Phenomenology of light sterile neutrinos

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Summary. — 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. While the standard 3-flavor framework
has been solidly established as the only one able to describe the huge amount of infor-
mation coming from solar, atmospheric, reactor and accelerator neutrino experiments, a
few "anomalous" results have emerged in short-baseline (SBL) neutrino oscillation mea-
surements, which cannot be accommodated in such a scheme (see [1] for a recent review).
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 de-
cay width of the Z boson, we know that there are only three light 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.

The 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 $|\Delta m_{12}^2| \ll |\Delta m_{13}^2| \ll |\Delta m_{1j}^2|(j =$

$4, \ldots, 3 + N_s$). This ensures that the oscillations induced by the new squared-mass differences, governed by the high frequency $\Delta_{14} \equiv \Delta m_{14}^2 L/4E$, are completely averaged in the experimental setups sensitive to the solar and atmospheric frequencies Δ_{12} and Δ_{13}. With the additional assumption that the admixtures among the actives flavors and the new mass eigenstates ($\nu_4, \ldots, \nu_{3+N_s}$) are small ($|U_{ej}|^2, |U_{\mu j}|^2, |U_{\tau j}|^2 \ll 1, j = 4, \ldots, 3 + N_s$), 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 ν_4 mass eigenstate (parametrized by the matrix element U_{e4}) leads to small deviations from the unitarity of the (ν_1, ν_2, ν_3) (sub-)system (see [2, 3]). In the atmospheric neutrinos, as first evidenced in [4], 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_ν of a few tens of MeV ($L/E_\nu \sim 1\,\text{m/MeV}$) are sensitive probes of neutrino oscillations potentially occurring at $\Delta m^2 \sim 1\,\text{eV}^2$. Their results are commonly interpreted in terms of a new mass-squared difference Δm^2 and of an effective mixing angle θ. In a 3+1 framework the following identifications hold: $\Delta m^2 \equiv \Delta m_{14}^2$ and $\sin^2 2\theta \equiv 4|U_{e4}|^2|U_{\mu4}|^2$. In fact, the anomalous result recorded at the LSND accelerator experiment [5, 6] 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 a the $\sim 3.8\sigma$ level [6]. The experiment KARMEN [7], 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. 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 [8] (differently from the past) MiniBooNE seems to lend support to the longstanding LSND anomaly.

An independent test of the LSND and MiniBooNE anomalies has been recently performed at the long-baseline accelerator experiments ICARUS [9] and OPERA [10]. In these setups, due to the high energy of the beam ($< E_\nu > \sim 17\,\text{GeV}$), the 3-flavor effects induced by non-zero θ_{13} play a negligible role. As a result, the experiments are sensitive to sterile neutrino oscillations, which due to the high value $L/E_\nu \sim 36.5\,\text{m/MeV}$ 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 [11] 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 ν_e beam contamination is not a

fixed quantity like in the 2-flavor scheme. A consistent 4-flavor analysis [11] of ICARUS and OPERA leads to a substantial weakening (by a factor of ~ 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 $\sin^2 2\theta < \text{few} \times 10^{-2}$.

2˙2. *The reactor and gallium anomalies*. – The new refined calculations of the reactor antineutrino spectra recently performed in [12, 13] 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 and have raised the so-called reactor antineutrino anomaly [14]. In fact, adopting the new fluxes, the SBL 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 [12], who have included thousands of β-branches in the calculations, the new determinations are not entirely performed with an *ab initio* procedure. In fact, approximately 10% of all the β-branches remains unknown and their contribution is accounted for by adding up a few fictitious effective β-branches. The resulting overall (electron) β 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 recent high statistics measurements of the antineutrino spectra performed by Daya Bay, Double Chooz and RENO, have evidenced an unexpected shoulder (or bump) around $5\,\text{MeV}$ in the prompt energy spectrum ($\sim 6\,\text{MeV}$ 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 [15]). The most plausible explanation is a bias in the reactor flux models, which are matter of intense investigation. This unexpected feature of the spectrum clearly evidences that our understanding of the reactor spectra is incomplete. Although the origin of the $5\,\text{MeV}$ 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 [16] 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 $\nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^-$. 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 Δm^2_{new} and an effective mixing angle θ_{new}. In a 3+1 framework the following identifications hold: $\Delta m^2_{new} \equiv \Delta m^2_{14}$ and $\sin^2 2\theta_{new} \equiv 4|U_{e4}|^2(1 - |U_{e4}|^2)$. The simultaneous explanation of both anomalies requires values of $\Delta m^2_{new} > 1\,\text{eV}^2$ and relatively large values of $\sin^2 2\theta_{new} \sim 0.17$ (corresponding to values of $|U_{e4}|^2 \sim 0.04$).

3. – 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.

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 δ, 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 $\nu_\mu \to \nu_e$ (and $\bar{\nu}_\mu \to \bar{\nu}_e$) appearance channel are sensitive to the 3-flavor CPV because, at long distances, the $\nu_\mu \to \nu_e$ conversion amplitude develops an interference term between the atmospheric (Δm^2_{13}-driven) and the solar (Δm^2_{12}-driven) oscillations, which depends on the *CP*-phase δ. As first evidenced in [17], 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 (δ_{14}). From the discussion made in [17] (see also [18]), it emerges that the conversion probability can be approximated as the sum of three terms

$$(1) \qquad\qquad P^{4\nu}_{\mu e} \simeq P^{\mathrm{ATM}} + P^{\mathrm{INT}}_{\mathrm{I}} + P^{\mathrm{INT}}_{\mathrm{II}}.$$

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 $\alpha \equiv \Delta m^2_{12}/\Delta m^2_{13} \simeq \pm 0.03$, which is of order ϵ^2. Keeping terms up to the third order, in vacuum, one finds

$$(2) \qquad\qquad P^{\mathrm{ATM}} \simeq 4 s^2_{23} s^2_{13} \sin^2\Delta \,,$$

$$(3) \qquad\qquad P^{\mathrm{INT}}_{\mathrm{I}} \simeq 8 s_{13} s_{12} c_{12} s_{23} c_{23} (\alpha\Delta) \sin\Delta \cos(\Delta + \delta_{13}) \,,$$

$$(4) \qquad\qquad P^{\mathrm{INT}}_{\mathrm{II}} \simeq 4 s_{14} s_{24} s_{13} s_{23} \sin\Delta \sin(\Delta + \delta_{13} - \delta_{14}) \,,$$

where $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$ and $\Delta \equiv \Delta m^2_{13} L / 4E$ 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 [17, 18] for details).
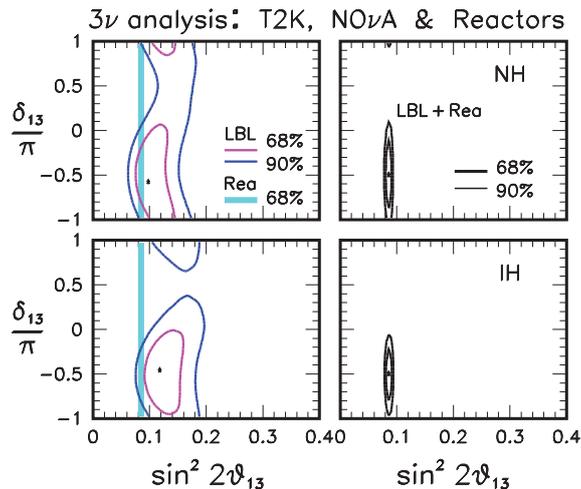
Fig. 1. – Left panels: regions allowed by the LBL experiments T2K and NOνA and by the θ_{13}-sensitive reactor experiments for normal hierarchy (upper panel) and inverted hierarchy (lower panel). Right panels: regions allowed by their combination. The mixing angle θ_{23} is marginalized away. The confidence levels refer to 1 d.o.f. ($\Delta\chi^2 = 1.0, 2.71$).

Remarkably, for the typical values of the mixing angles preferred by the current global $3 + 1$ fits [19, 20], 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 NOνA in the plane of the two parameters $[\theta_{13}, \delta_{13}]$ is expected. In addition, a similar sensitivity to the two CP-phases δ_{13} and δ_{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 [18], 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 θ_{13} determined by the reactor experiments Daya-Bay and RENO. The wiggling regions are determined by the combination of T2K and NOνA. For both LBL experiments, in addition to the old T2K ν_e appearance data [21], we include the latest results, which have reported the first $\bar{\nu}_e$ appearance data [22, 23] (T2K) and the first ν_e appearance results [24] (NOνA)([1]). 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 θ_{13} preferred by LBL and reactor experiments. As a consequence the NH is slightly favored over the IH.

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 $[\sin^2 \theta_{13}, \delta_{13}]$ for four different choices of the new CP-phase δ_{14}. We have fixed the 4-flavor parameters at the following values: $s_{14}^2 = s_{24}^2 = 0.025$, $s_{34}^2 = 0$, $\delta_{34} = 0$ and $\Delta m_{14}^2 = 1\,\text{eV}^2$. As a benchmark we also report the range allowed for θ_{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.

([1]) For NOνA we conservatively use the results obtained with the primary events selection method dubbed as LID.
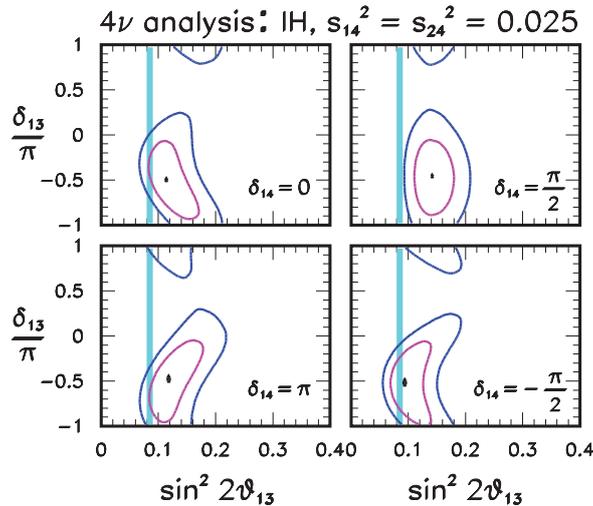
Fig. 2. – Regions allowed by the combination of T2K and NOνA for four representative values of the CP-phase δ_{14}. Inverted hierarchy is assumed. The mixing angle θ_{23} is marginalized away. The vertical band represents the region allowed by reactor experiments. The confidence levels are as in fig. 1.

In particular, it is interesting to note how, in the presence of 4ν effects, a better agreement among the two estimates of θ_{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 θ_{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. This conclusion has been recently corroborated by the prospective studies performed in [25, 26].

4. – 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.

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 4ν 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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