Neutrino electron scattering and electroweak gauge structure: Probing the masses of a new Z boson

O. G. Miranda†, V. B. Semikoz‡José W. F. Valle†

†Instituto de Física Corpuscular - C.S.I.C.
Departament de Física Teòrica, Universitat de València
46100 Burjassot, València, Spain
http://neutrinos.uv.es

‡Institute of the Terrestrial Magnetism, the Ionosphere and Radio Wave Propagation of the Russian Academy of Science, IZMIRAN, Troitsk, Moscow region, 142092, Russia.

Abstract.
Low-energy high-resolution neutrino-electron scattering experiments may play an important role in testing the gauge structure of the electroweak interaction. We discuss the use of strong radioactive neutrino sources (e.g. $^{51}$Cr) in underground experiments such as BOREXINO, HELLAZ and LAMA. We display the sensitivity of these detectors in testing the possible existence of extra neutral $E_6$ gauge bosons.

1 On leave from Departamento de Física CINVESTAV-IPN, A. P. 14-740, México 07000, D. F., México
2 E-mail: valle@flamenco.ific.uv.es
1. Introduction

Despite the success of the Standard Model (SM) in describing the electroweak interaction, there have been considerable interest in extensions of the gauge structure of the theory [1]. In this talk we discuss the proposal [2] of using $\nu_e e$ and $\bar{\nu}_e e$ scattering from terrestrial neutrino sources with improved statistics as a test of the electroweak gauge structure. The coupling constants governing $\nu_e e \rightarrow \nu_e e$ scattering in the SM have been well measured from $e^+ e^- \rightarrow l^+ l^-$ at high energies by the LEP Collaborations and have given strong constraints on additional neutral currents, specially on the mixing of the standard $Z$ boson with other hypothetical neutral gauge bosons. This carries an important weight in global fits of the electroweak data [3]. However, we argue that low-energy experiments can give complementary information, namely, they allow a better sensitivity to the mass of the new gauge boson than available from high energies, e.g. from LEP physics. On the other hand, although the Tevatron does give relatively good limits on $Z'$ masses, one may argue that a neutrino-electron experiment is a cleaner environment that will provide useful complementary information on the gauge structure of the electroweak interaction.

Using $\nu_e e$ and $\bar{\nu}_e e$ scattering from terrestrial neutrino sources has also been suggested as a test of non-standard neutrino electromagnetic properties, such as magnetic moments [4]. In contrast to reactor experiments such MUNU [5], a small (but intense) radioactive isotope source can be surrounded by detectors with full geometrical coverage. Here we demonstrate that a low-energy high-resolution experiment can play an important role in testing the structure of the neutral current weak interaction.

We explicitly determine the sensitivity of these radioactive neutrino source experiments as precision probes of the gauge structure of the electroweak interaction and illustrate how it works in a class of $E_6$-type models as well as models with left-right symmetry.
2. The $\nu e$ Cross Section

In a generic electroweak gauge model the differential cross section for the process $\nu_e e \rightarrow \nu_e e$ is given by

$$\frac{d\sigma}{dT} = \frac{2m_e G_F^2}{\pi} \left\{ (g_L + 1)^2 + g_R^2 (1 - \frac{T}{E_\nu})^2 - \frac{m_e}{E_\nu} (g_L + 1) g_R \frac{T}{E_\nu} \right\} \tag{1}$$

where $T$ is the recoil electron energy, and $E_\nu$ is the neutrino energy. For the SM case we have $g_{L,R} = \frac{1}{2}(g_V \pm g_A)$, with $g_V = \rho_{\nu e}(-1/2 + 2\kappa \sin^2 \theta_W)$ and $g_A = -\rho_{\nu e}/2$ where $\rho_{\nu e}$ and $\kappa$ describe the radiative corrections for low-energy $\nu_e e \rightarrow \nu_e e$ scattering [6]. For the case of $\overline{\nu} e e \rightarrow \overline{\nu} e e$ scattering we just need to exchange $g_L + 1$ with $g_R$ and vice versa.

As already mentioned, the values of the coupling constants governing $\nu_e e \rightarrow \nu_e e$ scattering in the SM have been well measured through the $e^+ e^- \rightarrow l^+ l^-$ process at LEP. A combined LEP fit at the Z peak gives [7] $g_V = -0.03805 \pm 0.00059$ and $g_A = -0.50098 \pm 0.00033$. These results have given strong constraints on the mixing of the standard Z boson with an additional $Z'$, in the framework of global fits of the electroweak data [3]. As a result we will, in what follows, focus mainly on the possibility of probing the $Z'$ mass at low-energy $\nu_e e \rightarrow \nu_e e$ scattering experiments. For convenience we define the parameter

$$\gamma = \frac{M_Z^2}{M_{Z'}^2} \tag{2}$$

and we will neglect the mixing angle $\theta'$ between the SM boson and the extra neutral gauge boson.

For extended models, the neutral contribution to the differential cross section will be, for $\theta' = 0$,

$$\delta \frac{d\sigma}{dT} = \gamma \Delta = \gamma \frac{2m_e G_F^2}{\pi} \left\{ D + E \frac{T}{E_\nu} \left( \frac{T}{E_\nu} - 2 \right) - F \frac{m_e}{E_\nu} \frac{T}{E_\nu} \right\} \tag{3}$$

with $\Delta$ in obvious notation and

$$D = 2(g_L + 1)\delta g_L + 2g_R \delta g_R \tag{4}$$
\[ E = 2g_R \delta g_R \]  \hspace{1cm} (5)

\[ F = (g_L + 1) \delta g_R + g_R \delta g_L \]  \hspace{1cm} (6)

where \( g_L \) and \( g_R \) are the SM model expressions and \( \delta g_{L,R} \) give the corrections due to new physics. In the particular case of the LRSM these corrections are given by [8, 9]

\[ \delta g_L = \frac{s_4^W}{r_W^2} g_L + \frac{s_2^W c_2^W}{r_W^2} g_R \]  \hspace{1cm} (7)

\[ \delta g_R = \frac{s_4^W}{r_W^2} g_R + \frac{s_2^W c_2^W}{r_W^2} g_L \]  \hspace{1cm} (8)

while for the \( E_6 \) models we have [10, 11],

\[ \delta g_L = 4 \rho s_W^2 \left( \frac{3 \cos \beta}{2 \sqrt{24}} + \frac{\sqrt{5} \sin \beta}{\sqrt{8}} \frac{\sqrt{5} \sin \beta}{\sqrt{8}} \frac{3 \cos \beta}{2 \sqrt{24}} + \frac{1}{3} \frac{\sqrt{5} \sin \beta}{3 \sqrt{8}} \right) \]  \hspace{1cm} (9)

\[ \delta g_R = 4 \rho s_W^2 \left( \frac{3 \cos \beta}{2 \sqrt{24}} + \frac{\sqrt{5} \sin \beta}{\sqrt{8}} \frac{\cos \beta}{\sqrt{24}} - \frac{1}{3} \frac{\sqrt{5} \sin \beta}{3 \sqrt{8}} \right) \]  \hspace{1cm} (10)

where, \( \rho \) includes the radiative corrections to the ratio \( M_W^2/M_Z^2 \cos \theta_W \) and \( \beta \) defines the \( E_6 \) model in which we are interested in.

The correction to the \( \nu_e e \) scattering depends on the model as well as on the energy region. In order to illustrate how this corrections affect the SM prediction we define the expression

\[ R = \frac{\Delta}{(\frac{d\sigma}{dT})^{SM}}. \]  \hspace{1cm} (11)

This ratio depends on the specific model through the angle \( \beta \) and depends also on the electron recoil energy, as well as on the neutrino energy. As we are interested in artificial neutrino sources we can study what would be the value of \( R \) in Eq. (11) for the case of a neutrino coming from a \(^{51}\text{Cr} \) source, which corresponds to a neutrino energy \( E_\nu = 746 \text{ KeV} \). We show this ratio in Fig. 1 as a function of \( \beta \) for different values of \( T \). We can see from the plot that the sensitivity is bigger at \( \cos \beta \simeq 0.8 \) and it is almost zero for \( \cos \beta \simeq -0.4 \). Of the most popular
Figure 1. Plot of the ratio given in eq. 11 as a function of the model for different values of $T$ and for $E_\nu = 746$ KeV.

models ($\chi$, $\eta$ and $\psi$ models) we can say that the $\chi$ model is the most sensitive to this scattering. A similar result can be obtained for the case of anti-neutrino sources, such as $^{147}$ Pm, now proposed for the LAMA experiment [12, 13]. We can also see from the figure that, in order to reach a constraint on $\gamma \simeq 0.1$ in the $\chi$ model we need a resolution of the order of 5%.

3. Experimental prospects

The first high-activity artificial neutrino sources have been recently developed in order to calibrate both GALLEX and SAGE solar neutrino experiments [14]. These are $^{51}$Cr sources producing neutrinos by electron capture through the reaction $^{51}$Cr + $e^-$ $\rightarrow^{51}$V + $\nu_e$. The main line is at 746 KeV and represents 90% of the neutrino flux. Besides the neutrino flux, there is also $\gamma$ emission which is stopped by a tungsten shielding. The activity of the GALLEX source was 1.67 ± 0.03 MCi.

An anti-neutrino source has recently been considered by the LAMA proposal in order to probe for the neutrino magnetic moment [12]. This is a $^{147}$Pm source that produces anti-neutrinos
Figure 2. Expected number of events per bin for the LAMA proposal. The additional contribution of an extra neutral gauge boson with $M_{Z'} = 330$ GeV in the $\chi$ model is also shown.

through the $^{147}Pm \rightarrow ^{147}Sm + e + \bar{\nu}_e$ beta decay. In this case we have an anti-neutrino spectrum with energies up to 235 KeV. The spectrum shape is well known and the activity of the source can be measured with an accuracy better than 1% \[15\]. A tungsten shielding of 20 cm radius plus a Cu shielding of 5 cm is considered in order to stop the $\gamma$ emission. In this case we can use as a good approximation for the anti-neutrino spectrum the expression

$$f(E_{\nu}) = \frac{1}{N} F(Z,p) E_{\nu}^2 (W - E_{\nu}) \sqrt{(W - E_{\nu})^2 - m_e^2}$$

(12)

where $F(Z,p)$ stands for the Coulomb correction to the spectrum, $N$ is a normalisation factor and $W = m_e + 235$ KeV.

The possibility of surrounding the source with a NaI(Tl) detector is now considered by the LAMA team. As a first step they plan to use a 400 tones detector (approximately $2 \times 10^{29}$ electrons) that will measure the electron recoil energy from 2 - 30 KeV; the source activity will be 5 MCi. A second stage with a one tone detector and 15 MCi of $^{147}Pm$ is under study.
We can now estimate the event rates expected both in the Standard Model as well as in extended models for the configuration discussed above. In order to do this we need to integrate over the neutrino energy spectrum and to take the average over the electron recoil energy resolution. The expected number of events per bin in the Standard Model is shown in Fig. 2. For definiteness we have considered 2 KeV width bins. In Fig. 2 we also show the excess in the number of events for the case of an extra neutral gauge boson in the \( \chi \) model for a \( Z' \) mass of 330 GeV. The prospects of the experiment to be sensitive to such an excess in the shape of the electron energy distribution will depend on the error achieved in the event numbers per bin. At the moment we can only estimate the statistical error, but not for the systematic.

In order to estimate the LAMA sensitivity to the mass of a \( Z' \) in the \( \chi \) model we have considered an experimental set up with 5 MCi source and a one tone detector. Assuming that the detector will measure exactly the SM prediction and taking into account only the statistical error, we obtain a sensitivity of the order of 600 GeV at 95 % C. L., comparable to the present Tevatron result. A more detailed analysis can be found in ref. [13].

In the case of the BOREXINO proposal [16], they have considered the use of a \( ^{51}Cr \) source that will be located at 10 m from the detector [17]; unfortunately the experimental set up does not allow one to surround the source and, therefore the statistics is not high enough to provide a strong sensitivity to the \( Z' \) mass. In this case, if we consider again that the experiment will measure the SM prediction, the sensitivity to the \( Z' \) mass in the \( \chi \) model will be 275 GeV, if only the statistical error is considered. If we take into account the background [18] the sensitivity will decrease to 215 GeV.

Finally we now move to the HELLAZ proposal. Although this collaboration has not considered the use of an artificial source, there is room to speculate about the experimental set up and expected event rates. For definiteness we assume in our analysis a \( ^{51}Cr \) source and the originally designed HELLAZ de-
Figure 3. Sensitivity to the $\gamma$ parameter for different models for the case of the HELLAZ proposal. The solid line correspond to the case of an energy region from 100 KeV - 250 KeV while the dotted line is for the region from 100 KeV - 550 KeV. We also show in the plot the present constraint from indirect searches [3].
tector \[19\]. Since the error will depend on the specific topology of the experiment, we have computed the sensitivity at 95 % C. L. for different values of the total error in the number of events per bin (a detailed explanation of this analysis can be found in \[4\]). The results, for four different models are shown in Fig. 3 where we have considered two possible energy regions for the detector. First we consider the case of an energy window from 100 KeV-250 KeV, that is the energy region that HELLAZ is considering for the study of solar neutrinos. We can see that the prospects for getting a better sensitivity than other indirect searches seems to be very realistic. On the other hand the chances of improving the Tevatron constraint seems feasible only if a high-statistics experiment is done. This can be achieved either by constructing a more intense source, by increasing the mass of the detector, by enriching the source several times (in order to increase the exposure time), or a combination of the above. Extending the energy window to 100 KeV-560 KeV is also helpful in getting a better sensitivity, as can be seen from the same Fig 3.

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