CP-Symmetry in Scattering of Neutrinos from Nuclei

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Abstract

The elastic scattering of longitudinal and transversal neutrinos on a spinless nucleus have been discussed taking into account the charge, magnetic, anapole and electric dipole moments of fermions and their weak neutral currents. Compound structure of the neutrino interaction cross section with nuclei have been defined. Invariance of the considered process concerning the C - and P-operations have been investigated in the polarization type dependence.

1. Introduction

It has been established that the behavior of massive neutrinos plays an important part in understanding the physical nature of elementary particles. One of the modes of doing this is to study the possible neutrino-nucleus interaction [1,2].

The neutrino interaction with field of emission may be expressed in the form [3,4] of electromagnetic current

\[ j^\text{em}_\mu = \bar{u}(p',s')[\gamma_\mu F_{1\nu}(q^2) - i\sigma_{\mu\lambda}q_\lambda F_{2\nu}(q^2) + \gamma_5\gamma_\mu G_{1\nu}(q^2) - i\gamma_5\sigma_{\mu\lambda}q_\lambda G_{2\nu}(q^2)]u(p, s), \]

where \( \sigma_{\mu\lambda} = [\gamma_\mu, \gamma_\lambda]/2 \), \( q = p - p' \) is the momentum transfer, \( p(s) \) and \( p'(s') \) imply the four-momentum (helicities) of initial and final neutrinos, \( F_{i\nu}(q^2) \) and \( G_{i\nu}(q^2) \) are the interaction vector and axial-vector parts respectively. The functions \( F_{1\nu}(0), F_{2\nu}(0) \) and \( G_{1\nu}(0) \) give the static estimates of the neutrino charge [5], magnetic [6] and electric dipole [7] moments, on which there exist experimental and cosmological bounds [8]. Insofar as \( G_{1\nu}(0) \) is concerned, it defines the size of the anapole moment [9], but its value has not yet been measured in the laboratory [10].

It is known that \( F_{i\nu}(q^2) \) are invariant with respect to C - and P-operations because the interaction of \( F_{i\nu}(q^2) \) with field of emission must be CP-symmetrical. The term \( G_{1\nu}(q^2) \) is CP-even but P-odd [9]. In contrast to this, the term \( G_{2\nu}(q^2) \) must be C-invariant but CP-antisymmetrical [11]. Therefore, the form factors \( G_{i\nu}(q^2) \) may be different from zero only in the case where P-symmetry is absent.

The violation of P-parity leads to the appearance of right-left asymmetry, for example, at the polarized neutrinos scattering on nuclei. In many works [2,12] the spin phenomena was studied with longitudinal neutrinos. Such an investigation is important not only for elucidation of compound structure of the interaction between leptons and hadrons but also for observation and refinement of the most diverse symmetries of elementary particles. However, the massive neutrino must have the longitudinal as well as the transversal polarization. The account of the latter gives the possibility to directly look at the nature of the discussed processes.
In the present work, we investigate the phenomena of symmetricality in the massive neutrinos interactions with an electroweak field of emission. Section 2 is dedicated to the elastic scattering of longitudinal polarized neutrinos on the nucleus electric ($Z$) and weak ($Z_W$) charges

$$\nu(\nu) + A(Z, Z_W) \gamma Z^0 \nu' (\nu') + A(Z, Z_W),$$

(2)
going at the expense of neutral and electromagnetic currents. In Sec. 3 the studied processes have been reanalysed for the transversal case of the neutrino polarization. In Sec. 4 we make some concluding remarks.

2. Longitudinal Polarized Neutrinos Scattering on a Nucleus

In the framework of the standard theory of electroweak interaction [13], the Hamiltonian of the neutrino interaction with field of a nucleus has the form

$$H = \frac{4\pi\alpha}{q^2}\pi(p', s')[\gamma_\mu F_{1\nu}(q^2) - i\sigma_{\mu\nu}q_\Lambda F_{2\nu}(q^2) +$$

$$+\gamma_5\gamma_\mu G_{1\nu}(q^2) - i\gamma_5\sigma_{\mu\nu}q_\Lambda G_{2\nu}(q^2)]u(p, s)J^\mu_1(q) +$$

$$+ \frac{G_F}{\sqrt{2}}\pi(p', s')\gamma_\mu(g_{V_\nu} + \gamma_5g_{A_\nu})u(p, s)J^\mu_2(q).$$

(3)

Here $J^\mu_1(q)$ are the nucleus electromagnetic ($x = \gamma$) and weak neutral ($x = Z^0$) currents [14], $g_{V_\nu}$ and $g_{A_\nu}$ are the corresponding constants of the neutrino interaction vector ($V$) and axial ($A$) parts.

In the case of the neutrino longitudinal polarization and of a zero-spin nucleus, the cross-section of the process (2) on the basis of (3) can be presented after the summing of $s'$ as follows:

$$d\sigma_{ew}(\theta, s) = d\sigma_{em}(\theta, s) + d\sigma_{int}(\theta, s) + d\sigma_{we}(\theta, s),$$

where to purely electromagnetic interaction answers the expression

$$\frac{d\sigma_{em}(\theta, s)}{d\Omega} = \sigma_{\nu'}(1 - \eta_{\nu'}^2)^{-1}\{[F_{1\nu} + 2\lambda_e s\sqrt{1 - \eta_{\nu}^2}G_{1\nu}]F_{1\nu} +$$

$$+\eta_{\nu}^2[F_{1\nu} + 4m_{\nu}^2(1 - \eta_{\nu}^2)^2F_{2\nu}]tg^2(2) - 8sE_{\nu}^2(1 - \eta_{\nu}^3/3)F_{2\nu}E_{\nu}tg^2(2) +$$

$$+(1 - \eta_{\nu}^2)[G_{2\nu}^2 + 4E_{\nu}^2G_{2\nu}tg^2(2)]F_{E}^2(q^2).$$

(5)

The contribution explained by the interference of electroweak interaction is written in the form

$$\frac{d\sigma_{int}(\theta, s)}{d\Omega} = \rho\sigma_{\nu'}(1 - \eta_{\nu'}^2)^{-1}g_{V_\nu}\{(1 -$$

$$- \lambda_e g_{A_\nu} g_{V_\nu} \sqrt{1 - \eta_{\nu}^2}[F_{1\nu} + \lambda_e s\sqrt{1 - \eta_{\nu}^2}G_{1\nu}] + \eta_{\nu}^2F_{1\nu}tg^2(2)\}F_{E}(q^2).$$

(6)

In the same way one can present the cross-section of purely weak interaction with neutral currents

$$\frac{d\sigma_{we}(\theta, s)}{d\Omega} = \frac{E_{\nu}^2G_{2\nu}^2}{8\pi^2}\{g_{V_\nu}^2(1 + \eta_{\nu}^2tg^2(2)) + g_{A_\nu}^2(1 - \eta_{\nu}^2) -$$
Here we have also used the size

\[ \sigma_\nu = \frac{\alpha^2 \cos^2 \frac{q}{2}}{4E_\nu^2(1 - \eta_\nu^2)\sin^2 \frac{q}{2}} \eta_\nu = \frac{m_\nu}{E_\nu}, \quad \rho = \frac{G_F q^2}{2\pi\sqrt{2}a}, \]

\[ F_E(q^2) = ZF_c(q^2), \quad F_{EV}(q^2) = ZZW F_c^2(q^2), \quad F_W(q^2) = ZWF_c(q^2), \]

\[ Z_W = \frac{1}{2}\{\beta_V^{(1)}(Z + N) + \beta_V^{(1)}(Z - N)\}, \quad A = Z + N, \quad M_T = \frac{1}{2}(Z - N), \]

where \( \theta \) is the scattering angle, \( E_\nu \) and \( m_\nu \) are the neutrino mass and energy, \( F_c(q^2) \) is the charge \( (F_c(0) = 1) \) form factor of a nucleus with isospin \( T \) and its projection \( M_T, \beta_V^{(0)} \) and \( \beta_V^{(1)} \) are constants of isoscalar and isovector components of vector neutral hadronic current.

The presence of the multiplier \( s \) in Eqs. (5)-(7) implies their antisymmetricality concerning the substitution of the left-handed \( (s = -1) \) particle with the right-handed \( (s = +1) \) and vice versa. We see in addition that Eqs. (5)-(7) for the neutrino \( (\lambda_e = +1) \) and the antineutrino \( (\lambda_e = -1) \) are different.

Taking into account Eqs. (5)-(7), the size of charge asymmetry

\[ A_{\text{ch}}^{\nu} = A_{\text{ch}}^{\text{em}} + A_{\text{ch}}^{\text{int}} + A_{\text{ch}}^{\text{we}} = \frac{d\sigma_\nu^{\nu} - d\sigma_{\text{ew}}^{\nu}}{d\sigma_\nu^{\nu} + d\sigma_{\text{ew}}^{\nu}} \] (8)

is defined by the corresponding contributions

\[ A_{\text{ch}}^{\text{em}}(\theta) = 2s\sqrt{1 - \eta_\nu^2}F_{1\nu}G_{1\nu}\{(1 + \eta_\nu^2tg^2\frac{\theta}{2})F_{1\nu}^2 + \]

\[ + (1 - \eta_\nu^2)G_{2\nu}^2 + 4E_\nu^2[s\sqrt{1 - \eta_\nu^2}G_{2\nu} - (1 - \eta_\nu^2)F_{2\nu}]^2tg^2\frac{\theta}{2}\}^{-1}, \]

\[ A_{\text{ch}}^{\text{int}}(\theta) = s\sqrt{1 - \eta_\nu^2}(G_{1\nu} - \frac{g_{A\nu}}{g_{V\nu}}F_{1\nu})\{(1 + \eta_\nu^2tg^2\frac{\theta}{2})F_{1\nu}^2 - \]

\[ - \frac{g_{A\nu}}{g_{V\nu}}(1 - \eta_\nu^2)G_{1\nu}\}^{-1}, \]

\[ A_{\text{ch}}^{\text{we}}(\theta) = -2s\frac{g_{A\nu}}{g_{V\nu}}\sqrt{1 - \eta_\nu^2}\{(1 + \eta_\nu^2tg^2\frac{\theta}{2}) + \frac{g_{A\nu}^2}{g_{V\nu}^2}(1 - \eta_\nu^2)\}^{-1}. \]

(9)

(10)

(11)

These formulas show clearly that C-invariance of the considered process can be violated only in the case when the mirror symmetry is absent. Indeed, taking \( s = 0 \), we find

\[ A_{\text{ch}}^{\text{em}}(\theta) = 0, \quad A_{\text{ch}}^{\text{int}}(\theta) = 0, \quad A_{\text{ch}}^{\text{we}}(\theta) = 0, \]

(12)

which are true at the conservation of P-parity.

Many authors state that one must use the electromagnetic current \( (11) \) in the form \( (15) \) in which an \( i \) is absent. If we start with such a procedure, assuming that the interaction magnetic and electric dipole terms must not be Hermitian even with \( q^2 < 0 \), we would establish the other expressions for the processes cross-sections instead of (5) and (6). They lead to the implication \( (16) \) that C-invariance of elastic scattering is basically violated at the expense of the neutrino nonzero rest mass. One can also make a conclusion that this influence does not relate to the behavior of P-symmetry.
Taking into account that nonconservation of P-parity at the neutrino interaction conveniently characterize by the right-left asymmetry, we have

\[ A_{RL}^{ee} = A_{RL}^{em} + A_{RL}^{int} + A_{RL}^{we} = \frac{d\sigma_{RL}^{R}}{d\sigma_{RL}^{ew}} - \frac{d\sigma_{RL}^{L}}{d\sigma_{RL}^{ew}}, \tag{13} \]

from Eqs. (5)-(7), we get

\[ A_{RL}^{em}(\theta) = 2\sqrt{1 - \eta_{\mu}^{2}}[\lambda_{c}F_{1\nu}G_{1\nu} - 
- 4E_{\nu}^{2}(1 - \eta_{\nu}^{2})F_{2\nu}G_{2\nu}tg^{2}\theta/2\{(1 + \eta_{\nu}^{2}tg^{2}\theta/2)F_{1\nu}^{2} + 
+ (1 - \eta_{\nu}^{2})[G_{1\nu}^{2}ctg^{2}\theta/2 + 4E_{\nu}^{2}(G_{2\nu}^{2} + (1 - \eta_{\nu}^{2})F_{2\nu}^{2})]tg^{2}\theta/2\}^{-1}, \tag{14} \]

\[ A_{RL}^{int}(\theta) = \lambda_{c}\sqrt{1 - \eta_{\mu}^{2}}[G_{1\nu} - g_{AV}/g_{V\nu}[(1 + \eta_{\nu}^{2})tg^{2}\theta/2]F_{1\nu} - 
- \eta_{\nu}^{2}G_{1\nu}]^{-1}, \tag{15} \]

\[ A_{RL}^{we}(\theta) = -2\lambda_{c}g_{AV}^{2}/g_{V\nu}^{2}\sqrt{1 - \eta_{\mu}^{2}}\{(1 + \eta_{\nu}^{2}tg^{2}\theta/2) + (1 - \eta_{\nu}^{2})\}^{-1}. \tag{16} \]

The availability of the multiplier \( \lambda_{c} \) in these formulas implies the influence of the interaction C-antisymmetrical structure on the conservation of P-symmetry. Indeed, the average cross-sections, Eqs. (3)-(7), over the two values of \( \lambda_{c} \) would leads us to the equalities

\[ A_{RL}^{em}(\theta) = -8E_{\nu}^{2}(1 - \eta_{\nu}^{2})F_{2\nu}G_{2\nu}tg^{2}\theta/2\{(1 + \eta_{\nu}^{2})tg^{2}\theta/2\}F_{1\nu}^{2} + 
+ (1 - \eta_{\nu}^{2})[G_{1\nu}^{2} + 4E_{\nu}^{2}(G_{2\nu}^{2} + (1 - \eta_{\nu}^{2})F_{2\nu}^{2})]tg^{2}\theta/2\}^{-1}tg^{2}\theta/2, \tag{17} \]

\[ A_{RL}^{int}(\theta) = 0, \quad A_{RL}^{we}(\theta) = 0, \tag{18} \]

which take place at C-invariance.

Thus, it follows that regardless of the behavior of charge symmetry, the right-left asymmetry of the process (2) can be explained by the interference of the interaction axial-vector terms with its vector terms, if neutrinos do not possess any new properties.

3. Interaction of Transversal Polarized Neutrinos with an Electroweak Field of a Nucleus

Starting from (3) and assuming that the neutrinos are strictly transversal, for the elastic scattering cross-section we find an explicit expression which can be reduced after the summing of \( s' \) to the form

\[ d\sigma_{ew}(\theta, \varphi, s) = d\sigma_{em}(\theta, \varphi, s) + d\sigma_{int}(\theta, \varphi, s) + d\sigma_{we}(\theta, \varphi, s). \tag{19} \]

As well as in (4), each term here corresponds to the most diverse process and has the different structure:

\[ \frac{d\sigma_{em}(\theta, \varphi, s)}{d\Omega} = \sigma_{\nu}^{1/2}\eta_{\nu}^{2}\{F_{1\nu}^{2} + \eta_{\nu}^{2}F_{2\nu}^{2} + 4m_{\nu}^{2}(1 - \eta_{\nu}^{2})^{2}F_{2\nu}^{2}\}tg^{2}\theta/2 + \]
\[ +2\lambda_c s\eta_\nu \sqrt{1 - \eta_\nu^2} F_{1\nu} G_{1\nu} t g^2 \frac{\theta}{2} \cos^2 \varphi + \]
\[ + (1 - \eta_\nu^2) \{ G_{1\nu}^2 + 4E_{\nu}^2 G_{2\nu}^2 \} t g^2 \frac{\theta}{2} \} F_{E_\nu}^2 (q^2), \]
\[ \frac{d\sigma_{\text{int}}(\theta, \varphi, s)}{d\Omega} = \rho_\nu^2 (1 - \eta_\nu^2)^{-1} g_{V_\nu} \{ F_{1\nu} + \eta_\nu^2 [1 + \]
\[ + \lambda_c s \frac{g_{A_\nu}}{g_{V_\nu}} \eta_\nu^{-1} \sqrt{1 - \eta_\nu^2} \cos^2 \varphi] F_{1\nu} t g^2 \frac{\theta}{2} - \]
\[ - \lambda_c s \eta_\nu \sqrt{1 - \eta_\nu^2} \cos^2 \varphi + \lambda_c s \frac{g_{A_\nu}}{g_{V_\nu}} \eta_\nu^{-1} \sqrt{1 - \eta_\nu^2} \} F_{E_\nu}^2 (q^2), \]
\[ \frac{d\sigma_{\text{we}}(\theta, \varphi, s)}{d\Omega} = \frac{E_{\nu}^2 G_{E_\nu}^2}{8\pi^2} \{ g_{V_\nu}^2 \cos^2 \varphi + g_{V_\nu}^2 (1 - \eta_\nu^2) - \]
\[ - 2\lambda_c g_{V_\nu} g_{A_\nu} \eta_\nu \sqrt{1 - \eta_\nu^2} \cos^2 \varphi \} F_{E_\nu}^2 (q^2) \cos^2 \frac{\theta}{2}, \]
where \( \varphi \) is the azimuthal angle.

Using (20)-(22) and taking (8), for the C-odd asymmetry in the case of the neutrino transversal polarization we get

\[ A_{\text{ch}}^\text{em}(\theta, \varphi) = 2\lambda_c s \eta_\nu \sqrt{1 - \eta_\nu^2} F_{1\nu} G_{1\nu} \{ (1 + \eta_\nu^2 t g^2 \frac{\theta}{2} ) \} F_{1\nu}^2 + \]
\[ + (1 - \eta_\nu^2) \{ G_{1\nu}^2 + 4E_{\nu}^2 (G_{2\nu}^2 + (1 - \eta_\nu^2) F_{2\nu}^2 ) t g^2 \frac{\theta}{2} \} \} t g^2 \frac{\theta}{2} \cos^2 \varphi, \]
\[ A_{\text{ch}}^\text{int}(\theta, \varphi) = -\lambda_c s \eta_\nu \sqrt{1 - \eta_\nu^2} G_{1\nu} - \frac{g_{A_\nu}}{g_{V_\nu}} F_{1\nu} \} \{ (1 + \eta_\nu^2 t g^2 \frac{\theta}{2} ) \} F_{1\nu} - \]
\[ - \frac{g_{A_\nu}}{g_{V_\nu}} (1 - \eta_\nu^2) G_{1\nu} \} t g^2 \frac{\theta}{2} \cos^2 \varphi, \]
\[ A_{\text{ch}}^\text{we}(\theta, \varphi) = -2\lambda_c s \eta_\nu \frac{g_{A_\nu}}{g_{V_\nu}} \sqrt{1 - \eta_\nu^2} \{ (1 + \eta_\nu^2 t g^2 \frac{\theta}{2} ) + \]
\[ + \frac{g_{A_\nu}^2}{g_{V_\nu}^2} (1 - \eta_\nu^2) \} t g^2 \frac{\theta}{2} \cos^2 \varphi. \]

The solutions (23)-(25) at \( s = 0 \) coincide with the corresponding size from (12) and that, consequently, the behavior of C-invariance in the P-symmetrical interactions does not depend on the type of polarization.

In the same way one can see that the P-odd characteristics of elastic scattering, according to (13), (20)-(22), has the form

\[ A_{\text{RL}}^\text{em}(\theta, \varphi) = 2\lambda_c s \eta_\nu \sqrt{1 - \eta_\nu^2} F_{1\nu} G_{1\nu} \} \{ (1 + \eta_\nu^2 t g^2 \frac{\theta}{2} ) \} F_{1\nu}^2 + \]
\[ + (1 - \eta_\nu^2) \{ G_{1\nu}^2 \cos \theta t g^2 \frac{\theta}{2} + 4E_{\nu}^2 (G_{2\nu}^2 \cos \theta t g^2 \frac{\theta}{2} ) \} + \]
\[ - \frac{g_{A_\nu}}{g_{V_\nu}} F_{1\nu} \} \{ (1 + \eta_\nu^2 t g^2 \frac{\theta}{2} ) \} F_{1\nu} - \]
\[ A_{\text{RL}}^\text{int}(\theta, \varphi) = -\lambda_c s \eta_\nu \sqrt{1 - \eta_\nu^2} G_{1\nu} - \frac{g_{A_\nu}}{g_{V_\nu}} F_{1\nu} \} \{ (1 + \eta_\nu^2 t g^2 \frac{\theta}{2} ) \} F_{1\nu} - \]
\[ A_{\text{RL}}^\text{we}(\theta, \varphi) = -2\lambda_c s \eta_\nu \frac{g_{A_\nu}}{g_{V_\nu}} \sqrt{1 - \eta_\nu^2} \} \{ (1 + \eta_\nu^2 t g^2 \frac{\theta}{2} ) + \]
\[ + \frac{g_{A_\nu}^2}{g_{V_\nu}^2} (1 - \eta_\nu^2) \} t g^2 \frac{\theta}{2} \cos^2 \varphi. \]
\[ - \frac{g_A}{g_{V_\nu}} (1 - \eta_\nu^2) G_{1\nu}^{-1} \tan \frac{\theta}{2} \cos^2 \varphi, \]  

\[ A_{RL}^{ew}(\theta, \varphi) = -2 \lambda c \eta_\nu \frac{g_A}{g_{V_\nu}} \sqrt{1 - \eta_\nu^2} \left( (1 + \eta_\nu^2 \tan^2 \theta) + \frac{g_A^2}{g_{V_\nu}^2} (1 - \eta_\nu^2) \right)^{-1} \tan \frac{\theta}{2} \cos^2 \varphi. \]  

However, due to C-parity, it follows from (26)-(28) that

\[ A_{RL}^{im}(\theta, \varphi) = 0, \quad A_{RL}^{int}(\theta, \varphi) = 0, \quad A_{RL}^{ew}(\theta, \varphi) = 0. \]  

Comparing (17) and (18) with (29), it is easy to observe the differences which may serve as an indication to the type of polarization dependence of C-invariant processes right-left asymmetry.

4. Conclusion

We have established an explicit form of the differential cross sections describing the elastic electroweak scattering of longitudinal and transversal polarized neutrinos (antineutrinos) on spinless nuclei as a consequence of the availability of rest mass, charge, magnetic, anapole and electric dipole moments of elementary particles and their weak neutral currents. With the use of these formulas a proof has been obtained regardless of the nature of C, nonconservation of P can be explained by the interference of the interaction vector and axial-vector parts.

One of the new features of our results is the connection between the P-odd phenomena and possible polarization types. Unlike the behavior of C-parity in the P-symmetrical scattering, coefficients of right-left asymmetries \( A_{RL}^{ew}(\theta) \) and \( A_{RL}^{ew}(\theta, \varphi) \) in the C-invariant processes with longitudinal and transversal neutrinos are different.

Furthermore, if neutrinos are of high energies (\( E_\nu \gg m_\nu \)) then \( A_{RL}^{ew}(\theta, \varphi) = 0 \), and the size of \( A_{RL}^{ew}(\theta) \) is reduced to the form

\[ A_{RL}^{ew}(\theta) = -\frac{2 F_{2\nu} G_{2\nu}}{F_{2\nu}^2 + G_{2\nu}^2}. \]  

It is expected that measurement of right-left asymmetry \( A_{RL}^{ew}(\theta) \) for any two values of large energies will testify in favor of the equality of the neutrino magnetic and electric dipole moments.

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