RIGHT-HANDED VECTOR *V* AND AXIAL *A* COUPLINGS IN WEAK INTERACTIONS

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In this paper a scenario admitting the participation of the right-handed vector V_{R} and axial A_{R} couplings with the conservation of the left-handed standard $(V,A)_{\mathrm{L}}$ couplings is considered. The research is based on the muon capture by proton. We consider muon capture at the level of the Fermi theory, whose Hamiltonian describes the four-fermion point (contact) interaction. Neutrinos are assumed to be massive and to be Dirac fermions. We propose neutrino observables, it means transverse components of the neutrino polarization, both T-odd and T-even. That would be a test verifying the participation of the $(V,A)_{\mathrm{R}}$ couplings in muon capture. The measurements of nuclear observables and of longitudinal neutrino polarization do not offer such possibilities because of the suppressing of interferences between the $(V,A)_{\mathrm{L}}$ and $(V,A)_{\mathrm{R}}$ couplings caused by the neutrino mass. Using the current data from μ-decay and inverse μ-decay, the magnitude of effects coming from the transverse components of the neutrino polarization can be determined. Our considerations are model-independent. We give the lower bound of 305 GeV on the mass of the right-handed gauge boson. This limit is compatible with the current bounds on the mass of the W_{R} received from the weak interaction processes at low energy.

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1. Introduction

The present theory of weak interactions (the Standard Model of electroweak interactions [1–3]) describes only what has been measured so far. These are, most of all, the measurements of nuclear observables and of observables for massive leptons. It means the measurement of the electron helicity [4], the indirect measurement of the neutrino helicity [5], the asymmetry in the distribution of the electrons from β-decay [6], the experiment with muon decay confirming parity violation [7]. Basing their inferences on these results, among others, Feynman, Gell-Mann and Sudarshan, Marshak [8, 9] established that only left-handed vector V, axial A couplings are involved 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. The Fermi Hamiltonian, being low-energy approximation of the Salam–Weinberg model, has thus a vector–axial $(V - A)$ structure, and the three remaining scalar S, tensor T, pseudoscalar P couplings are eliminated by the assumption that only left-handed states can take part. The $V - A$ theory has a chiral symmetry.

The investigation of the completeness of the Lorentz structure and of the handedness structure of weak interactions at low energies can be reduced to two main scenarios. The first conception assumes the participation of the scalar S, tensor T and pseudoscalar P couplings in addition to the standard vector V and axial A couplings. Wu [10] indicated explicitly that possibility. According to her, both left-handed $(V, A)_{\mathrm{L}}$ couplings and exotic right-handed $(S, T, P)_{\mathrm{R}}$ couplings may be responsible for the negative electron helicity observed in β-decay. Mursula *et al.* [11] analyzed all the available data on the charged leptonic weak interactions while testing different models which admit the participation of additional (S, T, P) couplings beside the standard (V, A) couplings.

The other conception assumes that the right-handed vector V_{R} and axial A_{R} couplings participate in weak interactions beside left-handed standard $(V, A)_{\mathrm{L}}$ couplings. This scenario is studied and analyzed in this work. There are many theoretical and experimental papers devoted to this problem. The models with $\mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{SU}(2)_{\mathrm{R}} \times \mathrm{U}(1)$ as the gauge group emerged first in the framework of a class of grand unified theories (GUT) [12]. The manifest left-right symmetry model [13] predicts the existence of the additional heavy vector bosons of the masses much larger than the masses of the bosons of the Standard Model. Bég considered the bounds on the admixtures of the right-handed currents obtained from the measurements of the lepton polarization in semileptonic decays and by the determination of the parameters characterizing the spectrum in muon decay. Herczeg model is the generalization of the manifest left-right symmetric model, in which the fermions couple to distinct charged gauge-boson fields W_{L} and W_{R} with the different coupling constants g_{L} and g_{R}, respectively [14]. The effective Hamiltonian has the structure of the four-fermion point interaction, for both muon decay and semileptonic processes. There are many experimental constraints on the possible mass of the right-handed vector bosons W_{R} obtained from weak interaction processes at low energy and from high energy collider experiments. The lower mass limits for the W_{R} received at the Tevatron collider are $M_{\mathrm{R}} \geq 652$ GeV (95% CL, CDF-collaboration [15]) and

$M_{\rm R} \geq 720$ GeV (95% CL, D0-collaboration [16]), respectively. The lower bound obtained from $K_0 - \overline{K_0}$ mass difference is $M_{\rm R} \geq 1.6$ TeV [17]. Jodidio *et al.* [18] measured the positron spectrum from muon decay, which allowed them to give the lower bound of 432 GeV (90% CL) on the possible mass of a new vector boson. Maalampi *et al.* [19] explored the structure of the charged leptonic weak currents in the framework of the $\mathrm{SU}(2)_{\rm L} \times \mathrm{SU}(2)_{\rm R} \times \mathrm{U}(1)$ models. They fitted the parameters of this model to experimental results obtained from pseudoscalar meson decay, muon decay, nuclear β-decay and inverse muon decay. It allowed them to determine the values of the mass ratio of the charged gauge bosons and the mixing angle. Shul'gina [20] introduced the admixtures of the right-handed $(V,A)_{\rm R}$ currents into the interaction lagrangian, which helped to explain, *e.g.*, the neutron paradox. Recent measurements of the longitudinal polarization of the positrons emitted by the polarized ^{107}In and ^{12}N nuclei gave the lower limit of 306 GeV (90% CL) on the mass of the right-handed gauge boson [21]. The recommended lower constraint on the mass of the additional gauge boson is $M_{\rm R} > 549$ GeV [22]. Zrałek *et al.* [23] considered the possibility of the existence of neutrino magnetic moments in the framework of the left-right symmetry models. That could be especially interesting in the context of the solar neutrino deficit. However, all these limits are *model-dependent* and they can be considerably weakened. The stringent bound $M_{\rm R} \geq 1.6$ TeV can be relaxed to the 300 GeV range [24,25] if one assumes that the Cabbibo-Kobayashi-Maskawa matrix elements for the right-handed quarks and for the left-handed quarks are not identical, and also that the $\mathrm{SU}(2)_{\rm L,R}$ gauge coupling constants are distinct, $g_{\rm L} \neq g_{\rm R}$. Therefore one should give the bounds for the nonstandard $(V,A)_{\rm R}$ couplings *without model assumptions* [26]. There are the present limits on all possible coupling constants obtained from normal muon decay and inverse muon decay [22].

However, to verify uniquely a scenario admitting the possible participation of the right-handed $(V,A)_{\rm R}$ couplings beside the standard $(V,A)_{\rm L}$ couplings in weak interactions at low energies, one proposes *neutrino observables* in the process of μ-capture by proton. Both T-odd and T-even transverse components of the neutrino polarization are taken into account. Only in the quantities of this type the interference terms between the standard $(V,A)_{\rm L}$ and nonstandard $(V,A)_{\rm R}$ couplings appear and they do not depend *explicite* on the neutrino mass. It is analogical to the situation analyzed by Lee and Yang in β-decay [27]. They proposed an observable which was pseudoscalar under space inversion to determine uniquely if parity is violated. Only in this quantity interferences between couplings for the parity-conserving interactions C and the parity-nonconserving interactions C' can appear. Using the current data from μ-decay and inverse μ-decay, the magnitude of effects coming from the transverse components of the neutrino polarization can be determined. At the end, we can derive the lower limit on the mass of the right-handed gauge bosons (assuming, for example, manifest left-right symmetry).

Recently Sromicki [28] measured the CP-odd transverse electron polarization in ^{8}Li β-decay. The final results indicated the compatibility with the Standard Model prediction and CP-conservation in β-decay. Armbruster *et al.* [29] measured the energy spectrum of electron neutrinos ν_e from μ-decay at rest in the KARMEN experiment using the reaction $^{12}\mathrm{C}(\nu_e, e^-)^{12}\mathrm{N}_{\mathrm{g.s.}}$. They determined the upper limit of $|g^S_{\mathrm{RL}} + 2g^T_{\mathrm{RL}}| \leq 0.78$ (90% CL) on the possible interference term between scalar S and tensor T couplings. Abe *et al.* [30] searched for T-odd transverse components of the muon polarization in $K^+ \to \pi^0 + \mu^+ + \nu_\mu$ decay at rest. They pointed out that the contribution to this observable from the Standard Model is of the order of 10^{-7}, so nonzero values of this quantity would indicate the beginning of new physics beyond the Standard Model. In our case, there is no contribution to the transverse neutrino polarization from the Standard Model (massless Dirac neutrinos), so nonzero values of such observable would be the unique proof of the participation of the $(V,A)_{\mathrm{R}}$ couplings and of the production of the right-handed neutrinos. These last experiments made at high precision show that the problem of the completeness of the Lorentz structure and of the handedness structure of weak interactions is still explored.

The purpose of this paper is motivated by the desire to test how right-handed vector V_{R} and axial A_{R} couplings with the participation of left-handed standard $(V,A)_{\mathrm{L}}$ couplings enter different observables such as: longitudinal and transverse neutron polarization, longitudinal neutrino polarization and, most of all, transverse neutrino polarization.

The structure of the work is as follows: Sect. 2 concentrates on the qualitative description of muon capture and on the assumptions concerning the calculations. In Sect. 3 the results obtained for the transverse, longitudinal neutron polarization and longitudinal neutrino polarization, among others, are presented. In Sect. 4 the results for the transverse neutrino polarization are dealt with. Sect. 5 gives the conclusions. In these considerations the system of natural units with $\hbar = c = 1$, Dirac Hermitian matrices γ_λ and the four-plus metric are used [31].

2. Muon capture by proton

The research is based on the reaction of the muon capture by proton $\mu^- + p \to n + \nu_\mu$. In the Standard Model it is a coherent low-energy process at the lepton-quark level. The typical energy transfer is of the order of 1 MeV and therefore the space-time area within the interactions coincides with the size of the muonic atom, because of that both hadrons and leptons participating in this process are point objects. In the light of the above muon capture is considered at the level of the Fermi theory, whose Hamiltonian describes the local, derivative-free, lepton-number-conserving, four-fermion point (contact) interaction. Right-handed $(V,A)_{\rm R}$ couplings are assumed to take part in muon capture in addition to left-handed standard $(V,A)_{\rm L}$ couplings. The coupling constants are denoted as $C_V^{\rm L}$, $C_A^{\rm L}$ and $C_V^{\rm R}$, $C_A^{\rm R}$ respectively to the neutrino handedness.

$$\begin{aligned} H_{\mu^-} = {} & C_V^{\rm L}(\overline{\Psi}_\nu\gamma_\lambda(1+\gamma_5)\Psi_\mu)(\overline{\Psi}_n\gamma_\lambda\Psi_p) \\ & + C_A^{\rm L}(\overline{\Psi}_\nu i\gamma_5\gamma_\lambda(1+\gamma_5)\Psi_\mu)(\overline{\Psi}_n i\gamma_5\gamma_\lambda\Psi_p) \\ & + C_V^{\rm R}(\overline{\Psi}_\nu\gamma_\lambda(1-\gamma_5)\Psi_\mu)(\overline{\Psi}_n\gamma_\lambda\Psi_p) \\ & + C_A^{\rm R}(\overline{\Psi}_\nu i\gamma_5\gamma_\lambda(1-\gamma_5)\Psi_\mu)(\overline{\Psi}_n i\gamma_5\gamma_\lambda\Psi_p)\,, \end{aligned} \tag{1}$$

where $\Psi_\mu, \Psi_\nu, \Psi_p, \Psi_n$ — Dirac bispinors for the muon, muonic neutrino, proton and neutron. The above Hamiltonian can be derived from the one by Lee and Yang [27], when the following expression is put $C_V + C_{V'}\gamma_5 = C_V^{\rm L}(1+\gamma_5) + C_V^{\rm R}(1-\gamma_5)$, $C_A + C_{A'}\gamma_5 = C_A^{\rm L}(1+\gamma_5) + C_A^{\rm R}(1-\gamma_5)$, where $C_V^{\rm L} = (C_V + C_{V'})/2$, $C_V^{\rm R} = (C_V - C_{V'})/2$, $C_A^{\rm L} = (C_A + C_{A'})/2$, $C_A^{\rm R} = (C_A - C_{A'})/2$, $C_V, C_A, C_{V'}, C_{A'}$ - the vector and axial couplings for the parity-conserving interactions and the parity-nonconserving interactions. The remaining couplings are omitted $C_S = C_{S'} = C_P = C_{P'} = C_T = C_{T'} = 0$. The Fermi Hamiltonian, Eq. (1), can be modified if one puts $C_V^{\rm L} - C_A^{\rm L}\gamma_5 = (C_V^{\rm L} - C_A^{\rm L})(1+\gamma_5)/2 + (C_V^{\rm L} + C_A^{\rm L})(1-\gamma_5)/2$, $C_V^{\rm R} + C_A^{\rm R}\gamma_5 = (C_V^{\rm R} + C_A^{\rm R})(1+\gamma_5)/2 + (C_V^{\rm R} - C_A^{\rm R})(1-\gamma_5)/2$, and then, one obtains the effective Hamiltonian of the form:

$$\begin{aligned} H_{\mu^-} = {} & \frac{C_V^{\rm L} - C_A^{\rm L}}{2}(\overline{\Psi}_\nu\gamma_\lambda(1+\gamma_5)\Psi_\mu)(\overline{\Psi}_n\gamma_\lambda(1+\gamma_5)\Psi_p) \\ & + \frac{C_V^{\rm L} + C_A^{\rm L}}{2}(\overline{\Psi}_\nu\gamma_\lambda(1+\gamma_5)\Psi_\mu)(\overline{\Psi}_n\gamma_\lambda(1-\gamma_5)\Psi_p) \\ & + \frac{C_V^{\rm R} + C_A^{\rm R}}{2}(\overline{\Psi}_\nu\gamma_\lambda(1-\gamma_5)\Psi_\mu)(\overline{\Psi}_n\gamma_\lambda(1+\gamma_5)\Psi_p) \\ & + \frac{C_V^{\rm R} - C_A^{\rm R}}{2}(\overline{\Psi}_\nu\gamma_\lambda(1-\gamma_5)\Psi_\mu)(\overline{\Psi}_n\gamma_\lambda(1-\gamma_5)\Psi_p)\,. \end{aligned} \tag{2}$$

Muonic neutrinos are assumed to be massive and of Dirac nature. The nonrelativistic approximation is applied both for the nucleons and the muon in the $1s$ state. To describe muon capture the following observables are used: $\vec{P}_\mu$ — the initial muon polarization in the $1s$ state, $\vec{S}_\nu$ — the operator of the neutrino spin, $\vec{q}$ — the momentum of the outgoing neutrino, $\vec{J}_n$ — the operator of the neutron spin. $\vec{P}_\mu$ and $\vec{q}$ are assumed to be perpendicular to each other. To illustrate the calculation method the definition of the T-even components of the transverse neutrino polarization is given $\langle \vec{S}_\nu \cdot \hat{\vec{P}}_\mu \rangle_f \equiv \mathrm{Tr}[\vec{S}_\nu \cdot \hat{\vec{P}}_\mu \rho_f]$, where ρ_f — the density operator of the final state (neutrino–neutron), $\hat{\vec{P}}_\mu$ — the direction of the muon polarization in the $1s$ state. The calculations are made with the Reduce computer program.

3. Longitudinal and transverse neutron non-polarization and longitudinal neutrino non-polarization

In this section the results for the longitudinal and transverse neutron polarization and for the longitudinal neutrino polarization are presented. The final results are as follows:

$$\begin{aligned}\langle \hat{\vec{q}} \cdot \vec{J}_n \rangle_f &= \frac{|\ \phi_\mu(0)\ |^2}{4\pi} \Bigg\{ \frac{q}{E}\Big(|\ C_A^{\mathrm{L}}\ |^2 - |\ C_A^{\mathrm{R}}\ |^2 \Big) \\ &\quad + \mathrm{Re}\left[\left(2\frac{q}{M} + \frac{q}{E} \right) \Big(C_V^{\mathrm{R}} C_A^{R*} - C_V^{\mathrm{L}} C_A^{L*} \Big) \right. \\ &\quad \left. + \frac{m_\nu}{E}\frac{q}{M} \Big(C_V^{\mathrm{R}} C_A^{L*} - C_V^{\mathrm{L}} C_A^{R*} \Big) \right] \Bigg\}, \end{aligned} \tag{3}$$

$$\begin{aligned}\left\langle \vec{J}_n \cdot \left(\hat{\vec{P}}_\mu \times \hat{\vec{q}} \right) \right\rangle_f &= \frac{|\ \phi_\mu(0)\ |^2}{4\pi} |\vec{P}_\mu| \mathrm{Im} \left\{ \left(\frac{q}{E} + \frac{q}{M} \right) \Big(C_V^{\mathrm{R}} C_A^{R*} - C_V^{\mathrm{L}} C_A^{L*} \Big) \right. \\ &\quad \left. + \frac{m_\nu}{E}\frac{q}{M} \Big(C_V^{\mathrm{R}} C_A^{L*} - C_V^{\mathrm{L}} C_A^{R*} - C_A^{\mathrm{L}} C_A^{R*} - C_V^{\mathrm{L}} C_V^{R*} \Big) \right\}, \end{aligned} \tag{4}$$

$$\begin{aligned}\langle \vec{S}_\nu \cdot \hat{\vec{q}} \rangle_f &= \frac{|\ \phi_\mu(0)\ |^2}{4\pi} \Bigg\{ \mathrm{Re}\left[\frac{q}{M} \Big(C_V^{\mathrm{L}} C_A^{L*} - C_V^{\mathrm{R}} C_A^{R*} \Big) \right. \\ &\quad \left. + \frac{m_\nu}{E}\frac{q}{M} \Big(C_V^{\mathrm{L}} C_A^{R*} - C_V^{\mathrm{R}} C_A^{L*} \Big) \right] \\ &\quad + \left(\frac{1}{2}\frac{q}{E} + \frac{q}{2M} \right) \Big(|\ C_V^{\mathrm{R}}\ |^2 - |\ C_V^{\mathrm{L}}\ |^2 \Big) \\ &\quad + \left(\frac{3}{2}\frac{q}{E} + \frac{q}{2M} \right) \Big(|\ C_A^{\mathrm{R}}\ |^2 - |\ C_A^{\mathrm{L}}\ |^2 \Big) \Bigg\}, \end{aligned} \tag{5}$$

where, $\phi_\mu(0)$ — the value of the large radial component of the muon Dirac bispinor for $r = 0$, $\hat{\vec{q}}$ — the direction of the neutrino momentum, $|\vec{P}_\mu|$ — the value of the muon polarization in the $1s$ state, $q/2M$ — the momentum corrections, q, E, m_ν, M — the value of the neutrino momentum, its energy, its mass and the nucleon mass, respectively.

It can be noticed that in these observables the occurrence of the interferences between the right-handed $(V, A)_{\rm R}$ and left-handed $(V, A)_{\rm L}$ couplings depends *explicite* on the muonic neutrino mass. Thus, the so-called "conspiracy" of interference terms appears here. This "conspiracy" makes the measurement of the relative phase between these two coupling types impossible because a very small mass of the neutrino ($m_\nu < 0.17$ MeV CL = 90% [22]) at its high energy ($E_\nu \simeq 100$ MeV) suppresses such an interference in practice. The additional interference attenuation is further caused by the momentum corrections. The factor $(m_\nu/E)(q/M) \simeq 17 \times 10^{-5}$ is very small. We can see that new interference contributions can not be detected at the present level of experimental precision. Longitudinal neutrino polarization behaves as a typical nuclear quantity. The "conspiracy" of interference terms caused by the neutrino mass occurs here. The measurement of this observable would not allow the unique determination of the possible participation of the $(V, A)_{\rm R}$ couplings. Therefore, the observables in which such difficulties do not appear are proposed.

4. Why transverse components of neutrino polarization?

In this section the results for two T-odd neutrino observables and for one T-even neutrino quantity are given. All these three cases concern the transverse neutrino polarization. In practice, that would mean the measurements of the components of the neutrino polarization perpendicular to its direction of momentum. The final results are as follows:

$$\begin{aligned}
&\left\langle \vec{S}_\nu \cdot (\hat{\vec{P}}_\mu \times \hat{\vec{q}}) \right\rangle_f \\
&\quad = \frac{|\ \phi_\mu(0)\ |^2}{4\pi} |\vec{P}_\mu| \mathrm{Im} \left\{ \left(\frac{q}{E} + \frac{q}{M} \right) \left(C_A^{\rm L} C_A^{R*} - C_V^{\rm L} C_V^{R*} \right) \right\},
\end{aligned} \tag{6}$$

$$\begin{aligned}
\left\langle \vec{S}_\nu \cdot (\vec{J}_n \times \hat{\vec{q}}) \right\rangle_f = \frac{|\ \phi_\mu(0)\ |^2}{4\pi} \mathrm{Im} \Bigg\{ & \left(\frac{q}{E} + \frac{q}{M} \right) \left(C_V^{\rm R} C_A^{L*} - C_V^{\rm L} C_A^{R*} \right) \\
& + \frac{q}{M} C_V^{\rm L} C_V^{R*} + \left(2\frac{q}{E} + \frac{q}{M} \right) C_A^{\rm L} C_A^{R*} \\
& + \frac{m_\nu}{E} \frac{q}{M} \left(C_V^{\rm R} C_A^{R*} - C_V^{\rm L} C_A^{L*} \right) \Bigg\},
\end{aligned} \tag{7}$$

$$\left\langle \vec{S}_\nu \cdot \hat{\vec{P}}_\mu \right\rangle_f = \frac{\mid \phi_\mu(0) \mid^2}{4\pi} |\vec{P}_\mu| \Bigg\{ \mathrm{Re} \left[\left(1 + \frac{q}{E}\frac{q}{M} \right) \left(C_V^{\mathrm{L}} C_V^{R*} - C_A^{\mathrm{L}} C_A^{R*} \right) \right] + \frac{1}{2}\frac{m_\nu}{E} \left(\mid C_V^{\mathrm{R}} \mid^2 - \mid C_A^{\mathrm{R}} \mid^2 + \mid C_V^{\mathrm{L}} \mid^2 - \mid C_A^{\mathrm{L}} \mid^2 \right) \Bigg\}. \quad (8)$$

The obtained result, Eq. (6), consists exclusively of the interference terms between the left-handed standard $(V, A)_{\mathrm{L}}$ couplings and the right-handed nonstandard $(V, A)_{\mathrm{R}}$ couplings, whose occurrence does not depend *explicite* on the muonic neutrino mass. It can be understood as the interference between the neutrino waves of negative and positive chirality. It creates the possibility of measuring the relative phase between the two coupling types. In the next observables, Eq. (7) and (8), we have the additional dependence on the neutrino mass which occurs only at the terms of the type: $\mid C_V^{\mathrm{R}} \mid^2, \mid C_A^{\mathrm{R}} \mid^2, \mid C_V^{\mathrm{L}} \mid^2, \mid C_A^{\mathrm{L}} \mid^2, C_V^{\mathrm{R}} C_A^{R*}, C_V^{\mathrm{L}} C_A^{L*}$. It gives a very small contribution in the relation to the main one coming from the interferences between the $(V, A)_{\mathrm{L}}$ and $(V, A)_{\mathrm{R}}$ couplings. There is no contribution to these observables from the Standard Model, in which neutrinos are massless.

Now, we will express our coupling constants $C_{V,A}^{\mathrm{L,R}}$ by Fetscher's couplings $g_{\epsilon\mu}^{\gamma}$ [26] assuming the universality of weak interactions. The induced couplings generated by the dressing of hadrons are neglected as their presence does not change qualitatively the conclusions about transverse neutrino polarization. Here, $\gamma = S, V, T$ indicates a scalar, vector, tensor interaction; ϵ, μ=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: $C_V^{\mathrm{L}} = A(g_{\mathrm{LL}}^V + g_{\mathrm{RL}}^V)$, $-C_A^{\mathrm{L}} = A(g_{\mathrm{LL}}^V - g_{\mathrm{RL}}^V)$, $C_V^{\mathrm{R}} = A(g_{\mathrm{LR}}^V + g_{\mathrm{RR}}^V)$, $C_A^{\mathrm{R}} = A(g_{\mathrm{LR}}^V - g_{\mathrm{RR}}^V)$, where $A \equiv (4G_F/\sqrt{2})\cos\theta_c$, $G_F = 1.16639(1) \times 10^{-5}\mathrm{GeV}^{-2}$ [22] is the Fermi coupling constant, θ_c is the Cabbibo angle ($\cos\theta_c = 0.9740 \pm 0.0010$ [22]). We can derive the contributions coming from the $C_{V,A}^{\mathrm{L,R}}$ coupling constants in μ-capture, using the current data [22]: $|C_V^{\mathrm{L}}| > 0.850A$, $|C_A^{\mathrm{L}}| > 1.070A$, $|C_V^{\mathrm{R}}| < 0.093A$, $|C_A^{\mathrm{R}}| < 0.027A$. From the above, we can see that the effects of the transverse neutrino polarization connected with the right-handed $(V, A)_{\mathrm{R}}$ couplings may be of the order of 7%. This value is *model-independent*. In this way, we can give the lower limit of $M_{\mathrm{R}} \geq 305$ GeV on the mass of the right-handed vector boson W_{R} (for manifest left-right symmetry, $m_\nu = 0$, without W_{L}–W_{R} mixing). It is compatible with the current bounds on the mass of the W_{R} received from the weak interaction processes at low energy [22].

When the neutrinos are massive and only standard $(V,A)_{\rm L}$ couplings participate in muon capture, the transverse components of the neutrino polarization could be observed in both cases:

$$\left\langle \vec{S}_{\nu} \cdot (\vec{J}_n \times \hat{\vec{q}}) \right\rangle_f = -\frac{\mid \phi_{\mu}(0) \mid^2}{4\pi} \frac{m_{\nu}}{E} \frac{q}{M} \mathrm{Im} \left(C_V^{\rm L} C_A^{L*} \right), \tag{9}$$

$$\left\langle \vec{S}_{\nu} \cdot \hat{\vec{P}}_{\mu} \right\rangle_f = \frac{\mid \phi_{\mu}(0) \mid^2}{8\pi} |\vec{P}_{\mu}| \frac{m_{\nu}}{E} \left(\mid C_V^{\rm L} \mid^2 - \mid C_A^{\rm L} \mid^2 \right). \tag{10}$$

However, we can see that the eventual effect of the nonzero transverse components of the neutrino polarization connected with the neutrino mass would be much weaker than the one coming from the nonstandard couplings. In such a scenario, the observable determined by the Eq. (6) always equals zero, $\langle \vec{S}_{\nu} \cdot (\hat{\vec{P}}_{\mu} \times \hat{\vec{q}}) \rangle_f = 0$. Because the direct measurement of the transverse neutrino polarization in μ^--capture by proton is very difficult now, one proposes to use the muonic neutrino–electron elastic scattering $\nu_{\mu} + e^- \to e^- + \nu_{\mu}$ to detect the effects of the transverse neutrino polarization connected with the nonstandard couplings. From the differential cross section for this process the possible neutrino–electron correlations in terms of the longitudinal and transverse neutrino polarization will be seen [32] (in preparation). Observing the change in the distribution of the electrons in relation to the distribution with standard neutrino, one would obtain a clear signal of the nonzero values of the transverse neutrino polarization. Maalampi *et al.* [19] considered the presence of muonic neutrinos of a given initial polarization in the inverse muon decay. In the future the experimental verification of the hypothesis concerning the transverse components of the neutrino polarization could be carried out by the Fermi laboratory. Currently at Fermilab, the BooNE experiment [33–35] (The Booster Neutrino Experiment) with the intense neutrino source is designed to search for the muonic neutrino oscillations, the mass difference, the mixing angle, the CP violation in the lepton sector, the muon–neutrino disappearance signal, the neutrino magnetic moment, and the helicity structure of the weak neutral current. This experiment will also look for the non-oscillation neutrino physics using, among others, the neutrino–electron elastic scattering. At Fermilab, essentially all of muon–neutrinos come from π^+-decay. However, on the quark level, in μ^--capture and π^+-decay, there is the same semileptonic interaction. Therefore the conclusions regarding transverse neutrino polarization in μ^--capture are also correct for the muon–neutrinos coming from π^+-decay.

5. Conclusions

The measurements of the T-odd, Eq. (6), transverse components of the neutrino polarization could verify the possibility of the right-handed $(V,A)_{\mathrm{R}}$ couplings participation in weak interactions. They would also be the proof of the production of the right-handed neutrinos. As far as the T-odd components of the transverse neutrino polarization are concerned, one would also obtain a proof of the symmetry breaking under time inversion T(CP) in a semileptonic process. The measurement of longitudinal neutrino polarization does not offer such possibilities because of the suppressing of interferences between the $(V,A)_{\mathrm{L}}$ and $(V,A)_{\mathrm{R}}$ couplings caused by the neutrino mass. In this way, that will always lead to the compatibility with the Standard Model. The similar regularity can be observed in nuclear observables: longitudinal, transverse neutron polarization and also probability of muon capture, and the quantities of only this type are measured today. The BooNE experiment, which is now being constructed, will be able to measure the nonstandard neutrino–electron correlations using the $\nu_\mu + e^- \rightarrow e^- + \nu_\mu$ process. This experiment will be started in the year 2001.

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