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Searching for sterile neutrinos at the ESSνSB

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Abstract: The ESSνSB project is a proposed neutrino oscillation experiment based on the European Spallation Source with the search for leptonic CP violation as its main aim. In this letter we show that a near detector at around 1 km distance from the beamline is not only very desirable for keeping the systematic errors affecting the CP search under control, but would also provide a significant sensitivity probe for sterile neutrino oscillations in the region of the parameter space favored by the long-standing LSND anomaly. We find that the effective mixing angle $\theta_{\mu e}$ can be probed down to $\sin^2(2\theta_{\mu e}) \simeq 2(8) \cdot 10^{-3}$ at 5σ assuming 15% bin-to-bin (un)correlated systematics.

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Contents

1 Introduction

Since the first evidence for neutrino oscillations in 1998, the experimental progress in the field has been remarkable. Today the standard three-flavor paradigm of neutrino oscillations is well tested and most of the parameters it contains are known to high precision [1]. This framework includes six parameters out of which three are mixing angles, two are independent mass squared differences and one is a, yet unknown, CP violating phase. However, there are a number of experimental anomalies that do not fit into this picture. The observation of an excess of $\bar{\nu}_e$ events at 3.8σ at the LSND experiment [2] could be explained by introducing one or more additional *sterile* neutrino states, with an additional mass squared difference of $\Delta m^2_{41} \sim \mathcal{O}(\text{eV}^2)$ in order to allow for $\nu_\mu \to \nu_e$ oscillations in the observed range of L/E. However, KARMEN did not observe any signal for similar values of L/E [3]. The dedicated MiniBooNE experiment [4–6] has to this day not confirmed or disproved the LSND anomaly. On the other hand, ν_e [7–10] and $\bar{\nu}_e$ [11–13] disappearance experiments seem to observe a deficit which would be compatible with sterile neutrino oscillations in the eV^2 range, while no deficit at all has been observed in any of the ν_μ disappearance experiments [14, 15]. Overall, global analyses show strong tension between different data sets [16–18] and further experimental input will be needed to clarify the situation.

The European Spallation Source ν-Beam [19, 20] (ESSνSB) is a proposal for a neutrino oscillation experiment based upon the accelerator facilities of the future European Spallation Source (ESS) and optimized for the goal of a high significance search for CP violation. The relatively large value of θ_{13} recently discovered [21–25] guarantees a comparatively high signal, which implies that the bottleneck of CP violation searches for the next generation of neutrino oscillation facilities will typically be systematics errors rather than statistics or backgrounds. The effect of such systematic uncertainties can be alleviated in two ways. If the statistics is high enough, placing the detector close to the second oscillation maximum enhances the relative importance of the CP-violating component of the oscillation probability, increasing the sensitivity of the facility and reducing the impact of systematic errors [26]. Indeed, the optimization of the ESSνSB showed a clear preference for this location which was adopted as its baseline design. The second way of controlling the negative impact of systematic uncertainties on the CP violation search is the inclusion of a near detector. The idea is that the two detectors would observe the same flux in absence of oscillations, thus reducing the impact of flux uncertainties. The optimal way to do this is to place the near detector at a non-negligible distance of the neutrino source (such as 1 or 2 km), since otherwise the geometric acceptance of the detector would make the observed flux very different from the one expected at the far detector. However, even though the primary goal of a near detector at the ESSνSB facility would be the cancellation of systematic errors, it could also be used to test for new physics in the neutrino sector. Indeed, since the neutrino flux at the ESSνSB would be peaked in the $\mathcal{O}(0.2\,\mathrm{GeV})$ range, a near detector placed at a baseline of 1 km would be ideal for testing oscillations of sterile neutrinos in the parameter range indicated by the LSND anomaly. Furthermore, the high power of the beam (5 MW) would enable the possibility to test very small values of the oscillation probability with a very high significance.

In the following we will study the sensitivity of the ESSνSB setup, using only a near detector placed at 1 km from the source, to oscillations in the $\nu_\mu \to \nu_e$ appearance channel. In order to do so, we will adopt a phenomenological approach where the oscillation probability reads

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta_{\mu e}) \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right). \tag{1.1}$$

Here, $\theta_{\mu e}$ is an effective mixing angle, $\Delta m^2_{41} \equiv m^2_4 - m^2_1$ is the active-sterile squared mass difference, L is the distance from the source, and E is the neutrino energy. This approach is a reasonable approximation as long as we are dealing with small enough values of L/E such that the active-active neutrino oscillations have not developed significantly yet.

In the following we will investigate the sensitivity of the ESSνSB in two separate scenarios,

$$\begin{array}{rll} \text{Case I:} & \text{no active — sterile mixing} & \text{and} \\ \text{Case II:} & 3 \cdot 10^{-3} \lesssim \sin^2(2\theta_{\mu e}) \lesssim 1 \cdot 10^{-2}, & 0.2\ \mathrm{eV}^2 \lesssim \Delta m^2_{41} \lesssim 1.2\ \mathrm{eV}^2. \end{array}$$

Case I corresponds to a scenario without steriles (as suggested by ν_μ disappearance experiments) while Case II corresponds to a situation in which the active-sterile oscillation parameters take values which are close to the allowed regions shown in figure 7 of ref. [16], where a global analysis of several $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ experiments was performed. It should be stressed again that a mixing angle $\sin^2 2\theta_{\mu e} = 0.01$ may be in some tension with the results from ν_μ and $\bar{\nu}_\mu$ disappearance experiments.

2 Setup and simulation details

The GLoBES software [27, 28] has been used in order to simulate the ESSνSB experiment. Since the flux peak would be located around 250 MeV, a distance to the detector of 1 km would be needed in order to match the maximum of the oscillation, assuming a squared mass splitting $\Delta m^2_{41} \sim \mathcal{O}(1\ \mathrm{eV})$ (as LSND [2] and MiniBooNE [4–6] results seem to indicate). Since the main goal of the ESSνSB experiment would be the search for CP violation, we have considered the same detector technology as for the far detector. This choice would minimize the effect of systematic errors coming from neutrino interaction cross sections and detector performance, which would be the primary purpose of the near detector at the ESSνSB. Therefore, we consider a 1 kt water Cherenkov detector and we assume it to be identical to the far detector in terms of efficiencies and background rejection capabilities. The response of the detector has been simulated using migration matrices, signal and background rejection efficiencies from ref. [29].

Neutrino fluxes have been explicitly simulated for a near detector placed at 1 km from the source [30]. A beam power of 5 MW and 1.7×10^7 operating seconds per year with 2.5 GeV protons, as for the long baseline experiment [20], is assumed. In order to respect the configuration of the long baseline experiment (which is optimized for CP violating searches) we keep the same ratio of neutrino (2 years) and antineutrino (8 years) running times.[1] In absence of oscillations, this would yield a total of 4.00×10^6 (2.29×10^6) unoscillated ν_μ ($\bar{\nu}_\mu$) events at the detector during a 10 year life-time of the experiment, where efficiencies have already been accounted for.

On the other hand, we find that the expected total number of background events in the ν_e and $\bar{\nu}_e$ channels would be ~ 34400 and ~ 23100, respectively, assuming identical background rejection capabilities as in refs. [20, 29]. The largest contributions to the background event rates would come from ν_μ mis-identified as ν_e, and from neutral current (NC) events mis-identified as charged-current (CC) events. In principle, if a sterile neutrino exists and has sizable mixing with the active sector, the background rates should also be affected by oscillations. Nevertheless, we find the impact of this effect on the sensitivity of the setup to be negligible, and therefore oscillations have not been considered for the background rates in our analysis.

In a similar fashion, a sterile neutrino would have an observable effect in the $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ channels. The sensitivity to a sterile neutrino through disappearance data would be strongly limited by systematic errors, however. In fact, the results for our setup using only the $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ disappearance channels would just be able to slightly improve current bounds on the effective mixing angle in this channel, $\theta_{\mu\mu}$. A second possibility could be to combine appearance and disappearance data, since the effects in the two channels should be partially correlated. However we have numerically checked that, for the proposed setup and within a 3+1 oscillation framework, where the two oscillation probabilities can be expressed in terms of one mass splitting and two mixing angles, the addition of disappearance data does not yield an observable improvement over the results obtained using only the appearance channels. Therefore, the ν_μ disappearance channels will not be considered in this work.

The neutrino fluxes at the ESSνSB will be peaked within a relatively narrow energy range, see ref. [20]. The energy resolution for a water Cherenkov detector would limit the size of the energy bins to ~ 100 MeV, implying that only a few energy bins would contain a sizable number of events. However, we have found that the sensitivity of the setup would

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[1] We note, however, that in order to optimize the experiment to search for a sterile neutrino, a different ratio may be desirable, in particular taking into account the different size of neutrino and antineutrino cross sections. See also ref. [31] for optimizations to standard oscillation physics.

be compromised if the analysis was done as a counting experiment only (without energy bin separation). The main reason for this is that the signal and background spectra show a different dependence with neutrino energy, which implies that different energy bins will have a different signal-to-background ratio. Therefore, we compute a binned χ^2 in neutrino energy, with nine 100 MeV bins between 0.1 and 1 GeV.

Given the high statistics at the near detector, the performance will be limited by systematics. Thus, we will show our results in two scenarios with a different implementation of systematic errors. For the more optimistic option an overall 15% uncertainty, uncorrelated between the different channels and between the signal and background components but fully correlated among the bins of each channel, is considered. For the more conservative option, on the other hand, we allow uncorrelated systematics among the different energy bins in each channel, so as to account for uncertainties in the shape of the fluxes and cross sections. However, in order to accommodate an overall normalization shift for the signal in this case, we would be effectively multiplying the penalty in terms of χ^2 by the number of bins with respect to the more optimistic case. Therefore, in this conservative scenario we also add an additional 15% normalization uncertainty which is correlated among all bins in order to avoid this behaviour. A modified version of the GLoBES software as in ref. [32] was used for this implementation of the systematics. A pull-term corresponding to each uncertainty is added to the χ^2, and the result is then marginalized over the nuisance parameters to search for the minimum. The procedure is then repeated for all points in the $(\sin^2(2\theta_{\mu e}), \Delta m^2_{41})$ parameter space, and contours for equal values of the χ^2 are drawn.

Finally, since in this work we are mainly interested in the performance of the ESSνSB with regard to sterile neutrino oscillations, the far detector is not considered in our simulations. The presence of sterile neutrinos of the type considered here is also not likely to adversely affect the ESSνSB measurement of CP-violation at the far detector. Since the sterile neutrino oscillations would be averaged out at the far detector and no additional CP violating phases in the 3+1 scenario considered here can play a role, the effect of the sterile neutrinos would be similar in the neutrino and antineutrino channels and would manifest as an increase in the expected ν_e and $\bar{\nu}_e$ backgrounds, since part of the original ν_μ and $\bar{\nu}_\mu$ will oscillate through the sterile state. Thus, a resulting tension with the expected background level could presumably be accommodated in the fit by varying the values of θ_{13} and/or θ_{23}, but would not affect the value of the CP violating phase in the fit. Therefore, the CP violating discovery potential would remain unaffected, while the values of the mixing angles may be slightly modified. We do not expect this modification to be very significant. Indeed, we have estimated that for $\sin^2(2\theta_{\mu e}) = 1 \cdot 10^{-2}$ this additional background would be of the same order than the intrinsic beam contamination and, as can be seen in ref. [20], while this represents the dominant source of background at the ESSνSB the signal to background ratio is rather large and the experiment is statistics, rather than background, limited.

3 Results

The left panel of figure 1 shows the expected 3 and 5σ exclusion limits of the ESSνSB under the assumption of no active-sterile neutrino mixing (Case I). As expected from the baseline

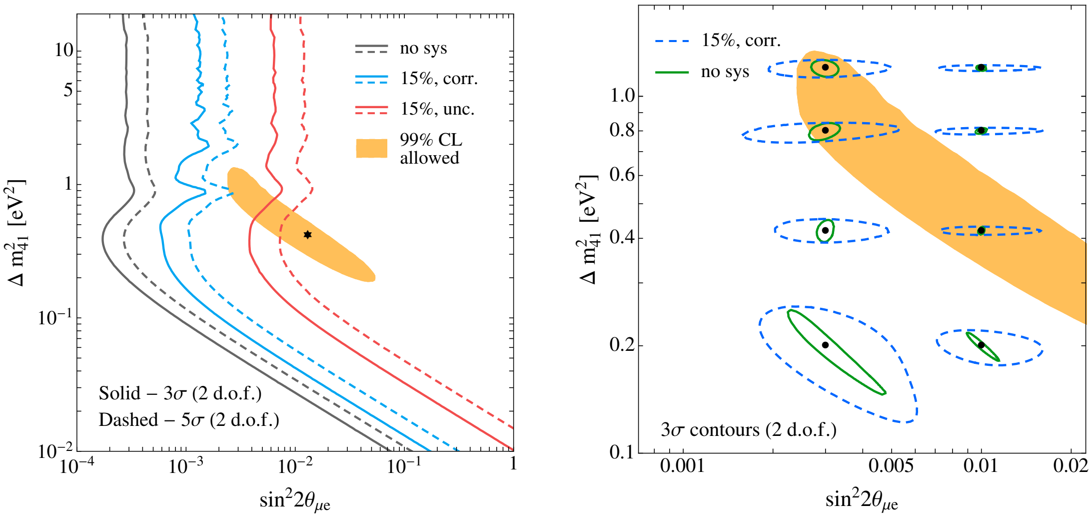

Figure 1. Left: the 3 and 5σ exclusion contours for totally correlated and totally uncorrelated bin-to-bin systematics of 15%. The no-systematics limit is also shown. The shaded region corresponds to the allowed region at 99% CL obtained from a global fit to ν_e disappearance and $\nu_\mu \to \nu_e$ appearance experiments, taken from figure 7 of ref. [16]. Right: the expected confidence regions for several possible choices of active-sterile neutrino oscillation parameters (Case II) at 3 σ. Results are shown for correlated bin-to-bin systematics of 15% and for the case where the systematic uncertainties are completely switched off in the analysis, as indicated in the legend.

length of 1 km and typical neutrino energy of $\sim 0.3\,\mathrm{GeV}$, the best sensitivity is achieved around $\Delta m^2_{41} \simeq 0.3\,\mathrm{eV}^2$. Below this value, the sensitivity in $\sin^2(2\theta_{\mu e})$ quickly deteriorates as the oscillations do not have sufficient time to develop. On the other hand, for larger values of the mass splitting the oscillations enter the averaged regime. For comparison with the current experimental situation, the allowed region at 99% CL from a global fit to ν_e disappearance and $\nu_\mu \to \nu_e$ appearance experiments is also shown, see ref. [16]. As seen in the figure, the final results will be dominated by systematic errors. Assuming bin-to-bin correlated 15% systematic errors the currently allowed region could be completely excluded at 5σ from this measurement alone, while the sensitivity in the more conservative scenario of completely uncorrelated errors is somewhat more limited. However, we find that also in this scenario most of the preferred region, including the best fit, is covered with 5σ significance. Finally, we also show in this panel that in the limit of no systematic uncertainties values of $\sin^2(2\theta_{\mu e})$ down to $\sim 10^{-4}$ could be probed.

The right panel of figure 1, on the other hand, shows the expected 3σ confidence regions under the assumption of active-sterile neutrino mixing with oscillation parameters close to the allowed confidence regions found in ref. [16] for a combined fit to $\bar{\nu}_e$ disappearance and ν_e and $\bar{\nu}_e$ appearance (Case II). In this case, results are only shown for the case with no systematics and the case with 15% bin-to-bin correlated systematic errors, for which a great precision can be achieved in most cases for both variables. In the case of bin-to-bin uncorrelated systematic errors, we find the following results: (i) in the case of small mixing angles, $\sin^2 2\theta_{\mu e} < 10^{-2}$, the confidence regions are compatible with $\theta_{\mu e} = 0$ (as can be extracted from the sensitivity contours shown in the left panel in the same figure); (ii) for larger values of the mixing angle ($\sin^2 2\theta_{\mu e} \sim 0.01$) the confidence regions are no longer compatible with $\theta_{\mu e} = 0$, but multiple solutions appear at different values of Δm^2_{41}.

4 Summary and conclusions

In this letter we have discussed the possibility of using a near detector at the recently proposed ESSνSB neutrino oscillation experiment in order to look for active-sterile neutrino oscillations in the range indicated by the LSND anomaly, $\Delta m^2_{41} \sim 1\,\mathrm{eV}^2$ and $\sin^2 2\theta_{\mu e} \sim 10^{-2}$. Our study is based on the performance of a 1 kt near water Cherenkov detector at a distance of 1 km from the source. Under the assumption of no active-sterile neutrino mixing, we find that the ESSνSB setup would be able to completely exclude the currently allowed region from a global fit to ν_e disappearance and $\nu_\mu \to \nu_e$ appearance data with a confidence of 5σ, assuming bin-to-bin correlated systematical errors at the 15% level. Even in the more conservative scenario of fully uncorrelated bin-to-bin systematics, most of the preferred region would also be covered with 5σ significance. On the other hand, if active-sterile mixing takes place with oscillation parameters in the range currently favored by global analyses, the ESSνSB experiment would be able to pinpoint their values with extremely good accuracy.

Finally it should also be noted that, in order not to interfere with the main goal of the ESSνSB (i.e., the discovery of leptonic CP violation), no optimization for sterile neutrino searches has been performed in this work. Therefore, if a signal of the existence of sterile neutrinos was to be found, some room for improvement over the results obtained here may be possible.

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