Testing new physics with future COHERENT experiments

O. G. Miranda, G. Sanchez Garcia and O. Sanders

1 Departamento de Física, Centro de Investigación y de Estudios Avanzados del IPN, Apdo. Postal 14-740, 07000 Ciudad de México, México.

Several experimental proposals expect to confirm the recent measurement of the coherent elastic neutrino-nucleus scattering (CEvNS). Motivated in particular by the next generation experiments of the COHERENT collaboration, we study their sensitivity to different tests of the Standard Model and beyond. We analyze the resolution that can be achieved by each future proposed detector in the measurement of the weak mixing angle; we also perform similar analysis in the context of Non-Standard Interaction (NSI) and in the case of an oscillation into a sterile neutrino state. We show that the future perspectives are interesting for these types of new physics searches.

PACS numbers:

I. INTRODUCTION

Despite the coherent elastic neutrino-nucleus scattering (CEvNS) was proposed more than forty years ago [1], it was only recently that the COHERENT collaboration observed this process for the first time by using a CsI[Na] detector exposed to the neutrino flux generated at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory [2].

In a CEvNS process, an incident neutrino interacts coherently with the protons and neutrons within the nucleus. As a result, there is an enhancement in the cross section, which turns out to be quadratic in the number of nucleons. The necessary condition in order to observe this phenomenon is that the energy of the neutrino must be sufficiently low so that the momentum transfer satisfies $qR << 1$, with $R$ the nuclear radius. Since its first
detection, COHERENT data have been studied for different purposes such as tests of NSI neutrino interactions [3–5], measurements of nuclear neutron distributions [6], weak mixing angle [7, 8] and neutrino electromagnetic properties [5, 9].

In the future, the COHERENT program [10] will include a set of four detectors, each based on different materials and technologies capable of observing low-energy nuclear recoils: the currently used CsI[Na] scintillating crystal, with which CEvNS was detected for the first time, and three future experiments that are still being developed: a set of p-type point-contact Germanium detectors, a single-phase liquid Argon detector, and an array of NaI[Ti] crystals. Each detector has a different threshold, baseline and mass, all of which are summarized in table I. In this work we study the future experimental setups proposed by the COHERENT collaboration in order to test the sensitivity of CEvNS to the weak mixing angle and to the search of new physics by two different mechanisms; the first one through the introduction of parameters which describe NSI interactions and the other by introducing the possibility of a specific neutrino flavor to oscillate into a sterile one. Different works have already studied part of the potential of these detectors in different context [11–14].

Here we focus on the potential of the specific configurations reported by the COHERENT collaboration for its future stages [10] in order to have a complementary forecast that includes cases that have not been covered, such as the future perspectives for the measurement of a weak mixing angle for these detectors.

| $T_{thres}$ | Baseline | Det. Tec. | Fid. Mass |
|-------------|-----------|-----------|-----------|
| $^{133}$Cs$^{127}$I | 5 keV | 19.3 m | Scintillator | 14.6 kg |
| $^{72}$Ge | 5 keV | 22 m | HPGc PPC | 10 kg |
| $^{23}$Na$^{127}$I | 13 keV | 28 m | Scintillator | 2000 kg |
| $^{40}$Ar | 20 keV | 29 m | Liquid scintillator | 1000 kg |

*TABLE I: Current and future experimental setups for the COHERENT collaboration detectors [10].*
II. COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING

Before discussing the future perspectives for CEvNS in a specific SNS experiment, we discuss in this section the main characteristics of the neutrino flux, cross section and form factors involved in the prediction of the number of events measured by a given detector. The neutrino beam used by the COHERENT collaboration consists of $\nu_e$, $\nu_\mu$ and $\bar{\nu}_\mu$ fluxes coming from the SNS. These neutrinos are produced by the $\pi^+$ decay-at-rest in the form $\pi^+ \rightarrow \mu^+ \nu_\mu$ and thus producing a mono-energetic beam of muon neutrinos, known as ”prompt” neutrinos, which can be described by:

$$\frac{dN_{\nu_\mu}}{dE} = \eta \delta \left( E - \frac{m_\pi^2 - m_\mu^2}{2m_\pi} \right). \tag{1}$$

Eventually, the $\mu^+$’s also decay and produce anti-muon neutrinos together with electron neutrinos, known as ”delayed neutrinos”, and which can be modeled, for energies up to 52.8 MeV, as \[6\] :

$$\frac{dN_{\bar{\nu}_\mu}}{dE} = \eta \frac{64E^2}{m_\mu^3} \left( \frac{3}{4} - \frac{E}{m_\mu} \right) \tag{2}$$

$$\frac{dN_{\nu_e}}{dE} = \eta \frac{192E^2}{m_\mu^3} \left( \frac{1}{2} - \frac{E}{m_\mu} \right) \tag{3}$$

Being $\eta = rN_{POT}/4\pi L^2$ a normalization factor with $r = 0.08$ the number of neutrinos per flavor, $N_{POT} = 1.76 \times 10^{23}$, the number of protons on target, and $L$ the distance between the source and the detector. The total neutrino flux is considered to be the sum of the three previous contributions. For all our computations we will consider the same total flux and we set it as equal to that of the first COHERENT measurement \[2\]; in this way our comparison of results will be done using the same standard time window.

Regarding the CEvNS cross section, this has been computed to be \[15\] \[18\] :

$$\left( \frac{d\sigma}{dT} \right)_{SM}^{coh} = \frac{G_F^2 M}{\pi} \left[ 1 - \frac{MT^2}{2E_\nu^2} \right] \left[ Zg_\nu^2 F_Z(q^2) + Ng_\nu^2 F_N(q^2) \right]^2. \tag{4}$$
Here, $M$ is the mass of the nucleus, $E_\nu$ is the neutrino energy, and $T$ is the nucleus recoil energy; $F_{Z,N}(q^2)$ are the corresponding nuclear form factors that are especially important at higher momentum transfer, as can be the case of neutrinos coming from the SNS. In other cases, as for antineutrinos coming from nuclear reactors, these form factors have a minimal impact due to the low momentum transfer. We have computed our results by using a Helm form factor as well as a symmetrized Fermi one for both protons and neutrons; our results in all cases were essentially the same so in what follows, we will consider the Helm form factor for neutrons and the symmetrized Fermi one for protons. The neutral current vector couplings are given by:

$$g^p_V = \frac{1}{2} - 2s_Z^2$$

$$g^n_V = -\frac{1}{2}$$  \hspace{1cm} (5)$$

where $s_Z^2 = \sin^2 \theta_W = 0.23865$, which corresponds to the low energy limit as well. [19].

Recently, a new computation that studies in more detail the cross section for the case of a non-zero spin nucleus (taking into account the kinematics for relatively high momentum transfer) has been reported [20]. It has been stated that kinematic corrections could be important, while axial couplings due to the nuclear spin have less impact. In this picture, the CEvNS cross section is given by [20]:

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{\pi} g_c \left( 1 - \frac{T M}{2 E_\nu} \right) \sum_{f,f'} F_f F_{f'}^* \left[ g^f_V g^{f'}_V \left( A_f A_{f'} \left( 1 - \frac{y \tau}{2} \right)^2 + \Delta A_f \Delta A_{f'} \left( \frac{y}{2} \right)^2 \right) \right.$$  

$$+ g^f_A g^{f'}_A \left( A_f A_{f'} \left( \frac{y \tau}{2} \right)^2 + \Delta A_f \Delta A_{f'} \left( 1 - \frac{y}{2} \right)^2 \right)$$

$$+ 2 g^f_V g^{f'}_A \left( A_f A_{f'} \left( 1 - \frac{y \tau}{2} \right) \left( \frac{y \tau}{2} + \Delta A_f \Delta A_{f'} \frac{y}{2} \left( 1 - \frac{y}{2} \right) \right) \right) \right]$$  \hspace{1cm} (6)$$

Where the sums on both $f$ and $f'$ run over $p$ and $n$, with $A_p = Z$, $A_n = N$, and $\Delta A_f$ is the difference between the corresponding nucleons with spin projection along the incident neutrino axis and those with spin projection opposite to it. The Bjorken $y$ is given by $y = T / E_\nu$ and $s$ is the total energy squared. It has also been discussed in the same reference that the contributions due to $\Delta A_f$ and $g^f_A g^{f'}_A$ are small and, therefore, we will not consider them. After these approximations, Eqs. (4) and (6) are still different by a factor $g_c$. This factor arises if we require [20] that the interaction of the incident neutrino happens only
when the nucleon has an initial momentum \( \vec{p} = -(\vec{q}/2)(1 - m_N/M) \), and acquires a final momentum \( \vec{p} + \vec{q} \), with \( m_N \) the mass of the nucleon. In this picture, the factor \( g_c \) is given by the product of three different factors, two of which are of order unity, while the last one is reported to be linear in \( T \) \cite{20}. Under this assumption we found the factor \( g_c \) is given by:

\[
g_c = 1 + \frac{MT}{m_N E_\nu}. \tag{7}
\]

In general, once we take an expression for the cross section, the number of events measured by a detector is given by:

\[
N^{th} = N_D \int_T A(T)dT \int_{E_{min}}^{52.8 \text{MeV}} dE \lambda(E_\nu, T) \frac{d\sigma}{dT}, \tag{8}
\]

where \( A(T) \) is an acceptance function, \( \lambda(E_\nu, T) \) is the neutrino flux and \( N_D \) is, depending on the detector, the number of targets in it and is given by \( N_A M_{det}/M_D \), with \( N_A \) the Avogadro’s number, \( M_{det} \) the mass of the detector, and \( M_D \) its molar mass. The limits of the \( T \) integral depend on both the detector’s threshold and on the maximum recoil energy for a fixed \( E_\nu \), which to our purposes is well approximated by \( T_{\text{max}}(E_\nu) \simeq 2E_\nu^2/M \). On the other hand, the integral over \( E_\nu \) has an upper limit of 52.8 MeV, which corresponds to the maximum energy of the neutrinos coming from the SNS.

Before computing a forecast of the sensitivity to future new experiments, we have computed what would be the expected number of events in the case of the recent COHERENT detection of CEvNS for the previous two formulations of the cross section. To this purpose, by closely following the procedure described in Ref. \cite{6}, we have computed the expected number of events by recoil energy bins for the case of the CsI detector using an average neutron rms radius of 5.5 fm for both Cs and I, which was found to be the best fit to the COHERENT data \cite{6}; we take the acceptance function as given in \cite{21}. Table I shows the specific values for the detector’s mass and its distance to the neutrino source.

We show the results of this computation in Fig. I where we show the expected number of events when we consider the cross section as in Eq. \cite{4} as well as when we consider the case of a linear kinematic correction due to the factor \( g_c \). It is possible to notice that the introduction of the kinetic factor \( g_c \) yields to a relatively larger number of events. We have
checked that this effect translates into a small shift in the central value of a given fit, but has no impact in the width of the errors. Therefore, for our computations of the future expectations we will show the results obtained with the more simple and usual approach of Eq. (4).

Regarding future experiments, throughout the following sections we will study the cases of Ge, Ar and NaI detectors, which are reported by the COHERENT collaboration to start measuring CEvNS in the near future. Table I gives information about the estimated mass, threshold and baseline on each case, all of which will be considered in our following computations to predict the current estimated number of events by using Eq. (8).

\[ \text{FIG. 1: Expected number of events for the CsI COHERENT case. The solid (blue) line corresponds to the usual approach to the cross section as given in Eq. (4) while the dotted (red) line corresponds to the more detailed case discussed in Ref. [20]. The points correspond to the experimental data [2].} \]

III. SENSITIVITY TO THE WEAK MIXING ANGLE

Future CEvNS measurements will determine with accuracy the weak mixing angle value. Any deviation from the Standard Model prediction [22, 23] for this important quantity will be an indicator of new physics. Although the current estimates for the weak mixing angle from the CsI measurement are not competitive [5], future information from CEvNS may be of important relevance for this test of the SM at very low energies [7, 8]. For example, this information can be useful for the APV measurement where a small deviation from the
prediction has been found [7]. As already mentioned, we have studied the future sensitivity to the weak mixing angle for the next generation of COHERENT experiments [10]. To this purpose, we have assumed that a futuristic $\chi^2$ analysis will be given by the minimization of the function:

$$\chi^2 = \left( \frac{N_{\text{exp}} - (1 + \alpha)N_{\text{th}}(X)}{\sigma} \right)^2 + \left( \frac{\alpha}{\sigma_\alpha} \right)^2,$$

where $N_{\text{exp}}$ is the measured number of events, which, as we are dealing with a future experiment, we will consider as given by the SM prediction. $N_{\text{th}}(X)$ represents the predicted number of events as a function of a set of variable parameters $X$, which in this case corresponds only to the weak mixing angle. This general expression will also be used in the following sections. The statistical uncertainty is given by $\sigma = \sqrt{N_{\text{exp}}}$, and the parameter $\alpha$ quantifies the systematic error with an associated uncertainty $\sigma_\alpha$.

The results are shown in Table II and Fig. 2 where we have taken five different scenarios for each detector. First we have fixed the error to a pesimistic value of 30%, then to the case in which we considered it to be of 15%, and also an optimistic case of 5%. We have also computed an ideal case on which there is no systematic errors with two different efficiencies given by 100 and 50%. With these different scenarios, we expect to have a broad idea of the possible constraints that these future experiments can obtain and what type of error would be more important to control. In all our computations we have considered an acceptance function equal to the unity for all $T$.

We can see from Table II and Fig. 2 that, as expected, a detector with larger mass, such as the NaI case, will give better constraints, provided that the systematic errors are under control. In any case, even the more modest case of the Germanium detector with a 10 kg array could give a competitive measurement (for low energies) if the systematics can be maintained under control.

IV. SENSITIVITY TO NSI

Besides the precision tests of the Standard Model, there has been a lot of interest in different extensions of the SM to explain, for instance, the neutrino mass pattern. A useful phenomenological approach is that of non-standard interactions (NSI) [24–26]. In general,
FIG. 2: Expected sensitivity to $\sin^2 \theta_W$ for the different detectors under consideration: Germanium, Argon, and NaI, respectively. The different curves are for a 100 % efficiency and no systematic errors (solid), for a systematic error of 5 % (dashed), 15 % (dashed-dotted), and 30 % (dashed double-dotted). Finally, the case of an efficiency of 50 % and no systematic error is also shown (dotted line).

| Experiment | 50 % eff | 100 % eff | $\sigma_{syst} = 5 \%$ | $\sigma_{syst} = 30 \%$ |
|------------|----------|------------|-------------------|------------------|
| Ge         | 5.9      | 4.2        | 5                 | 20               |
| Ar         | 1.2      | 0.9        | 3                 | 19               |
| NaI        | 1.0      | 0.7        | 3                 | 19               |

TABLE II: Expected sensitivity, in percent, to the weak mixing angle. For each experiment we show the 1σ expected sensitivity in the case of a 50 % (100 %) efficiency of the experiment. For a non-zero systematic error of 5 (30) %, the efficiency was considered to be 100 %.

Neutral current non-standard interactions can be parametrized by introducing a Lagrangian of the form:

$$\mathcal{L}^{NSI}_{\nu H} = -\frac{G_F}{\sqrt{2}} \sum_{q=u,d} \sum_{\alpha,\beta=e,\mu,\tau} \left[ \nu_\alpha \gamma^\mu (1 - \gamma^5) \nu_\beta \right] \left( \bar{q}_\alpha \gamma_\mu (1 - \gamma^5) q \right) + \epsilon^{qL}_{\alpha\beta} \left[ \bar{q}_\alpha \gamma_\mu (1 + \gamma^5) q \right].$$

(10)

Here the interaction is modeled between the neutrino and the up and down quarks within the nucleons, so the index $q$ runs over $u$ and $d$. The subscripts $\alpha$ and $\beta$ run over the three
flavors $e, \mu$, and $\tau$. The Lagrangian in Eq. (10) contains flavor preserving, non-universal, non-standard terms which are proportional to $\varepsilon^{V}_{\alpha \beta}$ (with $V = L, R$). Also, it contains the so-called flavor-changing terms proportional to $\varepsilon^{V}_{\alpha \beta}$ with $\alpha \neq \beta$; all these coupling constants are taken in terms of the Fermi constant. Thus, for an electron (anti)neutrino source, the cross section for $T \ll E_\nu$ now reads [16, 27–30]:

$$
\frac{d\sigma}{dT}(E_\nu, T) \simeq \frac{G_F^2 M}{\pi} \left(1 - \frac{MT}{2E_\nu^2}\right) \left\{ [Z (g_V^p + 2 \varepsilon^{uV}_{ee} + \varepsilon^{dV}_{ee}) F^V_Z(Q^2) + N (g_V^n + \varepsilon^{uV}_{ee} + 2 \varepsilon^{dV}_{ee}) F^V_N(Q^2)]^2 
+ \sum_{\alpha} [Z (2 \varepsilon^{uV}_{\alpha e} + \varepsilon^{dV}_{\alpha e}) F^V_Z(Q^2) + N (\varepsilon^{uV}_{\alpha e} + 2 \varepsilon^{dV}_{\alpha e}) F^V_N(Q^2)]^2 \right\},
$$

(11)

FIG. 3: Expected sensitivity to $\varepsilon^{uV}_{e\tau}$ for the different detectors under consideration: Germanium, Argon, and NaI, respectively. Again, the different curves are for a hundred percent efficiency and no systematic errors (solid), for a systematic error of 5% (dashed), 15% (dashed-dotted), and 30% (dashed double-dotted). Finally, the case of an efficiency of 50% and no systematic error is also shown (dotted line).

The cross section for a muon (anti)neutrino source has the same form and can be obtained by exchanging the indices $e \leftrightarrow \mu$. For simplicity, here we will only consider the possibility of having NSI interactions coming from the electron neutrino source; this is a natural choice since the muon NSI parameters are usually more restricted from other experiments [24–26]. This means that the number of events measured by a detector at the SNS will be given by:

$$
N^\text{th} = N_D \int_T A(T) dT \int_{E_{\text{min}}}^{32.8\text{MeV}} dE \sum_a \frac{dN_a}{dE} \frac{d\sigma_a}{dT},
$$

(12)
TABLE III: Expected sensitivity to the flavor changing NSI parameter $\varepsilon_{\tau e}^{uV}$. For each experiment we quote the 90 % CL expected sensitivity in the case of a 50 % (100 %) efficiency of the experiment. For a non-zero systematic error of 5 (30) %, the efficiency was considered to be of 100 %.

| experiment | $50 \, \% \text{ eff}$ | $100 \, \% \text{ eff}$ | $\sigma_{\text{syst}} = 5 \, \%$ | $\sigma_{\text{syst}} = 30 \, \%$ |
|------------|---------------------|---------------------|----------------------|----------------------|
| Ge         | $|\varepsilon_{\tau e}^{\nu}^{uV}| < 0.128$ | $|\varepsilon_{\tau e}^{\nu}^{uV}| < 0.107$ | $|\varepsilon_{\tau e}^{\nu}^{uV}| < 0.123$ | $|\varepsilon_{\tau e}^{\nu}^{uV}| < 0.320$ |
| Ar         | $|\varepsilon_{\tau e}^{\nu}^{uV}| < 0.057$ | $|\varepsilon_{\tau e}^{\nu}^{uV}| < 0.048$ | $|\varepsilon_{\tau e}^{\nu}^{uV}| < 0.096$ | $|\varepsilon_{\tau e}^{\nu}^{uV}| < 0.312$ |
| NaI        | $|\varepsilon_{\tau e}^{\nu}^{uV}| < 0.0504$ | $|\varepsilon_{\tau e}^{\nu}^{uV}| < 0.041$ | $|\varepsilon_{\tau e}^{\nu}^{uV}| < 0.090$ | $|\varepsilon_{\tau e}^{\nu}^{uV}| < 0.295$ |

where $a = \bar{\nu}_\mu, \nu_\mu, \nu_e$, with $\frac{d \sigma}{d T}$ given by Eq. (11) for $a = e$ and by Eq. (4) for the other two cases.

The study of the sensitivity to the NSI parameters is of relevance since any positive signal will hint for new physics; on the other hand, constraints on these parameters will potentially discard models of new physics. This is the case, for instance, for the first measurement of CEvNS where the reported constraints [2–5] disfavored a class of models [31, 32, 32] that were motivated by the Dark-LMA solution [33–36]. Future constraints from COHERENT collaboration will allow to put stronger constraints on the NSI parameters. The use of intense neutrino sources close to a CEvNS detector allow for a powerful setup that strongly constraints NSI parameters, competitive with any other neutrino experiment as already pointed out in Refs. [16, 27].

As in the previous section, we have studied the potential of the future setups for the SNS and computed the expected sensitivity for the different future detectors that are to be installed. For simplicity, we made the analysis by considering only one NSI parameter to be non-zero at a time. Again, we have computed the $\chi^2$ analysis of Eq. (9) with $N^{\text{th}}$ given by Eq. (12), and $X$ representing the corresponding NSI parameter. This time we have also considered the five different scenarios for the futuristic systematic uncertainties. That is, we have fixed this error to either 5, 15 and 30%, to the ideal case on which there is not a systematic error and that on which we have a detector’s efficiency of 50%. Fig. 3 shows the results for $\varepsilon_{\tau e}^{\nu V}$, while Fig. 4 shows the corresponding results for $\varepsilon_{e e}^{\nu V}$. We can notice that, for the case of non-universal parameters we show two different intervals where the $\varepsilon_{e e}^{\nu V}$ values
FIG. 4: Expected sensitivity to $\epsilon_{ee}^{uV}$ for the different detectors under consideration: Germanium, Argon, and NaI, respectively. As in previous cases, the different curves are for a hundred percent efficiency and no systematic errors (solid), for a systematic error of 5% (dashed), 15% (dashed-dotted), and 30% (dashed double dotted). Finally, the case of an efficiency of 50% and no systematic error is also shown (dotted line).

can lie. This is a well known degeneracy that appears in the CEvNS case [27]. We show the numerical restrictions for both the flavor-changing and non-universal parameters in Table III and Table IV, respectively. As in the previous section, we can see the importance of the systematic errors, the efficiency, and the mass of the detector. For example, we can notice that for the case of a two tons NaI detector, the sensitivity is such that, even with a 30% error, the experiment can tell between the two degenerate allowed regions for $\epsilon_{ee}^{uV}$, as can be seen in Table IV.
TABLE IV: Expected sensitivity to the non-universal NSI parameter $\varepsilon_{ee}^{uV}$. For each experiment we quote the 90 % CL expected sensitivity in the case of a 50 % (100 %) efficiency of the experiment. For a non-zero systematic error of 5 (30) %, the efficiency was considered to be of 100 %.

V. SENSITIVITY TO THE STERILE NEUTRINO HYPOTHESIS

Currently, the three neutrino oscillation picture is well established and most of its parameters are well measured [37-39]. However, there are different neutrino flux anomalies that cannot be explained by considering neutrino oscillations between three neutrino flavors [40]. For instance, the LSND observes an appearance of a $\bar{\nu}_e$ on a $\bar{\nu}_\mu$ flux, MiniBoone measures an excess of $\nu_e$ and $\bar{\nu}_e$ that agrees with the LSND results. On the other hand, for electron antineutrinos, a dissappearance of $\bar{\nu}_e$ is observed in experiments with reactor neutrinos. These effects may be explained by considering a fourth non-interacting, sterile neutrino flavor. Expected constraints, considering different experimental setups, have been considered for the CEvNS case [41,43].

By considering each neutrino flavor state as a linear combination of mass eigenstates

$$\nu_l = \sum_m U_{lm} \nu_m$$

where $U$ is a unitary mixing matrix, we can find the oscillation probability to be given by [44]:

$$\mathrm{exp.} \quad 50 \% \text{ eff} \quad 100 \% \text{ eff} \quad \sigma_{syst} = 5 \% \quad \sigma_{syst} = 30 \%$$

| exp. | $-0.040 < \varepsilon_{ee}^{uV} < 0.052$ | $-0.029 < \varepsilon_{ee}^{uV} < 0.035$ | $-0.038 < \varepsilon_{ee}^{uV} < 0.042$ | $-0.187 < \varepsilon_{ee}^{uV} < 0.550$ |
|------|----------------------------------|----------------------------------|---------------------------------|---------------------------------|
| Ge   | $0.311 < \varepsilon_{ee}^{uV} < 0.405$ | $0.329 < \varepsilon_{ee}^{uV} < 0.393$ | $0.321 < \varepsilon_{ee}^{uV} < 0.402$ | |
| Ar   | $-0.009 < \varepsilon_{ee}^{uV} < 0.009$ | $-0.006 < \varepsilon_{ee}^{uV} < 0.007$ | $-0.023 < \varepsilon_{ee}^{uV} < 0.023$ | $-0.180 < \varepsilon_{ee}^{uV} < 0.541$ |
| NaI  | $0.351 < \varepsilon_{ee}^{uV} < 0.369$ | $0.353 < \varepsilon_{ee}^{uV} < 0.366$ | $0.336 < \varepsilon_{ee}^{uV} < 0.384$ | |
|      | $0.345 < \varepsilon_{ee}^{uV} < 0.357$ | $0.347 < \varepsilon_{ee}^{uV} < 0.356$ | $0.332 < \varepsilon_{ee}^{uV} < 0.374$ | $0.213 < \varepsilon_{ee}^{uV} < 0.519$ |
\[ P_{\nu_{\alpha}, \nu_{\beta}} = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E} \right) + 2 \sum_{i>j} \text{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin \left( \frac{\Delta m_{ij}^2 L}{2E} \right) \] (14)

where the latin subscripts correspond to the mass eigenstates and the greek ones correspond to the \(e, \mu, \tau, s\) neutrino flavors, \(\Delta m_{ij}^2 = m_i^2 - m_j^2\), \(L\) is the distance from the neutrino source to the detector, and \(E_\nu\) is the neutrino energy. Assuming CPT invariance, the anti-neutrino case is found by interchanging each matrix element with its complex conjugate, resulting in a reverse of the signs.

Due to the short source to detector distance, the oscillations between the three active states can be neglected. Therefore, the probability of oscillation from active to sterile states can be studied in a two-flavor approximation:

\[ P_{\nu_{\alpha}, \nu_s} = \sin^2 2\theta_{\alpha\beta} \sin^2 \left( \frac{1.27 \Delta m_{i4}^2 L}{E_\nu} \right) \] (15)

For simplicity, we will consider two different cases. First, the oscillation from \(\nu_e \rightarrow \nu_s\) and then the corresponding case for muon (anti)neutrinos. To take into account the oscillation of the neutrinos produced at the SNS, we take the probability that the considered neutrino keeps the same flavor as:

\[ P_{\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \left( \frac{1.27 \Delta m_{i4}^2 L}{E_\nu} \right) \] (16)

this oscillation probability is multiplied by the neutrino flux and integrated over the neutrino energy spectrum, so the total number of events expected is given in this two cases by:

\[ N_{th} = N_D \int_T A(T) dT \int_{E_{min}}^{52.8\text{MeV}} dE \sum_{\alpha} \frac{dN_{\alpha}}{dE} \frac{d\sigma}{dT} P_{\alpha}(\theta_{\alpha\alpha}, \Delta m_{i4}^2) \] (17)

where the fluxes for the different neutrino flavors, \(\alpha\), are defined by Eqs. (1-3). As in the case of NSI, we considered a \(\chi^2\) function in order to forecast the sensitivity of COHERENT future experiments. In this case, since neutrino oscillation probability is a function of two variables (\(\sin^2 2\theta_{\alpha\alpha}, \Delta m_{i4}^2\)), we will take the \(\chi^2\) function as the one described in Eq. (9) with \(N_{th}(X) = N_{th}(\sin^2 2\theta_{\alpha\alpha}, \Delta m_{i4}^2)\) as in Eq. (17).
FIG. 5: Expected sensitivity for a muon neutrino oscillation into a sterile neutrino state, for the different detectors under consideration: Germanium (left), Argon (middle), and NaI (right), respectively. The different curves are for a hundred percent efficiency and no systematic errors; for a systematic error of 5 %, and 15 %. Finally, the case of an efficiency of 50 % is also shown.

FIG. 6: Expected sensitivity for an electron neutrino oscillation into a sterile neutrino state, for the different detectors under consideration: Germanium (left), Argon (middle), and NaI (right), respectively. The different curves are for a hundred percent efficiency and no systematic errors; for a systematic error of 5 %, and 15 %. Finally, the case of an efficiency of 50 % is also shown.

For this case, our analysis considers only one parameter at a time. That is, we only consider either $\sin \theta_{ee}$ or $\sin \theta_{\mu\mu}$ different from zero and compute the corresponding effect in the electron (muon) neutrino number of events. In Figs. 5 and 6 we show the sensitivity to the allowed regions of the parameters $\sin^2 2\theta_{ee}$ and $\Delta m^2_{14}$ for the different systematic errors.
and efficiencies that we have already discussed. The results are shown at 90 % CL.

Although for some cases the expected sensitivity is not competitive, we can notice that for the more ambitious detectors with larger mass there is sensitivity to the relevant region of sterile neutrino searches.

VI. DISCUSSION AND CONCLUSIONS

The measurement of CEvNS by the COHERENT collaboration has been a break through that opens the door to new measurements of this elusive process. Motivated by the future program of the same collaboration, we have studied the expected sensitivity for precision tests of the Standard Models as well as for new physics searches. We have focused particularly in the case of the measurement of the weak mixing angle, the sensitivity to NSI and the future constraints on a sterile neutrino state.

We have studied the different proposed detectors on equal footing, in the sense that we have considered the same total neutrino flux coming from the spallation neutron source and we have also considered the same efficiencies and systematic errors. We have illustrated quantitavely that the most ambitious large mass detector arrays will give better constraints on new physics, provided that systematics are under control. We have also estimated the weakness of the constraints if the efficiency is compromised.

Acknowledgments

This work was supported by CONACYT-Mexico under grant A1-S-23238 and by SNI (Sistema Nacional de Investigadores). OGM would also like to thank the collaboration of COFI.

[1] D. Z. Freedman, Phys. Rev. D9, 1389 (1974).
[2] D. Akimov et al. (COHERENT), Science 357, 1123 (2017), 1708.01294.
[3] P. Coloma, M. C. Gonzalez-Garcia, M. Maltoni, and T. Schwetz, Phys. Rev. D96, 115007 (2017), 1708.02899.
[4] J. Liao and D. Marfatia, Phys. Lett. B775, 54 (2017), 1708.04255.
[5] D. K. Papoulias and T. S. Kosmas, Phys. Rev. D97, 033003 (2018), 1711.09773.

[6] M. Cadeddu, C. Giunti, Y. F. Li, and Y. Y. Zhang, Phys. Rev. Lett. 120, 072501 (2018), 1710.02730.

[7] M. Cadeddu and F. Dordei (2018), 1808.10202.

[8] X.-R. Huang and L.-W. Chen (2019), 1902.07625.

[9] M. Cadeddu, C. Giunti, K. A. Kouzakov, Y. F. Li, A. I. Studenikin, and Y. Y. Zhang, Phys. Rev. D98, 113010 (2018), 1810.05606.

[10] D. Akimov et al. (COHERENT) (2018), 1803.09183.

[11] P. B. Denton, Y. Farzan, and I. M. Shoemaker, JHEP 07, 037 (2018), 1804.03660.

[12] J. Billard, J. Johnston, and B. J. Kavanagh, JCAP 1811, 016 (2018), 1805.01798.

[13] W. Altmannshofer, M. Tammaro, and J. Zupan (2018), 1812.02778.

[14] D. Aristizabal Sierra, J. Liao, and D. Marfatia (2019), 1902.07398.

[15] A. Drukier and L. Stodolsky, Phys. Rev. D30, 2295 (1984), [,395(1984)].

[16] J. Barranco, O. G. Miranda, and T. I. Rashba, JHEP 12, 021 (2005), hep-ph/0508299.

[17] K. Patton, J. Engel, G. C. McLaughlin, and N. Schunck, Phys. Rev. C86, 024612 (2012), 1207.0693.

[18] D. K. Papoulias and T. S. Kosmas, Adv. High Energy Phys. 2015, 763648 (2015), 1502.02928.

[19] C. Patrignani et al. (Particle Data Group), Chin. Phys. C40, 100001 (2016).

[20] V. A. Bednyakov and D. V. Naumov, Phys. Rev. D98, 053004 (2018), 1806.08768.

[21] D. Akimov et al. (COHERENT) (2018), 1804.09459.

[22] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D98, 030001 (2018).

[23] J. Erler and R. Ferro-Hernández, JHEP 03, 196 (2018), 1712.09146.

[24] Y. Farzan and M. Tortola, Front.in Phys. 6, 10 (2018), 1710.09360.

[25] O. G. Miranda and H. Nunokawa, New J. Phys. 17, 095002 (2015), 1505.06254.

[26] T. Ohlsson, Rept. Prog. Phys. 76, 044201 (2013), 1209.2710.

[27] K. Scholberg, Phys. Rev. D73, 033005 (2006), hep-ex/0511042.

[28] D. Aristizabal Sierra, V. De Romeri, and N. Rojas, Phys. Rev. D98, 075018 (2018), 1806.07424.

[29] J. B. Dent, B. Dutta, S. Liao, J. L. Newstead, L. E. Strigari, and J. W. Walker, Phys. Rev. D97, 035009 (2018), 1711.03521.

[30] M. Lindner, W. Rodejohann, and X.-J. Xu, JHEP 03, 097 (2017), 1612.04150.
[31] Y. Farzan, Phys. Lett. B748, 311 (2015), 1505.06906.
[32] Y. Farzan and I. M. Shoemaker, JHEP 07, 033 (2016), 1512.09147.
[33] O. G. Miranda, M. A. Tortola, and J. W. F. Valle, JHEP 10, 008 (2006), hep-ph/0406280.
[34] F. J. Escrihuela, O. G. Miranda, M. A. Tortola, and J. W. F. Valle, Phys. Rev. D80, 105009 (2009), [Erratum: Phys. Rev.D80,129908(2009)], 0907.2630.
[35] P. Coloma and T. Schwetz, Phys. Rev. D94, 055005 (2016), [Erratum: Phys. Rev.D95,no.7,079903(2017)], 1604.05772.
[36] M. C. Gonzalez-Garcia and M. Maltoni, JHEP 09, 152 (2013), 1307.3092.
[37] P. F. de Salas, D. V. Forero, C. A. Ternes, M. Tortola, and J. W. F. Valle, Phys. Lett. B782, 633 (2018), 1708.01186.
[38] F. Capozzi, E. Lisi, A. Marrone, and A. Palazzo, Prog. Part. Nucl. Phys. 102, 48 (2018), 1804.09678.
[39] I. Esteban, M. C. Gonzalez-Garcia, A. Hernandez-Cabezudo, M. Maltoni, and T. Schwetz (2018), 1811.05487.
[40] S. Gariazzo, C. Giunti, M. Laveder, and Y. F. Li, JHEP 06, 135 (2017), 1703.00860.
[41] B. Dutta, Y. Gao, R. Mahapatra, N. Mirabolfathi, L. E. Strigari, and J. W. Walker, Phys. Rev. D94, 093002 (2016), 1511.02834.
[42] T. S. Kosmas, D. K. Papoulias, M. Tortola, and J. W. F. Valle, Phys. Rev. D96, 063013 (2017), 1703.00054.
[43] B. C. Cañas, E. A. Garcés, O. G. Miranda, and A. Parada, Phys. Lett. B776, 451 (2018), 1708.09518.
[44] C. Giunti and C. W. Kim, Fundamentals of Neutrino Physics and Astrophysics (2007), ISBN 9780198508717.