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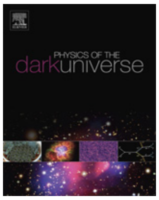

Light sterile neutrinos in particle physics: Experimental status

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ABSTRACT

Most of the neutrino oscillation results can be explained by the three-neutrino paradigm. However several anomalies in short baseline oscillation data, corresponding to an L/E of about 1 m/MeV, could be interpreted by invoking a hypothetical fourth neutrino. This new state would be separated from the three standard neutrinos by a squared mass difference $\Delta m^2_{new} \sim 0.1$–$1\ \mathrm{eV}^2$ and would have mixing angles of $\sin^2 2\theta_{ee} \gtrsim 0.01$ and $\sin^2 2\theta_{\mu e} \gtrsim 0.001$, in the electron disappearance and appearance channels, respectively. This new neutrino, often called sterile, would not feel standard model interactions but mix with the others. Such a scenario calling for new physics beyond the standard model has to be either ruled out or confirmed with new data. After a brief review of the anomalous oscillation results we discuss the forthcoming laboratory experiments aiming to clarify the situation.

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1. Introduction

The well established standard neutrino oscillation framework satisfactorily explains most of neutrino data. It relies on three flavors (ν_e, ν_μ, ν_τ), mixture of three mass states (ν_1, ν_2, ν_3) separated by squared mass differences of $\Delta m^2_{21} = \Delta m^2_{\mathrm{sol}} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\ \mathrm{eV}^2$ and $|\Delta m^2_{31}| \approx |\Delta m^2_{32}| = \Delta m^2_{\mathrm{atm}} = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ \mathrm{eV}^2$ [1], where "sol" and "atm" stand historically for solar and atmospheric experiments providing compelling evidence for neutrino oscillation (see [2] and references therein for a recent review). Beyond this minimal extension of the standard model, anomalous results have been reported in LSND [3], MiniBooNE [4,5], and radioactive source experiments [6–9]. In addition a new evaluation of the reactor neutrino fluxes [10,11] led to a reinterpretation of the results of short baseline reactor experiments [12], the so-called Reactor Antineutrino Anomaly.

If not related to non understood experimental issues, results of the global fit of short-baseline neutrino oscillation experiments (see [13] for instance) show that the data can be explained by the addition of one or two sterile neutrinos to the three active neutrinos of the standard model, the so-called $(3+1)$ and $(3+2)$ scenarios, respectively. However some tension remains between appearance and disappearance data in the global fits, see [14].

It is worth noting that sterile neutrinos would affect the oscillation probabilities of the active flavors and therefore could influence cosmological processes [15]. These aspects will not be further discussed in this experimental review focusing on terrestrial experiments, but more details can be found in [16].

2. Anomalous oscillation results and sterile neutrinos

In this section we focus on neutrino oscillation results with an L/E of about 1 m/MeV. A comprehensive review of all short baseline oscillation results and detailed statements on the current oscillation anomalies can be found in [17].

In 1995 the LSND experiment reported an excess in the $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance channel [3]. A similar experiment, KARMEN [18], did not report such an excess, however. In 2002 the MiniBooNE experiment confirmed this excess in both ν_e to ν_μ and $\bar{\nu}_e$ to $\bar{\nu}_\mu$ channels [4,5]. The MiniBooNE results will be soon complemented by using a 170-ton LAr TPC in the same neutrino beam; the MicroBooNE experiment [19] will check if the low-energy excess is due to ν_e charged current quasielastic events. Event rates measured by many reactor experiments at short distances, when compared with a newly evaluated antineutrino flux, are indicating the disappearance of $\bar{\nu}_e$ [12]. In addition the results from the gallium solar neutrino calibration experiments reported also a deficit of ν_e in a similar L/E range [7–9].

The individual significances of these anomalies lie between 2.5 to 3.8 σ, and these results, not fitting the three-neutrino-flavor framework, are difficult to explain by systematics effects. If not experimental artifacts it is puzzling that each of them could be

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explained by oscillation to sterile neutrinos with a large mass squared difference, $\Delta m^2_{\text{new}} \gtrsim 0.1\ \text{eV}^2$, corresponding to an L/E of about 1 m/MeV.

Indeed the minimal neutrino mixing scheme provides only two squared-mass differences. A third one would be required for new short-baseline neutrino oscillations. It then requires the introduction of a sterile neutrino ν_s [20–23]. The minimal model consists of a hierarchical $3+1$ neutrino mixing, acting as a perturbation of the standard three-neutrino mixing in which the three active neutrinos ν_e, ν_μ, ν_τ are mainly composed of three massive neutrinos ν_1, ν_2, ν_3 with light masses m_1, m_2, m_3. The sterile neutrino would mainly be composed of a heavy neutrino ν_4 with mass m_4 such that $\Delta m^2_{\text{new}} = \Delta m^2_{41}$, and $m_1, m_2, m_3 \ll m_4$.

In $3+1$ neutrino mixing, the effective flavor transition and survival probabilities in short-baseline neutrino oscillation experiments are given by

$$\begin{aligned} P^{\text{new}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} &= \sin^2 2\theta_{\alpha\beta}\, \Delta_{41}\ (\alpha \neq \beta), \\ P^{\text{new}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} &= 1 - \sin^2 2\theta_{\alpha\alpha}\, \Delta_{41} \end{aligned} \tag{1}$$

where $\Delta_{41} = \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$, and for $\alpha, \beta = e, \mu, \tau, s$, with the transition amplitudes

$$\begin{aligned} \sin^2 2\theta_{\alpha\beta} &= 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2, \\ \sin^2 2\theta_{\alpha\alpha} &= 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right). \end{aligned} \tag{2}$$

The interpretation of both LSND and MiniBooNE anomalies in terms of light sterile neutrino oscillations requires mixing of the sterile neutrino with both electron and muon neutrinos. In addition, both OPERA and ICARUS experiments recently reported negative results for the search ν_e from the ν_μ CNGS beam [24,25], although not testing fully the relevant space of oscillation parameters. Therefore when considering all data together no satisfactory global fit can be obtained (see [14] for instance). This is mainly due to the non-observation of ν_μ disappearance at the eV-scale [26], that is a generic prediction if the LSND signal implies a sterile neutrino. This negative results is not strong enough to rule out this hypothesis, however.

All these facts motivate the experimental program being briefly summarized in this review. In what follows, we focus on the 3 active $+1$ sterile neutrino mixing scheme with Δm^2_{new} of the order of 0.1–1 eV^2.

3. Clarification of the anomalies: experimental program

To definitively test the short baseline oscillation hypothesis the new experiments must be sensitive to an oscillation pattern either in the energy spectrum, or in the spatial distribution of the neutrino interactions, or both. To cover the Δm^2 region of 0.1–1 eV^2 with MeV/GeV neutrinos the distance between the emitter and the detector has to be on the scale of 1–10 m/1–10 km, respectively. Statistical and systematics uncertainties must be at the level of a few percents or less. Such an experiment could be performed close to nuclear reactors, with intense radioactive sources used as neutrino emitters, or with accelerator based experiments. We review below the various projects that have been proposed to clarify the neutrino anomalies, leaving out R&D efforts.

3.1. Reactor-based proposals

Nuclear reactors are very intense sources of 1–10 MeV electron antineutrinos. In the 1980s their expected fluxes were obtained with a precision of 5% through the measurement of the integral β-spectra of uranium and plutonium isotopes irradiated into a reactor core, followed by their phenomenological conversion into $\bar{\nu}_e$ spectra [27,28]. But in 2011 this prediction was corrected leading to an increase of the emitted flux by about 4%, with a similar precision [10,11]. The revised comparison of the latest with the measured rate of interactions in detectors located at 100 m or less from the cores revealed the Reactor Antineutrino Anomaly [12]. It is worth noting that there remains some lack of knowledge of the reactor neutrino fluxes. It has been recently pointed out that the detailed treatment of forbidden transitions in the computation of reactor neutrino spectra may lead to an increase of the systematic uncertainty by a few percents [29]. Moreover, while writing this article a new deviation with respect to the expected reactor neutrino spectral shape predictions [27,28,10,11] has been announced by the RENO and Double Chooz collaborations at the Neutrino 2014 conference [30–32], and confirmed later by the Daya Bay collaboration at the ICHEP 2014 conference [33]. This deviation in the prompt signal energy spectrum is being observed between about 4 to 7 MeV (visible energy) with a significance of more than 3 standard deviations. The origin of this structure is still unknown. Therefore further investigations of reactor neutrino spectra as well as more precise data are needed.

New reactor experiments searching for short baseline oscillation, with L/E $\sim$ 1 m/MeV, should first look for an oscillation pattern imprinted in the energy distribution of events. Of course the analysis must be complemented by an integral rate measurement. According to global fits the relevant range of oscillation lengths, $L_{\text{osc}} \sim 2.5E/\Delta m^2_{\text{new}}$ is between 1 and 10 m. Therefore short baselines, a few ten's of meters, are mandatory and compact reactor cores, with typical dimensions of 1 m, are preferable in comparison with larger commercial reactors to prevent washing out the hypothetical oscillation pattern at the L/E's of interest. Experimentally the detection technique of most experiments in preparation relies on the inverse β-decay (IBD) reaction, $\bar{\nu}_e + p \to e^+ + n$, where the positron carries out the $\bar{\nu}_e$ energy while the neutron tagging provides a discriminant signature against backgrounds. Indeed an accidental pair from γ-ray radioactivity contaminants or induced by the reactor core, followed by a neutron capture or a high energy γ from the core could easily mimic the signal. This background can partially be suppressed through passive shielding while the remaining contribution can be measured in-situ at the analysis stage, leading to an increase of the uncertainty due to statistical fluctuations of the background rate, however. Correlated backgrounds induced by cosmic rays can also alter the signal. By definition a single correlated event can mimic the IBD process. All current projects are foreseen at shallow depths or even at the surface, the latter case being extremely challenging and not yet experimentally demonstrated at the desired precision. More problematic could be the possible correlated backgrounds induced by the reactor core itself. It must be suppressed through passive shielding, depending strongly on the site configuration and on the type of reactor core. This background superimposes on the top of the signal and it cannot be measured in situ, unfortunately. It is therefore mandatory to optimize the experimental setup through simulation to minimize it, while taking large safety margins due to the difficulty of assessing the remaining contribution in the fiducial volume. Table 1 provides a list of current projects being carried out at reactors. The Nucifer experiment [34] is currently taking data close to the Osiris nuclear reactor in Saclay. Though not optimized for a sterile neutrino search it could provide first new constraints by 2015. The Stereo experiment [17] will be constructed next to the ILL reactor in Grenoble in 2014 and aims taking data middle of 2015. The DANSS [35] and Neutrino4 [36] experiments are under construction in Russia and should provide first data in 2015. Finally a comprehensive project for searching sterile neutrinos at reactor in US is currently in its R&D phase [37]; depending on its

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