Scattering of neutrinos on a polarized electron target as a test for new physics beyond the Standard Model

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In this paper, we analyze the scattering of the neutrino beam on the polarized electron target, and predict the effects of two theoretically possible scenarios beyond the Standard Model. In both scenarios, Dirac neutrinos are assumed to be massive.

First, we consider how the existence of CP violation phase between the complex vector $V$ and axial $A$ couplings of the Left-handed neutrinos affects the azimuthal dependence of the differential cross section. This asymmetry does not vanish in the massless neutrino limit. The azimuthal angle $\phi_{e'}$ of outgoing electron momentum is measured with respect to the transverse component of the initial electron polarization $\eta_{e'}^T$. We indicate the possibility of using the polarized electron target to measure the CP violation in the $\nu_e e^-$ scattering. The future superbeam and neutrino factory experiments will provide the unique opportunity for the leptonic CP violation studies, if the large magnetized sampling calorimeters with good event reconstruction capabilities are build.

Next, we take into account a scenario with the participation of the exotic scalar $S$ coupling of the Right-handed neutrinos in addition to the standard vector $V$ and axial $A$ couplings of the Left-handed neutrinos. The main goal is to show how the presence of the R-handed neutrinos, in the above process changes the spectrum of recoil electrons in relation to the expected Standard Model prediction, using the current limits on the non-standard couplings. The interference terms between the standard and exotic couplings in the differential cross section depend on the angle $\alpha$ between the transverse incoming neutrino polarization and the transverse electron polarization of the target, and do not vanish in the limit of massless neutrino. The detection of the dependence on this angle in the energy spectrum of recoil electrons would be a signature of the presence of the R-handed neutrinos in the neutrino-electron scattering. To make this test feasible, the polarized artificial neutrino source needs to be identified.

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I. INTRODUCTION

Standard Model (SM) of electro-weak interactions has a vector-axial (V-A) Lorentz structure, i.e. only left-handed (L-handed chirality states) and massless Dirac neutrinos may take part in the charged and neutral weak interactions. The observed CP violation in the decays of neutral kaons and B-mesons is described by a single phase of the CKM matrix.

The vector $g_L^T$ and axial-vector $g_L^A$ neutral current coupling constants are assumed to be real numbers, which means that $Im(g_L^T) = Im(g_L^A) = 0$. The values of these two couplings are derived from neutrino electron scattering and from $e^+e^- \rightarrow l^+l^-$ annihilation studies, but in the fitting procedure the imaginary parts are fixed to their Standard Model values.

However, in the general case of complex $g_L^T$ and $g_L^A$ couplings, we have one additional free parameter: the relative phase between these couplings denoted as $\beta_{V,A}$. The CP-odd interference contribution enters the differential cross section for the scattering of left-handed neutrinos on the polarized electron target (PET), if $|\sin(\beta_{V,A})| \neq 0$. The experimental measurement of the azimuthal angle $\phi_{e'}$ of outgoing electron momentum could be used to test the CP symmetry in lepton sector of electroweak interactions. The observation of asymmetry in the angular distribution of recoil electrons, caused by the interference terms between the standard complex couplings would give additional information about the coupling constants.

The magnetized sampling calorimeters (e.g. MINOS far detector) are composed of many steel layers, which are magnetized using a coil through a hole in the center of the planes to an average field of about 1.5 T. In a piece of magnetized iron, there are lots of unpaired electrons all pointing the same direction. The Moeller polarimeters determine the polarization of the electron beam by measuring the cross section asymmetry in the scattering
TABLE I: Current limits on the non-standard couplings

| Coupling constants | SM | Current limits |
|--------------------|----|----------------|
| $|g_{LL}^L|$       | 1  | > 0.960        |
| $|g_{RR}^L|$       | 0  | < 0.060        |
| $|g_{RL}^L|$       | 0  | < 0.110        |
| $|g_{LR}^L|$       | 0  | < 0.039        |
| $|g_{LL}^S|$       | 0  | < 0.550        |
| $|g_{RR}^S|$       | 0  | < 0.125        |
| $|g_{RL}^S|$       | 0  | < 0.424        |
| $|g_{LR}^S|$       | 0  | < 0.066        |
| $|g_{LL}^T|$       | 0  | 0              |
| $|g_{RR}^T|$       | 0  | < 0.036        |
| $|g_{RL}^T|$       | 0  | < 0.122        |
| $|g_{LR}^T|$       | 0  | 0              |

of polarized electrons by polarized electrons. Polarized electrons are scattered off a polarized ferromagnetic foil, and the foil polarization is determined by measurements of the magnetization of the foil and its thickness. So, there is the well-known and commonly used in accelerator physics technique for developing PETs.

Although the SM agrees well with all experimental data up to available energies, the experimental precision of present measurements still does not rule out the possible participation of the exotic scalar $S$, tensor $T$ and pseudoscalar $P$ couplings of the right-handed (R-handed chirality states) Dirac neutrinos beyond the SM. The current upper limits on the all non-standard couplings, obtained from the normal and inverse muon decay, are presented in the Table II. In the SM, only $g_{LL}^V$ is non-zero value.

New effects due to the exotic right-handed weak interactions (ERWI) could be detected by the measurement of neutrino observables (NO) which consist only of the interferences between the standard $V-A$ and ERWI, and do not depend on the neutrino mass. The NO include the information on the transverse components of neutrino spin polarization (TCNSP), both T-even and T-odd. These quantities vanish in the SM, so the detection of the non-zero values of the TCNSP would be a direct signature of the R-handed neutrino presence in the weak interactions. The scattering of intense and polarized neutrino beam, coming from the artificial neutrino source, on the polarized electron target could detect the effects from the ERWI. Presently the measurement of such observables is only theoretically possible. We give an example how the polarized neutrino flux can be produced if the exotic scalar coupling $C_{S}^{L}$ is present in the theory of muon capture interaction.

The main goal of the first part of our paper (Section II) is to show that the differential cross section for the $(\nu_{\mu}e^{-})$ scattering of left-handed and longitudinally polarized muon neutrinos on the PET may be sensitive to the CP-violating effects, if one assumes the complex standard couplings $g_{V}^{L}$, $g_{A}^{L}$. The main goal of the other part (Section III) is to show how the presence of the R-handed neutrinos, in the $(\nu_{\mu}e^{-})$ scattering process, changes the energy spectrum of recoil electrons in relation to the expected SM prediction, using the current limits on the non-standard couplings. We concern the scattering of transversely polarized muon neutrino beam on the PET to probe ERWI effects and include a theoretical discussion of the possibility of developing such a beam.

Our analysis is model-independent and is made in the massless neutrino limit. All the calculations are made in the limit of vanishing neutrino mass with the Michel-Wightman density matrices for the polarized incoming neutrino beam (Appendix C) and for the polarized electron target, respectively. We use the system of natural units with $\hbar = c = 1$, Dirac-Pauli representation of the $\gamma$-matrices and the $(+,−,−,−)$ metric.

II. LEFT HANDED NEUTRINO SCATTERING ON A POLARIZED ELECTRON TARGET

The Standard Model (SM) of electroweak interactions is based on the gauge group SU(2) × U(1). The left-handed fermion fields $\psi_i = (\nu_i \ell_i)$ and $(u_i d_i)$ of the $i$th fermion family transform as doublets under SU(2), where $d_i \equiv \sum_j V_{ij} d_j$ and $V$ is the Cabibbo-Kobayashi-Maskawa mixing matrix. The vector and axial-vector couplings in SM are

$$
\begin{align*}
\mathcal{L}_{V} & \equiv t_{L}^{2}(i) - 2q(i) \sin^{2} \theta_{W} \\
\mathcal{L}_{A} & \equiv t_{A}^{2}(i),
\end{align*}
$$

where $t_{L}^{2}(i)$ is the weak isospin of fermion $i$ (+1/2 for $u_i$ and $\nu_i$; −1/2 for $d_i$ and $\ell_i$), $q_i$ is the charge of $\psi_i$ in units of $e$ and $\theta_{W}$ is the weak angle. Because of the model-dependent interpretation of the coupling constants values, they are assumed to be real numbers. For example, the total cross section for high energy neutral-current $(\nu_{\mu}e^{-})$ scattering is

$$
\sigma_{SM}(\nu_{\mu}e^{-} \rightarrow \nu_{\mu}e^{-}) \propto \frac{2G_{F}^{2}m_{e}E_{\nu}(g_{V}^{L^{2}} + g_{A}^{L^{2}} + g_{V}^{L}g_{A}^{L} \cos(\beta_{VA}))}{3\pi},
$$

but in the model-independent (MI) analysis we obtain:

$$
\sigma_{MI}(\nu_{\mu}e^{-} \rightarrow \nu_{\mu}e^{-}) \propto \frac{2G_{F}^{2}m_{e}E_{\nu}}{3\pi}(|g_{V}^{L}|^{2} + |g_{A}^{L}|^{2} + |g_{V}^{L}||g_{A}^{L}| \cos(\beta_{VA})),
$$

where $g_{V}^{L} = |g_{V}^{L}|e^{i\beta_{V}}$, $g_{A}^{L} = |g_{A}^{L}|e^{i\beta_{A}}$ are the complex coupling constants, $\text{Re}(g_{V}g_{A}^{*}) = |g_{V}^{L}||g_{A}^{L}| \cos(\beta_{VA})$ and $\beta_{VA} = \beta_{V} - \beta_{A}$ is the relative phase between the $g_{V}^{L}$ and $g_{A}^{L}$ couplings.
The effective vector and axial-vector neutral coupling constants obtained from the absolute neutrino-electron scattering event rate are

\[ g_V^L \simeq 0 \quad , \quad g_A^L \simeq 0.5 \quad \text{or} \quad g_V^L \simeq 0.5 \quad , \quad g_A^L \simeq 0 \ . \]

However, from our MI expression \(^{(3)}\) one can see that the solution (with CP-violating phase):

\[ |g_V^L| = |g_A^L| \simeq 0.35 \quad \text{and} \quad \beta_{VA} = \pm \frac{\pi}{2} \]

provides to the same total cross section value as the SM fit \(^{(4)}\). In the next subsection we present how the existence of non zero \(\beta_{VA}\) phase is related to CP-odd interference contribution in the differential cross section. The fermion-antifermion pair production cross-sections have only T-even contributions, but their experimental observations are essential to determine a single solution from possible parameters \(^{(1)}\). Even if \(\beta_{VA} = 0\) the scattering of left-handed neutrinos on the PET provides a new approach to decide which of the two coupling types, (mainly) pure \(g_A^L\) or pure \(g_V^L\) coupling, is realized in nature. This approach is model independent in contrast to \(e^+e^-\) experiments which make the assumption that the neutral current is dominated by the exchange of a single \(Z^0\).

As is well-known, CP violation has been observed only in the decays of neutral kaons and B-mesons. The Standard Model describes the existing data by a single phase of the CKM matrix, \(^{(11)}\). However, the baryon asymmetry of the Universe can not be explained by the CKM phase only, and at least one new source of CP violation is required \(^{(12)}\). The first direct confirmation of a time reversal violation has been published by CPLEAR Collaboration in 1998 \(^{(12)}\). Many non-standard models take into account new CP-violating phases, and can be probed in observables where the SM CP-violation is suppressed, while alternative sources can generate a sizable effect, e.g. the electric dipole moment of the neutron, the transverse lepton polarization in three-body decays of charged kaons \(K^+\) \(^{(13, 14)}\), transverse polarization of the electrons emitted in the decay of polarized \(^8\)Li nuclei \(^{(15)}\). There is no direct evidence of CP violation in the leptonic processes, i.e. a neutrino-electron scattering. However, the future superbeam and neutrino factory experiments \(^{(16)}\) will be able to measure the CP violating effects in the lepton sector, where both neutrino and antineutrino oscillation will be observed. We indicate that the scattering of neutrinos on the PET has similar scientific possibilities.

### A. CP violation in standard \(\nu e\) scattering

In this subsection, we consider the possibility of the CP violation in the \(\nu_e e^-\) scattering, when the incoming muon neutrino beam consists only of the L-handed and longitudinally polarized neutrinos. We assume that these neutrinos are detected in the standard \(V - A\) NC weak interactions with the PET and both the recoil electron scattering angle \(\theta_e\) and the azimuthal angle of outgoing electron momentum \(\phi_e\) shown in Fig. \(^{(1)}\) are measured with a good angular resolution. Because we allow for the non-conservation of the combined symmetry CP, the amplitude includes the complex coupling constants denoted as \(g_V^L, g_A^L\) respectively to the initial neutrino of L-chirality:

\[
M_{\nu_e e} = \frac{G_F}{\sqrt{2}} \left\{ g_V^L (\bar{\nu}_e \gamma^\alpha u_e) (\bar{\nu}_\mu \gamma_\alpha (1 - \gamma_5) u_{\nu_\mu}) + g_A^L (\bar{\nu}_e \gamma^5 \gamma^\alpha u_e) (\bar{\nu}_\mu \gamma_\alpha \gamma_5 (1 - \gamma_5) u_{\nu_\mu}) \right\},
\]

where \(u_e\) and \(\bar{\nu}_e\) (\(u_{\nu_\mu}\) and \(\bar{\nu}_{\nu_\mu}\)) are the Dirac bispinors of the initial and final electron (neutrino) respectively. \(G_F = 1.16639(1) \times 10^{-5} \text{GeV}^{-2}\) \(^{(5)}\) is the Fermi constant.

The formula for the differential cross section including the CP-odd contribution \((\bar{q} \cdot (\hat{n}_e \times \hat{p}_{e'}))\) is T-odd

\[
\left( \frac{d^2\sigma}{dy d\phi_e} \right)_{(VA)} = \frac{E_\nu m_e G_F^2}{4 \pi^2} \left( 1 - \hat{n}_e \cdot \hat{q} \right) \left\{ |g_V^L|^2 \left[ -\hat{n}_e \cdot \hat{p}_{e'} \sqrt{\frac{2m_e}{E_{e'}}} + y(\sqrt{y^2} - 2\sqrt{y}) + \frac{m_e}{E_{e'}} y + (y - 2)y + 2 \right] \right.
\]

\[ + |g_A^L|^2 \left[ y^2 - \hat{n}_e \cdot \hat{p}_{e'} \sqrt{\frac{2m_e}{E_{e'}}} + y - y \frac{m_e}{E_{e'}} + 2 \right] \]

and \(Im(g_V^L g_A^{L*}) = \frac{1}{2} \left| g_V^L \right| \sin(\beta_{VA}) \), proportional to the magnitude of the transverse electron target spin polarization, with \(\hat{n}_e \perp \hat{q}\) is of the form:

\[
\left( \frac{d^2\sigma}{dy d\phi_e} \right)_{(VA)} = \frac{E_\nu m_e G_F^2}{4 \pi^2} \left( 1 - \hat{n}_e \cdot \hat{q} \right) \left\{ |g_V^L|^2 \left[ -\hat{n}_e \cdot \hat{p}_{e'} \sqrt{\frac{2m_e}{E_{e'}}} + y(\sqrt{y^2} - 2\sqrt{y}) + \frac{m_e}{E_{e'}} y + (y - 2)y + 2 \right] \right.
\]

\[ + |g_A^L|^2 \left[ y^2 - \hat{n}_e \cdot \hat{p}_{e'} \sqrt{\frac{2m_e}{E_{e'}}} + y - y \frac{m_e}{E_{e'}} + 2 \right] \]

and \(Im(g_V^L g_A^{L*}) = \frac{1}{2} \left| g_V^L \right| \sin(\beta_{VA})\), proportional to the magnitude of the transverse electron target spin polarization, with \(\hat{n}_e \perp \hat{q}\) is of the form:
FIG. 1: Figure shows the reaction plane for the $\nu_e e^-$ scattering. $\hat{\eta}_\nu$ - the unit 3-vector of the initial neutrino polarization in its rest frame, $\eta_\nu^\perp$ - the transverse electron polarization vector of target and the production plane of $\nu_\mu$-neutrinos for the reaction of $\mu^- + p \rightarrow n + \nu_\mu$. In Section II, the scattering of left handed neutrinos is considered, which have no transverse polarization $\eta_\nu^\perp = 0$. For the considerations described in Section III, the muon capture reaction is used as a source of transversely polarized neutrinos.

\[
\begin{align*}
+ & \text{Im}(g_\nu^L g_A^L) \hat{q} \cdot (\hat{\eta}_e \times \hat{p}_e') \sqrt{y \left( \frac{2m_e}{E_\nu} + y \right)} \\
+ & \text{Re}(g_\nu^L g_A^L) \left[ (\hat{\eta}_e \cdot \hat{p}_e')(y - 1) \sqrt{y \left( \frac{2m_e}{E_\nu} + y \right) + (2 - y)y} \right]
\end{align*}
\]  \hspace{1cm} (7)

where $\hat{\eta}_\nu \cdot \hat{q} = -1$ is the longitudinal polarization of the incoming L-handed neutrino, $\hat{q}$ - the incoming neutrino momentum, $\hat{p}_e'$ - the outgoing electron momentum, $\hat{\eta}_e$ - the unit 3-vector of the initial electron polarization in its rest frame, see Fig.1. The measurement of the azimuthal angle of outgoing electron momentum $\phi_e'$ is only possible when the electron target polarization is known. The polarization vector for electrons is parallel to the magnetic field vector. The variable $y$ is the ratio of the kinetic energy of the recoil electron $T_e$ to the incoming neutrino energy $E_\nu$:

\[
y = \frac{T_e}{E_\nu} = \frac{m_e}{E_\nu} \frac{2 \cos^2 \theta_e'}{\left( 1 + \frac{m_e}{E_\nu} \right)^2 - \cos^2 \theta_e'}. \quad \hspace{1cm} (8)
\]

It varies from 0 to $2/(2 + m_e/E_\nu)$. $\theta_e'$ - the polar angle between the direction of the outgoing electron momentum $\hat{p}_e'$ and the direction of the incoming neutrino momentum $\hat{q}$ (recoil electron scattering angle), $m_e$ - the electron mass.

After the simplification of the vector products and using the complex number identities in the formula (7) for the cross section, we obtain with $\hat{\eta}_e \perp \hat{q}$ the new form:

\[
\]
FIG. 2: Plot of the $\frac{d\sigma}{dyd\phi_e'}(V_A)$ as a function of the azimuthal angle $\phi_e'$ for the $(\nu_\mu e^-)$ scattering, $E_{\nu} = 1$ GeV, $y = 0.5$, $\hat{\eta}_\nu \cdot \hat{q} = -1$ and $|\hat{\eta}_e'\perp| = 1$: a) the case of the pure and real axial-vector coupling i.e. $g_{A}^V = 0.5$ and $g_{A}^L = 0$ (solid line), b) the case of the pure and real vector coupling i.e. $g_{A}^V = 0$ and $g_{V}^L = 0.5$ (dotted line), c) CP violation, the case of the complex coupling constants $|g_{V}^L| = |g_{A}^L| = 0.354$ with the relative phase $\beta_{V_A} = \frac{\pi}{2}$ (dashed line).

\[
\left( \frac{d^2\sigma}{dyd\phi_e'} \right)_{(V_A)} = \frac{E_{\nu} m_e G_{F}^{2}}{4\pi^{2}} \left( 1 - \hat{\eta}_\nu \cdot \hat{q} \right) \left\{ |\eta_e'| \sqrt{m_e E_{\nu}} (2 - y (2 + m_e E_{\nu})) \right\} \left[ \cos(\phi_e') \left( 2 |g_{V}^L||g_{A}^L| \cos(\beta_{V_A}) y + (2 - y) |g_{A}^L|^2 - y |g_{V}^L|^2 \right) - 2 |g_{V}^L||g_{A}^L| \cos(\beta_{V_A}) \right]
\]
\[
+ \left[ (|g_{V}^L|^2 + |g_{A}^L|^2) (y^2 - 2y + 2) + 2 |g_{V}^L||g_{A}^L| \cos(\beta_{V_A}) y (2 - y) - \frac{m_e}{E_{\nu}} y (|g_{V}^L|^2 - |g_{A}^L|^2) \right] \}
\]

It can be noticed that the interference terms between the standard $g_{V,A}^L$ couplings depend on the value of the $\beta_{V_A}$ phase. However, the angular asymmetry of recoil electrons is not vanishing even if $\beta_{V_A} = 0$. The CP-violating phase enters the cross section and changes the angle at which the number of recoil electrons will be maximal ($\phi_{e'}^{max}$).

III. SCATTERING OF TRANSVERSELY POLARIZED MUON NEUTRINO BEAM ON A POLARIZED ELECTRON TARGET

So far the scattering of left-handed and longitudinally polarized neutrino beam on a polarized electron target (SLoPET) was proposed to probe the neutrino magnetic moments \[17\] \[18\] and the flavor composition of a (anti)neutrino beam \[10\].

There were also the ideas of using the scattering of transversely polarized neutrino beam on the unpolarized electron target to probe the nonstandard properties
of neutrinos. Barbieri et al. proposed to measure the azimuthal asymmetry of recoil electrons caused by the non-vanishing interference between the weak and electromagnetic interaction amplitudes. Ciechanowicz et al. indicated that the azimuthal asymmetry of recoil electron event rates could be generated by the interference between the standard L-handed Dirac neutrinos and exotic S, T, P interference between the standard and the R-handed ones in the laboratory differential cross section. All the terms with interference, proportional to the magnitude of the transverse neutrino polarization, do not vanish in the massless neutrino limit and depend on the azimuthal angle between the transverse neutrino polarization and the outgoing electron momentum. However, in both cases, the neutrino detectors with a good angular resolution would have to measure both the recoil electron scattering angle and the azimuthal angle of outgoing electron momentum.

There exist the non-standard models, in which the exotic couplings of the Right-handed neutrinos can appear. We mean here three classes of such models: left-right symmetric models (LRSM), contacts interactions (CI) and leptoquarks (LQ). For example, the CI can be introduced both for the vector coupling of the L-handed neutrinos and scalar, tensor couplings of the R-handed ones. Such interactions would allow to probe the scale for compositeness of quarks and leptons. As to the LQ models, if the R-handed neutrinos are taken into account, there are possible couplings of these neutrinos to the scalar and vector LQ. An original discussion concerning the LQ did not allow for the R-handed neutrinos. In such models the R-handed neutrino can couple to R-handed gauge boson with a mass larger than for the observed standard boson \( m_1 = 80 \text{GeV} \). Recently TWIST Collab. has measured the Michel parameter \( \rho \) in the normal \( \mu^+ \) decay and has set new limit on the \( W_L - W_R \) mixing in the LRSM. Their result \( \rho = 0.75080 \pm 0.00044 \text{(stat.)} \pm 0.000093 \text{(syst.)} \pm 0.00023 \) is in good agreement with the SM prediction \( \rho = 3/4 \), and sets new upper limit on mixing angle \( |\chi| < 0.030 \) (90\% CL).

In this part of our paper we show that the scattering of transversely polarized muon neutrino beam on a polarized electron target (SToPET) may be sensitive to the interference effects between the L- and R-handed neutrinos in the differential cross section for the \( (\mu^-, e^-) \) scattering process. Our analysis is made for the case, when the outgoing electron direction is not observed. It means that the azimuthal angle of the recoil electron momentum would not be measured and nevertheless the new effects could be observed. We consider the minimal extension of the standard \( V - A \) weak interaction to indicate the new tests of the Lorentz structure of the charged- and neutral-current weak interactions. An admittance of all the ERWI does not change qualitatively the conclusions from the investigations.

To show how the recoil electron spectrum may depend on the angle between the transverse neutrino polarization and transverse target electron polarization, we use the muon neutrino beam produced in the reaction where the proton at rest captures the polarized muon \( (\mu^- + p \rightarrow n + \nu_e) \), see Appendix A. The production plane is spanned by the direction of the initial muon polarization \( \mathbf{P}_\mu \) (the muon is fully polarized, i.e. \( |\mathbf{P}_\mu| = 1 \)) and of the outgoing neutrino momentum \( \mathbf{q} \). Eq. (1) \( \mathbf{P}_\mu \) and \( \mathbf{q} \) are assumed to be perpendicular to each other because this leads to the unique conclusions as to the possible presence of the R-handed neutrinos. When admitting additional exotic scalar coupling \( C_S \) in muon capture interaction, Eq. (A.1), the outgoing muon-neutrino flux is a mixture of the L-handed neutrinos produced in the standard \( V - A \) charged weak interaction and the R-handed ones produced in the exotic scalar \( S \) charged weak interaction (the transition amplitude and the neutrino observables are presented in Appendix A). This mixture is detected in the neutral current (NC) weak interaction. We mean that the incoming L-handed neutrinos are detected in the standard \( V - A \) neutral weak interaction, while the initial R-handed ones are detected in the exotic scalar \( S \) one. Then in the final state all the neutrinos are L-handed. Below we give the transition amplitude for this type of neutral current:

\[
M_{\nu_e} = \frac{G_F}{\sqrt{2}} \left\{ (\overline{\nu}_e \gamma^\alpha (g_V^L - g_A^L \gamma_5) u_e) (\overline{\nu}_e, \gamma^\alpha (1 - \gamma_5) u_e) \right. \\
+ \left. \frac{1}{2} g_S^R (\overline{\nu}_e u_e) (\overline{\nu}_e (1 + \gamma_5) u_e) \right\},
\]

(10)

The coupling constants are denoted with the superscripts as \( L \) and \( R \) as \( g_V^L \), \( g_A^L \) and \( g_S^R \) respectively to the incoming neutrino of L- and R-chirality. Standard couplings \( g_V^L \), \( g_A^L \) are assumed to be real, i.e. \( \beta_V^L = 0, \beta_A^L = 0 \).

### A. Laboratory differential cross section

Because we consider the case when the outgoing electron direction is not observed, the formula for the laboratory differential cross section is presented after integration over the azimuthal angle \( \phi_e \) of the recoil electron momentum. The result of the calculation performed with the amplitude \( M_{\nu_e} \), in Eq. (10), is divided into three parts, standard \( (V, A) \), exotic \( (S) \) and interference \( (V S + A S) \):
\[
\frac{d\sigma}{dy} = \left( \frac{d\sigma}{dy} \right)_{(V,A)} + \left( \frac{d\sigma}{dy} \right)_{(S)} + \left( \frac{d\sigma}{dy} \right)_{(VS+AS)},
\]

(11)

with,

\[
\left( \frac{d\sigma}{dy} \right)_{(V,A)} = \frac{E_\nu m_\nu G_F^2}{2\pi} (1 - \hat{\eta}_\nu \cdot \hat{q}) \left\{ (g_\nu^V + g_\nu^A)^2 (1 + \hat{\eta}_e \cdot \hat{q}) + (g_\nu^L - g_\nu^R)^2 \left[ 1 - (\hat{\eta}_e \cdot \hat{q}) \left( 1 - \frac{m_\nu}{E_\nu (1 - y)} \right) \right] \right\} (1 - y)^2
\]

\[-\left[ (g_\nu^V)^2 - (g_\nu^A)^2 \right] (1 + \hat{\eta}_e \cdot \hat{q}) \frac{m_\nu}{E_\nu} y,\]

(12)

where, \(\hat{\eta}_\nu \cdot \hat{q}\) is the longitudinal polarization of the incoming L-handed neutrino. We shall point out that the standard (SM) part has been already published in Ref. [17]. The exotic part of the cross section may contribute merely for the R-handed neutrino scattering (\(\hat{\eta}_\nu \cdot \hat{q} \approx +1\)):

\[
\left( \frac{d\sigma}{dy} \right)_{(S)} = \frac{E_\nu m_\nu G_F^2}{2\pi} (1 + \hat{\eta}_\nu \cdot \hat{q}) |g_S^R|^2 \left\{ \left[ \left( \frac{2 m_\nu}{E_\nu} + y \right) y \right] \right\},\]

(13)

In the interference part we have angular correlations with the transverse component of the neutrino polarization \(\hat{\eta}_\nu^\perp\), both T-odd and T-even. The correlation coefficients depend linearly on the exotic coupling constant \(g_S^R\). Hence, this contribution could be a tool suitable to investigate the effects due to scalar interactions of the R-handed neutrinos:

\[
\left( \frac{d\sigma}{dy} \right)_{(VS+AS)} = -\frac{E_\nu m_\nu G_F^2}{4\pi} \left\{ \hat{q} \cdot (\hat{\eta}_e^\perp \times \hat{\eta}_\nu^\perp) \left[ \text{Im}(g_\nu^V g_S^R) \left( 1 + \frac{m_\nu}{2 E_\nu} y \right) \right. \right. \]

\[\left. \left. + \text{Im}(g_\nu^L g_S^R) \left( 1 - \frac{m_\nu}{2 E_\nu} y \right) \right) \right\} \left( 1 - \frac{m_\nu}{2 E_\nu} (y - 4) \right) \]

(14)

It can be noticed that the occurrence of the interference terms between the standard \(g_\nu^V,A\) and exotic \(g_S^R\) couplings does not depend on the neutrino mass and they pertain in the massless neutrino limit. The independence on the \(m_\nu\) makes the measurement of the relative phases between these couplings possible. The terms with the interference between the standard \(g_\nu^V,A\) and exotic \(g_S^R\) couplings, Eqs. [14], include only the contributions from the transverse component of the initial neutrino polarization \(\hat{\eta}_\nu^\perp\) and the transverse component of the polarized electron target \(\hat{\eta}_e^\perp\). Both transverse components are perpendicular with respect to the \(\hat{q}\).

If one assumes the production of only L-handed neutrinos in the standard \((V - A)\) and non-standard \(S\) weak interactions, there is no interference between the \(g_\nu^V,A\) and \(g_S^R\) couplings in the differential cross section, when \(m_\nu \rightarrow 0\). We do not consider this scenario.

### B. CP conservation in \(\nu e\) scattering at low-energy

In this subsection, we will consider the CP-symmetric scenario with the standard \((V - A)_L\) and \(S_R\) weak interactions. From the general formula for the cross section, we get with \(\hat{\eta}_e \perp \hat{q}\) for \(|\hat{\eta}_\nu^\perp| = 1:\n
\[
\frac{d\sigma}{dy} = \left( \frac{d\sigma}{dy} \right)_{(V,A)} + \left( \frac{d\sigma}{dy} \right)_{(S)} + \left( \frac{d\sigma}{dy} \right)_{(VS+AS)},
\]

(15)

\[
\left( \frac{d\sigma}{dy} \right)_{(VS+AS)} = -\frac{E_\nu m_\nu G_F^2}{4\pi} y |\hat{\eta}_\nu^\perp| \cos(\alpha) |g_S^R|^2 \left\{ (1 + \frac{m_\nu}{2 E_\nu} y) |g_\nu^V| + (1 - \frac{m_\nu}{2 E_\nu} (y - 4)) |g_\nu^L| \right\},
\]

(16)

where \(\left( \frac{d\sigma}{dy} \right)_{(V,A)}\), \(\left( \frac{d\sigma}{dy} \right)_{(S)}\) are given by Eqs. [12] [13] and \(\alpha\) is the angle between the \(\hat{\eta}_\nu^\perp\) and \(\hat{\eta}_e^\perp\), Fig. 1. We see that the CP-even interference terms enter the cross
dently, in Appendix A, we have estimated the trans-

\[ d\sigma / dy = (d\sigma / dy)_{(V,A)} + (d\sigma / dy)_{(S)} + (d\sigma / dy)_{(V+S+AS)}, \]

\[ (d\sigma / dy)_{(V+S+AS)} = -\frac{E_{\nu}m_{e}G_{F}}{4\pi}y|\vec{\eta}_{\nu}\cdot \vec{q}| |g_{S}^{R}| \{(1 + \frac{m_{e}}{2E_{\nu}}y)|g_{V}^{L}| \cos(\alpha + \beta_{V S}) + (1 - \frac{m_{e}}{2E_{\nu}}(y - 4))|g_{A}^{L}| \cos(\alpha + \beta_{A S})\}. \]  

where \( \beta_{V S} = \beta_{V}^{L} - \beta_{S}^{R} \), \( \beta_{A S} = \beta_{A}^{L} - \beta_{S}^{R} \) are the relative phases between the \( g_{V}^{L}, g_{S}^{R} \) and \( g_{A}^{L}, g_{S}^{R} \) couplings, respectively.
It can be seen that the CP-odd interference contribution enters the cross section and will be substantial at the $\alpha + \beta_{\nu S} = 0, \pi$ and $\alpha + \beta_{\nu S} = \pi, \pi$, and it vanishes for the $\alpha + \beta_{\nu S} = \pi/2$ and $\alpha + \beta_{\nu S} = \pi/2$, respectively.

The situation is illustrated in the Fig. 4 for the same limits as for the CP-symmetric case with $E_e = 100$ MeV (long-dashed and short-dashed lines, respectively). The phases $\beta_{\nu S}$ and $\beta_{\nu S}$ in Eq. 14, when different from 0 or $\pi$, may result from CP-violation in NC weak interaction ($\nu_{\mu} e^-$). The angle $\alpha$ is defined in accordance with Fig. 1 and relates the direction of $\hat{\eta}_e^+ \nu$ to the direction of $\hat{\eta}_e^+ \nu$. So with the proper choices of $\alpha$, the phases $\beta_{\nu S}$ and $\beta_{\nu S}$ could be detected by measuring the maximal asymmetry of the cross section $d\sigma / dy$.

On the other hand, if knowing these phases prior to $(\nu_{\mu} e^-)$ scattering, it would be possible to test CP-symmetry in muon capture. In case of CP-violation, the neutrino transverse polarization vector $\eta_{\nu}^e$ would be turned aside from the production plane $(\hat{q}, \hat{P}_{\mu})$, having the CP-breaking component $<S_{\nu} \cdot (\hat{P}_{\mu} \times \hat{q}) >_{f}$, see Fig. 1 and Eq. (A3). For illustration purposes let us take $\beta_{\nu S} = \beta_{\nu S} = 0$ (i.e. CP-symmetry in $\nu_{\mu} e^-$). Next, we measure the angular correlation $\hat{\eta}_e^+ \cdot \eta_e^- \sim \cos(\alpha)$, in order to see the direction of $\eta_e^- \nu$ along which the maximal asymmetry is oriented. If this direction were turned aside from $\hat{P}_{\mu}$, it would be evidence for CP-breaking.

IV. CONCLUSIONS

In the first part of the paper, we show that the SLoPET can be used to measure the CP violation in the pure leptonic process, Fig. 2. The azimuthal asymmetry of the recoil electrons does not depend on the neutrino mass and is not vanishing even if $\beta_{\nu A} = 0$. The CP-breaking phase $\beta_{\nu A}$ could be detected by measuring the maximal asymmetry of the cross section. The future superbeam and neutrino factory experiments will provide the unique opportunity for the leptonic CP violation studies, if the large magnetized sampling calorimeters with good event reconstruction capabilities are build.

In the second part, we show that the SToPET may be used to detect the effects caused by the interfering $L$- and $R$-handed neutrinos. In spite of the integration over the azimuthal angle $\phi_{\nu_e}$ of the recoil electron momentum, the terms with the interference between the standard $(V, A)_L$ and exotic $S_R$ couplings in the laboratory differential cross section depend on the angle $\alpha$, Fig. 1, between the transverse incoming neutrino polarization and the transverse electron polarization of the target and are present even in the massless neutrino limit. The observation of the dependence on this angle $\alpha$ in the recoil electron energy spectrum would be a clear signal of the R-handed neutrinos in the $\nu e$ scattering.

It can be noticed that the disagreement with the SM would be substantial for the small polar angle $\theta_e$, both for the CP-even and CP-odd cases, Fig. 3.

To search for the effects connected with the ERWI, the strong polarized neutrino beam and the polarized electron target is required. The electron target should be polarized perpendicular to the direction of the incoming neutrino beam, $\hat{n}_e \cdot \hat{q} = 0$, because it leads to the unique conclusions as to the R-handed neutrinos. If one has the polarized artificial neutrino source, the direction of the transverse neutrino polarization with respect to the production plane will be fixed. So having the assigned direction of the polarization axis of electron target and turning the polarization axis of neutrino source, the dependence of the event number on the angle $\alpha$ could be tested.

It seems worthy of exploring high energy region in the $L$- and $R$-handed neutrinos interference. Because of the angular correlation between the transverse spin polarizations of the neutrino and electron and at the large kinetic energy transfer to the recoil electron, we see strong angular asymmetry in the cross section $d\sigma / dy$ for the small values of the polar recoil angle, see Eq. 18. We expect for this fact some interest in the accelerator laboratories working with neutrino beams, accompanied by the progress in the spin polarization engineering. For the future outline, we shall inspect the other examples, which could be interesting from the point of observable effects caused by the exotic neutrino states. We plan to work mainly on the weak interaction processes that are known from experiment or have been already under consideration in the literature.

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APPENDIX A: MUON CAPTURE BY PROTON

The amplitude for the muon capture by proton ($\mu^- + p \rightarrow n + \nu_{\mu}$), as a production process of massive muon-neutrinos, is commonly of the form:

$$M_{\mu^-} = (C_V^L + 2Mg_M)(\bar{\nu}_e \gamma_5 (1 - \gamma_5) u_{\mu})(\bar{u}_n \gamma^\lambda u_{\mu}) + (C_A^L + m_{\mu} q \frac{g_F}{2M}) (\bar{\nu}_e i \gamma_5 \gamma_\lambda (1 - \gamma_5) u_{\mu})(\bar{u}_n i \gamma^5 \gamma^\lambda u_{\mu})$$
where the fundamental coupling constants are denoted as $C^L_V$, $C^L_A$ and $C^R_S$ respectively to the outgoing neutrino of L- and R-chirality. Since we do not preclude the CP-asymmetry between SM and exotic sectors, we allow for these coupling constants to be the complex numbers. $g_M, g_P$ - the induced weak couplings of the left-handed neutrinos, i.e. the weak magnetism and induced pseudoscalar, respectively; $m_\mu$, $q$, $E_\nu$, $m_\nu$, $M$ - the muon mass, the absolute value of the neutrino momentum, its energy, its mass and the nucleon mass; $u_\mu$, $\bar{u}_\mu$ - the Dirac bispinors of initial proton and final neutron; $u_\nu$, $\bar{u}_\nu$ - the Dirac bispinors of initial muon and final neutrino.

Following the results of Ref. [28], in the case of non-vanishing neutrino mass ($m_\nu \neq 0$), we take the transverse components of the neutrino spin polarization, T-even:

$$< S_\nu \cdot \hat{P}_\mu >_f = |P_\mu| (1 + \frac{q}{E_\nu}) Re((C^L_V + 2M g_M) C^R_S) + \frac{m_\nu}{2E_\nu} \sqrt{(C^L_V + 2M g_M)^2 - |C^L_A + m_\nu \frac{q}{2M} g_P|^2}$$

and T-odd:

$$< S_\nu \cdot (\hat{P}_\mu \times \hat{\eta}) >_f = -|P_\mu| (\frac{q}{E_\nu} + \frac{q}{2M}) Im((C^L_V + 2M g_M) C^R_S).$$

Here, $S_\nu$ is the spin operator of the neutrino in the muonic atom 1s state, and $\hat{\eta}$ is the direction of the neutrino polarization. $\hat{P}_\mu$ and $\hat{\eta}$ are perpendicular to each other; $\hat{P}_\mu \cdot \hat{\eta} = 0$.

It can be noticed that in the limit of vanishing neutrino mass, these observables consist only of the interference term between the standard $C^L_V$ coupling and exotic $C^R_S$ one. There is no contribution to these observables from the SM in which neutrinos are only L-handed and massless. The neutrino mass terms, $m_\nu/E_\nu$, in the above observables give a very small contribution in relation to the main one coming from the interference terms and they are neglected in the considerations. As the induced weak couplings enter additively the fundamental coupling and exotic $C^L_V, A$ couplings, they are omitted in the considerations, for their presence does not change qualitatively the conclusions concerning the transverse neutrino polarization.

Using the current data [7], we calculate the lower limits on the SM couplings: $|C^L_V| > 0.850(4G_F/\sqrt{2}) \cos \theta_c$ and $|C^L_A| > 1.070(4G_F/\sqrt{2}) \cos \theta_c$, and upper limit on the exotic scalar: $|C^R_S| < 0.974(4G_F/\sqrt{2}) \cos \theta_c$. Now, we may give the upper bound on the magnitude of the transverse neutrino polarization in the massless neutrino limit:

$$|\eta^+_{1\nu}| = \frac{1}{s} \sqrt{< S_\nu \cdot (\hat{P}_\mu \times \hat{\eta}) >_f^2 + < S_\nu \cdot \hat{P}_\mu >_f^2}.$$  

The transverse components, Eqs. (A.2) and (A.3), are calculated with the amplitude $M_{1\nu}$ and normalized with the $\mu$-capture probability $< 1 >_f$:

$$|\eta^+_{1\nu}| = \frac{1}{s} \left[ \frac{C^R}{C^L} \left( 1 + \frac{q}{2M} \right) \left[ 1 + \frac{q}{M} + \frac{3}{M} \frac{C^L_A}{C^L_V} \right]^2 + \left[ \frac{C^R}{C^L} \right]^2 - \frac{q}{M} \left[ C^L_A C^L_V \cos(\alpha^L_{AV}) \right] \right].$$

After inserting from above the limits on coupling constants and with the relative phase between the standard $C^L_V$ and $C^L_A$ couplings $\alpha^L_{AV} = \alpha^L_A - \alpha^L_V = \pi$, under the condition that $|\eta_{1\nu}| = 1$, one obtains: $|\eta^+_{1\nu}| \leq 0.318$, which means that the value of the longitudinal neutrino polarization is equal to $\eta_{1\nu} \cdot \eta = -0.948$.

**APPENDIX B: FOUR-VECTOR NEUTRINO POLARIZATION AND MICHEL-WIGHTMAN DENSITY MATRIX**

The formulas for the 4-vector of the massive neutrino polarization $S$ in its rest frame and for the initial neutrino moving with the momentum $q$, respectively, are as follows:

$$S = (0, \hat{\eta}_{1\nu}),$$

$$\hat{S}^c = \hat{\eta}_{1\nu} \cdot \frac{q}{m_\nu} \begin{pmatrix} E_\nu - \hat{\eta}_{1\nu} \cdot q \end{pmatrix} \begin{pmatrix} \frac{q}{m_\nu} \hat{\eta}_{1\nu} \cdot q \end{pmatrix},$$

$$\hat{S}^c' = \frac{E_\nu \hat{\eta}_{1\nu} \cdot \hat{q}}{m_\nu} \hat{\eta}_{1\nu} \cdot \hat{q},$$

$$S' = E_\nu \hat{\eta}_{1\nu} \cdot \hat{q} + \hat{\eta}_{1\nu} - (\hat{\eta}_{1\nu} \cdot \hat{q}) \hat{q}.$$
where $\hat{n}_\nu$ - the unit vector of the initial neutrino polarization in its rest frame. The formula for the Michel-Wightman density matrix $\Lambda^{(s)}$ is given by:

$$\Lambda^{(s)}_\nu = \sum_{r=1,2} u_r \overline{u}_r \sim [(q^\mu \gamma_\mu) + m_\nu + \gamma_5(S'^\mu \gamma_\mu)(q^\mu \gamma_\mu) + \gamma_5(S'^\mu \gamma_\mu)m_\nu],$$  \hspace{1cm} (B5)

$$S'^\mu \gamma_\mu = \hat{n}_\nu \cdot q \frac{(q^\mu \gamma_\mu)}{E_\nu m_\nu} - (\hat{n}_\nu - \frac{(\hat{n}_\nu \cdot q)q}{E_\nu(E_\nu + m_\nu)}) \cdot \gamma,$$  \hspace{1cm} (B6)

$$(S'^\mu \gamma_\mu)(q^\mu \gamma_\mu) = \frac{m_\nu}{E_\nu} \hat{n}_\nu \cdot q - (\hat{n}_\nu - \frac{(\hat{n}_\nu \cdot q)q}{E_\nu(E_\nu + m_\nu)}) \cdot \gamma(q^\mu \gamma_\mu),$$  \hspace{1cm} (B7)

$$(S'^\mu \gamma_\mu)m_\nu = \frac{\hat{n}_\nu \cdot q}{E_\nu}(q^\mu \gamma_\mu) - m_\nu(\hat{n}_\nu - \frac{(\hat{n}_\nu \cdot q)q}{E_\nu(E_\nu + m_\nu)}) \cdot \gamma,$$  \hspace{1cm} (B8)

and in the limit of vanishing neutrino mass $m_\nu$, we have

$$\lim_{m_\nu \to 0} \Lambda^{(s)}_\nu = \left[ 1 + \gamma_5 \left( \frac{\hat{n}_\nu \cdot q}{|q|} - \frac{(\hat{n}_\nu - \frac{(\hat{n}_\nu \cdot q)q}{|q|^2}) \cdot \gamma}{|q|^2} \right) \right] (q^\mu \gamma_\mu).$$  \hspace{1cm} (B9)

We see that in spite of the singularities $m_\nu^{-1}$ in the polarization four-vector $S'$, the density matrix $\Lambda^{(s)}_\nu$ remains finite including the transverse component of the neutrino spin polarization.

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