-up, energy estimators, pep and CNO constraints with LZ and HZ SSM

Without radiochemical constraint $\mu_{eff} < 4.0 \ge 10^{-11} \mu_B (90\% \text{ C.L.})$ With radiochemical constraint $\mu_{eff} < 2.6 \ge 10^{-11} \mu_B (90\% \text{ C.L.})$ adding systematics $\mu_{eff} < 2.8 \ge 10^{-11} \mu_B (90\% \text{ C.L.})$



Livia Ludhova: Limiting the effective magnetic moment of solar neutrinos with the Borexino detector TAUP 2017, Sudbury

2

Experimental limits for different effective M,

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

C. Giunti, A. Studenikin, "Electromagnetic interactions of neutrinos: A window to new physics", Rev. Mod. Phys. 87 (2015) 531 new 2017 Borexino PRD: $\mu_{\nu}^{eff} < 2.8 \cdot 10^{-11} \mu_B$ at 90% c.l.)

Particle Data Group, 2014-2018 and update of 2019



... better limits on \mathcal{V} effective magnetic moment ...



... comprehensive analysis of \mathcal{V} - \mathcal{C} scattering ...

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

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

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(Received 11 February 2017; published 14 March 2017)

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

Concluding remarks Kouzakov, Studenikin Phys. Rev. D 95 (2017) 055013

- cross section of V-e is determined in terms of 3x3 matrices
 of V electromagnetic form factors
- in short-baseline experiments one studies form factors in flavour basis
- long-baseline experiments more convenient to interpret in terms of fundamental form factors in mass basis
 - V millicharge when it is constrained in reactor short-baseline experiments (GEMMA, for instance) should be interpreted as

 $|e_{\nu_e}| = \sqrt{|(e_{\nu})_{ee}|^2 + |(e_{\nu})_{\mu e}|^2 + |(e_{\nu})_{\tau e}|^2}$

• V charge radius in V-e elastic scattering can't be considered as a shift $g_V \rightarrow g_V + \frac{2}{3} M_W^2 \langle r^2 \rangle \sin^2 \theta_W$, there are also contributions from flavor-transition charge radii



considered simultaneously *calculated* **CR** is infinite and gauge dependent quantity. For massless \mathbf{v} , a_{ν} and $\langle r_{\nu}^2 \rangle$ can be defined (finite and gauge independent) from scattering cross section.

Image: Second stateImage: Second



Physical Review D – Highlights 2018 – Editors' Suggestion

29.12.2018

Physical Review D - Highlights

Editors' Suggestion

<u>Neutrino charge radii from COHERENT elastic neutrino-nucleus scattering</u> <u>/prd/abstract/10.1103/PhysRevD.98.113010</u>

M. Cadeddu, C. Giunti, K. A. Kouzakov, Y. F. Li, A. I. Studenikin, and Y. Y. Zhang Phys. Rev. D **98**, 113010 (2018) – Published 26 December 2018



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

Show Abstract + ()

Particle Data Group, Review of Particle Properties (2018), update of 2019

poster # xxx

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Review of Particle Physics 2014 - 2016 - 2018 (2019) M. Tanabashi et al. (Particle Data Group) Phys. Rev. D 98 (2018) 030001



The European Physical Society Conference on High Energy Physics, 10-17 July 2019, Ghent, Belgium

Constraints on neutrino millicharge and charge radius from neutrino-atom scattering

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Introduction

In the standard model neutrinos are massless left-handed fermions which very weakly interact with matter via exchange of the W^{\pm} and Z^0 bosons. The development of our knowledge about neutrino masses and mixing provides a basis for exploring neutrino properties and interactions beyond the standard model (BSM). In this respect, the study of nonvanishing electromagnetic racteristics of massive neutrinos is of particular interest [1, 2]. It can help not only to shed light on whether neutrinos are Dirac or Majorana particles, but also to constrain the existing BSM theories and/or to hint at new physics. The effects of neutrino electromagnetic properties can be searched in astrophysical environments, where neutrinos propagate in strong magnetic fields and dense matter, and in laboratory measurements of neutrinos from various s ources. In the latter case, a very sensitive method is provided by the direct measurement of low-energy elas tic neutrino scattering on atomic electrons and nuclei in a detector. A general strategy of such experiments consists in determining deviations of the scattering cross section differential with respect to the energy transfer from the value predicted by the standard model of the electroweak interaction. In this contribution, we present our bounds on the neutrino millicharge [7] and charge radii [9] that have been derived from the data of the GEMMA [3] and COHERENT [4] scattering experiments, respectively, and included in the Particle Data Group's Review of Particle Inveice [5]

Electromagnetic properties of massive neutrinos

Here we briefly outline the general form of the electromagnetic interactions of Dirac and Maorana neutrinos. There are at least three massive neutrino fields ν_i with respective masses m_i (i = 1, 2, 3), which are mixed with the three active flavor neutrinos ν_c , ν_μ , ν_τ . Therefore, the effective lectromagnetic interaction Hamiltonian can be presented as [1, 2]

$$\mathcal{H}_{em}^{(\nu)} = j_{\mu}^{(\nu)} A^{\mu} = \sum_{i,f=1}^{3} \overline{\nu}_{f} \Lambda_{\mu}^{fi} \nu_{i} A^{\mu},$$

where we take into account possible transitions between different massive neutrinos. The physical effect of $\mathcal{H}_{ep}^{(w)}$ is described by the effective electromagnetic vertex, which in momentum-space representation depends only on the four-momentum $q = p_i - p_f$ transferred to the photon and can be expressed as follows:

 $\Lambda_{\mu}(q) = (\gamma_{\mu} - q_{\mu}q/q^2) [f_Q(q^2) + f_A(q^2)q^2\gamma_5] - i\sigma_{\mu\nu}q^{\nu} [f_M(q^2) + if_E(q^2)\gamma_5].$

Here $\Lambda_{\mu}(q)$ is a 3×3 matrix in the space of massive neutrinos expressed in terms of the four Hermitian 3×3 matrices of form factors

$$f_Q = f_Q^{\dagger}$$
, $f_M = f_M^{\dagger}$, $f_E = f_E^{\dagger}$, $f_A = f_A^{\dagger}$,

where Q, M, E, A refer respectively to the real charge, magnetic, electric, and anapole neutrino form factors. The Lorentz-invariant form of the vertex function (2) is also consistent with electronagnetic gauge invariance that implies four-current conservation For the coupling with a real photon in vacuum $(q^2 = 0)$ one has

 $f_O^{fi}(0) = e_{fi}, \quad f_M^{fi}(0) = \mu_{fi}, \quad f_E^{fi}(0) = \epsilon_{fi}, \quad f_A^{fi}(0) = a_{fi},$

where e_{fi} , μ_{fi} , ϵ_{fi} and a_{fi} are, respectively, the neutrino charge, magnetic moment, electric mo-ment and anapole moment of diagonal (f = i) and transition $(f \neq i)$ types. Even if the electric charge of a neutrino is zero, the electric form factor $f_Q(q^2)$ can still contain nontrivial information about neutrino electrostatic properties. A neutral particle can be characterized by a superposition of two charge distributions of opposite signs, so that the particle form factor $f_O(q^2)$ can be nonzero for $q^2 \neq 0$. The mean charge radius (in fact, it is the squared charge radius) of an electrically neutral neutrino is given by

$$\langle r_{\nu}^2 \rangle = \frac{1}{6} \left. \frac{df_Q(q^2)}{dq^2} \right|_{q^2=0},$$

which is determined by the second term in the power-series expansion of the neutrino charge form factor.

Elastic neutrino-electron scattering

Here we consider the process $\nu + e^- \rightarrow e^- + \nu$ where an ultrarelativistic neutrino with energy E_{ν} elastically scatters on an atomic electron in a detector at energy transfer T. The simplest model of the electron system in the detector is a free-electron model, where it is assumed that electrons are free and at rest. In the scattering experiments the observables are the kinetic energy T_r of the ecoil electron and/or its solid angle Ω_e . From the energy-momentum conservation one gets

$$= T$$
, $\cos \theta_e = \left(1 + \frac{m_e}{E_{\nu}}\right) \sqrt{\frac{T}{T + 2m_e}}$,

where θ_c is the angle of the recoil electron with respect to the neutrino beam. The cross section, which is differential with respect to the electron kinetic energy T_{e} can be presented in the form of a sum of helicity-conserving (w, Q) and helicity-flipping (μ) components [6]:

$$\frac{d\sigma}{dT_e} = \frac{d\sigma_{(w,Q)}}{dT_e} + \frac{d\sigma_{(\mu)}}{dT_e},$$

where $d\sigma_{(w,Q)}/dT_e$ is the electroweak cross section modified by the effect of the neutrino millicharge, charge radius and anapole moment, and $d\sigma_{(\mu)}/dT_e$ is the magnetic cross section due to the neutrino dipole magnetic and electric moments

At small Te values the contributions to the recoil-electron spectrum due to the weak, milliharge, and magnetic scattering channels exhibit qualitatively different Tr dependencies, namely

$$\mathcal{N}_{e^-}^{(w,Q)}(T_e) \propto \begin{cases} \cos t \\ \frac{2\pi \alpha^2}{m_e T_e^2} \left(\frac{e_\nu}{e_0}\right)^2 (e_\nu \neq 0), & \text{and} & \mathcal{N}_{e^-}^{(\mu)}(T_e) \propto \frac{\pi \alpha^2}{m_e^2 T_e} \left(\frac{\mu_\nu}{\mu_B}\right)^2, \end{cases}$$

where α is the fine structure constant, e_{ν} and μ_{ν} are the neutrino (effective) millicharge and magnetic moment, and e_0 and μ_B are an elementary electric charge and a Bohr magneton, respectively. For the ratio \mathcal{R} of the millicharge and magnetic-moment contributions to the recoil-electron energy spectrum one thus has



In case there are no observable deviations from the weak contribution to the electron sp it is possible to get the upper bound for the neutrino millicharge demanding that a possible e fect due to e_{ν} does not exceed one due to the neutrino (anomalous) magnetic moment μ_{ν} . This implies that $\mathcal{R} < 1$ and from the relation (9), using the GEMMA data [3], namely the detector energy threshold ~ 2.8 keV and the μ_{ν} bound $\mu_{\nu} < 2.9 \times 10^{-11} \mu_{Br}$ one obtains the following upper limit on the neutrino millicharge [7]:

 $|e_{\nu}| < 1.5 \times 10^{-12} e_0$

The e_{ν} range that expected to be probed in a few years with the GEMMA-II experiment (an effective threshold of 1.5 keV and the μ_{ν} sensitivity at the level of $1 \times 10^{-11} \mu_B$) is $|e_{\nu}| < 3.7 \times 10^{-13} e_0$

Coherent elastic neutrino-nucleus scattering

Here we consider the process $\nu_{\ell} + a(Z, N) \rightarrow a(Z, N) + \nu_{\ell'=e,\mu,\tau}$ where an utrarelativistic neutrinn with energy E_{ν} elastically scatters on an atomic nucleus, having Z protons and N neutrons, in a detector at energy-momentum transfer $q = (T, \tilde{q})$. For a spin-zero nucleus and $T_a \ll E_{\nu}$, where $T_a = T$ is the nuclear recoil kinetic energy, the differential cross section due to the weak and charge-radius scattering channels is given by [6, 9]

$$\frac{d\sigma_{(w,r_r)}}{dT_a} \simeq \frac{G_F^3 M_a}{\pi} \left(1 - \frac{M_a T_a}{2E_{\nu}^2}\right) \left\{ \left[\left(g_V^p - \delta_{\ell\ell}\right) F_Z(|\vec{q}|^2) + g_V^n F_N(|\vec{q}|^2) \right]^2 + F_Z^2(|\vec{q}|^2) \sum_{\ell \neq \ell} |\delta_{\ell\ell}|^2 \right\}, (10)$$

where M_a is the nuclear mass, $g_V^p = 1/2 - 2\sin^2\theta_W$ and $g_V^p = -1/2$ (the neglected radiative corrections are too small to affect the results). $F_{Z,N}(|\vec{q}|^2)$, such that $F_Z(0) = Z$ and $F_N(0) = N$, are the nuclear form factors, which are the Fourier transforms of the corresponding nucleon density distribution in the nucleus and describe the loss of coherence for $|\vec{a}|R \ge 1$, where R is the nuclea radius. The effect of the neutrino charge radii is accounted for through

$$\delta_{\ell\ell'} = \frac{2}{3} m_W^2 \sin^2 \theta_W \langle r_{\nu_{\ell\ell'}}^2 \rangle, \qquad \text{with} \qquad \langle r_{\nu_{\ell\ell'}}^2 \rangle = \sum_{i=1} U_{\ell i}^* U_{\ell'j} \langle r_{\nu_{ij}}^2 \rangle,$$

where U is the neutrino mixing matrix. The diagonal $(\ell = \ell')$ charge radii are already predicted in the standard model [8]

 $\langle r_{\nu_c}^2 \rangle_{SM} = -0.83 \times 10^{-32} \text{ cm}^2$, $\langle r_{\nu_c}^2 \rangle_{SM} = -0.48 \times 10^{-32} \text{ cm}^2$, $\langle r_{\nu_c}^2 \rangle_{SM} = -0.30 \times 10^{-32} \text{ cm}^2$. (11)

However, the transition $(\ell \neq \ell')$ charge radii are essentially the BSM quantities Fig. 1 shows the results of our fit [9] of the time-dependent COHERENT data [4]. In the analy sis, we used the Helm parametrization of the nuclear form factors $F_{Z,N}(|\vec{q}|^2)$ and the rms radii o the proton distribution $R_p(^{133}Cs) = 4.804$ fm and $R_p(^{127}I) = 4.749$ fm that have been determine with high accuracy with muonic atom spectroscopy [10].



Figure 1: 90% CL allowed regions in the $(r_{n}^{2}) - (r_{n}^{2})$ plane obtained from the fit of the time-dependent COHEREN energy spectrum without (left panel) and with (right panel) the transition charge radii. The red and blue point indicate the best-fit values, and the group point near the origin indicates the starting and model values in Eq. (11). Fixed R_{n} . We used the theoretical values $R_{n}^{(WG)} = 501$ fm and $R_{n}^{(WT)} = 4.94$ fm from the relativistic mean field M^{WT} and the individual of the individual values $R_{n}^{(WG)} = 501$ fm and $R_{n}^{(WT)} = 4.94$ fm from the relativistic mean field

Free R_{n} , R_{n} (see used the deconstant values R_{n} , C_{n}) = 0.01 m and R_{n} , T_{n} = 0.01 m m mode NL-Z2 nuclear model calculations [11]. Free R_{n} : R_{n} (³³Cs) and R_{n} (²²⁷) are allowed to vary in suitable intervals, with the lower sponding experimental R_{p} values (see above) and the upper bound of 6 fm.

In addition to the customary, diagonal charge radii, from the COHERENT data we have obtained for the first time limits on the neutrino transition charge radii [9]

$$(|\langle r_{\nu_{0\mu}}^2 \rangle|, |\langle r_{\nu_{er}}^2 \rangle|, |\langle r_{\nu_{\mu r}}^2 \rangle|,) < (22, 38, 27) \times 10^{-32} \text{ cm}^3$$

at 90% CL, marginalizing over reliable allowed intervals of the rms radii Rn(133Cs) and Rn(127I) This is an interesting information on the BSM physics which can generate the neutrino transitio charge radii [12]

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Experimental limits on v charge radius $\langle r_{v}^{2} \rangle$

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

Method	Experiment	Limit (cm ²)	C.L.	Reference
Reactor $\bar{\nu}_e$ - e^-	Krasnoyarsk TEXONO	$\begin{split} \langle r_{\nu_e}^2 \rangle &< 7.3 \times 10^{-32} \\ -4.2 \times 10^{-32} &< \langle r_{\nu_e}^2 \rangle &< 6.6 \times 10^{-32} \end{split}$	90% 90%	Vidyakin <i>et al.</i> (1992) Deniz <i>et al.</i> (2010) ^a
Accelerator ν_e - e^-	LAMPF LSND	$\begin{array}{l} -7.12 \times 10^{-32} < \langle r_{\nu_e}^2 \rangle < 10.88 \times 10^{-32} \\ -5.94 \times 10^{-32} < \langle r_{\nu_e}^2 \rangle < 8.28 \times 10^{-32} \end{array}$	90% 90%	Allen <i>et al.</i> $(1993)^{a}$ Auerbach <i>et al.</i> $(2001)^{a}$
Accelerator ν_{μ} - e^{-}	BNL-E734 CHARM-II	$\begin{array}{l} -4.22 \times 10^{-32} < \langle r_{\nu_{\mu}}^2 \rangle < 0.48 \times 10^{-32} \\ \langle r_{\nu_{\mu}}^2 \rangle < 1.2 \times 10^{-32} \end{array}$	90% 90%	Ahrens <i>et al.</i> $(1990)^{a}$ Vilain <i>et al.</i> $(1995)^{a}$

... updated by the recent constraints (effects of physics Beyond Standard Model)



 $(|\langle r_{\nu_{e\mu}}^2 \rangle|, |\langle r_{\nu_{e\tau}}^2 \rangle|, |\langle r_{\nu_{\mu\tau}}^2 \rangle|) < (22, 38, 27) \times 10^{-32} \,\mathrm{cm}^2$

M.Cadeddu, C. Giunti, K.Kouzakov, Yu-Feng Li, A. Studenikin, Y.Y.Zhang, Neutrino charge radii from COHERENT elastic neutrino-nucleus scattering, Phys.Rev.D 98 (2018) 113010 ... if one trusts $\boldsymbol{\mathcal{V}}$

to be precursor for

BESM physics ...



millichargec

of Y quantization electric charges Q gets dequantized



Experimental limits on different effective *Q*

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

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

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


50 years of **V** oscillation formulae Gribov & Pontecorvo (1969)

new developments in v spin and flavour scillations



generation of 💙 spin (flavour) oscillations by interaction with transversal matter current

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



inherent interplay of ${oldsymbol {\mathcal V}}$ spin and flavour oscillations in ${f B}$

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



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

The European Physical Society Conference on High Energy Physics 10-17 July 2019, Ghent, Belgium

Neutrino spin and spin-flavor oscillations in matter currents and magnetic fields

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Based on:

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

V. Shakhov, Bachelor Dissertation "Neutrino oscillations in arbitrarily directed magnetic fields and matter currents", MSU, 2019 flavor $\nu_e^L \leftarrow (j_\perp) \Rightarrow \nu_u^R$ oscillations engen-

dered by transversal matter currents: Quantum

rere recove we comme our studies of the effect of neutrino spin evolution induced by the transversal matter currents and develops a consistent derivation of the effect based on the direct calculation of the spin evolution effective Hamiltonian in the case when entrino is programming in matter transversal currents. Consider two favour neutrinos with two possible belicities as $p = \{a_i^{(i)}, a_{ij}^{(i)}, a_{ij}^{(i)}$

where $f^{\mu} = -\frac{\partial}{\partial t} a(1, \mathbf{v}), l = e, \mu$ indicates the neutrino flavour, i = 1, 2 indicate the neutrino mass state and the matter potential f^{μ} depends on the velocity of matter $\mathbf{v} = (v_i, v_i, v_i)$ and on the neutron number density in the laboratory reference fram $n = \frac{\partial}{\partial t + n^2}$. Each of the flavour neutrinos is a superposition of the neutrino mass states,

 $\nu_z^{\pm}=\nu_1^{\pm}\cos\theta+\nu_2^{\pm}\sin\theta,\quad \nu_x^{\pm}=-\nu_2^{\pm}\sin\theta+\nu_2^{\pm}\cos\theta,$

 $i\frac{d}{ds}\nu_f = \left(H_0^{eff} + \Delta H^{eff}\right)\nu_f,$

 $H^{eff} = H^{eff}_{c} + \Delta H^{eff}_{c}$

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

 $\Delta_{nn}^{nn'} = \left(\nu_n^{n} | H_{nn'} | \nu_n^{n'}\right)$

 $k, l = v, \mu, s, s' = \pm$. In evaluation of $\Delta_{kl}^{ss'}$ we have first introduced the neutrino flavor

 $v_{\alpha}^{s} = C_{\alpha} \left(\frac{u_{\alpha}^{s}}{\frac{e_{\alpha}}{E_{\alpha} + u_{\alpha}} u_{\alpha}^{s}} \right) \sqrt{\frac{(E_{\alpha} + m_{\alpha})}{2E_{\alpha}}} \exp \left(ip_{\alpha}x\right)$

 $u_{n}^{+} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad u_{n}^{-} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

for the typical term $\Delta_{\alpha\alpha'}^{\alpha'} = \langle \nu_{\alpha}^{s} | \Delta H^{SM} | \nu_{\alpha'}^{s'} \rangle$, that by fixing proper values of α, s, α

 $\Delta_{\mathbf{s}\mathbf{s}'}^{\mathbf{s}'} = \tilde{G}n \left\{ \mathbf{u}_{\mathbf{s}}^{\mathbf{s}''} \begin{bmatrix} \begin{pmatrix} 0 & 0 \\ 0 & 2 \end{pmatrix} \mathbf{v}_{1} + \begin{pmatrix} 0 & \gamma_{\mathbf{s}}^{-1} \\ \gamma_{\mathbf{s}'}^{-1} & 0 \end{pmatrix} \mathbf{v}_{\perp} \end{bmatrix} \mathbf{u}_{\mathbf{s}'}^{\mathbf{s}'} \right\} \delta_{\mathbf{s}'}^{\mathbf{s}'}$

hat the effective interaction Hamiltonian in the flavour basis has the following struc

 $H^{eff} = n \mathcal{G} \begin{pmatrix} 0 & \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} & 0 & \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} \\ \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} & 2\left(1 - v_{1} \right) & \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} & 0 \\ 0 & \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} & 0 & \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} \\ \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} & 0 & \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} & 2\left(1 - v_{1} \right) \end{pmatrix}.$

 $\left(\frac{\eta}{\gamma}\right)_{a\mu} = \frac{\cos^2\theta}{\gamma_{11}} + \frac{\sin^2\theta}{\gamma_{22}}, \quad \left(\frac{\eta}{\gamma}\right)_{a\mu} = \frac{\sin^2\theta}{\gamma_{11}} + \frac{\cos^2\theta}{\gamma_{22}}, \quad \left(\frac{\eta}{\gamma}\right)_{a\mu} = \frac{\sin 2\theta}{\gamma_{21}}.$ (20)

flavor neutrino evolution Hamiltonian in the magnetic field H_{μ}^{\prime} can be calculat same way. One just should start from the neutrino electromagnetic interacti-glam $L_{EH} = \frac{1}{\mu_{\mu\nu}\sigma_{\mu}\sigma_{\mu}\nu_{\mu}}F^{\mu\nu} + h.c.$

 $\left(-\left(\frac{s}{\gamma}\right)_{ac}B_{\parallel} - \mu_{ac}B_{\perp}e^{-i\phi} - \left(\frac{s}{\gamma}\right)_{ac}B_{\parallel} - \mu_{ac}B_{\perp}e^{-i\phi}$

 $\begin{array}{c} (\gamma)_{\mu} \rightarrow_{i} - \rho_{\mu\nu}\sigma_{i\nu} = -(\gamma)_{\mu\nu}\sigma_{i} - \frac{\rho_{\mu\nu}\sigma_{i\nu}}{\rho_{i}} = \rho_{\mu\mu}\sigma_{i\nu}e^{i\nu} \\ -\rho_{\mu\mu}B_{\mu}e^{i\nu} = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\nu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ -\rho_{\mu\mu}B_{\mu}e^{i\nu} = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ +\rho_{\mu\mu}B_{\mu}e^{i\nu} = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{1} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{1} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{1} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} \\ = \begin{pmatrix} q \\$

where ϕ is the angle between transversal components of magnetic field B_{\pm} and matter velocity v_{\pm} and

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

 $\left(\frac{\mu}{\gamma}\right)_{zz} = \frac{\mu_{11}}{\gamma_{12}} \cos 2\theta + \frac{1}{2} \left(\frac{\mu_{22}}{\gamma_{22}} - \frac{\mu_{11}}{\gamma_{13}}\right) \sin 2\theta,$

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

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

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

tian (21) explicitly accounts [10] for a possibility of real matter current j_{\perp} in respect to the vector of the t

 $\mu_{ss} = \mu_{ss} \sin^2 \theta + \mu_{ss} \cos^2 \theta - \mu_{ss} \sin 2\theta$

introduce the following formal notations:

adinal and transversal velocities of the matter

 $\gamma_{aa'}^{-1} = \frac{1}{2} \left(\gamma_a^{-1} + \gamma_{a'}^{-1} \right), \quad \tilde{\gamma}_{aa'}^{-1} = \frac{1}{2} \left(\gamma_a^{-1} - \gamma_{a'}^{-1} \right), \quad \gamma_a^{-1} = \frac{m_a}{E}.$ (18)

unnement eninger define mentring helicity states, and use sizes h

states ν_{k}^{i} and ν_{l}^{i} as superpositions of the mass states $\nu_{l,p}^{h}$. Then, using the exact free neutrino mass states spinors,

 $L_{int} = -f^{\mu} \sum \bar{\nu}_i(x) \gamma_{\mu} \frac{1 + \gamma_5}{2} \nu_1(x) = -f^{\mu} \sum \bar{\nu}_i(x) \gamma_{\mu} \frac{1 + \gamma_5}{2} \nu_i(x),$ (9)

Here below we continue our studies of the effect of neutrino spin evol

evolution equation in the flavour basis is

treatment

∆Heff can be expressed as [3]

 $\tilde{G} = \frac{G_Z}{3\sqrt{4}}, n = \frac{n_L}{\sqrt{1-a^2}}$ and

 H_B^{f} -

Neutrino spin $\nu_e^L \Leftrightarrow (j_\perp) \Rightarrow \nu_e^R$ and spin- | Probability of neutrino spin-flavor oscillations

0.00

(11)

(13)

(14)

(19)

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

lition $E_{eff} \ge \Delta_{eff}$.

Consider two states of neutrino $(v_{n_1}^{\beta_1}, v_{\mu}^{\beta_2})$. The corresponding oscillations are governed with evolution evolution

 $i\frac{d}{dt}\begin{pmatrix} v_1^1\\ v_2^V \end{pmatrix} = \begin{pmatrix} -\Delta M + \begin{pmatrix} \xi \\ y \\ z \end{pmatrix}_{\mathbb{R}} B_{1} + \hat{O}n(1-z\beta) & -\mu_{\alpha}B_{\alpha}e^{i\theta} + \begin{pmatrix} \xi \\ y \\ z \end{pmatrix}_{\alpha}\hat{O}nv_{\alpha} \\ -\mu_{\alpha}B_{1}e^{-i\theta} + \begin{pmatrix} \xi \\ y \\ z \end{pmatrix}_{\alpha}\hat{O}nv_{\alpha} & \Delta M - \begin{pmatrix} \xi \\ y \\ z \end{pmatrix}_{\alpha}B_{1} - \hat{O}n(1-z\beta) \begin{pmatrix} v_{\alpha}^{2}\\ v_{\alpha}^{2} \end{pmatrix}$ (24)

For the oscillation $v_s^L \Leftrightarrow (j_{\perp}, B_{\perp}) \Rightarrow v_s^R$ probability we get (7) with

 $E_{\text{ref}} = \sqrt{\left(\mu_{op}B_{\perp}\cos\phi - \left(\frac{\eta}{\gamma}\right)_{ze}\hat{G}nv_{\perp}\right)^2 + (\mu_{op}B_{\perp}\sin\phi)^2}$

 $\Delta_{\text{eff}} = \left| \Delta M - \frac{1}{2} \left(\frac{\mu_{11}}{\gamma_{11}} + \frac{\mu_{22}}{\gamma_{20}} \right) B_{\parallel} - \tilde{G}n(1 - v_{\parallel}) \right|, \quad \Delta M = \frac{\Delta m^2 \cos 2\theta}{4g\xi}.$

Resonance amplification of neutrino spin-flavor oscilla-

Arre we examine the case when the annihilade of oscillations sin² 28,4 in (7) is not small

the condition $E_{eff} \ge m_{eff}$. Consider the case when the effect of the magnetic field is negligible, thus we get

nd we use the criterion based on the demand that $\sin^2 2\theta_{eff} \ge \frac{1}{2}$ which is provided by

 $\left| \left(\frac{\eta}{\eta} \right) | \hat{G}nv_{\perp} \right| \ge |\Delta M - \hat{G}n(1 - v_{\parallel})|.$

In the further evaluations we use the approximation $\begin{pmatrix} 1 \\ 2 \end{pmatrix}_{\gamma\mu} \approx \frac{i \theta_1 M}{\gamma_0}$, where $\gamma_{\nu} = \gamma_{11} \sim \gamma_{22}$ is the neutrino effective gamma-factor. In the case $\eta_1 = 0$ we get

 $\frac{\hat{G}nv_{\perp}}{\hat{m}} \sin 2\theta + \hat{G}n \approx \hat{G}n$

inally, the criterion $\sin^2 2\theta_{eff} \ge \frac{1}{2}$ is fulfilled when the following condition is valid:

where it will restrict a strength prime basis here [11, 12]. Notice its covering the two field restrict the will be finded by the product the strength the basis basis of two fields of products the strength will be basis basis of two fields of the strength will be basis basis of two fields of the strength will be basis basis of two fields of the strength will be basis basis of two fields of the strength will be basis basis of two fields of the strength will be basis basis of two fields of the strength will be basis basis of two fields of the strength will be basis of th

also about $D \sim 30$ km. The transversal velocity of matter can be estimated accordingly $\psi_c \rightarrow D = 0.05^{\circ}$ km corresponts be $\varphi_m = 1.002$. The mass squared differences and axing angle are taken from the solar acetinis measurement, $\Delta m^2 = 1.73 \times 10^{-2} A^{\circ}$, $M^2 = 0.237 (\cos 2\theta - 0.066)$. Considermentings with energy $g_{\rm c}^2 = 10^{0} P$ and moving matter characterized by $\gamma_m = 1.002$. Thus $\psi_{\rm c}^2 \Delta M = 0.575^{\circ}$, $M^2 \to 10^{-2}$. Thus $\psi_{\rm c}^2 \Delta M = 0.575^{\circ}$, $M^2 \to 10^{-2}$. Thus, $\psi_{\rm c}^2 \Delta M = 0.575^{\circ}$, $W^2 \to 10^{-2}$. Thus, $\psi_{\rm c}^2 \Delta M = 0.575^{\circ}$, $W^2 \to 10^{-2}$. Thus, $\psi_{\rm c}^2 \Delta M = 0.575^{\circ}$.

 $n_0 \ge \frac{\Delta M}{C} = 10^{12} \text{eV}^3 \approx 10^{26} \text{cm}^{-3}$.

 $L_{\rm eff} = \frac{\pi}{\left(\frac{k}{2}\right)_{zz} \bar{G} m v_{\perp}} \approx 5 \times 10^{10} \rm km. \label{eq:Leff}$

Let pr 10km

The performed studies [9, 10] of neutrino spin $v_{c}^{0} \leftrightarrow \langle j_{c} \rangle \Rightarrow v_{c}^{0}$ and spin-flavor $v_{c}^{0} \leftrightarrow \langle j_{c} \rangle \rightarrow v_{c}^{0}$ oscillations engendered by the transversal matter currents in the presence of arbitrary magnetic fields allow one to consider possibilities of applications of these very interesting new effects in different strephysical settings.

The oscillation length can be within the scale of short gamma-ray bursts

rom the criterion $G_N \ge \Delta M$ we get the quite reasonable con-

The corresponding oscillation length is approximately

if the matter density equals $n_{\rm H} \approx 5 \times 10^{36} {\rm cm}^{-3}$.

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Conclusions

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(27)

(29)

(30)

tions $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_\mu^R$ by longitudinal matter current

The history of neutrino spin oscillations in] transversal matter currents and/or transversally polarized matter

For many space, until 2004, it was below that a settime below precedues and the interpreting space structures are built and the matchine structure interaction measurements and the structure structure interaction measurements and the structure structure interaction of the structure structure structure interaction of the structure structure structure interaction of the structure structure structure structure interaction of the structure structu For many source until 2004, it was believed that a postering believity procession and th

scillations may arise only in the case where then

ar magnetic field in the nontrino entifytame.¹⁵ Or historical notes reviewing studies of the discussed effect see in [2, 3, 4]. It should noted that the predicted effect exists regardless of a source of the background mat-transversal current or polarization (that can be a background magnetic field, for in-tead). ore that the existence of the discussed effect of neutrino spin oscillation

Note that the existance of the discussed effect of neurons open so-califonism expendence by the minimum limit of the existance of the discusse of the probability in the probability of the probability of the discussion of the probability of the discussion of the probability of the discussion of the transversion discussion of the discussion of the discussion of the discussion of the transversion discussion of the discussion

Neutrino spin oscillations $\nu_e^L \leftarrow (j_\perp) \Rightarrow \nu_e^R$ engendered by transversal matter currents: Semiclassical treatment

llowing the discussion in [1] consider, as an example, an electron neutrino spin pre-ssion in the case when neutrinos with the Standard Model interaction are propagating ough moving and polarized matter composed of electrons electrons may in the pre-ce of an electromagnetic field given by the electromagnetic-field tensor $F_{\mu\nu} = ({\bf E}, {\bf B})$. To derive the neutrino spin oscillation probability in the transversal matter cur-use the generalized Bargmann-Michel-Telegdi equation that describes the evolu-the three-dimensional neutrino spin vector S. dS 2.0.0

$\frac{dt}{dt} = \frac{1}{2} \left[\mathbf{S} \times (\mathbf{B}_0 + \mathbf{B}_0) \right],$	
netic field B_8 in the neutrino rest frame is determined by donal (with respect to the neutrino motion) magnetic and the laboratory frame.	the transver electric field
$\mathbf{P} = \left(\mathbf{P} + \frac{1}{\mathbf{P}} + \sqrt{1 - \mathbf{r}^2} \left[\mathbf{P} + \beta\right]\right)$	

where the may sal and longit

 $\mathbf{B}_{0} = \gamma \left(\mathbf{B}_{\perp} + \frac{i}{\gamma} \mathbf{B}_{\parallel} + \sqrt{1 - \gamma^{-2}} \left[\mathbf{E}_{\perp} \times \frac{\beta}{\beta} \right] \right)$ $\gamma = (1 - \beta^0)^{-1}$, β is the neutrino velocity. The matter term M_0 in Eq. (1) is also composed of the transversal M_{-1} and logarithmized M_{-2} neutrino

$\mathbf{M}_{0} = \mathbf{M}_{0_{2}} + \mathbf{M}_{0_{2}}$	(3
$ \begin{split} \mathbf{M}_{\mathbf{h}_{\mathbf{f}}} &= \gamma \beta \frac{s_{\mathbf{t}}}{\sqrt{1-s_{\mathbf{f}}^{2}}} \left\{ \rho_{\mathbf{t}}^{(2)} \left(1-\frac{s_{\mathbf{d}}}{1-\tau-s}\right) \right\} - \\ &- \frac{g^{(0)}}{1-\tau-s} \left\{ \zeta_{\mathbf{c}} \beta \sqrt{1-s_{\mathbf{f}}^{2}} + \left(\zeta_{\mathbf{c}} \mathbf{v}, \frac{g(\theta \mathbf{v}_{\mathbf{c}})}{1+\sqrt{1-s_{\mathbf{f}}^{2}}}\right) \right\}, \end{split} $	(4
$\begin{split} \mathbf{M}_{0_{4}} &= -\frac{s_{0}}{\sqrt{1-q^{2}}} \mathbf{v}_{e_{4}} \left(p_{1}^{(1)} + p_{1}^{(2)} \frac{(g_{1}\mathbf{v}_{2})}{1+\sqrt{1-q^{2}}} \right) + \\ &+ \zeta_{e_{1}} p_{1}^{(2)} \sqrt{1-v_{1}^{2}}. \end{split}$	(5
Here $u_1 = u_1\sqrt{1-c_1^2}$ is the invariant number density of namer p resorredness for which the stud speed of matter is zero. The ex- $\zeta_{n}^{\ell}\left(\oplus S_{n}^{\ell} \left(\hat{s}_{n}^{\ell} \right) \right)$ down, respectively, the speed of the reference fram- ness momentum of matter federons is resonable number of the stud- generative state of the background electrons in the above metricond referse conductions, h_{n}^{ℓ} calculated withinful extended Standad Model support singler right-handed metrics v_{2n} are respectively, $h_{n}^{\ell} = \frac{1}{c_{2n}^{\ell}} \int_{0}^{0} \mu_{n}^{\ell} = \frac{1}{c_{2n}^{\ell}} \int_{0}^{0} \mu_{n}^{\ell}$. For extraine conducts between two metrics instates a_{n}^{ℓ} as a_{n}^{ℓ} in present effect the fall and strong matter set full the following equation	sen in the ref- stors V_{ee} and is in which the if the polariza- ice frame. The ed with $SU(2)$ - $-\frac{G_F}{2\sqrt{2}\mu}$, where nee of the mag-
$i\frac{d}{dt}\begin{pmatrix} \boldsymbol{\mu}_{k}^{L}\\ \boldsymbol{\nu}_{k}^{R} \end{pmatrix} = \mu \begin{pmatrix} \frac{1}{2} \mathbf{M}_{0 } + \mathbf{B}_{0 } & \mathbf{B}_{\perp} + \frac{1}{2}\mathbf{M}_{0\perp} \\ \mathbf{B}_{\perp} + \frac{1}{2}\mathbf{M}_{0\perp} & -\frac{1}{2} \mathbf{M}_{0 } + \mathbf{B}_{0 } \end{pmatrix} \begin{pmatrix} \boldsymbol{\nu}_{k}^{L}\\ \boldsymbol{\nu}_{k}^{R} \end{pmatrix}$	(6)

as, the probability of the neutrino spin oscillations in the adiabatic appro $P_{t_{t}^2 \rightarrow \eta} \mu(x) = \sin^2 2\theta_{t} t \sin^2 \frac{\pi x}{L_{t}}, \ \sin^2 2\theta_{t} t = \frac{k_{t}^2}{k_{t}^2 + \Delta_{t}^2},$ $L_{\rm eff} = \frac{\pi}{\sqrt{\pi_{\rm eff}^2 + \Delta_{\rm eff}^2}}, \label{eq:Leff}$ $E_{\text{eff}} = \mu [\mathbf{B}_{\perp} + \frac{1}{2}\mathbf{M}_{1\perp}] \quad \Delta_{\text{eff}} = \frac{\mu}{2} [\mathbf{M}_{01} + \mathbf{B}_{02}].$

s it follows [1] that even in the absence of the transversal ma netic field the

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(14) (15) (16)

Since $|c_1^+|^2$, $|d_1^+|^2$ and $(d_1^+)^*c_1^+$ are time independent, they can be determined from the initial conditions. Now let's take into account the fact that only chiral state

can participate in weak interaction and, consequently, in processes of neutrin creation and detection. It means, that the spinor structure of the neutrino initia

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

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= 10^{16} G for the neutrino energy p netic moments $\mu_1 = \mu_2 = 10^{-29} \mu_B$.

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 $P_{ab \rightarrow ab} + P_{ab \rightarrow ab} + P_{ab \rightarrow ab} + P_{ab \rightarrow ab} = 1.$

As an illustration of the interplay of neutrino oscillations on different frequen-cies, it is intensiting to find a particular realistic set of parameters (the neutrino mass square difference, energy and magnetic moment, as well as the strength of a magnetic field) which also allows one to hope for significant phenomenological

a magnetic time) which also answers to the test programming periodimetrological consequences. Arguing so, consider as an example the neutrino flavour oscil-lations $\nu_e^I \rightarrow \nu_\mu^0$ in the transversal magnetic field B_{\perp} . Obviously, the stronger the magnetic field, the greater the influence it will have on the probability of the neutrino flavour oscillations. The stronger magnetic field are expected to exist it

flavour oscillations. The strongest magnetic field are expected to exist in urs, where the strength of the field can be of the value up to $B_{\perp} = 10^{36} G$.

$$\begin{array}{c|c} \underline{Main steps in V oscillations} & 62 years! \\ \hline \underline{Main steps in V oscillations} & 62 years! \\ \hline \underline{Main steps in V oscillations} & 62 years! \\ \hline \underline{Main steps in V oscillations} & 62 years! \\ \hline \underline{Main steps in V oscillations} & 62 years! \\ \hline \underline{Main steps in V oscillations} & 62 years! \\ \hline \underline{Main steps in V oscillations} & 62 years! \\ \hline \underline{Main steps in V oscillations} & 62 years! \\ \hline \underline{Main steps in V oscillations} & 62 years! \\ \hline \underline{Main steps in V oscillations} & 62 years! \\ \hline \underline{Main steps in V oscillations} & 62 years! \\ \hline \underline{Main steps in V oscillations} & 62 years! \\ \hline \underline{Main steps in V oscillations} & 62 years! \\ \hline \underline{Main steps in V oscillations} & 62 years! \\ \hline \underline{Main steps in V oscillations} & 62 years! \\ \hline \underline{Main steps in V oscillations} & 62 years! \\ \hline \underline{Main steps in Main voice oscillations} & 62 years! \\ \hline \underline{Main steps in Main sin matter > 30 years! \\ \hline \underline{Main steps in Main sin matter > 30 years! \\ \hline \underline{Main steps in Main sin matter > 30 years! \\ \hline \underline{Main steps in Main sin matter > 30 years! \\ \hline \underline{Main steps in Main sin matter > 30 years! \\ \hline \underline{Main steps in Main sin matter > 30 years! \\ \hline \underline{Main steps in Steps in$$



Probability of
$$\nu_{e_L}$$
 ν_{μ_R} oscillations in $B = |B_{\perp}|e^{i\phi(t)}$
 $P_{\nu_L\nu_R} = \sin^2\beta \sin^2\Omega z$ $\sin^2\beta = \frac{(\mu_{e\mu}B)^2}{(\mu_{e\mu}B)^2 + (\frac{\Delta_{LR}}{4E})^2}$
 $\Delta_{LR} = \frac{\Delta m^2}{2}(\cos 2\theta + 1) - 2EV_{\nu_e} + 2E\dot{\phi}$
 $\Omega^2 = (\mu_{e\mu}B)^2 + (\frac{\Delta_{LR}}{4E})^2$
Akhmedov, 1988
Lim, Marciano
 \dots similar to
MSW effect

In magnetic field $\nu_{e_L} \ \nu_{\mu_R}$

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

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

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

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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:

Relativistic equation (quasiclassical) for

$$s, \pi, V^{\mu} = (V^{0}, \vec{V}), A^{\mu} = (A^{0}, \vec{A}),$$

 $T_{\mu\nu} = (\vec{a}, \vec{b}), \Pi_{\mu\nu} = (\vec{c}, \vec{d})$
spin vector:

$$\vec{\zeta}_{\nu} = 2g_a \left\{ A^0[\vec{\zeta}_{\nu} \times \vec{\beta}] - \frac{m_{\nu}}{E_{\nu}}[\vec{\zeta}_{\nu} \times \vec{A}] - \frac{E_{\nu}}{E_{\nu}+m_{\nu}}(\vec{A}\vec{\beta})[\vec{\zeta}_{\nu} \times \vec{\beta}] \right\}$$

$$+ 2g_t \left\{ [\vec{\zeta}_{\nu} \times \vec{b}] - \frac{E_{\nu}}{E_{\nu}+m_{\nu}}(\vec{\beta}\vec{b})[\vec{\zeta}_{\nu} \times \vec{\beta}] + [\vec{\zeta}_{\nu} \times [\vec{a} \times \vec{\beta}]] \right\} +$$

$$+ 2ig'_t \left\{ [\vec{\zeta}_{\nu} \times \vec{c}] - \frac{E_{\nu}}{E_{\nu}+m_{\nu}}(\vec{\beta}\vec{c})[\vec{\zeta}_{\nu} \times \vec{\beta}] - [\vec{\zeta}_{\nu} \times [\vec{d} \times \vec{\beta}]] \right\}.$$

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

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

$$\label{eq:main_states} \begin{split} \vec{M} &= \gamma (A^0 \vec{\beta} - \vec{A}) \\ \vec{P} &= -\gamma [\vec{\beta} \times \vec{A}], \end{split}$$



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

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 are discussed for the case of neutrino propagation in relativistic fluxes of matter. (© 2004 MAIK "Nauka/Interperiodica".

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



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

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 trame.

... the effect of \mathbf{V} helicity conversions and oscillations induced by $\nu_{e_L} \rightarrow \nu_{e_R}, \quad \nu_{e_L} \rightarrow \nu_{\mu_R}$ transversal matter currents has been recently confirmed:

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\mathbf{V} (2 flavours x 2 helicities) evolution equation Standard Model Non-Standard Interactions Resonant amplification of \mathbf{v} oscillations:

$$\begin{split} & \nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_e^R \quad \text{by longitudinal matter current} \quad \mathbf{j}_{\mu} \\ & \nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_e^R \quad \text{by longitudinal } \mathbf{B}_{\mu} \\ & \nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_\mu^R \quad \text{by matter-at-rest effect} \end{split}$$

• $\nu_e^L \Leftarrow (j_{\perp}^{NSI}) \Rightarrow \nu_{\mu}^R$ by matter-at-rest effect P. Pustoshny, A. Studenikin, Phys. Rev. D98 (2018) no. 11, 113009



a model of short GRB $D\sim 20~km$

 $d \sim 20 \ km$

• Consider V escaping central neutron star with inclination angle α from accretion disk: $\mathbf{B} = B \sin \alpha \sim \frac{1}{2}B$

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

• transversal velocity of matter $v_{\perp} = \omega D = 0.067$ and $\gamma_n = 1.002$ Mon.Not.R 443 $E_{eff} = \left(\frac{\eta}{\gamma}\right)_{ee} \tilde{G}nv_{\perp} = \frac{\cos^2\theta}{\gamma_{11}}\tilde{G}nv_{\perp} \approx \tilde{G}n_0\frac{\gamma_n}{\gamma_{\nu}}v_{\perp}$ • G $\Delta_{eff} = \left|\left(\frac{\mu}{\gamma}\right)_{ee} B_{\parallel} + \eta_{ee}\tilde{G}n\beta\right| \approx \left|\frac{\mu_{11}}{\gamma_{\nu}}B_{\parallel} - \tilde{G}n_0\gamma_n\right|$ JCAP 177 $B_{\parallel}\beta = -1$ $\left|\frac{\mu_{11}B_{\parallel}}{\tilde{G}n_0\gamma_n}\right|$

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Resonance amplification of
spin-flavor oscillations
(in the absence of j.)
Criterion – oscillations are important:

$$\begin{aligned}
u_e^L &\leftarrow (j_{\perp}, B_{\perp}) \Rightarrow \nu_{\mu}^R \\
B = B_{\perp} + B_{\parallel} \to 0 \\
\sin^2 2\theta_{\text{eff}} = \frac{E_{\text{eff}}^2}{E_{\text{eff}}^2 + \Delta_{\text{eff}}^2} \geq \frac{1}{2}
\end{aligned}$$

$$\begin{aligned}
E_{eff} = \left| \mu_{e\mu} B_{\perp} + \left(\frac{\eta}{\gamma} \right)_{e\mu} \widetilde{G} n v_{\perp} \right| \geq \left| \Delta M - \frac{1}{2} \left(\frac{\mu_{11}}{\gamma_{11}} + \frac{\mu_{22}}{\gamma_{22}} \right) B_{\parallel} - \widetilde{G} n (1 - \boldsymbol{v} \beta) \right| \\
\text{neglecting } B = B_{\perp} + B_{\parallel} \to 0 : \qquad L_{eff} = \frac{\pi}{\left(\frac{\eta}{\gamma} \right)_{e\mu} \widetilde{G} n v_{\perp} \right|} \left| \geq \left| \Delta M - \widetilde{G} n (1 - \boldsymbol{v} \beta) \right| \\
& \sum_{e \neq 1} \left[\left(\frac{\eta}{\gamma} \right)_{e \mu} \widetilde{G} n v_{\perp} \right| \geq \left| \Delta M - \widetilde{G} n (1 - \boldsymbol{v} \beta) \right| \\
& \sum_{e \neq 1} \left[\frac{(\eta)}{(\gamma)} \sum_{e \mu} \widetilde{G} n v_{\perp} \right| \geq \left| \Delta M - \widetilde{G} n (1 - \boldsymbol{v} \beta) \right| \\
& \sum_{e \neq 1} \left[\widetilde{G} n \sim \Delta M \right] \\
& \Delta m^2 = 7.37 \times 10^{-5} \ eV^2 \\
& \sin^2 \theta = 0.297 \\
& p_0^{\nu} = 10^6 \ eV \end{aligned}$$

$$\begin{aligned}
\tilde{G} = \frac{G_F}{2\sqrt{2}} = 0.4 \times 10^{-23} \ eV^{-2} \\
& n_0 \sim \frac{\Delta M}{\widetilde{G}} = 10^{12} \ eV^3 \approx 10^{26} \ cm^{-3} \end{aligned}$$

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



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

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

arXiv: 1902.08195

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

$$\begin{split} & \psi_{e}^{L(R)} = \nu_{1}^{L(R)} \cos \theta + \nu_{2}^{L(R)} \sin \theta, \\ & \psi_{\mu}^{L(R)} = -\nu_{1}^{L(R)} \sin \theta + \nu_{2}^{L(R)} \cos \theta \\ & \text{in magnetic field } \mathbf{B} = (B_{\perp}, 0, B_{\parallel}) \\ & \mathbf{V}_{i}^{L}(t) = c_{i}^{+}\nu_{i}^{+}(t) + c_{i}^{-}\nu_{i}^{-}(t) \\ & \mathbf{V}_{i}^{R}(t) = d_{i}^{+}\nu_{i}^{+}(t) + d_{i}^{-}\nu_{i}^{-}(t) \\ & \mathbf{V}_{i}^{R}(t) = d_{i}^{+}\nu_{i}^{R}(t) + d_{i}^{-}\nu_{i}^{-}(t) \\ & \mathbf{V}_{i}^{R}(t) = d_{i}^{-}\nu_{i}^{R}(t) \\ & \mathbf{V}_{i}^{R}(t) = d_{i}^{-}\nu_{i}^{R}(t) \\ & \mathbf{V}_{i}^{R}(t) = d_{i}^{R}(t) \\ & \mathbf{V}_{i}^{R$$

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

$$\begin{split} \overline{\nu_{e}^{L} \leftrightarrow \nu_{\mu}^{L}} \quad P_{\nu_{e}^{L} \rightarrow \nu_{\mu}^{L}}(t) &= \left| \langle \nu_{\mu}^{L} | \nu_{e}^{L}(t) \rangle \right|^{2} \qquad \mu_{\pm} = \frac{1}{2} (\mu_{1} \pm \mu_{2}) \underset{\text{of } \checkmark}{\text{magnetic moments}} \\ P_{\nu_{e}^{L} \rightarrow \nu_{\mu}^{L}}(t) &= \sin^{2} 2\theta \Big\{ \cos(\mu_{1}B_{\perp}t) \cos(\mu_{2}B_{\perp}t) \sin^{2} \frac{\Delta m^{2}}{4p} t + \\ \mathbf{flavour} \\ &+ \sin^{2} \left(\mu_{+}B_{\perp}t \right) \sin^{2} (\mu_{-}B_{\perp}t) \Big\} \end{split}$$

$$P_{\nu_{e}^{L} \rightarrow \nu_{e}^{R}} = \left\{ \sin \left(\mu_{+}B_{\perp}t\right) \cos \left(\mu_{-}B_{\perp}t\right) + \cos 2\theta \sin \left(\mu_{-}B_{\perp}t\right) \cos \left(\mu_{+}B_{\perp}t\right) \right\}^{2}$$

$$spin - \sin^{2} 2\theta \sin \left(\mu_{1}B_{\perp}t\right) \sin \left(\mu_{2}B_{\perp}t\right) \sin^{2} \frac{\Delta m^{2}}{4p} t.$$

$$P_{\nu_{e}^{L} \rightarrow \nu_{\mu}^{R}}(t) = \sin^{2} 2\theta \left\{ \sin^{2} \mu_{-}B_{\perp}t \cos^{2} \left(\mu_{+}B_{\perp}t\right) + \sin^{2} \frac{\Delta m^{2}}{4p} t \right\}$$

$$\dots \text{ interplay of oscillations on vacuum } \omega_{vac} = \frac{\Delta m^{2}}{4p} \text{ and } \alpha_{vac} = \frac{\Delta m^{2}}{4p} \text{ on magnetic } \omega_{B} = \mu B_{\perp} \text{ frequencies}$$
A.Popov, A.S., Eur. Phys. J. C79 (2019) 144





 $\Delta m^2 = 7 \times 10^{-5} \mu_B.$



Fig. 3 The probability of the neutrino spin flavour oscillations $\nu_e^L \rightarrow \nu_{\mu}^R$ 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 $\mu_1 = \mu_2 = 10^{-20} \mu_B$.

• $P_{\nu_e^L \nu_\mu^R} = \sin^2(\mu_{e\mu} B_\perp t) = 0$ $\mu_{e\mu} = \frac{1}{2}(\mu_2 - \mu_1) \sin 2\theta$ $\mu_1 = \mu_2, \quad \mu_{ij} = 0, \quad i \neq j$

• For completeness:
$$\checkmark$$
 survival $\nu_e^L \leftrightarrow \nu_e^L$ probability
... depends on μ_{\checkmark} and B
 $P_{\nu_e^L \rightarrow \nu_e^L}(t) = \left\{ \cos\left(\mu_+ B_\perp t\right) \cos\left(\mu_- B_\perp t\right) - \cos 2\theta \sin\left(\mu_+ B_\perp t\right) \sin\left(\mu_- B_\perp t\right) \right\}^2$
 $-\sin^2 2\theta \cos(\mu_1 B_\perp t) \cos(\mu_2 B_\perp t) \sin^2 \frac{\Delta m^2}{4p} t$

of all probabilities (as it should be...):

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

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Neutrino spin and spin-flavor oscillations in matter currents and magnetic fields

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V. Shakhov, Bachelor Dissertation "Neutrino oscillations in arbitrarily directed magnetic fields and matter currents", MSU, 2019 Neutrino spin $\nu_e^L \iff (j_{\perp}) \implies \nu_e^R$ and spinflavor $\nu_e^L \leftarrow (j_\perp) \Rightarrow \nu_u^R$ oscillations engen-

dered by transversal matter currents: Quantum

treatment

∆Heff can be expressed as [3]

 $\tilde{G} = \frac{G_Z}{3\sqrt{4}}, n = \frac{n_L}{\sqrt{1-a^2}}$ and

 H_B^{f} -

The history of neutrino spin oscillations in] transversal matter currents and/or transversally polarized matter

For many space, until 2004, it was below that a settime below precedues and the interpreting space structures are built and the matchine structure interaction measurements and the structure structure interaction measurements and the structure structure interaction of the structure structure structure structure interaction of the structure structure interaction of the structure struct For many source until 2004, it was believed that a postering believity procession and th

scillations may arise only in the case where the

ar magnetic field in the nontrino entifytame.¹⁵ Or historical notes reviewing studies of the discussed effect see in [2, 3, 4]. It should noted that the predicted effect exists regardless of a source of the background mat-transversal current or polarization (that can be a background magnetic field, for in-tead). e.). te that the existence of the discussed effect of neutrino spin oscillation

Note that the existance of the discussed effect of neutrino quasa excitations expandent for the proceeding array of the proce

Neutrino spin oscillations $\nu_e^L \leftarrow (j_\perp) \Rightarrow \nu_e^R$ engendered by transversal matter currents: Semiclassical treatment

llowing the discussion in [1] consider, as an example, an electron neutrino spin pre-ssion in the case when neutrinos with the Standard Model interaction are propagating ough moving and polarized matter composed of electrons electrons may in the pre-ce of an electromagnetic field given by the electromagnetic-field tensor $F_{\mu\nu} = ({\bf E}, {\bf B})$. To derive the neutrino spin oscillation probability in the transversal matter or use the generalized Bargmann-Michel-Telegdi equation that describes the evo he three-dimensional neutrino spin vector **S**,

$\frac{dS}{dt} = \frac{z}{\gamma} \mathbf{S} \times (\mathbf{B}_0 + \mathbf{M}_0) ,$		(1
netic field B ₀ in the neutrino rest frame is determined by dinal (with respect to the neutrino motion) magnetic and the laboratory frame.	the trans electric	fick

where the may sal and longit

 $B_0 = \gamma \left(B_{\perp} + \frac{1}{\gamma} B_{\parallel} + \sqrt{1 - \gamma^{-2}} \left[E_{\perp} \times \frac{\beta}{\beta} \right] \right)$

 $\gamma=\left(1-\beta^{2}\right)^{\frac{-1}{2}},$ β is the neutrino velocity. The matter term M_{0} in Eq. (1) is also

$\mathbf{M}_0 = \mathbf{M}_{0_2} + \mathbf{M}_{0_1}$	(3)
$\begin{split} \mathbf{M}_{\mathbf{n}_{\mathbf{j}}} &= \gamma \beta \frac{u_{\mathbf{s}}}{\sqrt{1-u_{\mathbf{j}}^{2}}} \left\{ \rho_{\mathbf{s}}^{(1)} \left(1 - \frac{u_{\mathbf{s}}\theta}{1-\gamma^{-2}}\right) \right\} - \\ &- \frac{\mu_{\mathbf{s}}^{(0)}}{1-\gamma^{-2}} \left\{ \zeta_{\mathbf{s}} \theta \sqrt{1-u_{\mathbf{s}}^{2}} + \left(\zeta_{\mathbf{s}} \mathbf{v}_{\mathbf{s}} \frac{(\theta u_{\mathbf{s}})}{1+\sqrt{1-u_{\mathbf{j}}^{2}}} \right) \right\}, \end{split}$	(4)
$\mathbf{M}_{\mathbf{k}_{4}} = -\frac{i\pi}{\sqrt{1-i\delta}} \mathbf{v}_{\mathbf{k}_{4}} \left(\mu_{0}^{(1)} + \mu_{0}^{(2)} \frac{i(\omega_{4})}{1+\sqrt{1-i\delta}} \right) + + \mathbf{C}_{i,j} \mu_{i}^{(2)} \sqrt{1-v_{i}^{2}}.$ (6)	(5)
Here $u_0 = v_0 \sqrt{1-c_0^2}$ is the invariant number density of matter given in the variant point with the board apped of matter in zero. The variant $V_{\rm eff} = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dt_{\rm eff} = $	ef- nd he ca- he 2)- sre
$i \frac{d}{dt} \begin{pmatrix} \nu_c^L \\ \nu_c^L \end{pmatrix} = \mu \begin{pmatrix} \frac{1}{2} \mathbf{M}_{01} + \mathbf{B}_{01} & \mathbf{B}_{\perp} + \frac{1}{2} \mathbf{M}_{01} \\ \mathbf{B}_{\perp} + \frac{1}{2} \mathbf{M}_{01} & -\frac{1}{2} \mathbf{M}_{01} + \mathbf{B}_{02} \end{pmatrix} \begin{pmatrix} \nu_c^L \\ \nu_c^L \end{pmatrix}$. (6)	(6)
Thus, the probability of the neutrino spin oscillations in the adiabatic approximation given by $P_{ij} = e^{ij} p_{ij} + e^{ij} p_{ij} = e^{ij} p_{ij} + e^{ij} p_{ij} = e^{ij} p_{ij}$	is

 $L_{\rm eff} = \frac{\pi}{\sqrt{E_{\rm eff}^2 + \Delta_{\rm eff}^2}}, \label{eq:Leff}$ $E_{\text{eff}} = \mu [\mathbf{B}_{\perp} + \frac{1}{2}\mathbf{M}_{1\perp}] \quad \Delta_{\text{eff}} = \frac{\mu}{2} [\mathbf{M}_{01} + \mathbf{B}_{02}].$ lows [1] that even in the absence of the transversal m

field the

Consider two states of neutrino $(v_{n_1}^{\beta_1}, v_{\mu}^{\beta_2})$. The corresponding oscillations are governed with evolution evolution $i\frac{d}{dt}\begin{pmatrix} v_1^1\\ v_2^V \end{pmatrix} = \begin{pmatrix} -\Delta M + \begin{pmatrix} \xi \\ y \\ z \end{pmatrix}_{\mathbb{R}} B_{1} + \hat{O}n(1-z\beta) & -\mu_{\alpha}B_{\alpha}e^{i\theta} + \begin{pmatrix} \xi \\ y \\ z \end{pmatrix}_{\alpha}\hat{O}nv_{\alpha} \\ -\mu_{\alpha}B_{1}e^{-i\theta} + \begin{pmatrix} \xi \\ y \\ z \end{pmatrix}_{\alpha}\hat{O}nv_{\alpha} & \Delta M - \begin{pmatrix} \xi \\ y \\ z \end{pmatrix}_{\alpha}B_{1} - \hat{O}n(1-z\beta) \begin{pmatrix} v_{\alpha}^{2}\\ v_{\alpha}^{2} \end{pmatrix}$ (24) Here below we continue our studies of the effect of neutrino spin evo True recove we continue our indicis of the effect of neutrino spin evolution induced by the transversal matter currents and develop a convisiont derivation of the effect based on the direct calculation of the spin evolution effective Hamiltonian in the case when a neutron is popogasing in matter transversal currents. Consider two fascour neutrinos with two possible belicities up $-\left(e_{i}^{a},e_{j}^{a},i_{k}^{a},j_{k}^{a}\right)^{T}$ in moving matter composed of neutrons. The neutrino interaction Lagrangian reads For the oscillation $v_s^L \Leftrightarrow (j_{\perp}, B_{\perp}) \Rightarrow v_s^R$ probability we get (7) with $L_{int} = -f^{\mu} \sum \bar{\nu}_i(x) \gamma_{\mu} \frac{1 + \gamma_5}{2} \nu_1(x) = -f^{\mu} \sum \bar{\nu}_i(x) \gamma_{\mu} \frac{1 + \gamma_5}{2} \nu_i(x),$ (9) $E_{\text{ref}} = \sqrt{\left(\mu_{op}B_{\perp}\cos\phi - \left(\frac{\eta}{\gamma}\right)_{ze}\hat{G}nv_{\perp}\right)^2 + (\mu_{op}B_{\perp}\sin\phi)^2}$ where $f^{\mu} = -\frac{\partial \mu}{\partial N} n(\mathbf{i}, \mathbf{v})$, $l = e, \mu$ indicates the neutrino flavour, i = 1, 2 indicate the neutrino mass site and the matter potential P^{μ} depends on the velocity of matter $\Delta_{\text{eff}} = \left| \Delta M - \frac{1}{2} \left(\frac{\mu_{11}}{\gamma_{11}} + \frac{\mu_{22}}{\gamma_{20}} \right) B_{\parallel} - \tilde{G}n(1 - v_{\parallel}) \right|, \quad \Delta M = \frac{\Delta m^2 \cos 2\theta}{4g\xi}.$ where $p^{-} = -\frac{1}{\sqrt{2}} m(t, \Psi)$, $t = c_{+}\mu$ inscents the neutrino mission, t = 1, 2 indicating the neutrino mass state and the matter potential P^{0} depends on the velocity of matti- $\Psi = (v_{1}, v_{2}, v_{3})$ and on the neutron number density in the laboratory reference fram $n = \frac{1}{\sqrt{1-\mu_{1}}}$. Each of the flavour neutrinos is a superposition of the neutrino mass states $\nu_s^{\pm} = \nu_1^{\pm} \cos \theta + \nu_2^{\pm} \sin \theta$, $\nu_s^{\pm} = -\nu_1^{\pm} \sin \theta + \nu_2^{\pm} \cos \theta$. 0.00 reolution equation in the flavour basis is Resonance amplification of neutrino spin-flavor oscilla $i\frac{d}{ds}\nu_f = \left(H_0^{eff} + \Delta H^{eff}\right)\nu_f,$ (11) tions $\nu_e^L \Leftarrow (j_\perp) \Rightarrow \nu_\mu^R$ by longitudinal matter current $H^{eff} = H^{eff}_{c} + \Delta H^{eff}_{c}$ lition $E_{eff} \ge \Delta_{eff}$. $\Delta H^{eff} = \begin{pmatrix} \Delta_{ae}^{ae} & \Delta_{ae}^{ae} & \Delta_{ae}^{ae} & \Delta_{ae}^{ae} \\ \Delta_{ae}^{ae} & \Delta_{ae}^{ae} & \Delta_{ae}^{ae} & \Delta_{ae}^{ae} \\ \Delta_{\mu e}^{ae} & \Delta_{\mu e}^{ae} & \Delta_{\mu e}^{ae} & \Delta_{\mu e}^{ae} \\ \Delta_{\mu e}^{ae} & \Delta_{\mu e}^{ae} & \Delta_{\mu e}^{ae} & \Delta_{\mu e}^{ae} \end{pmatrix}$ (13) $\left| \left(\frac{\eta}{\eta} \right) | \hat{G}nv_{\perp} \right| \ge |\Delta M - \hat{G}n(1 - v_{\parallel})|.$ $\Delta_{ni}^{ni'} = \left(\nu_{n}^{i} |H_{ni}| \nu_{n}^{i'}\right)$ (14) $k, l = e, u, s, s' = \pm$. In evaluation of $\Delta^{tt'}$ we have first introduced the neutrino flavor states ν_{a}^{a} and ν_{a}^{a} as superpositions of the mass states ν_{a}^{a} . Then, using the exact fro $\frac{\hat{G}nv_{\perp}}{\hat{m}}\sin 2\theta + \hat{G}n \approx \hat{G}n$ $v_0^s = C_0 \left(\frac{v_0^s}{\frac{E_0^s + m_0}{E_0 + m_0}} \eta_0^s \right) \sqrt{\frac{(E_0 + m_0)}{2E_0}} \exp\left(ip_0 x\right)$ where it will restrict a set of parametery basis here [11, 12]. Noticino concerning the indication rate with indication given by an angle of from the plane of the access on delta propagates through the toroidal basis of vortice matter that notices with the splitt relation $z = D^{(1)} - \frac{1}{2}$ must the assis that is approximately a set of the access -2D and the distance from the concerning of the concerning of the neutron to the z basis of the concerned -2D and -2D and -2D and the distance -2D and -2D an moment minore define pentring belicity states, and are $u_{n}^{+} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad u_{n}^{-} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$ for the typical term $\Delta_{\alpha\alpha'}^{\alpha'} = \langle \nu_{\alpha}^{a} | \Delta H^{\beta M} | \nu_{\alpha'}^{a'} \rangle$, that by fixing proper values of α, s, s $\Delta_{\mathbf{s}\mathbf{s}'}^{\mathbf{s}'} = \tilde{G}n \left\{ \mathbf{u}_{\mathbf{s}}^{\mathbf{s}''} \begin{bmatrix} \begin{pmatrix} 0 & 0 \\ 0 & 2 \end{pmatrix} \mathbf{v}_{1} + \begin{pmatrix} 0 & \gamma_{\mathbf{s}}^{-1} \\ \gamma_{\mathbf{s}'}^{-1} & 0 \end{pmatrix} \mathbf{v}_{\perp} \end{bmatrix} \mathbf{u}_{\mathbf{s}'}^{\mathbf{s}'} \right\} \delta_{\mathbf{s}'}^{\mathbf{s}'}$ dinal and transversal velocities of the matter $\gamma_{aa'}^{-1} = \frac{1}{2} \left(\gamma_a^{-1} + \gamma_{a'}^{-1} \right), \quad \tilde{\gamma}_{aa'}^{-1} = \frac{1}{2} \left(\gamma_a^{-1} - \gamma_{a'}^{-1} \right), \quad \gamma_a^{-1} = \frac{m_a}{E}.$ (18) om the criterion $\bar{G}_N \ge \Delta M$ we get the quite reasonable con Tective interaction Hamiltonian in the flavour basis has the following struc $n_0 \ge \frac{\Delta M}{C} = 10^{10} \text{eV}^3 \approx 10^{26} \text{cm}^{-3}$. $H^{eff} = n \mathcal{G} \begin{pmatrix} 0 & \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} & 0 & \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} \\ \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} & 2\left(1 - v_{1} \right) & \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} & 0 \\ 0 & \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} & 0 & \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} \\ \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} & 0 & \left(\stackrel{e}{2} \right)_{\mu} v_{\perp} & 2\left(1 - v_{1} \right) \end{pmatrix}.$ The corresponding oscillation length is approximately $L_{\rm eff} = \frac{\pi}{\left(\frac{g}{\gamma}\right)_{\rm cr} \bar{G} m v_{\perp}} \approx 5 \times 10^{10} \rm km. \label{eq:Leff}$ 0.09 The oscillation length can be within the scale of short gamma-ray bursts Here we introduce the following formal notations: $\left(\frac{\eta}{\gamma}\right)_{\mu\mu} = \frac{\cos^2\theta}{\gamma_{11}} + \frac{\sin^2\theta}{\gamma_{22}}, \quad \left(\frac{\eta}{\gamma}\right)_{\mu\mu} = \frac{\sin^2\theta}{\gamma_{11}} + \frac{\cos^2\theta}{\gamma_{22}}, \quad \left(\frac{\eta}{\gamma}\right)_{\mu\mu} = \frac{\sin 2\theta}{\gamma_{21}}.$ (20) Let pr 10km The flavor neutrino evolution Hamiltonian in the magnetic field H_{H}^{L} can be calculat in the same way. One just should start from the neutrino electromagnetic interacti-Lagrangian $L_{EH} = \frac{1}{\mu_{\mu\nu}} \omega_{\mu\nu} \omega_{\mu\nu} F^{\mu\nu} + h.c.$ if the matter density equals $n_0 \approx 5 \times 10^{36} cm^{-3}$. Conclusions $\left(-\left(\frac{s}{\gamma}\right)_{ac}B_{\parallel} - \mu_{ac}B_{\perp}e^{-i\phi} - \left(\frac{s}{\gamma}\right)_{ac}B_{\parallel} - \mu_{ac}B_{\perp}e^{-i\phi}$ $\begin{array}{c} (\gamma)_{\mu} \rightarrow_{i} - \rho_{\mu\nu}\sigma_{i\nu} = -(\gamma)_{\mu\nu}\sigma_{i} - \frac{\rho_{\mu\nu}\sigma_{i\nu}}{\rho_{i}} = \rho_{\mu\mu}\sigma_{i\nu}e^{i\nu} \\ -\rho_{\mu\mu}B_{\mu}e^{i\nu} = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\nu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ -\rho_{\mu\mu}B_{\mu}e^{i\nu} = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ +\rho_{\mu\mu}B_{\mu}e^{i\nu} = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{\mu}e^{i\nu} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{1} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{1} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} - \rho_{\mu\mu}B_{1} \\ = \begin{pmatrix} q \\ \vdots \end{pmatrix}_{\mu\mu}B_{1} \\ = \begin{pmatrix} q \\$ where ϕ is the angle between transversal components of magnetic field B_1 and mat References $\left(\frac{\mu}{\gamma}\right)_{-1} = \frac{\mu_{11}}{\gamma_{11}}\cos^2\theta + \frac{\mu_{22}}{\gamma_{22}}\sin^2\theta + \frac{\mu_{12}}{\gamma_{12}}\sin 2\theta,$ $\left(\frac{\mu}{\gamma}\right)_{zz} = \frac{\mu_{11}}{\gamma_{12}} \cos 2\theta + \frac{1}{2} \left(\frac{\mu_{22}}{\gamma_{22}} - \frac{\mu_{11}}{\gamma_{13}}\right) \sin 2\theta,$ Ad NOV 2014 (2015) the petite (1915) 3 Pallet, A. Manello, Phys. Lett. B 207 ($\left(\frac{\mu}{\gamma}\right)_{uv} = \frac{\mu_{11}}{\gamma_{11}}\sin^2\theta + \frac{\mu_{22}}{\gamma_{22}}\cos^2\theta - \frac{\mu_{12}}{\gamma_{12}}\sin 2\theta,$ 1. B. Wagel, Phys. Rev. D 91 (2015) 1230

[9] F. Pashalay and A. Xadenika, Neuko Sam, Phys. Rev. B 98 (2018), 113005

Arre we examine the case when the annihilade of oscillations sin² 28,4 in (7) is not small nd we use the criterion based on the demand that $\sin^2 2\theta_{eff} \ge \frac{1}{2}$ which is provided by he condition $E_{eff} \ge \Delta_{eff}$. Consider the case when the effect of the magnetic field is negligible, thus we get

(27)

In the further evaluations we use the approximation $\begin{pmatrix} 1 \\ 2 \end{pmatrix}_{\gamma\mu} \approx \frac{i \theta_1 M}{\gamma_0}$, where $\gamma_{\nu} = \gamma_{11} \sim \gamma_{22}$ is the neutrino effective gamma-factor. In the case $\eta_1 = 0$ we get

Probability of neutrino spin-flavor oscillations

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

inally, the criterion $\sin^2 2\theta_{eff} \ge \frac{1}{2}$ is fulfilled when the following condition is valid:

also about $D \sim 20$ km. The transversal velocity of matter can be estimated accord $w_c \rightarrow D = 0.05$ what corresponds to $w_m = 1.002$. The mass squared difference and mixing angle are taken from the solar sentimes summerms, $\Delta m^2 = 7.37 \times 10^{-4} (\gamma^2, \sin^2 \theta = 0.202)$ (co.29 = 0.00). Con-mentino with energy $g_1^2 = 10^{-4} e^4$ and moving matter characterized by $\gamma_m = 1.020$. we get $\Delta M = 0.575 \times 10^{-4} M^2$.

(29) (30) The performed studies [9, 10] of neutrino spin $v_{c}^{0} \leftrightarrow \langle j_{c} \rangle \Rightarrow v_{c}^{0}$ and spin-flavor $v_{c}^{0} \leftrightarrow \langle j_{c} \rangle \rightarrow v_{c}^{0}$ oscillations engendered by the transversal matter currents in the presence of arbitrary magnetic fields allow one to consider possibilities of applications of these very interesting new effects in different strephysical settings.



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

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

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

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

$$\begin{split} \sin^2\theta \cos^2\theta \big| |c_1^+|^2 e^{-iE_1^+t} + |c_2^-|^2 e^{-iE_2^-t} \\ - |c_1^+|^2 e^{-iE_1^+t} - |c_1^-|^2 e^{-iE_1^-t} \big|^2. \end{split}$$

 $E_{i}^{s} \approx p + \frac{m_{i}^{2}}{2p} + \frac{\mu_{i}^{2}B^{2}}{2p} + \mu_{0}sB_{\perp}.$

 $\|c\|^2 \|c\|^2 \approx \frac{1}{2}$

 $P_{s_{\pm}^2 \rightarrow w_{\pm}^4}(x) = \sin^2 2\theta \left\{ \cos(\mu_1 B_{\perp} x) \cos(\mu_2 B_{\perp} x) \sin^2 \frac{\Delta m^2}{4\pi} x \right\}$

 $\nu_{t}^{L}(t) = \left(c_{1}^{+}e^{-tE_{1}^{+}t}\nu_{1}^{+}\right)$

 $+ \left(c_2^+ e^{-dE_2^+ l} \nu_l^+ + \right)$

Introduction

Matrix emitties have noticitid elementary integration (|k| < 1) and |k| < 1) and |k| < 1 , and |k| <In the case $B_{\perp} = 0$ the helicity states $\sum_{i=1}^{n-1} |a_i^+|^2 = 0, |a_i^+|^2 = |d_i^-|^2 = 1.$ nirary to the customary approach when the neutrino helicity states are used for Neutrino states in a magnetic field ider two flavour neutrinos with two helicities accounting for mixing $\nu_e^{L(R)} = \nu_1^{L(R)} \cos \theta + \nu_2^{L(R)} \sin \theta,$ $\nu_\pi^{L(R)} = -\nu_1^{L(R)} \sin \theta + \nu_2^{L(R)} \cos \theta,$ where $\nu_{i}^{s} \equiv \nu_{i}^{s}(0)$. In exactly the same of the wave function of a muon neutri Neutrino flavour oscil where $v_i^{U(k)}$ are the helicity neutrino mass states, i = 1, 2. Recall that for the rel-trivistic neutrinos the helicity states approximately coincide with the chiral states $(\delta^{(0)} = u_i \delta^{(0)-k})$. The detailed discussion on neutrino helicity and distributy can be found in [2]. Real relativistic neutrinos produced in a weak process are almost or homotop in the neutrino in the state of the states of the sta field The probability of the neutrino flavour ft-handed helicity states. Note that the helicity mass states $\nu_1^{L(d)}$ are not stationary states in the p Note that the helicity mass states $\nu_{i}^{(A)}$ are not stationary states in the poor a magnetic field. In our further evaluations we shall expand $\nu_{i}^{(A)}$ on notation statisticary states $\nu_{i}^{(A)}$ in the presence of a magnetic field. The wave function x_{i}^{a} (x_{i}^{a}) the presence of a constant and homogeneous arbitrary orie magnetic field can be found as the solution of the Dirac equation blicit form of the neutrino stationary states wave functions to calculate the oscil-ation probability. The dependence of the neutrino oscillation probability on the magnetic field is due to the matrix elements of the projectors (14)-(16) and the $(\gamma_A p^\mu - m_i - \mu_i \Sigma B) v_i^\mu(p) = 0,$ $\chi_{(M^{-1})} \rightarrow \pi_{(M^{-1})}(M^{-1}) \rightarrow (M^{-1})$ (2) where μ_i is the neutrino magnetic moment and the magnetic field is given by $B = (B_i, 0, B_j)$. In the discussed two-neutrino case the possibility for a nonzero-neutrino transmission moment μ_{ij} ($x \neq j$) is not considered and two equations for two neutrinos states x_i^{*} are decoupled. The equation (2) can be re-written in the equivalent form magnetic nets is one to the matrix elements of the projectors (14)-(16) and the energy spectrum (7) field dependence. The probability of oscillations $\nu_{a}^{2} \leftrightarrow \nu_{a}^{2}$ is simplified if one accounts for the relativistic neutrino energies ($\mu \gg \nu_{a}$) and also for realistic values of the neutrino magnetic moments and strengths of magnetic fields ($\mu \gg \mu B$). In this case we have $\hat{H}_{\mu\nu}^{\mu} = E_{\mu\nu}^{\mu}$ $\hat{H}_i = \gamma_0 \gamma p + \mu_i \gamma_0 \Sigma B + m_i \gamma_0.$ It is reasonably to suppose that $\mu B << m$, then the contribution $\frac{\mu_L^2 B^2}{2p}$ can be eglected in (23). In the considered case we also have ator that commutes with the Hamiltonian (4) can be chosen in t $\hat{S}_{i} = \frac{1}{N} \left[\Sigma B - \frac{i}{m_{i}} \gamma_{0} \gamma_{0} [\Sigma \times p] B \right],$ Finally, for the probability of flavour oscillations $\nu_a^L \leftrightarrow \nu_a^L$ we get $\frac{1}{N} = \frac{m_i}{\sqrt{m_i^2 B^2 + p^2 B_{\perp}^2}}.$ $E_{i}^{a} = \sqrt{m_{i}^{2} + p^{2} + \mu_{i}^{2}B^{2} + 2\mu_{i}s\sqrt{m_{i}^{2}B^{2} + p^{2}B_{\perp}^{2}}},$ Neutrino evolution in a magnetic field The spin operator \hat{S}_i commutes with the Hamiltonian $\hat{H}_{i:}$ and for the neutrinoid \hat{S}_i $\hat{S}_t |\nu_t^s\rangle = s |\nu_t^s\rangle$, $s = \pm 1$, $(w^{\dagger}|w^{\dagger}) = \delta_{ik}\delta_{ik}$ esponding projector op- $\hat{P}_{t}^{\pm} = \frac{1 \pm \hat{S}_{t}}{2}.$ It is clear that projectors act on the stationary states as follows $\langle \nu_k^{s'} | \hat{P}_i^s | \nu_i^s \rangle = \delta_{ik} \delta_{ss'}.$ Now in order to solve the problem of the neutrino flavour $\nu_n^L \leftrightarrow \nu_{\mu^n}^L$ spin $\nu_n^L \leftrightarrow \nu_n^R$ and spin-flavour $\nu_n^L \leftrightarrow \nu_n^R$ oscillations in the magnetic field we ex-pand the neutrino helicity states over the neutrino stationary states

 $\nu_t^L(t) = c_t^+ \nu_t^+(t) + c_t^- \nu_t^-(t),$ $\nu_t^R(t) = d_t^+ \nu_t^+(t) + d_t^- \nu_t^-(t),$

 $\begin{array}{l} |c_i^{\pm}|^2 \,=\, (\nu_i^L | \dot{P}_i^{\pm} | \nu_i^L) \\ |d_i^{\pm}|^2 \,=\, (\nu_i^R | \dot{P}_i^{\pm} | \nu_i^R) \\ (d_i^{\pm})^* c_i^{\pm} \,=\, (\nu_i^R | P_i^{\pm} | \nu_i^L) \end{array}$

Since $|c_1^+|^2$, $|d_1^+|^2$ and $(d_1^+)^*c_1^+$ are time independent, they can be determined from the initial conditions. Now let's take into account the fact that only chiral state

an participate in weak interaction and, consequently, in processes of neutrin reation and detection. It means, that the spinor structure of the neutrino initia

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

(14) (15) (16)

where cit and dit are independent on time.



$= \sqrt{m_i^2 B^2 + p^2 B^2}$			8V28* \$1 eV7	
$bd_1^{m-1} = \frac{1}{2} \left(1 + \frac{m_1 B_1}{\sqrt{m_1^2 B^2 + p^2 B_1^2}} \right),$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1 B_1 - (B_1 - (B_1))}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (C) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (D) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (D) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (D) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1^2}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (D) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1^2}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (D) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1^2}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (D) $(b_1^{m-1} c_1^{m-1} = \frac{m_1^2 B_1^2}{2\sqrt{m_1^2 B^2 + p^2 B_1^2}},$ (D) $(b_1^{m-1} c_1^{m-1} = m_1^2 $	9) 50) = ne	for neutrino masses of the (25) of the neutrino flavous for this particular choice fit is clearly seen that the $\lambda_{tac} = \frac{\Delta w_{t}}{4\rho}$ is modulated responding oscillation leng the typical dimensions of amplitude modulation still $\frac{1}{\sqrt{w_{t}-w_{tc}}}$	order $m \sim 0.1 \text{ eV}$. In Fig. 1 we oscillations $s_1^{\mu} \rightarrow s_2^{\mu}$ in the trans of parameters and the neutrino of amplitude of oscillations at the by the magnetic field frequency of this $L = 1/\mu B \sim 50$ km. This magnetars, but the discussed eff exists being slightly washed out.	show the probability versal magnetic field mergy $p = 1 MeV$ $t v accum frequencyt_B = \mu B_{\perp}. The cor-value indeed accedeslet of the oscillation$
$\begin{split} &= \left(c_1^{*}e^{-i\theta_1^{*}}u_2^{*}+c_1^{*}e^{-i\theta_2^{*}}u_2^{*}\right)\cos\theta \\ &+ \left(c_2^{*}e^{-i\theta_2^{*}}u_2^{*}+c_2^{*}e^{-i\theta_2^{*}}u_2^{*}\right)\sin\theta, G \\ &= \operatorname{cust} h \ \text{some varias}, G \\ &= \operatorname{cust} h \ \text$	n) on	63 43999944 64 62		

(22

(23)

124

(25

(2)

(28

DHHHMM.

Consider the mass square difference $\Delta m^2 = 7 \times 10^{-5} eV^2$ and the magnetic moments $\mu_1 = \mu_2 = \mu \sim 10^{-20} \mu_S$ that corresponds the Standard Model prediction

 $\mu_{ii}^D = \frac{3\epsilon G_F m_i}{8\sqrt{2}\pi^2} \approx 3.2 \times 10^{-29} \left(\frac{m_i}{1 \text{ eV}}\right) \mu_B,$

Figure 1: The probability of the neutrino flavour oscillations transversal magnetic field $B_{\perp} = 10^{16} G$ for the neutrino ene = 10⁻⁻⁻ G for the neutrino energy p = 1 MeVnetic moments $\mu_1 = \mu_2 = 10^{-20} \mu_B$. $\Delta m^2 - 7 \times 10^{-5} eV^2$ and



Figure 2: The probability of the neutrino spin oscillations $\nu_e^L \rightarrow \nu_e^R$ in the transversal magnetic field $B_\perp = 10^{46}~G$ for the neutrino energy p = 1~MeV $\Delta m^2 = 7 \times 10^{-5}~eV^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-26}\mu_B$.



Figure 3: The probability of the neutrino spin flavour oscillations $\nu_e^L \rightarrow \nu_g^R$ 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 $\mu_1 = \mu_2 = 10^{-26} \mu_B$.

Finally, the obtained closed expressions (25), (25), (27) and (20) show that the contron oscillation $P_{d-q}(x)$, $P_{d-q}(x)$, $P_{d-q}(x)$, and also service $P_{d-q}(x)$; probabilies scabiling using complexitation implying barries that are dependent on a six different frequencies. On this have separate the conductions of the neuroisso collision partners that angli gravide are important phenomenological convergences in the carged conditions propagation in extreme anomphysical convincements where magnetic fields are present.

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

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

 $\mu_{ss} = \mu_{ss} \sin^2 \theta + \mu_{ss} \cos^2 \theta - \mu_{ss} \sin 2\theta$

A. Popov, A. Studenikin "Neutrino eigenstates and flavour, spin and spin-flavour oscillations in a constant magnetic field" poster #34

 $P_{ab \rightarrow ab} + P_{ab \rightarrow ab} + P_{ab \rightarrow ab} + P_{ab \rightarrow ab} = 1.$

As an illustration of the interplay of neutrino oscillations on different for ties, it is interesting to find a particular realistic set of parameters (the ne mas square difference, energy and magnetic moment, as well as the stren magnetic field) which also allows one to hope for significant planomenol

consequences. Arguing so, consider an accumple the nutritical phenomenological consequences. Arguing so, consider an accumple the nutrition flavour wolf-lations $\nu_n^L \rightarrow \nu_n^L$ in the transversal magnetic field B_1 . Obviously, the stronger the magnetic field, the greater the influence it will have on the probability of the neutrino flavour oscillations. The strongest magnetic field are exected to avaid on

flavour oscillations. The strongest magnetic field are expected to exist in rs, where the strength of the field can be of the value up to $B_{\perp} = 10^{26} G$

Conclusions

velectromagnetic properties: Future prospects

- new constraints on \mathcal{M}_{v} (and q_{v}) from GEMMA and Borexino (?)
- charge radius in $\checkmark e$ elastic scattering can't be considered as a shift $g_V \rightarrow g_V + \frac{2}{3}M_W^2 \langle r^2 \rangle \sin^2 \theta_W$, there are also contributions from flavor-transition charge radii – new analysis (re-analysis) of data is needed



M, 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 \checkmark fluxes (for instance, in JUNO experiment) may reveal effect of collective spin-flavour oscillations due to Majorana

$$M_{v} \sim 10^{-21} \mu_{\rm B}$$

$\mathbf{3}$ \mathbf{v} electromagnetic interactions (new effects)

two new aspects of \mathbf{v} spin, spin-flavour and flavour oscillations

2-consistent treatment of **V** spin, flavour A.Popov, and spin-flavour oscillations in **B** Eur. Phys. J. C 79

(2019) 144

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

Thank you

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Back up slides

Large magnetic moment M_{\bullet}




Large magnetic moment $\mu_{u} = \mu_{u} (m_{u}, m_{e}, m_{e})$ • In the <u>L-R</u> symmetric models (SU(2) × SU(2) · U(4))

m.

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Kim, 1976

Ruderman 1978

Bell, Cirigliano, Ramsey-Musolf,

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supersymmetry

Voloshin, 1988

"On compatibility of small

with large \mathcal{M} , neutrino", Sov.J.Nucl.Phys. 48 (1988) 512

... there may be $SU(2)_{\nu}$ symmetry that forbids M, but not \mathcal{M}_{ν}

extra dimensions

Bar, Freire, Zee, 1990

- considerable enhancement of $M_{\rm s}$ to experimentally relevant range
- model-independent constraint μ_{a}



for BSM ($\Lambda \sim 1~{
m TeV}$) without fine tuning and under the assumption that $\delta m_{\nu} \leq 1 \text{ eV}$

... Atomic Ionization Effect...



... better limits on \mathcal{V} effective magnetic moment ...



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Astrophysical bound on q_{v}

... astrophysical bound on millicharge q_{v} from



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Studenikin, Tokarev,





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

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

In quasi-classical approach quantum states in rotating matter motion in circular orbits

$$R = \int_0^\infty \Psi_L^\dagger \mathbf{r} \, \Psi_L \, d\mathbf{r} = \sqrt{\frac{2N}{|2Gn_n\omega - \epsilon q_0B|}}$$

due to effective Lorentz force

 $\mathbf{F}_{eff} = q_{eff} \mathbf{E}_{eff} + q_{eff} \left[\boldsymbol{\beta} \times \mathbf{B}_{eff} \right] \begin{array}{l} \text{J.Phys.A: Math.Theor.} \\ \text{41(2008) 164047} \end{array}$

$$\begin{aligned} q_{eff}\mathbf{E}_{eff} &= q_m\mathbf{E}_m + q_0\mathbf{E} \qquad q_{eff}\mathbf{B}_{eff} = |q_mB_m + q_0B|\mathbf{e}_z \\ \text{where} \qquad q_m &= -G, \quad \mathbf{E}_m = -\nabla n_n, \quad \mathbf{B}_m = 2n_n\omega \\ \text{matter induced "charge", "electric" and \\ "magnetic" fields } \end{aligned}$$

... we predict :

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

E ~ 1 eV 1) low-energy V are trapped in circular orbits inside rotating neutron stars

$$R = \sqrt{\frac{2N}{Gn\omega}} \checkmark R_{NS} = 10 \ km$$



2) rotating neutron stars as filters for low-energy relic V? $T_{\nu} \sim 10^{-4} \text{ eV}$

• γ Star Turning mechanism (γ ST) A. Studenikin, I. Tokarev, Nucl. Phys. B 884 (2014) 396

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

New astrophysical constraint on
 v millicharge

$$\frac{|\triangle \omega|}{\omega_0} = 7.6\varepsilon \times 10^{18} \left(\frac{P_0}{10 \text{ s}}\right) \left(\frac{N_\nu}{10^{58}}\right) \left(\frac{1.4M_\odot}{M_S}\right) \left(\frac{B}{10^{14}G}\right)$$
$$|\triangle \omega| < \omega_0 \qquad \dots \text{to avoid contradiction of } \forall \text{ST impact}$$
with observational data on pulsars.

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

with observational data on pulsars ...



Astrophysical bound on M,







more fast star cooling

In order not to delay helium ignition ($\leq 5\%$ in Q)







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flavour oscillations spin

$P_{y,y}(x) = \sin^2 2\theta \cdot \sin^2 \frac{\Delta m}{\Delta c}$	K
$\Delta m^2 = m_2^2 - m_1^2$	

sin²Rx



resonance amplification of V oscillation probabilities amplitudes



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E. Akhmedov C.-S. Lim, W. Marciano

Neutrino spin oscillations (mixing due to Amy sin 20 vac P(Yerry) = Sin²2 Peff Sin² + X (2 m B₁)² Sin²2 Deff $(2MB_1)^2 + \Omega^2$ $Q = \frac{\Delta m_v^2}{2E} A(\theta_{vac}) - \sqrt{2} G_E$ (2 M B, resonance in neutrino spin oscillations Spin and spin-flavour gand 23



if

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

«It was assumed above that there exists a Бруно Понтекоры conservation law for the neutrino charge, according to which a neutrino cannot change $m_{ij} \neq 0$ into an antineutrino in any approximation. This then law has not yet been established; evidently it $v \leftrightarrow \overline{v}$ In vacuum 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»



 v_R Effects of \mathbf{v} magnetic moment: • spin precession and oscillations in B e / N Cisneros, Okun, Voloshin, Vysotsky, Valle, ۷ decay, Cherenkov radiation 🍸 decay in plasma Scattering Spin precession Raffelt, Schechter, Petkov, Akhmedov, Lim, Marciano, Smirnov, Pulido, Dvornikov, Grigoriev, Lobanov, Lokhov, Kouzakov, Ternov, Studenikin et al Kouzakov PRD 96 (2017) Electromagnetic interactions and oscillations of & AS, $L_B = \pi/\mu_{\nu}B \\ P_{\nu^L \to \nu^R}(x) = \sin^2\left(\frac{\pi x}{L_B}\right)$ ultrahigh-energy cosmic \mathbf{v} in interstellar space amplitude of flavour oscillations is modulated by $_{\mu_{\nu}B}$ frequency $P_{\nu_e^L \to \nu_\mu^L}(x) = [1 - P_{\nu^L \to \nu^R}(x)] \sin^2 2\theta \sin^2 \theta$ Popov & AS, Eur. Phys. J. C 79 ✓ flavour, spin and spin-flavour oscillations and (2019) no.2, 144 probability of spin oscillations consistent account for constant magnetic field depends on Δm $\left[P_{\nu_e^L \to \nu_e^R} = \left\{\sin\left(\mu_+ B_\perp t\right)\cos\left(\mu_- B_\perp t\right) + \cos 2\theta \sin\left(\mu_- B_\perp t\right)\cos\left(\mu_+ B_\perp t\right)\right\}^2 - \sin^2 2\theta \sin\left(\mu_1 B_\perp t\right)\sin\left(\mu_2 B_\perp t\right)\sin^2 \frac{\Delta m^2}{4p}t\right\}$ Pustoshny & AS, Phys. Rev. D98 (2018) 113009 spin and spin-flavour oscillations engendered by transversal matter current Studenikin 2004, 2017 transversal matter currents $\mathbf{j}_{\mathbf{i}}$ do change \mathbf{V} helicity new mechanism of EM radiation by \mathbf{V} Spin-light of \vee in Gamma-Ray Bursts JCAP 1711 (2017) no. 11, 024 "SL 💙 in astrophysical environments" Grigoriev, Lokhov, Studenikin, Ternov