Potential of CCDs for the study of sterile neutrino oscillations via Coherent Neutrino-Nucleus Elastic Scattering

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Abstract. We study the potential of a detector based on CCD sensors (CONNIE experiment) to study neutrino oscillations to sterile states using reactor neutrinos. We calculate the number of events expected in a 1 kg detector and determine the sensitivity to oscillations $\nu_e \rightarrow \nu_s$ in the $\Delta m^2_{41}$ vs. $\sin^2 \theta_{es}$ parameter space for various exposures. The sensitivity is compared with the regions excluded by the Daya Bay experiment under the assumption $\theta_{24} = \theta_{34} = 0$. This work was carried out independently of the CONNIE Collaboration using published information, and its results are not official.

1. Introduction
While the majority of neutrino oscillation measurements fit well in the 3 massive neutrino model, a handful of anomalous results [1] suggest the existence of at least one sterile neutrino with a mass splitting $\Delta m^2 \sim 1 eV^2$. Models considering sterile neutrinos (3+N) have been considered but different observations impose severe constraints. The 3+1 scenario can be probed with an experiment sensitive to all 3 active flavors ($\nu_e, \nu_\mu, \nu_\tau$) via a neutral current interaction.

In the Coherent Elastic Neutrino-Nucleus Scattering (CENNS) [2], a neutrino, or antineutrino, scatters off a nucleus as a whole. When the 4-momentum transfer is small compared to the reciprocal of the nucleus size ($Q^2 < 1/R^2$), the interaction with the constituent nucleons coherently enhances the cross section. The differential cross section is:

$$\frac{d\sigma}{dE_{\text{rec}}} = \frac{G_F^2}{8\pi} \left[Z(4\sin^2\theta_W - 1) + N\right]^2 M \left(2 - \frac{E_{\text{rec}}M}{Eq^2}\right) |f(q)|^2$$

where $E_{\text{rec}}$ is the nuclear recoil energy, $G_F$ is the Fermi constant, $M$ is the mass of the nucleus, $Z$, and $N$ are the number of protons and neutrons in the nucleus respectively, $\theta_W$ is the weak mixing angle, and $f(q)$ is the nuclear form factor, which is a function only of the 4-momentum transfer $q$. Since $\sin^2\theta_W \sim 0.231$, the term involving $Z$ nearly cancels numerically and the differential cross section is approximately proportional only to $N^2$. CENNS is a Standard Model (SM) process that has never been observed experimentally (see Note in [3]) primarily because the nuclear recoil energies $E_{\text{rec}}$ are very small ($\lesssim 15$ keV), and escape the capabilities of most detectors.
Charge Coupled Devices (CCD) with very low thresholds (∼10 eV) and relatively large sensitive mass (∼5 g per CCD), have been successfully used in the DAMIC experiment [4] at SNOLAB to perform direct DM searches in the low mass region < 10 GeV/c², demonstrating the unique capabilities of CCDs for the detection of low-energy recoils. This channel could be used as a probe to study oscillations between active and sterile states [5].

2. The CONNIE experiment
The Coherent Neutrino Nucleus Interaction Experiment (CONNIE) aims to detect for the first time the CENNS using an array of CCDs installed at 30 m from the Angra-II reactor at the Angra dos Reis nuclear power plant in Brazil. A prototype [6] was installed in 2014. The detector was upgraded to 80 g of mass (14 CCDs) in 2016.

The Angra-II reactor is a 3.95 GW th PWR reactor that generates ∼8.7×10²⁰ νₑ/s and a flux at the detector location of ∼7.7×10¹² νₑ cm⁻² s⁻¹.

Figure 2: Left: Reactor neutrino flux (normalized for Angra-II). The vertical dotted line at ∼1.2 MeV indicates the value for the maximum neutrino energy that contributes to the neutron capture process. Right: Expected CENNS energy spectrum in a Si detector.
3. Expected event rates

Assuming a 1 kg detector, an energy threshold of $\sim 28$ eV, and a Lindhard quenching factor gives an expected rate of $\sim 16.1$ events kg$^{-1}$ day$^{-1}$ [7].

It is possible to achieve a 5$\sigma$ significance (figure 3, right) with an exposure of 42 kg day: a 50 g detector operating for 840 days or a 100 g detector operating for 420 days or a 1 kg detector for 42 days.

4. Sterile neutrino oscillations. 3+1 Model

With a fourth light sterile neutrino (3+1 model), the mix between flavor eigenstates $\nu_\alpha (\alpha = e, \mu, \tau, s)$ and mass eigenstates $\nu_i (i = 1, 2, 3, 4)$ is $\nu_\alpha = \sum_i U_{\alpha i} \nu_i$, where the mixing matrix is now 4 $\times$ 4, including new mixings with the sterile state $U_{ai}$.

Under the approximation $1eV^2 \sim |\Delta m^2_{41}| \gg |\Delta m^2_{31}| \gg |\Delta m^2_{21}|$, one can choose $L/E$ such that $\Delta m^2_{31}/2E$ and $\Delta m^2_{21}/2E$ are $<< 1$. The survival probability of electron neutrinos in this experiment is:

\[
P(\nu_e \to \nu_{active}) = 1 - P(\nu_e \to \nu_s) = 1 - \sin^2 2\theta_{es} \sin \left( \frac{1.27 \Delta m^2 L}{E} \right) \tag{3}
\]

where $\sin^2 2\theta_{es} = 4|U_{e4}|^2|U_{s4}|^2$. In the case $\theta_{24} = \theta_{34} = 0$, $\sin^2 2\theta_{es} = \sin^2 2\theta_{14}$. This is the relevant probability since the detector is sensitive to all three active neutrino flavors through the CENNS.

5. Analysis

We divided the energy spectrum (figure 5, left) in 20 logarithmical uniform bins from 0.01 keV to 0.5 keV and defined the statistic:

\[
\chi^2(\sin^2 2\theta, \Delta m^2) = \sum_i^{nb} \frac{(D_i - P_i(\sin^2 2\theta, \Delta m^2))^2}{(\sigma_i^{stat})^2 + (\sigma_i^{sys})^2} \tag{4}
\]

where $D_i$ are the observed events and $P_i$ are the predicted events. The observed and predicted events have a signal and background component:

\[
D_i = S_i^D + B_i^D, \quad P_i(\sin^2 2\theta, \Delta m^2) = S_i^P(\sin^2 2\theta, \Delta m^2) + B_i^P \tag{5}
\]
Figure 4: Left: 3+1 model direct mass ordering scheme. Right Survival Probability $\nu_e \rightarrow \nu_{\text{active}}$

The background was assumed to be uniform in energy at $\sim 600$ events $\text{kg}^{-1} \text{day}^{-1}$, demonstrated for CCDs at sea level. We consider two sources of systematic error $\sigma_i$: an uncertainty on the background level $B^P_i$, $\delta^B_i$, and a contribution from the flux prediction $\delta^\text{sys}_i$ into the signal $S^i_P$. We assumed a $\delta^B_i$ around $\sim 0.5\%$, and a $\delta^\text{sys}_i$ around $\sim 5\%$. (fig. 5 right).

Figure 5: Left: Signal and background energy spectra used in the analysis. Right: Effect of the systematic error $\delta^\text{sys}_{\text{flux}}$ on the signal spectrum.

We constructed a reticule of $50 \times 50$ points in the parameter space. To calculate the sensitivity of a 1kg CONNIE detector we made the assumption that:

$$S^D_i = S^P_i(0,0), \quad B^D_i = B^P_i$$

which makes $\chi^2_{\text{min}} = 0$. The 90\% C.L region was extracted from the excursion $\chi^2 = 4.6$.

6. Results
The figure 6 shows the expected sensitivity for different exposures. In the case $\theta_{24} = \theta_{34} = 0$ this can be compared with the Daya Bay and Bugey limits [8].

7. Conclusions
The sensitivity of a CCD experiment like CONNIE to sterile neutrino oscillations in a 3+1 model was calculated. A 10 kg year exposure is competitive in the region $\Delta m^2 > 1\text{eV}$ with the
Figure 6: 90% C.L. sensitivity for a CONNIE experiment with exposure $E$ of 1, 10, 50 kg-year and 10 ton-year assuming $\theta_{24} = \theta_{34} = 0$. The Daya Bay and Bugey limits are also shown.

recent Daya Bay limits assuming $\theta_{24} = \theta_{34} = 0$. This result can be combined with $\nu_\mu$ and $\bar{\nu}_\mu$ like MINOS to constraint $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions. This will be subject of a future work.

Acknowledgments
We acknowledge support from CONACYT through project No. 240666 and grant 398495 (scholarship holder No: 570620), and from DGAPA-UNAM, PAPIIT grant No. IN108917.

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