

PROBLEM OF NEUTRINO HANDEDNESS
IN WEAK INTERACTIONS*S. CIECHANOWICZ[†], W. SOBKÓW[‡]Institute of Theoretical Physics, University of Wrocław
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In this paper we show that the neutrino observables, including an information about the transverse neutrino spin polarization, can be sensitive to the effects coming from the interference terms between the standard vector V , axial A couplings of l-handed neutrinos and exotic scalar S coupling of r-handed ones in the differential cross section. Our analysis is based on the electron neutrino–electron elastic scattering. This reaction is considered at the level of the four-fermion point interaction. Neutrinos are assumed to be massive and to be polarized Dirac fermions coming from the Sun.

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1. Introduction

According to the Standard Model (SM) of electro-weak interactions [1–3] only vector V and axial A couplings of left-handed Dirac neutrinos are present in the weak interaction processes. However on the other hand, a current precision of measurements still allows a deviation from the standard V – A structure of the charged and neutral weak interactions. There is some space for the scenarios with the exotic scalar S , tensor T and pseudoscalar P couplings of the right-handed Dirac neutrinos beyond the SM. The presence

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of new couplings would mean that the charged and neutral weak interactions can be mediated by heavy, charged, neutral bosons with spin-zero, one and two.

The current upper limits on the all non-standard couplings, obtained from the normal and inverse muon decay, are presented in the Table I [5]. The transition amplitude for the muon decay $\mu^- \rightarrow \bar{\nu}_e + \nu_\mu + e^-$ is as follows:

$$M_{\mu^-} = \frac{4G_F}{\sqrt{2}} \sum_{\gamma=S,V,T} \sum_{\varepsilon,\mu=L,R} g_{\varepsilon\mu}^\gamma \langle \bar{e}_\varepsilon | \Gamma^\gamma | (\nu_e)_n \rangle \langle (\bar{\nu}_\mu)_m | \Gamma_\gamma | \mu_\mu \rangle. \quad (1)$$

Here, $\gamma = S, V, T$ indicates the type of weak interaction, *i.e.* scalar S , vector V , tensor T ; $\varepsilon, \mu = L, R$ indicate the chirality of the electron or muon and the neutrino chiralities n, m are uniquely determined for given γ, ε, μ . It means that the neutrino chirality n or m is the same as the associated charged lepton for the V interaction, and opposite for the S, T interactions. In the SM, all of coupling constants are set to zero by hand, except for g_{LL}^V which is set to one.

TABLE I

Current limits on the non-standard couplings

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

The high-precision measurements of various observables at low energy area could observe or constrain physics beyond the SM. The suitable quantities should consist only of the interference terms between the standard $(V, A)_L$ and exotic $(S, T, P)_R$ couplings, which do not vanish in the massless neutrino limit. We mean here the neutrino observables, including the information about the transverse neutrino spin polarization (TNSP), both T -even and T -odd components. These observables vanish in the SM, so

non-zero values would be a clear signature of the exotic right-handed weak interactions (ERWI). Currently direct tests are still difficult, but the process of the neutrino–electron elastic scattering (NEES) could help in searching for new effects.

In this paper we indicate the new tests of the Lorentz structure of the weak interactions using the NEES as a detection process.

We use the system of natural units with $\hbar = c = 1$, Dirac–Pauli representation of the γ -matrices and the $(+, -, -, -)$ metric [4].

2. Helicity, chirality and exotic interactions

As is known, measuring oscillation tells us the difference of the neutrino mass square, so the number we find is a lower limit on the neutrino mass squared. If the mass of the neutrino does not equal zero, however small the mass is, the neutrino has two helicity eigenstates. The helicity operator is not Lorentz invariant. When taking a Lorentz boost with a speed faster than the neutrino, the helicity of the neutrino would change its sign in the new reference frame. The helicity of a neutrino depends on the projection of its spin along its momentum. The massive neutrino can be polarized perpendicular to its momentum, that is not possible for massless particles. Even in the limit of massless neutrino, a beam of neutrinos with non zero transverse polarization is still a mixture of right- and left-handed chirality states. A transversely polarized neutrino beam is not chiral.

The chirality is a good quantum number only if the particle is massless. This is because γ_5 does not commute with the Hamiltonian

$$i\hbar \frac{d}{dt} \gamma_5 = [\gamma_5, H] = 2mc^2 \gamma_5 \beta, \quad (2)$$

and hence the chirality is conserved only for a massless fermion.

The presence of the r-handed Dirac neutrinos allows to define the Dirac mass term:

$$\mathcal{L}_{\mathcal{D}} = m_D (\overline{\Psi}_L \Psi_R + \overline{\Psi}_R \Psi_L). \quad (3)$$

This term couples left- and right-handed components of the same field Ψ . It is the term that flips the chirality of a particle. So, right-handed neutrino exists in a updated model, but does not interact.

Assuming Lorentz invariance of the theory, one obtains the five bilinear Lorentz covariants; $\overline{u}u$ — the scalar S , $\overline{u}\gamma^5 u$ — pseudoscalar P , $\overline{u}\gamma^\mu u$ — vector V , $\overline{u}\gamma^5 \gamma^\mu u$ — pseudovector A and $\overline{u}\sigma^{\mu\nu} u$ — tensor T (antisymmetric tensor of second rank). These covariants may be expressed in terms of the l- and r-handed chirality states. The (V, A) couplings conserve the initial particle chirality and (S, T, P) couplings flip chirality. For example, in the

case of the V and S couplings for the neutrino–electron scattering ($\nu_e + e^- \rightarrow \nu_e + e^-$), one gets, respectively:

$$\bar{u}_{\nu'_e} \gamma^\mu P_L^2 u_{\nu_e} = u_{\nu'_e}^\dagger P_L \gamma^0 \gamma^\mu P_L u_{\nu_e}, \quad (4)$$

$$\bar{u}_{\nu'_e} P_L^2 u_{\nu_e} = u_{\nu'_e}^\dagger P_R \gamma^0 P_L u_{\nu_e},$$

where

$$P_{L,R} = \frac{1}{2} (1 \mp \gamma^5). \quad (5)$$

We see that the chiralities of the initial and final neutrino are identical (l-handed) in the standard V weak interaction, while the initial l-handed neutrino becomes the outgoing r-handed one in the exotic S weak interaction.

C.S. Wu pointed out that the exotic $(S, T, P)_R$ weak interactions may be responsible for the negative electron helicity observed in β -decay.

In muon decay experiments, we measure the energy spectrum of the final state charged lepton [5]. The theoretical value of the Michel ρ parameter in terms of the all possible coupling constants is [6]

$$\begin{aligned} \rho = & \frac{3}{4} \left(|g_{LL}^V|^2 + \frac{1}{4} |g_{LL}^S|^2 \right) + \frac{3}{4} \left(|g_{RR}^V|^2 + \frac{1}{4} |g_{RR}^S|^2 \right) \\ & + \frac{3}{16} \left(|g_{RL}^S - 2g_{RL}^T|^2 + |g_{LR}^S - 2g_{LR}^T|^2 \right). \end{aligned} \quad (6)$$

We see that the measurement $\rho = 0.75$ in itself does not determine the type of interaction. In the extreme, it is compatible with a pure scalar type interaction $g_{LL}^S = 2, g_{LL}^V = g_{RR}^V = g_{RR}^S = g_{RL}^S = g_{LR}^S = g_{RL}^T = g_{LR}^T = 0$. We can resolve this problem, however, by including the data from the neutrino–electron scattering (*i.e.* the inverse muon decay) [7, 8].

The Michel–Wightman density matrix [9] $\Lambda_\nu^{(s)}$ for the polarized massive neutrino, even for infinitesimally small mass m_ν , remains finite including the transverse component of neutrino polarization:

$$\lim_{m_\nu \rightarrow 0} \Lambda_\nu^{(s)} = \left[1 + \gamma_5 \left(\frac{\hat{\boldsymbol{\eta}}_\nu \cdot \mathbf{q}}{|\mathbf{q}|} - \left(\hat{\boldsymbol{\eta}}_\nu - \frac{(\hat{\boldsymbol{\eta}}_\nu \cdot \mathbf{q}) \mathbf{q}}{|\mathbf{q}|^2} \right) \cdot \boldsymbol{\gamma} \right) \right] (q^\mu \gamma_\mu), \quad (7)$$

where $\hat{\boldsymbol{\eta}}_\nu$ is the unit vector of the initial neutrino polarization in its rest frame, \mathbf{q} — the momentum of initial neutrino.

3. Electron neutrino–electron scattering

In our considerations, we analyze the polarized electron neutrino beam coming from the Sun. The incoming electron neutrino flux is the mixture of the l-handed neutrinos produced in the standard $V-A$ charged weak interaction and the r-handed ones produced by the spin flip mechanism. This mixture is detected in the neutral (NC) and charged current (CC) weak interaction. One assumes that the incoming l-handed neutrinos are detected in the standard $V-A$ weak interaction, while the initial r-handed neutrinos are detected in the exotic S one. In the final state all the neutrinos are l-handed. We analyze a minimal version of the SM extension, because the admittance of all exotic weak interactions does not change the qualitatively the conclusions. The reaction plane is spanned by the direction of the outgoing electron momentum $\hat{\mathbf{p}}_{e'}$ and of the incoming neutrino momentum $\hat{\mathbf{q}}$, Fig. 1.

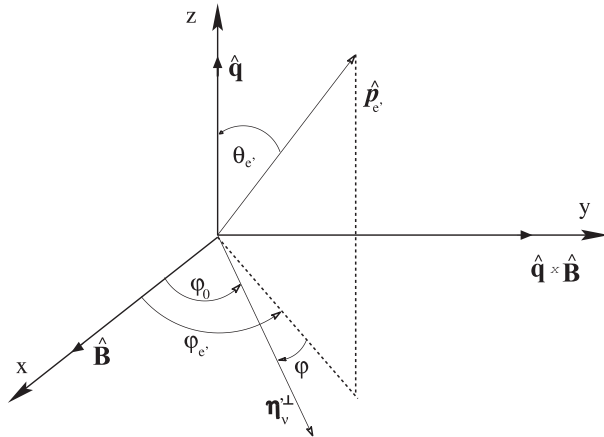


Fig. 1. The production plane of ν_e neutrinos, reaction plane for the $\nu_e e^-$ scattering with the transverse neutrino polarization vector $\boldsymbol{\eta}_\nu^{\perp}$. $\theta_{e'}$ is the angle between the direction of the outgoing electron momentum $\hat{\mathbf{p}}_{e'}$ and the direction of the incoming neutrino momentum $\hat{\mathbf{q}}$ (recoil electron scattering angle). $\phi_{e'}$ is the angle between the production plane and the reaction plane. ϕ is the angle between the reaction plane and the transverse neutrino polarization vector and is connected with the $\phi_{e'}$ in the following way: $\phi = \phi_0 - \phi_{e'}$. ϕ_0 is the angle between the production plane and the transverse neutrino polarization vector.

The transition amplitude for the $\nu_e e^-$ scattering is as follows:

$$M_{\nu_e e} = \frac{G_F}{\sqrt{2}} \left\{ (\bar{u}_{e'} \gamma^\alpha (c_V^L - c_A^L \gamma_5) u_e) (\bar{u}_{\nu_{e'}} \gamma_\alpha (1 - \gamma_5) u_{\nu_e}) + \frac{1}{2} c_S^R (\bar{u}_{e'} u_e) (\bar{u}_{\nu_{e'}} (1 + \gamma_5) u_{\nu_e}) \right\}, \quad (8)$$

where u_e and $\bar{u}_{e'}$ (u_{ν_μ} and $\bar{u}_{\nu_{\mu'}}$) 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 coupling constants are denoted as c_V^L , c_A^L and c_S^R , respectively, to the incoming neutrino of l- and r-chirality.

The laboratory differential cross section for the $\nu_e e^-$ scattering, in the limit of vanishing neutrino mass, has the form:

$$\frac{d^2\sigma}{dyd\phi_{e'}} = \left(\frac{d^2\sigma}{dyd\phi_{e'}} \right)_{(V,A)} + \left(\frac{d^2\sigma}{dyd\phi_{e'}} \right)_{(S)} + \left(\frac{d^2\sigma}{dyd\phi_{e'}} \right)_{(VS)}, \quad (9)$$

$$\begin{aligned} \left(\frac{d^2\sigma}{dyd\phi_{e'}} \right)_{(V,A)} = B \Big\{ & (1 - \hat{\boldsymbol{\eta}}_\nu \cdot \hat{\mathbf{q}}) \left[(c_V^L + c_A^L)^2 + (c_V^L - c_A^L)^2 (1 - y)^2 \right. \\ & \left. - \frac{m_e y}{E_\nu} \left((c_V^L)^2 - (c_A^L)^2 \right) \right] \Big\}, \end{aligned} \quad (10)$$

$$\left(\frac{d^2\sigma}{dyd\phi_{e'}} \right)_{(S)} = B \left\{ (1 + \hat{\boldsymbol{\eta}}_\nu \cdot \hat{\mathbf{q}}) \frac{1}{8} y \left(y + 2 \frac{m_e}{E_\nu} \right) |c_S^R|^2 \right\}, \quad (11)$$

$$\begin{aligned} \left(\frac{d^2\sigma}{dyd\phi_{e'}} \right)_{(VS)} = B \Big\{ & \sqrt{y \left(y + 2 \frac{m_e}{E_\nu} \right)} \left[-\hat{\boldsymbol{\eta}}_\nu \cdot (\hat{\mathbf{p}}_{e'} \times \hat{\mathbf{q}}) \text{Im}(c_V^L c_S^{R*}) \right. \\ & \left. + (\hat{\boldsymbol{\eta}}_\nu \cdot \hat{\mathbf{p}}_{e'}) \text{Re}(c_V^L c_S^{R*}) \right] \\ & \left. - y \left(1 + \frac{m_e}{E_\nu} \right) (\hat{\boldsymbol{\eta}}_\nu \cdot \hat{\mathbf{q}}) \text{Re}(c_V^L c_S^{R*}) \right\}, \end{aligned} \quad (12)$$

$$B \equiv \frac{E_\nu m_e G_F^2}{(2\pi)^2 2}, \quad (13)$$

$$y \equiv \frac{T_{e'}}{E_\nu} = \frac{m_e}{E_\nu} \frac{2 \cos^2 \theta_{e'}}{\left(1 + \frac{m_e}{E_\nu} \right)^2 - \cos^2 \theta_{e'}}, \quad (14)$$

where y is the ratio of the kinetic energy of the recoil electron $T_{e'}$ to the incoming neutrino energy E_ν (the inelasticity parameter). It varies from 0 to $2/(2 + m_e/E_\nu)$. m_e is the electron mass, $\hat{\boldsymbol{\eta}}_\nu \cdot \hat{\mathbf{q}}$ — the longitudinal polarization of the incoming neutrino.

The interference term, Eq. (12), includes only the transverse components of the initial neutrino spin polarization, both T -even and T -odd:

$$\begin{aligned} \left(\frac{d^2\sigma}{dyd\phi_{e'}} \right)_{(VS)} = B \Big\{ & \sqrt{\frac{m_e}{E_\nu} y \left[2 - \left(2 + \frac{m_e}{E_\nu} \right) y \right]} \\ & \times |c_V^L| |c_S^R| \left| \hat{\boldsymbol{\eta}}_\nu' \cdot \hat{\mathbf{p}}_{e'} \right| \cos(\phi - \alpha) \Big\}, \end{aligned} \quad (15)$$

where $\alpha \equiv \alpha_V^L - \alpha_S^R$ — the relative phase between the c_V^L and c_S^R couplings. This interference would be responsible for the appearance of the azimuthal asymmetry of the electrons recoiled after the subsequent neutrino scattering. We see that the interference contribution between the c_V^L and c_S^R couplings will be substantial at lower neutrino energies $E_\nu \leq m_e$ but negligibly small at large energies and vanishes for $\theta_{e'} = 0$ or $\theta_{e'} = \pi/2$.

After integration over the $\phi_{e'}$, the interference term vanishes and the cross section consists only of two terms:

$$\frac{d\sigma}{dy} = \left(\frac{d\sigma}{dy} \right)_{(V,A)} + \left(\frac{d\sigma}{dy} \right)_{(S)}, \quad (16)$$

$$\begin{aligned} \left(\frac{d\sigma}{dy} \right)_{(V,A)} = B' & \left\{ (1 - \hat{\boldsymbol{\eta}}_\nu \cdot \hat{\mathbf{q}}) \left[(c_V^L + c_A^L)^2 + (c_V^L - c_A^L)^2 (1 - y)^2 \right. \right. \\ & \left. \left. - \frac{m_e y}{E_\nu} \left((c_V^L)^2 - (c_A^L)^2 \right) \right] \right\}, \end{aligned} \quad (17)$$

$$\left(\frac{d\sigma}{dy} \right)_{(S)} = B' \left\{ (1 + \hat{\boldsymbol{\eta}}_\nu \cdot \hat{\mathbf{q}}) \frac{1}{8} y \left(y + 2 \frac{m_e}{E_\nu} \right) |c_S^R|^2 \right\}, \quad (18)$$

where $B' = 2\pi B$.

If one assumes that only l-handed neutrinos are produced in the standard ($V-A$) and non-standard S weak interactions (pure l-handed neutrino beam), there is no interference between the $c_{V,A}^L$ and c_S^L couplings in the differential cross section, when $m_\nu \rightarrow 0$, and the angular distribution of the recoil electrons has the azimuthal symmetry. We do not consider this scenario.

3.1. Astrophysical consequences of r-handed neutrinos

If a neutrino has a non-zero magnetic moment, the neutrino helicity can be flipped when it passes through a region with magnetic field perpendicular to the direction of propagation. It means that the left-handed neutrino that is active in SM would change into a right-handed one ($\hat{\boldsymbol{\eta}}_\nu \cdot \hat{\mathbf{q}} = 1$) that is sterile in SM:

$$\left(\frac{d^2\sigma}{dyd\phi_{e'}} \right)_{(V,A)} = (1 - \hat{\boldsymbol{\eta}}_\nu \cdot \hat{\mathbf{q}}) \cdot f(E_\nu, y) = 0. \quad (19)$$

Solutions based on neutrino “spin flip” in the Sun’s magnetic fields are proposed to explain the observed solar neutrino deficit [10]. They are important alternatives to LMA MSW solution, because no one signature of the LMA has been observed. Dependence of the survival probability on energy and significant regeneration effect (day/night asymmetry) are not observed in solar neutrino detectors.

The scattering due to the photon exchange between a neutrino and a charged particle in plasma leads to neutrino spin flip. The energy released in supernova implosion is taken partly away by sterile neutrinos without further interactions. In this scenario the neutrino magnetic moment should be bounded because of the observed neutrino signal of SN 1987A [11].

Our paper shows that the participation of the exotic couplings of the right-handed neutrinos can modify both astrophysical considerations. The right-handed neutrino is no longer “sterile”. The total cross section for $\nu_e e^-$ scattering with the coupling constants from the current data can be calculated from our general formulas (see Fig. 2). In this scenario the right-handed neutrinos can be detected by neutrino detectors and could help simultaneously to transfer the energy to presupernova envelope. Because of the SNO results [12] and comparison of signals in the Homestake [13] and Super-Kamiokande [14] experiments, we came to conclusion that solar neutrinos undergo the chirality conversion and right-handed neutrinos do interact via the exotic (S , T , P) charged and neutral currents.

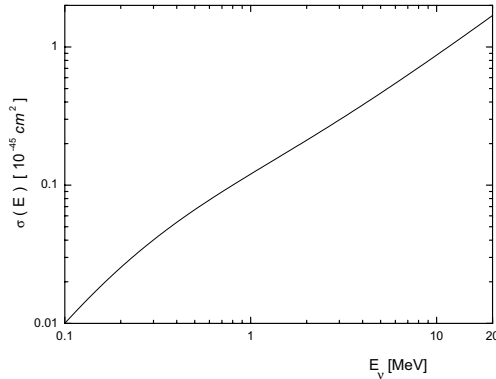


Fig. 2. Plot of the total cross section $\sigma(E)$ as a function of right-handed ($\hat{\eta}_\nu \cdot \hat{q} = 1$) neutrino energy E_ν for the $(\nu_e e^-)$ scattering. The exotic scalar coupling $c_S^R = g_{LL}^S + g_{LR}^S = 0.550 + 0.125 = 0.675$ of right-handed electron neutrinos is used.

If the conversions $\nu_{eL} \rightarrow \nu_{eR}$ in the Sun are possible, the azimuthal asymmetry of the recoil electrons generated by the interference terms between the standard $(V, A)_L$ and exotic S_R couplings should occur. If one assumes that a survival probability for the left-handed ${}^7\text{Be}$ -neutrinos is equal to $P_{eL} = 0.5$, the value of the transverse neutrino polarization as a function of this P_{eL} will be large, $|\eta'_\nu{}^\perp| = 2\sqrt{P_{eL}(1 - P_{eL})} = 1$. It means that in this case $\hat{\eta}_\nu \cdot \hat{q} = 1 - 2 \cdot P_{eL} = 0$, see Eq. (9) in [15]. The equation on the $|\eta'_\nu{}^\perp|$ arises from the density matrix for the relativistic neutrino chirality.

4. Conclusions

In this paper, we show that the scattering of the polarized electron-neutrino beam on the unpolarized electron target may be sensitive to the interference effects between the l- and r-handed neutrinos in the differential cross section for the $(\nu_e e^-)$ scattering. The terms with the interference between the $(V, A)_L$ and S_R couplings do not vanish in the massless neutrino limit and depend on the azimuthal angle between the outgoing electron momentum and the transverse neutrino polarization. The non-vanishing interferences would generate the azimuthal asymmetry of the recoil electrons. That would be the direct signature of the r-handed neutrinos in the $(\nu_e e^-)$ scattering. We also show that the participation of the exotic couplings of the r-handed neutrinos can modify astrophysical considerations. The r-handed neutrino is no longer sterile.

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