4 ν Models: Conciliating LSND Results with Solar and Atmospheric Neutrino Data

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The $(3+1)$-scheme in which the fourth (predominantly sterile) neutrino is isolated from a block of three flavour neutrinos by the mass gap $\Delta m^2_{LSND} \sim (0.4-10)$ eV^2 is revisited in the light of evidence that the atmospheric ($\nu_\mu \to \nu_\tau$) and the solar neutrino oscillations ($\nu_e \to \nu_\mu/\nu_\tau$) are dominantly active to active neutrino transitions, as is indicated by recent data. In this framework, I revisited the $(3+1)$-scheme and I find that the LSND result can be reconciled with existing bounds on ν_e- and ν_μ - disappearance at $95-99\%$ C.L..

1. Introduction

It is widely accepted that simultaneous explanation of the solar [1,2], atmospheric [2,3] and LSND results [4,5] in terms of neutrino conversion requires an existence of the sterile state [6,7]. Less appreciated and discussed fact is that explanation of the LSND result in the favored 4ν-schemes implies that the solar or atmospheric neutrinos (or both) are converted to sterile state. Indeed, it is claimed that the only 4ν-schemes which can explain the LSND result and accommodate oscillation solutions of the solar and atmospheric neutrino problems are the schemes of the $(2+2)$ type [6,7].

In the alternative $(3+1)$-scheme (see Fig. 1), three mass eigenstates form "flavour block" which has predominantly active flavour with small admixture of the sterile state and small mass splitting. The fourth mass eigenstate is separated from the flavour block by the LSND mass gap $\Delta m^2_{LSND} \approx (0.4-10)$ eV^2.

It is claimed that the $(3+1)$-mass scheme can not reproduce large enough probability of the $\bar\nu_\mu \to \bar\nu_e$ oscillations to explain the LSND result [6,7]. Indeed, the depth of $\bar\nu_\mu \to \bar\nu_e$ oscil-

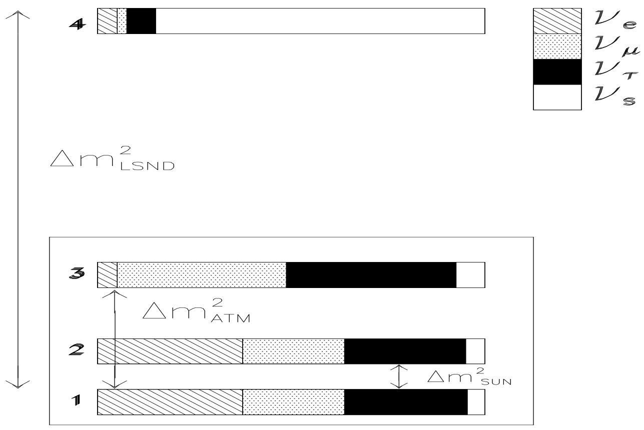

Figure 1. The neutrino mass and flavor spectrum in the $(3+1)$ scheme with normal mass hierarchy. The boxes correspond to the mass eigenstates. The sizes of different regions in the boxes determine flavors of the eigenstates: $|U_{\alpha i}|^2$, $\alpha = e, \mu, \tau, s$ and $i = 1, 2, 3, 4$.

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lations driven by the Δm^2_{LSND} equals

$$\sin^2 2\theta_{LSND} \equiv 4\, U^2_{\mu 4} U^2_{e4} \sim \epsilon^4, \qquad (1)$$

where $U_{\mu 4}$ and U_{e4}, are the admixtures of the ν_e and ν_μ in the 4th mass eigenstate. These admixtures are small being restricted by the accelerator and reactor experiments. As a consequence, the depth of oscillations is of the fourth order in the small parameter.

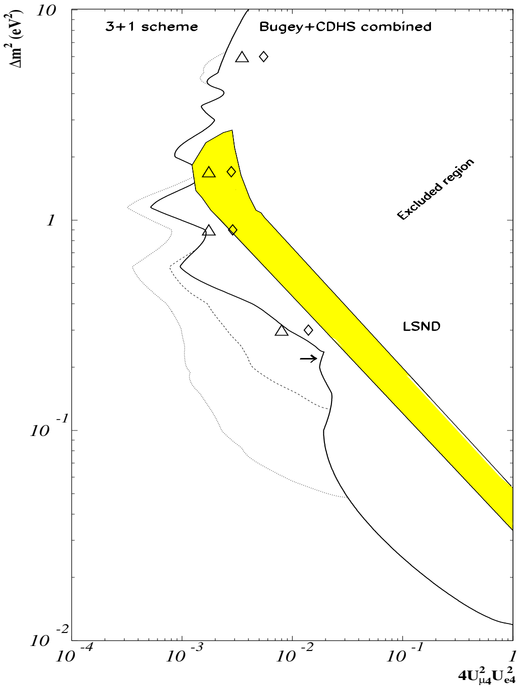

Figure 2. The LSND allowed region (shadowed) and the bounds on the oscillation parameters in the $(3+1)$ - scheme from the ν_e- and $\nu_\mu-$ disappearance experiments. The lines show the limits obtained as the products of the 90 % C.L. upper bounds on $|U_{e4}|^2$ and $|U_{\mu 4}|^2$. Solid line is the bound from Eq.3. Also shown are the bounds obtained as the product of bound from Bugey and expected bound from Mini-BooNE (dashed line) and BooNE (dotted line) experiments. The triangles and rombs show respectively the 95 and 99 % C.L. bounds from Eq.4.

There are three recent results which may change eventually the situation in favor of the $(3+1)$-scheme:

1. The data on atmospheric neutrinos disfavour oscillations to the sterile state [2]. The $\nu_\mu \to \nu_\tau$ oscillations give better fit of the experimental results.

2. Conversion of solar ν_e neutrinos to active neutrinos gives better global fit of experimental results than conversion to sterile neutrinos [2].

   If active neutrino channels dominate both in the solar and in atmospheric neutrino oscillations, the $(2+2)$ -mass scheme should be discarded and the oscillation interpretation of the LSND result becomes problematic. In this connection, it have been reconsidered the possibility to explain LSND results in the $(3+1)$ -mass scheme [10].

3. Latest analysis of the LSND data [5] shows in further shift of the allowed region of oscillation parameters to smaller values of mixing angle. This leads to a better agreement between the bounds obtained in CDHS [8] and Bugey [9] experiments and the LSND result in the context of $(3+1)$-mass scheme [11–13].

2. The $(3+1)$-scheme and LSND

The CDHS [8] and Bugey [9] experiments have published the 90% C.L. upper bounds on $\sin^2 2\theta_{ee}$ ($\approx 4\,U^2_{e4}$) and $\sin^2 2\theta_{\mu\mu}$ ($\approx 4\,U^2_{\mu 4}$) as functions of the Δm^2. These bounds transfer immediately to the bounds on $U^2_{\mu 4}$ and U^2_{e4}:

$$\begin{aligned} U^2_{e4} &\lesssim U^2_{Bugey}(\Delta m^2), \\ U^2_{\mu 4} &\lesssim U^2_{CDHS}(\Delta m^2). \end{aligned} \qquad (2)$$

The upper bound on $\sin^2 2\theta_{LSND}$ ($\equiv 4\,U^2_{\mu 4}U^2_{e4}$) is determined by [6,7]:

$$\sin^2 2\theta_{LSND} \lesssim 4\,U^2_{Bugey}(\Delta m^2) \cdot U^2_{CDHS}(\Delta m^2). \qquad (3)$$

The bound (3) shown in Fig. 2 excludes most of the region of parameters indicated by the LSND experiment. On this basis, it was concluded that $(3+1)$ -mass scheme cannot reproduce the LSND result [6,7]. The question is at which confidence level the LSND result is excluded by the combined

Bugey and CDHS bounds? The answer is given by the probability that the product of $U_{e4}^2 \cdot U_{\mu 4}^2$ is larger than certain value ρ. This probability is given by the integral

$$\mathcal{P}(\rho) \equiv \int_{\rho}^{\infty} dy \int_{\rho/y}^{\infty} dx P_e(x, \Delta m^2) P_\mu(y, \Delta m^2). (4)$$

Here the functions $P_\alpha(U_{\alpha 4}^2, \Delta m^2)$, $\alpha = e, \mu$, are the probabilities that experimental data from Bugey or CDHS correspond to a given value of $U_{\alpha 4}^2$ for fixed Δm^2. The 95% and 99% C.L. upper bounds (shown in Fig. 2), ρ_{95} and ρ_{99}, are determined by the conditions: $\mathcal{P}(\rho = \rho_{95}) = 0.05$, and $\mathcal{P}(\rho = \rho_{99}) = 0.01$.

3. Discussion

Simultaneous explanation of the LSND result as well as the solar and atmospheric neutrino data in terms of neutrino oscillations requires introduction of additional (sterile) neutrino. Recent experimental results give an indication that both in solar and in atmospheric neutrinos the oscillation channels to active component dominate. In the favored $(2+2)$ -scheme the sterile component should be involved significantly in the conversion of the solar and atmospheric neutrinos and therefore the (2+2) -scheme is disfavoured.

Summarizing, I revisited the (3+1)-scheme and show that the LSND result can be reconciled with the bounds on ν_e- (Bugey) and $\nu_\mu-$ (CDHS) disappearance at 95 % - 99% C.L.. The best agreement can be achieved at $\Delta m^2 = (1-2)$ eV^2.

The key consequences of the $(3+1)$-scheme which explains the LSND result are that the probabilities of the $\nu_e \leftrightarrow \nu_s$ and $\nu_\mu \leftrightarrow \nu_s$ oscillations with $\Delta m^2 = \Delta m^2_{LSND}$ should be at the level of present upper bounds, so that moderate improvements of the bounds should lead to discovery of oscillations in these channels. The Mini-BooNE (BooNE) experiment [14] can improve the CDHS bound for $\Delta m^2 < 0.6$ eV^2 (1 eV^2). In this connection, there is the possibility that the K2K - front detectors experiments [15] can improve the bound on ν_μ disappearance as described in [16].

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