Możliwość łamania symetrii CP w rozpraszaniu neutrin na spolaryzowanych elektronach tarczy

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Neutrinos in the Standard Model

- This seminar concerns the possibility of CP violation in the scattering of (anti)neutrino beam on a polarized electron target (SLoPET), when the incoming (anti)neutrino beam consists only of the left-chirality and longitudinally polarized (anti)neutrinos.

Neutrinos in the Standard Model

- According to the SM, neutrinos are Dirac fermions and left-chirality in $V - A$ (vector - axial vector) interaction, i.e. $\gamma_5 u_{\nu L} = -u_{\nu L}$. In relativistic limit (or $m_\nu \to 0$) left-chirality neutrino has negative helicity, while antineutrino has positive helicity.
- V-A structure explains the parity violation.
- It is worth to point out that although SM agrees with all experimental results up to presently available energies, experimental precision is not sufficient to rule out deviations from the V-A structure. There is a place for the exotic scalar, tensor couplings of right-chirality neutrinos, i. e. $\gamma_5 u_{\nu R} = +u_{\nu R}$. If $m_\nu \to 0$ right-chirality neutrino has positive helicity, while antineutrino has negative helicity.

What observables are needed?

CP violation in the Standard Model

- So far the CP violation (CPv) is observed only in the decays of neutral K- and B-mesons and described by a single phase of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix (CKM).
- There is no experimental evidence on the CPv in the leptonic and semileptonic weak interactions, e.g. muon decay and neutrino-electron elastic scattering, neutron decay.
- However, the future superbeam and neutrino factory experiments open the new possibilities of measuring the CP violation in the lepton sector, where both neutrino and antineutrino oscillation will be observed. We indicate that the scattering of neutrinos on the PET has similar scientific possibilities.
- As is known, baryon asymmetry of the Universe can not be explained by the CKM phase only, and new sources of the CP violation are required. Standard cosmological model gives $\eta \equiv \frac{n_b - n_{\overline{b}}}{n_\gamma} \simeq 10^{-18}$, while the observed value of $\eta \simeq 10^{-10}$.

Main goals

- The main goal is to show how the existence of CP violation phase between the complex vector V and axial A couplings of the left-chirality neutrinos affects the azimuthal dependence of the differential cross section. The measurement of the azimuthal angle of outgoing electron momentum $\phi_{e'}$ is only possible when the electron target polarization is known. The polarization vector for electrons is parallel to the magnetic field vector.
- So far the scattering of left-handed and longitudinally polarized neutrino beam on a polarized electron target (SLoPET) was proposed to probe the neutrino magnetic moments (Rashba, Semikos, Phys. Lett. B 479, 218 (2000)) and the flavor composition of a (anti)neutrino beam (Minkowski, Passera, Phys. Lett. B 541, 151 (2002)).

Left-chirality neutrino scattering on a polarized electron target

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

However, in the general case of complex g_V^L and g_A^L couplings, we have one additional free parameter: the relative phase between these couplings denoted as β_{VA}. The CP-odd interference contribution enters the differential cross section for the scattering of left-handed neutrinos on the polarized electron target (PET), if $|\sin(\beta_{VA})| \neq 0$. The experimental measurement of the azimuthal angle $\phi_{e'}$ of outgoing electron momentum could be used to test the CP symmetry in lepton sector of electroweak interactions. The observation of asymmetry in the angular distribution of recoil electrons, caused by the interference terms between the standard complex couplings, would give additional information about the coupling constants.

Left-chirality neutrino scattering on a polarized electron target

The vector and axial-vector couplings in SM are

$$\begin{aligned} g_V^L(i) &\equiv t_3^L(i) - 2q(i)\sin^2\theta_W \\ g_A^L(i) &\equiv t_3^L(i) \end{aligned} \tag{1}$$

where $t_3^L(i)$ is the weak isospin of fermion i ($+1/2$ for u_i and ν_i; $-1/2$ for d_i and l_i), q_i is the charge of ψ_i in units of e and θ_W is the weak angle. Because of the model-dependent interpretation of the coupling constants values, they are assumed to be real numbers.

Left-chirality neutrino scattering on a polarized electron target

For example, the total cross section for high energy neutral-current $(\nu_\mu e^-)$ scattering is

$$\sigma_{SM}(\nu_\mu + e^- \rightarrow \nu_\mu + e^-) \simeq \frac{2G_F^2 m_e E_{\nu_\mu}}{3\pi}(g_V^{L2} + g_A^{L2} + g_V^L g_A^L)\,, \tag{2}$$

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

$$\sigma_{MI}(\nu_\mu + e^- \rightarrow \nu_\mu + e^-) \simeq \frac{2G_F^2 m_e E_{\nu_\mu}}{3\pi}(|g_V^L|^2 + |g_A^L|^2 + |g_V^L||g_A^L|\cos(\beta_{VA}))\,, \tag{3}$$

where $g_V^L = |g_V^L|\,e^{i\beta_V^L}$, $g_A^L = |g_A^L|\,e^{i\beta_A^L}$, $\beta_{VA} = \beta_V^L - \beta_A^L$.

Left-chirality neutrino scattering on a polarized electron target

The effective vector and axial-vector neutral coupling constants obtained from the absolute neutrino-electron scattering event rate are

$$\begin{aligned} g_V^L \simeq 0 \ , \ g_A^L \simeq \pm 0.5 \ \text{ or} \\ g_V^L \simeq \pm 0.5 \ , \ g_A^L \simeq 0 \ . \end{aligned} \tag{4}$$

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

$$|g_V^L| = |g_A^L| \simeq 0.35 \ \text{ and } \ \beta_{VA} = \pm\frac{\pi}{2} \tag{5}$$

provides to the same total cross section value as the SM fit (4).

Left-chirality neutrino scattering on a polarized electron target

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

CP violation in standard νe scattering

We consider the possibility of the CP violation in the $\nu_\mu e^-$ scattering, when the incoming muon neutrino beam consists only of the L-handed and longitudinally polarized neutrinos. We assume that these neutrinos are detected in the standard $V - A$ NC weak interactions with the PET and both the recoil electron scattering angle θ_e' and the azimuthal angle of outgoing electron momentum ϕ_e' are measured with a good angular resolution. Because we allow for the non-conservation of the combined symmetry CP, the amplitude includes the complex coupling constants denoted as g_V^L, g_A^L respectively to the initial neutrino of left-chirality:

CP violation in standard νe scattering

$$M_{\nu_\mu e} = \frac{G_F}{\sqrt{2}}\Big\{ g_V^L(\overline{u}_{e'}\gamma^\alpha u_e)(\overline{u}_{\nu_{\mu'}}\gamma_\alpha(1-\gamma_5)u_{\nu_\mu}) + g_A^L(\overline{u}_{e'}\gamma^5\gamma^\alpha u_e)(\overline{u}_{\nu_{\mu'}}\gamma_5\gamma_\alpha(1-\gamma_5)u_{\nu_\mu})\Big\}, \tag{6}$$

$G_F = 1.16639(1)\times 10^{-5}$ GeV^{-2} is the Fermi constant.
The formula for the differential cross section including the CP-odd contribution $(\hat{\mathbf{q}}\cdot(\hat{\boldsymbol{\eta}}_e \times \hat{\boldsymbol{p}}_{e'})$ is T-odd and $Im(g_V^L g_A^{L*}) = |g_V^L||g_A^L|\sin(\beta_{VA}))$, proportional to the magnitude of the transverse electron target spin polarization, is of the form:

CP violation in standard νe scattering

$$\left(\frac{d^2\sigma}{dy d\phi_{e'}}\right)_{(VA)} = \frac{E_\nu m_e}{4\pi^2}\frac{G_F^2}{2}(1-\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}}\cdot\hat{\mathbf{q}}) \tag{7}$$

$$\begin{aligned}
&\cdot\Bigg\{|g_A^L|^2\left[-\hat{\boldsymbol{\eta}}_{\boldsymbol{e}}\cdot\hat{\boldsymbol{p}}_{\boldsymbol{e'}}\sqrt{\frac{2m_e}{E_\nu}+y}\,(\sqrt{y^3}-2\sqrt{y})+\frac{m_e}{E_\nu}y+(y-2)y+2\right]\\
&+|g_V^L|^2\left[y^2-\hat{\boldsymbol{\eta}}_{\boldsymbol{e}}\cdot\hat{\boldsymbol{p}}_{\boldsymbol{e'}}\sqrt{y^3}\sqrt{\frac{2m_e}{E_\nu}+y}-y(\frac{m_e}{E_\nu}+2)+2\right]\\
&+Im(g_V^L g_A^{L*})\,\hat{\mathbf{q}}\cdot(\hat{\boldsymbol{\eta}}_{\boldsymbol{e}}\times\hat{\boldsymbol{p}}_{\boldsymbol{e'}})\sqrt{y(\frac{2m_e}{E_\nu}+y)}\\
&+Re(g_V^L g_A^{L*})\left[\hat{\boldsymbol{\eta}}_{\boldsymbol{e}}\cdot\hat{\boldsymbol{p}}_{\boldsymbol{e'}}(y-1)\sqrt{y(\frac{2m_e}{E_\nu}+y)}+(2-y)y\right]\Bigg\},
\end{aligned} \tag{8}$$

CP violation in standard νe scattering

where $\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}} \cdot \hat{\mathbf{q}} = -1$ is the longitudinal polarization of the incoming L-handed neutrino, $\mathbf{q}$ - the incoming neutrino momentum, $\mathbf{p_{e'}}$ - the outgoing electron momentum, $\hat{\boldsymbol{\eta}}_{\boldsymbol{e}}$ - the unit 3-vector of the initial electron polarization in its rest frame. The variable y is the ratio of the kinetic energy of the recoil electron T_e to the incoming neutrino energy E_ν:

$$y \equiv \frac{T_e}{E_\nu} = \frac{m_e}{E_\nu} \frac{2cos^2\theta_{e'}}{(1 + \frac{m_e}{E_\nu})^2 - cos^2\theta_{e'}}. \tag{9}$$

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

CP violation in standard νe scattering

The formula for the differential cross section with $\hat{\boldsymbol{\eta}}_{\boldsymbol{e}} \perp \hat{\mathbf{q}}$ is as follows:

$$
\begin{aligned}
\left(\frac{d^2\sigma}{dy\,d\phi_{e'}}\right)_{(VA)} = {} & \frac{E_\nu m_e}{4\pi^2}\frac{G_F^2}{2}\left(1-\hat{\boldsymbol{\eta}}_{\boldsymbol{\nu}}\cdot\hat{\mathbf{q}}\right)\Bigg\{|\boldsymbol{\eta}_{\boldsymbol{e}}^{\perp}|\sqrt{\frac{m_e}{E_\nu}y[2-y(2+\frac{m_e}{E_\nu})]} \\
& \cdot\Bigg[cos(\phi_{e'})\left(2|g_V^L||g_A^L|cos(\beta_{VA})y+(2-y)|g_A^L|^2-y|g_V^L|^2\right) \\
& -2|g_V^L||g_A^L|cos(\phi_{e'}+\beta_{VA})\Bigg] \\
& +\Bigg[\left(|g_V^L|^2+|g_A^L|^2\right)\left(y^2-2y+2\right)+2|g_V^L||g_A^L|cos(\beta_{VA})y(2-y) \\
& -\frac{m_e}{E_\nu}y\left(|g_V^L|^2-|g_A^L|^2\right)\Bigg]\Bigg\}.
\end{aligned}
\tag{10}
$$

CP violation in standard νe scattering

It can be noticed that the interference terms between the standard $g^L_{V,A}$ couplings depend on the value of the β_{VA} phase. However, the angular asymmetry of recoil electrons is not vanishing even if $\beta_{VA} = 0$. The CP-violating phase enters the cross section and changes the angle at which the number of recoil electrons will be maximal ($\phi^{max}_{e'}$). For $\beta_{VA} = \frac{\pi}{2}$ and $|g^L_V| = |g^L_A| = 0.354$ this angle is quite large $\phi^{max}_{e'} \simeq \frac{\pi}{3}$. In the case of pure axial-vector g^L_A coupling we have different azimuthal dependence of the cross section ($\phi^{max}_{e'} = 0$) than in the case of pure vector g^L_V coupling ($\phi^{max}_{e'} = \pm\pi$).

The feasibility of developing the PET

The polarized target electrons are produced in ferromagnetic material that is magnetized with using external magnetic field. The target polarization value is determined from measurements of saturation curve and hysteresis loop. At flux density of $\simeq 2\,T$ the iron becomes magnetically saturated, yielding a target polarization of $\simeq 8\%$ (the magnetic moment per atom $\mu_{Fe} = 2.2\mu_B$ and the number of electrons $Z_{Fe} = 26$). Thus, we state that the PET with the transverse component of the initial electron polarization $|\boldsymbol{\eta}_e^{\perp}| \simeq 0.08$ is feasible.

Conclusions

We have shown that the SLoPET could be used to measure the CP violation in the pure leptonic process. The azimuthal asymmetry of the recoil electrons does not depend on the neutrino mass and is not vanishing even if $\beta_{VA} = 0$. The CP-breaking phase β_{VA} could be detected by measuring the maximal asymmetry of the cross section.

$$\Downarrow$$

Searching for the new relative phases requires very intense(anti)neutrino sources (10^{22} per year or more) and large polarized target of electrons ($10^{32} - 10^{35}$ target-electrons or more), and also long time duration of experiment (more than one year).

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