The reactor antineutrino anomaly

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Abstract. Recently, new reactor antineutrino spectra have been provided for ^{235}U, ^{239}Pu, ^{241}Pu, and ^{238}U, increasing the mean flux by about 3 percent. To a good approximation, this reevaluation applies to all reactor neutrino experiments. The synthesis of published experiments at reactor-detector distances below 100 m leads to a ratio of observed event rate to predicted rate of 0.976 ± 0.024. With our new flux evaluation, this ratio shifts to 0.943 ± 0.023, leading to a deviation from unity at 98.6% C.L. which we call the reactor antineutrino anomaly. The compatibility of our results with the existence of a fourth non-standard neutrino state driving neutrino oscillations at short distances is discussed. The combined analysis of reactor data, gallium solar neutrino calibration experiments, and MiniBooNE-ν data disfavors the no-oscillation hypothesis at 99.8% C.L. The oscillation parameters are such that $|\Delta m^2_{\rm new}| > 1.5$ eV^2 (95%) and $\sin^2(2\theta_{\rm new}) = 0.14 \pm 0.08$ (95%).

1. Introduction

Neutrino oscillation experiments over the last twenty years have established a picture of neutrino mixing and masses that explains the results of solar, atmospheric and reactor neutrino experiments [3]. These experiments are consistent with the mixing of ν_e, ν_μ and ν_τ with three mass eigenstates, ν_1, ν_2 and ν_3. In particular, the squared mass differences are required to be $|\Delta m^2_{31}| \simeq 2.4\,10^{-3}$ eV^2 and $\Delta m^2_{21}/|\Delta m^2_{31}| \simeq 0.032$.

Reactor experiments at distances below 100 m from the reactor core (ILL-Grenoble, Goesgen, Rovno, Krasnoyarsk, Savannah River and Bugey see [2] for references therein) have played an important role in the establishment of this pattern. The measured rate of $\bar{\nu}_e$ was found to be in reasonable agreement with that predicted from the reactor antineutrino spectra, though slightly lower than expected, with the measured/expected ratio at 0.976 ± 0.024, including recent revisions of the neutron mean lifetime [3] ($\tau_n = 885.7$ s).

2. New predicted cross section per fission

Fission reactors release about $10^{20}\,\bar{\nu}_e$ GW^{-1}s^{-1}, which mainly come from the beta decays of the fission products of ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu. The emitted antineutrino spectrum is then given by: $S_{\rm tot}(E_\nu) = \sum_k f_k S_k(E_\nu)$ where f_k refers to the contribution of the main fissile nuclei to the total number of fissions of the k$^{\rm th}$ branch, and S_k to their corresponding neutrino spectrum per fission.

In preparation for the Double Chooz reactor experiment, we have re-evaluated the specific reactor antineutrino flux, S_k, (ν/fission), improving the electron to antineutrino data conversion [1]. The method relies on detailed knowledge of the decays of thousands of fission products, while the previous conversion procedure used a phenomenological model based on 30 effective beta branches. Both methods are constrained by the well-measured ILL spectrum of fission induced electrons that accompanies the antineutrinos [1]. This new approach provided a better handle on the systematic errors of the conversion. Although it did not reduce the final error budget, it led to a systematic shift of about 3% in the normalization of ^{235}U, ^{239}Pu, and ^{241}Pu antineutrino fluxes, respectively.

Accounting for new reactor antineutrino spectra [1] the normalization of predicted antineutrino rates, $\sigma_{f,k}^{\rm pred}$, is shifted by +2.5%, +3.1%, +3.7%, +9.8% for k=^{235}U, ^{239}Pu, ^{241}Pu, and ^{238}U respectively. In the case of ^{238}U the completeness of nuclear databases over the years largely explains the +9.8% shift from the reference computations [1]. Our new computation takes into account the off-equilibrium correction [1] of the antineutrino fluxes.

3. Impact on past experimental results

In the eighties and nineties, experiments were performed at a few tens of meters from nuclear reactor cores at ILL, Goesgen, Rovno, Krasnoyarsk, Bugey (3 and 4) and Savannah River [2]. We only consider here experiments with baselines below 100 m to get rid of a possible (θ_{13}, Δm_{31}^2) driven oscillation effect at Palo Verde or CHOOZ. These experiments reported either the ratios (R) of the measured to predicted cross section per fission, or the observed event rate to the predicted rate. The prediction of the cross section per fission is defined as:

$$\sigma_f^{\rm pred} = \int_0^\infty S_{\rm tot}(E_\nu)\sigma_{\rm V-A}(E_\nu)dE_\nu = \sum_k f_k \sigma_{f,k}^{\rm pred}, \tag{1}$$

where the $\sigma_{f,k}^{\rm pred}$ are the predicted cross sections for each fissile isotope, $S_{\rm tot}$ is the model dependent reactor neutrino spectrum for a given average fuel composition (f_k) and $\sigma_{\rm V-A}$ is the theoretical cross section of reaction $\bar{\nu}_e + p \to e^+ + n$ (see [1, 2] for details). The new predicted cross section for any fuel composition can then be computed from Eq. (1).

The ratios of observed to predicted event rates (or cross section per fission), $R = N_{\rm obs}/N_{\rm pred}$, are summarized in Table 1. The observed event rates and their associated errors are unchanged with respect to the publications, the predicted rates are reevaluated separately in each experimental case. We observe a general systematic shift more or less significantly below unity. These reevaluations unveil a new *reactor antineutrino anomaly* [2], clearly illustrated in Fig. 1.

In order to quantify the statistical significance of the anomaly we can compute the weighted average of the ratios of expected over predicted rates, for all short baseline reactor neutrino experiments (including their possible correlations). We assume a 2.0% systematic uncertainty fully correlated among all 19 ratios in result of the common normalization uncertainty of the beta-spectra [2]. Potential experimental correlations coming from the use of similar or identical detector, detection technology and $\bar{\nu}_e$ source have also been taken into account as well as the slight non-gaussianity of the ratios R by enlarging to a small degree the error bars estimated through a Monte Carlo simulation. With the old antineutrino spectra the mean ratio is μ=0.976±0.024. With the new antineutrino spectra, we obtain μ=0.943±0.023, corresponding to a $-2.2\,\sigma$ effect. Clearly the new spectra induce a statistically significant deviation from the expectation.

Assuming the correctness of $\sigma_f^{\rm pred,new}$ the anomaly could be explained by a common bias in all reactor neutrino experiments. The measurements used different detection techniques (scintillator counters and integral detectors). Neutrons were tagged either by their capture in metal-loaded scintillator, or in proportional counters, thus leading to two distinct systematics. As far as the neutron detection efficiency calibration is concerned, we note that different types of radioactive sources emitting MeV or sub-MeV neutrons were used (Am-Be, ^{252}Cf, Sb-Pu, Pu-Be). It should

Table 1. $N_{\mathrm{obs}}/N_{\mathrm{pred}}$ ratios based on old and new spectra. Off-equilibrium corrections have been applied when justified. The err column is the total error published by the collaborations including the error on S_{tot}, the corr column is the part of the error correlated among experiments.

#	result	Det. type	τ_n (s)	^{235}U	^{239}Pu	^{238}U	^{241}Pu	old	new	err(%)	corr(%)	L(m)
1	Bugey-4	^{3}He+H$_2$O	888.7	0.538	0.328	0.078	0.056	0.987	0.942	3.0	3.0	15
2	ROVNO91	^{3}He+H$_2$O	888.6	0.614	0.274	0.074	0.038	0.985	0.940	3.9	3.0	18
3	Bugey-3-I	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.988	0.946	4.8	4.8	15
4	Bugey-3-II	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.994	0.952	4.9	4.8	40
5	Bugey-3-III	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.915	0.876	14.1	4.8	95
6	Goesgen-I	^{3}He+LS	897	0.620	0.274	0.074	0.042	1.018	0.966	6.5	6.0	38
7	Goesgen-II	^{3}He+LS	897	0.584	0.298	0.068	0.050	1.045	0.992	6.5	6.0	45
8	Goesgen-II	^{3}He+LS	897	0.543	0.329	0.070	0.058	0.975	0.925	7.6	6.0	65
9	ILL	^{3}He+LS	889	$\simeq 1$	—	—	—	0.832	0.802	9.5	6.0	9
10	Krasn. I	^{3}He+PE	899	$\simeq 1$	—	—	—	1.013	0.936	5.8	4.9	33
11	Krasn. II	^{3}He+PE	899	$\simeq 1$	—	—	—	1.031	0.953	20.3	4.9	92
12	Krasn. III	^{3}He+PE	899	$\simeq 1$	—	—	—	0.989	0.947	4.9	4.9	57
13	SRP I	Gd-LS	887	$\simeq 1$	—	—	—	0.987	0.952	3.7	3.7	18
14	SRP II	Gd-LS	887	$\simeq 1$	—	—	—	1.055	1.018	3.8	3.7	24
15	ROVNO88-1I	^{3}He+PE	898.8	0.607	0.277	0.074	0.042	0.969	0.917	6.9	6.9	18
16	ROVNO88-2I	^{3}He+PE	898.8	0.603	0.276	0.076	0.045	1.001	0.948	6.9	6.9	18
17	ROVNO88-1S	Gd-LS	898.8	0.606	0.277	0.074	0.043	1.026	0.972	7.8	7.2	18
18	ROVNO88-2S	Gd-LS	898.8	0.557	0.313	0.076	0.054	1.013	0.959	7.8	7.2	25
19	ROVNO88-3S	Gd-LS	898.8	0.606	0.274	0.074	0.046	0.990	0.938	7.2	7.2	18

be mentioned that the Krasnoyarsk, ILL, and SRP experiments operated with nuclear fuel such that the difference between the real antineutrino spectrum and that of pure ^{235}U was less than 1.5%. They reported similar deficits to those observed at other reactors operating with a mixed fuel. Hence the anomaly cannot be associated with a single fissile isotope neither with a single detection technique. All these elements argue against a trivial bias in the experiments, but a detailed analysis of the most sensitive of them, involving experts, would certainly improve the quantification of the anomaly. The other possible explanation of the anomaly is based on a real physical effect and is detailed in Section 5.

4. Other experimental results considered here

In addition to the rate information we included the shape on provided the Bugey-3 and ILL published data [2] in our combined analysis. We also considered the previously quoted anomalies affecting other short baseline electron neutrino experiments Gallex, Sage and MiniBooNE, reviewed in [4] to quantify the compatibility with these anomalies. We reanalyzed the Gallex and Sage calibration runs with ^{51}Cr and ^{37}Ar radioactive sources as in [5, 4] with an observed average deficit of $R_G = 0.86 \pm 0.06\,(1\sigma)$. However we included possible correlations between these four measurements leading to a slightly more conservative result, with the no-oscillation hypothesis disfavored at 97.7% C.L. We also reanalyzed the MiniBooNE electron neutrino excess assuming the very short baseline neutrino oscillation explanation of [4]. Further details of this analysis are provided in [2].

5. The fourth neutrino hypothesis

The reactor antineutrino anomaly could be explained through the existence of a fourth non-standard sterile neutrino. For simplicity we restrict our analysis to the 3+1 four-neutrino scheme. The three active neutrino masses are assumed to be separated from an isolated sterile neutrino mass by $|\Delta m^2_{\mathrm{new}}| \gg 10^{-2}$ eV^2, responsible for very short baseline reactor neutrino oscillations.

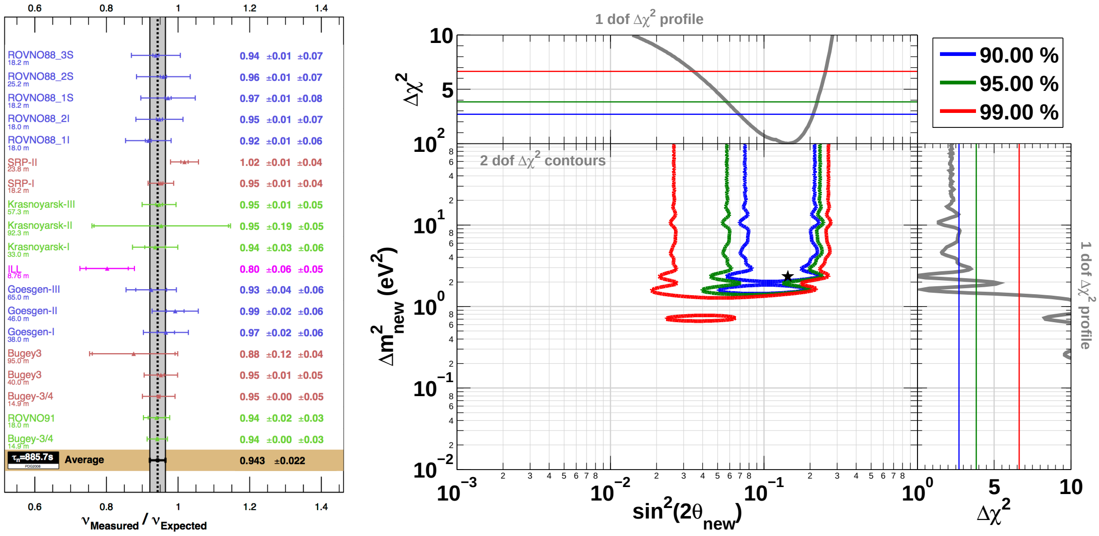

Figure 1. Left: weighted average (with correlations) of 19 measurements of reactor neutrino experiments operating at short baselines. A summary of experiment details is given in Table 1. Right: Allowed regions in the $\sin^2(2\theta_{\text{new}}) - \Delta m^2_{\text{new}}$ plane from the combination of reactor neutrino experiments, Gallex and Sage calibration sources experiments, MiniBooNE reanalysis, and the ILL and Bugey-3-energy spectra. The data are well fitted by the 3+1 neutrino hypothesis, while the no-oscillation hypothesis is disfavored at 99.8% C.L.

For energies above the inverse beta decay threshold and baselines below 100 m, we adopt the approximated oscillation formula, $P_{ee} = 1 - \sin^2(2\theta_{\text{new}}) \sin^2\left(\Delta m^2_{\text{new}} L/4E_{\bar{\nu}_e}\right)$.

The ILL experiment may have seen a hint of oscillation in their measured positron energy spectrum [2], but Bugey-3's results do not point to any significant spectral distortion more than 15 m away from the antineutrino source (note that the large spatial extension of the Bugey nuclear core is sufficient to wash out most of the oscillation pattern). Hence, in a first approximation, hypothetical oscillations could be seen as an energy-independent suppression of the $\bar{\nu}_e$ rate by a factor of $\frac{1}{2}\sin^2(2\theta_{\text{new}})$, thus leading to $\Delta m^2_{\text{new}} \gtrsim 1$ eV^2. Considering the weighted average of all reactor experiments we get an estimate of the mixing angle, $\sin^2(2\theta_{\text{new}}) \sim 0.115$. The ILL positron spectrum is thus in agreement with the oscillation parameters found independently in our re-analyses, mainly based on rate information. Because of the differences in the systematic effects in the rate and shape analyses, this coincidence is in favor of a true physical effect rather than an experimental anomaly.

The no-oscillation hypothesis is disfavored at 99.8% C.L. The significance is dominated by the gallium and reactor data. Allowed regions in the $\sin^2(2\theta_{\text{new}}) - \Delta m^2_{\text{new}}$ plane are displayed in Fig. 1, together with the marginal $\Delta\chi^2$ profiles for $|\Delta m^2_{\text{new}}|$ and $\sin^2(2\theta_{\text{new}})$. The combined fit leads to the following constraints on oscillation parameters: $|\Delta m^2_{\text{new}}| > 1.5$ eV^2 (95% C.L.) and $\sin^2(2\theta_{\text{new}}) = 0.14 \pm 0.08$ (95% C.L.).

References

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