Abstract

We study interference effect in elastic $\nu_e e^-$ scattering process in presence of nonstandard neutrino interactions (NSI). The strength of interference predicted by standard model (SM) is $-1.09$, while that measured in LAMPF and LSND experiment is $-1.01 \pm 0.18$, which are in good agreement with each other. We use interference effect (1) to investigate how NSIs could affect the total size of interference, (2) how interference can be used to constrain NSIs and (3) how the allowed region for new physics can be reduced from four to a single, but more symmetric allowed region.

Key words: Neutrino mass, Nonstandard neutrino interactions, Interference effect, New physics.

1 Introduction

It is known that neutrinos are massless within the standard model, contrary to this, plethora of neutrino oscillation experiments confirm that neutrinos change their flavor while propagating from source to detector, thus providing evidence that neutrinos are massive [1 2 3 4 5]. General trend to accommodate the masses of neutrino through effective four fermions operator is extensively discussed in literature [6 7]. The effective operators approach provides a plausible way to study the effects of new interactions in low energy electroweak precision measurements. These new interactions are predicted by various models such as R-parity violating supersymmetric model [8], heavy neutral vector bosons ($Z'$) model and the lepto-quarks model [9].

The electroweak precision measurements have verified the universality and flavor conserving processes of the SM [9 10]. But if neutrinos are given masses
then it is strongly suggested that it may have some new interactions at some high energy scale $(\gtrsim 1\text{TeV})$\cite{11}. Such interactions are called nonstandard neutrino interactions (NSIs). The NSIs include nonuniversal flavor conserving as well as flavor changing currents (also called flavor diagonal and flavor non-diagonal, respectively), contrary to the standard model where both charge current (CC) and neutral current (NC) are universal and flavor conserving. To explore new physics, the study of nonuniversality and flavor violation couplings is of crucial importance. Currently, constraining NSI coupling parameters, both in model dependent and model independent way, are extensively studied in electroweak precision measurements\cite{9, 10}.

We study NSIs arising in neutrino-fermion scattering processes and focus on the elastic $\nu_e e^-\text{scattering}$. The major interest in this process is due to the fact that it is one of the few processes for which SM predicts a large destructive interference between CC and NC, thus providing the reason for lowering the $\nu_e e^-$ cross section by 40\% compared to that in the absence of interference. The presence of interference effect has been discovered by CCFR neutrino experiment at Fermilab\cite{12} and successively improved the results by LAMPF and short baseline terrestrial LSND experiments\cite{14, 15, 16, 17}, and found good agreements with the theory. The discovery of interference effect has provided a crucial test for verifying the gauge structure of SM\cite{13}. The interference effect is deeply concerned with the fact that it can occur if the incoming and outgoing neutrinos are the same in a scattering process. For instance, in $\nu_e e^-\text{scattering}$ the interference could occur only if the incoming and outgoing neutrinos are $\nu_e$\cite{14, 15, 16, 17}. We exploit this logic to study NSIs using interference effect. This effect can be used both for constraining NSIs in universal flavor conserving scattering and for knowing the gauge structure of any new physics. Based on the fact of flavor conservation (incoming and outgoing neutrino should be the same) we can not ignore the interference between CC, NC as established in SM, and in addition, the interference of NSIs with CC, NC. These facts impose us to reexamine the strength of interference in the presence of NSI. If there exists any NSIs at low energy, it must interfere with the CC and NC of the SM. More accurate strength of total interference can be obtain using more and more accurate measurements of $\nu_e e^-\text{scatterings}$\cite{14, 15, 16, 17}.

An important aspect of the interference parameter is that its strength is energy independent. Whatever energy is used for scattering, the total strength of interference is the same. Using this reasoning, we can use interference effect as a probe to investigate any NSIs, if exist. The impacts of interference between SM interactions and NSIs has been discussed in ref.\cite{18}. It is shown in this ref\cite{18} that how a small residual NSIs could interfere with SM interacations and leads to a drastic loss in sensitivity in $\theta_{13}$.

In this paper, we investigate NSIs using interference as parameter in the low energy $\nu_e e^-\text{scattering process}$. The same analysis can be performed for the other scattering processes like $\nu_\mu e$ and $\nu_\tau e$. We demonstrate how interference parameter can be used to constrain NSIs. We obtain new bounds on NSIs using\footnote{Work in progress}.
interference parameter following the approach of keeping one operator at a time. The lower bounds on $\epsilon_{ee}^L$ and $\epsilon_{ee}^R$ obtained are more stringent in our case where as upper bounds relax the allowed region. These bounds are complimentary to one or another obtained using various different methods in ref [6,7]. On the other hand, we obtain a single allowed region instead of four. Four allowed regions are obtained when neutrinos and anti-neutrino data is simultaneously used. This analysis has recently been done by J.Barranco et. al. (see ref. [7]). Our approach helps to take into account the two parameters instead of single parameter at a time which is commonly followed in the literature (see ref. [6,7]).

2 NSI Lagrangian

The most general form of the effective four-fermion interaction Lagrangian for low energy ($\nu_\alpha f \rightarrow \nu_\beta f$ ) process in the presence of NSI is given by [6],

$$L_{eff} = -2\sqrt{2} G_f [\bar{\nu}_\alpha \gamma_\mu L \nu_\alpha] [\bar{f} \gamma^\mu P f] - 2\sqrt{2} \sum_{p,f,\alpha} g_p^f G_f [\bar{\nu}_\alpha \gamma_\mu L \nu_\alpha] [\bar{f} \gamma^\mu P f]$$

$$- \sum_{\alpha,\beta} \epsilon_{ee}^{\alpha\beta} 2\sqrt{2} G_f [\bar{\nu}_\alpha \gamma_\mu L \nu_\alpha] [\bar{f} \gamma^\mu P f]$$ (1)

where $P = L, R = \frac{1}{2} (1 \mp \gamma_5)$ with $G_F$ as the Fermi constant and $f$ is any of the first generation fermion ($e, u, d$), $g_p^f$ are the standard neutral current coupling constants and $\epsilon_{ee}^{\alpha\beta}$ are the nonstandard flavor diagonal ($\alpha = \beta$) and flavor nondiagonal ($\alpha \neq \beta$) effective coupling parameters.

For the specific process of $\nu_e e-$scattering, the total effective Lagrangian becomes,

$$L_{eff} = -2\sqrt{2} G_f [\bar{\nu}_e \gamma_\mu L \nu_e] [\bar{e} \gamma^\mu Pe] - 2\sqrt{2} g^f_0 G_f [\bar{\nu}_e \gamma_\mu L \nu_e] [\bar{e} \gamma^\mu Pe]$$

$$- \epsilon_{ee}^{ee} 2\sqrt{2} G_f [\bar{\nu}_e \gamma_\mu L \nu_e] [\bar{e} \gamma^\mu Pe]$$ (2)

Notice that first and third terms have been obtained in this form after Fierz rearrangement. For the detail on effective lagrangian formalism of NSIs see ref. [6,7].

3 Interference effect in SM and measurements

Using the standard model part of lagrangian in (2), the total cross section can be calculated as

$$\sigma^{\nu_e} = \sigma^{\sigma} [(g_L + 2)^2 + \frac{g_R^2}{3}]$$ (3)
where \( \sigma^o = \frac{G^2_m e E_{\nu e}}{2\pi} = (4.31 \times 10^{-45}) \frac{e^2}{M_{eV}} \times E_{\nu e} \), \( g_L = -1 + 2 \sin^2 \theta_w \) and \( g_R = 2 \sin^2 \theta_w \).

To make the interference term more explicit, we rewrite (3) in the form,

\[
\sigma^{\nu e} = \sigma^{CC} + \sigma^{NC} + \sigma^I
\]

where \( \sigma^{CC} = 4\sigma^o \), \( \sigma^{NC} = \sigma^o (g_L^2 + \frac{g_R^2}{3}) \), \( \sigma^I = 4\sigma^o g_L = 2\sigma^o I^{SM} \),

where

\[
I^{SM} = 2g_L
= 2(-1 + 2 \sin^2 \theta_w)
\]

Assuming \( \sin^2 \theta_w = 0.23 \), \( \sigma^{NC} \) and \( \sigma^I \) can calculated within the SM as \( \sigma^{NC} = 0.36\sigma^o \), \( \sigma^I = 2(-1.1)\sigma^o \) where \( I^{SM} = 2g_L = -1.1 \) [17].

Including the radiative corrections [17, 19], we obtain \( \sigma^{NC} = 0.37\sigma^o \) and \( \sigma^I = 2(-0.09)\sigma^o \) with \( I^{SM} = -1.09 \). The total cross section becomes,

\[
\sigma^{\nu e} = 4\sigma^o + 0.37\sigma^o + 2(-1.09)\sigma^o
\]

From the third term, it is clear that the standard model predicts destructive interference between \( CC \) and \( NC \) having absolute value of 1.09.

From eq. (5), we can see that interference between \( CC \) and \( NC \) is a function of the weak mixing angle \( \theta_W \). The strength of interference in SM is -1.09 corresponds to 0.5 radian (for \( \sin^2 \theta_w = 0.23 \)) of \( \theta_W \). We can see from figure (1), that the maximum size of destructive interference corresponds to -2 and it vanishes at 0.8 radian and beyond this we have constructive interference. Although, at the SM energy scale the physical size of interference is -1.09 and the remaining is the unphysical region, but these information which is deduced from the nature of interference can be used to test the gauge structure of any interaction beyond the SM.

Now for experimental measurement of the size of interference we have from eq. (4),

\[
I = \frac{\sigma^{\nu e} - (\sigma^{CC} + \sigma^{NC})}{2\sigma^o}
\]

\[
I = \frac{\sigma^{exp} - 2\sigma^o}{2\sigma^o} - 2.185
\]

where \( \sigma^{\nu e} \equiv \sigma^{exp} \) and \( \sigma^{CC} = 4\sigma^o \), \( \sigma^{NC} = 0.37\sigma^o \) were used to obtain the eq. (6).

Using \( \sigma^{exp} = [10.1 \pm 1.1(stat.) \pm 1.0(syst.) \times E_{\nu e}(MeV) \times 10^{-45}cm^2] \) in eq.(4) from the LSND experiment [17], and solving for \( I \), we get \( I^{LSND} = -1.01 \pm 0.18 \).

Comparing \( I^{SM} \) and \( I^{LSND} \), one can see a discrepancy of 0.08 which is 8% with respect to the best value of LSND experiment. The destructive interference(-ev sign) is in agreement with both, the theory and experiment.

Note that for the experimental measurement of interference, the inputs for \( CC \) and \( NC \) cross sections were taken from separate experiments for purely leptonic processes. For \( CC \), muon decay measurement was taken and for \( NC \), \( \nu_{\mu}e^{-} \)-scattering measurement were used [14, 15, 16, 17].
Inspite of this agreement between theory and experiment for the strengh of interference we can not ignore impact of NSIs (if there exist any due to massive neutrinos) on the total size and sign of interference. This is because of the fact that in the total interference term some currents may interact constructively and some destructively which cancel each others effect and thus the over all size remain the same or may change by a small amount, which in turn make the total cross section as unchanged.

In the following section, we follow the same approach as adopted in [14, 15, 16, 17],(1) to investigate how NSIs could affect the total size of interference, (2) how interference can be used to constrain NSIs and how the allowed region for new physics can be reduced from four to a single, but more symmetric allowed region.

4 Interference effect and NSIs

In the presence of NSIs, total cross section calculated as [7]

\[
\sigma^{\nu_e e} = \sigma^o \left[ \tilde{g}_L^2 + \frac{\tilde{g}_R^2}{3} \right]
\]  

where

\[
\tilde{g}_L = 2 + g_L + e^{\epsilon_{eL}}_{ee}, \quad \tilde{g}_R = g_R + e^{\epsilon_{eR}}_{ee}, \quad g_L = -0.54, \quad g_R = 0.46
\]

Rewriting (7) as,

\[
\sigma^{\nu_e e} = \sigma^{CC} + \sigma^{NC} + \sigma^{NSI} + \sigma^I
\]  

where

\[
\sigma^{CC} = 4\sigma^o, \quad \sigma^{NC} = (g_L^2 + \frac{1}{3}g_R^2)\sigma^o = 0.37\sigma^o, \quad \sigma^{NSI} = \{(\epsilon_{ee}^{L})^2 + \frac{1}{3}(\epsilon_{ee}^{R})^2\}\sigma^o
\]

\[
\sigma^I = 2\{(2g_L + g_L(\epsilon_{ee}^{L}) + 2(\epsilon_{ee}^{L}) + \frac{1}{3}g_R(\epsilon_{ee}^{R}))\}\sigma^o = 2I_{total}\sigma^o
\]

where

\[
I_{total} = \{(2g_L + g_L(\epsilon_{ee}^{L}) + 2(\epsilon_{ee}^{L}) + \frac{1}{3}g_R(\epsilon_{ee}^{R})\}\}
\]  

In eq. (8), the first term is the SM interference term, the second and fourth are interference terms between NC and NSIs and third term is the interference between the CC and NSIs. One important point which is noticeable is that from fourth term where the interference between right handed coupling constant of SM \(g_R\) and right handed coupling parameter of NSI \(\epsilon_{ee}^{R}\) occurs, while contrary to this, the interference in the SM is only between the CC and NC. There is no interference due to the right handed part of NC in SM.

Substituting \(g_L = -0.54\) and \(g_R = 0.46\), the total interference \(I_{total}\) can be written as,

\[
I_{total} = -1.09 + 1.46(\epsilon_{ee}^{L}) + 0.15(\epsilon_{ee}^{R})
\]  

5
The first term which is the SM interference term is obviously destructive while the sign of the second and third terms, which are NSI terms, depends on the signs of $\epsilon_{ee}^L$ and $\epsilon_{ee}^R$. If these are negative, the interference will be destructive and if the signs are positive there will be constructive interference.

Using single parameter approach, (considering one operator at a time) we get bounds from the interference term for the measured value of LSND ($I^{\text{LSND}} = -1.01 \pm 0.18$)

$$-0.07 < \epsilon_{ee}^L < 0.17$$
$$-0.35 < \epsilon_{ee}^R < 0.81$$ (11)

If we assume that the discrepancy between theory and experimental size of interference, which is 0.08 comes from NSIs then using eq. (8), and single parameter a time we find

$$\epsilon_{ee}^L = 0.05 \quad \epsilon_{ee}^R = 0.52$$

Both from these absolute values of $\epsilon_{ee}^L$ and $\epsilon_{ee}^R$, and bounds in eq. (10) it clear that the right hand NSIs parameters have lagers values. The upper bound on $\epsilon_{ee}^L$ are quite compitable with that obtained before in [6, 7]. The interference ($I$) as a function of weak mixing angle $\theta_W$, NSI parameters ($\epsilon_{ee}^L$ and $\epsilon_{ee}^R$) is shown in fig (2). In case of NSI parameters ($\epsilon_{ee}^L$ and $\epsilon_{ee}^R$), one parameter at a time was considered, while the other parameter is kept zero.

If NSIs is taken into consideration and if they interfere with SM currents, then the total interference ($I$) in any experiment will be modified from eq. (6) to the form,

$$I = \frac{\sigma^{\nu e} - (\sigma^{CC} + \sigma^{NC} + \sigma^{NSI})}{2\sigma^0}$$

$$I = \frac{\sigma^{\exp}}{2\sigma^0} - 2.185 - \{(\epsilon_{ee}^L)^2 + \frac{1}{3}(\epsilon_{ee}^R)^2\}$$ (12)

where $\sigma^{NSI} = \{(\epsilon_{ee}^L)^2 + \frac{1}{3}(\epsilon_{ee}^R)^2\}\sigma^0$

For $I = I^{SM} = -1.09$ and $\sigma^{\exp} = [10.1 \pm 1.1(\text{stat.}) \pm 1.0(\text{syst.}) \times E_{\nu e}(\text{MeV}) \times 10^{-45}\text{cm}^2]$ from LSND experiment [17] and $\sigma^0 = (4.31 \times 10^{-45})\text{cm}^2/\text{MeV} \times E_{\nu e}$, eq. (11) becomes,

$$(\epsilon_{ee}^L)^2 + \frac{1}{3}(\epsilon_{ee}^R)^2 = (0.26 \uparrow, -0.1 \downarrow)$$ (13)

This has been plotted in figure below.

The most important feature of using interference parameter for constraining NSIs is to look for the overlaped region between the total cross section eq. (8) and the interference term eq. (10). We get a single overlaped region, which is more symmetric with respect to the lower and upper bounds. Alreadly, analysis has been done to get overlaped regions using $\nu_{e}e$ and $\bar{\nu}_{e}e$ -scattering data [7]. In that case four allowed regions were obtained. Our analysis reduces the four
allowed regions to a single more symmetric allowed region as shown in figure (4). The allowed region is bounded by the limits:

\[-0.25 < \epsilon^{L}_{ee} < 0.25\]
\[-1.65 < \epsilon^{R}_{ee} < 1.65\]

5 Conclusions

The interference effect between CC and NC in $\nu_e e$–scattering process has been observed in the standard model. The size of this interference in the SM is $-1.09$, whereas that measured in LSND experiment is $-1.01 \pm 0.18$. The theory vs experiment discrepancy is 8%. Here we have reanalysed the interference effect to use it as probe for NSIs. We used the interference effect to investigate how NSIs could affect the total size of interference, how interference can be used to constrain NSIs and how the allowed region for new physics can be reduced from four to one single, but more symmetric allowed region.

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The interference in SM versus the weak mixing angle $\theta_W$.

Interference as function of weak mixing angle $\theta_W$ (the curve), interference as function of NSIs parameter $\epsilon_{ee}^{eL}$ when $\epsilon_{ee}^{eR} = 0$ (bold line), interference as function of NSIs parameter $\epsilon_{ee}^{eR}$ when $\epsilon_{ee}^{eL} = 0$ (dashed line).
Contours $\sigma^{\text{NSI}}/\sigma^0 = (\epsilon^{eL}_{ee})^2 + \frac{1}{3}(\epsilon^{eR}_{ee})^2$ vs. $\epsilon^{eL}_{ee}$ and $\epsilon^{eR}_{ee}$.

Bounds on the NSIs from total cross section are between the
Bounds on the NSIs from total cross section are between the two ellipses and bounds on NSIs from total interference is between two linear lines. from LSND experiment. Allowed regions at 1$\sigma$ are between the two ellipses and between two lines. The dark shaded region is single overlaped region.

\[ 0.25 < \epsilon_{ee}^{eL} < 0.25, \quad -1.65 < \epsilon_{ee}^{eR} < 1.65 \]