Tests of physics beyond the Standard Model with future low energy neutrino experiments

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Neutrino-electron scattering can be used to probe neutrino electromagnetic properties at low-threshold underground detectors with good recoil electron energy resolution. We study the sensitivity of Helium detector experiments, such as HELLAZ, for artificial anti-neutrino sources. We show that, for a $^{90}$Sr $-$ Y source, one expects a sensitivity to the neutrino magnetic moment at the level of $\mu_\nu = 2 \times 10^{-11} \mu_B$. We also report the sensitivity that these experiments could have in searching for an additional gauge boson in $E_6$ models.

1. Introduction

The solar neutrino problem has motivated the study of new solutions based on neutrino physics. The most popular solutions are based on the idea of neutrino oscillations either in vacuum or in the Sun due to the enhancement arising from matter effects \cite{1}. In addition there is considerable interest in alternative interpretations such as the resonant spin-flavor solution \cite{2}. Recent analysis shows that this solution give a better fit than those obtained for the favoured neutrino oscillation solutions \cite{3,4}, although not in a statistically significant way.

This kind of scenario has motivated the search for a neutrino magnetic moment by using reactor experiments such as MUNU \cite{5}. In this talk I will concentrate on a different idea \cite{6}: the use of a radioactive isotopic source with a low-energy detector such as Helium detectors (HELLAZ-HERON). These detectors are sensitive to the antineutrino flux through neutrino-electron scattering.

I will also discuss the proposal \cite{7} of using the same type of experiments as a test of the electroweak gauge structure. It will be shown that these experiments could give complementary tests of physics beyond the Standard Model.

2. Experimental prospects for neutrino magnetic moment searches

The use of low energy experiments in order to constraint the neutrino magnetic moment (NMM) has been widely discussed in the literature. The stronger bound comes from a reactor experiment \cite{8} and gives $\mu_\nu = 1.8 \times 10^{-10} \mu_B$. The MUNU collaboration is now running and tries to improve this constraint down to $\mu_\nu = 3 \times 10^{-11} \mu_B$ by measuring a reactor antineutrino flux with a new detector \cite{9}.

The idea of using artificial neutrino sources (ANS) to search for a NMM was first proposed by Vogel and Engel \cite{10}. Since then, there has been several experimental proposals going in this direction. LAMA collaboration is planned to search for a NMM of the order of $10^{-11} \mu_B$ \cite{11}. BOREXINO \cite{12} has also been proposed as an alternative to search for a NMM \cite{13}. Recently this proposal has been studied taking into account a $^{90}$Sr source \cite{14,15}; in this case, a sensitivity of $\mu_\nu \sim 1.6 \times 10^{-11} \mu_B$ seems to be reachable. A different proposal is the use of an intense ANS with a neutrino energy of few KeV \cite{16}. In this cases a low mass detector is needed.

Here we will discuss the potential of an artificial neutrino source in testing the NMM in a large mass detector with both angular and recoil electron energy resolution \cite{17}. I will concentrate on the case of Helium detectors proposals such as HELLAZ \cite{18}.

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For this purus a $^90\text{Sr} - ^90\text{Y}$ anti-neutrino source is considered. This source has been studied by a Moscow group [13] and its potential has been discussed for the BOREXINO case [13,14]. In order to get a number for the HELLAZ sensitivity to the neutrino magnetic moment we have made a similar analysis to the one performed in Ref. [13]. There are other experimental proposals that consider Helium [18] (or Xenon [19]) as a target for detecting neutrino-electron scattering. The following analysis could be extended to study them.

The differential cross section for the process $\nu_e e \rightarrow \nu_e e$ is given by

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

where $T$ is the recoil electron energy, and $E_\nu$ is the neutrino energy. In the SM case we have $g_{L,R} = \frac{1}{2}(g_V \pm g_A)$, with $g_A = -\mu_\nu/e$ and $g_V = \rho_\nu e(-1/2 + 2\sin^2\theta_W)$ where $\rho_\nu e$ and $\kappa$ describe the radiative corrections for low-energy $\nu_\nu e \rightarrow \nu_\nu e$ scattering [20]. For the case of $\bar{\nu}_e e \rightarrow \bar{\nu}_e e$ scattering we just need to exchange $g_L$ with $g_R$ and vice versa.

If neutrino has a magnetic moment $\mu_\nu$, there will be an additional contribution, given as

$$\frac{d\sigma^{\text{em}}}{dT} = \pi \alpha^2 \mu_\nu^2 \left\{ \frac{1}{T} - \frac{1}{E_\nu} \right\},$$  \hspace{1cm} (2)

which adds incoherently to the weak cross section.

For the case of HELLAZ an angular resolution of 35 mrad is expected and the expected electron recoil energy resolution is $\sigma_T/keV = 22\sqrt{T}/MeV$ [18]. Therefore, we need to integrate the differential cross section (either electroweak or electromagnetic) over the error funtions:

$$\langle \sigma \rangle = \int d(\theta) dTW(\theta) W(T) \lambda(\theta,T) \times \frac{d\sigma^W}{dT}(\frac{m_\nu p T}{(p\cos\theta - T)^2})$$  \hspace{1cm} (3)

with

$$W(T) = \frac{1}{2} \left[ \text{Erf} \left( \frac{T_2 - T}{\sqrt{2}\sigma_T} \right) - \text{Erf} \left( \frac{T_1 - T}{\sqrt{2}\sigma_T} \right) \right]$$  \hspace{1cm} (4)

and $W(\theta)$ a similar expresion for the electron recoil angle. Here $T_1 = 100$ KeV, $T_2 = 1$ MeV and $\theta_1 = 0$ and $\theta_2 = \arccos(\frac{T}{\sqrt{T^2 + 2m_\nu T}})$. $\lambda(\theta,T)$ accounts for the antineutrino energy spectrum.

The total number of events will be given by

$$N_0 = N_e(\sigma) \times F(R,D,L) \int_{t_0}^{t_0 + t_0} dt' I(t'),$$  \hspace{1cm} (5)

where $N_e = 2 \times 10^{30}$ is the total number of electrons in the detector, $t_{tr} = 5$ days is the source transportation time and $t_{ex}$ is the exposure time, that we consider as 180 days, $I(t) = I_0 \exp(-t/\tau)$ is the intensity of the source. We are considering $I_0 = 5$ M Ci and $\tau = 28$ y. The factor $F(R,D,L)$ accounts for the real fraction of the detector fiducial volume that is sensitive to the neutrino flux and depends on the topology of the experimental set up. We consider the detector as a cylinder 20m long ($L = 20$ m) and 5m radius ($R = 5$ m) [21].

The fiducial volume for this configuration will depend on the distance, $D$ from source to the center of the detector. In the case of a source located just at the walls of the detector ($R = D = 5$m) We have $F(R, R, L) = 0.774$. For a source located at 15 m we will have $F(R, D, L) = 0.919$.

The expected background for 180 days will be, $N_B = 1980$ [21], and the total 1$\sigma$ uncertainty will be $\delta N_0 = \sqrt{N_B + N_0 (1 + \delta_A^2)}$, with $\delta_A = 0.01$ the estimated uncertainty of the anti-neutrino flux.

We can compute the total number of events expected both in the Standard Model, as well as in the case of a non-zero neutrino magnetic moment:

$$N(\mu_\nu) = N_0 \left[ 1 + \mu_\nu^2 < \frac{\langle \sigma^{\text{em}} \rangle}{\langle \sigma^{\text{SM}} \rangle} \right],$$  \hspace{1cm} (6)

Where $N_0$ es the Standard Model expectation for the number of events computed from Eq. (3) and $< \sigma^{\text{SM}} >$ is the averaged differential cross sections for the Standard Model as given by Eq. (3), $\mu_\nu^2 < \sigma^{\text{em}} >$ is a similar expresion for the case of a neutrino magnetic moment, $\mu_\nu$.

If the experiment measures a number of events in complete agreement with the SM, then we will get a bound

$$\mu_\nu \leq \sqrt{\frac{\epsilon_{90} < \sigma^{\text{SM}} >}{< \sigma^{\text{em}} >}},$$  \hspace{1cm} (7)

with $\epsilon_{90} = 1.645\delta N_0/N_0$. 

We can take this value as the characteristic sensitivity to a neutrino magnetic moment search for HELLAZ. For a source located at 5 m from the center of the detector, we found that the sensitivity will be $\mu_\nu = 1.6 \times 10^{-11} \mu_B$. While for the more pessimistic case of a 15 m distance the sensitivity reduces to $\mu_\nu = 3.1 \times 10^{-11} \mu_B$. This result is similar to the one expected in the BOREXINO proposal [13]. Although in the HELLAZ proposal a lower recoil energy threshold is expected (100 KeV vs 250 KeV in BOREXINO) the difference in mass (and therefore in the number of electrons) makes decrease the number of events.

3. Experimental prospects for $Z'$ searches

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. 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 [22]. In what follos, we will focus 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 $\gamma = \frac{M_{Z'}}{M_Z}$ and neglect the mixing angle $\theta'$ between the SM boson and the extra neutral gauge boson.

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

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

with $\Delta$ in obvious notation and

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

$$E = 2g_R \delta g_R$$

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

where $g_L$ and $g_R$ are the SM model expressions and $\delta g_{L,R}$ give the corrections due to new physics. The specific form of $\delta g_L$ and $\delta g_R$ can be found in [22] for the case of a LRSM [24], and also for the case of $E_6$ models [25].

The correction to the $\nu_e e$ scattering depends on the model. In the analysis done in Ref. [23], we showed 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 ($\chi$, $\eta$ 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 $^{147}Pm$ [21], proposed for the LAMA experiment [23,10]. This source produces antineutrinos through the $^{147}Pm \rightarrow ^{147}Sm + e^- + \gamma$ beta decay. In this case we have an antineutrino spectrum with energies up to 235 KeV.

The possibility of surrounding this ANS with a NaI(Tl) detector is now under consideration by the LAMA collaboration [27]. 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 estimate the event rates expected both in the Standard Model as well as in extended models for the configuration discussed above. We can compute the expected number of events per bin in the Standard Model. For definiteness we have considered 2 KeV width bins. For the case of an extra neutral gauge boson, we would expect an excess in the number of events per bin.

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. [23].

Coming back to the Helium detectors. We have considered the experimental set up of the HELLAZ proposal, and a 5 Mci $^{51}Cr$ source. A similar source has been used to calibrate both GALLEX and SAGE solar neutrino experiments [28]. In this case the sensitivity for the mass of an extra gauge boson will be $M_{Z'} \simeq 450$ GeV, if the source is located at 5 m from the center of the detector. And $M_{Z'} \simeq 260$ GeV if the distance is 15 m. For this analysis 10 KeV width bins were considered [5].
Finally, in the case of the BOREXINO proposal. Considering the $^{51}$Cr neutrino source as mentioned in Ref. [13], we found that the sensitivity to the $Z'$ mass in the $\chi$ model will be 305 GeV, if only the statistical error is considered. If we take into account the background the sensitivity will decrease to 230 GeV.

4. Conclusions

As a conclusion we can say that the new generation of low-energy solar neutrino-type detectors using strong artificial neutrino sources could give complementary information about non-standard neutrino electromagnetic properties as well as for the structure of the electroweak interaction.

Acknowledgements

This work was supported by CONACYT México under grant J32220-E.

I would like to thanks Javier Segura, Victor B. Semikoz, José W. F. Valle and the people from the LAMA collaboration, with whom the results of this work have been done.

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