THE REACTOR NEUTRINO ANOMALY: STATUS AND RECENT DEVELOPMENTS

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The observed antineutrino flux from nuclear reactors is consistently lower than predicted. This anomaly could hint at oscillations of active neutrinos into a new sterile neutrino species, or it could simply be a reflection of underestimated systematic uncertainties in the theoretical flux prediction. We review the status of both hypothesis in view of recent developments. In particular, we scrutinize recent Daya Bay results, which aim to determine whether the deficit depends on the isotope from which neutrinos are produced (as would be likely if the problem is with the flux prediction), or is independent thereof (as would be expected if the sterile neutrino hypothesis is true). We also comment on new short-baseline data, and we discuss reactor data in the context of a global fit.

1 The Reactor Anomaly — Sterile Neutrinos or Flux Uncertainties?

Most "anomalies" in particle physics data are triggered by new, and sometimes controversial, experimental results. A notable exception is the reactor neutrino anomaly,[1] which was triggered by new and refined theoretical predictions of the antineutrino flux from nuclear reactors[2;3]. The new calculations yield a results that is about 3.5% ($\sim 3\sigma$) larger than the fluxes measured by a large number of short and long baseline experiments. One possibility to understand this apparent deficit of observed neutrino event rates is by postulating the existence of a fourth, sterile, neutrino flavor ν_s. Reactor $\bar{\nu}_e$ could then oscillate into undetectable $\bar{\nu}_s$.

However, it is also quite possible that the observed anomaly is nothing but a reflection of the shortcomings of theoretical flux predictions. There is agreement in the community that the new predictions are superior to the previously used ones from the 1980s, but it is also well known that predicting reactor neutrino fluxes is a very challenging task: thousands of individual beta decay branches contribute to the spectrum, and for many isotopes, only very limited information is available in nuclear data tables because they are too short-lived to allow for laboratory studies.

Consequently, neutrino fluxes and spectra are predicted by fitting "effective beta decay spectra" to the observed electron spectra from uranium and plutonium fission – a method that is still fraught with large and difficult to control systematic uncertainties.[4–6]

In this talk, which is based on refs. [7,8] and builds on previous work from refs. [9,10], we assess the current status of the reactor anomaly and put it in the context of other hints for the existence of sterile neutrinos, and of the strong exclusion limits from null searches.

1.1 Isotope-Dependent Neutrino Fluxes from Daya Bay

A novel experimental method for distinguishing the sterile neutrino hypothesis from the hypothesis of flux misprediction is offered by high-statistics measurements in the Daya Bay experiment: by measuring the neutrino spectrum as a function of time (and therefore as a function of the evolving reactor fuel composition), the collaboration is able to extract the individual neutrino spectra generated by the fission chains of the four main fissile isotopes ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu.[11] If the reactor anomaly is due to oscillations into sterile neutrinos, one expects the flux deficit to be the same for all isotopes. In the case of a flux misprediction, it is likely that different isotopes are affected differently.

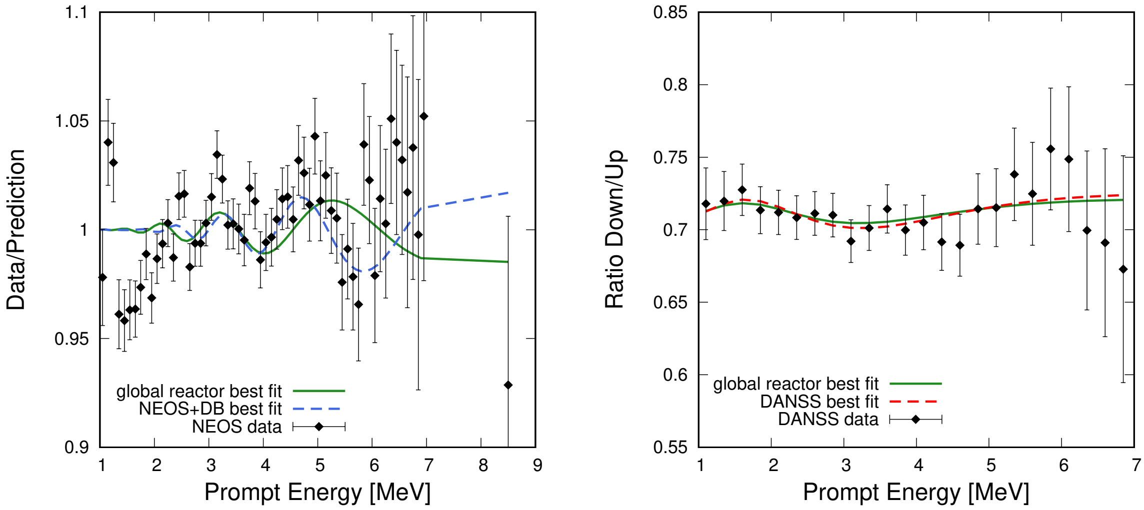
Indeed, Daya Bay observe a discrepancy between the predicted and observed fluxes mostly for ^{235}U, while theory and data agree quite well for ^{239}Pu. (^{238}U and ^{241}Pu are subdominant in Daya Bay, so no statistically significant statement can be made about them.) This leads to a preference for the hypothesis of flux misprediction with $\Delta\chi^2 = 7.9$ (2.8σ).[11] In ref. [7], we have reanalyzed the Daya Bay data. We agree with the collaboration's results when making the same assumptions. However, several comments are in order:

- The Daya Bay collaboration compare their data to the central values of the neutrino fluxes predicted in refs. [2,3], but neglect the theoretical uncertainties quoted in these papers. The reason for this approach is that it is unclear how reliable the estimated theoretical uncertainties are. Including the quoted values for the uncertainties, Daya Bay's preference for mispredicted fluxes reduces to $\Delta\chi^2 = 6.3$.

- It is also noteworthy that, while the data prefer mispredicted fluxes over sterile neutrinos, the overall goodness of fit is excellent for both hypotheses: a χ^2 goodness-of-fit test yields a p-value of 0.18 for the sterile neutrino hypothesis, and a p-value of 0.73 for the hypothesis of mispredicted fluxes. We implement the latter hypothesis by assigning independent normalization factors to the fluxes from all four isotopes and profiling over them in the fit.

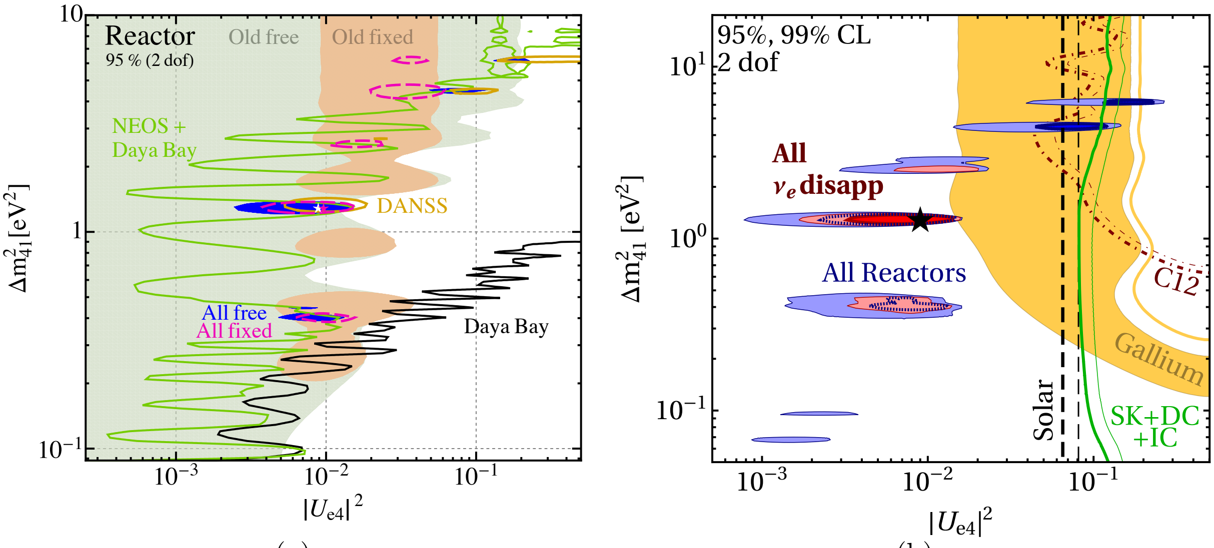
1.2 Impact of NEOS and DANSS

Another new aspect in the discussion of the reactor neutrino anomaly are the recent data releases by NEOS[12] and DANSS.[13] The results of both experiments are independent of the theoretical flux predictions: NEOS normalize their data to the flux measurement in Daya Bay,[14] while DANSS employ a movable detector and take data at two different baselines. As shown in fig. 1, both experiments report spectral distortions, which can be interpreted as another 3σ hint for $\bar{\nu}_e \to \bar{\nu}_s$ oscillations. This implies that the fit to all reactor data continues to prefer oscillations into sterile neutrinos even when no assumptions are made on the normalization of the theoretical flux predictions. This is illustrated in fig. 2 (a), which shows the preferred parameter region in the plane spanned by the mass squared difference Δm^2_{41} and the mixing matrix element U_{e4} which measures the mixing of ν_e and ν_s. We see that DANSS alone (orange contours) prefers oscillations at the 95% CL, while NEOS alone is consistent with no oscillations at this confidence level. The global fit to all reactor data prefers oscillations no matter whether the prediction for the flux normalization is used (pink contours) or not (blue region).



(a) (b)

Figure 1 – Spectral distortions observed in (a) NEOS [12] and (b) DANSS [13]. For NEOS, the vertical axis shows the ratio of the observed event rate to the prediction based on the Daya Bay flux measurement. [14] For DANSS, the vertical axis shows the ratio of observed event rates at two different baselines (12.7 m and 10.7 m from the reactor core. Plots taken from ref. [8].



(a) (b)

Figure 2 – (a) Allowed values of the mixing matrix element U_{e4} and the mass squared difference Δm^2_{41} in a $3+1$ model from reactor data alone. The regions labeled "old" correspond to all data except Daya Bay, DANSS, and NEOS. "Free" refers to a conservative analysis in which the normalization of the flux prediction is allowed to float freely for each of the four main fissile isotopes, while "fixed" refers to a fit in which the normalization is fixed within the quoted uncertainties [2;3]. We observe a preference for oscillations even for free flux normalization. (b) Results from the fit to all $\nu_e/\bar{\nu}_e$ disappearance data. We observe a strong preference for oscillations, but also mild tension between the parameter region preferred by reactors and the one preferred by the gallium anomaly. Plots taken from ref. [8].

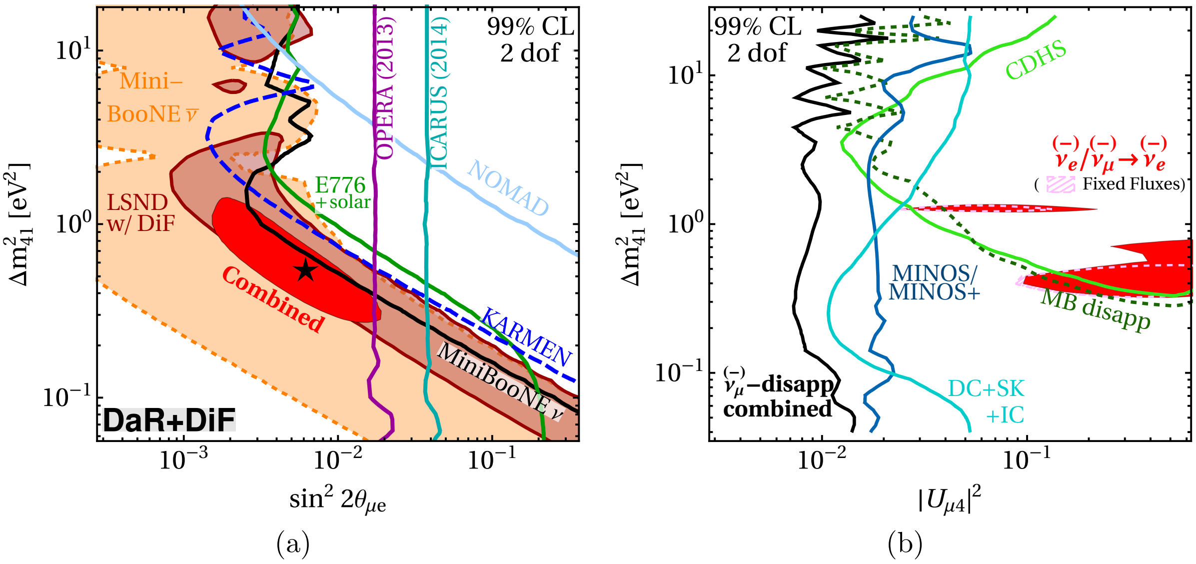


Figure 3 – (a) Preferred values of the effective ν_μ–ν_e mixing angle at short baseline $\theta_{\mu e}$ and the mass squared difference Δm^2_{41} in a 3+1 scenario. We observe that the hints from LSND and MiniBooNE are consistent with the null results in this channel. (b) Constraints on the mixing matrix element $U_{\mu 4}$ (corresponding to ν_μ–ν_s mixing) and Δm^2_{41}. We see that the strong exclusion limits from MiniBooNE disappearance data, IceCube, MINOS/MINOS+, and CDHS disfavor the parameter regions that are preferred by ν_e disappearance and ν_e appearance data. Plots taken from ref. [8].

2 Global Status of Light Sterile Neutrinos

We now put the results from our reactor fit into a broader context. In fig. 2 (b) we show how the hints from reactor experiments compare to the parameter region preferred by the gallium anomaly[15–19], and to various exclusion limits (see Table I of ref.[8] for a complete list of references). We observe that the significant preference for $\nu_e/\bar{\nu}_e$ disappearance into sterile states persists. The exclusion bounds are not yet able to conclusively test the preferred parameter regions. We also observe mild tension between gallium and reactor data. A parameter goodness-of-fit test[20] comparing reactor and gallium data assigns a p-value of 0.09 to this tension. (The parameter goodness-of-fit test quantifies the statistical penalty one has to pay for combining data sets. It does so by measuring the increase in χ^2 of the global best fit point compared to the individual best fit points of subsets of the data.)

Moving from the $\nu_e/\bar{\nu}_e$ disappearance channel to the $\nu_\mu \to \nu_e$ oscillation channel, we find that also in this channel short-baseline oscillations driven by a sterile state ν_s are preferred, see fig. 3 (a). This is of course driven by the long-standing LSND[21] and MiniBooNE[22;23] anomalies. Even though OPERA[24] and ICARUS[25;26] have added new exclusion limits to this channel, a large parameter region remains allowed.

The picture changes when ν_μ disappearance data is included, see fig. 3 (b). In this channel, the already strong exclusion limits discussed in ref. [10] have been further strengthened by new data from IceCube[27–29] and MINOS/MINOS+[30] (see also ref. [31]). Together with data from ν_e disappearance and ν_e appearance, a 3+1 model can be overconstrained. This can be seen by looking at the oscillation probabilities in the limit where $4\pi E/\Delta m^2_{41} \ll L \ll 4\pi E/\Delta m^2_{31}$. (Here, E is the neutrino energy and L is the baseline.) At baselines satisfying this condition, oscillations driven by Δm^2_{41} average to an overall event deficit constant in energy, while oscillations driven by Δm^2_{31} and Δm^2_{21} cannot develop yet. The oscillation probabilities for the three relevant oscillation channels in this regime are

$$
\begin{aligned}
P_{\nu_e \to \nu_e} &\simeq 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)\,, \\
P_{\nu_\mu \to \nu_\mu} &\simeq 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)\,, \\
P_{\nu_\mu \to \nu_e} &\simeq 2|U_{\mu 4}|^2|U_{\mu 4}|^2\,.
\end{aligned} \tag{1}
$$

We see that they depend on only two parameters, U_{e4} and $U_{\mu 4}$. This is why we can use ν_e data to predict the range of $U_{\mu 4}$ values required to explain the anomalies. This region is shown in red in fig. 3 (b). We see that it is in strong tension with the null results.

To quantify the tension, we have carried out parameter goodness-of-fit, which yields a very bad p-value of 8.3×10^{-6}. This suggests that at least one of the anomalies is explained by a mundane effect rather than a sterile neutrino, or that some of the null results are overly optimistic, or that there is more new physics beyond the simple $3+1$ model. It is thus crucial to further scrutinize the data – both the anomalies and the null results. We have checked that removing a single experiment from the global fit does not significantly improve the parameter goodness-of-fit, unless the experiment removed is LSND. We also do not expect that adding more than one sterile neutrino will significantly improve the fit.[10]

3 Light Sterile Neutrinos and Cosmology

Important constraints on sterile neutrino models also arise from cosmology. In particular, cosmological observations constrain the energy density in relativistic degrees of freedom, parameterized as an effective number of neutrino species N_{eff}, as well as the sum of neutrino masses $\sum m_\nu$. The current 95% CL constraints are $N_{\text{eff}} < 3.56$ and $\sum m_\nu < 0.23$ eV,[32] clearly disfavoring an eV-scale sterile neutrino. It is, however, important to keep in mind that cosmology can only constrain particle species that are abundant in the early Universe. A number of mechanisms have been proposed to prevent ν_s production at early times:

- Entropy production in the SM sector after neutrinos have decoupled in order to dilute sterile neutrinos prior to recombination[33;34]. Note that such scenarios still suffer from Big Bang Nucleosynthesis (BBN) constraints on N_{eff}.[35]

- New interactions in the sterile neutrino sector.[36;37] In such scenarios, sterile neutrinos feel a strong, temperature-dependent potential that suppresses mixing with active neutrinos until the temperature has dropped so low that ν_s production is inefficient even for large mixing angles. Note that nowadays, minimal versions of this scenario appear disfavored.[38;39]

- A late phase transition that changes the properties of sterile neutrinos. As an example, a sterile sector could involve a scalar field that gives a large mass to ν_s at early times, preventing their efficient production. At low temperature, a phase transition occurs to a vacuum state in which ν_s retain only an $\mathcal{O}$(eV) mass[40]. More work is required to assess how easy and natural it is to realize such a scenario in a concrete model.[39].

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