Testing the Standard Model and beyond with the LENA proposal

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Abstract. We discuss the possibility of a precision measurement of the electroweak mixing angle and a probe for new physics in the leptonic process of neutrino electron scattering. In the new physics schemes we explore the case of non standard neutrino interactions (NSI). The LENA proposal, currently under discussion, considers a large detector and the use of an artificial, ⁵¹Cr, radioactive neutrino source with of 5 MCi intensity. We also discuss the possible use of the solar neutrino flux as a neutrino source, in particular the case of the ⁷Be emission line.

1. Introduction

The evidence of neutrino oscillations reveal the implication of massive neutrinos, this fact can be acknowledged as the first evidence of new physics beyond the Standard Model [1, 2]. The Standard Model of electroweak interactions has been extremely successful, experiments confirm its predictions to a very high degree of accuracy. Yet many open questions remain, especially in the neutrino sector. The clear knowledge of neutrino properties will play a very important role to show us the right physical laws beyond the Standard Model.

There are several proposals of large future neutrino experiments. Large sized detectors would combine the technological advantages of previous oscillation experiments; characteristics such as low energy threshold and direction determination will be a key feature in liquid scintillators, water Cerenkov and liquid Argon detectors. LENA [3] is one among other multipurpose experiments in R&D phase that would extend our current knowledge of the neutrino oscillation phenomenon and can also test physics beyond the Standard Model [4, 5]. In this talk we study in detail the LENA proposal as a tool to search for new physics [6].

The weak mixing angle is a very important parameter in the Standard Model, while it has been measured with high accuracy only at high energies, at low energies it is still a challenge to achieve similar accuracy. In neutrino nucleon scattering there is the controversial result of NuTeV [7], reporting an almost 3 σ deviation from the value determined in global precision electroweak fits.

When systematic uncertainties are recalculated in the NuTeV data an error for sin²θ_W of 1 – 5% is found [8, 9]. In neutrino electron scattering the accuracy attained by reactor experiments is
over 10%, the TEXONO collaboration measured $\sin^2 \theta_W = 0.251 \pm 0.031 \text{(stat)} \pm 0.024 \text{(sys)}$ [10]. The study of low energy neutrino electron scattering could be also an excellent probe for various kinds of new physics, such as non-standard interactions (NSI) potentially associated to the mechanism of neutrino mass generation [11, 12, 13] and/or new gauge bosons [14, 15, 16].

2. LENA potential with an artificial $^{51}$Cr neutrino source

The LENA proposal has considered the use of an artificial radioactive neutrino source for oscillometry tests. Here we study, as an application of that kind of source: (A) the precise determination of the electroweak mixing by measuring the neutrino electron differential cross section and (B) the sensitivity to new physics such as NSI and/or additional neutral gauge bosons.

2.1. LENA sensitivity to the electroweak mixing angle with an artificial source

The $\nu_e e$ differential cross section in the Standard Model is given as

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

with $G_F$ the Fermi constant, $m_e$ the electron mass, $T$ the kinetic energy of the recoil electron and $E_\nu$, the neutrino energy. The coupling constants at tree level are expressed as $g_L = \frac{1}{2} + \sin^2 \theta_W$ and $g_R = \sin^2 \theta_W$. Radiative corrections to the $\nu_e e$ process give a modification to these coupling constants of around 2% [17] and will be included in all our calculations.

We consider a $^{51}$Cr source of 5 MCi intensity with a monochromatic neutrino line at 747 keV as the one in the LENA proposal [3], in the deployment time of the source a signal of $1.9 \times 10^5$ neutrino events is expected. The number of events per energy bin is calculated as

$$N_i = n_e \phi_{Cr} \Delta t \int_{T_i}^{T_{i+1}} \int \frac{d\sigma}{dT} R(T, T')dT'dT,$$

with $n_e$ the number of electron targets, $\phi_{Cr}$ the neutrino flux and $\Delta t$ the half-life of the radioactive source. The resolution function $R(T, T')$ accounts for the distribution of the measured recoil electron energy, $T$, around the true energy $T'$,

$$R(T, T') = \frac{1}{\sigma \sqrt{2\pi}} \exp\left[-\frac{(T - T')^2}{2\sigma^2}\right],$$

with the energy resolution, $\sigma = 0.075 \sqrt{T/MeV}$.

If we assume that the detector will measure the SM prediction, Fig. 1, an idealistic $\chi^2$ analysis can be performed for different given errors for the data to obtain an expected sensitivity to $\sin^2 \theta_W$. We use the $\chi^2$ function with the form

$$\chi^2 = \sum_i \frac{(N_i^{\text{theo}} - N_i^{\text{exp}})^2}{\sigma_i^2},$$

$N_i^{\text{theo}}$ is the expected number of events for different values of $\sin^2 \theta_W$ for a given bin $i$, $N_i^{\text{exp}}$ is the 'experimental' value given by the expected number of events for the SM prediction and $\sigma_i^2$ is the error per bin. We have assigned different values to the error $\sigma_i^2$. The results of the statistical analysis are shown in Fig. 2, for three different values of the experimental error (0.5, 1 and 5 %). In the left panel we show a less optimistic scenario where the number of events is not divided in energy bins but is integrated over the whole energy range. The right panel shows
Figure 1. LENA spectrum obtained from Eq. 2, assuming the SM value of $\sin^2 \theta_W = 0.2313$.

Figure 2. Expected sensitivity to the electroweak mixing angle of a $^{51}$Cr neutrino source with the LENA detector. We show the result of a simulated $\chi^2$ analysis of the total number of events with a given total 'error' of 0.5, 1 and 5% taking the whole energy range (left panel) or dividing the sample in bins(right panel).

the case where we divide the energy range in seven bins of 50 keV width. If we compare this analysis with the NuTeV results [8, 9] we find that an experimental error of the order of 1.-2.5 % would be required in order to improve their determination of the electroweak mixing angle.

A total experimental error in the LENA detector of the order of 2 % would suffice to improve the present sensitivity on the electroweak mixing angle given from the more precise calculations of the NuTeV measurements, as in the case of the two recent evaluations of the systematical errors of the experiment [8, 9].

2.2. LENA sensitivity to new physics, NSI and SM gauge structure

We first consider the sensitivity to the non standard neutrino interaction (NSI) parameters that could be generically associated to the generation of neutrino mass through a low-scale seesaw mechanism or through scalar boson mediation [11, 13]. A generic effective four-fermion NSI Lagrangian is given as

$$-\mathcal{L}_{\text{NSI}}^{\text{eff}} = \varepsilon_{\alpha \beta}^{P} 2 \sqrt{2} G_F (\bar{\nu}_\alpha \gamma_\mu \nu_\beta)(\bar{f} \gamma^\mu P f).$$

Here $G_F$ is the Fermi constant and $\varepsilon_{\alpha \beta}^{P}$ parametrize the strength of the NSI. This term must be added to the Standard Model Lagrangian. For laboratory experiments $f$ is a first generation SM fermion ($e, u$ or $d$). The chiral projectors $P$ denote $\{L, R = (1 \pm \gamma^5)/2\}$, while $\alpha$ and $\beta$ denote the three neutrino flavors: $e, \mu$ and $\tau$. We can obtain restrictions on the strength of the NSI
parameters. To illustrate the physics potential of LENA to this type of new physics we focus on the sensitivity to non universal NSI parameters for the interaction of neutrinos with electrons, a similar analysis could be done for the flavor changing NSI parameters.

The differential cross section for neutrino electron scattering is modified in presence of the new interactions. The coupling constants for the Eq. (1) will be modified to $g_R \to g_R + \varepsilon^{R}_{ee}$ and $g_L \to g_L + \varepsilon^{L}_{ee}$.

After performing an idealistic statistical analysis, similar as the one explained in the previous section, we find that for a 5% error in the measured event number per bin the constraint on $\varepsilon^{L}_{ee}$ would be below a few percent, while for the case of a 1% error the constraint on this parameter will lie below the percent level, in Fig. 3 we compare the estimated sensitivity to the NSI parameters attainable by LENA with previous limits from reactor and solar neutrino data.

This limits can be put in the context of specific extensions to the SM, some of them as those arising from a $E_6$ gauge group [14, 15, 16] involve an additional gauge boson. In that case the non universal NSI parameters will be expressed as [15]

\[
\begin{align*}
\varepsilon^{L}_{ee} &= 2\gamma \sin^2 \theta_{W} \rho_{pe}^{NC} \left( \frac{3 \cos \beta}{2 \sqrt{6}} + \frac{\sin \beta}{3} \sqrt{\frac{5}{8}} \right)^2 \\
\varepsilon^{R}_{ee} &= 2\gamma \sin^2 \theta_{W} \rho_{pe}^{NC} \left( \frac{\cos \beta}{2 \sqrt{6}} - \frac{\sin \beta}{3} \sqrt{\frac{5}{8}} \right), \left( \frac{3 \cos \beta}{\sqrt{24}} + \frac{\sin \beta}{3} \sqrt{\frac{5}{8}} \right)
\end{align*}
\]

(6)

where $\gamma = \frac{M_{Z}^2}{M_{Z}^2}$, with $M_{Z}$ the mass of the $Z$ boson, and $M'_{Z}$ the mass of the extra gauge boson. As an example we take the $\chi$ model ($\cos \beta = 1$) discussed in [15]. After the idealistic statistical analysis we find that it would be possible to put a lower bound in $M'_{Z}$ from 360 GeV to 1.1 TeV if the total error is assumed to be from 0.5% to 5%. This limit would be complementary to those expected at the Large Hadron Collider [18]. Never the less in specific models with different couplings for leptons and quarks, as in the case of leptophilic scenarios [19, 20] the LENA sensitivities would be dominant. The LENA proposal also has potential to restrict models with trilinear $R$-parity violating couplings [21].

Figure 3. Expected LENA sensitivity at 90% CL to non-universal NSI using a $^{51}$Cr neutrino source. The shaded areas correspond to a binned data sample divided in seven bins of 50 keV each and an 'error' per bin of either 1 (grey inner region) or 5% (magenta outer region). For comparison we show current limits to these parameters from an analysis coming from solar and KamLAND neutrino data [22] (dashed line) as well as from an analysis to the LEP and reactor data [23] (solid line).
3. LENA potential with solar neutrinos

A similar analysis can be done considering solar neutrinos collected by the LENA detector. We take as an example the case of the monoenergetic line of $^7$Be neutrinos of $E = 0.862$ MeV. LENA will be capable to detect this part of the solar spectrum in a similar fashion as the Borexino experiment [24].

To estimate the sensitivity of LENA to $\sin^2 \theta_W$ with solar neutrinos we need to take into account the dependence of the signal on the survival probability, $P_{ee}$. With $\sin^2 \theta_W$ and $P_{ee}$ as free parameters in the statistical analysis we have, for the number of events per bin,

$$N_i = n_e \phi_{C,r} \Delta t \int_{T_i}^{T_{i+1}} \left( P_{ee} \frac{d\sigma^{\nu_{ee}}}{dT} + (1 - P_{ee}) \frac{d\sigma^{\nu_{\tau\tau}}}{dT} \right) R(T, T')dT' dT.$$  

(7)

The differential cross section for the electron-neutrino is given by Eq. (1). For muon or tau neutrinos one has the coupling constants: $\frac{g^\nu_{\mu\tau}}{L} = -\frac{1}{2} + \sin^2 \theta_W$, and $\frac{g^\nu_{\mu\tau}}{R} = \sin^2 \theta_W$.

In Fig. 4 is shown the result of the estimated sensitivity to $\sin^2 \theta_W$. We find that a better determination of the Beryllium spectrum is needed in order to have a precise measurement of $\sin^2 \theta_W$. However, in the optimistic case of an error in the number of events per bin of 1 %, there would be a sensitivity to the electroweak mixing parameter of the order $\sim 2\%$.

4. Conclusions

We showed that by using a Chromium neutrino source LENA could provide a precise measurement of the electroweak mixing angle in a region of energy that is not easy to study with other experiments. LENA can also be applied to probe physics beyond the Standard Model. Here we discussed the case of non universal non standard neutrino interactions, and the possible existence of new electroweak neutral gauge bosons.

The accuracy in the determination of the electroweak mixing parameter expected in LENA lies below the percent level for the most optimistic expectations on the systematical error. These results indicate that LENA holds very good prospects.

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