Sterile neutrino decay and the LSND experiment

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Abstract. We propose a new explanation of the intriguing LSND evidence for electron antineutrino appearance in terms of heavy (mostly sterile) neutrino decay via a coupling with a light scalar and light (mostly active) neutrinos. We perform a fit to the LSND data, as well as all relevant null-result experiments, taking into account the distortion of the spectrum due to decay. By requiring a coupling \( g \approx 10^{-5} \), a heavy neutrino mass \( m_4 \approx 100 \text{ keV} \) and a mixing with muon neutrinos \( |U_{\mu 4}|^2 \approx 10^{-2} \), we show that this model explains all existing data evading constraints that disfavor standard (3+1) neutrino models.

The confirmation of the solar [1] and atmospheric [2] neutrino oscillations by reactor [3] and accelerator [4] experiments and the bounds from laboratory neutrino mass measurements [5] have set the “standard” neutrino picture in terms of three light active neutrinos with two mass square differences. However, the observed excess of \( \bar{\nu}_e \) in the LSND experiment [6] was interpreted as evidence of \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \) transitions with a mass square splitting, \( \Delta m^2_{\text{LSND}} \approx 1 - 10 \text{ eV}^2 \), that cannot be accommodated by the other two, \( \Delta m^2_{\text{sol}} \approx 8 \times 10^{-5} \text{ eV}^2 \) and \( \Delta m^2_{\text{atm}} \approx 2.5 \times 10^{-3} \text{ eV}^2 \). The most natural solution would be to introduce a fourth neutrino [7] with the appropriate mass to give the hinted mass square difference. However, this does not turn out to lead to a satisfactory description of all data in terms of neutrino oscillations [8] because of tight constraints from solar [1], atmospheric [2], and null-result short-baseline (SBL) experiments [9]. In view of this, during the last years, other alternative explanations have been proposed [10, 11]. Unlike in Ref [10] where decay was invoked to evade SBL results, here we propose (see Ref. [12] for details) a new explanation of LSND in terms of heavy (mostly sterile) neutrino decay. This new massive state, \( n_4 \), must have a small mixing with the muon neutrino, \( U_{\mu 4} \), and the signal is explained by its decay into a combination of light neutrinos, being predominantly of electron type.

A natural way to introduce neutrino decay is by means of a term in the Lagrangian, which couples neutrinos to a light scalar. We assume for the scalar mass \( m_{\phi} \), the terms in the Lagrangian which provide the decay are given, in the mass basis, by

\[
\mathcal{L} = - \sum_l g_{4l} \bar{\nu}_{lL} n_{4R} \phi + \text{h.c.},
\]

where \( l = 1, 2, 3 \) and, in general, the coupling matrix \( g_{4l} \) is complex.

In the case of Majorana particles, neutrinos are identical to antineutrinos. Weak interactions couple to left-handed (chiral) neutrinos and right-handed (chiral) antineutrinos while the propagation states are those of definite helicity. In the relativistic case, one can identify neutrinos and antineutrinos with helicity states up to terms of order \( m/E_\nu \). It follows from Eq. (1) that not only the decay \( n \rightarrow \bar{\nu} + \phi \) can occur, but also \( n \rightarrow \nu + \phi \) is possible [13]. Hence, the expected
number of $\bar{\nu}_e$ events with neutrino energy in the interval $[E_{\bar{\nu}_e}, E_{\bar{\nu}_e} + dE_{\bar{\nu}_e}]$ is given by [12]

\[
\frac{dN}{dE_{\bar{\nu}_e}} = C \sigma(E_{\bar{\nu}_e}) \left[ \phi_0 \frac{dP_{\nu_\mu \to \bar{\nu}_e}(E_{\nu_\mu})}{dE_{\bar{\nu}_e}} + \int_{E_{\bar{\nu}_e}}^{E_{\max}} dE_{\bar{\nu}_e} \phi_\mu(E_{\bar{\nu}_e}) \frac{dP_{\nu_\mu \to \bar{\nu}_e}(E_{\nu_\mu})}{dE_{\bar{\nu}_e}} \right],
\]

where $\phi_\mu(E_{\nu_\mu})$ is the muon $\bar{\nu}_\mu$ spectrum, $\phi_0 = \int dE_{\bar{\nu}_e} \phi_\mu(E_{\bar{\nu}_e})$ and $dP_{\nu_\mu \to \bar{\nu}_e}(E_{\nu_\mu})/dE_{\bar{\nu}_e}$ is the differential probability that a neutrino of flavor $\alpha$ with energy $E_{\nu_\alpha}$ is converted into a neutrino of flavor $\beta$ with energy in the interval $[E_{\nu_\beta}, E_{\nu_\beta} + dE_{\nu_\beta}]$. The indexes $r, s$ take the value ‘$-$’ (‘+’) for neutrinos (antineutrinos). The detection cross section is given by $\sigma(E_{\bar{\nu}_e})$ and $C$ is an overall constant containing the number of target particles, efficiencies and geometrical factors.

Unlike other explanations of the LSND result based on sterile neutrinos, our model does not require mixing of the electron neutrino with the heavy mass state, so for simplicity we assume $U_{e4} = 0$. Hence the differential probability for $\nu_\mu^r \to \nu_e^s$ conversion can be written as [12]

\[
\frac{dP_{\nu_\mu \to \bar{\nu}_e}(E_{\nu_\mu})}{dE_{\bar{\nu}_e}} = |U_{\mu 4}|^2 \left( 1 - e^{-\Gamma_4 t} \right) \Theta(E_{\nu_\mu} - E_{\nu_e}) \times \begin{cases} E_{\nu_\mu}/E_{\nu_e}^2 & r = s, \\ (E_{\nu_\mu} - E_{\nu_s})/E_{\nu_e}^2 & r \neq s, \end{cases}
\]

where $\Gamma_4$ is the decay rate of $n_4$ as follows from Eq. (1) [13].

Our analysis of LSND data (Fig. 1), which does not use the much less significant decay in flight (DIF) sample, gives a best fit value of $\chi^2_{\text{min}} = 5.6/9$ dof for oscillations and $\chi^2_{\text{min}} = 10.8/9$ dof for decay. The reason for the slightly worse fit for decay is the spectral distortion implied by the energy distribution of the decay products. Nevertheless, the overall goodness of fit (GOF) is still acceptable, 29%, giving as best fit values $|U_{\mu 4}|^2 = 0.016$ and $\bar{g} m_4 = 3.4$ eV, where $\bar{g}^2 \equiv \sum |g_{4l}|^2$.

As is well known, (3+1) neutrino models are disfavored due to the tension between LSND and SBL experiments, which have not observed either appearance or disappearance so far [9]. We have also studied their compatibility in the decay scenario. Under the assumption $U_{e4} = 0$, no $\bar{\nu}_e$ disappearance is expected in SBL reactor experiments. However, since the explanation of the LSND signal within this scenario requires mixing of $\nu_\mu$ with the heavy state, one expects some effect in $\nu_\mu$ disappearance experiments. The main constraints on the allowed LSND-KARMEN region come from the CDHS experiment [9] and from atmospheric neutrino data [14]. Nevertheless, the different expression for the $\nu_\mu$ survival probability in the decay scenario provides a rather poor sensitivity to $U_{\mu 4}$, which comes via $|U_{\mu 4}|^4$, unlike the case of oscillations, that it comes via $|U_{\mu 4}|^2$. The results are shown in Fig. 2, where appearance and disappearance experiments are shown to be in perfect agreement, with large overlap of the allowed regions.
Mixing between active and sterile neutrinos, and couplings between active neutrinos and a light scalar, have been extensively studied, both in laboratory experiments and, for their implications in the evolution of the early Universe and of supernovae. The decay of pions and kaons has been used to set bounds on the mixing of heavy neutrinos for masses above MeV [15]. In our model, the most stringent bounds on the coupling from laboratory experiments, coming from light scalar emission in pion and kaon decays, are of order $\bar{g}^2 < \text{few} \times 10^{-5}$ [16]. On the other hand, a coupling $\bar{g} \sim 10^{-5}$ would imply that $n_4$ and $\phi$ are strongly coupled to active neutrinos inside the supernova, and hence, they are trapped within the neutrinosphere, avoiding any energy loss due to particles escaping from the core. This value of the coupling would also imply that as soon as $n_4$ are produced in the Early Universe, they are thermalized along with the scalar, leading to 1.57 extra number of relativistic degrees of freedom at BBN.

In summary, we have presented an explanation of the LSND evidence for $\bar{\nu}_e$ appearance based on the decay of a heavy (mostly sterile) neutrino into a light scalar particle and light neutrinos. It is needed $|U_{\mu 4}|^2 \sim 10^{-2}$ and $gm_4 \sim 1$ eV, and hence for $\bar{g} \sim 10^{-5}$, $m_4 \sim 100$ keV. In addition, the decay model also predicts a detectable signal in the upcoming MiniBooNE experiment [17].

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