Sterile Neutrinos

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Abstract. Several anomalies recorded in short-baseline neutrino experiments suggest the possibility that the standard 3-flavor framework may be incomplete and point towards a manifestation of new physics. Light sterile neutrinos provide a credible solution to these puzzling results. Here, we present a concise review of the status of the neutrino oscillations within the 3+1 scheme, the minimal extension of the standard 3-flavor framework endowed with one sterile neutrino species. We emphasize the potential role of LBL experiments in the searches of CP violation related to sterile neutrinos and their complementarity with the SBL experiments.

1. Introduction
A long series of neutrino oscillation experiments performed in the last two decades has established that neutrinos are massive and mix. In the standard 3-flavor framework the three flavor eigenstates ($\nu_e, \nu_\mu, \nu_\tau$) mix with three mass eigenstates ($\nu_1, \nu_2, \nu_3$) through a unitary matrix entailing three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$) and one CP-violating phase $\delta$. All the three mixing angles are now known to be different from zero ($\theta_{12} \simeq 34^\circ, \theta_{23} \simeq 39^\circ$ and $\theta_{13} \simeq 9^\circ$), while the preferred value of the CP-violating phase lies around $\delta \simeq -\pi/2$, although with low statistical significance [1, 2, 3, 4, 5].

In the 3-flavor scheme the neutrino oscillations are driven by two independent squared-mass differences, $\Delta m^2_{12} = m_2^2 - m_1^2 \simeq 7.5 \times 10^{-5}\,\text{eV}^2$ (known as the “solar splitting”) and $|\Delta m^2_{13}| = |m_3^2 - m_1^2| \simeq 2.4 \times 10^{-3}\,\text{eV}^2$ (dubbed as the “atmospheric splitting”). The neutrino mass hierarchy (i.e. the sign of $\Delta m^2_{13}$) is currently unknown and, together with the CP-violating phase $\delta$, is at the center of an intense campaign of new experimental searches.

While the standard 3-flavor framework has been solidly established as the only one able to describe the huge amount of information coming from solar, atmospheric, reactor and accelerator neutrino experiments, a few “anomalous” results have emerged in short-baseline (SBL) neutrino oscillation measurements, which cannot be accommodated in such a scheme. The most popular interpretation of such anomalies is based on a simple extension of the 3-flavor paradigm, involving new additional light neutrinos (with mass in the eV range) which mix with the ordinary neutrinos. From the LEP measurement of the invisible decay width of the $Z$ boson [6], we know that there are only three light (with mass below one half of the $Z$ boson mass) neutrinos which couple to the $Z$ boson. Therefore, the new putative light neutral fermions must be “sterile”, i.e. singlets of the Standard Model gauge group, to be contrasted with the ordinary “active” neutrino species, which are members of weak isospin doublets.

From a theoretically standpoint, it seems natural to expect the existence of such new gauge singlets as they appear in many extensions of the Standard Model. Indeed, the most popular models of neutrino mass-generation, the so-called see-saw mechanisms, normally involve sterile
neutrinos. Although the majority of such extensions entail sterile neutrinos with mass close to the grand unification scale or the TeV scale, a priori there is no theoretical constraint on the mass of these particles. In fact, several models have been investigated in which much lighter sterile neutrinos arise (see the overview given in [7]). In essence, the theory only tells us that sterile neutrinos can exist, without giving any certain information on their number and their mass-mixing properties, which ultimately have to be determined by the experiments.

At a phenomenological level, sterile neutrinos must be introduced without spoiling the basic success of the standard 3-flavor framework. This can be achieved in the so-called $3 + N_s$ schemes, where $N_s$ new mass eigenstates are assumed to exist, separated from the three standard ones by large mass splittings, with a hierarchical spectrum $|\Delta m^2_{12}| \ll |\Delta m^2_{13}| \ll |\Delta m^2_{ij}| (j = 4, ..., 3 + N_s)$. This ensures that the oscillations induced by the new squared-mass differences, governed by the high frequency $\Delta_{14} \equiv \Delta m^2_{14} L/4E$, are completely averaged in the experimental setups sensitive to the solar and atmospheric frequencies $\Delta_{12}$ and $\Delta_{13}$. With the additional assumption that the admixtures among the actives flavors and the new mass eigenstates $(\nu_4, ..., \nu_{3+N_s})$ are small $(|U_{ej}|^2, |U_{\mu j}|^2, |U_{\tau j}|^2 \ll 1, j = 4, ..., 3 + N_s)$, the $3 + N_s$ schemes leave almost unchanged the standard oscillation amplitudes.

The $3 + N_s$ schemes predict sizable effects primarily at the short baselines. However, sterile neutrinos may leave their signs also in non-short-baseline experiments, where their manifestation is more subtle. In the solar sector, for example, the admixture of the electron neutrino with the $\nu_4$ mass eigenstate (parametrized by the matrix element $U_{e4}$) leads to small deviations from the unitarity of the $(\nu_1, \nu_2, \nu_3)$ (sub)-system (see [8, 9, 10]). In the atmospheric neutrinos, as first evidenced in [11], at very high $[O(\text{TeV})]$ energy a striking MSW resonant behavior is expected, which leads to a distortion of the zenith angle distributions. As we will discuss below, sterile neutrino oscillations can be probed also in the long-baseline (LBL) accelerator experiments, and this circumstance is of particular interest in view of the underway world-wide program of new LBL facilities. In what follows we concisely describe the anomalous SBL results and discuss their mutual (in-)consistency. We also describe the potential role of LBL experiments in the searches of CP violation related to sterile neutrinos and emphasize their complementarity with the SBL experiments.

2. The short-baseline anomalies

2.1. The LSND and MiniBoone anomaly

Accelerator experiments with baselines $L$ of a few tens of meters and neutrino energies $E_\nu$ of a few tens of MeV ($L/E_\nu \sim 1$ m/MeV) are sensitive probes of neutrino oscillations potentially occurring at $\Delta m^2 \sim 1$ eV$^2$. Their results are commonly interpreted in terms of a new mass-squared difference $\Delta m^2$ and of an effective mixing angle $\theta$. In a 3+1 framework the following identifications hold: $\Delta m^2 \equiv \Delta m^2_{14}$ and $\sin^2 2\theta \equiv 4|U_{e4}|^2|U_{\mu 4}|^2$.

In fact, the anomalous result recorded at the LSND accelerator experiment [12, 13] was the first piece of data pointing towards light sterile neutrinos. Such an experiment, designed to study $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions, evidenced an excess of electron antineutrino events at the $\sim 3.8 \sigma$ level [13]. The experiment KARMEN [14], which is very similar to LSND, observed no such a signal, but could not rule out all the mass-mixing parameter regions allowed by LSND. In particular, due to the smaller baseline (17.5 m vs 30 m) KARMEN could not exclude values of $\Delta m^2 \leq 2$ eV$^2$ also leaving marginal room for a solution at $\Delta m^2 \sim 7$ eV$^2$ (see the combined analysis of LSND and KARMEN performed in [15]).

The experiment MiniBooNE, designed to test the LSND anomaly, and sensitive both to $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions, has given differing results during the last few years. According to the latest data release [16] (differently from the past) MiniBooNE seems to lend support to the longstanding LSND anomaly. As a matter of fact, a combined analysis of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channels evidences an excess in the range $200 < E_\nu < 1250$ MeV at the $\sim 3.8 \sigma$ level.
It must be noted that most of the signal comes from the low-energy region $E_\nu < 475$ MeV (not included in some of the previous analyses performed by the MiniBooNE collaboration), where the background evaluation is particularly problematic.

An independent test of the LSND and MiniBooNE anomalies has been recently performed at the long-baseline accelerator experiments ICARUS [17, 18] and OPERA [19]. In these setups, due to the high energy of the beam ($< E_\nu > \sim 17$ GeV), the 3-flavor effects induced by non-zero $\theta_{13}$ play a negligible role. As a result, the experiments are sensitive to sterile neutrino oscillations, which due to the high value $L/E_\nu \sim 36.5$ m/MeV get completely averaged, and appear as an energy independent enhancement of the expected rate of events. Both collaborations have performed the analysis in an effective 2-flavor description. In [20] it has been shown that in the 3+1 scheme important corrections arise due to the presence of a new genuinely 4-flavor interference term in the transition probability. In addition, in the 4-flavor framework the $\nu_e$ beam contamination is not a fixed quantity like in the 2-flavor scheme. A consistent 4-flavor analysis [20] of ICARUS and OPERA leads to a substantial weakening (by a factor of $\sim 3$) of the upper bounds on the sterile neutrino mixing. ICARUS and OPERA are not sensitive enough to rule out the mass-mixing region preferred by LSND and MiniBooNE, and can only restrict the allowed region to values of $\sin^2 2\theta < few \times 10^{-2}$.

### 2.2. The reactor and gallium anomalies

The new refined calculations of the reactor antineutrino spectra recently performed in [21, 22] have provided the main driving force for the renewed interest into light sterile neutrinos. These calculations indicate fluxes which are $\sim 3.5\%$ higher than previous estimates (corresponding to events rates $\sim 6\%$ higher) and have raised the so-called reactor antineutrino anomaly [23]. In fact, adopting the new fluxes, the SBL ($L \leq 100$ m) reactor measurements show a clear deficit (a $\sim 3\sigma$ effect) with respect to the theoretical expectations.

Despite the effort made by the authors of [21], who have included thousands of $\beta$-branches in the calculations, the new determinations are not entirely performed with an ab initio procedure. In fact, approximately 10\% of all the $\beta$-branches remains unknown and their contribution is accounted for by adding up a few fictitious effective $\beta$-branches. The resulting overall (electron) $\beta$ spectrum is then “anchored” to that measured by the ILL experiment in the 1980s. Therefore, at present, a systematic error in the ILL measurement cannot be excluded as the origin of the reactor anomaly.

The high statistics measurements of the antineutrino spectra performed by Daya Bay [24], Double Chooz [25] and RENO [26] have evidenced an unexpected shoulder (or bump) around 5 MeV in the prompt energy spectrum ($\sim 6$ MeV in $\bar{\nu}_e$ spectrum), deviating from the predictions at the $\sim 4\sigma$ level as an excess in the number of $\bar{\nu}_e$. The bump structure appears to be similar at the near and far detectors and is positively correlated with the reactor power. This strongly disfavors a possible explanation in terms of new-physics (for example super-light sterile neutrinos [27]). The most plausible explanation is a bias in the reactor flux models, which are matter of intense investigation (see [28, 29, 30, 31, 32]). This unexpected feature of the spectrum clearly evidences that our understanding of the reactor spectra is incomplete. Although the origin of the 5 MeV energy structure may be not related to the reactor neutrino anomaly (that may be due to sterile neutrino oscillations), both discrepancies reinforce the case for a revision of the current reactor flux predictions and their uncertainties.

An apparently unrelated deficit has been evidenced in the calibration campaign conducted at the solar neutrino experiments GALLEX and SAGE [33, 34] with high intensity radioactive sources. The exact statistical significance of the deficit fluctuates in the range $[2.7\sigma, 3.1\sigma]$ depending on the assumptions made on the theoretical estimate of the cross section $\nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^-$ (see the discussion presented in [34]). While the anomaly may well represent a signal of new physics, other (more prosaic) possibilities remain open such as a systematic error in the
Ge extraction efficiency or in the theoretical estimate of the cross-section.

Both the reactor and gallium anomalies can be interpreted in terms of a phenomenon of electron neutrino disappearance driven by sterile neutrino oscillations. In an effective 2-flavor scheme the results can be fitted by a new mass-squared difference $\Delta m_{\text{new}}^2$ and an effective mixing angle $\theta_{\text{new}}$. In a $3+1$ framework the following identifications hold: $\Delta m_{\text{new}}^2 \equiv \Delta m_{14}^2$ and $\sin^2 2\theta_{\text{new}} \equiv 4|U_{e4}|^2 (1 - |U_{e4}|^2)$.

The simultaneous explanation of both anomalies requires values of $\Delta m_{\text{new}}^2 > 1$ eV$^2$ and relatively large values of $\sin^2 2\theta_{\text{new}} \sim 0.17$ (corresponding to values of $|U_{e4}|^2 \sim 0.04$).

3. Sterile neutrino oscillations: An undecidable problem

The important question arises as to whether the anomalies described above can be simultaneously interpreted within a consistent theoretical framework. To this purpose many analyses have been performed in the literature (see for example the overview given in [7]).

A first important conclusion derived from these works is that those models incorporating more than one sterile neutrino are disfavored at least for three reasons: I) They are incompatible with primordial nucleosynthesis II) They introduce an absolute neutrino mass content that cannot be tolerated by cosmological data (indeed, the 3+1 scheme is already borderline in such a respect); III) Differently from the past, they are no more necessary to explain (through CP violation effects) the mismatch between the neutrino and antineutrino excesses previously found in MiniBooNE, and now much reduced in the latest data release.

We are thus left with the 3+1 scheme arguably favored by Occam’s razor [35], which however, has its own troubles. Indeed, interpreted in this framework, the anomalous reactor and gallium $\bar{\nu}_e$-disappearance measurements point towards a non-zero value of the parameter $|U_{e4}|^2$. On the other hand, all searches of a possible $\bar{\nu}_\mu$ disappearance induced by sterile neutrino oscillations have given negative outcome [36, 37, 38, 39], implying a stringent upper bound on the amplitude of $|U_{\mu4}|^2$. The different results of the $\bar{\nu}_e$ and $\bar{\nu}_\mu$ disappearance searches are perfectly consistent but (taken together) are in strong tension with the positive signal of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ conversion found at LSND and MiniBooNE, which requires a (too large) value for the product $|U_{e4}|^2|U_{\mu4}|^2$ (see the discussion presented in [35, 40, 41, 42]). Adding further sterile neutrino species does not help in reducing such a tension, which indeed persists also in the more general 3+2 and 3+3 schemes (see [35, 43]).

In spite of this tension, the 3+1 scheme offers a very good overall description of the SBL anomalies, improving by six standard deviations the goodness of fit of the 3-flavor framework [44]. Therefore, we are in the presence of two contrasting findings about sterile neutrinos. In this situation, it is impossible to answer to the question posed at the beginning of this section and one is enforced to leave the last word to the experiments.

4. Sterile neutrinos, CP violation and long-baseline experiments

The short-baseline experiments are without doubt the best place where to look for sterile neutrinos and certainly, if a discovery will come, it will come from a SBL experiment. However, the SBL experiments have an intrinsic limitation which would impede the further study of the properties of the 3+1 scheme. In particular, they are insensitive to the three CP-violation phases present in such a scheme. In fact, CP-violation is an exquisite 3-flavor phenomenon, whose observation requires the sensitivity to the interference between at least two independent oscillation frequencies. In a SBL experiment only the new largest oscillation frequency ($\Delta_{14} \sim 1$) is visible, while both the atmospheric and the solar splittings are substantially unobservable ($\Delta_{13} \simeq \Delta_{12} \simeq 0$). Therefore this class of experiments is blind to CP-violation effects.\footnote{This is strictly true only in the 3+1 scheme. In the 3+$N$s schemes, the SBL experiments are sensitive to a restricted number ($N$s – 1) of phases over a total of 2$N$s + 1.}
Other kinds of experiments are necessary to access the CP violation (CPV) induced by sterile neutrinos. These experiments already exist and are the LBL experiments already operational or planned for the future. In fact, these experiments originally designed to seek the standard CP-phase $\delta$, are also capable to provide information on other CP-phases. This is not obvious a priori and it is true only because, as we will see in a moment, a new interference term arises in the presence of sterile neutrinos, which has exactly the same order of magnitude of the standard 3-flavor interference term. Therefore, it is in part a (fortunate) fortuity that the same setups are also sensitive to the new CPV phases endowed with the sterile neutrinos.

We recall that the LBL setups, when working in the $\nu_{\mu} \rightarrow \nu_e$ (and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) appearance channel are sensitive to the 3-flavor CPV because, at long distances, the $\nu_{\mu} \rightarrow \nu_e$ conversion amplitude develops an interference term between the atmospheric ($\Delta m_{13}^2$-driven) and the solar ($\Delta m_{12}^2$-driven) oscillations, which depends on the CP-phase $\delta$. As first evidenced in [45], in the presence of sterile neutrinos a new interference term arises, which depends not only from $\delta \equiv \delta_{13}$ but also from one new CP-phase ($\delta_{14}$). From the discussion made in [45], it emerges that the conversion probability can be approximated as the sum of three terms

$$P_{\mu e}^{4\nu} \simeq P_{\mu e}^{\text{ATM}} + P_{\mu e}^{\text{INT}}.$$  \hfill (1)

The first term represents the positive-definite atmospheric transition probability, the second term (which can assume both positive and negative values) is related to the standard solar-atmospheric interference, while the third term is driven by the atmospheric-sterile interference. The transition probability depends on the three small mixing angles $\theta_{13}, \theta_{14}, \theta_{24}$, which can be all assumed to be of the same order of magnitude $\epsilon \sim 0.15$ and on the ratio of the solar and atmospheric squared-mass splittings $\alpha \equiv \Delta m_{12}^2/\Delta m_{13}^2 \simeq \pm 0.03$, which is of order $\epsilon^2$. Keeping terms up to the third order, in vacuum, one finds

$$P_{\mu e}^{\text{ATM}} \simeq 4s_{23}^2 s_{13}^2 \sin^2 \Delta,$$  \hfill (2)

$$P_{\mu e}^{\text{INT}}(I) \simeq 8s_{13} s_{12} c_{12} s_{23} c_{23} (\alpha \Delta) \sin \Delta \cos(\Delta + \delta_{13}),$$  \hfill (3)

$$P_{\mu e}^{\text{INT}}(II) \simeq 4s_{14} s_{24} s_{13} s_{23} \sin \Delta \sin(\Delta + \delta_{13} - \delta_{14}),$$  \hfill (4)

where $s_{ij} \equiv \sin \theta_{ij}$, $c_{ij} \equiv \cos \theta_{ij}$ and $\Delta \equiv \Delta m_{12}^2 L/4E$ is the atmospheric oscillating frequency, which depends on the baseline $L$ and the neutrino energy $E$. The matter effects slightly modify the transition probability leaving the picture described above almost unaltered (see [45, 4] for details).

Remarkably, for the typical values of the mixing angles preferred by the current global 3+1 fits [46, 47], the amplitude of the (atmospheric-sterile) interference term is almost identical to that of the standard (solar-atmospheric) interference term. As a consequence, a substantial impact on the regions reconstructed by the experiments T2K and NOvA in the plane of the two parameters $[\theta_{13}, \delta_{13}]$ is expected. In addition, a similar sensitivity to the two CP-phases $\delta_{13}$ and $\delta_{14}$ is expected in the combination of the two LBL experiments with the reactor data.

Figure 1 shows the results of the 3-flavor analysis [4], updated with the latest post-summer data, which will be used as a term of comparison for the 4-flavor analysis. The vertical band delimits the range of $\theta_{13}$ determined by the reactor experiments Daya-Bay and RENO. The wiggling regions are determined by the combination of T2K and NOvA. For both LBL experiments, in addition to the old T2K $\nu_e$ appearance data [48], we include the latest results, which have reported the first $\bar{\nu}_e$ appearance data [49, 50] (T2K) and the first $\nu_e$ appearance results [51] (NOvA). From Fig. 1 we see that there is slight preference in favor of $\delta_{13} \sim -\pi/2$. Also we can observe that in the IH case, there is a mismatch between the values of $\theta_{13}$ preferred by LBL and reactor experiments. As a consequence the NH is slightly favored over the IH.

\footnote{For NOvA we conservatively use the results obtained with the primary events selection method dubbed as LID.}
Figure 1. Left panels: regions allowed by the LBL experiments T2K and NOνA and by the θ₁₃-sensitive reactor experiments for normal hierarchy (upper panel) and inverted hierarchy (lower panel). Right panels: regions allowed by their combination. The mixing angle θ₂₃ is marginalized away. The confidence levels refer to 1 d.o.f. (Δχ² = 1.0, 2.71).

Figure 2 displays the results of the 4-flavor analysis for the case of IH. The four panels represent the regions allowed by T2K + NOνA in the usual plane [sin²θ₁₃, δ₁₃] for four different choices of the new CP-phase δ₁⁴. We have fixed the 4-flavor parameters at the following values:

Figure 2. Regions allowed by the combination of T2K and NOνA for four representative values of the CP-phase δ₁⁴. Inverted hierarchy is assumed. The mixing angle θ₂₃ is marginalized away. The vertical band represents the region allowed by reactor experiments. The confidence levels are as in Fig. 1.
$s_{14}^2 = s_{24}^2 = 0.025$, $s_{34}^2 = 0$, $\delta_{34} = 0$ and $\Delta m_{14}^2 = 1 \text{ eV}^2$. As a benchmark we also report the range allowed for $\theta_{13}$ by reactors, which is identical to the standard case. A quick comparison of the four panels of Fig. 2 with the 3-flavor case (left lower panel of Fig. 1) shows the noticeable impact of the 4-flavor effects on the allowed regions.

In particular, it is interesting to note how, in the presence of 4$\nu$ effects, a better agreement among the two estimates of $\theta_{13}$ derived from reactors and LBL can be obtained. This occurs for $\delta_{14} \simeq -\pi/2$. As we have discussed for the 3-flavor case, the mismatch of the $\theta_{13}$ estimates from LBL and reactors tends to disfavor the inverted hierarchy. The same conclusion is no more true in the 4-flavor scheme, since the two estimates can be brought in agreement for an appropriate choice of the new CP-phase ($\delta_{14} \simeq -\pi/2$) (see the right bottom panel of Fig. 2). This circumstance indicates that light sterile neutrinos may constitute a potential source of fragility in the capability of the two LBL experiments of discriminating between the two neutrino mass hierarchies.

5. Conclusions

We have presented a concise discussion of the current phenomenology of light sterile neutrinos. The present situation appears quite confused and new experimental input is indispensable to shed light on the issue. Such a goal requires the realization of new and more sensitive experiments, able (in case of negative outcome) to definitely rule out the sterile neutrino hypothesis, and (in case of positive outcome) provide a clear observation of the oscillatory pattern in the energy and/or space domains, which is the distinctive and indisputable signature of the flavor oscillation phenomenon.

It is important to realize that the new more sensitive experimental tests (see [7] for a comprehensive overview) will be extremely useful independently of their outcome. In case of a positive signal (evidence of sterile neutrino oscillations) we would be faced with an extraordinary discovery: new physics beyond the Standard Model would manifest in a completely unexpected form, well different from the mainstream high-energy realizations commonly investigated. On the other hand, in case of a negative result, the new experiments will be able to put a stringent upper bound on the new mass-mixing parameters, thus ruling out definitively the light sterile neutrino hypothesis as the explanation of the puzzling experimental anomalies.

In the case of a discovery at a new short-baseline experiment we will face the challenge of determining all the parameters that govern the extended framework and in particular the new CP-violating phases. We have shown that in this context LBL experiments can give an important contribution being sensitive to new CP-violation phenomena. Therefore the two classes of experiments (SBL and LBL) will be complementary and synergic in the searches of sterile neutrinos. While a discovery of a sterile neutrino can come only from the observation of the oscillating pattern (in energy or/and space) at the new SBL experiments, the full exploration of the 4$\nu$ model will become possible only with the contribution of LBL setups, which are sensible interferometers able to probe the new enlarged CPV sector.

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