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Neutrino oscillations in the presence of the crust magnetization

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ABSTRACT

It is noted that the crustal magnetic spectrum exhibits the signal from the partly correlated domain dipoles on the space-scale up to approximately 500 km. This suggests the nonzero correlation among the dynamical variables of the ferromagnetic magnetization phenomenon on the small domain scale inside the earth's crust also. Therefore the influence of the mean of the zero component of the polarization on the CP matter-induced violation indexes is discussed.

1. Introduction: magnetization of the lithosphere

The nonzero magnetization of the geological structures of the crust of the earth was reported some time ago in the geophysical publications [1,2]. Hence the neutrino oscillation phenomenon in the presence of the magnetization of the earth's lithosphere is presented. The geomagnetic analysis [3,4] says that, due to the magnetized crust which possesses the induced and remanent magnetization of the ferromagnetic origin, the spacial magnetic field power spectrum differs from the core exponential form. But the main inference from the statistical analysis is that the dominant part of the crustal magnetic spectrum has the intermediate form, which is expected from the partly correlated domain dipoles on the intermediate space-scale (up to approximately 500 km) of the coherently magnetized geological structures [4]. It is the signal of the (anti) parallel correlations of the spins of the ferromagnetic (mainly iron's) domains on the far longer scale than the exchange energy is able to explain, which in turn suggests the initial condition for the analysis i.e. that they were formed as such.

2. The effective νSM Hamiltonian and νSM transition rate

The low-energy effective Standard Model (νSM) potential Hamiltonian for the Dirac neutrino (D) charged current interaction with the electrons of the medium has the following form:

$$(\mathcal{H}^{0D}_{--})_{ij} = \sqrt{2} G_F N_e (A^e_{LL})_{ij} \left(\left\langle \frac{\pi^\mu_e}{E_e} \right\rangle - \left\langle \frac{m_e s^\mu_e}{E_e} \right\rangle \right) n_\mu \quad (1)$$

where the first and second term originate in the vector (V) and axial-vector (AV) currents, respectively [5,6]. Indexes $i, j = 1,2,3$ are for three massive neutrinos ν_i and index e stands for the background electrons. The quantities N_e, E_e and m_e are the electron density, energy and mass, respectively. The space component $\vec{n}$ of the four-vector $n^\mu = (1, \vec{n})$ points to the direction of the neutrino momentum. $(A^e_{LL})_{ij} = |\varepsilon^C_L|^2 U^{L*}_{ei} U^L_{ej}$ is the νSM coupling [7], where U^L is the unitary neutrino mixing matrix in the charged (C) current interaction, and the $V-AV$ factor ε^C_L is the global νSM coupling constant.

The mechanical four-momentum $\pi^\mu_e \equiv (\pi^0_e, \vec{\pi}_e)$ is defined as $\pi^\mu_e = p^\mu_e - eA^\mu$, where A^μ is the electromagnetic four-potential acting on the background electron. The electron polarization four-vector s^μ_e is equal to

$$s^\mu_e = \left[\frac{\vec{\pi}_e \cdot \vec{\lambda}_e}{m_e}, \; \vec{\lambda}_e + \frac{\vec{\pi}_e (\vec{\pi}_e \cdot \vec{\lambda}_e)}{m_e (m_e + E_e)} \right] \equiv (s^0_e, \vec{s}_e) \quad (2)$$

where $\vec{\lambda}_e = \chi^\dagger_e \vec{\sigma} \chi_e$ ($\chi^\dagger_e \chi_e = 1$) is the electron's polarization and χ_e is its two component spinor. The quantities $\langle \pi^\mu_e / E_e \rangle$ and $\langle m_e s^\mu_e / E_e \rangle$ are the thermodynamical means. Finally, the νSM meets both the relation $(\mathcal{H}^{0\overline{D}}_{++})_{ij} = 0$ and $(\mathcal{H}^{0\overline{D}}_{++})_{ik} = -(\mathcal{H}^{0D}_{--})^*_{ik}$ in the case of the Dirac antineutrino ($\overline{D}$).

2.1. The thermodynamical means

With the isotropy assumption of the electron momentum [7], $\langle \vec{\pi}_e \rangle \approx 0$, we obtain $\langle \pi^\mu_e / E_e \rangle \equiv (\langle \pi^0_e / E_e \rangle, \langle \vec{\pi}_e / E_e \rangle) \approx (1, \vec{0})$ for the V term in Eq. (1). From Eq. (2) wee see that for the AV term in Eq. (1) the crust unpolarized matter condition $\langle \vec{s}_e \rangle \approx 0$ leads to $\langle m_e s^\mu_e / E_e \rangle \approx (\langle \vec{\pi}_e \cdot \vec{\lambda}_e / E_e \rangle, \vec{0})$.

As besides the initial condition mentioned in Section 1, the crust impact on the correlations seen in the magnetic power spectrum around the globe has mainly the ferromagnetic origin [1] hence for the temperatures in the crust [8] the magnetic moments inside each of the ferromagnetic domains are overwhelmingly parallel arranged [9]. Due to the potential A^μ inside one domain there appears the nonzero mean correlation between polarization $\vec{\lambda}_e$ and mechanical momentum $\vec{\pi}_e$ inside each of the ferromagnetic domains, having the same sign for every one of

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them. It results in the nonzero mean value of the zero polarization component $\langle s_e^0 \rangle \neq 0$ along the whole experimental baseline L (which stands in the fundamental opposition to the earth's crust mean space component behavior $\langle \vec{s}_e \rangle \approx \vec{0}$). The full solid-state analysis should follow. To test the impact of the described phenomenon on the neutrino oscillation in the crust the natural baselines of $L \leq 874$ km for the current experiments could be used. But the specially builded plants with the short but totaly ferromagnetic baselines are thinkable also.

2.2. The $\aleph_e$ magnetization form of the potential Hamiltonians and transition rate formula

The above considerations lead to the Dirac neutrino and antineutrino νSM Hamiltonians:

$$(\mathcal{H}^{0D}_{--})_{ij} = \sqrt{2} G_F N_e (A^e_{LL})_{ij} (1 - \aleph_e)$$

$$(\mathcal{H}^{0\overline{D}}_{++})_{ij} = -(\mathcal{H}^{0D}_{--})^*_{ij} \tag{3}$$

where

$$\aleph_e \equiv \left\langle \frac{\vec{\pi}_e \cdot \vec{\lambda}_e}{E_e} \right\rangle. \tag{4}$$

Here $\aleph_e$ is the only nonzero term connected with the magnetization of the background electrons. The νSM effective Hamiltonians $\mathcal{H}$ for the neutrino or antineutrino are, in the helicity—mass base $|\lambda, i\rangle$, $\lambda = \pm\frac{1}{2}$, $i = 1,2,3$, the 3×3 dimensional matrices:

$$\mathcal{H}^D = \mathcal{M} + \mathcal{H}^{0D}_{--}, \quad \mathcal{H}^{\overline{D}} = \mathcal{M} + \mathcal{H}^{0\overline{D}}_{++}$$

$$\mathcal{M} = diag(E^0_1, E^0_2, E^0_3). \tag{5}$$

$\mathcal{M}$ is the vacuum mass term, $E^0_i = E_\nu + m_i^2/2E_\nu$, and E_ν is the energy for the massless neutrino [7]. In the νSM and for the homogenous medium and (in practise) relativistic neutrinos, the α to β flavor oscillation probability $P_{\alpha\to\beta}(L)$ factors out in the differential transition rate formula [6]:

$$\frac{d\sigma_{\beta\alpha}}{d\Omega_\beta} = f_D A^L_{\varepsilon\varepsilon} \sum_{i;i'} U^L_{\beta i} U^{L*}_{\beta i'} U^{L*}_{\alpha i} U^L_{\alpha i'} e^{i\Delta m^{eff2}_{ii'} L/(2E_\nu)}$$

$$\equiv \frac{d\sigma_\beta}{d\Omega_\beta}(m_i = 0) \times P_{\alpha\to\beta}(L) \tag{6}$$

where f_D is the kinematical factor, $A^L_{\varepsilon\varepsilon}$ is the function of the energies and momenta of the particles in the detection process, and $\Delta m^{eff2}_{ii'}$ is the neutrinos effective square mass difference in the medium calculated with Eqs. (3)–(5).

3. The numerical results. Advancing steps in the analysis

The variety of neutrino oscillation observables could be used for the purpose of the vacuum oscillation parameters estimation. As the experiments are performed on the earth hence the dependance of these observables on the crust magnetization has to be well understood. The simplest one is the oscillation probability $P_{\alpha\to\beta}(L)$ plotted on Fig. 1 up to the limit baseline L=874 km (taken as the approximate maximum value of the neutrino path in the earth's crust). Then the transition rate given by Eq. (6) for the number of events in the detector follows. Yet, in the full oscillation data analyzes the number of the events is useful for the preliminary analyzes only. What matters is the functional dependance of the observable on the probability oscillation in the particular phenomena also. The steps from the observable unsensitive to the $\aleph_e$ magnetization to the sensitive

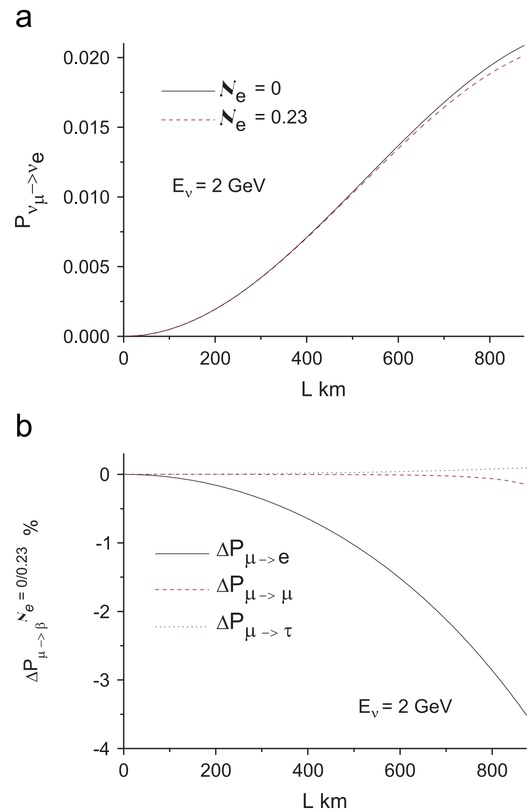

Fig. 1. Panel: (a) The (noticeable) change of $P_{\nu_\mu\to\nu_e}$ with $\aleph_e$. (b) The relative change of $\Delta P^{0/\aleph_e}_{\mu\to\beta} \equiv 100\%(P^{\aleph_e}_{\mu\to\beta} - P^0_{\mu\to\beta})/P^0_{\mu\to\beta}$, $(\beta = e, \mu, \tau)$, with $\aleph_e$ is even more visible. The curves for $\aleph_e = 0$ vs. $\aleph_e = 0.23$ are plotted. The neutrino energy is taken to be $E_\nu = 2$ GeV.

ones are as follows:

1. The observable unsensitive to the $\aleph_e$ magnetization of the earth's crust is $R_{\mu/e}$, the ratio-of-ratios for the muon vs. electron atmospheric neutrinos [7]. Its weak dependance on $\aleph_e$ is connected with the general fact that the linear dependance of the transition rates on $\mathcal{H}^{0D}_{--}$ and $\mathcal{H}^{0\overline{D}}_{++}$ cancels out (due to opposite signs for D and $\overline{D}$ in Eq. (3)). Hence $R_{\mu/e}$ would be perfect for the vacuum parameters estimation. Unfortunately the experimental errors for $R_{\mu/e}$ are bigger than 3%.
2. The observables dependent on the $\aleph_e$ magnetization:
   (a) The up–down asymmetry $A^{up-down}_\alpha$ in the atmospheric neutrinos experiments [7] seems to be unprofitable for the decision about the solitary earth's crust $\aleph_e$ dependance. Therefore the following paper is going to be devoted to the all-directions analyzes on $\aleph_e$ dependance in the 'through-earth' up–down asymmetry.
   (b) The CP matter-induced violation $A^{CP}_{\alpha\to\beta}$ is sensitive to $\aleph_e$ (see Section 3.1).
   (c) The $\aleph_e$-CP matter-induced asymmetry defined below is the observable (very) sensitive to the $\aleph_e$ magnetization. The accelerator neutrino could be taken into account also.

3.1. The observable sensitive to magnetization: The CP matter-induced violation

Even when the fundamental Lagrangian is CP symmetric (the mixing matrix U^L phase $\delta = 0$), we could observe the matter-induced violation of the CP symmetry expressed in the (non-vanishing)