Eur Phys J C **32**, s01, s151–s164 (2003)
DOI: 10.1140/epjcd/s2003-01-012-6

EPJ C direct
electronic only

Right-handed Dirac neutrinos in νe^- scattering and azimuthal asymmetry in recoil electron event rates

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Received: 1 Jul 2003 / Accepted: 28 Jul 2003 / Published online: 2 Sep 2003

Abstract. In this paper a scenario with the participation of the exotic scalar S, tensor T and pseudoscalar P couplings of the right-handed neutrinos in addition to the standard vector V, axial A couplings of the left-handed neutrinos in the low-energy $(\nu_\mu e^-)$ and $(\nu_e e^-)$ scattering processes is considered. Neutrinos are assumed to be massive Dirac fermions and to be polarized. Both reactions are studied at the level of the four-fermion point interaction. The main goal is to show that the physical consequence of the presence of the right-handed neutrinos is an appearance of the azimuthal asymmetry in the angular distribution of the recoil electrons caused by the non-vanishing interference terms between the standard and exotic couplings, proportional to the transverse neutrino polarization vector. The upper limits on the expected effect of this asymmetry for the low-energy neutrinos ($E_\nu < 1\,MeV$) are found. We also show that if the neutrino helicity rotation ($\nu_L \to \nu_R$) in the solar magnetic field takes place, the similar effect of the azimuthal asymmetry of the recoil electrons scattered by the solar neutrinos should be observed. This effect would also come from the interference terms between the standard $(V, A)_L$ and exotic $(S, T, P)_R$ couplings. New-type neutrino detectors with good angular resolution could search for the azimuthal asymmetry in event number.

PACS: 13.15.+g, 13.88.+e

1 Introduction

The standard vector-axial $(V - A)$ structure of the neutral and charged weak interactions describes only what has been measured so far. We mean here the measurement of the electron helicity [1], the indirect measurement of the neutrino helicity [2], the asymmetry in the distribution of the electrons from β-decay [3] and the experiment with muon decay [4] which confirmed parity violation [5]. Feynman, Gell-Mann and independently Sudarshan, Marshak [6] established that only left-handed vector V, axial A couplings can take part in weak interactions because this yields the maximum symmetry breaking under space inversion, under charge conjugation; the two-component neutrino theory of negative helicity; the conservation of the combined symmetry CP and of the lepton number. It means that produced neutrinos (antineutrinos) in $V - A$ interaction can only be left-handed (right-handed). However Wu [7] pointed out that exotic scalar S, tensor T and pseudoscalar P weak interactions may be responsible for the negative electron helicity observed in β-decay. It would suggest that the generated neutrinos (antineutrinos) in the (S, T, P) interactions may also be *right-handed* (*left-handed*). The experimental precision of present measurements still does not rule out the possible participation of the exotic (S, T, P) couplings of the right-handed neutrinos beyond the the Standard Model (SM) [8, 9, 10].

So Sromicki at the PSI [11] searched for T-odd transverse electron polarization in ^8Li β-decay. Armbruster *et al.* [12] measured the energy spectrum of electron-neutrinos ν_e from μ-decay at rest in the KARMEN experiment using the reaction $^{12}C(\nu_e, e^-)^{12}N_{g.s.}$. They gave the upper limit on the magnitude of interference between scalar S and tensor T couplings. Shimizu *et al.* [13] determined the ratio of the strengths of scalar and tensor couplings to the standard vector coupling in $K^+ \to \pi^0 + e^+ + \nu_e$ decay at rest assuming the only left-handed neutrinos for all interactions. Bodek *et al.* at the PSI [14] looked for the evidence of the violation of time reversal invariance measuring T-odd transverse positron polarization in μ^+-decay. They also admitted the presence of the only left-handed neutrinos produced in the scalar interaction. The emiT collaboration presented new limits on the time reversal invariance violating D coefficient using the polarized neutron beta-decay [15]. Presently at PSI, the experiment with the decay of polarized neutrons is prepared to search for the time reversal violating effects. A non-zero value of the T-odd transverse component of the electron polarization would be a signal of the violation of this symmetry [16]. The transverse electron polarization for the electrons in the decay of polarized muons was calculated by Shekhter and Okun [17] in 1958. The recent results presented by the DELPHI Collaboration [18] concerning the measurement of the Michel parameters and the neutrino helicity in τ lepton decays still admit the deviation from the standard $V - A$ structure of the charged current weak interaction.

New high-precision low-energy tests of the Lorentz structure using the electron-neutrinos coming from the strong and polarized low-energy artificial neutrino source or from the Sun would be sensitive to the effects caused by the interference terms between the standard $(V, A)_L$ couplings of the left-handed neutrinos and exotic $(S, T, P)_R$ couplings of the right-handed neutrinos in the neutrino-electron scattering.

So far the neutrino-electron scattering was proposed to measure the azimuthal asymmetry in the recoil electron event rates produced by the non-zero neutrino magnetic moments in the case of the solar neutrinos [19, 20]. This asymmetry is caused by the non-vanishing interference between the weak and electro-magnetic interaction amplitudes, proportional to μ_ν, and depends on the azimuthal angle between the transverse component of the neutrino polarization and the momentum of the outgoing recoil electron.

The first concept of the use of the artificial neutrino source comes from Alvarez who proposed a ^{65}Zn [21]. The ^{51}Cr and ^{37}Ar neutrino sources were proposed by Raghavan [22] in 1978 and Haxton [23] in 1988, respectively. The idea of using the artificial neutrino source (reactor neutrinos) to search for the neutrino magnetic moments was first proposed by Vogel and Engel [24]. The strong ^{51}Cr source was used for the calibration of the GALLEX neutrino experiment [25]. Miranda *et al.* [26] proposed the use of the ^{51}Cr source to probe the gauge structure of the electroweak interaction. Currently at Gran Sasso, the Borexino neutrino experiment [27] with the unpolarized ^{51}Cr source is designed to search for the neutrino magnetic moment. There are also proposed the other experiments to test the non-standard properties of neutrinos, in which both the recoil electron scattering angle and the azimuthal angle would be measured with good precision: the Hellaz [28], the Heron [29].

In this paper, we show that there is the other possible scenario of the appearance of the azimuthal asymmetry in the differential cross section for the neutrino-electron scattering. The participation of the exotic $(S,T,P)_R$ couplings in addition to the standard $(V,A)_L$ couplings can generate the azimuthal asymmetry in the event number because in the final state (after scattering) all the neutrinos are left-handed, and the interference terms between the standard and exotic couplings do not depend on the neutrino mass. The main goal is to find the upper limits on the expected magnitude of the azimuthal asymmetry in the angular distribution of the recoil electrons for the low-energy $(\nu_\mu e^-)$ and $(\nu_e e^-)$ scattering processes $(E_\nu = 0.746\, MeV, E_\nu = 0.863\, MeV)$, using the current limits on the non-standard couplings [30]. This paper is also a generalization of the considerations made in the [31]. The obtained results are analyzed in the context of the future low-energy high-precision neutrino experiments.

In our considerations the system of natural units with $\hbar = c = 1$, Dirac-Pauli representation of the γ-matrices and the $(+,-,-,-)$ metric are used [32].

2 Muon capture by proton as production process of neutrinos

To show how the transverse components of the neutrino polarization, both T-even and T-odd, may appear, we use the reaction of the muon capture by proton $(\mu^- + p \to n + \nu_\mu)$ as a production process of muon-neutrinos. The production plane is spanned by the direction of the initial muon polarization $\hat{\mathbf{P}}_\mu$ and of the outgoing neutrino momentum $\hat{\mathbf{q}}$, Fig. 1. $\hat{\mathbf{P}}_\mu$ and $\hat{\mathbf{q}}$ are assumed to be perpendicular to each other because this leads to the unique conclusions as to the possible presence of the right-handed neutrinos. Govaerts and Lucio-Martinez [33] considered the nuclear muon capture on the proton and ^3He both within and beyond SM admitting the general Lorentz invariant four-fermion contact interaction and assuming the Dirac massless neutrino. However, they did not calculate the neutrino observables. One assumes that the outgoing neutrino flux is a mixture of the left-handed neutrinos produced in the standard $V-A$ charged weak interaction and the right-handed ones produced in the exotic scalar S, pseudoscalar P, tensor T charged weak interactions. In this scenario the interacting muon is always left-handed. The complex fundamental coupling constants are denoted as C_V^L, C_A^L and C_S^R, C_P^R, C_T^R respectively to the outgoing neutrino L- and

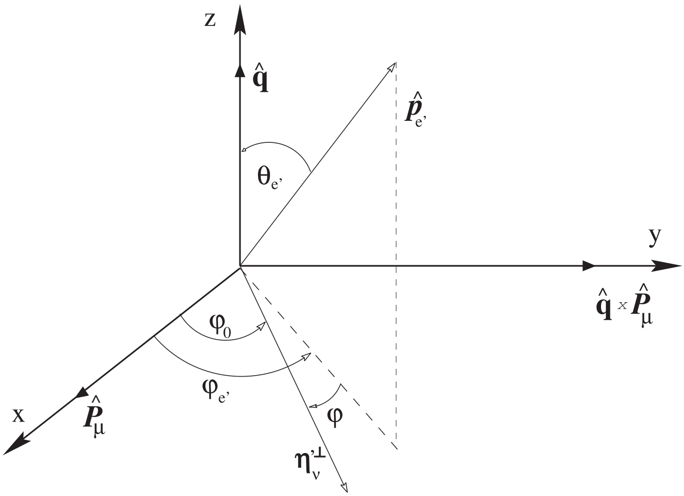

Fig. 1. The production plane and reaction plane for ν_μ neutrinos with the transverse neutrino polarization vector $\boldsymbol{\eta}_{\boldsymbol{\nu}}^{\prime\perp}$

R-chirality:

$$\begin{aligned}\mathcal{M}_{\mu^-} \;=\; & (C_V^L + 2Mg_M)(\overline{u}_\nu\gamma_\lambda(1-\gamma_5)u_\mu)(\overline{u}_n\gamma^\lambda u_p) \\ & + (C_A^L + m_\mu\frac{q}{2M}g_P)(\overline{u}_\nu i\gamma_5\gamma_\lambda(1-\gamma_5)u_\mu)(\overline{u}_n i\gamma^5\gamma^\lambda u_p) \\ & + C_S^R(\overline{u}_\nu(1-\gamma_5)u_\mu)(\overline{u}_n u_p) + C_P^R(\overline{u}_\nu\gamma_5(1-\gamma_5)u_\mu)(\overline{u}_n\gamma_5 u_p) \\ & + C_T^R(\overline{u}_\nu\sigma_{\lambda\,\rho}(1-\gamma_5)u_\mu)(\overline{u}_n\sigma^{\lambda\,\rho}u_p),\end{aligned} \tag{1}$$

where g_M, g_P - the induced 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 value of the neutrino momentum, its energy, its mass and the nucleon mass; $u_p, \overline{u}_n$ - the Dirac bispinors of initial proton and final neutron; $u_\mu, \overline{u}_\nu$ - the Dirac bispinors of initial muon and final neutrino.

The received formulas for the neutrino observables, in the case of non-vanishing neutrino mass ($m_\nu \neq 0$), when the induced couplings are enclosed and $\hat{\mathbf{P}}_\mu$, $\hat{\mathbf{q}}$ are perpendicular to each other ($(\hat{\mathbf{P}}_\mu \cdot \hat{\mathbf{q}}) = 0$), are as follows:
T-even transverse component of the neutrino polarization

$$\begin{aligned}< \mathbf{S}_\nu \cdot \hat{\mathbf{P}}_\mu >_f = & \frac{|\,\phi_\mu(0)\,|^2}{4\pi}|\mathbf{P}_\mu| Re\{(1 + \frac{q}{E_\nu}\frac{q}{2M})(C_V^L + 2Mg_M)C_S^{R*} \\ & + \frac{q}{E_\nu}\frac{q}{2M}(C_A^L + m_\mu\frac{q}{2M}g_P)C_P^{R*} + 2\frac{q}{E_\nu}\frac{q}{2M}(C_V^L + 2Mg_M)C_T^{R*} \\ & + 2(1 + \frac{q}{E_\nu}\frac{q}{2M})(C_A^L + m_\mu\frac{q}{2M}g_P)C_T^{R*} \\ & + \frac{1}{2}\frac{m_\nu}{E_\nu}(|\,C_V^L + 2Mg_M\,|^2 - |\,C_A^L + m_\mu\frac{q}{2M}g_P\,|^2 + |\,C_S^R\,|^2 - 2\,|\,C_T^R\,|^2)\}.\end{aligned} \tag{2}$$

T-odd transverse component of the neutrino polarization:

$$< \mathbf{S}_\nu \cdot (\hat{\mathbf{P}}_\mu \times \hat{\mathbf{q}}) >_f = \frac{\mid \phi_\mu(0) \mid^2}{4\pi} |\mathbf{P}_\mu| Im\{-(\frac{q}{E_\nu} + \frac{q}{2M})(C_V^L + 2Mg_M)C_S^{R*} \quad (3)$$
$$- \frac{q}{2M}(C_A^L + m_\mu \frac{q}{2M} g_P)C_P^{R*} - 2\frac{q}{2M}(C_V^L + 2Mg_M)C_T^{R*}$$
$$- 2(\frac{q}{E_\nu} + \frac{q}{2M})(C_A^L + m_\mu \frac{q}{2M} g_P)C_T^{R*} + 2\frac{m_\nu}{E_\nu}\frac{q}{2M}(C_S^R C_T^{R*} - C_T^R C_P^{R*})\},$$

where $\mathbf{S}_\nu$ - th operator of the neutrino spin; $|\mathbf{P}_\mu|$ - the value of the muon polarization in $1s$ state; $\phi_\mu(0)$ - the value of the large radial component of the muon Dirac bispinor for $r = 0$. The above neutrino observables are calculated with the use of the density matrix of the final state.

It can be noticed that the neutrino observables consist only of the interference terms between the standard $(V, A)_L$ couplings of the left-handed neutrinos and exotic $(S, T, P)_R$ ones of the right-handed neutrinos in the limit of vanishing neutrino mass. It can be understood as the interference between the neutrino waves of negative and positive chirality. There is no contribution to these observables from the SM in which neutrinos are only left-handed and massless. The mass terms in the above neutrino observables give a very small contribution in relation to the main one coming from the interference terms and they are neglected in the considerations. If one assumes the production of the only left-handed neutrinos in all the interactions, i.e. both for the standard $V-A$ and (S, T, P) interactions, there is no interference between the standard $C_{V,A}^L$ and $C_{S,T,P}^L$ couplings in the limit of vanishing neutrino mass. We see that the induced couplings enter additively to the fundamental $C_{V,A}^L$ couplings and they are omitted in the considerations because their presence does not change qualitatively the conclusions concerning the transverse neutrino polarization.

All the fundamental coupling constants $C_{V,A}^L, C_{S,T,P}^R$ can be expressed by the couplings $g_{\epsilon\mu}^\gamma$ for the normal and inverse muon decay [30], assuming the universality of weak interactions. Here, $\gamma = S, V, T$ indicates a scalar, vector, tensor interaction; $\epsilon, \mu = L, R$ indicate the chirality of the electron or muon and the neutrino chiralities are uniquely determined for given γ, ϵ, μ. We get the following relations:

$$C_V^L = A(g_{LL}^V + g_{RL}^V), \; -C_A^L = A(g_{LL}^V - g_{RL}^V), \quad (4)$$

$$C_S^R = A(g_{LL}^S + g_{RL}^S), \; -C_P^R = A(g_{LL}^S - g_{RL}^S), \; C_T^R = A(g_{LL}^T + g_{RL}^T), \quad (5)$$

where $A \equiv (4G_F/\sqrt{2})cos\theta_c$, $G_F = 1.16639(1) \times 10^{-5} GeV^{-2}$ is the Fermi coupling constant [30], θ_c is the Cabbibo angle. We calculate the lower limits on the $C_{V,A}^L$ and upper limit on the $C_{S,T,P}^R$, using the current data [30]: $|C_V^L| > 0.850\,A$, $|C_A^L| > 1.070\,A$, $|C_S^R| < 0.974\,A$, $|C_P^R| < 0.126\,A$, $|C_T^R| < 0.122\,A$. In this way, we get the upper bound on the magnitude of the transverse neutrino polarization vector proportional to the value of the muon polarization:

$$|\boldsymbol{\eta}_{\boldsymbol{\nu}}^{\perp}| = \frac{\sqrt{< \mathbf{S}_\nu \cdot (\hat{\mathbf{P}}_\mu \times \hat{\mathbf{q}}) >_f^2 + < \mathbf{S}_\nu \cdot \hat{\mathbf{P}}_\mu >_f^2}}{s < \mathbf{1} >_\mathbf{f}} \leq 0.414\,|\mathbf{P}_\mu| \tag{6}$$

$$|\boldsymbol{\eta}_{\boldsymbol{\nu}}^{\prime\perp}| = \frac{|\boldsymbol{\eta}_{\boldsymbol{\nu}}^{\perp}|}{|\mathbf{P}_\mu|} \leq 0.414, \tag{7}$$

where s is the neutrino spin ($s = 1/2$) and the probability of muon capture $< \mathbf{1} >_\mathbf{f}$ is of the form:

$$\begin{aligned} < \mathbf{1} >_\mathbf{f} = & \frac{|\phi_\mu(0)|^2}{4\pi}\{(1 + 2\frac{q}{E_\nu}\frac{q}{2M}) \mid C_V^L + 2Mg_M \mid^2 + \mid C_S^R \mid^2 \\ & + (3 + 2\frac{q}{E_\nu}\frac{q}{2M}) \mid C_A^L + m_\mu \frac{q}{2M} g_P \mid^2 + (12 + 8\frac{q}{E_\nu}\frac{q}{2M}) \mid C_T^R \mid^2 \\ & + 2Re[\frac{q}{E_\nu}\frac{q}{M}(-(C_V^L + 2Mg_M)(C_A^{L*} + m_\mu \frac{q}{2M} g_P^*) \\ & + C_T^R C_P^{R*} + C_S^R C_T^{R*}) + \frac{m_\nu}{E_\nu}((C_V^L + 2Mg_M)C_S^{R*} \\ & - 6(C_A^L + m_\mu \frac{q}{2M} g_P)C_T^{R*})]\}. \end{aligned} \tag{8}$$

The obtained limit on the $|\boldsymbol{\eta}_{\boldsymbol{\nu}}^{\perp}|$ has to be divided by $|\mathbf{P}_\mu|$ to have the physical value of the $|\boldsymbol{\eta}_{\boldsymbol{\nu}}^{\prime\perp}|$ generated by the exotic (S, T, P) interactions. It means that the value of the longitudinal neutrino polarization is equal to $\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}} = -0.910$. The formula for the T-even longitudinal component of the neutrino polarization is as follows:

$$\begin{aligned} < \mathbf{S}_\nu \cdot \hat{\mathbf{q}} >_f = & \frac{|\phi_\mu(0)|^2}{4\pi}\{-(\frac{3}{2}\frac{q}{E_\nu} + \frac{q}{2M}) \mid C_A^L + m_\mu \frac{q}{2M} g_P \mid^2 \\ & - (\frac{1}{2}\frac{q}{E_\nu} + \frac{q}{2M}) \mid C_V^L + 2Mg_M \mid^2 + \frac{1}{2}\frac{q}{E_\nu} \mid C_S^R \mid^2 + (6\frac{q}{E_\nu} + 8\frac{q}{2M}) \mid C_T^R \mid^2 \\ & + 2Re[\frac{q}{2M}(C_V^L + 2Mg_M)(C_A^{L*} + m_\mu \frac{q}{2M} g_P^*) + \frac{q}{2M} C_S^R C_T^{R*} + \frac{q}{2M} C_T^R C_P^{R*} \\ & - \frac{m_\nu}{E_\nu}\frac{q}{2M}(\frac{1}{2}(C_A^L + m_\mu \frac{q}{2M} g_P)C_P^{R*} + (C_A^L + m_\mu \frac{q}{2M} g_P)C_T^{R*} \\ & + \frac{1}{2}(C_V^L + 2Mg_M)C_S^{R*} + (C_V^L + 2Mg_M)C_T^{R*})]\}. \end{aligned} \tag{9}$$

We see that in the longitudinal neutrino polarization and the probability of muon capture, the occurrence of the interference terms between the standard $C_{V,A}^L$ couplings and exotic $C_{S,T,P}^R$ ones depends explicitly on the neutrino mass. The dependence on the neutrino mass causes the "conspiracy" of the interference terms and makes the measurement of the relative phase between these couplings impossible because term $(m_\nu/E_\nu)(q/2M)$ is very small and the standard $C_{V,A}^L$ couplings of the left-handed neutrinos dominate in agreement with the SM prediction. Therefore, the neutrino observables in which such difficulties do not appear are proposed. In this way, the conclusions as to the existence of the right-handed neutrinos can depend on the type of measured observables.

If $m_\nu \to 0$, $q/E_\nu \to 1$ and the neutrino mass terms vanish in all the observables.

3 Neutrino-electron scattering as detection process

The produced mixture of the muon-neutrinos is detected in the neutral current weak interaction. We assume that the incoming left-handed neutrinos are detected in the $V-A$ neutral weak interaction, while the initial right-handed ones are detected in the exotic scalar S, tensor T and pseudoscalar P neutral weak interactions. Then in the final state all the neutrinos are left-handed.

To describe $(\nu_\mu e^-)$ scattering the following observables are used: $\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}}$ - the unit 3-vector of the initial neutrino polarization in its rest frame, $\mathbf{q}$ - the incoming neutrino momentum, $\mathbf{p_{e'}}$ - the outgoing electron momentum. The coupling constants are denoted as g_V^L, g_A^L and g_S^R, g_T^R, g_P^R respectively to the incoming neutrino L- and R-chirality:

$$\begin{aligned}\mathcal{M}_{\nu e} &= \frac{G_F}{\sqrt{2}}\{(\overline{u}_{e'}\gamma_\alpha(g_V^L - g_A^L\gamma_5)u_e)(\overline{u}_{\nu'}\gamma^\alpha(1-\gamma_5)u_\nu) \\ &+ \frac{1}{2}[(g_S^R(\overline{u}_{e'}u_e)(\overline{u}_{\nu'}(1+\gamma_5)u_\nu) + g_T^R(\overline{u}_{e'}\sigma_{\alpha\beta}u_e)(\overline{u}_{\nu'}\sigma^{\alpha\beta}(1+\gamma_5)u_\nu) \\ &+ (g_P^R(\overline{u}_{e'}\gamma_5 u_e)(\overline{u}_{\nu'}\gamma_5(1+\gamma_5)u_\nu)]\},\end{aligned} \tag{10}$$

where u_e and $\overline{u}_{e'}$ (u_ν and $\overline{u}_{\nu'}$) are the Dirac bispinors of the initial and final electron (neutrino) respectively.

3.1 Laboratory differential cross section

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

$$\begin{aligned}\frac{d^2\sigma}{dyd\phi_{e'}} &= (\frac{d^2\sigma}{dyd\phi_{e'}})_{(V,A)} \\ &+ (\frac{d^2\sigma}{dyd\phi_{e'}})_{(S,T,P)} + (\frac{d^2\sigma}{dyd\phi_{e'}})_{(VS)} + (\frac{d^2\sigma}{dyd\phi_{e'}})_{(AT)},\end{aligned} \tag{11}$$

$$\begin{aligned}(\frac{d^2\sigma}{dyd\phi_{e'}})_{(V,A)} &= \frac{E_\nu m_e}{4\pi^2}\frac{G_F^2}{2}\{(1-\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}}\cdot\hat{\mathbf{q}})[(g_V^L+g_A^L)^2 \\ &+ (g_V^L-g_A^L)^2(1-y)^2 - \frac{m_e y}{E_\nu}((g_V^L)^2-(g_A^L)^2)]\},\end{aligned} \tag{12}$$

$$\begin{aligned}(\frac{d^2\sigma}{dyd\phi_{e'}})_{(S,T,P)} &= \frac{E_\nu m_e}{4\pi^2}\frac{G_F^2}{2}(1+\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}}\cdot\hat{\mathbf{q}})\{\frac{1}{8}y(y+2\frac{m_e}{E_\nu})|g_S^R|^2 + \frac{1}{8}y^2|g_P^R|^2 \\ &+ ((2-y)^2 - \frac{m_e}{E_\nu}y)|g_T^R|^2 + y(y-2)\frac{1}{2}[Re(g_S^R g_T^{*R}) \\ &+ Re(g_P^R g_T^{*R})]\},\end{aligned} \tag{13}$$

$$\begin{aligned}(\frac{d^2\sigma}{dyd\phi_{e'}})_{(VS)} &= \frac{E_\nu m_e}{4\pi^2}\frac{G_F^2}{2}\{\sqrt{y(y+2\frac{m_e}{E_\nu})}[-\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}}\cdot(\hat{\mathbf{p}}_{\mathbf{e'}}\times\hat{\mathbf{q}})Im(g_V^L g_S^{R*}) \\ &+ (\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}}\cdot\hat{\mathbf{p}}_{\mathbf{e'}})Re(g_V^L g_S^{R*})] - y(1+\frac{m_e}{E_\nu})(\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}}\cdot\hat{\mathbf{q}})Re(g_V^L g_S^{R*})\},\end{aligned} \tag{14}$$

$$\begin{aligned}(\frac{d^2\sigma}{dyd\phi_{e'}})_{(AT)} &= \frac{E_\nu m_e}{4\pi^2}\frac{G_F^2}{2}\{2\sqrt{y(y+2\frac{m_e}{E_\nu})}[-\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}}\cdot(\hat{\mathbf{p}}_{\mathbf{e'}}\times\hat{\mathbf{q}})Im(g_A^L g_T^{R*}) \\ &+ (\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}}\cdot\hat{\mathbf{p}}_{\mathbf{e'}})Re(g_A^L g_T^{R*})] - 2y(1+\frac{m_e}{E_\nu})(\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}}\cdot\hat{\mathbf{q}})Re(g_A^L g_T^{R*})\},\end{aligned} \tag{15}$$

where

$$y \equiv \frac{T_e}{E_\nu} = \frac{m_e}{E_\nu}\frac{2cos^2\theta_{e'}}{(1+\frac{m_e}{E_\nu})^2 - cos^2\theta_{e'}}, \quad (16)$$

where y - the ratio of the kinetic energy of the recoil electron T_e to the incoming neutrino energy E_ν, $\theta_{e'}$ - 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), m_e - the electron mass, $\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}}$ - the longitudinal polarization of the incoming neutrino, $\phi_{e'}$ - the angle between the production plane and the reaction plane spanned by the $\hat{\mathbf{p}}_{e'}$ and $\hat{\mathbf{q}}$, Fig. 1. All the calculations are made with the Michel-Wightman density matrix [34] for the polarized incoming neutrinos in the limit of vanishing neutrino mass (see Appendix). The interference terms between the standard and exotic couplings, Eqs. (14, 15), include only the contributions from the transverse components of the initial neutrino polarization, both T-even and T-odd:

$$\begin{aligned}(\frac{d^2\sigma}{dyd\phi_{e'}})_{(VS)} + (\frac{d^2\sigma}{dyd\phi_{e'}})_{(AT)} &= B|\boldsymbol{\eta}_{\boldsymbol{\nu}}^{'\perp}|\sqrt{\frac{m_e}{E_\nu}y[2-(2+\frac{m_e}{E_\nu})y]} \quad (17)\\ \times\{|g_V^L||g_S^R|cos(\phi - \alpha_{SV}) &+ 2|g_A^L||g_T^R|cos(\phi-\alpha_{TA})\},\end{aligned}$$

where $\alpha_{SV} \equiv \alpha_S^R - \alpha_V^L$, $\alpha_{TA} \equiv \alpha_T^R - \alpha_A^L$- the relative phases between the g_S^R, g_V^L and g_T^R, g_A^L couplings respectively, ϕ - the angle between the reaction plane and the transverse neutrino polarization vector and is connected with the $\phi_{e'}$ in the following way; $\phi = \phi_0 - \phi_{e'}$, where ϕ_0 - the angle between the production plane and the transverse neutrino polarization vector, Fig. 1.

The presence of the interference terms between the standard and exotic couplings in the cross section depending on the $\phi_{e'}$ generates the azimuthal asymmetry in the angular distribution of the recoil electrons. Because the right-handed neutrinos are produced and detected in the exotic (S, T, P) interactions, one uses the same upper limits on the g_S^R, g_T^R, g_P^R as for the C_S^R, C_T^R, C_P^R, assuming the universality of weak interactions. We take the values $|\boldsymbol{\eta}_{\boldsymbol{\nu}}^{'\perp}| = 0.414$, $\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}} = -0.910$ for the muon-neutrinos to get the upper limit on the expected effect of the azimuthal asymmetry in the cross section. The situation is illustrated in the Fig. 2. The plot for the SM is made with the use of the present experimental values for $g_V^L = -0.040 \pm 0.015$, $g_A^L = -0.507 \pm 0.014$ [30], when $\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}} = -1$, Fig. 2 (solid line). If one integrates over the $\phi_{e'}$, both interference terms vanish and the cross section $d\sigma/dy$ consists of only two terms.

If one assumes the production of only left-handed neutrinos in the standard $(V-A)$ and non-standard (S, T, P) weak interactions, there is no interference between the $g_{V,A}^L$ and $g_{S,T,P}^L$ couplings in the differential cross section, when $m_\nu \to 0$, and the azimuthal distribution of the recoil electrons is symmetric. We do not consider this scenario.

Considering the low-energy intense artificial (^{51}Cr) and natural (Sun) electron-neutrino sources, we show the upper limit on the expected magnitude of the azimuthal asymmetry in the cross section for the electron-neutrinos, Fig. 3. It can be noticed that the possible effect is much larger than for the muon-neutrinos at the same neutrino energy $E_\nu = 0.746\,MeV$. In the case of the

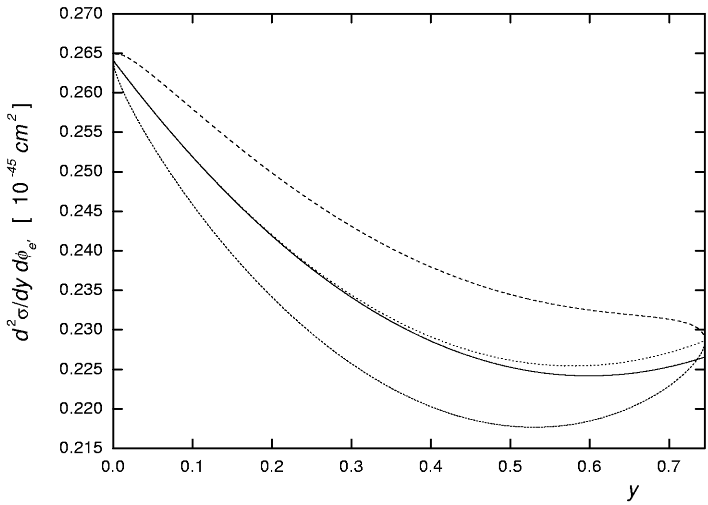

Fig. 2. Plot of the $\frac{d^2\sigma}{dyd\phi_{e'}}$ as a function of y for the $(\nu_\mu e^-)$ scattering, $E_\nu = 0.746\,MeV$; a) SM with the left-handed neutrino (solid line), b) the case of the exotic S, T, P couplings of the right-handed neutrinos for $\phi - \alpha_{SV} = 0, \phi - \alpha_{TA} = 0$ (long-dashed line), $\phi - \alpha_{SV} = \pi, \phi - \alpha_{TA} = \pi$ (short-dashed line) and $\phi - \alpha_{SV} = \pi/2, \phi - \alpha_{TA} = \pi/2$ (dotted line), respectively

$(\nu_e e^-)$ scattering, the charged current weak interaction must be included, i. e. $g_V^L + 1$, $g_A^L + 1$. We use the same upper limits on the exotic couplings as for the g_S^R, g_T^R, g_P^R, assuming the universality of weak interactions. We also take the values $|\boldsymbol{\eta}_{\boldsymbol{\nu}}^{'\perp}| = 0.414$, $\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}} = -0.910$. The plot for the SM is made with the same values of the standard coupling constants as for the $(\nu_\mu e^-)$ process, i. e. $-0.040 + 1$, $-0.507 + 1$, when $\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}} = -1$, Fig. 3 (solid line).

4 Astrophysical sources of right-handed neutrinos – neutrino spin flip

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

$$(\frac{d^2\sigma}{dyd\varphi})_{(V,A)} = (1 - \hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}}) \cdot f(E_\nu, y) \quad = 0. \tag{18}$$

The mechanism of neutrino "spin flip" in the Sun's convection zone is proposed to explain the observed depletion of the solar neutrinos [35]. The most restrictable bound on the neutrino magnetic moment arrives from astrophysical consideration of a supernova explosion. The scattering due to the photon

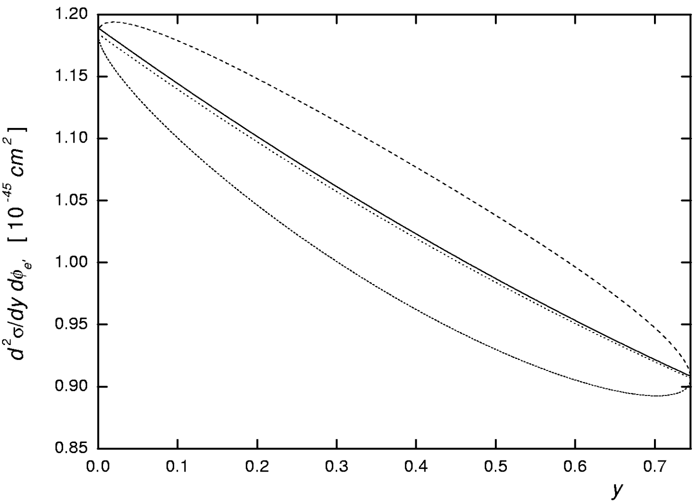

Fig. 3. Plot of the $\frac{d^2\sigma}{dyd\phi_{e'}}$ as a function of y for the $(\nu_e e^-)$ scattering, $E_\nu = 0.746\,MeV$; a) SM with the left-handed neutrino (solid line), b) the case of the exotic S, T, P couplings of the right-handed neutrinos for $\phi - \alpha_{SV} = 0, \phi - \alpha_{TA} = 0$ (long-dashed line), $\phi - \alpha_{SV} = \pi, \phi - \alpha_{TA} = \pi$ (short-dashed line) and $\phi - \alpha_{SA} = \pi/2, \phi - \alpha_{TA} = \pi/2$ (dotted line), respectively

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[36]. Our paper shows that the participation of the exotic couplings of the right-handed neutrinos can modify the 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 (Sect. 2) can be calculated from our general formulas (see Fig. 4). In this scenario the right-handed neutrinos can be detected by neutrino detectors and could help simultaneously to transfer the energy to presupernova envelope.

If the conversions $\nu_{eL} \to \nu_{eR}$ in the Sun are possible, the azimuthal asymmetry in the angular distribution of the recoil electrons generated by the interference terms between the standard $(V, A)_L$ and exotic $(S, T, P)_R$ couplings should occur. If one assumes that a survival probability for the left-handed ^7Be-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, $|\boldsymbol{\eta}_\nu^{'\perp}| = 2\sqrt{P_{eL}(1 - P_{eL})} = 1$, (for this case $\hat{\boldsymbol{\eta}}_\nu \cdot \hat{\mathbf{q}} = 1 - 2 \cdot P_{eL} = 0$), see Eq. (9) in [19]. The equation on the $|\boldsymbol{\eta}_\nu^{'\perp}|$ arises from the density matrix for the relativistic neutrino chirality. The situation is illustrated in the Fig. 5 for the same limits on the exotic couplings as for the ^{51}Cr-neutrinos and $E_\nu = 0.863\,MeV$. In this way, the expected effect of the azimuthal asymmetry would be much stronger than for the ^{51}Cr-neutrinos.

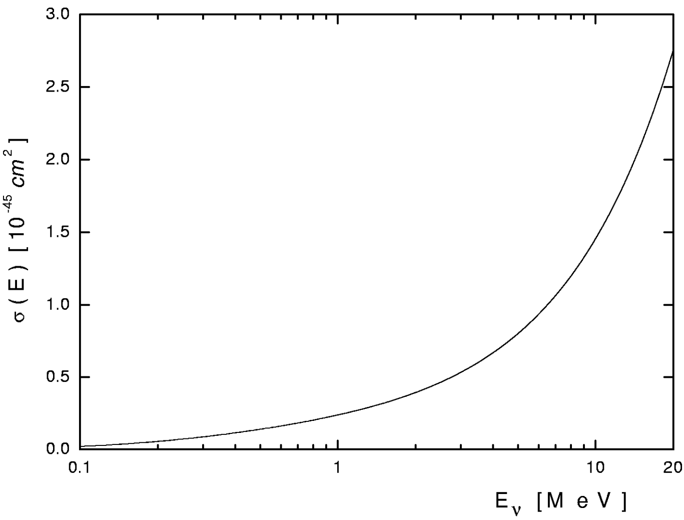

Fig. 4. Plot of the total cross section $\sigma(E)$ as a function of right-handed ($\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}} = 1$) neutrino energy E_ν for the $(\nu_e e^-)$ scattering

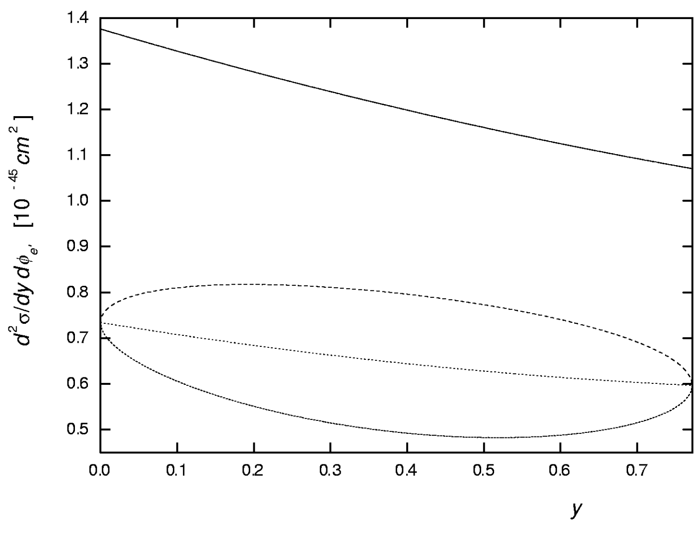

Fig. 5. Plot of the $\frac{d^2\sigma}{dy d\phi_{e'}}$ as a function of y for the $(\nu_e e^-)$ scattering, $E_\nu = 0.863\,MeV$; a) SM with the left-handed neutrino (solid line) for $\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}} = -1$, b) the case of the exotic S, T, P couplings of the right-handed neutrinos for $\phi - \alpha_{SV} = 0, \phi - \alpha_{TA} = 0$ (long-dashed line), $\phi - \alpha_{SV} = \pi, \phi - \alpha_{TA} = \pi$ (short-dashed line) and $\phi - \alpha_{SA} = \pi/2, \phi - \alpha_{TA} = \pi/2$ (dotted line), respectively, when $\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}} = 0$, $|\boldsymbol{\eta}'^{\perp}_{\boldsymbol{\nu}}| = 1$

5 Conclusions

In this paper, we show that the production of the R-handed neutrinos in the exotic (S,T,P) weak interactions in addition to the L-handed ones in the standard $V-A$ weak interaction should manifest in the observation of the azimuthal asymmetry of the electrons recoiled after the subsequent neutrino scattering. This asymmetry would be due to the terms with the interference between $(V,A)_L$ and $(S,T,P)_R$ weak interactions, which stay present even in the limit of massless neutrino. The scenario with interfering L- and R-handed neutrinos could be tested with the intense electron-neutrino beams, e.g. from the artificial polarized ^{51}Cr source, Fig. 3. If the neutrino helicity flip in the solar magnetic field takes place, the similar effect of the azimuthal asymmetry in the event number for the solar neutrinos should appear, Fig. 5 (^7Be-neutrinos). It would indicate the neutrino spin flip scenario ($\nu_L \to \nu_R$) as a possible solution of the observed solar neutrino deficit. In both cases, the azimuthal asymmetry would arise from the interference terms between the standard $(V,A)_L$ and $(S,T,P)_R$ exotic couplings, proportional to the transverse neutrino polarization vector.

It is well-known that according to the SM the angular distribution of the recoil electrons does not depend on the azimuthal angle $\phi_{e'}$, i.e. is the azimuthally symmetric. The detection of the azimuthal asymmetry would be a signature of the R-handed neutrinos. It can be noticed that the expected effect would be much stronger for the low-energy neutrino-electron scattering ($E_\nu < 1\,MeV$) than for the high-energy ones. The artificial neutrino source has to be polarized to have the assigned direction of the transverse neutrino polarization vector with respect to the production plane because it would allow to measure the $\phi_{e'}$. In the case of the solar neutrinos, the $\boldsymbol{\eta}_{\boldsymbol{\nu}}^{'\perp}$ would be directed along the solar magnetic field. The neutrino detectors with the good angular resolution have to observe the direction of the recoil electrons and to analyze all the possible reaction planes corresponding to the given recoil electron scattering angle in order to verify if the azimuthal asymmetry in the cross section appears.

Acknowledgements. This work was supported in part by the grant 2P03B 15522 of The Polish Committee for Scientific Research and by the Foundation for Polish Science.

6 Appendix

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

$$S = (0, \hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}}), \tag{19}$$

$$S' = \frac{\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \mathbf{q}}{E_\nu} \cdot \frac{1}{m_\nu} \begin{pmatrix} E_\nu \\ \mathbf{q} \end{pmatrix} + \begin{pmatrix} 0 \\ \hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \end{pmatrix} - \frac{\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \mathbf{q}}{E_\nu(E_\nu + m_\nu)} \begin{pmatrix} 0 \\ \mathbf{q} \end{pmatrix}, \tag{20}$$

$$S^{0'} = \frac{|\mathbf{q}|}{m_\nu}(\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}}), \quad (21)$$

$$\mathbf{S}' = \frac{E_\nu}{m_\nu}(\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}})\hat{\mathbf{q}} + \hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} - (\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}})\hat{\mathbf{q}}, \quad (22)$$

where $\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}}$ - the unit vector of the initial neutrino polarization in its rest frame. The formulas for the Michel-Wightman density matrix [34] in the case of the polarized neutrino with the non-zero mass,

$$\begin{aligned} \Lambda_\nu^{(s)} &= \sum_{r=1,2} u_r \overline{u}_r \sim [1 + \gamma_5(S^{'\mu}\gamma_\mu)][(q^\mu\gamma_\mu) + m_\nu] \quad (23) \\ &= [(q^\mu\gamma_\mu) + m_\nu + \gamma_5(S^{'\mu}\gamma_\mu)(q^\mu\gamma_\mu) + \gamma_5(S^{'\mu}\gamma_\mu)m_\nu], \end{aligned}$$

$$(S^{'\mu}\gamma_\mu) = \frac{\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \mathbf{q}}{E_\nu m_\nu}(q^\mu\gamma_\mu) - (\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} - \frac{(\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \mathbf{q})\mathbf{q}}{E_\nu(E_\nu + m_\nu)}) \cdot \boldsymbol{\gamma}, \quad (24)$$

$$(S^{'\mu}\gamma_\mu)(q^\mu\gamma_\mu) = \frac{m_\nu}{E_\nu}\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \mathbf{q} - (\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} - \frac{(\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \mathbf{q})\mathbf{q}}{E_\nu(E_\nu + m_\nu)}) \cdot \boldsymbol{\gamma}(q^\mu\gamma_\mu), \quad (25)$$

$$(S^{'\mu}\gamma_\mu)m_\nu = \frac{\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \mathbf{q}}{E_\nu}(q^\mu\gamma_\mu) - m_\nu(\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} - \frac{(\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \mathbf{q})\mathbf{q}}{E_\nu(E_\nu + m_\nu)}) \cdot \boldsymbol{\gamma}, \quad (26)$$

and in the limit of vanishing neutrino mass, we have

$$\lim_{m_\nu \to 0} \Lambda_\nu^{(s)} = [1 + \gamma_5[\frac{\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \mathbf{q}}{|\mathbf{q}|} - (\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} - \frac{(\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \mathbf{q})\mathbf{q}}{|\mathbf{q}|^2}) \cdot \boldsymbol{\gamma}]](q^\mu\gamma_\mu). \quad (27)$$

We see that in spite of the singularities m_ν^{-1} in the longitudinal component $(\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}})$, the Michel-Wightman density matrix, in the limit of vanishing neutrino mass m_ν, remains finite including the transverse component of neutrino polarization.

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