Global status of light sterile neutrinos

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Abstract. The reactor, Gallium and LSND anomalies in favor of the light sterile neutrinos in short baseline neutrino oscillations are reviewed. The status of global fits including short baseline neutrino oscillation data and constraints from solar, atmospheric as well as long baseline reactor and accelerator neutrino experiments is presented. Finally the prospective of the future short baseline neutrino oscillation experiments is highlighted.

1. Introduction

Neutrino oscillation data from solar, atmospheric, reactor and accelerator neutrino experiments have established a well-determined three-neutrino oscillation framework [1] with two independent mass squared differences, the solar (SOL) mass splitting with \( \Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq 7.5 \times 10^{-5} \text{eV}^2 \) and the atmospheric (ATM) mass splitting \( \Delta m^2_{\text{ATM}} = |\Delta m^2_{31}| \simeq 2.4 \times 10^{-3} \text{eV}^2 \). However, there are several experimental anomalies in short baseline (SBL) neutrino oscillations which require a much larger mass square difference \( \Delta m^2_{\text{SBL}} \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}} \), and cannot be incorporated in the three neutrino oscillation framework:

- the Reactor antineutrino Anomaly [2], which is a deficit of the reactor electron antineutrino rates in the short-baseline reactor antineutrino experiments in comparison to the theoretical calculations of the reactor antineutrino fluxes [3, 4]. The statistical significance of the reactor antineutrino anomaly is about 2.8\( \sigma \).
- the Gallium neutrino Anomaly [5, 6], which is an about 2.9\( \sigma \) deficit in the short-baseline electron neutrino disappearance measured in the Gallium radioactive source experiments GALLEX [7] and SAGE [8].
- the LSND Anomaly, which is a signal of the \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \) transition in the short-baseline accelerator neutrino experiment LSND, with a statistical significance of about 3.8\( \sigma \) [9, 10].

The additional \( \Delta m^2_{\text{SBL}} \) requires a fourth massive neutrino in addition to the three standard massive neutrinos. Since from the invisible width of the \( Z \) boson in the LEP measurement, we know that there are only three active neutrinos [11], the fourth massive neutrino corresponds to a sterile neutrino in the flavor basis [12], which means that there is no standard weak interactions between the sterile neutrino and standard model particles. In this work, we present in the \( (3+1) \) neutrino mixing scheme a global fit [13] of the short baseline neutrino oscillation data taking into account the constraints from solar, atmospheric and long baseline reactor and accelerator neutrino oscillation data. The prospective of the future short baseline neutrino experiments is also highlighted in comparison to the global allowed regions.
Figure 1. Allowed regions in the $\sin^2 2\theta_{ee} - \Delta m^2_{41}$ plane obtained from: (left) the combined fit of $\nu_e$ and $\bar{\nu}_e$ disappearance data; (right) the combined fit of $\nu_e$ and $\bar{\nu}_e$ disappearance data and the $\beta$-decay constraints of the Mainz and Troitsk experiments [30].

2. Global $\nu_e$ and $\bar{\nu}_e$ disappearance

First, let us discuss in this section the global fit of $\nu_e$ and $\bar{\nu}_e$ disappearance. In our analysis, we have included the following data from the $\nu_e$ and $\bar{\nu}_e$ disappearance channels:

- the reactor $\bar{\nu}_e$ disappearance data from the Bugey-4 [14], ROVNO91 [15], Bugey-3 [16], Gosgen [17], ILL [18], Krasnoyarsk [19], Rovno88 [20], SRP [21], Chooz [22], Palo Verde [23], Double Chooz [24], and Daya Bay [25] reactor experiments with new theoretical calculations of the reactor antineutrino fluxes [3, 4];
- the $\nu_e$ disappearance data from the GALLEX [7] and SAGE [8] Gallium radioactive source experiments with the statistical method discussed in Refs. [5, 6];
- the solar and KamLAND neutrino constraint on $\sin^2 2\theta_{ee}$ [6, 26];
- the KARMEN [27] and LSND [28] $\nu_e + ^{12}\text{C} \rightarrow ^{12}\text{N}_{g.s.} + e^-$ scattering data;
- the T2K near detector constraints [29];
- the $\beta$-decay constraints from the Mainz and Troitsk experiments [30].

In Fig. 1, we present the allowed regions in the $\sin^2 2\theta_{ee} - \Delta m^2_{41}$ plane obtained from: (left) the combined fit of $\nu_e$ and $\bar{\nu}_e$ disappearance data; (right) the combined fit of $\nu_e$ and $\bar{\nu}_e$ disappearance data and the $\beta$-decay constraints of the Mainz and Troitsk experiments [30]. Note that oscillation data cannot put any upper bound on the mass square difference because of the average effects. With additional $\beta$-decay constraints, one can obtain an upper bound of about 100 eV$^2$ for $\Delta m^2_{41}$. This will give a corresponding lower bound on the oscillation length which is good for future short baseline reactor and radioactive source experiments.

Sensitivities of the ongoing reactor (left) and the radioactive source (right) experiments in comparison to the global allowed region of the $\nu_e$ and $\bar{\nu}_e$ disappearance are shown in Fig. 2. One can find that the reactor and source experiments will cover most of region with large $\sin^2 2\theta_{ee}$ and $\Delta m^2_{41} < 10$ eV$^2$, KATRIN will explore the large $\Delta m^2_{41}$ part of the allowed region.

3. Global fits of short baseline data

In this section, we first discuss the individual fit result of the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance and $\bar{\nu}_\mu$ disappearance data:
Figure 2. Sensitivities of the ongoing reactor (left) and radioactive source (right) experiments in comparison to the global allowed region of the $\nu_e$ and $\bar{\nu}_e$ disappearance.

Figure 3. Individual fitting of the $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance (left) and $\bar{\nu}_\mu$ disappearance (right) data. The shadowed allowed regions are from the global fitting of all appearance data.

- the $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance data of LSND [10], MiniBooNE [31], KARMEN [33], BNL-E776 [32], NOMAD [34], OPERA [36], and ICARUS [35] experiments,
- the constraints on the $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance obtained from the data of the CDHSW experiment [37], from the analysis [38] of the data of atmospheric neutrino oscillation experiments, from the analysis of the MINOS neutral-current data [39] and from the analysis of the SciBooNE-MiniBooNE neutrino [40] and antineutrino [41] data.

In Fig. 3 we show the individual fitting result of the $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance (left) and $\bar{\nu}_\mu$ disappearance (right) data. The shadowed allowed regions are from the global fitting of all the appearance data. There are only limits for the $\bar{\nu}_\mu$ disappearance data.

In Fig. 4 we illustrate the allowed regions in the $\sin^2 2\theta_{\mu e} - \Delta m^2_{21}$ plane in the the global fitting of all the short baseline neutrino oscillation data. The left and right panels correspond to the case with and without considering the low energy bins of MiniBooNE. For the former case,
Figure 4. Allowed regions in the $\sin^2 2\theta_{e\mu} - \Delta m^2_{41}$ plane in the the global fitting of all the short baseline neutrino oscillation data. The left and right panels correspond to the case with and without including the low energy bins of MiniBooNE.

Figure 5. Sensitivities of future experiments in the $\nu_e$ and $\bar{\nu}_e$ disappearance channel (left), the $\bar{\nu}_e$ and $\nu_e$ appearance channel (middle), and $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance channel compared with the global allowed regions in the right panel of Fig. 4.

there is strong tension between the appearance and disappearance data, which has a very small parameter goodness of fit (i.e., 0.06%). Considering that the low-energy bins of the MiniBooNE experiment have an anomalous excess because of the large background, we are motivated to consider the pragmatic fit in the right panel of Fig. 4. In this case, we are left with a parameter goodness of fit of 7%, which is acceptable from the point of view of global fits.

Finally, we show in Fig 5 the sensitivities of future experiments in the $\nu_e$ and $\bar{\nu}_e$ disappearance channel (left), the $\bar{\nu}_e$ and $\nu_e$ appearance channel (middle), and $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance channel compared with the global allowed regions in the right panel of Fig. 4. It is evident that the ongoing experiments will give a definitive answer on the existence of active-sterile short-baseline oscillations connected with the Gallium, reactor and LSND anomalies.

4. Conclusion
In this work, we have reviewed the reactor, Gallium and LSND anomalies in favor of the light sterile neutrinos in short baseline neutrino oscillations. we presented the status of global fits of
light sterile neutrinos including all short baseline neutrino oscillation data and constraints from solar, atmospheric as well as long baseline reactor and accelerator neutrino experiments. We also highlighted the prospective of the ongoing short baseline neutrino oscillation experiments to test the hypothesis of light sterile neutrinos.

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References

[1] Patrignani C et al. [Particle Data Group] 2016 Chin. Phys. C 40 100001
[2] Mention G et al. 2011 Phys. Rev. D 83 053006
[3] Mueller T A et al. 2011 Phys. Rev. C 83 054615
[4] Huber P 2011 Phys. Rev. C 84 024617
[5] Giunti C and Laveder M 2011 Phys. Rev. C 83 065504
[6] Giunti C et al. 2012 Phys. Rev. D 86 113014
[7] Kaether F et al. 2010 Phys. Lett. B 685 47
[8] Abdurashitov J N et al. (SAGE) 2009 Phys. Rev. C 80 015807
[9] Athanassopoulos C et al. (LSND) 1995 Phys. Rev. Lett. 75 2650
[10] Aguilar A et al. (LSND) 2001 Phys. Rev. D 64 112007
[11] Giunti C and Kim C W 2007 Fundamentals of Neutrino Physics and Astrophysics (Oxford University Press, Oxford, UK)
[12] Pontecorvo B 1968 Sov. Phys. JETP 26 984
[13] Gariazzo S et al. 2016 J. Phys. G 43 033001
[14] Declais Y et al. (Bugey) 1994 Phys. Lett. B 338 383
[15] Kuvshinnikov A et al. 1991 JETP Lett. 54 253
[16] Achkar B et al. (Bugey) 1995 Nucl. Phys. B 434 503
[17] Zacek G et al. Phys. Rev. D34 (1986) 2621.
[18] Hoummada A et al. 1995 Applied Radiation and Isotopes 46 449
[19] Krasnoyarsk G S et al. 1990 Sov. Phys. JETP 71 424
[20] Afonin A I et al. 1988 Sov. Phys. JETP 67 213
[21] Greenwood Z D et al. 1996 Phys. Rev. D 53 6054
[22] Apollonio M et al. (CHOOZ) 2003 Eur. Phys. J. C 27 331
[23] Boehm F et al. (Palo Verde) 2001 Phys. Rev. D 64 112001
[24] Abe Y et al. (Double Chooz) 2014 JHEP 1410 86
[25] An F P et al. (Daya Bay) 2016 Phys. Rev. Lett. 116 061801
[26] Giunti C and Li Y F 2009 Phys. Rev. D 80 113007
[27] Armbruster B et al. (KARMEN) 1998 Phys. Rev. C 57 3414
[28] Auerbach L B et al. (LSND) 2001 Phys. Rev. C 64 065501
[29] Abe K et al. (T2K) 2015 Phys. Rev. D 91 051102
[30] Giunti C et al. 2013 Phys. Rev. D 87 013004
[31] Aguilar-Arevalo A et al. (MiniBooNE) 2013 Phys. Rev. Lett. 110 161801
[32] Borodovsky L et al. (BNL-E776) 1992 Phys. Rev. Lett. 68 274
[33] Armbruster B et al. (KARMEN) 2002 Phys. Rev. D 65 112001
[34] Astier P et al. (NOMAD) 2003 Phys. Lett. B 570 19
[35] Antonello M et al. (ICARUS) 2013 Eur. Phys. J. C 73 2599
[36] Agafonova N et al. (OPERA) 2013 JHEP 1307 004
[37] Dydek F et al. (CDHSW) 1984 Phys. Lett. B 134 281
[38] Maltoni M and Schwetz T 2007 Phys. Rev. D 76 093005
[39] Adamson P et al. (MINOS) 2011 Phys. Rev. Lett. 107 011802
[40] Mahn K B M et al. (SciBooNE-MiniBooNE) 2012 Phys. Rev. D 85 032007
[41] Cheng G et al. (SciBooNE-MiniBooNE) 2012 Phys. Rev. D 86 052009