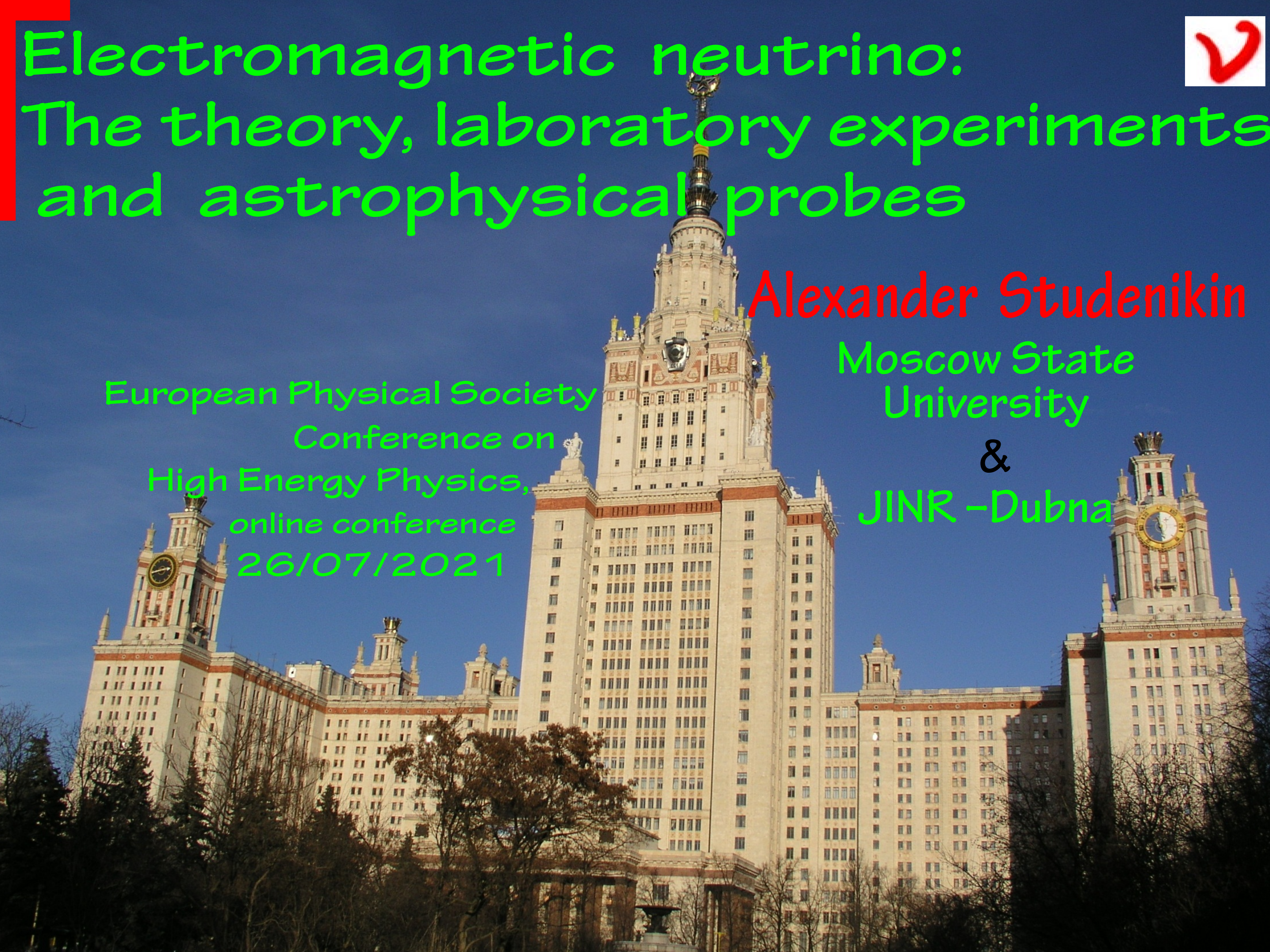
Electromagnetic neutrino: The theory, laboratory experiments and astrophysical probes



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European Physical Society
Conference on
High Energy Physics,
online conference
26/07/2021

Outline

① (short) reminder of ν electromagnetic properties

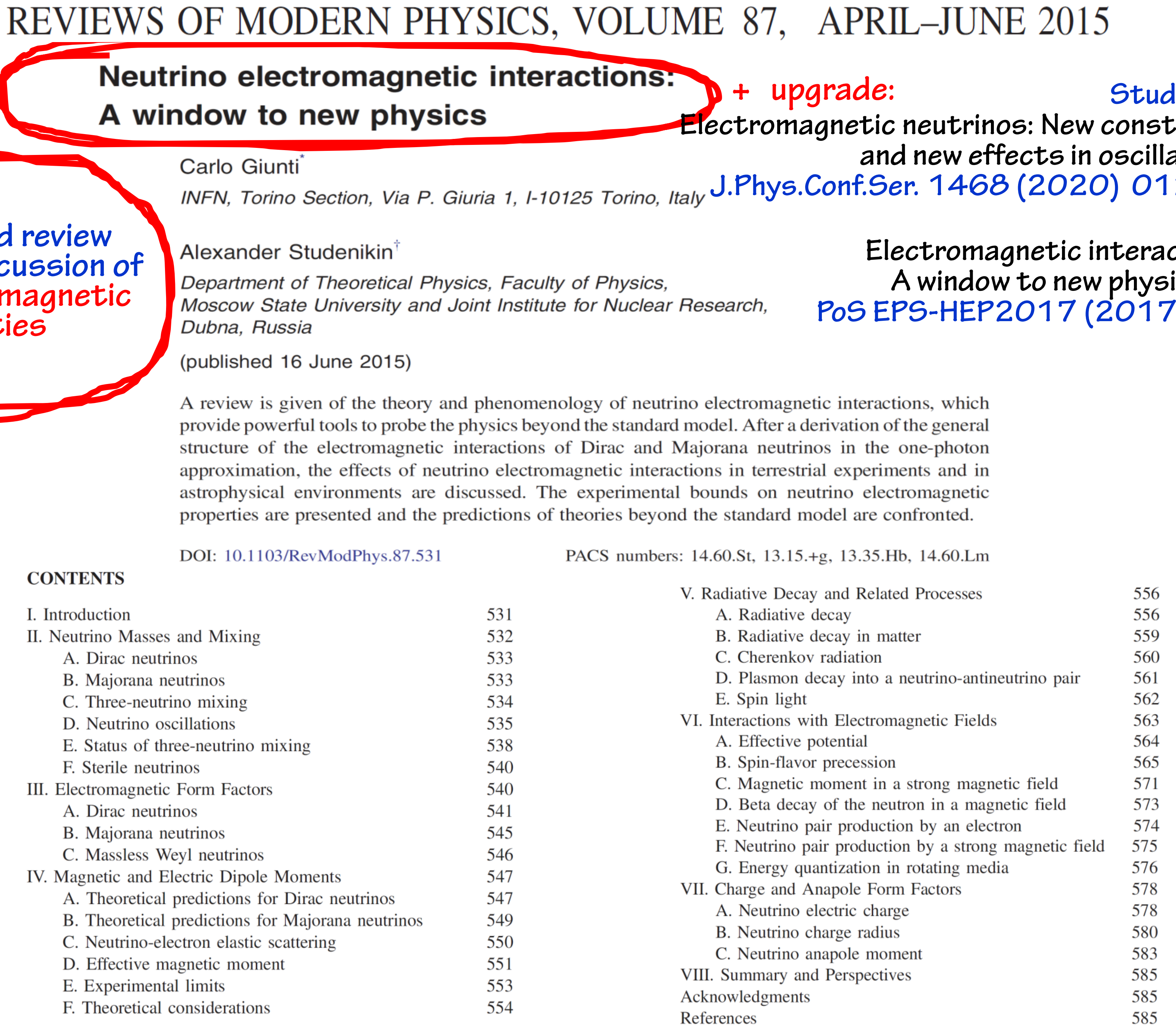
② constraints on μ_ν, d_ν, q_ν and $<r_\nu^2>$ from laboratory experiments

③ effects of electromagnetic ν interactions in astrophysics

④ astrophysical probes of electromagnetic ν

⑤ new effects in ν oscillations related to electromagnetic ν interactions

. . . two interesting new phenomena in ν spin (flavor) oscillations in moving and polarized mater and magnetic field



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

Neutrino electromagnetic interactions: A window to new physics

+ upgrade:

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Electromagnetic neutrinos: New constraints
and new effects in oscillations,
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Electromagnetic interactions:
A window to new physics – II,
PoS EPS-HEP2017 (2017) 137

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Detailed review
and discussion of
electromagnetic
properties

(published 16 June 2015)

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

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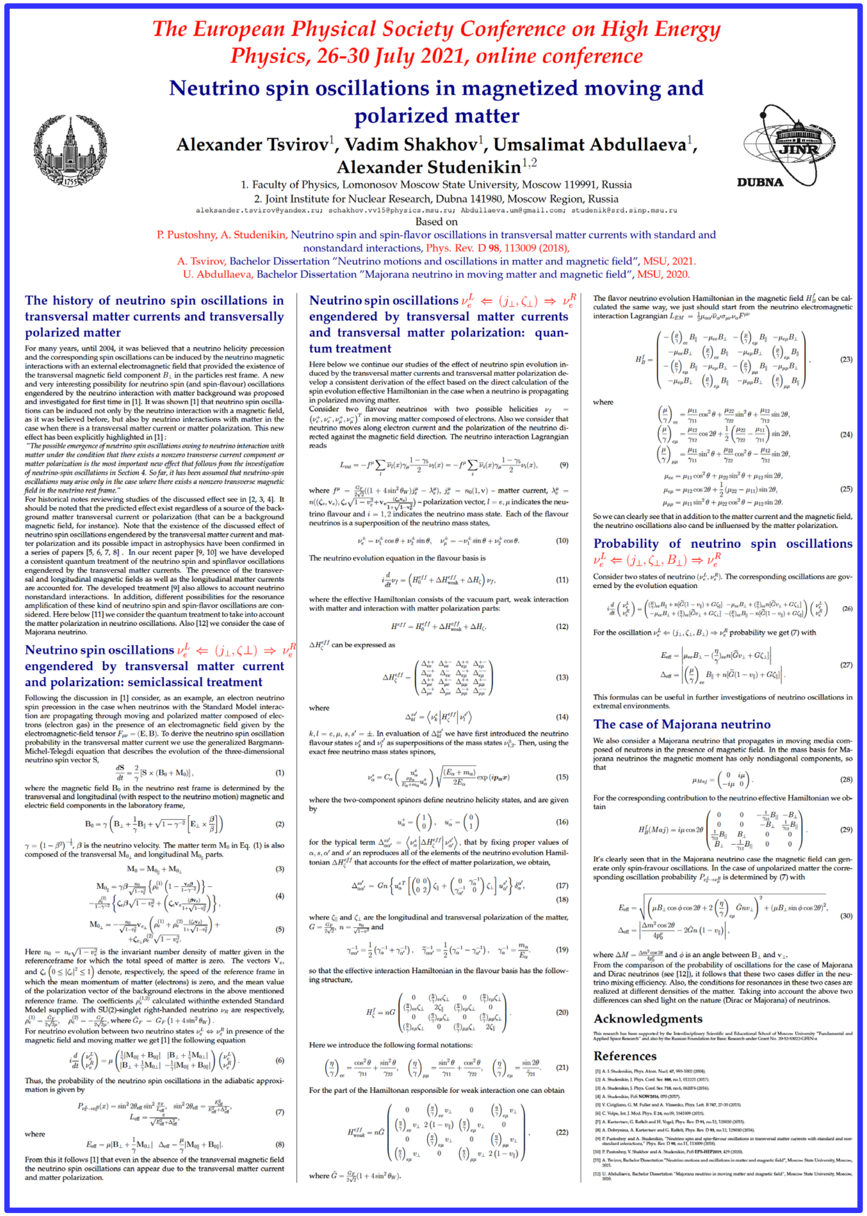
CONTENTS

ν oscillations in magnetic fields



The European Physical Society Conference on High Energy Physics, 26-30 July 2021, online conference

Neutrino spin oscillations in magnetized moving and polarized matter

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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 **98**, 113009 (2018),
A. Tsvirov, Bachelor Dissertation "Neutrino motions and oscillations in matter and magnetic field", MSU, 2021.
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The history of neutrino spin oscillations in transversal matter currents and transversally polarized matter

Neutrino spin oscillations $\nu_e^L \Leftarrow (j_\perp, \zeta_\perp) \Rightarrow \nu_e^R$ engendered by transversal matter current and polarization: semiclassical treatment

Neutrino spin oscillations $\nu_e^L \Leftarrow (j_\perp, \zeta_\perp) \Rightarrow \nu_e^R$ engendered by transversal matter currents and transversal matter polarization: quantum treatment

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

The case of Majorana neutrino

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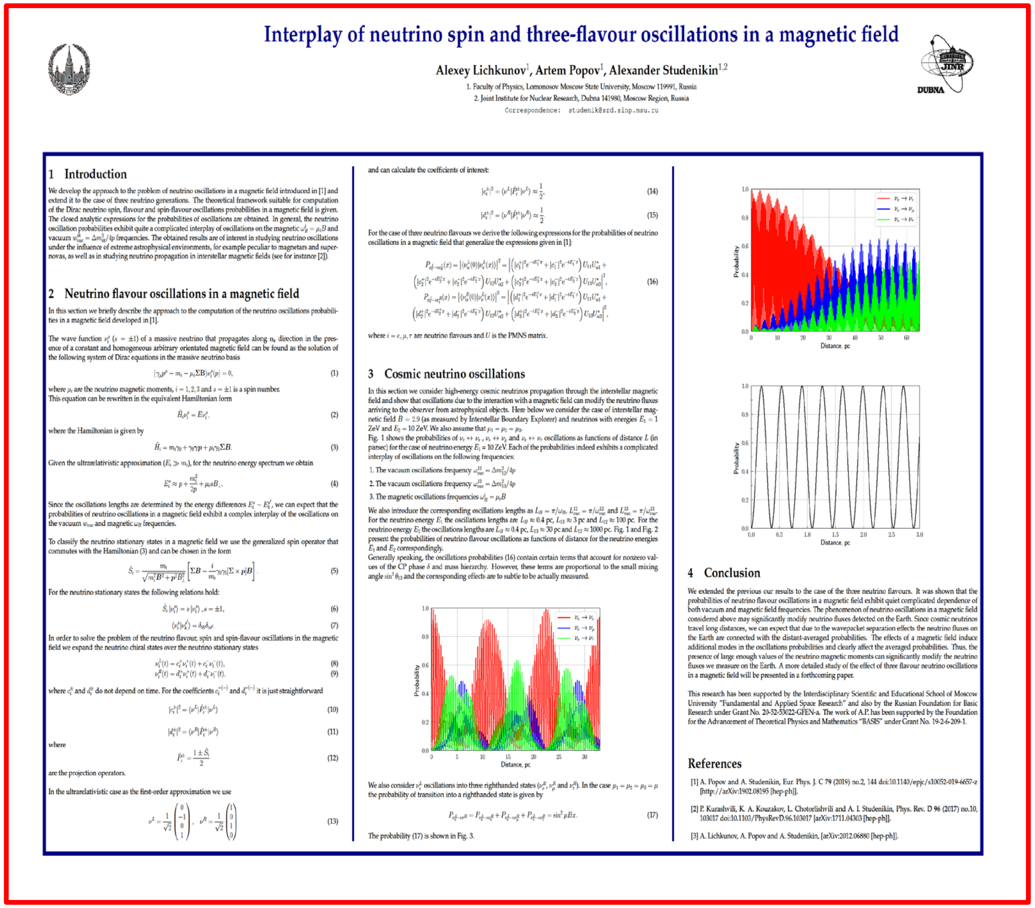
poster # 515

U.Abdullaeva, A.Tsvirov, V.Shakhov, A. Studenikin

Neutrino spin oscillations in magnetized moving and polarized matter



Interplay of neutrino spin and three-flavour oscillations in a magnetic field

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1 Introduction

2 Neutrino flavour oscillations in a magnetic field

3 Cosmic neutrino oscillations

4 Conclusion

References

A.Lichkunov, A.Popov, A. Studenikin

poster # 509

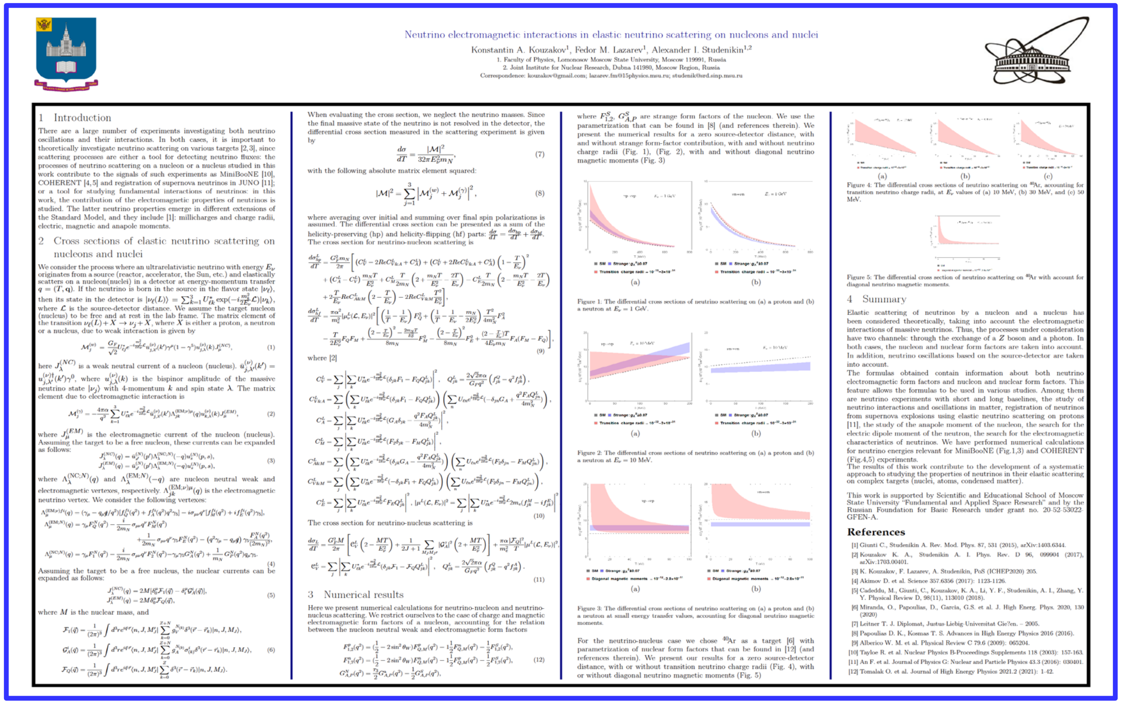
Interplay of neutrino spin and three-flavour oscillations in a magnetic field

poster
517

ν scattering

K.Kouzakov, F.Lazarev, A. Studenikin

Neutrino electromagnetic interactions in elastic neutrino scattering on nucleons and nuclei



Neutrino electromagnetic interactions in elastic neutrino scattering on nucleons and nuclei

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poster
551

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Collective effects in neutrino scattering on solid and liquid targets

Collective effects in neutrino scattering on solid and liquid targets

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Abstract

In the case of low-energy neutrino scattering by electrons and solids bound in liquids and solids, the collective effects in the electronic and nuclear subsystems of the target have to be considered. We develop an apparatus based on the formalism of the dynamical structure factor to take into account the collective effects. Numerical illustrations are given for the case of the He-4 superfluid target.

Introduction

- At present, detectors to search for light particles of dark matter are being discussed in the literature. To achieve sensitivity for low-energy signals at level of ∼1 meV condensed matter targets are being proposed [1].
- Such detectors can also be used to study low-energy neutrino scattering in order both to test the Standard Model and to search for Physics beyond the Standard Model [2].

Background

Kinematical regime

$$E_\nu \ll m, \qquad T \leq \frac{2E_\nu^2}{m} \ll E_\nu, \qquad E_\nu \ll \frac{1}{R_{\rm nuc}},$$

where T is the energy transfer, m is the atomic mass, and $R_{\rm nuc}$ is the nuclear radius.

The differential cross section for an atom

According to [3]:

$$\frac{d\sigma}{dT} = \frac{G_F^2 m}{\pi}\left[C_V^2\left(1-\frac{2mT}{E_\nu^2}\right)+C_A^2\left(1+\frac{2mT}{E_\nu^2}\right)\right]$$

$$C_V(q^2) = Z\left(\tfrac{1}{2}-2\sin^2\theta_W\right)-\tfrac{1}{2}N+Z\left(\mp\tfrac{1}{2}+2\sin^2\theta_W\right)F_{\rm el}(q^2)$$
$$C_A^2(q^2) = \tfrac{g_A^2}{4}\left[(Z_+-Z_-)-(N_+-N_-)\right]^2+\tfrac{1}{4}\left[(L_+-L_-)\,F_{\rm el}(q^2)\right]^2,$$

where q is the momentum transfer, with $q^2 = 2mT$, the plus (minus) stands for $\nu = \nu_e$ ($\nu = \nu_{\mu,\tau}$), and Z (N) is the number of protons (neutrons). $F_{\rm el}(q^2)$ is the Fourier transform of the electron density, $g_A = 1.25$, and $Z_\pm$ and $N_\pm$ ($L_\pm$) are the numbers of protons and neutrons (electrons) with spin parallel (+) or antiparallel (−) to the nucleus spin (the total electron spin).

General formalism

The differential cross section for the system of $\mathcal{N}$ atoms:

$$\boxed{\frac{d\sigma}{dT} = \int_0^\infty dq^2 \int_0^{2\pi} d\varphi_q \frac{G_F^2}{4\pi^2}\left[C_V^2\left(1-\frac{q^2}{E_\nu^2}\right)+C_A^2\left(1-\frac{q^2}{E_\nu^2}\right)\right] S(T,\mathbf{q})},$$

where

$$S(T,\mathbf{q}) = \sum_{i,f} w_i \left|\langle f|\sum_{j=1}^{\mathcal{N}} e^{i\mathbf{q}\mathbf{R}_j}|i\rangle\right|^2 \delta(T-E_f+E_i)$$

is the dynamical structure factor, with $\mathbf{R}_j$ being the position of the jth atom and w_i the probability for the system to be in the initial state $|i\rangle$.

Illustration: Neutrino scattering on liquid ^{4}He

$\mathcal{N}$ free atoms

$$S(T,\mathbf{q}) = \mathcal{N}\delta\left(T-\tfrac{q^2}{2m}\right),$$

$$\frac{d\sigma}{dT} = \mathcal{N}C_V^2\frac{G_F^2 m}{\pi}\left(1-\frac{mT}{2E_\nu^2}\right),$$

where $C_V^2 = C_V^2(q^2=2mT)$

$\mathcal{N}$ bound atoms (liquid)

$$S(T,\mathbf{q}) = \frac{\mathcal{N}q}{2mu}\delta(T-uq)$$

$$\frac{d\sigma}{dT} = \mathcal{N}C_V^2\frac{G_F^2 T^2}{2\pi m u^3}\left(1-\frac{T^2}{4u^2E_\nu^2}\right),$$

where $C_V^2 = C_V^2(q^2=T^2/u^2)$ and u is the phonon speed in liquid ^{4}He

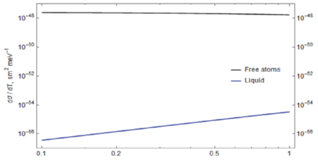

Figure: The differential cross section for tritium antineutrino scattering at $E_\nu = 10$ keV normalized to the number of helium atoms $\mathcal{N}$.

Conclusions

- The theory of low-energy neutrino scattering by a target in a condensed state has been developed
- It is shown that taking collective effects into account in the neutrino scattering by superfluid He-4 qualitatively changes the dependence of the differential cross section on the energy transfer
- This fact must be taken into account both in the preparation and in the data analysis of future neutrino experiments with detectors based on liquid He-4 and other materials (for example, such as graphene [4])
- The obtained results will be used in the search for the electromagnetic properties of neutrinos [5]

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Acknowledgments

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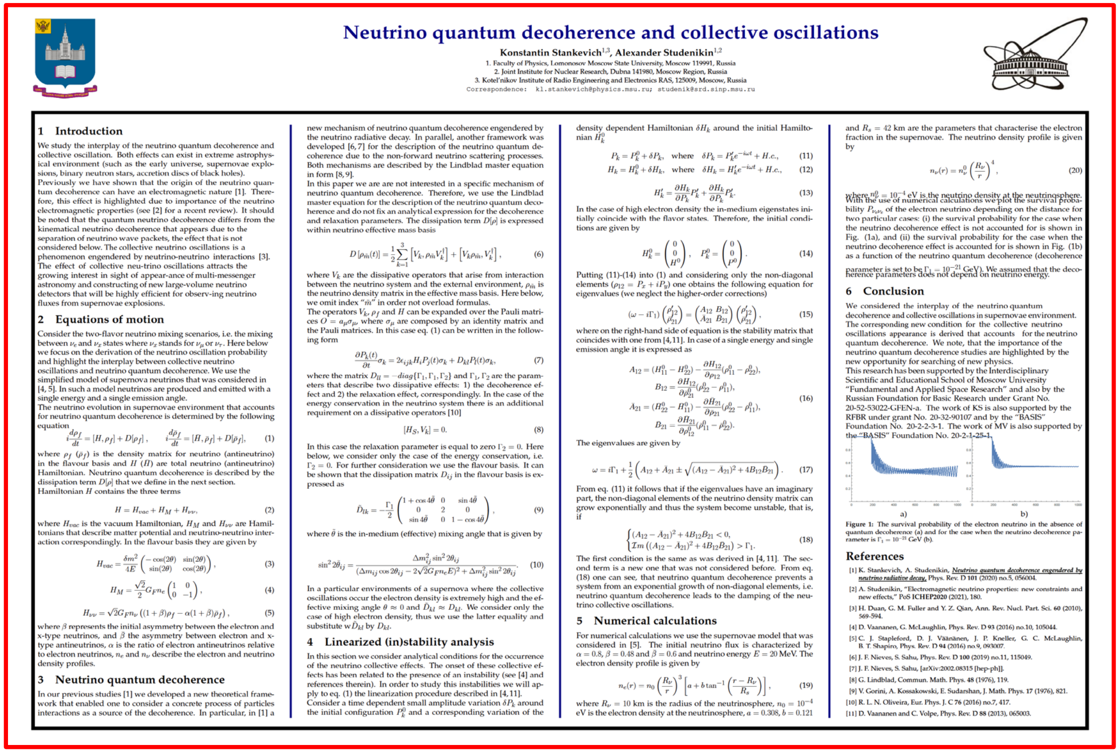

Neutrino quantum decoherence and collective oscillations

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1 Introduction

We study the interplay of the neutrino quantum decoherence and collective oscillation. Both effects can exist in extreme astrophysical environment (such as the early universe, supernovae explosions, binary neutron stars, accretion discs of black holes).
Previously we have shown that the origin of the neutrino quantum decoherence can have an electromagnetic nature [1]. Therefore, this effect is highlighted due to importance of the neutrino electromagnetic properties (see [2] for a recent review). It should be noted that the quantum neutrino decoherence differs from the kinematical neutrino decoherence that appears due to the separation of neutrino wave packets, the effect that is not considered below. The collective neutrino oscillations is a phenomenon engendered by neutrino-neutrino interactions [3]. The effect of collective neu-trino oscillations attracts the growing interest in sight of appear-ance of multi-messenger astronomy and constructing of new large-volume neutrino detectors that will be highly efficient for observ-ing neutrino fluxes from supernovae explosions.

2 Equations of motion

Consider the two-flavor neutrino mixing scenarios, i.e. the mixing between ν_e and ν_x states where ν_x stands for ν_μ or ν_τ. Here below we focus on the derivation of the neutrino oscillation probability and highlight the interplay between collective neutrino oscillations and neutrino quantum decoherence. We use the simplified model of supernova neutrinos that was considered in [4, 5]. In such a model neutrinos are produced and emitted with a single energy and a single emission angle.
The neutrino evolution in supernovae environment that accounts for neutrino quantum decoherence is determined by the following equation

$$i\frac{d\rho_f}{dt} = [H, \rho_f] + D[\rho_f] , \qquad i\frac{d\bar{\rho}_f}{dt} = [\bar{H}, \bar{\rho}_f] + D[\bar{\rho}_f], \tag{1}$$

where ρ_f ($\bar{\rho}_f$) is the density matrix for neutrino (antineutrino) in the flavour basis and H ($\bar{H}$) are total neutrino (antineutrino) Hamiltonian. Neutrino quantum decoherence is described by the dissipation term $D[\rho]$ that we define in the next section.
Hamiltonian H contains the three terms

$$H = H_{vac} + H_M + H_{\nu\nu}, \tag{2}$$

where H_{vac} is the vacuum Hamiltonian, H_M and $H_{\nu\nu}$ are Hamiltonians that describe matter potential and neutrino-neutrino interaction correspondingly. In the flavour basis they are given by

$$H_{vac} = \frac{\delta m^2}{4E}\begin{pmatrix} -\cos(2\theta) & \sin(2\theta) \\ \sin(2\theta) & \cos(2\theta) \end{pmatrix}, \tag{3}$$

$$H_M = \frac{\sqrt{2}}{2}G_F n_e \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \tag{4}$$

$$H_{\nu\nu} = \sqrt{2}G_F n_\nu \left((1+\beta)\rho_f - \alpha(1+\bar{\beta})\bar{\rho}_f\right), \tag{5}$$

where β represents the initial asymmetry between the electron and x-type neutrinos, and $\bar{\beta}$ the asymmetry between electron and x-type antineutrinos, α is the ratio of electron antineutrinos relative to electron neutrinos, n_e and n_ν describe the electron and neutrino density profiles.

3 Neutrino quantum decoherence

In our previous studies [1] we developed a new theoretical framework that enabled one to consider a concrete process of particles interactions as a source of the decoherence. In particular, in [1] a new mechanism of neutrino quantum decoherence engendered by the neutrino radiative decay. In parallel, another framework was developed [6, 7] for the description of the neutrino quantum decoherence due to the non-forward neutrino scattering processes. Both mechanisms are described by the Lindblad master equation in form [8, 9].
In this paper we are are not interested in a specific mechanism of neutrino quantum decoherence. Therefore, we use the Lindblad master equation for the description of the neutrino quantum decoherence and do not fix an analytical expression for the decoherence and relaxation parameters. The dissipation term $D[\rho]$ is expressed within neutrino effective mass basis

$$D\left[\rho_{\tilde{m}}(t)\right] = \frac{1}{2}\sum_{k=1}^{3}\left[V_k, \rho_{\tilde{m}}V_k^\dagger\right] + \left[V_k\rho_{\tilde{m}}, V_k^\dagger\right], \tag{6}$$

where V_k are the dissipative operators that arise from interaction between the neutrino system and the external environment, $\rho_{\tilde{m}}$ is the neutrino density matrix in the effective mass basis. Here below, we omit index "$\tilde{m}$" in order not overload formulas.
The operators V_k, ρ_f and H can be expanded over the Pauli matrices $O = a_\mu\sigma_\mu$, where σ_μ are composed by an identity matrix and the Pauli matrices. In this case eq. (1) can be written in the following form

$$\frac{\partial P_k(t)}{\partial t}\sigma_k = 2\epsilon_{ijk}H_i P_j(t)\sigma_k + D_{kl}P_l(t)\sigma_k, \tag{7}$$

where the matrix $D_{ll} = -diag\{\Gamma_1, \Gamma_1, \Gamma_2\}$ and Γ_1, Γ_2 are the parameters that describe two dissipative effects: 1) the decoherence effect and 2) the relaxation effect, correspondingly. In the case of the energy conservation in the neutrino system there is an additional requirement on a dissipative operators [10]

$$[H_S, V_k] = 0. \tag{8}$$

In this case the relaxation parameter is equal to zero $\Gamma_2 = 0$. Here below, we consider only the case of the energy conservation, i.e. $\Gamma_2 = 0$. For further consideration we use the flavour basis. It can be shown that the dissipation matrix D_{ij} in the flavour basis is expressed as

$$\tilde{D}_{lk} = -\frac{\Gamma_1}{2}\begin{pmatrix} 1+\cos 4\tilde{\theta} & 0 & \sin 4\tilde{\theta} \\ 0 & 2 & 0 \\ \sin 4\tilde{\theta} & 0 & 1-\cos 4\tilde{\theta} \end{pmatrix}, \tag{9}$$

where $\tilde{\theta}$ is the in-medium (effective) mixing angle that is given by

$$\sin^2 2\tilde{\theta}_{ij} = \frac{\Delta m_{ij}^2 \sin^2 2\theta_{ij}}{(\Delta m_{ij}\cos 2\theta_{ij} - 2\sqrt{2}G_F n_e E)^2 + \Delta m_{ij}^2 \sin^2 2\theta_{ij}}. \tag{10}$$

In a particular environments of a supernova where the collective oscillations occur the electron density is extremely high and the effective mixing angle $\theta \approx 0$ and $\tilde{D}_{kl} \approx D_{kl}$. We consider only the case of high electron density, thus we use the latter equality and substitute w$\tilde{D}_{kl}$ by D_{kl}.

4 Linearized (in)stability analysis

In this section we consider analytical conditions for the occurrence of the neutrino collective effects. The onset of these collective effects has been related to the presence of an instability (see [4] and references therein). In order to study this instabilities we will apply to eq. (1) the linearization procedure described in [4, 11].
Consider a time dependent small amplitude variation δP_k around the initial configuration P_k^0 and a corresponding variation of the density dependent Hamiltonian δH_k around the initial Hamiltonian H_k^0

$$P_k = P_k^0 + \delta P_k, \quad \text{where} \quad \delta P_k = P_k' e^{-i\omega t} + H.c., \tag{11}$$

$$H_k = H_k^0 + \delta H_k, \quad \text{where} \quad \delta H_k = H_k' e^{-i\omega t} + H.c., \tag{12}$$

$$H_k' = \frac{\partial H_k}{\partial P_k}P_k' + \frac{\partial H_k}{\partial \bar{P}_k}\bar{P}_k'. \tag{13}$$

In the case of high electron density the in-medium eigenstates initially coincide with the flavor states. Therefore, the initial conditions are given by

$$H_k^0 = \begin{pmatrix} 0 \\ 0 \\ H^0 \end{pmatrix}, \quad P_k^0 = \begin{pmatrix} 0 \\ 0 \\ P^0 \end{pmatrix}. \tag{14}$$

Putting (11)-(14) into (1) and considering only the non-diagonal elements ($\rho_{12} = P_x + iP_y$) one obtains the following equation for eigenvalues (we neglect the higher-order corrections)

$$(\omega - i\Gamma_1)\begin{pmatrix} \rho_{12}' \\ \bar{\rho}_{21}' \end{pmatrix} = \begin{pmatrix} A_{12} & B_{12} \\ \bar{A}_{21} & \bar{B}_{21} \end{pmatrix}\begin{pmatrix} \rho_{12}' \\ \bar{\rho}_{21}' \end{pmatrix}, \tag{15}$$

where on the right-hand side of equation is the stability matrix that coincides with one from [4, 11]. In case of a single energy and single emission angle it is expressed as

$$\begin{aligned} A_{12} &= (H_{11}^0 - H_{22}^0) - \frac{\partial H_{12}}{\partial \rho_{12}}(\rho_{11}^0 - \rho_{22}^0), \\ B_{12} &= \frac{\partial H_{12}}{\partial \bar{\rho}_{21}^0}(\bar{\rho}_{22}^0 - \bar{\rho}_{11}^0), \\ \bar{A}_{21} &= (\bar{H}_{22}^0 - \bar{H}_{11}^0) - \frac{\partial \bar{H}_{21}}{\partial \bar{\rho}_{21}}(\bar{\rho}_{22}^0 - \bar{\rho}_{11}^0), \\ \bar{B}_{21} &= \frac{\partial \bar{H}_{21}}{\partial \rho_{12}^0}(\rho_{11}^0 - \rho_{22}^0). \end{aligned} \tag{16}$$

The eigenvalues are given by

$$\omega = i\Gamma_1 + \frac{1}{2}\left(A_{12} + \bar{A}_{21} \pm \sqrt{(A_{12} - \bar{A}_{21})^2 + 4B_{12}\bar{B}_{21}}\right). \tag{17}$$

From eq. (11) it follows that if the eigenvalues have an imaginary part, the non-diagonal elements of the neutrino density matrix can grow exponentially and thus the system become unstable, that is, if

$$\begin{cases} (A_{12} - \bar{A}_{21})^2 + 4B_{12}\bar{B}_{21} < 0, \\ \mathcal{I}m\left((A_{12} - \bar{A}_{21})^2 + 4B_{12}\bar{B}_{21}\right) > \Gamma_1. \end{cases} \tag{18}$$

The first condition is the same as was derived in [4, 11]. The second term is a new one that was not considered before. From eq. (18) one can see, that neutrino quantum decoherence prevents a system from an exponential growth of non-diagonal elements, i.e. neutrino quantum decoherence leads to the damping of the neutrino collective oscillations.

5 Numerical calculations

For numerical calculations we use the supernovae model that was considered in [5]. The initial neutrino flux is characterized by $\alpha = 0.8$, $\beta = 0.48$ and $\bar{\beta} = 0.6$ and neutrino energy $E = 20$ MeV. The electron density profile is given by

$$n_e(r) = n_0\left(\frac{R_\nu}{r}\right)^3\left[a + b\tan^{-1}\left(\frac{r - R_\nu}{R_s}\right)\right], \tag{19}$$

where $R_\nu = 10$ km is the radius of the neutrinosphere, $n_0 = 10^{-4}$ eV is the electron density at the neutrinosphere, $a = 0.308$, $b = 0.121$ and $R_s = 42$ km are the parameters that characterise the electron fraction in the supernovae. The neutrino density profile is given by

$$n_\nu(r) = n_\nu^0\left(\frac{R_\nu}{r}\right)^4, \tag{20}$$

where $n_\nu^0 = 10^{-4}$ eV is the neutrino density at the neutrinosphere.
With the use of numerical calculations we plot the survival probability $P_{\nu_e\nu_e}$ of the electron neutrino depending on the distance for two particular cases: (i) the survival probability for the case when the neutrino decoherence effect is not accounted for is shown in Fig. (1a), and (ii) the survival probability for the case when the neutrino decoherence effect is accounted for is shown in Fig. (1b) as a function of the neutrino quantum decoherence (decoherence parameter is set to be $\Gamma_1 = 10^{-21}$ GeV). We assumed that the decoherence parameters does not depend on neutrino energy.

6 Conclusion

We considered the interplay of the neutrino quantum decoherence and collective oscillations in supernovae environment. The corresponding new condition for the collective neutrino oscillations appearance is derived that accounts for the neutrino quantum decoherence. We note, that the importance of the neutrino quantum decoherence studies are highlighted by the new opportunity for searching of new physics.

This research has been supported by the Interdisciplinary Scientific and Educational School of Moscow University "Fundamental and Applied Space Research" and also by the Russian Foundation for Basic Research under Grant No. 20-52-53022-GFEN-a. The work of KS is also supported by the RFBR under grant No. 20-32-90107 and by the "BASIS" Foundation No. 20-2-2-3-1. The work of MV is also supported by the "BASIS" Foundation No. 20-2-1-25-1.

a) b)

Figure 1: The survival probability of the electron neutrino in the absence of quantum decoherence (a) and for the case when the neutrino decoherence parameter is $\Gamma_1 = 10^{-21}$ GeV (b).

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\# 504

ν quantum
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K. Stankevich, A. Studenikin

Neutrino quantum decoherence
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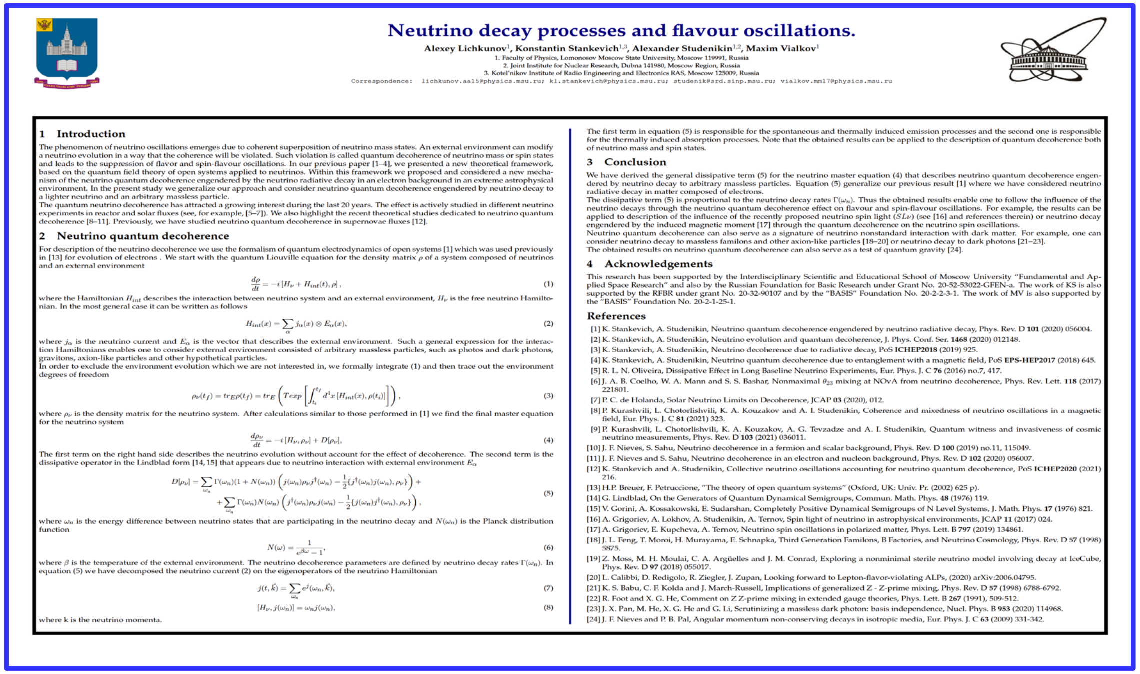

Neutrino decay processes and flavour oscillations.

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1 Introduction

The phenomenon of neutrino oscillations emerges due to coherent superposition of neutrino mass states. An external environment can modify a neutrino evolution in a way that the coherence will be violated. Such violation is called quantum decoherence of neutrino mass or spin states and leads to the suppression of flavor and spin-flavour oscillations. In our previous paper [1–4], we presented a new theoretical framework, based on the quantum field theory of open systems applied to neutrinos. Within this framework we proposed and considered a new mechanism of the neutrino quantum decoherence engendered by the neutrino radiative decay in an electron background in an extreme astrophysical environment. In the present study we generalize our approach and consider neutrino quantum decoherence engendered by neutrino decay to a lighter neutrino and an arbitrary massless particle.
The quantum neutrino decoherence has attracted a growing interest during the last 20 years. The effect is actively studied in different neutrino experiments in reactor and solar fluxes (see, for example, [5–7]). We also highlight the recent theoretical studies dedicated to neutrino quantum decoherence [8–11]. Previously, we have studied neutrino quantum decoherence in supernovae fluxes [12].

2 Neutrino quantum decoherence

For description of the neutrino decoherence we use the formalism of quantum electrodynamics of open systems [1] which was used previously in [13] for evolution of electrons . We start with the quantum Liouville equation for the density matrix ρ of a system composed of neutrinos and an external environment

$$\frac{d\rho}{dt} = -i\left[H_\nu + H_{int}(t), \rho\right], \tag{1}$$

where the Hamiltonian H_{int} describes the interaction between neutrino system and an external environment, H_ν is the free neutrino Hamiltonian. In the most general case it can be written as follows

$$H_{int}(x) = \sum_\alpha j_\alpha(x) \otimes E_\alpha(x), \tag{2}$$

where j_α is the neutrino current and E_α is the vector that describes the external environment. Such a general expression for the interaction Hamiltonians enables one to consider external environment consisted of arbitrary massless particles, such as photos and dark photons, gravitons, axion-like particles and other hypothetical particles.
In order to exclude the environment evolution which we are not interested in, we formally integrate (1) and then trace out the environment degrees of freedom

$$\rho_\nu(t_f) = tr_E\rho(t_f) = tr_E\left(Texp\left[\int_{t_i}^{t_f} d^4x\left[H_{int}(x), \rho(t_i)\right]\right]\right), \tag{3}$$

where ρ_ν is the density matrix for the neutrino system. After calculations similar to those performed in [1] we find the final master equation for the neutrino system

$$\frac{d\rho_\nu}{dt} = -i\left[H_\nu, \rho_\nu\right] + D[\rho_\nu], \tag{4}$$

The first term on the right hand side describes the neutrino evolution without account for the effect of decoherence. The second term is the dissipative operator in the Lindblad form [14, 15] that appears due to neutrino interaction with external environment E_α

$$\begin{aligned} D[\rho_\nu] = &\sum_{\omega_n}\Gamma(\omega_n)(1 + N(\omega_n))\left(j(\omega_n)\rho_\nu j^\dagger(\omega_n) - \frac{1}{2}\{j^\dagger(\omega_n)j(\omega_n), \rho_\nu\}\right) + \\ &+ \sum_{\omega_n}\Gamma(\omega_n)N(\omega_n)\left(j^\dagger(\omega_n)\rho_\nu j(\omega_n) - \frac{1}{2}\{j(\omega_n)j^\dagger(\omega_n), \rho_\nu\}\right), \end{aligned} \tag{5}$$

where ω_n is the energy difference between neutrino states that are participating in the neutrino decay and $N(\omega_n)$ is the Planck distribution function

$$N(\omega) = \frac{1}{e^{\beta\omega} - 1}, \tag{6}$$

where β is the temperature of the external environment. The neutrino decoherence parameters are defined by neutrino decay rates $\Gamma(\omega_n)$. In equation (5) we have decomposed the neutrino current (2) on the eigenoperators of the neutrino Hamiltonian

$$j(t, \vec{k}) = \sum_{\omega_n} e^j(\omega_n, \vec{k}), \tag{7}$$

$$[H_\nu, j(\omega_n)] = \omega_n j(\omega_n), \tag{8}$$

where k is the neutrino momenta.

The first term in equation (5) is responsible for the spontaneous and thermally induced emission processes and the second one is responsible for the thermally induced absorption processes. Note that the obtained results can be applied to the description of quantum decoherence both of neutrino mass and spin states.

3 Conclusion

We have derived the general dissipative term (5) for the neutrino master equation (4) that describes neutrino quantum decoherence engendered by neutrino decay to arbitrary massless particles. Equation (5) generalize our previous result [1] where we have considered neutrino radiative decay in matter composed of electrons.
The dissipative term (5) is proportional to the neutrino decay rates $\Gamma(\omega_n)$. Thus the obtained results enable one to follow the influence of the neutrino decays through the neutrino quantum decoherence effect on flavour and spin-flavour oscillations. For example, the results can be applied to description of the influence of the recently proposed neutrino spin light ($SL\nu$) (see [16] and references therein) or neutrino decay engendered by the induced magnetic moment [17] through the quantum decoherence on the neutrino spin oscillations.
Neutrino quantum decoherence can also serve as a signature of neutrino nonstandard interaction with dark matter. For example, one can consider neutrino decay to massless familons and other axion-like particles [18–20] or neutrino decay to dark photons [21–23].
The obtained results on neutrino quantum decoherence can also serve as a test of quantum gravity [24].

4 Acknowledgements

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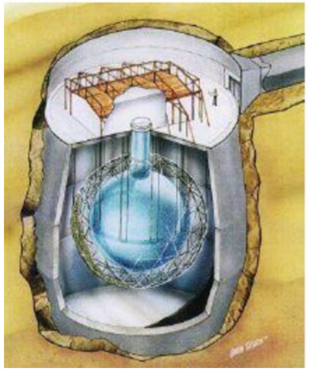
A. Studenikin, M.Vialkov

Neutrino decay processes and
flavour oscillations

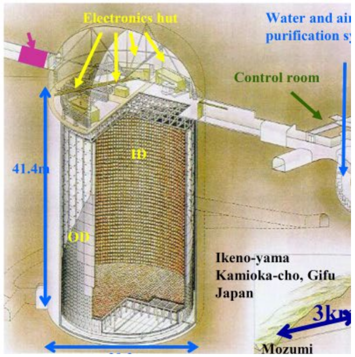
Arthur McDonald

The Nobel Prize in Physics 2015

Takaaki Kajita



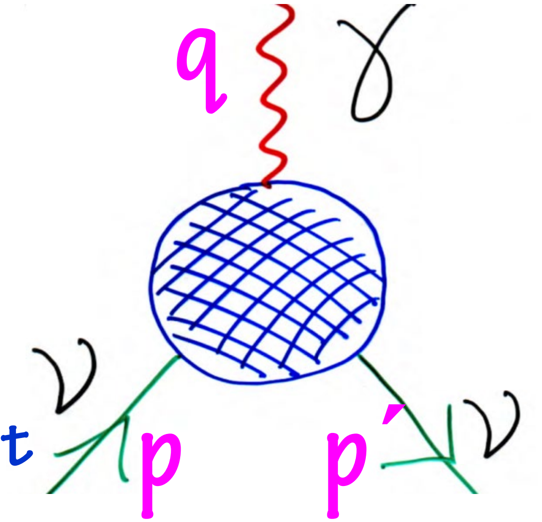
«for the discovery of neutrino oscillations, which shows that neutrinos have mass»



$$m_\nu \neq 0$$

electromagnetic properties (flash on theory)

ν electromagnetic vertex function



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

Matrix element of electromagnetic current is a Lorentz vector

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

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

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

vectors q_μ and l_μ

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

● Lorentz covariance (1) and electromagnetic gauge invariance (2) $\Longrightarrow$

Matrix element of electromagnetic current between neutrino states

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

where vertex function generally contains 4 form factors

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

1. electric

dipole

2. magnetic

3. electric

4. anapole

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

Dirac ν

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

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

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

Majorana ν

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

$$f_Q = f_M = f_E = 0$$

…as early as 1939, W.Pauli…

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

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

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

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

… beyond ν
SM…

and

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

! form factors are matrices in ν mass eigenstates space.

Dirac ν

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

Majorana ν

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

2) CP invariance + Hermiticity

⇓

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

are relatively real (no relative phases).

1) CP invariance + hermiticity

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

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

… quite different EM properties …

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

are most well studied and theoretically understood among form factors

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

$$\boxed{\mu_\nu \ = \ f_M(0)}$$

ν magnetic moment

$$\boxed{\epsilon_\nu \ = \ f_E(0)}$$

ν electric moment ???

... Why ν electromagnetic properties are important ?

...Why ν em properties

to new physics ?

... How does it all relate to ν oscillations ?

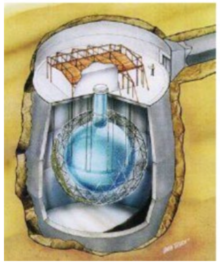
$$\Longrightarrow \quad m_\nu \neq 0 \quad ●$$

magnetic moment $\mu_\nu \neq 0$ ●

Arthur McDonald

The Nobel Prize in Physics 2015

Takaaki Kajita



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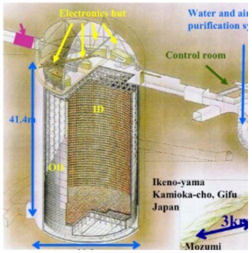


in Standard Model

● $m_\nu = 0$!!!

In the easiest generalization of SM

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

if $\boxed{m_i \sim 1\ eV}$ $\Longleftarrow$ KATRIN limit

then $\boxed{\mu_{ii}^{D} \sim 3.2 \times 10^{-19}\mu_B}$!

many orders of magnitude smaller than present experimental limits:

- $\mu_\nu \sim 10^{-11}\mu_B$ reactor ν limits GEMMA 2012
- $\mu_\nu \sim 10^{-11} \div 10^{-12}\mu_B$ astrophysical (ν_{solar} and ν_{SN}) limits

  Borexino 2017

μ_ν is no less extravagant than possibility of $q_\nu \neq 0$

- limitations imposed by general principles of any theory are very strict
- $\boxed{q_\nu \leq 3 \times 10^{-21}e}$ from neutrality of hydrogen atom
- much weaker constraints are imposed by astrophysics

ν

Laboratory experimental constraints on μ_ν , q_ν and $< r^2_\nu >$

magnetic moment

millicharge

charge radius

Particle Data Group
Review of Particle Properties (2014-2020)
update of 2021

ν magnetic moment

. . . most easily accepted are
dipole magnetic and electric moments

however most accessible for experimental studies are charge radii $<r^2_\nu>$

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

Cross-section:

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

!

where the Standard Model contribution

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

T is the electron recoil energy and

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

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

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

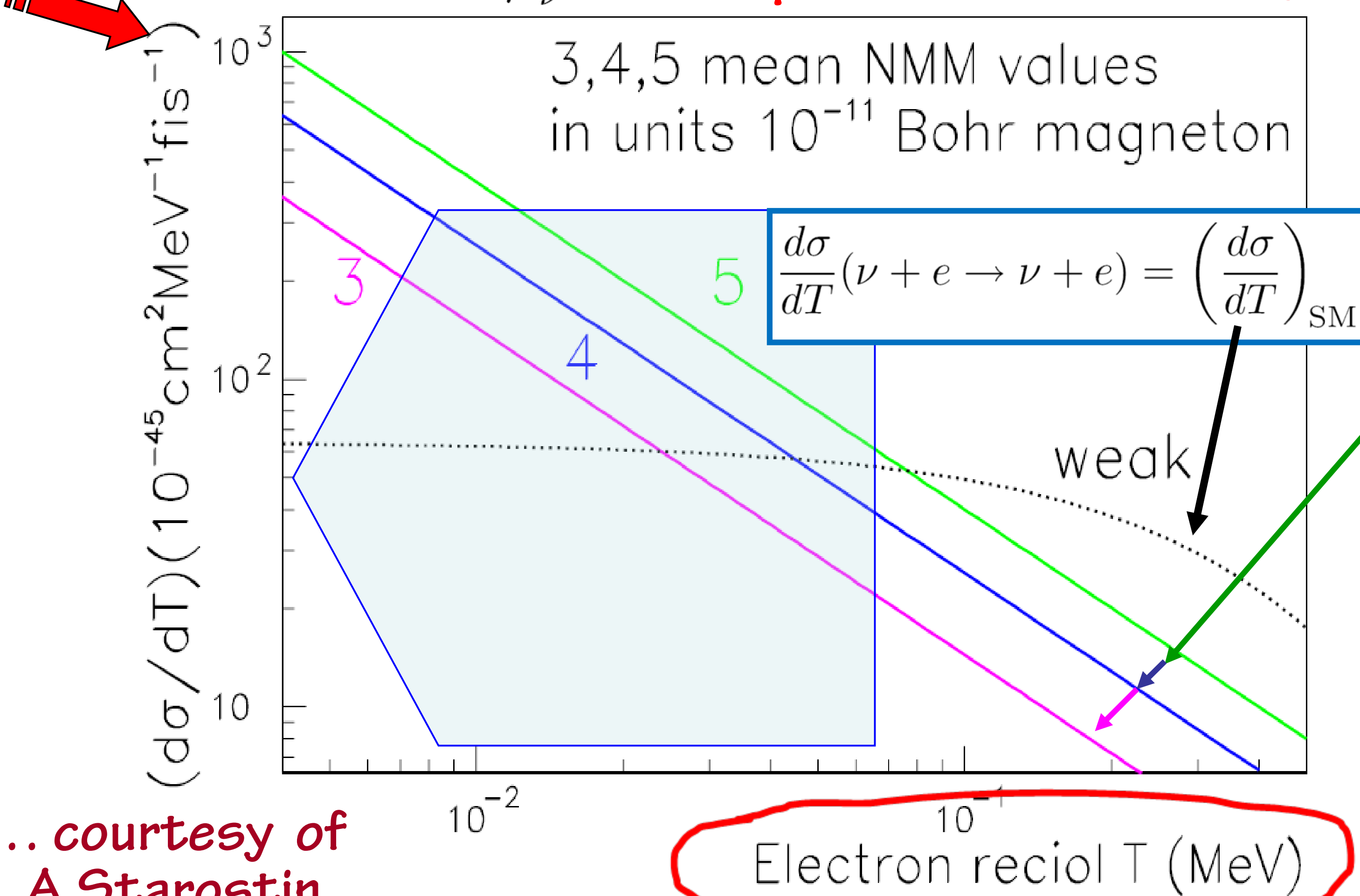
$$g_V = \begin{cases} 2\sin^2\theta_W + \frac{1}{2} & \text{for } \nu_e\,, \\ 2\sin^2\theta_W - \frac{1}{2} & \text{for } \nu_\mu, \nu_\tau\,, \end{cases} \qquad g_A = \begin{cases} \frac{1}{2} & \text{for } \nu_e\,, \\ -\frac{1}{2} & \text{for } \nu_\mu, \nu_\tau \end{cases}$$

for anti-neutrinos $g_A \to -g_A$

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

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

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



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

… courtesy of
A.Starostin…

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

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

!

World best experimental (reactor) limit

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

June 2012 ●

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

… quite realistic prospects for future …

- ● GEMMA-2 / νGeN experiment

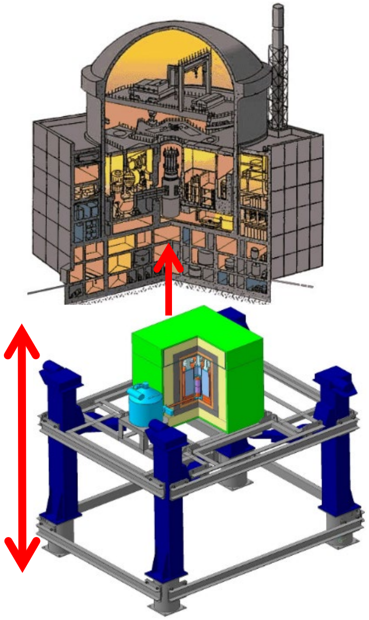
… searching for μ_ν and CEνNS unprecedentedly low threshold $\boxed{T \sim 200 \quad eV}$

$$\boxed{\mu_\nu \sim (5-9) \times 10^{-12} \mu_B}$$

2021 + few years of data taking ?

… courtesy of Alexey Lobashevsky, first results on CEνNS will be reported at TAUP 2021…

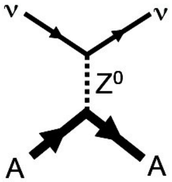
experiment at Kalinin nuclear power plant

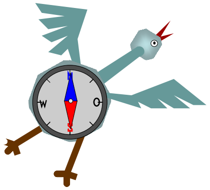


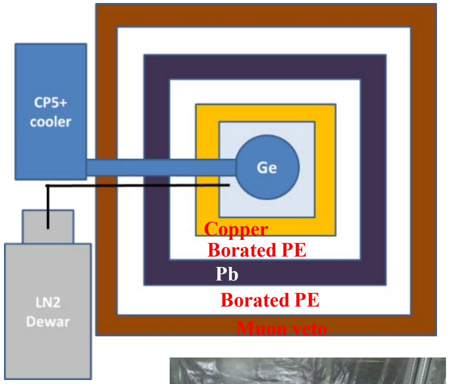
The GEMMA-3/νGeN projects investigate fundamental properties of neutrino at Kalinin Nuclear Power Plant (KNPP) with a low background innovative semiconductor HPGe detectors. In particular, the searches for CEνNS and magnetic moment of neutrino are performed. Such investigations allow us to perform a search for the New Physics using non-standard neutrino interactions, investigation of the nuclear structure, and many other applications, including reactor monitoring.

The setup is been constructing at ~ 10 m from powerful 3.1 GW reactor's core under an enormous antineutrino flux of more than > $5{\cdot}10^{13}$ ν/(s·cm^2). The location also allows to have good shielding against cosmic radiation ~ 50 m w.e. Backgrounds from surrounding and cosmic radiation are suppressed by passive and active shielding.

Measurements at LSM underground laboratory (Modane, France) proved very good radiopurity of all components. The movable platform allows to suppress systematic uncertainties connected with unknown information about neutrino flux and backgrounds. In November 2019, the first HPGe detector was moved to the experimental room at KNPP and we started commissioning measurements.







… courtesy V. Brudanin and E. Yakushev …

results and plans

The measurements at JINR demonstrated a possibility to acquire signal below 200 eV (with trigger efficiency of about 70%). Energy resolution of the first detector measured with pulse generator is 78.0(3) eV (FWHM).

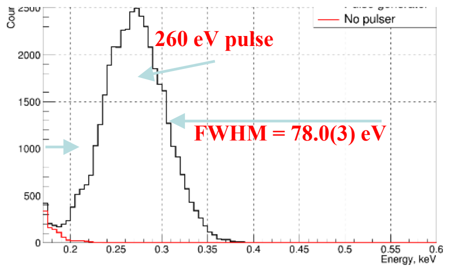
The preliminary background measurements at KNPP showed that all visible lines are from cosmogenic isotopes and decreasing with time. Resolution of cosmogenic lines are: 10.37 keV – 187(3) eV (FWHM), for 1.3 keV – 124(9) eV (FWHM).

Improvement in comparison with GEMMA-I:

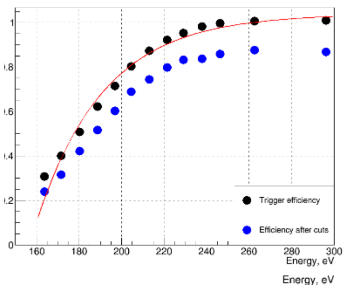
- ✓ Energy threshold: 2 keV → 200 eV (achived)
- ✓ Neutrino flux: $2.6 \cdot 10^{13}\ \nu/(s \cdot cm^2) \rightarrow 5 \cdot 10^{13}\ \nu/(s \cdot cm^2)$ (place is ready)
- ✓ Mass: 1.5 kg → 5.5 kg (first detector is at place, waiting for others to be ready)
- ✓ $\mu_\nu < 2.9 \cdot 10^{-11} \mu_B$ (world best limit) → $\mu_\nu < (5\text{-}9) \cdot 10^{-12} \mu_B$ (after few years of data taking)

A good background index has been achieved! Due to the influence of COVID-19, measurements at the KNPP are just restarted. We will continue investigations of the neutrino properties with aim to achieve sensitivity to the detection of CEvNS in a region of full coherence.

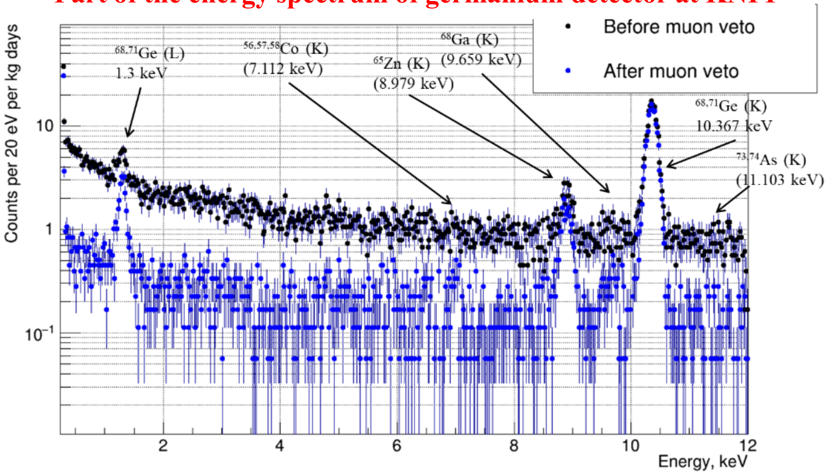
Measurements with pulse generator near energy threshold



Measurements of detector's efficiency



Part of the energy spectrum of germanium detector at KNPP



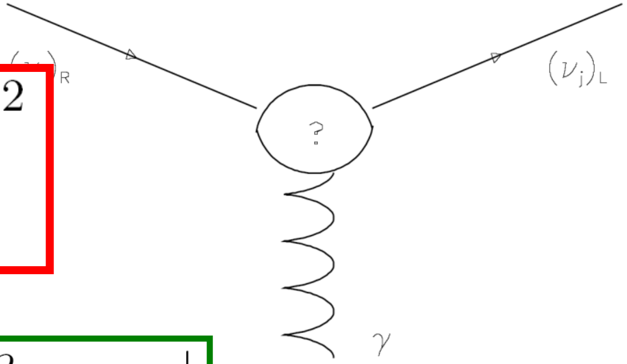
Preliminary! Further Background decrease is expected!

... courtesy V. Brudanin and E. Yakushev ...

Effective ν magnetic moment in experiments

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

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



where **neutrino mixing matrix**

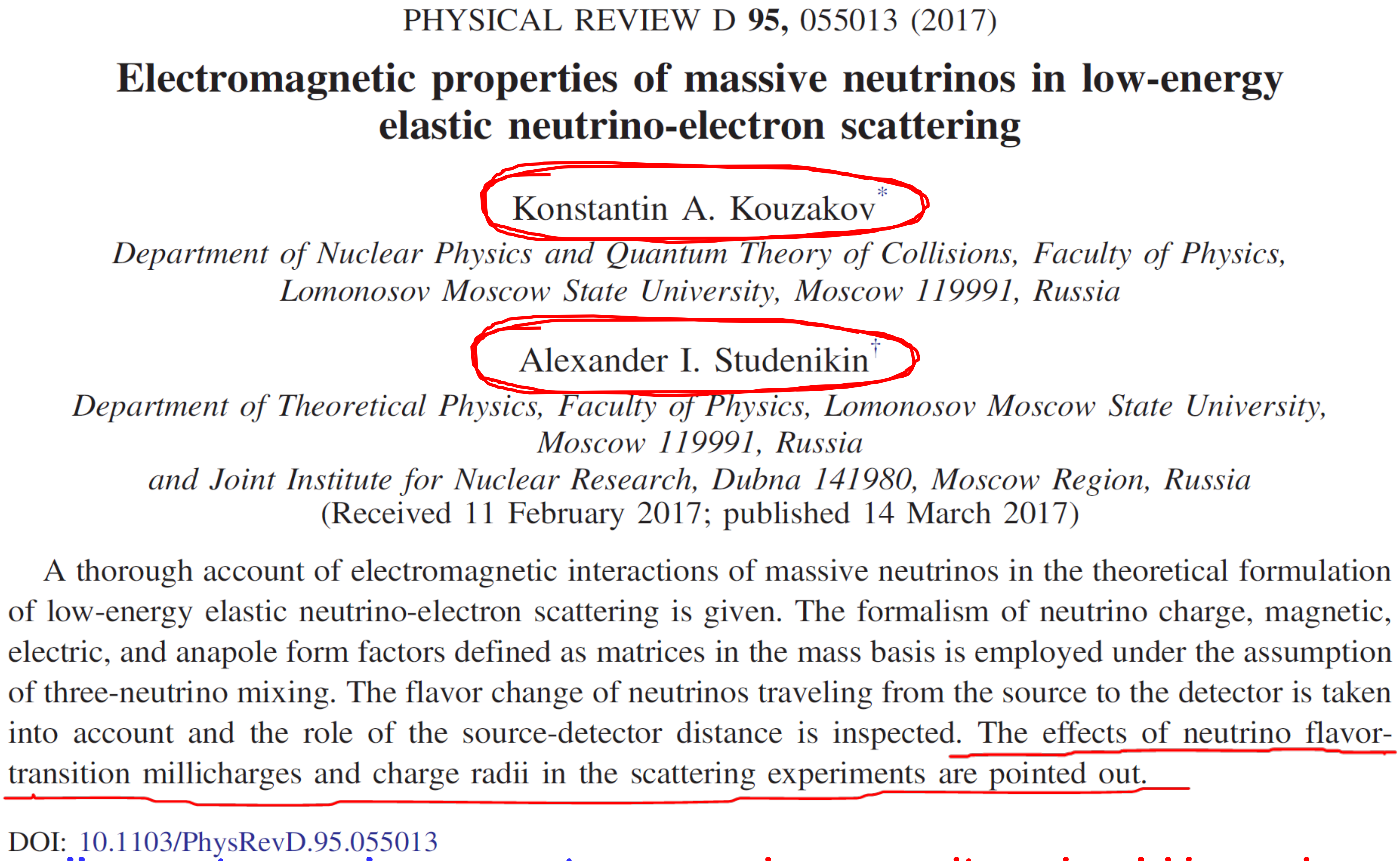
$$\boxed{\mu_{ij} \equiv |\beta_{ij} - \varepsilon_{ij}|}$$

magnetic and electric moments

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

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

… comprehensive analysis of ν-e scattering …



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

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

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(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

Mitglied der Helmholtz-Gemeinschaft

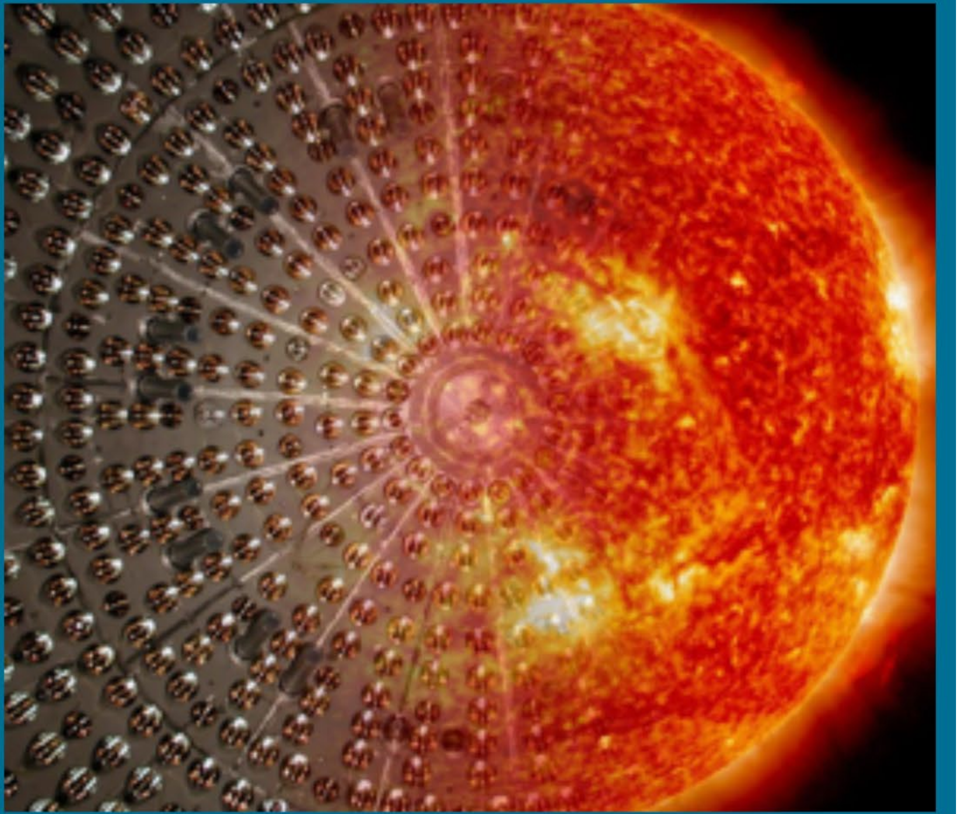
TAUP 2017
Topics in Astroparticle
and Underground Physics

JÜLICH
FORSCHUNGSZENTRUM

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
Limiting μ_ν with Borexino Phase-II solar neutrino data

NEW

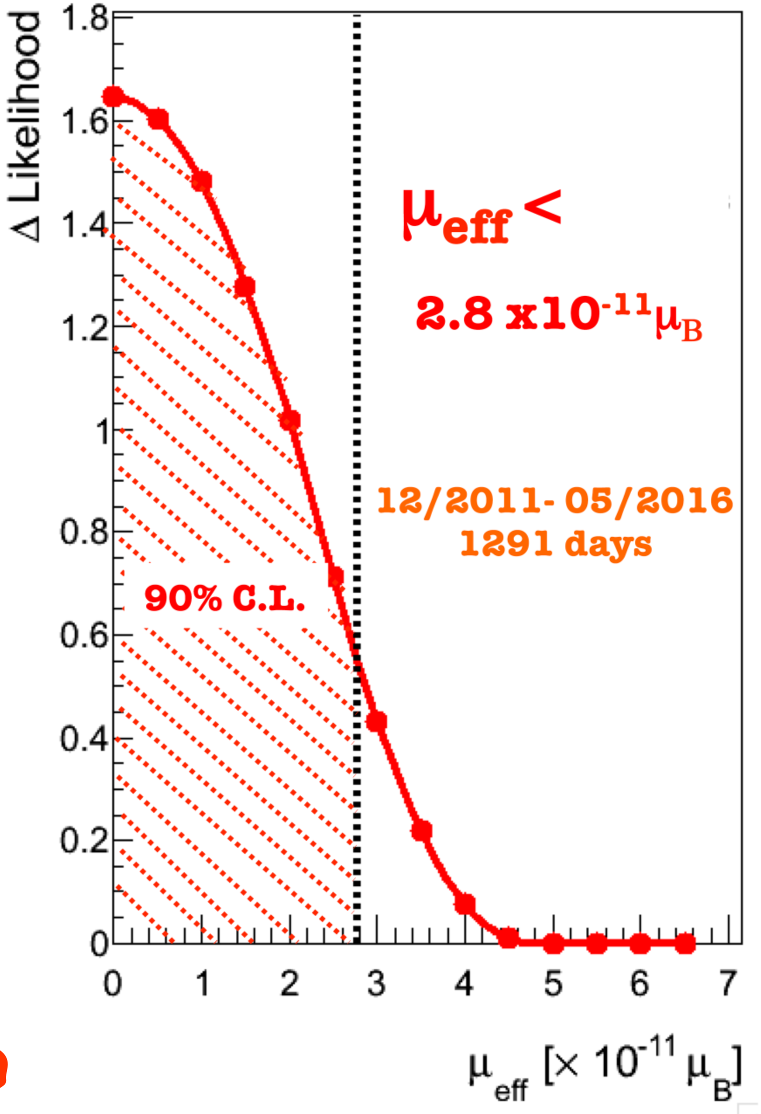
NMM results from Phase 2

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

Without radiochemical constraint
$\mu_{eff} < 4.0 \times 10^{-11} \mu_B$ (90% C.L.)

With radiochemical constraint
$\mu_{eff} < 2.6 \times 10^{-11} \mu_B$ (90% C.L.)
adding systematics
$\mu_{eff} < 2.8 \times 10^{-11} \mu_B$ (90% C.L.)

Profiling μ_{eff} with σ_{EM} for pp &^{7}Be



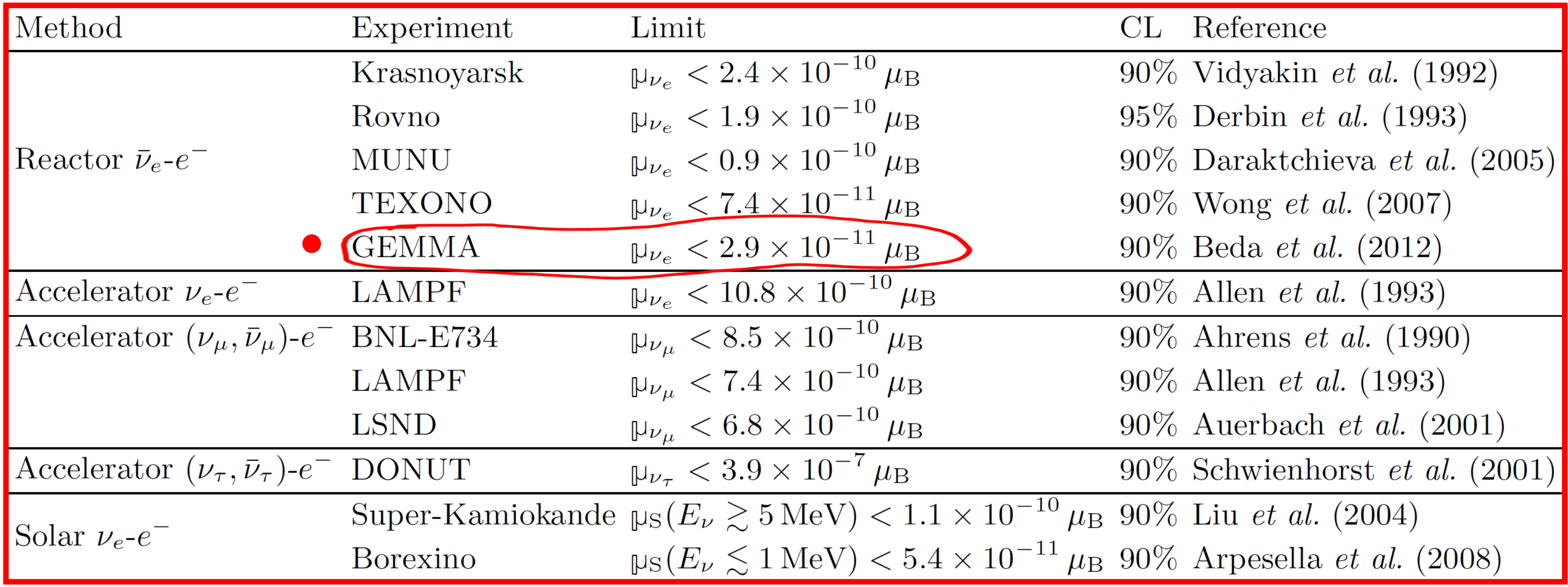
μ_{eff} <

$2.8 \times 10^{-11} \mu_B$

12/2011- 05/2016
1291 days

90% C.L.

Experimental limits for different effective μ_ν



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

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, 2014-2020 and update of 2021

… A remark on electric charge of ν … Beyond Standard Model…

ν neutrality $Q=0$ is attributed to

gauge invariance
+
anomaly cancellation constraints

imposed in SM of electroweak interactions

- …General proof:

$SU(2)_L \times U(1)_Y$

In SM : $\boxed{Q = I_3 + \frac{Y}{2}}$

Foot, Joshi, Lew, Volkas, 1990;
Foot, Lew, Volkas, 1993;
Babu, Mohapatra, 1989, 1990
Foot , He (1991)

In SM (without ν_R triangle anomalies cancellation constraints → certain relations among particle hypercharges that is enough to fix all Y so that they, and consequently Q, are quantized

$\boxed{Q=0}$

- $\boxed{Q=0}$ is proven also by direct calculation in SM within different gauges and methods

Bardeen, Gastmans, Lautrup, 1972;
Cabral-Rosetti, Bernabeu, Vidal, Zepeda, 2000;
Beg, Marciano, Ruderman, 1978;
Marciano, Sirlin, 1980; Sakakibara, 1981;
● Dvornikov, Studenikin, 2004
(for SM in one-loop calculations)

- … Strict requirements for Q quantization may disappear in extensions of standard $SU(2)_L \times U(1)_Y$ EW model if ν_R with $Y \neq 0$ are included : in the absence of Y quantization electric charges Q gets dequantized → millicharged ν

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

②

two not seen contributions:

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

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

ν-e cross-section

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

Bounds on q_ν from … unobserved effects of New Physics

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

!

Studenikin, Europhys. Lett. 107 (2014) 210011

Particle Data Group, 2016-2020 and update of 2021

Expected new constraints from GEMMA:

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

!

2021 + few years data taking

νGeN experiment

$\mu_\nu \sim (5-9) \times 10^{-12} \mu_B$

… low threshold …

$T \sim 200\ \ eV$

Constraints on q_ν

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

!

in ν Table of Particle Data Group since 2016

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

ν charge radii

… most accessible for experimental studies are charge radii $<r^2_\nu>$

… astrophysical bounds ???

ν charge radius and anapole moment

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

1. electric

dipole

2. magnetic

3. electric

4. anapole

Although it is usually assumed that ν are electrically neutral (charge quantization implies $Q \sim \frac{1}{3}e$),

ν can dissociates into charged particles so that $f_Q(q^2) \neq 0 \; for \; q^2 \neq 0$

$$\boxed{f_Q(q^2) = f_Q(0) + q^2 \frac{df_Q}{dq^2}(0) + \cdots ,}$$

where the massive ν charge radius

$$\boxed{\langle r_\nu^2 \rangle = -6 \frac{df_Q}{dq^2}(0)}$$

For massless ν

anapole moment

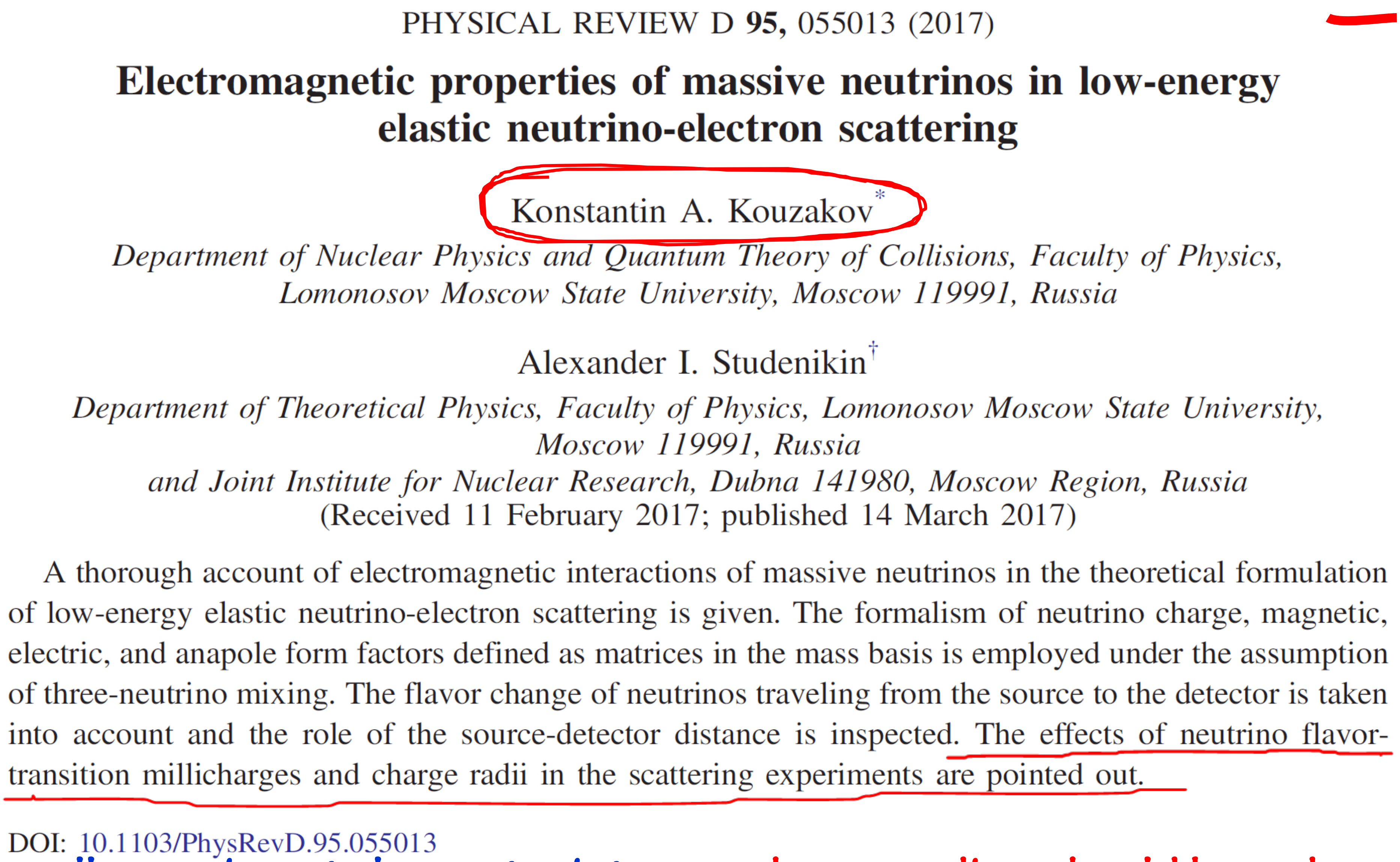
$$\boxed{a_\nu = f_A(q^2) = \frac{1}{6}\langle r_\nu^2 \rangle}$$

Interpretation of charge radius as an observable is rather delicate issue: $\langle r_\nu^2 \rangle$ represents a correction to tree-level electroweak scattering amplitude between ν and charged particles, which receives radiative corrections from several diagrams (including γ exchange) to be considered simultaneously ⟹ calculated CR is infinite and gauge dependent quantity. For massless ν, a_ν and $\langle r_\nu^2 \rangle$ can be defined (finite and gauge independent) from scattering cross section.

? ? ? For massive ν ? ? ?

Bernabeu, Papavassiliou, Vidal,
Nucl.Phys. B 680 (2004) 450

… comprehensive analysis of ν-e 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

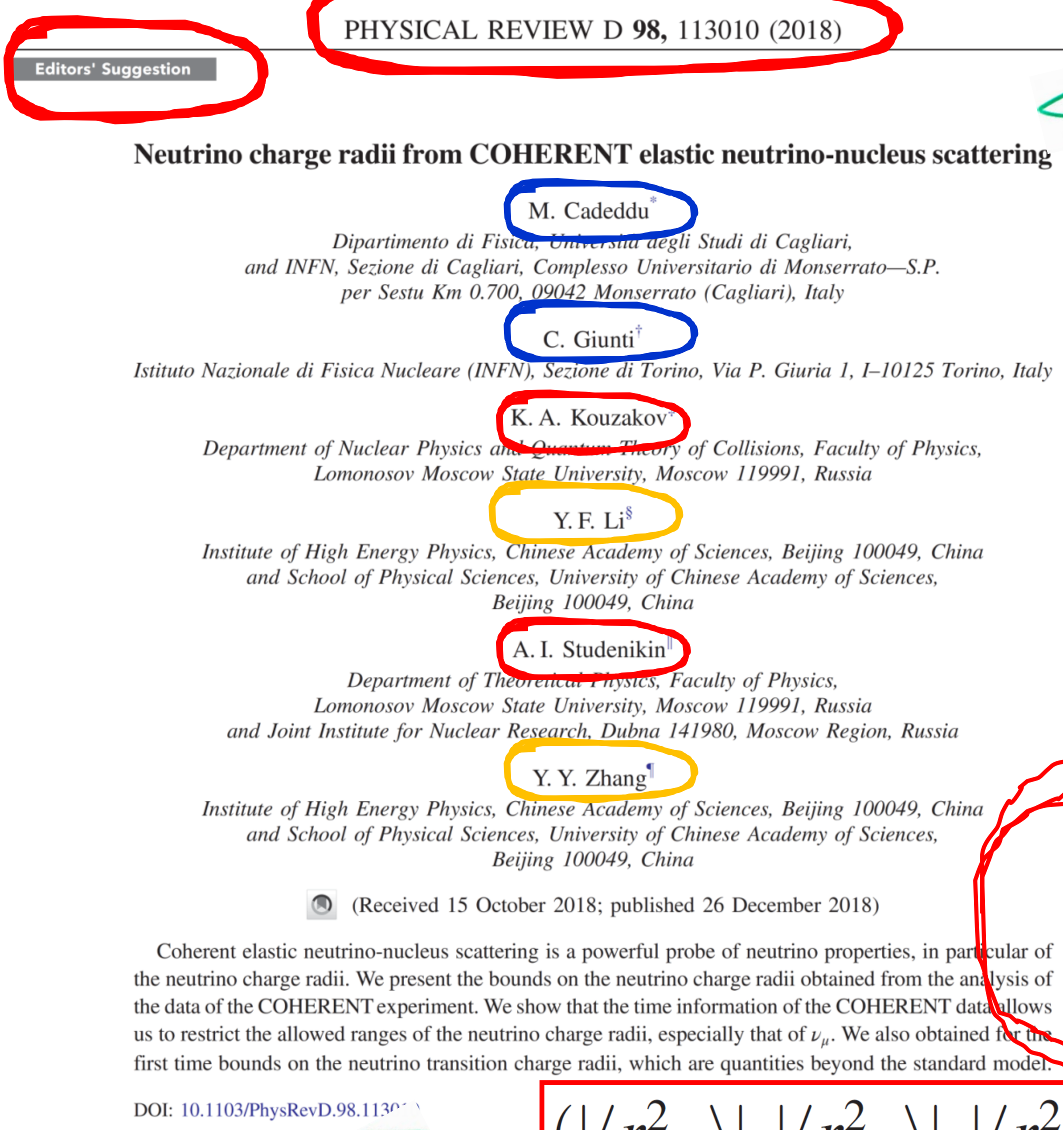
Phys. Rev. D 95 (2017) 055013

- cross section of ν-e is determined in terms of 3x3 matrices of ν 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
- ν millicharge when it is constrained in reactor short-baseline experiments (GEMMA, for instance) should be interpreted as

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

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

!



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

Editors' Suggestion

Neutrino charge radii from COHERENT elastic neutrino-nucleus scattering

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and INFN, Sezione di Cagliari, Complesso Universitario di Monserrato—S.P.
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Beijing 100049, China

(Received 15 October 2018; published 26 December 2018)

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

DOI: 10.1103/PhysRevD.98.113

Ch – It – Ru

collaboration

Physical Review D

– Highlights 2018 –

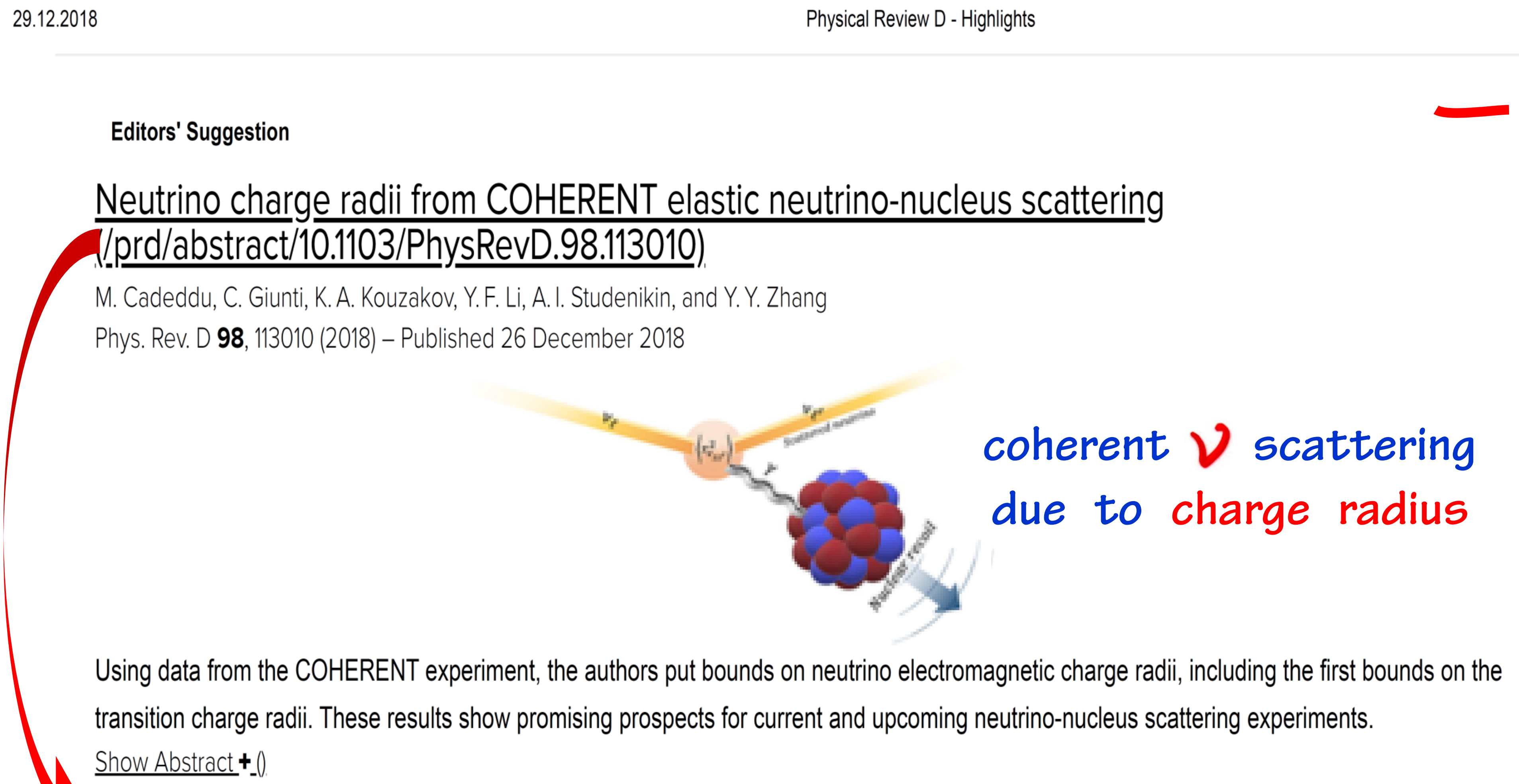
Editors' Suggestion

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

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

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

Physical Review D – Highlights 2018 – Editors' Suggestion



29.12.2018 Physical Review D - Highlights

Editors' Suggestion

Neutrino charge radii from COHERENT elastic neutrino-nucleus scattering (/prd/abstract/10.1103/PhysRevD.98.113010)

M. Cadeddu, C. Giunti, K. A. Kouzakov, Y. F. Li, A. I. Studenikin, and Y. Y. Zhang

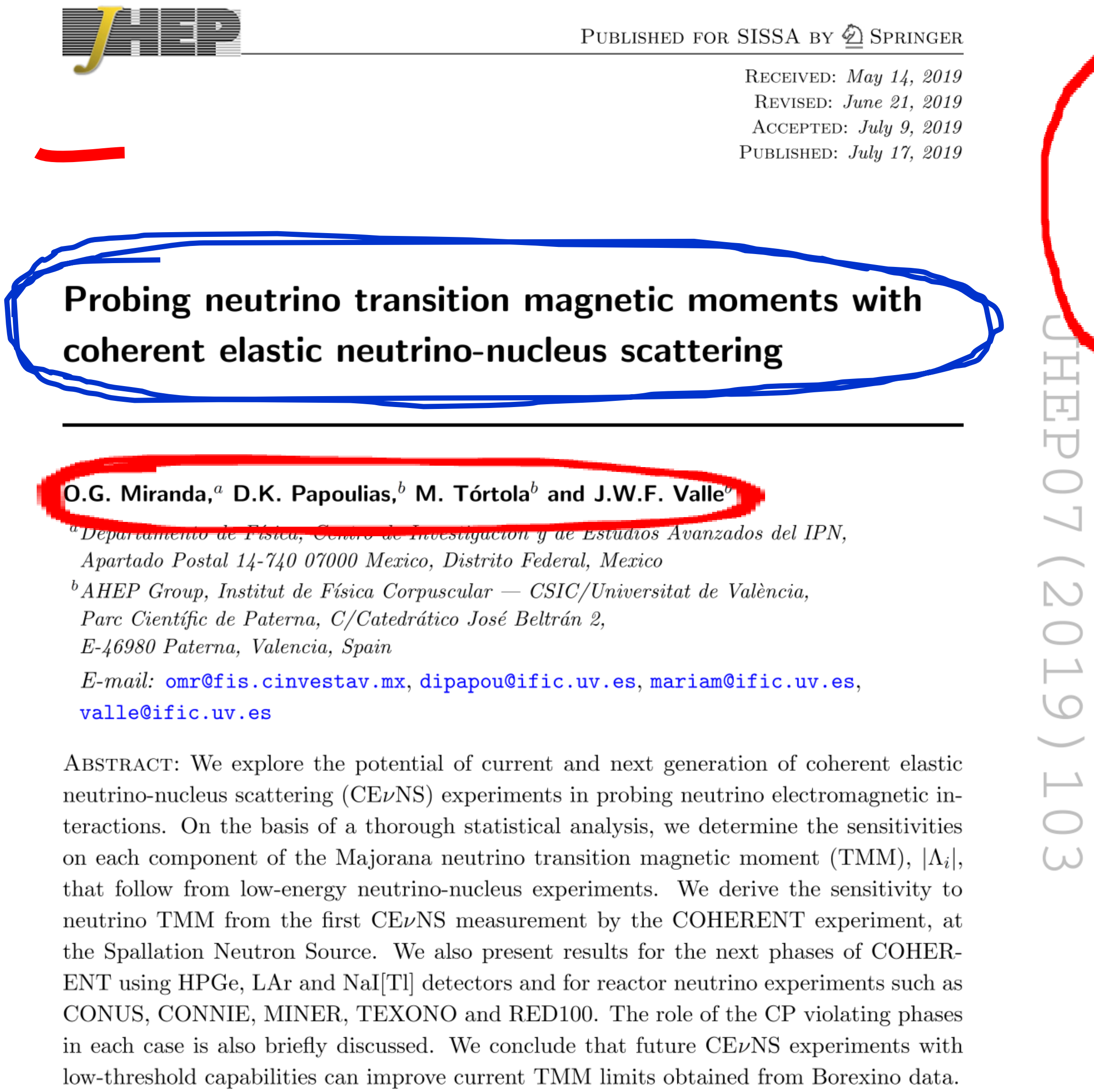
Phys. Rev. D **98**, 113010 (2018) – Published 26 December 2018

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 + ()

coherent ν scattering
due to charge radius

Particle Data Group,
Review of Particle Properties (2018-2020),
update of 2021



JHEP

Published for SISSA by Springer

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Accepted: *July 9, 2019*
Published: *July 17, 2019*

Probing neutrino transition magnetic moments with coherent elastic neutrino-nucleus scattering

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Apartado Postal 14-740 07000 Mexico, Distrito Federal, Mexico
[b] *AHEP Group, Institut de Física Corpuscular — CSIC/Universitat de València,*
Parc Científic de Paterna, C/Catedrático José Beltrán 2,
E-46980 Paterna, Valencia, Spain

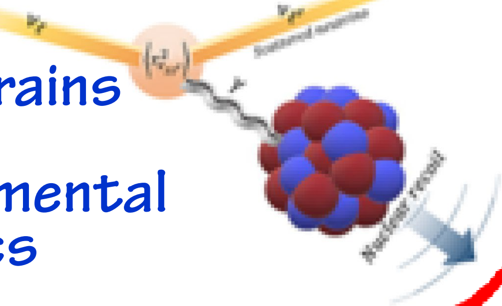
E-mail: omr@fis.cinvestav.mx, dipapou@ific.uv.es, mariam@ific.uv.es, valle@ific.uv.es

Abstract: We explore the potential of current and next generation of coherent elastic neutrino-nucleus scattering (CEνNS) experiments in probing neutrino electromagnetic interactions. On the basis of a thorough statistical analysis, we determine the sensitivities on each component of the Majorana neutrino transition magnetic moment (TMM), $|\Lambda_i|$, that follow from low-energy neutrino-nucleus experiments. We derive the sensitivity to neutrino TMM from the first CEνNS measurement by the COHERENT experiment, at the Spallation Neutron Source. We also present results for the next phases of COHERENT using HPGe, LAr and NaI[Tl] detectors and for reactor neutrino experiments such as CONUS, CONNIE, MINER, TEXONO and RED100. The role of the CP violating phases in each case is also briefly discussed. We conclude that future CEνNS experiments with low-threshold capabilities can improve current TMM limits obtained from Borexino data.

JHEP07(2019)103

- Neutrino, electroweak, and nuclear physics from COHERENT … with refined quenching factor , Cadeddu, Dordei, Giunti, Li, Zhang, PRD 2020

coherent ν scattering



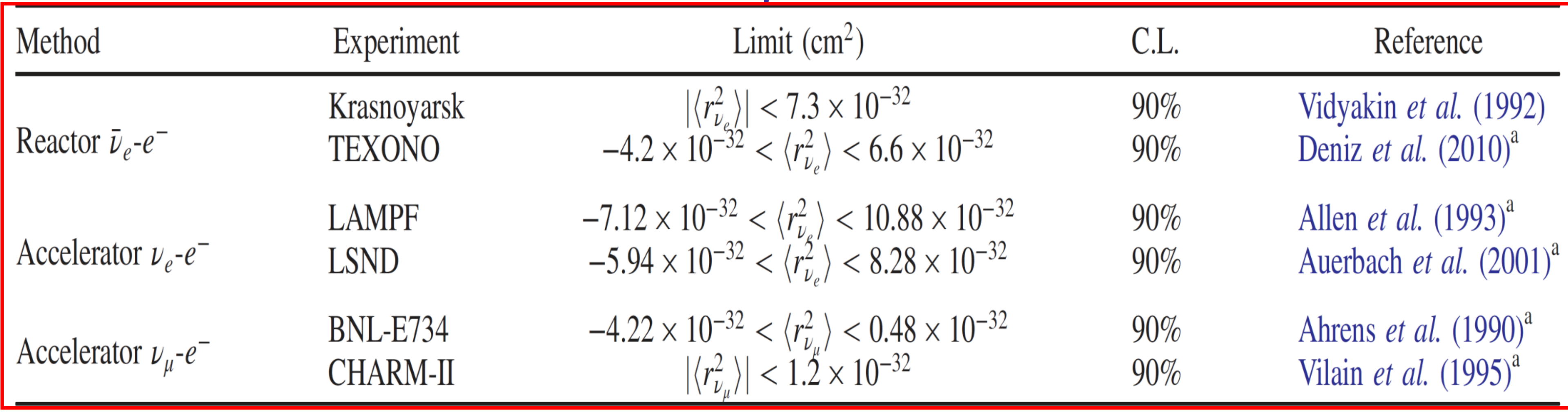
constrains
on
fundamental
physics

COHERENT data have been used for different purposes:

- nuclear neutron distributions
  Cadeddu, Giunti, Li, Zhang
  PRL 2018
- weak mixing angle
  Cadeddu & Dordei, PRD 2019
  Huang & Chen 2019
- ν electromagnetic properties
  Papoulias & Kosmas PRD 2018
- ν non-standard interactions
  Coloma, Gonzalez-Garcia,
  Maltoni, Schwetz PRD 2017
  Liao & Marfatia PLB 2017

Experimental limits on ν charge radius $<r_{\nu}^{2}>$

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	$\lvert\langle r_{\nu_e}^2\rangle\rvert < 7.3\times10^{-32}$	90%	Vidyakin *et al.* (1992)
	TEXONO	$-4.2\times10^{-32} < \langle r_{\nu_e}^2\rangle < 6.6\times10^{-32}$	90%	Deniz *et al.* (2010)[a]
Accelerator ν_e-e^-	LAMPF	$-7.12\times10^{-32} < \langle r_{\nu_e}^2\rangle < 10.88\times10^{-32}$	90%	Allen *et al.* (1993)[a]
	LSND	$-5.94\times10^{-32} < \langle r_{\nu_e}^2\rangle < 8.28\times10^{-32}$	90%	Auerbach *et al.* (2001)[a]
Accelerator ν_μ-e^-	BNL-E734	$-4.22\times10^{-32} < \langle r_{\nu_\mu}^2\rangle < 0.48\times10^{-32}$	90%	Ahrens *et al.* (1990)[a]
	CHARM-II	$\lvert\langle r_{\nu_\mu}^2\rangle\rvert < 1.2\times10^{-32}$	90%	Vilain *et al.* (1995)[a]

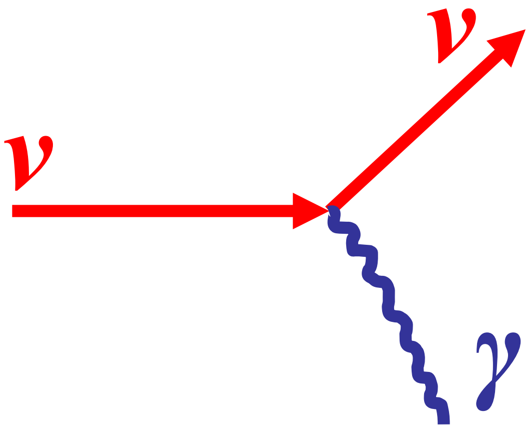
… updated by the recent constraints (effects of physics Beyond Standard Model)

$$(|\langle r_{\nu_{e\mu}}^2\rangle|, |\langle r_{\nu_{e\tau}}^2\rangle|, |\langle r_{\nu_{\mu\tau}}^2\rangle|) < (22, 38, 27)\times10^{-32}\ \mathrm{cm}^2,$$

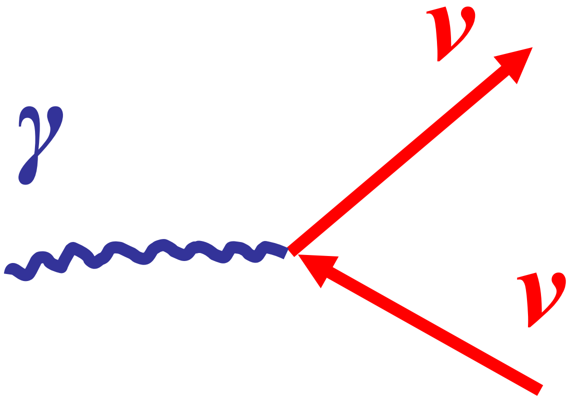
M.Cadeddu, C. Giunti, K.Kouzakov,
Yu-Feng Li, A. Studenikin, Y.Y.Zhang,
Neutrino charge radii from COHERENT elastic neutrino-nucleus scattering, Phys.Rev.D 98 (2018) 113010

Astrophysical
versus
GEMMA & Borexino
bounds on μ_ν

ν electromagnetic interactions

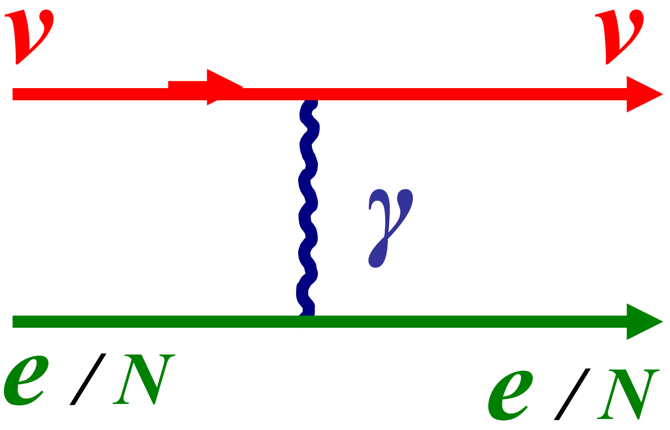


ν decay, Cherenkov radiation,
ν spin-light (SL ν)

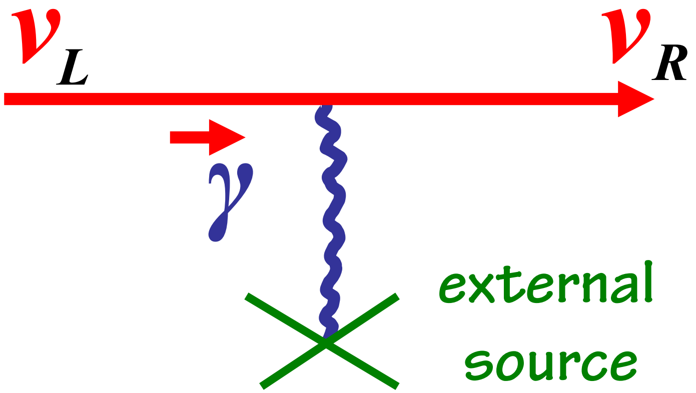


γ decay in plasma

!!!



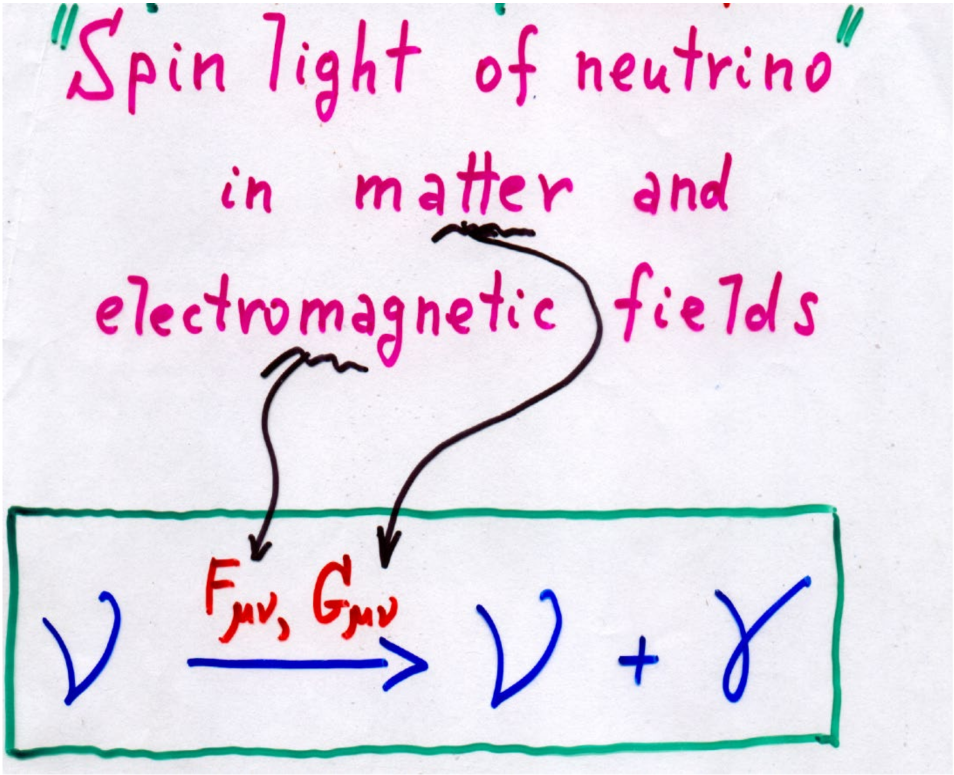
Scattering



Spin precession

• New mechanism of electromagnetic radiation

$SL\nu$



"Spin light of neutrino" in matter and electromagnetic fields

$$\nu \xrightarrow{F_{\mu\nu},\, G_{\mu\nu}} \nu + \gamma$$

A. Egorov, A. Lobanov, A. Studenikin,
Phys.Lett. B 491 (2000) 137
Lobanov, Studenikin,
Phys.Lett. B 515 (2001) 94
Phys.Lett. B 564 (2003) 27
Phys.Lett. B 601 (2004) 171
Studenikin, A.Ternov,
Phys.Lett. B 608 (2005) 107
A. Grigoriev, Studenikin, Ternov,
Phys.Lett. B 622 (2005) 199
Studenikin,
J.Phys.A: Math.Gen. 39 (2006) 6769
J.Phys.A: Math.Theor. 41 (2008) 16402

Grigoriev, A. Lokhov, Studenikin, Ternov,
Nuovo Cim. 35 C (2012) 57
Phys.Lett.B 718 (2012) 512

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

The effect of plasmon mass on Spin Light of Neutrino in dense matter

Phys.Lett. B 718 (2012) 512

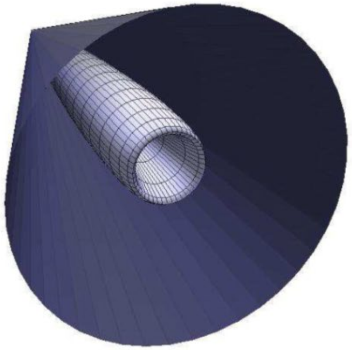


Figure 1: 3D representation of the radiation power distribution.

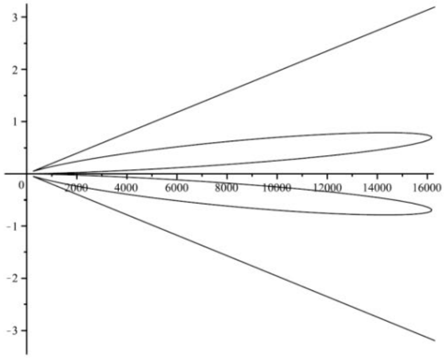


Figure 2: The two-dimensional cut along the symmetry axis. Relative units are used.

4. Conclusions

We developed a detailed evaluation of the spin light of neutrino in matter accounting for effects of the emitted plasmon mass. On the base of the exact solution of the modified Dirac equation for the neutrino wave function in the presence of the background matter the appearance of the threshold for the considered process is confirmed. The obtained exact and explicit threshold condition relation exhibit a rather complicated dependance on the matter density and neutrino mass. The dependance of the rate and power on the neutrino energy, matter density and the angular distribution of the $SL\nu$ is investigated in details. It is shown how the rate and power wash out when the threshold parameter $a = m_\gamma^2/4\tilde{n}p$ approaching unity. From the performed detailed analysis it is shown that the $SL\nu$ mechanism is practically insensitive to the emitted plasmon mass for very high densities of matter (even up to $n = 10^{41} cm^{-3}$) for ultra-high energy neutrinos for a wide range of energies starting from $E = 1$ TeV. This conclusion is of interest for astrophysical applications of $SL\nu$ radiation mechanism in light of the recently reported hints of $1 \div 10$ PeV neutrinos observed by IceCube [17].

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Spin light of neutrino in astrophysical environments

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JCAP11(2017)024

Astrophysical bounds on μ_ν

① … important for astrophysics consequence of μ_ν is appearance ν_R … examples 1-3 …

a) helicity change in ν magnetic moment scattering on e (p, n)

(active) (sterile)

$\nu_L \Rightarrow \nu_R$

effective μ_ν

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

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

b) spin (spin-flavor) precession in $B_\perp$

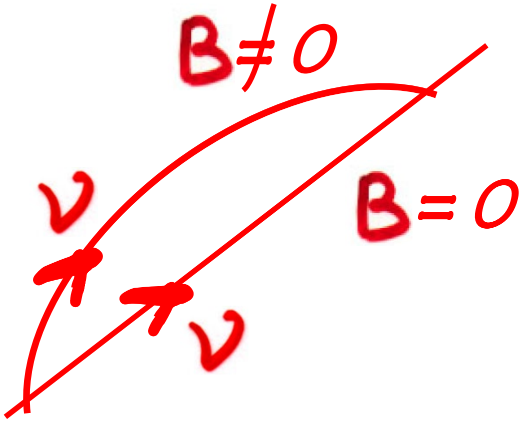
$$\mu_{ij} \rightarrow |\mu_{ij} - \epsilon_{ij}|$$

electric dipole moment [redacted]

c) spin (spin-flavor) precession in transversal matter currents $j_\perp$ or polarization $\zeta_\perp$

$\nu_L \xleftrightarrow{j_\perp} \nu_R$ $\nu_L \xleftrightarrow{\zeta_\perp} \nu_R$

② … important for astrophysics consequence of $q_\nu \neq 0$ is ν deviation from a rectilinear trajectory



Astrophysics bounds on μ_ν

… example 4 …

1) SN 1987A provides energy-loss limit on μ_ν (also d_ν and transition moments) related to observed duration of ν signal

…in magnetic moment scattering $\nu_e^L + e \to \nu_e^R + e$

due to change of helicity $\nu_L \Rightarrow \nu_R$

Dar, Nussinov & Rephaeli,
Goldman et al, Notzol, Voloshin,
Ayla et al, Balantekin et 1988

proto-neutron star formed in core-collapse SN can cool faster since ν_R are sterile and not trapped in a core like ν_L for a few sec

escaping ν_R will cool the core very efficient and fast (~ 1 s)

the observed 5-10 s pulse duration in Kamioka II and IMB is in agreement with the standard model ν_L trapping …

⇓

$$\boxed{\mu_\nu^D \sim 10^{-12} \mu_B}$$

… inconsistent with SN1987A observed cooling time

Barbieri, Mahapatra
Lattimer, Cooperstein,
1988
Raffelt, 1996

Astrophysics bounds on μ_ν

… example 5 …

2) SN 1987A provides energy-loss limit on μ_ν
related to observed ν energies

… helicity change in ν magnetic moment scattering $\nu_e^L + e \to \nu_e^R + e$
on e (p , n)

ν_R from inner SN core have larger energy than ν_L emitted from neutrino sphere

then $\nu_R \overset{B}{\Longleftrightarrow} \nu_L$ in galactic B and higher-energy ν_L would arrive to detector as a signal of SN 1987A

⇨ from absence of anomalous high-energy ν

Nötzold
1988

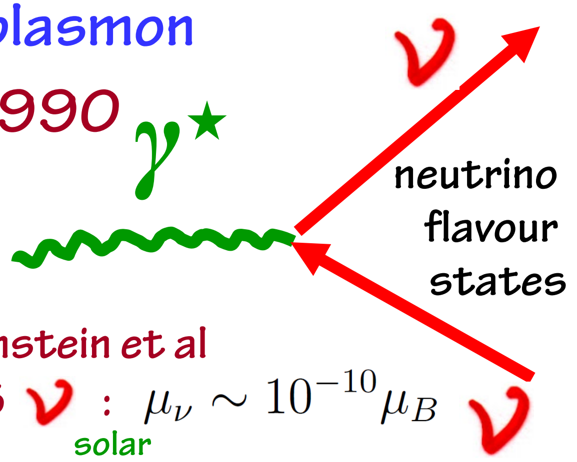
$$\Downarrow$$

$$\boxed{\mu_\nu^D \sim 10^{-12}\mu_B}$$

② Astrophysical bound on μ_ν

… example 6…

comes from cooling of **red giant** stars by plasmon decay $\gamma^\star \longrightarrow \nu\nu$ G.Raffelt, PRL 1990



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

J.Bernstein et al 1963 ν_{solar} : $\mu_\nu \sim 10^{-10}\mu_B$

Matrix element

$$|M|^2 = M_{\alpha\beta}p^\alpha p^\beta, \quad M_{\alpha\beta} = 4\mu^2(2k_\alpha k_\beta - 2k^2\epsilon^*_\alpha\epsilon_\beta - k^2 g_{\alpha,\beta}), \quad \epsilon_\alpha k^\alpha = 0$$

Decay rate

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

= 0 in vacuum $\omega = k$

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

Energy-loss rate per unit volume

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

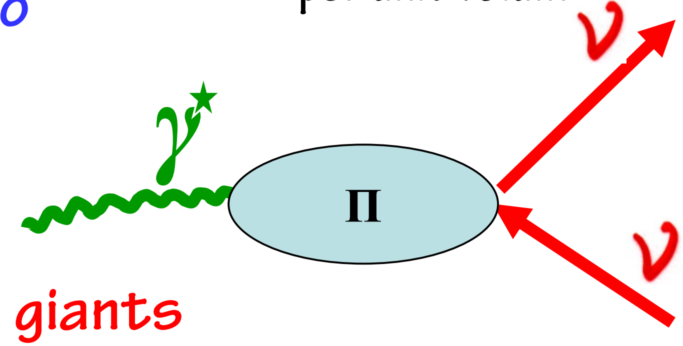
$$\mu^2 \to \sum_{a,b}\left(|\mu_{a,b}|^2 + |\epsilon_{a,b}|^2\right)$$

distribution function of plasmons

Astrophysical bound on μ_ν

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

Energy-loss rate per unit volume



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

more fast star cooling

slightly reducing the core temperature

delay of helium ignition in low-mass red giants

(due to nonstandard ν losses)

astronomical observable

can be related to luminosity of stars before and after helium flash

… in order not to delay helium ignition in an unacceptable way

(a significant brightness increase is constraint by observations …)

… best astrophysical limit on ν magnetic moment…

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

G.Raffelt, PRL 1990

D+M

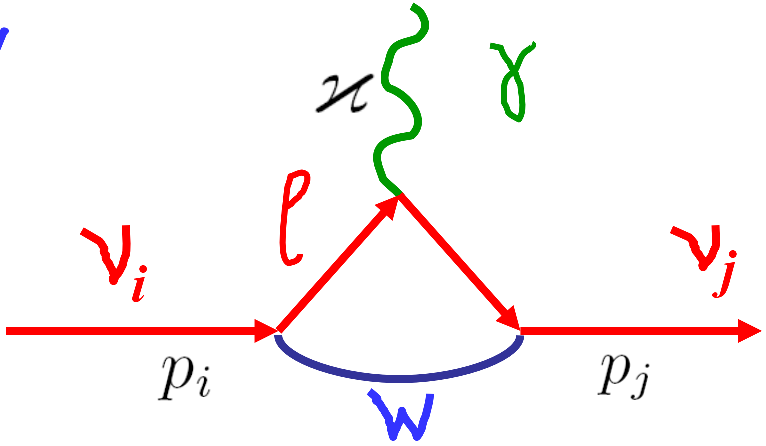
$$\mu^2 \to \sum_{a,b}\left(|\mu_{a,b}|^2 + |\epsilon_{a,b}|^2\right)$$

Neutrino radiative decay

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

$$m_i > m_j$$

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



Radiative decay rate

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

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

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

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

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

2) SN 1987A ν burst (all flavours),

3) spectral distortion of CMBR

Raffelt 1999

Kolb, Turner 1990;

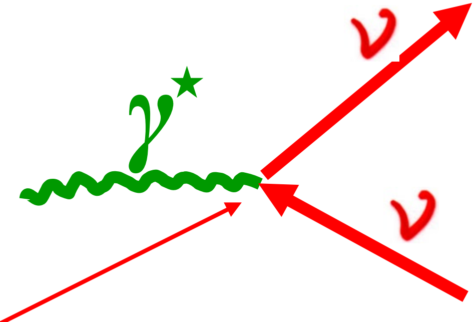
Ressell, Turner 1990

Astrophysical bounds on q_ν

Constraints on neutrino millicharge from red giants cooling

- **Plasma process** (photon decay)

$$\gamma^\star \rightarrow \nu\nu$$



Interaction Lagrangian

$$\boxed{L_{int} = -iq_\nu \bar{\psi}_\nu \gamma^\mu \psi_\nu A^\mu}$$

millicharge

Decay rate

$$\boxed{\Gamma_{q_\nu} = \frac{q_\nu{}^2}{12\pi}\omega_{pl}\left(\frac{\omega_{pl}}{\omega}\right)}$$

Dobroliubov, Ignatiev 1990;
Babu, Volkas 1992;
Mohapatra, Nussinov 1992 ...

Delay of helium ignition in low-mass red gians due to nonstandard ν losses

- $\boxed{q_\nu \leq 2 \times 10^{-14} e}$ ...to avoid delay of helium ignition in low-mass red giants

Halt, Raffelt,
Weiss, PRL1994

- $\boxed{q_\nu \leq 3 \times 10^{-17} e}$ ... absence of anomalous energy-dependent dispersion of SN1987A ν signal, most model independent
- $\boxed{q_\nu \leq 3 \times 10^{-21} e}$ ... from "charge neutrality" of neutron...

- … astrophysical bound on millicharge q_ν from

ν energy quantization
in rotating
magnetized star

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

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

Millicharged ν in rotating magnetized star

Balatsev, Tokarev, Studenikin,
Phys.Part.Nucl., 2012,
Phys.Atom.Nucl., Nucl.Phys. B, 2013,

- Studenikin, Tokarev, Nucl.Phys.B (2014)

Modified Dirac equation for ν wave function

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

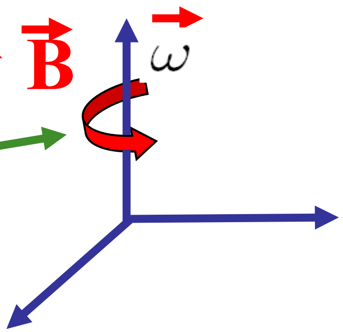
external magnetic field

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

matter potential

rotating matter

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



rotation angular frequency

ν energy is quantized in rotating and magnetized star

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

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

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

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

integer number

matter rotation frequency

millicharge

scalar potential of electric field

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

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

In quasi-classical approach

ν quantum states in rotating matter

ν motion in circular orbits

$$\boxed{R = \int_0^\infty \Psi_L^\dagger \, \mathrm{r} \, \Psi_L \, d\mathbf{r} = \sqrt{\frac{2N}{|2Gn_n\omega - \epsilon q_0 B|}}}$$

due to effective Lorentz force

$$\boxed{\mathbf{F}_{eff} = q_{eff}\mathbf{E}_{eff} + q_{eff}\,[\boldsymbol{\beta} \times \mathbf{B}_{eff}]}$$

A. Studenikin,
J.Phys.A: Math.Theor.
41(2008) 164047

$$q_{eff}\mathbf{E}_{eff} = q_m\mathbf{E}_m + q_0\mathbf{E} \qquad q_{eff}\mathbf{B}_{eff} = |q_m B_m + q_0 B|\mathbf{e}_z$$

where $\boxed{q_m = -G, \quad \mathbf{E}_m = -\boldsymbol{\nabla} n_n, \quad \mathbf{B}_m = 2n_n\boldsymbol{\omega}}$

matter induced “charge”, “electric” and “magnetic” fields

- # ν Star Turning mechanism (νST)

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

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

- New astrophysical constraint on ν millicharge

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

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

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

.. best astrophysical bound ...

new developments in ν spin and flavour oscillation

… new astrophysical probes of ν

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

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

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

② inherent interplay of ν spin and flavour oscillations in B

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

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

① ✓

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

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

oscillations engendered

by transversal matter currents $j_\perp$

$(\cancel{\mu_\nu B})$

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

— Main steps in ν oscillations

64 years !

early history of ν oscillations

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

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

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

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

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

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

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

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

Bruno Pontecorvo

1913-1993

only in $B_\perp$ and matter at rest

> 30 years !

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

Consider two different neutrinos: ν_{e_L}, ν_{μ_R}, $m_L \neq m_R$

with magnetic moment interaction

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

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

ν evolution equation

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

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

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

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

$$\nu_{e_L} \leftrightarrow \nu_{\mu_R} \qquad \boxed{B = |\mathbf{B}_\perp| e^{i\phi(t)}}$$

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

$$\boxed{\Delta_{LR} = \frac{\Delta m^2}{2}(\cos 2\theta + 1) - 2EV_{\nu_e} + 2E\dot{\phi}} \qquad \boxed{\Omega^2 = (\mu_{e\mu} B)^2 + \left(\frac{\Delta_{LR}}{4E}\right)^2}$$

- Resonance amplification of oscillations in matter:

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

Akhmedov, 1988
Lim, Marciano

… similar to
MSW effect

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

ELEMENTARY PARTICLES AND FIELDS
Theory

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

Neutrino in Electromagnetic Fields and Moving Media

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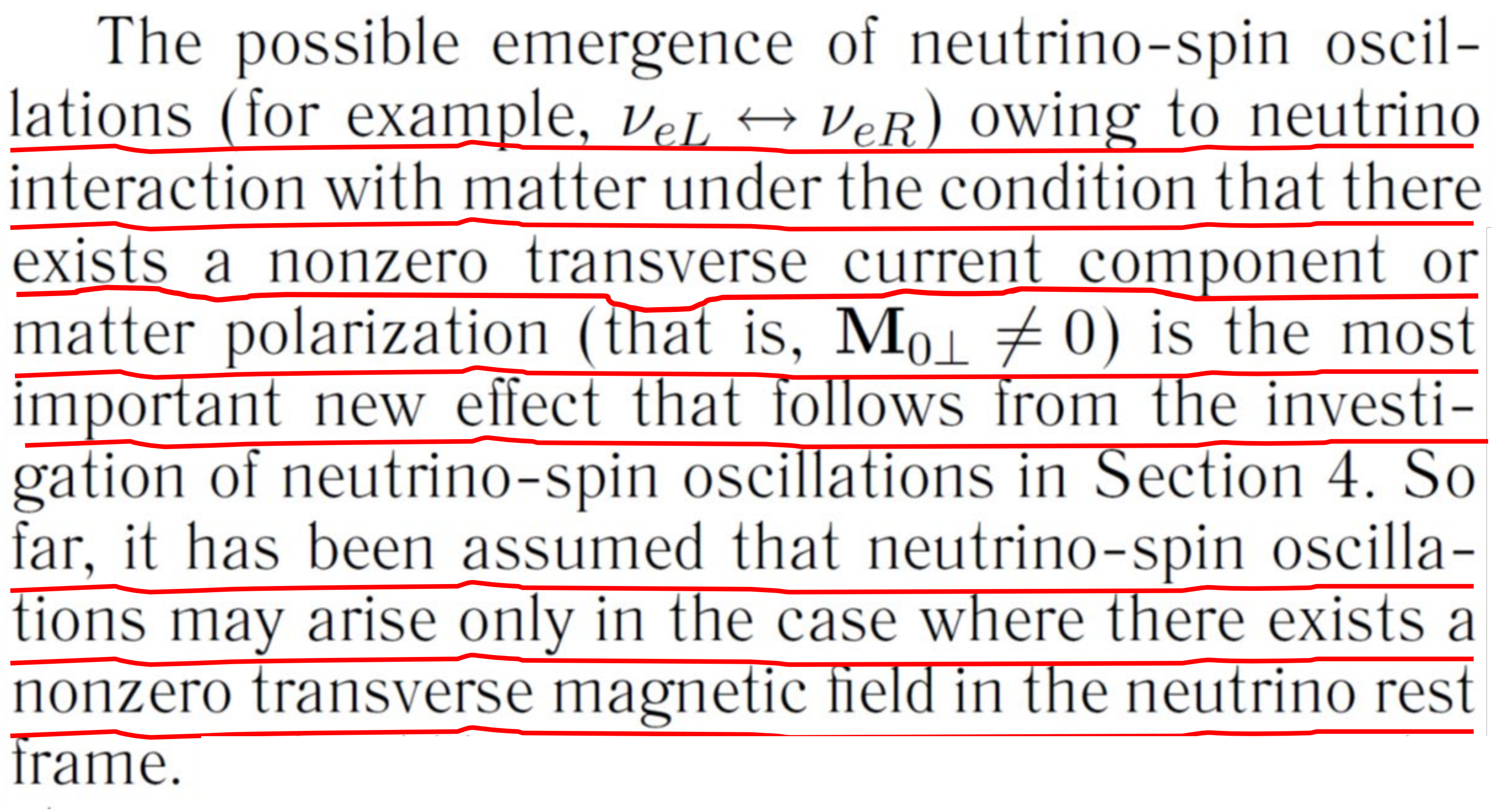
Received March 26, 2003; in final form, August 12, 2003



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

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

Consider

spin

spin-flavour

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

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

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

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

A.Studenikin,

"Neutrinos in electromagnetic fields and moving media",

Phys. Atom. Nucl. 67 (2004)

- transversal current $\mathbf{j}_\perp$

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

matter density

$\parallel$

$\perp$

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

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

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

… the effect of ν helicity conversions and oscillations induced by transversal matter currents has been recently confirmed in studies of ν propagation in astrophysical media:

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

- V. Ciriglianoa, G. M. Fuller, and A. Vlasenko,
  A new spin on neutrino quantum kinetics
  Phys. Lett. B747 (2015) 27

- A. Kartavtsev, G. Raffelt, and H. Vogel,
  Neutrino propagation in media: flavor-, helicity-, and pair correlations, Phys. Rev. D91 (2015) 125020 …

,

Neutrino spin (spin-flavour) oscillations in transversal matter currents

… quantum treatment …

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

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

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

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

$l = e,\ or\ \mu$

$i = 1,\ 2$

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

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

$$\boxed{\begin{aligned} \nu_e^\pm &= \nu_1^\pm \cos\theta + \nu_2^\pm \sin\theta, \\ \nu_\mu^\pm &= -\nu_1^\pm \sin\theta + \nu_2^\pm \cos\theta \end{aligned}}$$

ν flavour and mass states

P. Pustoshny, A. Studenikin ,

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

ν (2 flavours x 2 helicities) evolution equation

$$i\frac{d}{dt}\nu_f^s = \Big(\underset{\substack{\uparrow\\ \text{vacuum}}}{H_0} + \underbrace{\underset{\substack{\uparrow\\ \text{matter at rest}}}{\Delta H_0^{SM}} + \underset{\substack{\uparrow\\ \text{moving matter}}}{\Delta H_{j_{||}+j_\perp}^{SM}}}_{\text{Standard Model}} + \underset{\substack{\uparrow\\ B}}{\Delta H_{B_{||}+B_\perp}^{SM}} + \underbrace{\underset{\substack{\uparrow\\ \text{matter at rest}}}{\Delta H_0^{NSI}} + \underset{\substack{\uparrow\\ \text{moving matter}}}{\Delta H_{j_{||}+j_\perp}^{NSI}}}_{\text{Non-Standard Interactions}}\Big)\nu_f^s$$

Resonant amplification of ν oscillations:

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

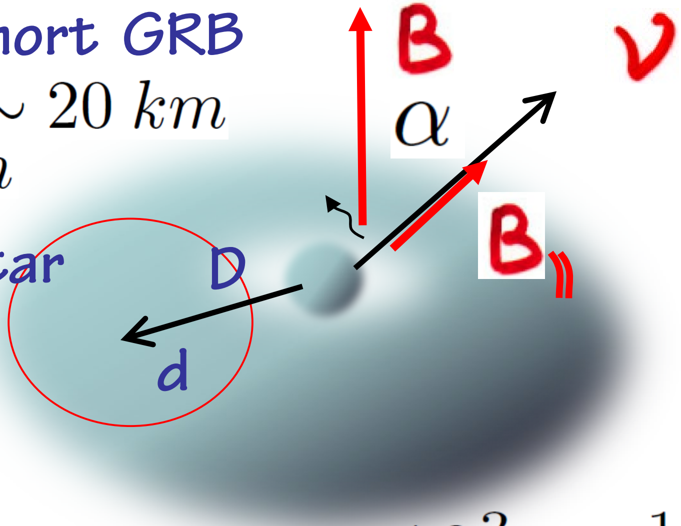
P. Pustoshny, A. Studenikin, Phys. Rev. D98 (2018) no. 11, 113009

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

a model of short GRB

$D \sim 20\ km$

$d \sim 20\ km$



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

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

- Perego et al, Mon.Not.Roy.Astron.Soc. 443 (2014) 3134
- Grigoriev, Lokhov, Studenikin, Ternov, JCAP 1711 (2017) 024

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

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

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

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

resonance condition

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

-

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

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

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

Criterion – oscillations are important: $$\boxed{\sin^2 2\theta_{\rm eff} = \frac{E_{\rm eff}^2}{E_{\rm eff}^2 + \Delta_{\rm eff}^2} \geq \frac{1}{2}}$$

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

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

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

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

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

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

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

$$\boxed{n_0 \sim \frac{\Delta M}{\tilde{G}} = 10^{12} \ eV^3 \approx 10^{26} \ cm^{-3}} \qquad \boxed{L_{eff} = \frac{\pi}{(\frac{\eta}{\gamma})_{e\mu} \tilde{G} n v_\perp} \approx 5 \times 10^{11} \ km}$$

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

②

ν

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

$\boxed{\nu_e^L \leftrightarrow \nu_\mu^L}$ $\boxed{\nu_e^L \leftrightarrow \nu_e^R}$ $\boxed{\nu_e^L \leftrightarrow \nu_\mu^R}$

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

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

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

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

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

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

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

$\hat{H}_i\nu_i^s = E\nu_i^s$ $\hat{H}_i = \gamma_0\boldsymbol{\gamma p} + \mu_i\gamma_0\boldsymbol{\Sigma B} + m_i\gamma_0$ $(s = \pm1)$ $\mu_{ij}(i \neq j) = 0$ ●

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

"bra-ket" products

● $\hat{S}_i = \frac{1}{N}\left[\boldsymbol{\Sigma B} - \frac{i}{m_i}\gamma_0\gamma_5[\boldsymbol{\Sigma}\times\boldsymbol{p}]\boldsymbol{B}\right]$ $\hat{S}_i\,|\nu_i^s\rangle = s\,|\nu_i^s\rangle\,, s = \pm1$ $\langle\nu_i^s|\nu_k^{s'}\rangle = \delta_{ik}\delta_{ss'}$ ●

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

● ν energy spectrum

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

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

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

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

magnetic moments of ν mass states

flavour

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

spin

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

spin-flavour

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

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

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

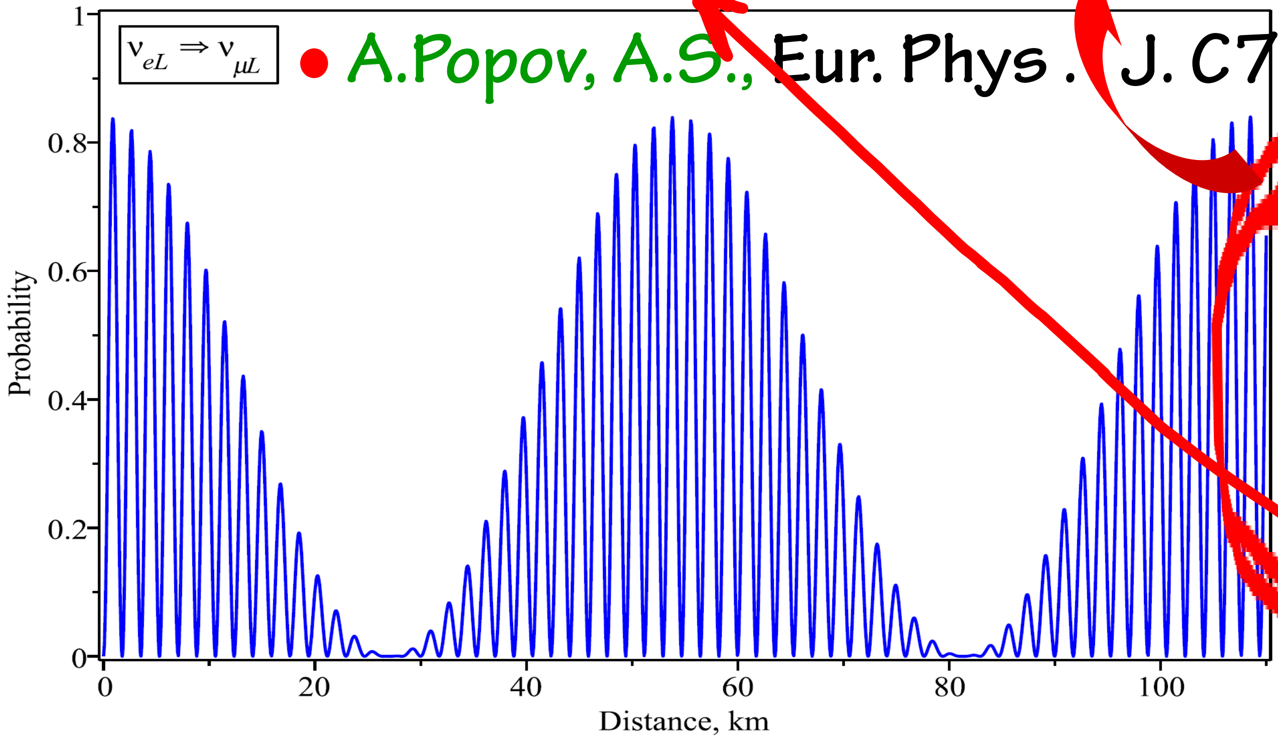
- For the case $\mu_1 = \mu_2$; probability of flavour oscillations

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

flavour

no spin oscillations

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



… amplitude of flavour oscillations on vacuum frequency

$$\omega_{vac} = \frac{\Delta m^2}{4p}$$

is modulated by magnetic frequency

$$\omega_B = \mu B_\perp$$

Fig. 1 The probability of the neutrino flavour oscillations $\nu_e^L \to \nu_\mu^L$ in the transversal magnetic field

- $B_\perp = 10^{16}\ G$ for the neutrino energy $p = 1\ MeV$, $\Delta m^2 = 7 \times 10^{-5}\ eV^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-20} \mu_B$.

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

③ New effect in ν flavor oscillation in moving matter

$$\boxed{\nu_e^L \Leftarrow (j_{||}, j_\perp) \Rightarrow \nu_\mu^L} \qquad \boldsymbol{j}_\perp = n\boldsymbol{v}_\perp$$

longitudinal transversal
matter currents

Invariant number density

Studenikin, Nuovo Cim. C42 (2019) n.6;
arXiv: 1912.12491

- Equal role of $\boldsymbol{j}_\perp$ and $\boldsymbol{B}_\perp$ in generation of

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

- Probability of ν flavor oscillations $\nu_e^L \Leftarrow (j_{||}, j_\perp) \Rightarrow \nu_\mu^L$ in moving matter

$$\boxed{P^{(j_{||}+j_\perp)}_{\nu_e^L\to\nu_\mu^L}(t) = \left(1 - P^{(j_\perp)}_{\nu_e^L\to\nu_e^R} - P^{(j_\perp)}_{\nu_e^L\to\nu_\mu^R}\right) P^{(j_{||})}_{\nu_e^L\to\nu_\mu^L}}$$

$$\boxed{P^{(j_{||})}_{\nu_e^L\to\nu_\mu^L}(t) = \sin^2 2\theta_{eff}\sin^2\omega_{eff}t, \quad \omega_{eff} = \frac{\Delta m^2_{eff}}{4p_0^\nu}}$$

probability of flavor oscillations in $j_{||}$

probability of spin survival
(not spin flip)

$$\boxed{P^{j_\perp}_{\nu_e^L\to\nu_e^R}(t) = \frac{\left(\frac{\eta}{\gamma}\right)^2_{ee} v_\perp^2}{\left(\frac{\eta}{\gamma}\right)^2_{ee} v_\perp^2 + (1-\boldsymbol{v\beta})^2}\sin^2\omega^{j_\perp}_{ee}t}$$

$$\boxed{P^{j_\perp}_{\nu_e^L\to\nu_\mu^R}(t) = \frac{\left(\frac{\eta}{\gamma}\right)^2_{e\mu} v_\perp^2}{\left(\frac{\eta}{\gamma}\right)^2_{e\mu} v_\perp^2 + \left(\frac{\Delta M}{\widetilde{G}n} - (1-\boldsymbol{v\beta})\right)^2}\sin^2\omega^{j_\perp}_{e\mu}t}$$

spin oscillations in $\boldsymbol{j}_\perp$

spin-flavor oscillations in $\boldsymbol{j}_\perp$

$$\boxed{\omega^{j_\perp}_{ee} = \widetilde{G}n\sqrt{\left(\frac{\eta}{\gamma}\right)^2_{ee} v_\perp^2 + (1-\boldsymbol{v\beta})^2}}$$

… is modulated by
two "matter"
frequencies …

$$\boxed{\omega^{j_\perp}_{e\mu} = \widetilde{G}n\sqrt{\left(\frac{\eta}{\gamma}\right)^2_{e\mu} v_\perp^2 + \left(\frac{\Delta M}{\widetilde{G}n} - (1-\boldsymbol{v\beta})\right)^2}}$$

$$\left(\frac{\eta}{\gamma}\right)_{ee} = \frac{\cos^2\theta}{\gamma_{11}} + \frac{\sin^2\theta}{\gamma_{22}} \qquad {\gamma_{\alpha\alpha'}}^{-1} = \frac{1}{2}(\gamma_\alpha^{-1} + \gamma_{\alpha'}^{-1}) \qquad \gamma_\alpha^{-1} = \frac{m_\alpha}{E_\alpha}$$

$$\left(\frac{\eta}{\gamma}\right)_{e\mu} = \frac{\sin 2\theta}{\tilde{\gamma}_{21}} \qquad \tilde{\gamma}^{-1}_{\alpha\alpha'} = \frac{1}{2}(\gamma_\alpha^{-1} - \gamma_{\alpha'}^{-1})$$

PHYSICAL REVIEW D **103,** 115027 (2021)

Manifestations of nonzero Majorana *CP*-violating phases in oscillations of supernova neutrinos

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(Received 14 February 2021; accepted 18 May 2021; published 22 June 2021)

We investigate effects of nonzero Dirac and Majorana *CP*-violating phases on neutrino-antineutrino oscillations in a magnetic field of astrophysical environments. It is shown that in the presence of strong magnetic fields and dense matter, nonzero *CP* phases can induce new resonances in the oscillations channels $\nu_e \leftrightarrow \bar{\nu}_e$, $\nu_e \leftrightarrow \bar{\nu}_\mu$, and $\nu_e \leftrightarrow \bar{\nu}_\tau$. We also consider all other possible oscillation channels with ν_μ and ν_τ in the initial state. The resonances can potentially lead to significant phenomena in neutrino oscillations accessible for observation in experiments. In particular, we show that neutrino-antineutrino oscillations combined with Majorana-type *CP* violation can affect the $\bar{\nu}_e/\nu_e$ ratio for neutrinos coming from the supernovae explosion. This effect is more prominent for the normal neutrino mass ordering. The detection of supernovae neutrino fluxes in the future experiments, such as JUNO, DUNE, and Hyper-Kamiokande, can give an insight into the nature of *CP* violation and, consequently, provides a tool for distinguishing the Dirac or Majorana nature of neutrinos.

DOI: 10.1103/PhysRevD.103.115027

I. INTRODUCTION

CP symmetry implies that the equations of motion of a system remain invariant under the *CP* transformation, that is a combination of charge conjugation (*C*) and parity inversion (*P*). In 1964, with the discovery of the neutral kaon decay [1], it was confirmed that *CP* is not an underlying symmetry of the electroweak interactions theory, thus opening a vast field of research in *CP* violation. Currently, *CP* violation is a topic of intense studies in particle physics that also has important implications in cosmology. In 1967, Sakharov proved that the existence of *CP* violation is a necessary condition for generation of the baryon asymmetry through baryogenesis in the early Universe [2]. A review of possible baryogenesis scenarios can be found in [3].

Today we have solid understanding of *CP* violation in the quark sector, that appears due to the complex phase in the Cabibbo-Kobayashi-Maskawa matrix parametrization. Its magnitude is expressed by the Jarlskog invariant $\mathcal{J}_{\mathrm{CKM}} = (3.18 \pm 0.15) \times 10^{-5}$ [4], which seems to be excessively small to engender baryogenesis at the electroweak phase transition scale [3]. However, in addition to experimentally confirmed *CP* violation in the quark sector, *CP* violation in the lepton (neutrino) sector hypothetically exists (see [5] for a review). Leptonic *CP* violation is extremely difficult to observe due to weakness of neutrino interactions. In 2019, a first breakthrough happened when NOνA [6] and T2K [7] collaborations reported constraints on the Dirac *CP*-violating phase in neutrino oscillations. Hopefully, future gigantic neutrino experiments, such as DUNE [8] and Hyper-Kamiokande [9], also JUNO [10] with detection of the atmospheric neutrinos, will have a good chance significantly improve this results. Note that leptonic *CP* violation plays an important role in baryogenesis through leptogenesis scenarios [11].

The *CP*-violation pattern in the neutrino sector depends on whether neutrino is a Dirac or Majorana particle. The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix in the most common parametrization has the following form

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Phys.Rev.D 103 (2021) 115027

… the role of Majorana CP-violating phases in neutrino oscillations

$$\nu_e \leftrightarrow \bar{\nu}_{e,\mu,\tau}$$

in strong B and dense matter of supernovae for two mass hierarchies

⇓

… Majorana CP phases induce new resonances

⇓

… a tool for distinguishing Dirac-Majorana nature of ν

Conclusions

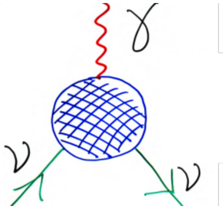
① ② ③

① Electromagnetic Properties of ν

MSU **Alexander Studenikin** JINR

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

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



① νEP theory - ν vertex function

matrices in ν mass eigenstates space

$$\Lambda^{if}_\mu(q) = f^{if}_Q(q^2)\gamma_\mu + f^{if}_M(q^2)i\sigma_{\mu\nu}q^\nu + f^{if}_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + f^{if}_A(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5,$$

electric charge

magnetic moment

electric moment

anapole moment

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

Dirac ν Majorana

q_{if}, μ_{if}, ε_{if}, a_{if} $\neq 0$ ⇐

$q_{if}=0$, $\mu_{if}\,(i\neq f)$, $\varepsilon_{if}\,(i\neq f)$, a_{if} } CPT + charge concervation

Hermiticity and discrete symmetries of EM current $\langle\nu(p')|J^{EM}_\mu|\nu(p)\rangle = \bar u(p')\Lambda_\mu(q)u(p)$ put constraints on form factors

② $$\mu^D_{jj} = \frac{3e_0G_Fm_j}{8\sqrt{2}\pi^2} \approx 3.2\times10^{-19}\mu_B\left(\frac{m_j}{1\text{ eV}}\right)$$

Fujikawa & Shrock, 1980

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

③ ν EMP ⇓ experimental bounds

$$\mu^{eff}_\nu < \begin{matrix}2.9\\2.8\\\sim0.1\end{matrix} \times 10^{-11}\mu_B$$

GEMMA Coll. 2012

Borexino Coll. 2017

Astrophysics, Raffelt ea 1988

Arcoa Dias ea 2015

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

reactor ν scattering

AS '14, Chen ea '14

AS '14 (astrophysics)

neutrality of matter

ν electromagnetic properties: Future prospects

- new constraints on μ_ν (and q_ν) from GEMMA-3 / νGeN and Borexino (?)

- XENON1T an excess in electronic recoil events in 1-7 keV over known backgrounds

$$\boxed{\mu_\nu \in (1.4,\ 2.9) \times 10^{-11}\ \mu_B}$$

arXiv: 2006.0972
30 June, 2020

- new setup to observe coherent elastic neutrino-atom scattering using electron antineutrinos from tritium decay and a liquid helium target - upper limit :

$$\boxed{\mu_\nu < 7 \times 10^{-13} \mu_B}$$

M. Cadeddu, F.Dordei, C.Giunti, K.Kouzakov, E. Picciau, A.Studenikin,
Potentialities of a low-energy detector based on 4 He evaporation to observe atomic effects in coherent neutrino scattering and physics perspectives,
Phys. Rev. D100 (2019) no.7, 073014

ν electromagnetic interactions (new effects)

three new aspects of ν spin, spin-flavour and flavour oscillations

① generation of ν spin and spin-flavour oscillations by ν interaction with transversal matter current $j_\perp$ and polarization $\zeta_\perp$

Studenikin, 2014, 2019;
Pustoshny, Studenikin
Phys.Rev. (2018);

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Poster # 515

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

Popov, Studenikin,
Eur. Phys .J. C (2019);

Lichkunov, Popov, Studenikin,
Poster # 509

③ new effects in ν oscillations due to Majorana CP phases in magnetized dense matter of supernovae (ν fluxes for JUNO, DUNE & HK)

Popov, Studenikin
Phys.Rev.D 103 (2021) 115027

q_ν two very useful papers of the year μ_ν

Hindawi
Advances in High Energy Physics
Volume 2020, Article ID 5908904, 10 pages
https://doi.org/10.1155/2020/5908904

Research Article

Constraints on Neutrino Electric Millicharge from Experiments of Elastic Neutrino-Electron Interaction and Future Experimental Proposals Involving Coherent Elastic Neutrino-Nucleus Scattering

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In several extensions of the Standard Model of Particle Physics (SMPP), the neutrinos acquire electromagnetic properties such as the electric millicharge. Theoretical and experimental bounds have been reported in the literature for this parameter. In this work, we first carried out a statistical analysis by using data from reactor neutrino experiments, which include elastic neutrino-electron scattering (ENES) processes, in order to obtain both individual and combined limits on the neutrino electric millicharge (NEM). Then, we performed a similar calculation to show an estimate of the sensitivity of future experiments of reactor neutrinos to the NEM, by involving coherent elastic neutrino-nucleus scattering (CENNS). In the first case, the constraints achieved from the combination of several experiments are $-1.1 \times 10^{-12} e < q_\nu < 9.3 \times 10^{-13} e$ (90% C.L.), and in the second scenario, we obtained the bounds $-1.8 \times 10^{-14} e < q_\nu < 1.8 \times 10^{-14} e$ (90% C.L.). As we will show here, these combined analyses of different experimental data can lead to stronger constraints than those based on individual analysis, where CENNS interactions would stand out as an important alternative to improve the current limits on NEM.

1. Introduction

In the SMPP, the neutrinos are massless, electrically neutral, and only interact weakly with leptons and quarks. Nevertheless, the neutrino oscillation experiments show that neutrinos have mass and are also mixed [1–4]. Hence, the idea of extending the SMPP so as to explain the origin of neutrino mass. Different extensions of SMPP allow the neutrino to have properties such as magnetic and electric dipole moments as well as anapole moment and electric millicharge [5–7]. Even in the Standard Model, it is well-known that the neutrinos also can have nonzero charge radius, as shown in reference [8, 9]. Among these properties, the neutrino magnetic moment (NMM) has been quite studied in several research works, where different experimental constraints to this parameter were obtained, for instance, from reactor neutrino experiments [10–14], solar neutrinos [15, 16], and astrophysical measurements [17, 18]. The limits achieved for the NMM are around $10^{-11}\mu_B$, while the prediction of the simplest extension of the Standard Model, by including right-handed neutrinos, is $3.2 \times 10^{-19}\mu_B$ [19]. Furthermore, considering the representation of three active neutrinos, the magnetic moment is described by a 3×3 matrix whose components are the diagonal and transition magnetic moments. A complete analysis by considering the NMM matrix and using data from solar, reactor, and accelerator experiments was presented in reference [20, 21]. In addition to NMM, the study of the remainder form factors is also important as they are a tool to probe new physics. Among them, the NEM has also been under consideration in the literature, and several constraints have been found mainly from reactor experiments and astrophysical measurements. The most restrictive bound on NEM so far, $q_\nu \lesssim 3.0 \times 10^{-21} e$, was obtained in [18] based on the neutrality of matter. A limit

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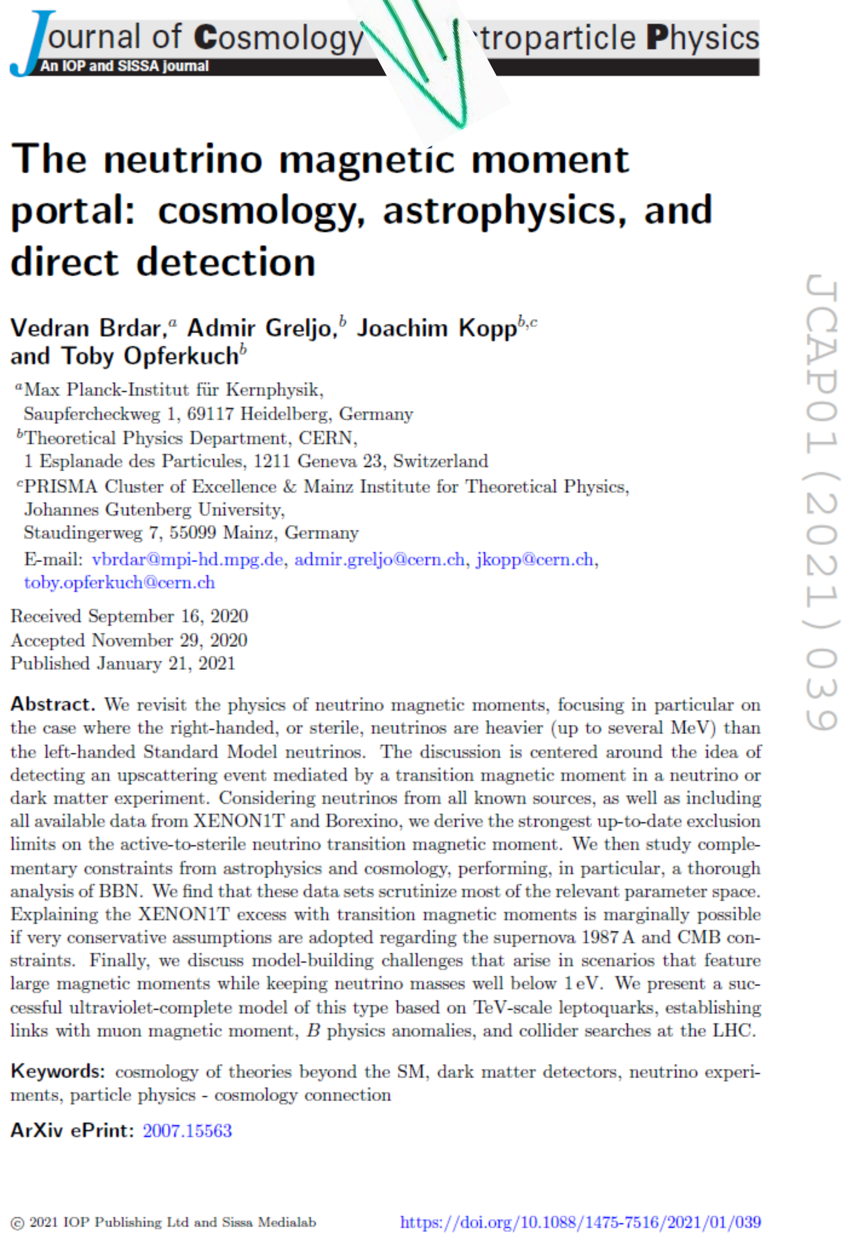

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

The neutrino magnetic moment portal: cosmology, astrophysics, and direct detection

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Abstract. We revisit the physics of neutrino magnetic moments, focusing in particular on the case where the right-handed, or sterile, neutrinos are heavier (up to several MeV) than the left-handed Standard Model neutrinos. The discussion is centered around the idea of detecting an upscattering event mediated by a transition magnetic moment in a neutrino or dark matter experiment. Considering neutrinos from all known sources, as well as including all available data from XENON1T and Borexino, we derive the strongest up-to-date exclusion limits on the active-to-sterile neutrino transition magnetic moment. We then study complementary constraints from astrophysics and cosmology, performing, in particular, a thorough analysis of BBN. We find that these data sets scrutinize most of the relevant parameter space. Explaining the XENON1T excess with transition magnetic moments is marginally possible if very conservative assumptions are adopted regarding the supernova 1987 A and CMB constraints. Finally, we discuss model-building challenges that arise in scenarios that feature large magnetic moments while keeping neutrino masses well below 1 eV. We present a successful ultraviolet-complete model of this type based on TeV-scale leptoquarks, establishing links with muon magnetic moment, B physics anomalies, and collider searches at the LHC.

Keywords: cosmology of theories beyond the SM, dark matter detectors, neutrino experiments, particle physics - cosmology connection

ArXiv ePrint: 2007.15563

https://doi.org/10.1088/1475-7516/2021/01/039

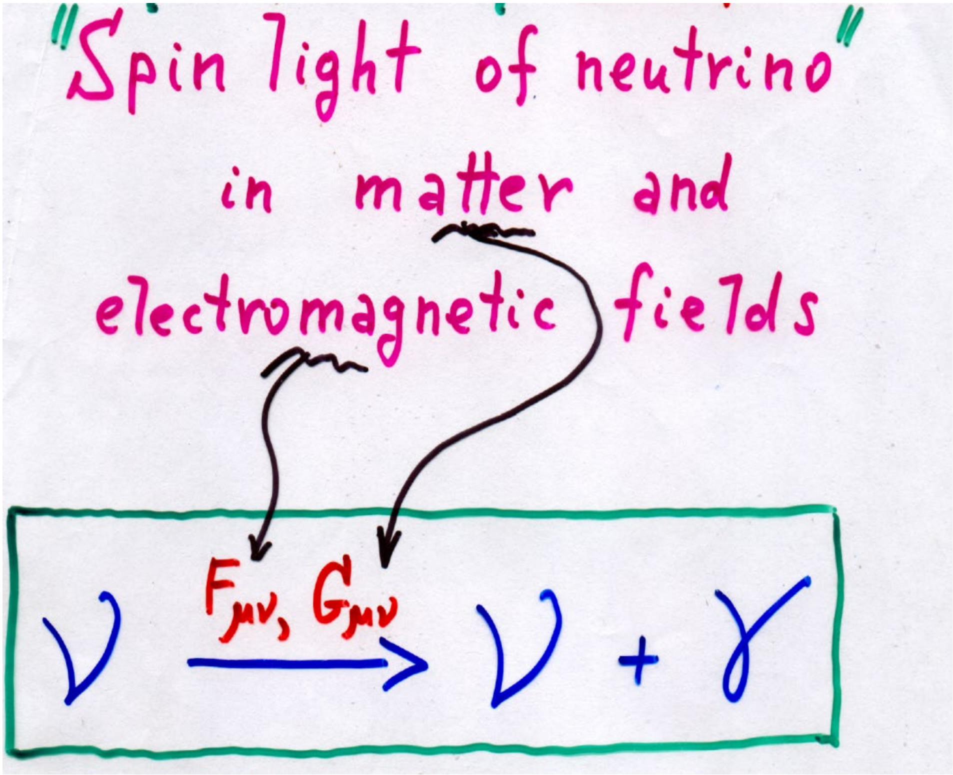
Thank you

Backup slides

spin light of ν

New mechanism of electromagnetic radiation

$SL\nu$



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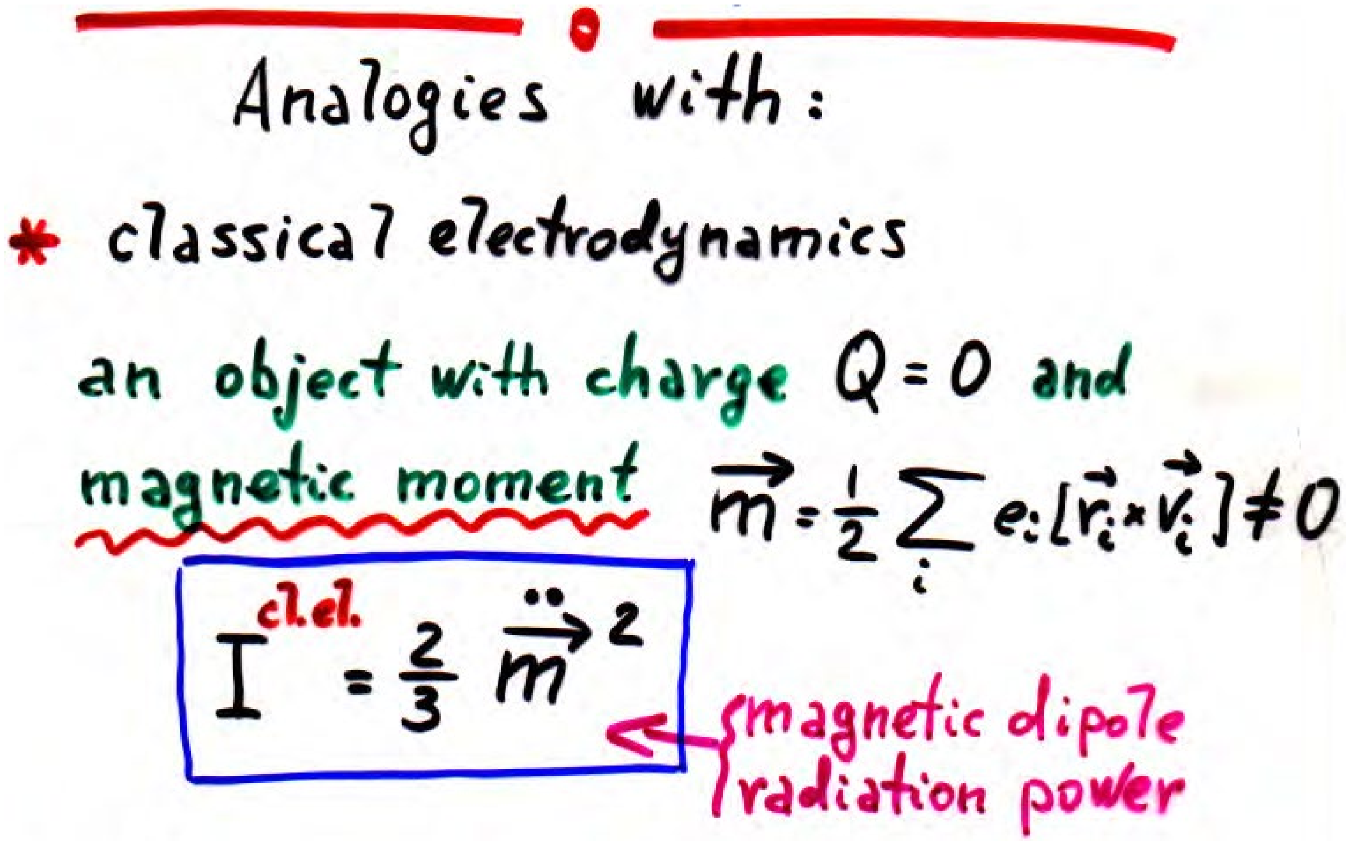
Phys.Lett.B 718 (2012) 512

New mechanism of electromagnetic radiation

? Why **Spin Light** of neutrino $SL\nu$ / of electron SLe in matter.



Analogies with:

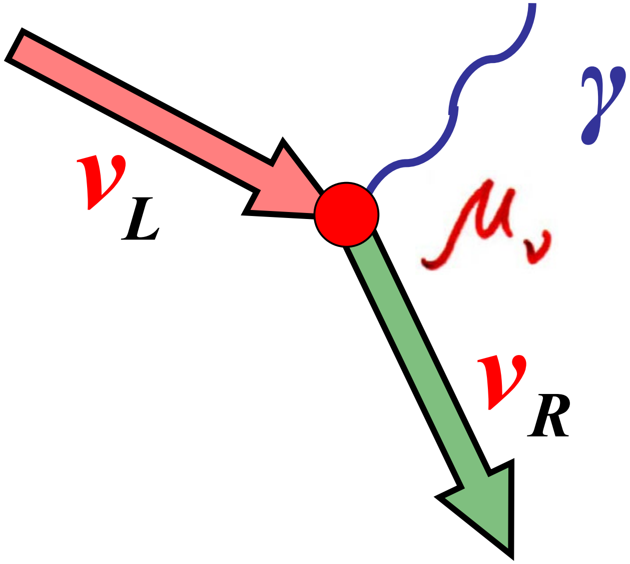
* classical electrodynamics

an object with charge $Q = 0$ and magnetic moment $\vec{m} = \frac{1}{2}\sum_i e_i[\vec{r}_i \times \vec{v}_i] \neq 0$

$$\boxed{I^{cl.el.} = \frac{2}{3}\ddot{\vec{m}}^2}$$

← magnetic dipole radiation power

Neutrino – photon coupling



broad neutrino lines
account for interaction
with environment

"Spin light of neutrino in matter"

$SL\nu$

- … within the quantum treatment based on method of exact solutions …

Modified Dirac equation for neutrino in matter

Addition to the vacuum neutrino Lagrangian

$$\Delta L_{eff} = \Delta L_{eff}^{CC} + \Delta L_{eff}^{NC} = -f^{\mu}\left(\bar{\nu}\gamma_{\mu}\frac{1+\gamma^5}{2}\nu\right)$$

matter current

where $$f^{\mu} = \frac{G_F}{\sqrt{2}}\left((1+4\sin^2\theta_W)j^{\mu} - \lambda^{\mu}\right)$$

matter polarization

$$\boxed{\left\{i\gamma_{\mu}\partial^{\mu} - \frac{1}{2}\gamma_{\mu}(1+\gamma_5)f^{\mu} - m\right\}\Psi(x) = 0}$$

A.Studenikin, A.Ternov, hep-ph/0410297; *Phys.Lett.B* **608 (2005) 107**

It is supposed that there is a macroscopic amount of electrons in the scale of a neutrino de Broglie wave length. Therefore, **the interaction of a neutrino with the matter (electrons) is coherent.**

L.Chang, R.Zia,'88; J.Panteleone,'91; K.Kiers, N.Weiss, M.Tytgat,'97-'98; P.Manheim,'88; D.Nötzold, G.Raffelt,'88; J.Nieves,'89; V.Oraevsky, V.Semikoz, Ya.Smorodinsky,89; W.Naxton, W-M.Zhang'91; M.Kachelriess,'98; A.Kusenko, M.Postma,'02.

This is the most general equation of motion of a neutrino in which the effective potential accounts for both the **charged** and **neutral-current** interactions with the background matter and also for the possible effects of the matter **motion** and **polarization**.

Quantum theory of spin light of neutrino

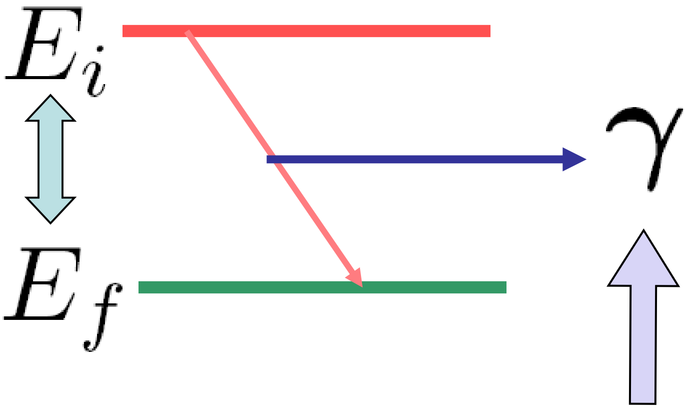
$SL\nu$

Quantum treatment of *spin light of neutrino* in matter
showns that this process originates from the **two subdivided phenomena:**

the **shift** of the neutrino **energy levels** in the presence of the background matter, which is different for the two opposite **neutrino helicity states**,

$$E = \sqrt{\mathbf{p}^2\left(1 - s\alpha\frac{m}{p}\right)^2 + m^2} + \alpha m$$

$$s = \pm 1$$



the radiation of the photon in the process of the neutrino transition from the **“excited” helicity state** to the **low-lying helicity state** in matter

A.Studenikin, A.Ternov, Phys.Lett.B 608 (2005) 107;
A.Grigoriev, A.Studenikin, A.Ternov, Phys.Lett.B 622 (2005) 199;
Grav. & Cosm. 14 (2005) 132;

neutrino-spin self-polarization effect in the matter

A.Lobanov, A.Studenikin, Phys.Lett.B 564 (2003) 27;
Phys.Lett.B 601 (2004) 171

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

The effect of plasmon mass on Spin Light of Neutrino in dense matter

Phys.Lett. B 718 (2012) 512

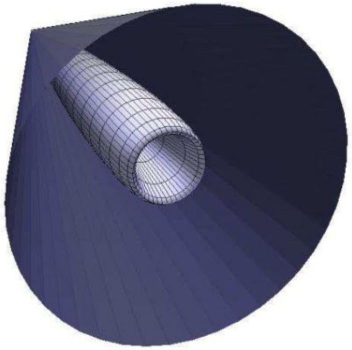


Figure 1: 3D representation of the radiation power distribution.

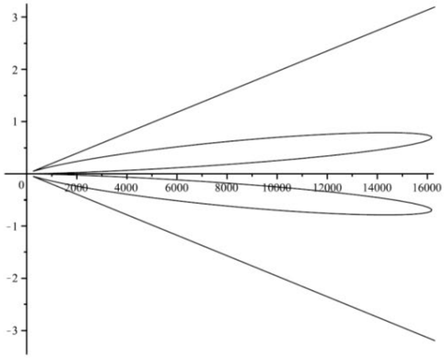


Figure 2: The two-dimensional cut along the symmetry axis. Relative units are used.

4. Conclusions

We developed a detailed evaluation of the spin light of neutrino in matter accounting for effects of the emitted plasmon mass. On the base of the exact solution of the modified Dirac equation for the neutrino wave function in the presence of the background matter the appearance of the threshold for the considered process is confirmed. The obtained exact and explicit threshold condition relation exhibit a rather complicated dependance on the matter density and neutrino mass. The dependance of the rate and power on the neutrino energy, matter density and the angular distribution of the $SL\nu$ is investigated in details. It is shown how the rate and power wash out when the threshold parameter $a = m_\gamma^2/4\tilde{n}p$ approaching unity. From the performed detailed analysis it is shown that the $SL\nu$ mechanism is practically insensitive to the emitted plasmon mass for very high densities of matter (even up to $n = 10^{41} cm^{-3}$) for ultra-high energy neutrinos for a wide range of energies starting from $E = 1$ TeV. This conclusion is of interest for astrophysical applications of $SL\nu$ radiation mechanism in light of the recently reported hints of $1 \div 10$ PeV neutrinos observed by IceCube [17].

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Spin light of neutrino in astrophysical environments

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JCAP11(2017)024

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

SLν in neutron matter of real astrophysical objects [4]

☐ **Plasma effects [5]**

- Photon dispersion with plasmon mass in the degenerate electron gas: $\boxed{\omega = \sqrt{\mathbf{k}^2 + m_\gamma^2}}$

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

- Threshold condition for the *SLν* [10]: $\boxed{\frac{m_\gamma^2 + 2\,m_\gamma m_\nu}{4\tilde{n}p} < 1}$
  ($Y_e = n_e/n_n$)
- **Neutron matter:** $\tilde{n} = \frac{1}{2\sqrt{2}}G_F n_n \simeq 3.2 \times \left(\frac{n_n}{10^{38}\,\mathrm{cm}^{-3}}\right)\mathrm{eV},$
  (antineutrinos act)

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

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

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

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

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

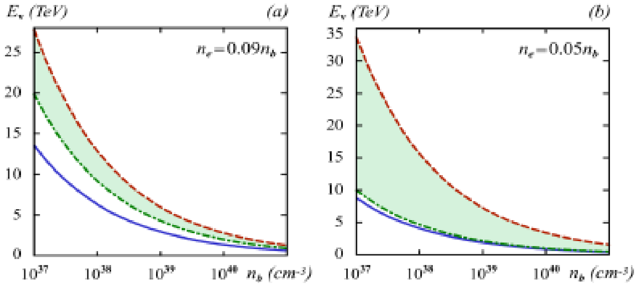


Figure 2. The allowed range of electron antineutrino energies for the $SL\nu$ in the matter of a neutron star depending on the neutron density. Solid line: the $SL\nu$ process threshold without account for the $\bar{\nu}_e e$-scattering; dash-dotted line: the $SL\nu$ process threshold with account for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

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

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

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

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

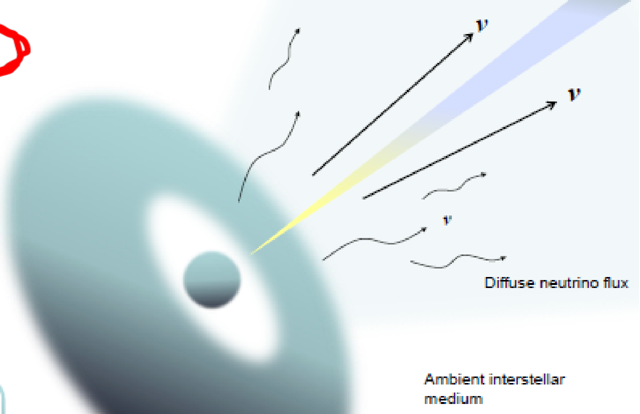
Neutrino 2018 (Heidelberg) & ICHEP 2018 (Seoul), June-July 2018

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

Factors for best *SLν* generation efficiency

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

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



Matter characteristics[6]:

- neutrinos
  $n_\nu \sim 10^{32}\ \mathrm{cm}^{-3}$
- electrons
  $Y_e = 0.01$
  $T = 0.1\ \mathrm{MeV}$
  $\rho = 5 \times 10^3\ \mathrm{g/cm}^3$

$\Rightarrow$

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

Radiation time

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

Neutrino parameters:

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

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

Backup slides

energy quantization
in rotating
magnetized star

- … astrophysical bound on millicharge q_ν from

ν energy quantization
in rotating
magnetized star

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

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

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

. . . we predict :

$E \sim 1\ eV$

1) low-energy ν are trapped in circular orbits inside rotating neutron stars

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

$$\boxed{\begin{aligned} R_{NS} &= 10\ km \\ n &= 10^{37} cm^{-3} \\ \omega &= 2\pi \times 10^{3}\ \ s^{-1} \end{aligned}}$$

2) rotating neutron stars as filters for low-energy relic ν ?

$$T_\nu \sim 10^{-4}\ \mathrm{eV}$$

… we predict :

3) high-energy ν are deflected inside a rotating astrophysical transient sources (GRBs, SNe, AGNs)

absence of light in correlation with ν signal reported by ANTARES Coll.

M.Ageron et al,
Nucl.Instrum.Meth. A692 (2012) 184

Millicharged ν as star rotation engine

- Single ν generates feedback force with projection on rotation plane

- $F = (q_0 B + 2Gn_n\omega)\sin\theta$

single ν torque

- $$M_0(t) = \sqrt{1 - \frac{r^2(t)\Omega^2\sin^2\theta}{4}}\,Fr(t)\sin\theta$$

total N_ν torque

$$M(t) = \frac{N_\nu}{4\pi}\int M_0(t)\sin\theta d\theta d\varphi$$

- Should effect initial star rotation (shift of star angular velocity)

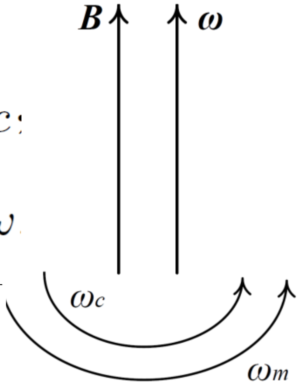
$$\boxed{|\triangle\omega| = \frac{5N_\nu}{6M_S}(q_0 B + 2Gn_n\omega_0)}$$

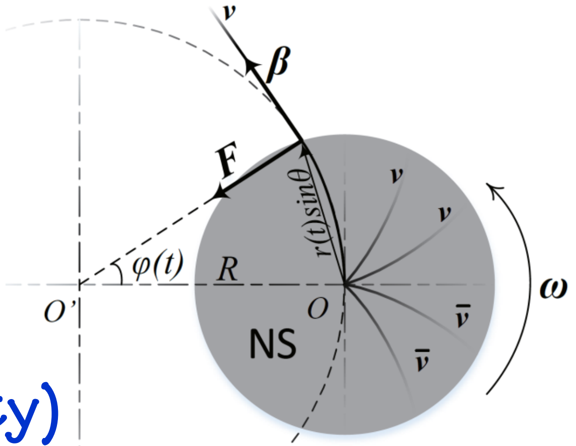
$$\Delta\omega = \omega - \omega_0$$

$$\Omega = \omega_m + \omega_c;$$

$$\omega_m = \frac{2Gn_n}{p_0 + Gn_n}\omega,$$

$$\omega_c = \frac{q_0 B}{p_0 + Gn_n}$$





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

Backup slides

interference of flavor and spin oscillations in B

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

no flavour oscillations

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

spin

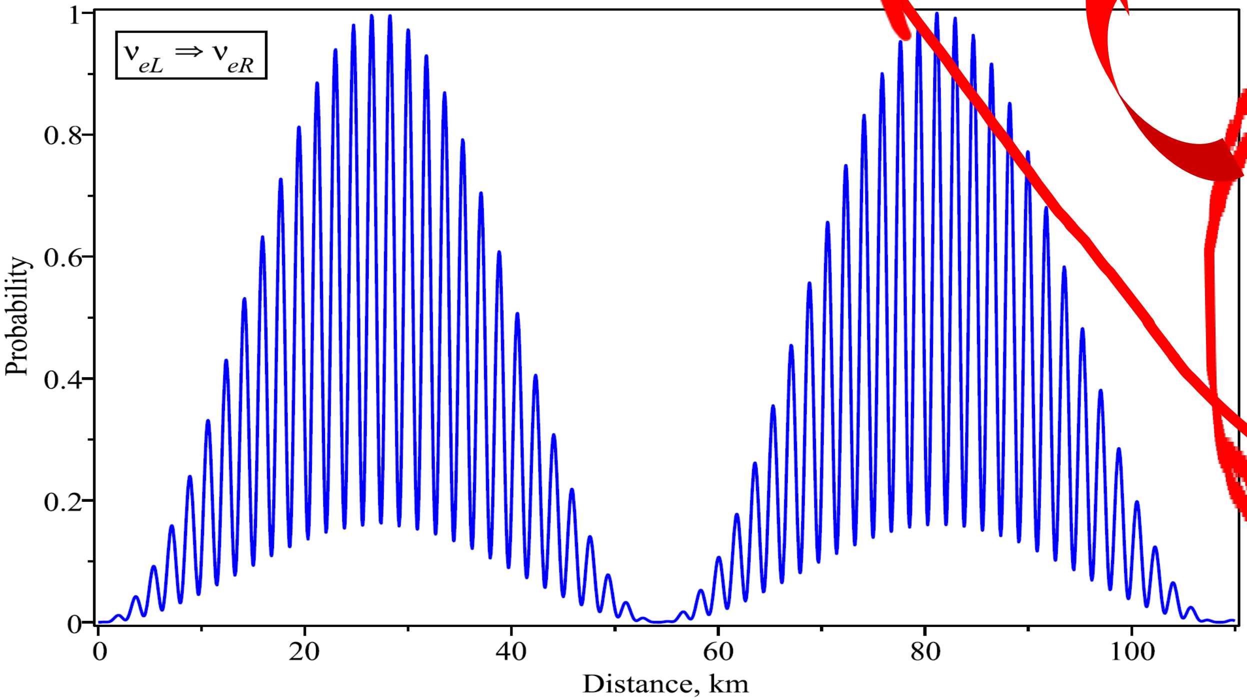


Fig. 2 The probability of the neutrino spin oscillations $\nu_e^L \to \nu_e^R$ in the transversal magnetic field $B_\perp = 10^{16}$ G for the neutrino energy $p = 1\ MeV$, $\Delta m^2 = 7 \times 10^{-5}\ eV^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-20}\mu_B$.

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

A.Popov, A.S., Eur. Phys. J. C 79 (2019) 144

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

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

spin-flavour

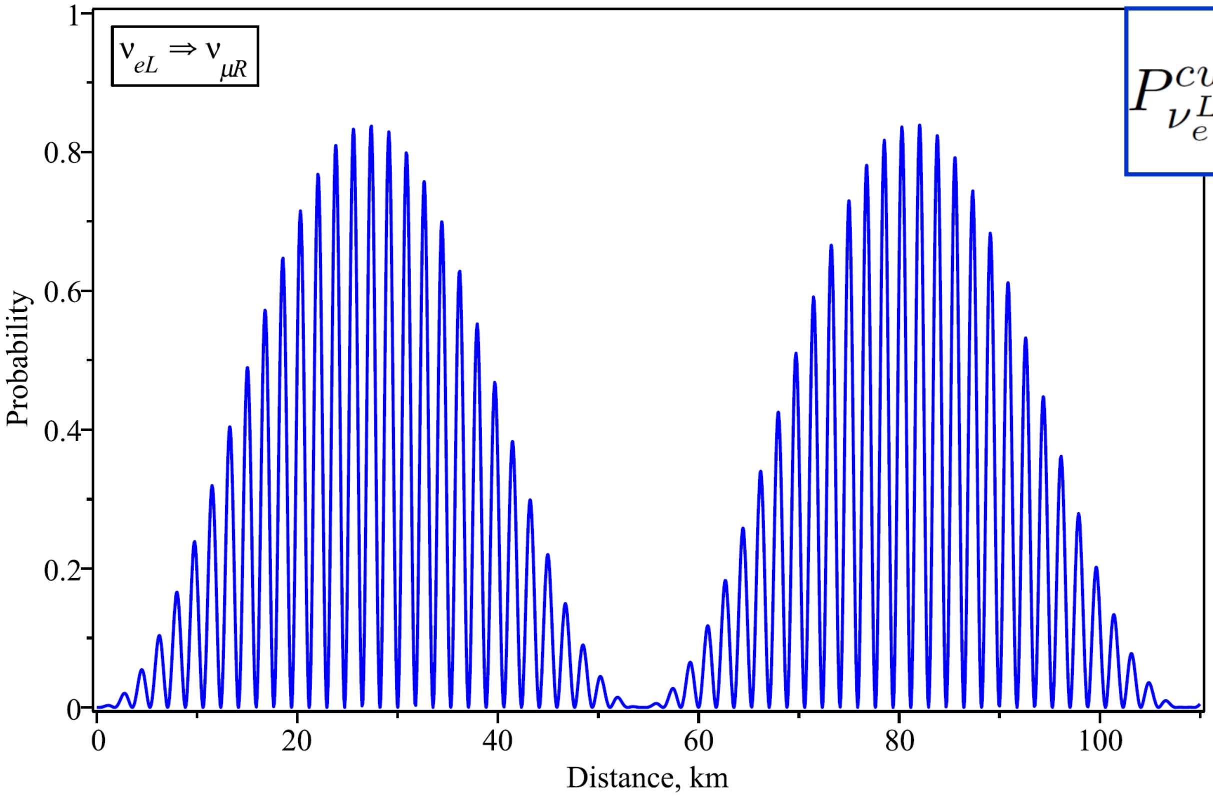


Fig. 3 The probability of the neutrino spin flavour oscillations $\nu_e^L \to \nu_\mu^R$ in the transversal magnetic field $B_\perp = 10^{16}\ G$ for the neutrino energy $p = 1\ MeV$, $\Delta m^2 = 7 \times 10^{-5}\ eV^2$ and magnetic moments $\mu_1 = \mu_2 = 10^{-20}\mu_B$.

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

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

... interplay of oscillations

on vacuum $\boxed{\omega_{vac} = \frac{\Delta m^2}{4p}}$

and

on magnetic $\boxed{\omega_B = \mu B_\perp}$

frequencies

... in literature:

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

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

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

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

… depends on μ_ν and B

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

$\sum$ of all probabilities (as it should be…) :

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

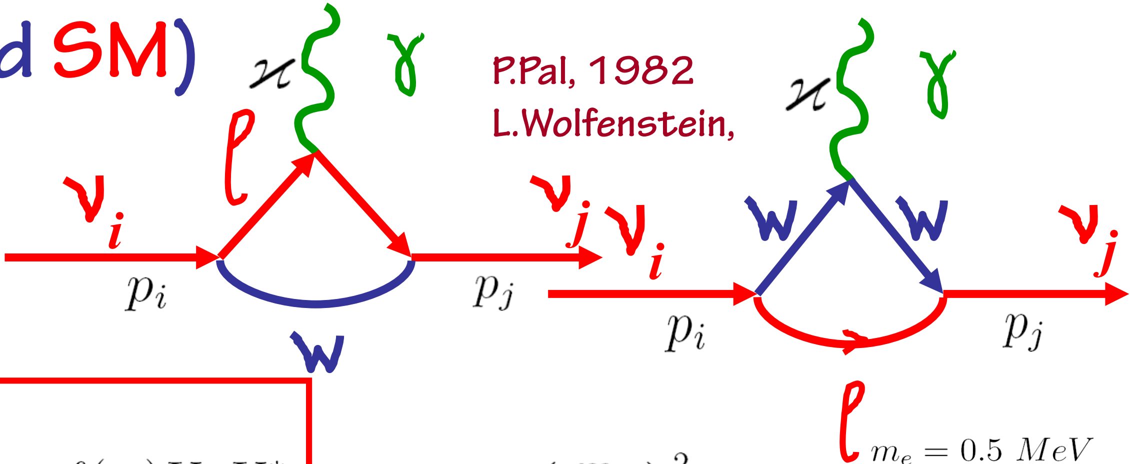
A.Popov, A.S., Eur. Phys .J. C79 (2019) 144

the discovered correspondence between flavour and spin oscillations in B can be important in studies of ν propagation in astrophysical environments

Backup slides

Large magnetic moment μ_ν

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



P.Pal, 1982
L.Wolfenstein,

- Dirac neutrino

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

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

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

- $m_i, m_j \ll m_l, m_W$

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

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

- Majorana neutrino only for

$$\boxed{i \ \cancel{\neq}\ j}$$

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

or

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

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

… depending on relative CP phase of ν_i and ν_j

The first nonzero contribution from neutrino transition moments

$$f_{r_l} \to \cancel{-\frac{3}{2}} + \frac{3}{4}\left(\frac{m_l}{m_W}\right)^2 \ll 1$$

GIM cancellation

$$\left.\begin{array}{c}\mu_{ij}\\ \epsilon_{ij}\end{array}\right\} = \frac{3eG_F m_i}{32\sqrt{2}\pi^2}\left(1 \pm \frac{m_j}{m_i}\right)\left(\frac{m_\tau}{m_W}\right)^2 \sum_{l=\ e,\ \mu,\ \tau}\left(\frac{m_l}{m_\tau}\right)^2 U_{lj}U^*_{li}$$

$$\mu_B = \frac{e}{2m_e}$$

- $$\left.\begin{array}{c}\mu_{ij}\\ \epsilon_{ij}\end{array}\right\} = 4 \times 10^{-23}\mu_B\left(\frac{m_i \pm m_j}{1\ eV}\right) \sum_{l=\ e,\ \mu,\ \tau}\left(\frac{m_l}{m_\tau}\right)^2 U_{lj}U^*_{li}$$

… neutrino radiative decay is very slow

- Dirac ν diagonal (i=j) magnetic moment

$$\epsilon^D_{ii} = 0$$ for CP-invariant interactions

$$\mu^M_{ii} = \epsilon^M_{ii} = 0$$

$$\mu_{ii} = \frac{3eG_F m_i}{8\sqrt{2}\pi^2}\left(1 - \frac{1}{2}\sum_{l=\ e,\mu,\tau} r_l \mid U_{li}\mid^2\right) \approx 3.2 \times 10^{-19}\left(\frac{m_i}{1\ eV}\right)\mu_B$$

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

Lee, Shrock, Fujikawa, 1977

- no GIM cancellation
- μ^D_{ii} - to leading order - independent on U_{li} and $m_{\ l=e,\ \mu,\ \tau}$
- $$\mu^2_e = \sum_{i=1,2,3} \mid U_{ie}\mid^2 \mu^2_{ii}$$ …possibility to measure fundamental μ^D_{ii}

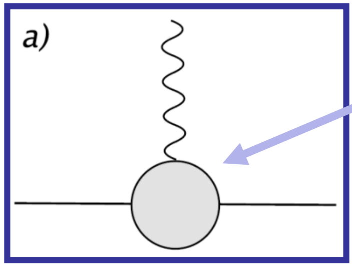
$\mu^D_{ii} = 0$ for massless ν (in the absence of right-handed charged currents)

3.3 Naïve relationship between m_ν and μ_ν

… problem to get large μ_ν and still acceptable m_ν

If μ_ν is generated by physics beyond the SM at energy scale Λ,

P. Vogel e.a., 2006

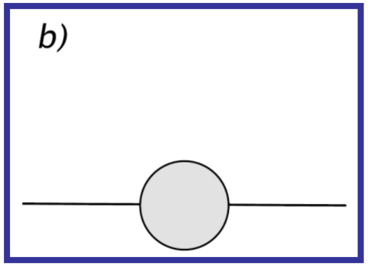


then

$$\boxed{\mu_\nu \sim \frac{eG}{\Lambda},}$$

…combination of constants and loop factors…

contribution to m_ν given by



, then

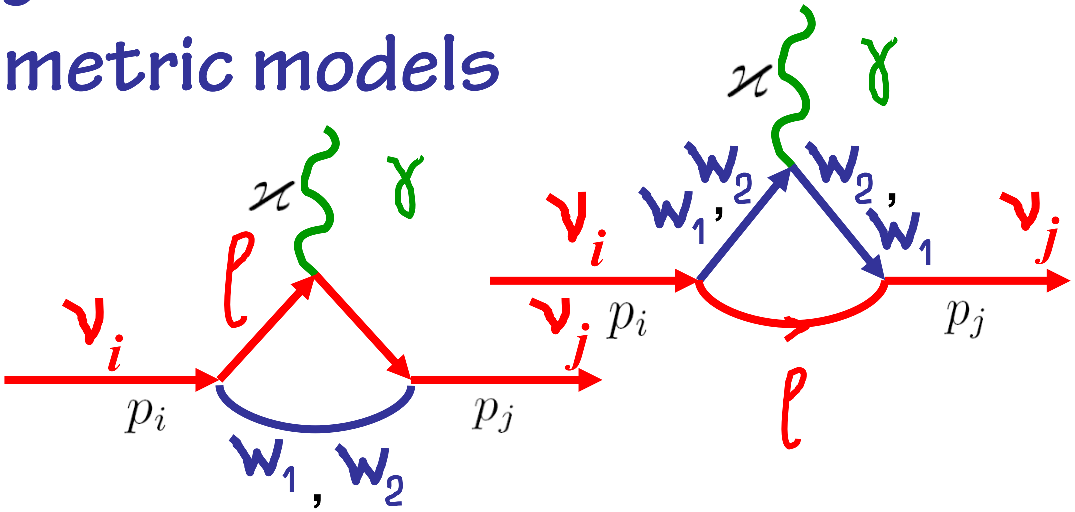
$$\boxed{m_\nu \sim G\Lambda}$$

$$m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B} \sim \frac{\mu_\nu}{10^{-18}\mu_B}[\Lambda(\mathrm{TeV})]^2 \quad \mathrm{eV}$$

Voloshin, 1988;
Barr, Freire,
Zee, 1990

3.6 Neutrino magnetic moment in left-right symmetric models

$SU_L(2) \times SU_R(2) \times U(1)$



Gauge bosons mass states $W_1 = W_L \cos\xi - W_R \sin\xi$
$W_2 = W_L \sin\xi + W_R \cos\xi$

with mixing angle ξ of gauge bosons $W_{L,R}$ with pure $(V \pm A)$ couplings

Kim, 1976; Marciano, Sanda, 1977;
Beg, Marciano, Ruderman, 1978

$$\boxed{\mu_{\nu_l} = \frac{eG_F}{2\sqrt{2}\pi^2}\left[\underline{m_l}\left(1 - \frac{m^2_{W_1}}{m^2_{W_2}}\right)\sin 2\xi + \frac{3}{4}\underline{m_{\nu_l}}\left(1 + \frac{m^2_{W_1}}{m^2_{W_2}}\right)\right]}$$

… charged lepton mass … … neutrino mass …

Large magnetic moment

$\mu_\nu = \mu_\nu(m_\nu, m_{B^+}, m_{e^-})$

- In the L-R symmetric models $(SU(2)_L \times SU(2)_R \times U(1))$

Kim, 1976
Beg, Marciano, Ruderman, 1978

- **Voloshin, 1988**
  "On compatibility of small m_ν with large μ_ν neutrino",
  Sov.J.Nucl.Phys. 48 (1988) 512
  … there may be $SU(2)_\nu$ symmetry that forbids m_ν but not μ_ν

Z.Z.Xing, Y.L.Zhou,
"Enhanced electromagnetic transition dipole moments and radiative decays of massive neutrinos due to the seesaw-induced non-unitary effects"
Phys.Lett.B 715 (2012) 178

- Bar, Freire, Zee, 1990
- supersymmetry
- extra dimensions
- model-independent constraint μ_ν

considerable enhancement of μ_ν to experimentally relevant range

$\boxed{\mu_\nu^D \leq 10^{-15}\mu_B}$

$\boxed{\mu_\nu^M \leq 10^{-14}\mu_B}$

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

Bell, Cirigliano, Ramsey-Musolf, Vogel, Wise, 2005

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Large neutrino magnetic moments in the light of recent experiments

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Abstract: The excess in electron recoil events reported recently by the XENON1T experiment may be interpreted as evidence for a sizable transition magnetic moment $\mu_{\nu_e\nu_\mu}$ of Majorana neutrinos. We show the consistency of this scenario when a single component transition magnetic moment takes values $\mu_{\nu_e\nu_\mu} \in (1.65\text{–}3.42) \times 10^{-11}\mu_B$. Such a large value typically leads to unacceptably large neutrino masses. In this paper we show that new leptonic symmetries can solve this problem and demonstrate this with several examples. We first revive and then propose a simplified model based on $\mathrm{SU}(2)_H$ horizontal symmetry. Owing to the difference in their Lorentz structures, in the $\mathrm{SU}(2)_H$ symmetric limit, m_ν vanishes while $\mu_{\nu_e\nu_\mu}$ is nonzero. Our simplified model is based on an approximate $\mathrm{SU}(2)_H$, which we also generalize to a three family $\mathrm{SU}(3)_H$-symmetry. Collider and low energy tests of these models are analyzed. We have also analyzed implications of the XENON1T data for the Zee model and its extensions which naturally generate a large $\mu_{\nu_e\nu_\mu}$ with suppressed m_ν via a spin symmetry mechanism, but found that the induced $\mu_{\nu_e\nu_\mu}$ is not large enough to explain recent data. Finally, we suggest a mechanism to evade stringent astrophysical limits on neutrino magnetic moments arising from stellar evolution by inducing a medium-dependent mass for the neutrino.

Keywords: Beyond Standard Model, Neutrino Physics

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… one of recent studies …

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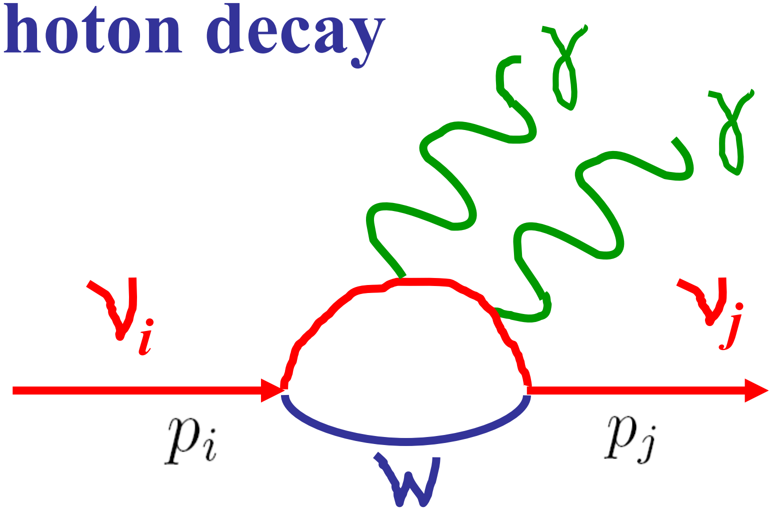
3.8

Neutrino radiative two-photon decay

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

$$m_i > m_j$$



fine structure constant

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

$$\boxed{f(r_l) \approx \frac{3}{2}\left(\cancel{1} - \frac{1}{2}\left(\frac{m_l}{m_W}\right)^2\right) \to (m_i/m_l)^2}$$

Nieves, 1983; Ghosh, 1984

… there is no GIM cancellation…

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

Astrophysics bounds on μ_ν

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

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

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

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

Bounds depend on

- modeling of astrophysical system,
- on assumption on he neutrino properties .

Generic assumption:

- absence of other nonstandard interactions accept for μ_ν

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

ν spin evolution in presence of general external fields

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

General types non-derivative interaction with external fields

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

scalar, pseudoscalar, vector, axial-vector, tensor and pseudotensor fields: $s, \pi, V^\mu = (V^0, \vec{V}), A^\mu = (A^0, \vec{A}),$ $T_{\mu\nu} = (\vec{a}, \vec{b}), \Pi_{\mu\nu} = (\vec{c}, \vec{d})$

Relativistic equation (quasiclassical) for ν spin vector:

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

- Neither S nor π nor V contributes to spin evolution

- **Electromagnetic interaction**

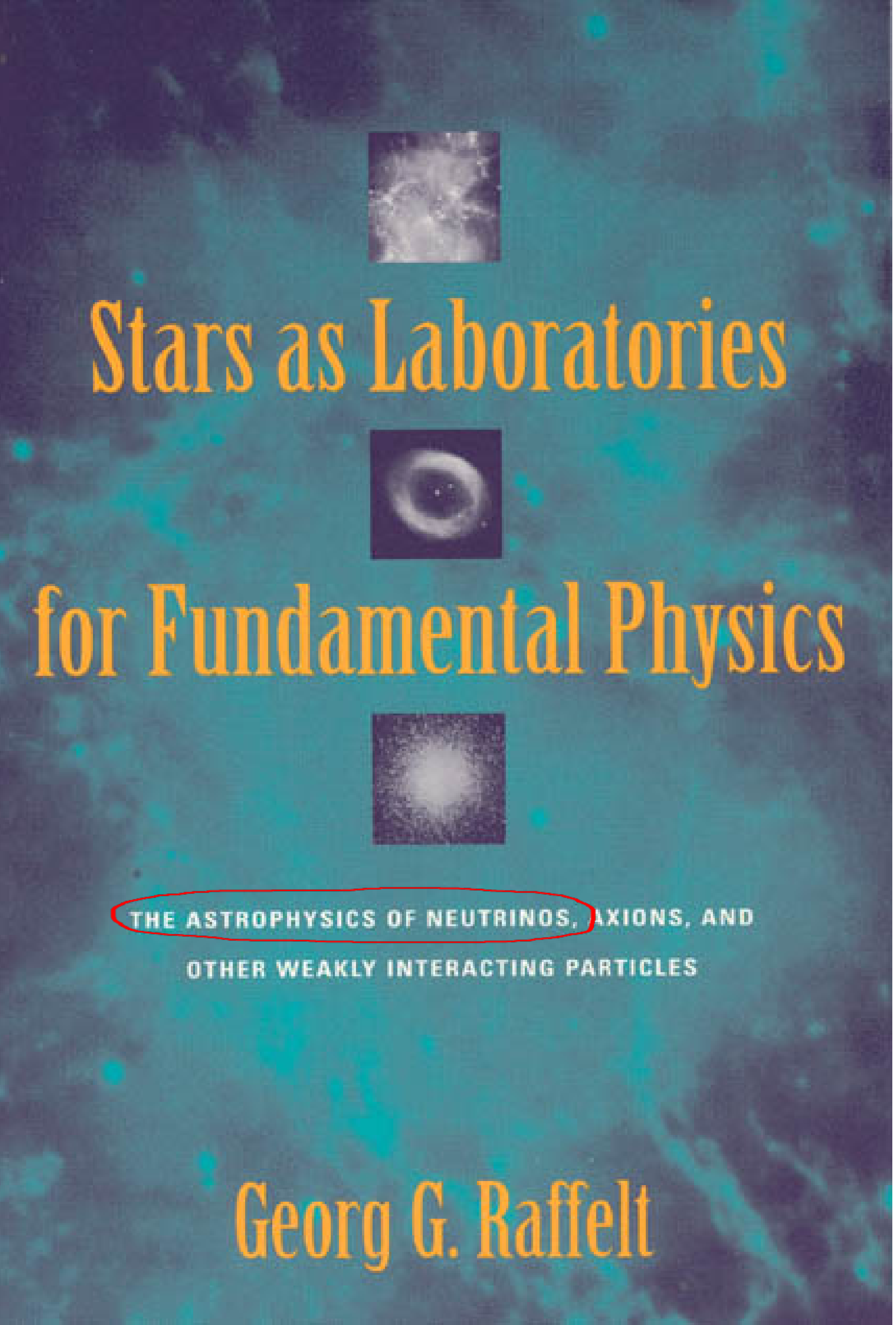
  $T_{\mu\nu} = F_{\mu\nu} = (\vec{E}, \vec{B})$

- **SM weak interaction**

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

  $\vec{M} = \gamma(A^0\vec{\beta} - \vec{A})$

  $\vec{P} = -\gamma[\vec{\beta} \times \vec{A}],$



Stars as Laboratories for Fundamental Physics

THE ASTROPHYSICS OF NEUTRINOS, AXIONS, AND OTHER WEAKLY INTERACTING PARTICLES

Georg G. Raffelt

•CONTENTS

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