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Sterile neutrino fits to short baseline data

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Abstract

Neutrino oscillation models involving extra mass eigenstates beyond the standard three $(3 + N)$ are fit to global short baseline experimental data. We find that $3 + 1$ has a best fit of $\Delta m^2_{41} = 1.75$ eV^2 with a $\Delta\chi^2_{null\text{-}min}$ (dof) of 52.34 (3). The $3 + 2$ fit has a $\Delta\chi^2_{null\text{-}min}$ (dof) of 56.99 (7). For the first time, we show Bayesian credible intervals for a $3 + 1$ model. These are found to be in agreement with frequentist intervals. The results of these new fits favor a higher Δm^2 value than previous studies, which may have an impact on future sterile neutrino searches such as the Fermilab SBN program.

1. Introduction

The well-established discoveries of neutrino mass and three-active-flavor mixing can be phenomenologically incorporated into the Standard Model [1], resulting in a model that we can call the "νSM". This model successfully predicts neutrino oscillations in many experiments. However, the masses and mixings must be incorporated in an *ad hoc* manner. This leads one to ask if there is more "new physics" in the neutrino sector that is yet to be discovered that can give us a clearer picture of the underlying theory.

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A set of 2σ to 4σ anomalies have been observed in short baseline (SBL) oscillation experiments that may indicate new physics. SBL experiments have $L/E \sim 1$ m/MeV, where L is the distance from the source to the detector and E is the neutrino energy. Anomalies are observed from the Liquid Scintillator Neutrino Detector (LSND) experiment [2], the Mini Booster Neutrino Experiment (MiniBooNE) [3,4], the collection of SBL reactor experiments (often called the "reactor anomaly") [5,6], and the source calibration data from the gallium-based experiments, SAGE and GALLEX [7,8]. Any interpretation must also consider similar SBL experiments that have seen no anomalous oscillations (called "null experiments") [9–18].

Oscillations between active and light sterile neutrinos represent a possible explanation for the combination of anomalous and null SBL data sets. Sterile neutrinos are beyond-Standard Model, non-weakly-interacting additions to the neutrino family. Introducing these new particles extends the number of mass states and expands the mixing matrix [19] in the νSM. This allows oscillations with squared mass splittings, Δm^2, that are large compared to those in the νSM. Experimental anomalies suggest a mass scale $\sim$1 eV^2. Models with one $(3+1)$, two $(3+2)$, and three $(3+3)$ additional sterile neutrino states are generically called "$3+N$" models.

This paper explores the viable parameter space for oscillation models involving sterile neutrinos. The most obvious signature of oscillation to sterile neutrinos is disappearance of an active flavor. Potential $\nu_e \to \nu_s$ signals have been observed in neutrino and antineutrino mode by the reactor and gallium-based experiments. A $\nu_\mu \to \nu_s$ at a compatible Δm^2 is yet to be observed, and we will show that this places strong constraints on the phenomenology. If disappearance occurs, then the model also predicts appearance, $\nu_\mu \to \nu_e$ at the same Δm^2 value(s). This could be consistent with the LSND and MiniBooNE results, which are seen for both neutrinos and antineutrinos.

This global fit does not make use of the limits from cosmology. This is because reasonable mechanisms can be put forward within cosmology reduce or remove the constraint, as discussed in Ref. [20]. Other fitting efforts, such as Refs. [21,22], incorporate cosmological data into a Bayesian analysis.

2. $3+N$ fits to short baseline data

The νSM model has three massive neutrinos leading to two distinct differences between the squared masses, Δm^2_{21} and Δm^2_{32}. The 3×3 lepton mixing matrix, called the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix, connects the mass eigenstates to the weak interaction eigenstates.

For vacuum oscillations in a $3+N$ model, the probability for finding a neutrino in flavor state β after propagating a distance L and being produced as a flavor state α is given by [23]

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{j>i} \mathrm{Re}[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}] \sin^2\left(\left[\frac{1.27\ \mathrm{GeV}}{\mathrm{eV}^2\ \mathrm{km}}\right]\frac{\Delta m^2_{ji} L}{E}\right)$$
$$+ 2\sum_{j>i} \mathrm{Im}[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}] \sin\left(\left[\frac{2.54\ \mathrm{GeV}}{\mathrm{eV}^2\ \mathrm{km}}\right]\frac{\Delta m^2_{ji} L}{E}\right), \qquad (1)$$

where E is the neutrino energy and $\Delta m^2_{ji} = m^2_j - m^2_i$. Furthermore, the corresponding antineutrino oscillation probability can be obtained by replacing $U \to U^\dagger$.