The Reactor Antineutrino Anomaly

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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[4–7]) 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). The cross section of the detection reaction of $\bar{\nu}_e$ on free protons $\bar{\nu}_e + p \rightarrow e^+ + n$ is inversely proportionnal to the neutron lifetime, whose uncertainty is the dominant source of systematic for the cross section. The new world average should evolve and settle to 881.4(1.4) s in 2011 (Ref.[11,12] and private communication from K. Schreckenbach) increasing the cross section by 0.5% compared to the value used in this work.

In preparation for the Double Chooz reactor experiment, we have re-evaluated the specific reactor antineutrino flux (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.[8]

2 New Predicted Cross Section per Fission

Fission reactors release about $10^{20}\,\bar{\nu}_e$ $\mathrm{GW}^{-1}\mathrm{s}^{-1}$, 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: $S_{\mathrm{tot}}(E_\nu) = \sum_k f_k S_k(E_\nu)$ where f_k refers to the contribution of the main fissile nuclei to the total number of fissions of the k^{th} branch, and S_k to their corresponding neutrino spectrum per fission.

For the last 25 years the $\bar{\nu}_e$ spectra have been estimated from measurements of the total electron spectra associated with the beta decays of all fission products of ^{235}U, ^{239}Pu, and ^{241}Pu. Thin target foils of these isotopes were irradiated with thermal neutrons at the ILL reactor.[8] The measured spectra then had to be converted from electron to antineutrino spectra invoking a set of 30 effective beta-branches, adjusted to reproduce the total electron spectrum.[14]

Recently we revisited the conversion procedure with a novel mixed-approach combining the accurate reference of the ILL electron spectra with the physical distribution of beta branches of all fission products provided by the nuclear databases.[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. This normalization shift has been attributed to two main systematic effects in the original conversion of the ILL electron data. At low energy ($E_\nu < 4$ MeV) the implementation of Coulomb and weak magnetism corrections to the Fermi theory in the new approach turned out to deviate from the effective linear correction ($0.65 \times (E_\nu - 4$ MeV) in %) used in the previous work. At high energy ($E_\nu > 4$ MeV), the converted antineutrino spectra become very sensitive to the knowledge of the charge Z of the nuclei contributing to the total spectrum. In the previous approach, only the mean dependence of Z versus the end-point of the effective beta-branches had been used while in the new conversion we had access to the complete distribution, nucleus by nucleus. These two effects could be numerically studied and confirmed on various independent sets of beta-branches. Because ^{238}U nuclei undergo fission with fast neutrons, the associated electron spectrum could not be measured in the thermal neutron flux of the ILL reactor. Therefore the *ab initio* summation of the $\bar{\nu}_e$ from all possible beta decays of fission products was performed to predict the neutrino spectrum.[9] In Ref.[1] we provided a new prediction with an estimated relative uncertainty of the order of 15% in the 2-8 MeV range. This uncertainty of *ab initio* calculations is still too large to be generalized to all isotopes but it is sufficiently accurate in the case of ^{238}U, which contributes to less than 10% of the total fission rate for all reactors considered in this work. An ongoing measurement at the FRM II reactor in Garching will soon provide experimental constraints.[10]

Experiments at baselines below 100 m 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:

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

where the $\sigma_{f,k}^{\mathrm{pred}}$ are the predicted cross sections for each fissile isotope, S_{tot} is the model dependent reactor neutrino spectrum for a given average fuel composition (f_k) and $\sigma_{\mathrm{V-A}}$ is the theoretical cross section of reaction $\bar{\nu}_e + p \to e^+ + n$:

$$\sigma_{\mathrm{V-A}}(E_e)[\mathrm{cm}^2] = \frac{846.7\,10^{-43}}{\tau_n[\mathrm{s}]}\, p_e[\mathrm{MeV}]\, E_e[\mathrm{MeV}]\,(1 + \delta_{\mathrm{rec}} + \delta_{\mathrm{wm}} + \delta_{\mathrm{rad}}), \quad (2)$$

where δ_{rec}, δ_{wm} and δ_{rad} are respectively the nucleon recoil, weak magnetism and radiative corretions to the cross section (see[1,2] for details).

Accounting for new reactor antineutrino spectra[1] the normalization of predicted antineutrino rates, $\sigma_{f,k}^{\text{pred}}$, 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.[9] The new predicted cross section for any fuel composition can be computed from Eq. (1). By default our new computation takes into account the so-called off-equilibrium correction[1] of the antineutrino fluxes (increase in fluxes caused by the decay of long-lived fission products).

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 (so called 3 and 4) and Savannah River.[4–7] We only consider here experiments with baselines below 100 m to get rid of a possible (θ_{13}, Δm^2_{31}) driven oscillation effect at Palo Verde or CHOOZ.

The ratios of observed event rates to predicted event rates (or cross section per fission), $R = N_{\text{obs}}/N_{\text{pred}}$, 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).

Table 1: $N_{\text{obs}}/N_{\text{pred}}$ 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 (multiple-baseline or same detector).

#	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

We consider the following experimental rate information: Bugey-4 and Rovno91, the three Bugey-3 experiments, the three Goesgen experiments and the ILL experiment, the three Krasnoyarsk experiments, the two Savannah River results (SRP), and the five Rovno88 experiments. $\overrightarrow{\mathrm{R}}$ is the corresponding vector of 19 ratios of observed to predicted event rates. We assume a 2.0% systematic uncertainty fully correlated among all 19 ratios in result of the common normalization uncertainty of the beta-spectra measured in.[8] In order to account for the potential experimental correlations, we fully correlated the experimental errors of Bugey-4 and Rovno91, of the three Goesgen and the ILL experiments, the three Krasnoyarsk experiments, the five Rovno88 experiments, and the two SRP results. We also fully correlated the Rovno88 (1I and 2I) results with Rovno91, and we added an arbitrary 50% correlation between the Rovno88 (1I and 2I) and the

Bugey-4 measurement. We motivated these latest correlations by the use of similar or identical integral detectors.

In order to account for the non-gaussianity of the ratios R we developed a Monte Carlo simulation to check this point and found that the ratios distribution is almost Gaussian, but with slightly longer tails, which we decided to take into account in our calculations (in contours that appear later we enlarged the error bars). With the old antineutrino spectra the mean ratio is μ=0.976±0.024, and the fraction of simple Monte-Carlo experiments with $r \geq 1$ is 17.1% ($-0.95\,\sigma$ from expectation). With the new antineutrino spectra, we obtain μ=0.943±0.023, and the fraction of simple Monte-Carlo experiments with $r \geq 1$ is 1.3%, corresponding to a $-2.2\,\sigma$ effect (while a simple calculation assuming normality would lead to $-2.4\,\sigma$). Clearly the new spectra induce a statistically significant deviation from the expectation. In the following we define an experimental cross section $\sigma_f^{\rm ano} = 0.943 \times \sigma_f^{\rm pred,new}$ 10^{-43} cm^2/fission. With the new antineutrino spectra, we observe that for the data sample the minimum χ^2 is $\chi^2_{\rm min,data} = 19.6$. The fraction of simple Monte-Carlo experiments with $\chi^2_{\rm min} < \chi^2_{\rm min,data}$ is 25%, showing that the distribution of experimental ratios in $\overrightarrow{\rm R}$ around the mean value is representative given the correlations.

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 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. Theother possible explanation of the anomaly is based on a real physical effect and is detailed in Section 5.

We used shape information from the Bugey-3 and ILL published data[4,5] for our combined analysis described in Section 5. From the analysis of the shape of their energy spectra at different source-detector distances,[5,6] the Goesgen and Bugey-3 measurements exclude oscillations such that $0.06 < \Delta m^2 < 1$ eV^2 for $\sin^2(2\theta) > 0.05$. We used Bugey-3's 40 m/15 m ratio data from[5] as it provides the best limit. As already noted in Ref.[13] the data from ILL showed a spectral deformation compatible with an oscillation pattern in their measured over predicted events ratio. It should be mentioned that the parameters best fitting the data reported by the authors of Ref.[13] were $\Delta m^2 = 2.2$ eV^2 and $\sin^2(2\theta) = 0.3$. We reanalyzed the data of Ref.[13] in order to include the ILL shape-only information in our analysis of the reactor antineutrino anomaly. We reproduced the contour in Fig. 14 of Ref.,[4] for the shape-only analysis (while we reproduced that of Ref.[13] which excludes the no-oscillation hypothesis at 2σ for the rate-only analysis in the previous section). The shape-only information of the data is compatible with the no-oscillation hypothesis at 1σ.

4 Other experimental results considered here

We considered the previously quoted anomalies affecting other short baseline electron neutrino experiments Gallex, Sage and MiniBooNE, reviewed in Ref.[15] Our goal is to quantify the compatibility with those anomalies. We first reanalyzed the Gallex and Sage calibration runs

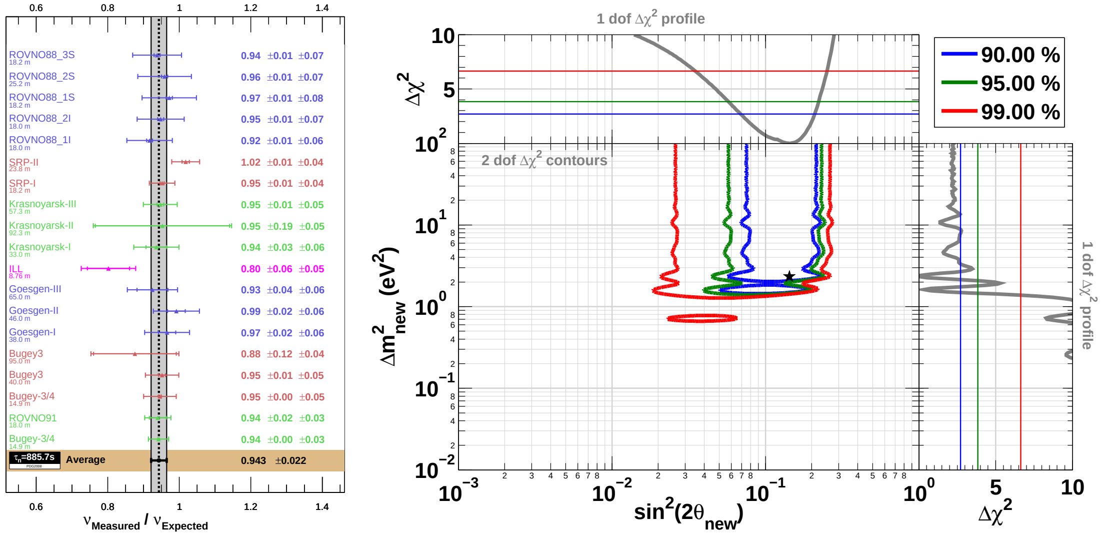

Figure 1: Left: weighted average (with correlations) of 19 measurements of reactor neutrino experiments operating at short baselines. A summary of experiment details is given in Table 1. Right: Allowed regions in the $\sin^2(2\theta_{\rm new}) - \Delta m^2_{\rm new}$ plane from the combination of reactor 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.

with ^{51}Cr and ^{37}Ar radioactive sources emitting ~ 1 MeV electron neutrinos.,[16] following the methodology developed in Ref.[15,17] However we decided to include possible correlations between these four measurements in this present work. Details are given in.[2] This has the effect of being slightly more conservative, with the no-oscillation hypothesis disfavored at 97.7% C.L., instead of 98% C.L. in Ref.[15] Gallex and Sage observed an average deficit of $R_G = 0.86 \pm 0.06\,(1\sigma)$.

We also reanalyzed the MiniBooNE electron neutrino excess assuming the very short baseline neutrino oscillation explanation of Ref.[15] Details of our reproduction of the latter 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 neutrino, corresponding in the flavor basis to a sterile neutrino ν_s (see[3] and references therein) with a large $\Delta m^2_{\rm new}$ value. For simplicity we restrict our analysis to the 3+1 four-neutrino scheme in which there is a group of three active neutrino masses separated from an isolated neutrino mass, such that $|\Delta m^2_{\rm new}| \gg 10^{-2}$ eV^2. The latter would be responsible for very short baseline reactor neutrino oscillations. For energies above the inverse beta decay threshold and baselines below 100 m, we adopt the approximated oscillation formula:

$$P_{ee} = 1 - \sin^2(2\theta_{\rm new}) \sin^2\left(\frac{\Delta m^2_{\rm new} L}{4 E_{\bar{\nu}_e}}\right) \tag{3}$$

where active neutrino oscillation effects are negligible at these short baselines.

The ILL experiment may have seen a hint of oscillation in their measured positron energy spectrum ,[4,13] but Bugey-3's results do not point to any significant spectral distortion more than 15 m away from the antineutrino source. 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 $\frac{1}{2}\sin^2(2\theta_{\rm new,R})$, thus leading to $\Delta m^2_{\rm new,R} \gtrsim 1$ eV^2 and accounting for Bugey-3 and Goesgen shape analyses.[5,6] Considering the weighted averaged of all reactor experiments we get an estimate of the mixing angle, $\sin^2(2\theta_{\rm new,R}) \sim 0.115$. 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. Including the finite spatial extension of the nuclear reactors and the ILL and Bugey-3 detectors, we found that the small dimensions of the ILL nuclear core lead to small corrections of the oscillation pattern imprinted on the positron spectrum. However the large extension of the Bugey nuclear core is sufficient to wash out most of the oscillation pattern at 15 m. This explains the absence of shape distortion in the Bugey-3 experiment.

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 $\sin^2(2\theta_{\rm new}) - \Delta m^2_{\rm new}$ plane are displayed in Fig. 1, together with the marginal $\Delta\chi^2$ profiles for $|\Delta m^2_{\rm new}|$ and $\sin^2(2\theta_{\rm new})$. The combined fit leads to the following constraints on oscillation parameters: $|\Delta m^2_{\rm new}| > 1.5$ eV^2 (95% C.L.) and $\sin^2(2\theta_{\rm new}) = 0.14 \pm 0.08$ (95% C.L.).

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