Status and Prospects of eV Sterile Neutrino Searches

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Abstract

In this talk, we present the results of the global analysis [1] on the $3 + 1$ neutrino scenario. After a brief discussion of the neutrino oscillation probabilities in the presence of a sterile neutrino, we describe the main experimental results. We pay particular attention to the anomalies in the reactor neutrino experiments and the $\nu_e$ excess in the appearance channel oscillation channel. The combined analysis of the data shows some tensions between the disappearance and the appearance oscillation results.

1 Introduction

The excess of electron neutrinos observed by LSND and MiniBooNE can be explained by the oscillation of a muon neutrino into an electron neutrino driven by mass parameter $\Delta m^2_{41} \sim 1\text{eV}^2$. The combined results of both experiments show an excess significance of $6\sigma$.

In addition to those experiments, there are some anomalies that can also be explained by the existence of a sterile neutrino with mass in the same range. This is the case of the Gallium anomaly or the Reactor anomaly. All these anomalies, that have been measured in the electron disappearance channel, consist on a deficit in the number of expected events. The survival probability of $\nu_e$ or $\bar{\nu}_e$ in the presence of a $\nu_s$ with a mass of the order of $\Delta m^2 \geq 1\text{eV}^2$ can reduce the significance of those anomalies.

Looking into the muon-disappearance channel measurements, there no evidence for such new particle. In this channel, we have contributions from MiniBooNE looking for the number of $\nu_\mu$ events. Similar results were found using Long-Baseline experiments like MINOS/MINOS+ or NOνA, and atmospheric neutrinos like DeepCore or IceCube.

In this talk, we are going to describe the status of the oscillation experiments able to observe a sterile neutrino with a mass around 1 eV. In section 2, we will describe the neutrino evolution in the presence of a sterile neutrino. Using the framework, several experiments has analyzed their data, finding different results, we will describe the most relevant in section 3. Those results will be combined into a global analysis. In section 4, we will present the results of the global analysis. Finally, the conclusions of the work will be presented in section 5.
2 Scenario 3+1

In the standard neutrino picture (3 active neutrinos), the evolution is described by the Schrodinger equation that depends on two mass parameters, the difference between the mass squared of the three massive states ($\Delta m_{12}^2$ and $\Delta m_{31}^2$), and the lepton mixing matrix, that correlates massive and the flavor states. The mixing matrix $(U)$ is described by 3 rotation angles and a complex phase ($\theta_{12}, \theta_{13}, \theta_{23}$ and $\delta_{13}$). If we consider the existence of a sterile neutrino, the Schrodinger equation can be written as

$$\frac{d\bar{\nu}}{dt} = \frac{1}{2E} [U^\dagger \text{diag}(0, \Delta m_{12}^2, \Delta m_{31}^2, \Delta m_{41}^2) U \pm V_{\text{mat}}] \bar{\nu}$$

(1)

where we have included the mass difference of the new state ($\Delta m_{41}^2$). In the case of four neutrinos, $U$ is a $4 \times 4$ complex. To parameterize the mixing matrix, we need to add three additional rotation angles and two complex, $U \equiv R(\theta_{34}) R(\theta_{24}, \delta_{24}) R(\theta_{14}) R(\theta_{13}, \delta_{13}) R(\theta_{12}, \delta_{12})$. If neutrinos propagate though the matter, the coherent interaction of the neutrino with the medium will modify the neutrino evolution. That interaction is described by the potential $V_{\text{mat}} = \sqrt{2} G_F \text{diag}(N_e - N_n, -N_e, -N_n, 0)$ for an electrically neutral medium. $N_e$ and $N_n$ represent the electron and neutron densities along the neutrino path.

Solving Eq. 1 we obtain the probability that $\nu_\alpha$ oscillate into $\nu_\beta$ ($P_{\alpha\beta}$) as a function of the neutrino energy and the baseline. Working in the short-baseline limit ($\Delta m_{12}^2 L/4E << 1$ and $\Delta m_{31}^2 L/4E << 1$), we can derive some approximated expressions for the oscillation probability, that will be very useful to analyze the results in the next section. Since all the neutrino sources that we are going to consider consist on beams of electron or muon neutrinos, we will focus mainly in the following oscillation channels

$$P_{ee}^{SBL} = 1 - 4|U_{e4}|^2 (1 - |U_{e4}|^2) \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$P_{\mu e}^{SBL} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

$$P_{\mu \mu}^{SBL} = 1 - 4|U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2) \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

(2)

As shown by the previous equations, the different oscillation channels are not independent, they are correlated by the lepton mixing matrix. If there is an oscillation of $\nu_e$ to $\nu_\mu$ that requires $|U_{e4}|^2 \neq 0$ and $|U_{\mu 4}|^2 \neq 0$, and therefore we also must observe an oscillation in the electron and muon disappearance channels.

3 Oscillation experiment results

In this section we will make a brief summary of the most relevant oscillation results for the detection of a sterile neutrino with masses around 1 eV.

In nuclear reactors, anti-electron neutrinos are created via the fission of four isotopes $^{235}U$, $^{238}U$, $^{239}Pu$ and $^{241}Pu$. Theoretical evaluations of the flux [2, 3] indicate a deficit of 5% in the number of events observed, this called Reactor anomaly. For baselines larger than $L \geq 50$ m, the oscillation driven by a sterile neutrino with mass around the eV scale would be averaged out, as can be obtained from Eq. 2. That would be observed as a deficit on the flux, so it can explain the anomaly. The hypothesis of the sterile neutrino also predict that the flux created by all the isotopes should be equally affected. The yield to the neutrino flux depends on each isotope. The measurement of the fuel correlation with the $\bar{\nu}_e$ flux done by Daya-Bay [4] rejects the hypothesis of a constant neutrino flux, finding a discrepancy of 7.8% between the predicted yield for the $^{235}U$. That suggests that the anomaly primarily comes from that isotope. Another present in the reactor neutrino flux is found.
around $\sim 5$ MeV, where has been observed an excess of the flux predicted over the measurements. The origin of that spectral distortion can also be the $^{235}U$ isotope [5].

For baselines shorter than $L \leq 20m$, the energy distortion introduced by a sterile neutrino of 1 eV on the reactor anti-neutrino flux can be detected. That is the goal of the experiment DANSS [6], a movable detector that measures the reactor neutrino flux between $\sim 10$ m and $\sim 12.7$ m from the reactor core. Another experiment that could also measure that oscillation is NEOS [7], placed $\sim 23$ m from the core. Both experiments have observed an oscillation that is compatible with an eV sterile neutrino. The latest results from DANSS [6] shows some disagreement in the allowed regions.

In the Sun, $\nu_e$ are created via nuclear fusion reactions in an energy range that extend up to $\sim 20$ MeV. That flux was measured by experiments that used Gallium as a target, like GALLEX and SAGE. In those experiments, electron neutrinos are absorbed by the Gallium creating Germanium and an electron. In both experiments, the detector response was tested using a radioactive source ($^{61}$Cr, $^{37}$Ar). The results showed a 15% deficit in the expected signal, that corresponds to a 3$\sigma$ [8] of significance the measurement uncertainties. This Gallium anomaly can be explained with a sterile neutrino [9] with mass larger or equal to 0.1 eV. New evaluations of the cross-section [10] has reduced the anomaly significance to $\sim 2.3\sigma$.

LSND is a beam dump experiment that searched for $\bar{\nu}_\mu \to \bar{\nu}_e$ from the $\mu^+$ decay at rest [11] (DAR). Using the $\nu_\mu$ flux originated by $\pi^+$ decay in flight (DIF), the searched for the same oscillation using neutrinos. The detection of $\bar{\nu}_e$ via Inverse Beta Decay (IBD) shows an excess compatible with $\Delta m_{31}^2 = 0.2 - 10eV^2$ range. The DIF measurement, which is populated with a lot of background, shows an excess compatible with the signal of anti-neutrinos. MiniBooNE search for the neutrino and anti-neutrinos in a $\nu_\mu$ [12]. The experimental configuration shows the same $L/E$ as LSND. The results of the $\nu_\mu \to \nu_e$ shows an excess of both $\nu_e$ and $\bar{\nu}_e$ that is compatible with $0.1 < \Delta m_{31}^2 < 1$. MiniBooNE can also look for sterile neutrinos in the muon-disappearance channel. Although the detector sensitivity is small for $\Delta m_{31}^2 \leq 1eV^2$, the results don't show any evidence of oscillation.

Similar to the muon-disappearance analysis done by MiniBooNE, there are several other experiments where there is no evidence of a sterile neutrino. In particular, that is the result found in the analysis carry on by Long-Baseline experiments like MINOS/MINOS+ [13] or NOνA [14]. Those experiments uses a near to far detector ratio to cancel most of the flux uncertainties. NOνA uses a $\nu_\mu$ beam that peaks at 2 GeV and a baseline of $\sim 800$ km, and search for a deficit in the number of Neutral Currents in the far detector. To avoid an oscillation in the near detector, the analysis is limited to $\Delta m_{31}^2 \in [0.05, 0.5] eV^2$. In the case of MINOS/MINOS+, the far detector (735 km) is located on the neutrino beam direction. Each detector used a different energy beam that peaks at 3 GeV/7 GeV. Using a near to far detector comparison, those experiments have been able to search for sterile neutrino via the $\nu_\mu$ disappearance channel in two different mass regimes. For $\Delta m_{31}^2 \in [0.05, 0.5] eV^2$, the oscillation is developed in the far detector whereas for masses in the range $\Delta m_{41}^2 \in [1, 100] eV^2$, the oscillation would be observed in the near detector. For masses above 100 eV, both detectors would observe a deficit.

The study of the atmospheric neutrinos has not found any robust evidence of a sterile neutrino has been. The baseline for the neutrinos created in the atmosphere is of the order of $\sim 1000$ km, and the flux extends from $\sim 100$ MeV to $\sim 10$ TeV. For the experiments that are able to measure the flux up to $\sim 10$ GeV, like DeepCore [15] or Super-Kamiokande [16], the energy distortion introduced by the oscillation of a 1 eV cannot be observed. So, the oscillation shows up as a deficit in the flux. At the TeV scale, the anti-neutrino flux will undergo through a flavor resonance (total flavor conversion) for trajectories crossing the Earth’s mantle. That resonance can be measured by neutrino telescope experiments, like IceCube [17], that are able to measure the high energy part of the atmospheric flux. Although the latest results of IceCube, that are based on 8 years of data, exclude the no-sterile hypothesis at 90% CL, in the global analysis, we used the result that contains just 1 year of data, where the no-oscillation hypothesis was allowed at 1$\sigma$ CL.
4 Global analysis

In the analysis of all the reactor data, we deal with the flux uncertainties following the theoretical prediction [2, 3] (fixed fluxes) or we assume a free normalization (free fluxes) for the contribution of each isotope. Combining all the reactor data, there is preference of $\sim 3\sigma$ for the sterile neutrino hypothesis. If we include in the analysis all the electron-disappearance data the exclusion of the no-oscillation hypothesis increases driven by the gallium anomaly.

The combined result of all the data in the muon-disappearance channel leads a strong suppression on $|U_{\mu 4}|$. For masses around $\leq 1\ eV$, the constraint comes from the high energy atmospheric neutrinos measured by IceCube. For larger masses, the results of MiniBooNE and MINOS/MINO+ constraint the mixing angle.

In the appearance channel, the results are dominated by LSND and MiniBooNE. The combined analysis excludes the no-oscillation hypothesis to $\sim 6\sigma$, although the global analysis has a poor goodness of fit due to the MiniBooNE which doesn’t fit well in the $3+1$ oscillation scenario.

In order to show whether there is any inconsistency between the different data sets, we can divide the all the data into several pieces to compare the results between them. We have divided the data between disappearance and appearance measurements, in such a way we can compare the prediction for the mixing elements $|U_{e4}|^2$ and $|U_{\mu 4}|^2$ from independent data. The results of the analysis are presented in terms of the effective mixing angle $\sin^2 2\theta_{\mu e} \equiv 4 |U_{e4}|^2 |U_{\mu 4}|^2$, Fig. 1, and it shows that there are some inconsistencies between the appearance and the disappearance results.

![Figure 1: Results of the appearance and the disappearance global analysis. All the contours correspond to the 99.73% CL. For the reactor data, we consider two different possibilities, free fluxes or fixed fluxes. About the LSND results, we consider two options with or without DIF data. We refer to the text for more information.](image_url)
5 Conclusions

In this talk, we present the results of the global analysis [1] of the $3 + 1$ neutrino oscillation scenario. The anomalies found in the $\nu_e$ disappearance channel and the event excess in the electron-appearance points towards the existence of a sterile neutrino with mass a around 1 eV. On the other side, the muon-disappearance channel place a strong constraint on $U_{\mu 4}$. The combined analysis shows a strong tension between the appearance and the disappearance channels.

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