Testing new physics with future low energy neutrino experiments

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Abstract: The development of new low-energy detectors and strong artificial neutrino sources opens new opportunities to study new physics, such as additional gauge bosons in extended models and neutrino magnetic moments. In this talk we report the sensitivity that future experiments such as BOREXINO, HELLAZ and LAMA could have in searching for an additional gauge boson in different E_6 models as well as in the left-right symmetric model. We also discuss the sensitivity of a detector with good angular and recoil electron energy resolution in searching for a neutrino magnetic moment by using different artificial neutrino sources.

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 $\overline{\nu_e} e$ scattering from terrestrial neutrino sources with improved statistics as a test of the electroweak gauge structure. The coupling constants governing $\nu_e e \to \nu_e e$ scattering in the SM have been well measured from $e^+e^- \to l^+l^-$ 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 $\overline{\nu_e} e$ 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. We will also discuss the case of a low-energy detector with both angular and recoil electron energy resolution, such as the HELLAZ proposal. These experiments could play an important role in constraining the neutrino magnetic moment (NMM).

In sections 2 and 3 we concentrate in the Z' searches. 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. In section 4 we discuss the potential of a detector with angular and recoil energy resolution in searching for a NMM. In both cases the use of an artificial neutrino source (ANS) is considered. Finally, in section 5 we give the conclusions.

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2. The νe Cross Section

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

$$\frac{d\sigma}{dT} = \frac{2m_e G_F^2}{\pi}\{(g_L+1)^2 + g_R^2(1-\frac{T}{E_\nu})^2 - \frac{m_e}{E_\nu}(g_L+1)g_R\frac{T}{E_\nu}\} \qquad (2.1)$$

where T is the recoil electron energy, and E_ν is the neutrino energy. In the SM case we have $g_{L,R} = \frac{1}{2}(g_V \pm g_A)$, with $g_A = -\rho_{\nu e}/2$ and $g_V = \rho_{\nu e}(-1/2 + 2\kappa \sin^2\theta_W)$ where $\rho_{\nu e}$ and κ describe the radiative corrections for low-energy $\nu_e e \to \nu_e e$ scattering [6]. For the case of $\overline{\nu_e} e \to \overline{\nu_e} e$ 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 $\nu_e e \to \nu_e e$ scattering in the SM have been well measured through the $e^+e^- \to l^+l^-$ 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 $\nu_e e \to \nu_e e$ scattering experiments. For convenience we define the parameter

$$\gamma = \frac{M_Z^2}{M_{Z'}^2} \qquad (2.2)$$

and we will neglect the mixing angle θ' between the SM boson and the extra neutral gauge boson.

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

$$\delta\ \frac{d\sigma}{dT} = \gamma\Delta = \gamma\frac{2m_e G_F^2}{\pi} \times \{D + E\frac{T}{E_\nu}(\frac{T}{E_\nu} - 2) - F\frac{m_e}{E_\nu}\frac{T}{E_\nu}\} \qquad (2.3)$$

with Δ in obvious notation and

$$D = 2(g_L+1)\delta g_L + 2g_R\delta g_R \qquad (2.4)$$

$$E = 2g_R\delta g_R \qquad (2.5)$$

$$F = (g_L+1)\delta g_R + g_R\delta g_L \qquad (2.6)$$

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]

$$\delta g_L = \frac{s_W^4}{r_W^2}g_L + \frac{s_W^2 c_W^2}{r_W^2}g_R \qquad (2.7)$$

$$\delta g_R = \frac{s_W^4}{r_W^2}g_R + \frac{s_W^2 c_W^2}{r_W^2}g_L \qquad (2.8)$$

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

$$\delta g_L = 4\rho s_W^2(\frac{3\cos\beta}{2\sqrt{24}} + \frac{\sqrt{5}}{\sqrt{8}}\frac{\sin\beta}{6}) \times (\frac{3\cos\beta}{\sqrt{24}} + \frac{1}{3}\frac{\sqrt{5}}{\sqrt{8}}\sin\beta) \qquad (2.9)$$

$$\delta g_R = 4\rho s_W^2(\frac{3\cos\beta}{2\sqrt{24}} + \frac{\sqrt{5}}{\sqrt{8}}\frac{\sin\beta}{6}) \times (\frac{\cos\beta}{\sqrt{24}} - \frac{1}{3}\frac{\sqrt{5}}{\sqrt{8}}\sin\beta) \qquad (2.10)$$

where, ρ includes the radiative corrections to the ratio $M_W^2/M_Z^2 cos\theta_W$ and β 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

$$R = \frac{\Delta}{(\frac{d\sigma}{dT})^{SM}}. \qquad (2.11)$$

This ratio depends on the specific model through the angle β 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. (2.11) for the case of a neutrino coming from a ^{51} Cr source, which corresponds to a neutrino energy $E_\nu = 746$ KeV. We show this ratio in Fig. 1 as a function of β 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 models (χ, η and ψ models) we can say that the χ 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 $\gamma \simeq .1$ in the χ model we need a resolution of the order of 5 %.

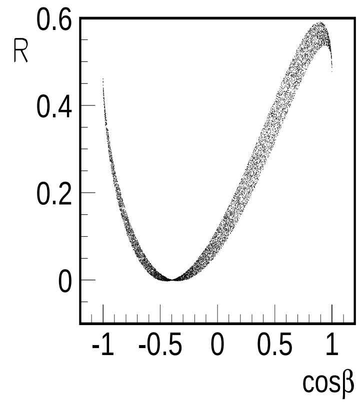

Figure 1: Plot of the ratio given in eq. 2.11 as a function of the model for different values of T and for $E_\nu = 746$ KeV.

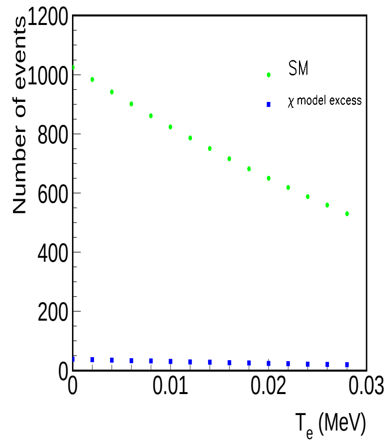

Figure 2: Expected number of events per bin for the LAMA proposal. The additional contribution of an extra neutral gauge boson with $M_{Z'} = 330$ GeV in the χ model is also shown.

3. Experimental prospects for Z' searches.

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 $^{51}\ Cr + e \to ^{51}\ V + \nu_e$. The main line is at 746 KeV and represents 90 % of the neutrino flux. Besides the neutrino flux, there is also γ 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 antineutrinos through the $^{147}Pm \to ^{147} Sm + e + \overline{\nu_e}$ beta decay. In this case we have an antineutrino 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 γ emission. In this case we can use as a good approximation for the anti-neutrino spectrum the expression

$$f(E_\nu) = \frac{1}{N} F(Z,p) E_\nu^2 (W - E_\nu) \times \sqrt{(W-E_\nu)^2 - m_e^2} \quad (3.1)$$

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

The possibility of surrounding this ANS with a NaI(Tl) detector is now under consideration by the LAMA collaboration. As a first step they plan to use a 400 tones detector (approximately 2×10^{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 χ 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 the systematic.

In order to estimate the LAMA sensitivity to the mass of a Z' in the χ 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 χ 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. In a recent paper [19] it has been considered the use of another ANS for the BOREXINO proposal; in this case the neutrino flux will be bigger and therefore, the expectations for a good sensitivity could increase.

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 detector [20]. 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 [2]). 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.

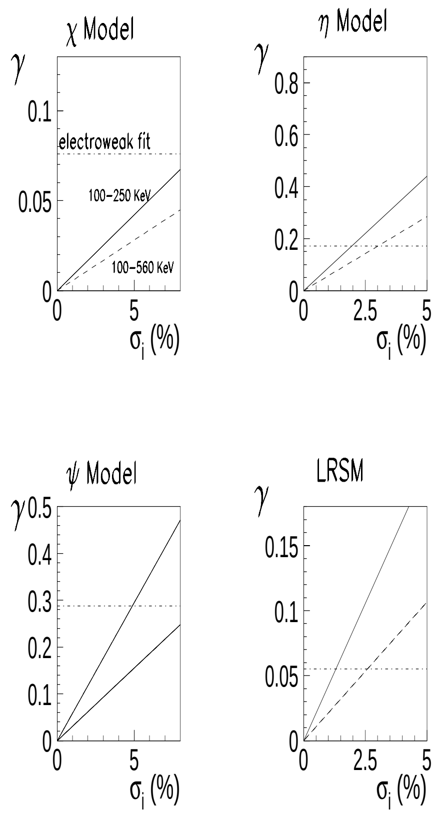

Figure 3: Sensitivity to the γ parameter for different models for the case of the HELLAZ proposal. The solid line correspond to the case of an energy region from 100 KeV - 250 KeV while the dotted line is for the region from 100 KeV - 550 KeV. We also show in the plot the present constraint from indirect searches [3]

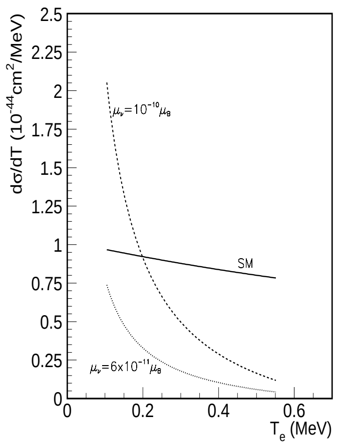

Figure 4: Differential cross section in terms of T for the SM case and for the neutrino magnetic moment contribution for two different values of μ_ν in the case of a Cr source.

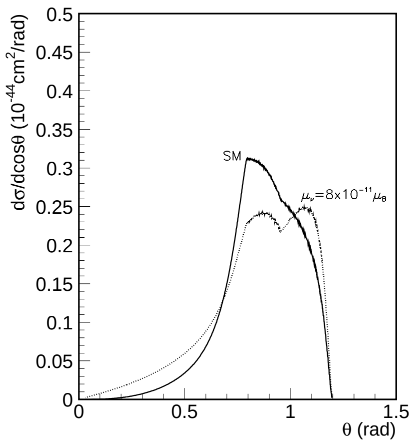

Figure 5: Angular distribution of events for the SM case and for the case of a neutrino magnetic moment $\mu_\nu = 8\times 10^{-11}$. We consider a $Sr-Y$ source and a threshold of $T_{th} = 100KeV$; the recoil energy is integrated, considering the cuts imposed by the threshold and the kinematical limits.

4. Testing neutrino magnetic moments

The use of low energy experiments in order to constraint the NMM has been widely discussed in the literature. The stronger bound on the neutrino magnetic moment comes from a reactor experiment [21] and gives $\mu_\nu = 1.8\times 10^{-10}\mu_B$. The MUNU collaboration is now running and tries to improve this constraint by measuring a reactor antineutrino flux with a new detector. There are several proposals to search for a neutrino magnetic moment using artificial neutrino sources. LAMA collaboration is planned to search for a NMM of the order of $10^{-11}\mu_B$ [12]. BOREXINO [16] has also been proposed as an alternative to search for a neutrino magnetic moment [17]. Recently this case has been studied taking into account a new ANS such as the $^{90}\ Sr$ source [19, 22]; in this case, a sensitivity of $\mu_\nu \sim 0.6\times 10^{-10}\mu_B$ seems to be reachable. A new proposal is the use of an intense Tritium source [23] with a neutrino energy spectrum up to 18.6 KeV. In this case a low mass detector has been considered and the source is planned to surround the detector.

Here we discuss the potential of an artificial neutrino source in testing the neutrino magnetic moment in a large mass detector with both angular and recoil electron energy resolution. Such a study could be interesting for a detector like that in the HELLAZ proposal.

If neutrino has a neutrino magnetic moment μ_ν, in addition to the SM cross section given in Eq. (2.1), there will be an additional contribution given as

$$\frac{d\sigma^{mm}}{dT} = \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\{\frac{1}{T} - \frac{1}{E_\nu}\}, \qquad (4.1)$$

which adds incoherently to the weak cross section.

We have plotted both contributions to the differential cross section in Fig. (4). A ^{51}Cr source has been considered. Two different values of μ_ν are shown. We can see from this figure that, for low values of T, the neutrino magnetic moment signal is of the same order of the SM one for $\mu_\nu \sim 0.6 - 1\times 10^{-10}\mu_B$. As we are thinking in a detector with angular resolution we could also plot the differential cross section in terms of the recoil angle. However, for the case of a monochromatic neutrino source, such as the ^{51}Cr source, the qualitative behavior is the same both in T as in θ, as can be seen in [24].

We can also consider the case of a $^{90}Sr - ^{90}Y$ anti-neutrino source. This source has been studied by a Moscow group [25] and its potential has

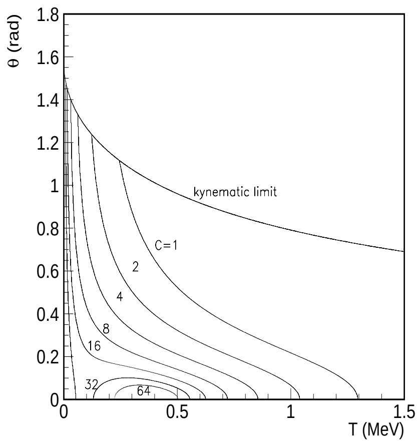

Figure 6: Curves of equal ratio $C \equiv \frac{d\sigma^{mm}}{dT} / \frac{d\sigma^{W}}{dT}$ for $\bar{\nu}_e$ and taking $\mu_\nu = 10^{-10}\mu_B$. Two are the effects which increase the ratio C: for low T the magnetic moment contribution becomes larger.

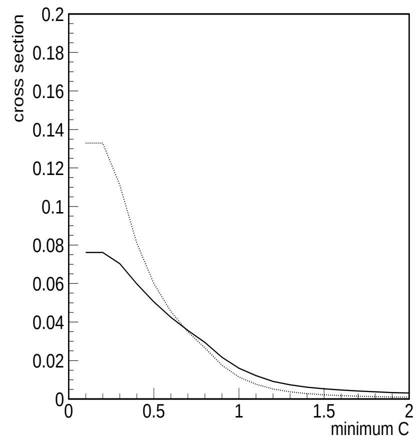

Figure 7: Weak and magnetic moment ($\mu_\nu = 6\,10^{-11}\mu_B$) integrated cross sections; we integrate both over angles θ and energies T. The region of integration is limited by the curves of equal ratio C ; the limiting value C is displayed in the horizontal axis; also, we consider a threshold for T: $T \geq T_{th} = 100\,KeV$. Both variables (T,θ) are also limited by the kinematics.

been recently studied for the BOREXINO case [19, 22]. In order to compute the differential cross section for this source, we must consider the corresponding antineutrino energy spectrum and integrate it over. As we are considering a detector with energy and angular resolution, we can express the result either in terms of the electron recoil energy, T, or in term of the recoil angle, as has already been done in [26]. The differential cross section, averaged over the antineutrino energy distribution will be

$$\langle \frac{d\sigma}{d(cos\theta)} \rangle_{E_\nu} = \int \frac{d^2\sigma}{dTd(cos\theta)} dT = \tag{4.2}$$
$$\int \Theta_{\text{p. s.}} f(T,\theta) \frac{d\sigma(T,\theta)}{dT} \frac{m_e p T}{(pcos\theta - T)^2} dT$$

In this equation $\Theta_{\text{p. s.}}$ accounts for the allowed phase space and $f(T,\theta) = f(E_\nu(T,\theta)) \equiv dn/dE_\nu$ is the neutrino energy spectrum as a function of T and θ. We have integrated T in the range $.1MeV < T < 0.5MeV$, the energy range to which HELLAZ could be sensitive. The result is shown in Fig 5 both for the Standard Model case as well as for the case of a neutrino magnetic moment $\mu_\nu = 8 \times 10^{-11}$.

It is possible to see from Fig. 5 that, besides the additional contribution to the differential cross section, the shape for the NMM signal is also different from that of the standard model. In particular the magnetic moment contribution is slightly bigger than the Standard Model one both for small angles and for big angles, meanwhile, in the intermediate region, the SM one is bigger.

We can try to optimize the best region in the $\theta - T$ on which the non-standard effect is maximum. This can be done by considering the curves in the (T,θ) plane given by the condition

$$C = \frac{d\sigma^{mm}/dT}{d\sigma^{W}/dT}. \tag{4.3}$$

This curves are shown in Fig. 6, for $\mu_\nu = 10^{-10}\mu_B$. They are characterized by a given ratio of the magnetic moment differential cross section to the SM one. Therefore, for C=1 we will get the curve where the magnetic moment signal is equal than the SM one, for C=2 the the magnetic moment signal is twice the SM one, and so on.

Given that the iso-curves (Fig. 6) reflect the presence of a favored region for searching for a magnetic moment, thanks to the dynamical zero, it seems interesting to integrate the cross section over regions in the (T,θ) plane limited by the iso-curves. In this way, we are optimizing the region of integration to look for magnetic moment.

Figure 7 shows the result of integrating the differential cross section given in Eq. (4.3) over T and θ in regions such that $d\sigma^{mm}/d\sigma^{W} > C$. A neutrino magnetic moment $\mu_\nu = 6 \times 10^{-11}\mu_B$ has been assumed. Of course, as the limiting ratio C is taken larger, the magnetic moment signal becomes larger than the SM one. However, the integral in this case is small. Note that if one integrates over the whole region (C=0) one can probe the complete cross section, but the value of NMM relative to SM decreases. Therefore it is interesting to study intermediate regions such as the region limited by $C = 0.7$, where the contribution of the neutrino magnetic moment is comparable with that of the weak interaction, although the statistics is a 30 % of the total one.

5. Conclusions

As a conclusion we can say that the new generation of low-energy solar neutrino-type detectors using strong artificial neutrino sources may open new experimental possibilities in testing the structure of the electroweak interaction as well as in testing non-standard neutrino electromagnetic properties.

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