Precise Determination of the $^{235}$U Reactor Antineutrino Cross Section per Fission

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Abstract. We consider the possibility that the reactor antineutrino anomaly is due to a miscalculation of one or more of the $^{235}$U, $^{238}$U, $^{239}$Pu, and $^{241}$Pu reactor antineutrino fluxes. From the fit of the data we obtain the precise determination $\sigma_{f,235} = (6.33 \pm 0.08) \times 10^{-43}$ cm$^2$/fission of the $^{235}$U cross section per fission, which is more precise than the calculated value and differs from it by 2.2σ. The cross sections per fission of the other fluxes have large uncertainties and in practice their values are undetermined by the fit. We conclude that it is very likely that at least the calculation of the $^{235}$U flux must be revised.

The reactor antineutrino anomaly [1] is due to the 2011 recalculation [2, 3] of the reactor antineutrino flux, which is about 3% higher than the previous estimate [4, 5] and implies a deficit of the rate of $\bar{\nu}_e$ observed in several reactor neutrino experiments.

It is possible that the reactor antineutrino anomaly is due to the oscillations of the reactor $\bar{\nu}_e$'s into sterile neutrinos with a mass at the eV scale (see the review in Ref. [6]). However, it is also possible that the reactor antineutrino anomaly is due to a flaw in the calculation of one or more of the $^{235}$U, $^{238}$U, $^{239}$Pu, and $^{241}$Pu fluxes that compose the reactor antineutrino flux. In this paper we consider this second possibility and we investigate which of the four fluxes could be the cause of the reactor antineutrino anomaly [7].

The prime suspect as a cause for the reactor antineutrino anomaly is the $^{235}$U antineutrino flux, because some of the experiments which observed a deficit of electron antineutrinos used research reactors, which produce an almost pure $^{235}$U antineutrino flux. However, since other experiments used commercial reactors with significant contributions of the $^{238}$U, $^{239}$Pu, and $^{241}$Pu electron antineutrino fluxes, a detailed calculation is necessary in order to reach a definite and quantitative conclusion.

The theoretical prediction for the event rate of an experiment labeled with the index $a$ is usually expressed by the cross section per fission $\sigma_{f,a} = \sum_k f_k^a \sigma_{f,k}$, with $k = 235, 238, 239, 241$. Here $f_k^a$ is the antineutrino flux fraction from the fission of the isotope with atomic mass $k$ and $\sigma_{f,k}$ is the corresponding cross section per fission, which is given by the integrated product of the antineutrino flux and the detection cross section.

The cross sections per fission of the four fissile isotopes calculated by the Saclay group in Ref. [1] are listed in Table 1. These values must be increased by 1.2%, 1.4%, and 1.0% for $^{235}$U, $^{239}$Pu, and $^{241}$Pu, respectively, according to the improved inversion of the ILL electron spectra of Huber [3]. The resulting values listed in Table 1 coincide with those given in Table XX of Ref. [8].

The experiments which measured the absolute antineutrino flux are listed in Table 2. For each
Table 1. Cross sections per fission of the four fissile isotopes calculated by the Saclay (S) group in Ref. [1] and those obtained from the Huber (SH) correction in Ref. [3]. The units are $10^{-43} \text{cm}^2/\text{fission}$. The uncertainties are those estimated by the Saclay group in Ref. [1].

| Isotope  | Saclay (S) | Saclay+Huber (SH) | Uncertainty |
|----------|------------|-------------------|-------------|
| $\sigma_{f,235}$ | 6.61       | 6.69              | 2.11%       |
| $\sigma_{f,238}$ | 10.10      | 10.10             | 8.15%       |
| $\sigma_{f,239}$ | 4.34       | 4.40              | 2.45%       |
| $\sigma_{f,241}$ | 5.97       | 6.03              | 2.15%       |

For the short-baseline experiments (Bugey-4 [9], Rovno91 [10], Bugey-3 [11], Gosgen [12], ILL [13,14], Krasnoyarsk87 [15], Krasnoyarsk94 [16,17], Rovno88 [18], SRP [19]), we calculated the Saclay+Huber ratios $R_{a,SH}^{exp}$ by rescaling the corresponding Saclay value $R_{a,S}^{exp}$ in Ref. [1]:

$$R_{a,SH}^{exp} = R_{a,S}^{exp} \sum_k f_k^a \sigma_{f,k}^S / \sum_k f_k^a \sigma_{f,k}^{SH} \quad (a = 1, \ldots, 17, 19, 20).$$

We considered the Krasnoyarsk99-34 experiment [20] that was not considered in Refs. [1,21], by rescaling the value of the corresponding experimental cross section per fission in comparison with the Krasnoyarsk94-57 result. For the long-baseline experiments Chooz [22] and Palo Verde [23], we applied the rescaling with the ratios $R_{a,S}^{exp}$ given in Ref. [21], divided by the corresponding survival probability $P_{sur}$ caused by $\vartheta_{13}$. For Nucifer [24] Daya Bay [25], RENO [26, 27], and Double Chooz [28] we use the ratios provided by the respective experimental collaborations.

The experimental uncertainties and their correlations listed in Table 2 have been obtained from the corresponding experimental papers. In particular:

- The Bugey-4 and Rovno91 experiments have a correlated 1.4% uncertainty, because they used the same detector [9].
- The Rovno88 experiments have a correlated 2.2% reactor-related uncertainty [18]. In addition, each of the each of the two groups of integral (Rovno88-11 and Rovno88-21) and spectral (Rovno88-1S, Rovno88-2S, and Rovno88-3S) measurements have a correlated 3.1% detector-related uncertainty [18].
- The Bugey-3 experiments have a correlated 4.0% uncertainty obtained from Tab. 9 of [9].
- The Gosgen and ILL experiments have a correlated 3.8% uncertainty, because they used the same detector [12]. In addition, the Gosgen experiments have a correlated 2.0% reactor-related uncertainty [12].
- The 1987 Krasnoyarsk87-33 and Krasnoyarsk87-92 experiments have a correlated 4.1% uncertainty, because they used the same detector at 32.8 and 92.3 m from two reactors [15]. The Krasnoyarsk94-57 experiment was performed in 1990-94 with a different detector at 57.0 and 57.6 m from the same two reactors [16]. The Krasnoyarsk99-34 experiment was performed in 1997-99 with a new integral-type detector at 34 m from the same reactor of the Krasnoyarsk87-33 experiment [29]. There may be reactor-related uncertainties correlated among the four Krasnoyarsk experiments, but, taking into account the time separations and the absence of any information, we conservatively neglected them.
Table 2. List of the experiments which measured the absolute reactor antineutrino flux. For each experiment numbered with the index $a$, the index $k = 235, 238, 239, 241$ indicate the four isotopes $^{235}$U, $^{238}$U, $^{239}$Pu, and $^{241}$Pu, $f_a^k$ are the fission fractions, $R_{a,SH}^{exp}$ is the ratio of measured and predicted rates, $\sigma_{a,exp}^\%$ is the corresponding relative experimental uncertainty, $\sigma_{a,cor}^\%$ is the relative systematic uncertainty which is correlated in each group of experiments indicated by the braces, and $L_a$ is the source-detector distance.

| $a$ | Experiment       | $f_{235}^a$ | $f_{238}^a$ | $f_{239}^a$ | $f_{241}^a$ | $R_{a,SH}^{exp}$ | $\sigma_{a,exp}^\%$ | $\sigma_{a,cor}^\%$ | $L_a$ [m] |
|-----|------------------|------------|------------|------------|------------|------------------|-------------------|-------------------|----------|
| 1   | Bugey-4          | 0.538      | 0.078      | 0.328      | 0.056      | 0.932            | 1.4               | 1.4               | 15       |
| 2   | Rovno91          | 0.606      | 0.074      | 0.277      | 0.043      | 0.930            | 2.8               | 1.4               | 18       |
| 3   | Rovno88-11       | 0.607      | 0.074      | 0.277      | 0.042      | 0.907            | 6.4               | 3.1               | 18       |
| 4   | Rovno88-21       | 0.603      | 0.076      | 0.276      | 0.045      | 0.938            | 6.4               | 2.2               | 18       |
| 5   | Rovno88-1S       | 0.606      | 0.074      | 0.277      | 0.043      | 0.962            | 7.3               | 3.1               | 25       |
| 6   | Rovno88-2S       | 0.557      | 0.076      | 0.313      | 0.054      | 0.949            | 7.3               | 3.1               | 18       |
| 7   | Rovno88-2S       | 0.606      | 0.074      | 0.274      | 0.046      | 0.928            | 6.8               | 3.1               | 18       |
| 8   | Bugey-3-15       | 0.538      | 0.078      | 0.328      | 0.056      | 0.936            | 4.2               | 4.0               | 15       |
| 9   | Bugey-3-40       | 0.538      | 0.078      | 0.328      | 0.056      | 0.942            | 4.3               | 4.0               | 15       |
| 10  | Bugey-3-95       | 0.538      | 0.078      | 0.328      | 0.056      | 0.867            | 15.2              | 4.0               | 95       |
| 11  | Gosgen-38        | 0.619      | 0.067      | 0.272      | 0.042      | 0.955            | 5.4               | 4.0               | 37.9     |
| 12  | Gosgen-46        | 0.584      | 0.068      | 0.298      | 0.050      | 0.981            | 5.4               | 3.8               | 45.9     |
| 13  | Gosgen-65        | 0.543      | 0.070      | 0.329      | 0.058      | 0.915            | 6.7               | 3.8               | 64.7     |
| 14  | ILL              | 1          | 0          | 0          | 0          | 0.792            | 9.1               | 3.8               | 8.76     |
| 15  | Krasnoyarsk87-33 | 1          | 0          | 0          | 0          | 0.925            | 5.0               | 4.1               | 32.8     |
| 16  | Krasnoyarsk87-92 | 1          | 0          | 0          | 0          | 0.942            | 20.4              | 4.1               | 92.3     |
| 17  | Krasnoyarsk94-57 | 1          | 0          | 0          | 0          | 0.936            | 4.2               | 2.0               | 57       |
| 18  | Krasnoyarsk99-34 | 1          | 0          | 0          | 0          | 0.946            | 3.0               | 2.0               | 34       |
| 19  | SRP-18           | 1          | 0          | 0          | 0          | 0.941            | 2.8               | 2.0               | 18.2     |
| 20  | SRP-24           | 1          | 0          | 0          | 0          | 1.006            | 2.9               | 2.0               | 23.8     |
| 21  | Nucler           | 0.926      | 0.061      | 0.008      | 0.005      | 1.014            | 10.7              | 7.2               | 0        |
| 22  | Chooz            | 0.496      | 0.076      | 0.031      | 0.066      | 0.996            | 3.2               | 0.0               | ≈ 1000   |
| 23  | Palo Verde       | 0.600      | 0.070      | 0.270      | 0.060      | 0.997            | 5.4               | 0.0               | ≈ 800    |
| 24  | Daya Bay         | 0.561      | 0.076      | 0.307      | 0.056      | 0.946            | 2.0               | 0.0               | ≈ 550    |
| 25  | RENO             | 0.569      | 0.073      | 0.301      | 0.056      | 0.946            | 2.1               | 0.0               | ≈ 410    |
| 26  | Double Chooz     | 0.511      | 0.087      | 0.340      | 0.062      | 0.935            | 1.4               | 0.0               | ≈ 415    |

- Following Ref. [21], we considered the two SRP measurements as uncorrelated, because the two measurements would be incompatible with the correlated uncertainty estimated in Ref. [19].

In order to investigate which of the fluxes of the fissile isotopes is responsible for the anomaly, we consider the theoretical ratios

$$R_{th}^a = \frac{\sum_k f_k^a r_k \sigma_{f,k}^{SH}}{\sum_k f_k^a \sigma_{f,k}^{SH}},$$

(2)

where the coefficient $r_k$ is the needed correction for the flux of the $k$ fissile isotope. We derive the values of the coefficients $r_k$ by fitting the experimental ratios $R_{a,SH}^{exp}$ with the least-squares function

$$\chi^2 = \sum_{a,b} \left( R_{th}^a - R_{a,SH}^{exp} \right) (V^{-1})_{ab} \left( R_{th}^b - R_{b,SH}^{exp} \right),$$

(3)
Figure 1. Marginal $\Delta \chi^2 = \chi^2 - \chi^2_{\text{min}}$ for the coefficients $r_k$ of the four antineutrino fluxes obtained from the fit of the reactor antineutrino data in Table 2 with the least-squares function in Eq. (3) (a) and that in Eq. (5) (b).

where $V$ is the covariance matrix constructed with the uncertainties in Table 2.

The fit of the data in Table 2 gives $\chi^2_{\text{min}} = 16.5$ with 22 degrees of freedom, which correspond to an excellent 78% goodness of fit. On the other hand, the null hypothesis (all $r_k = 1$) has $\chi^2 = 97.8$ with 26 degrees of freedom, which corresponds to a disastrous goodness of fit.

Figure 1(a) shows the marginal $\Delta \chi^2 = \chi^2 - \chi^2_{\text{min}}$ for the coefficients $r_k$ of the four antineutrino fluxes obtained from the fit. One can see that the values of $r_{238}$, $r_{239}$, and $r_{241}$ are not sharply constrained: they are compatible with unity, but significantly different values are allowed. On the other hand, $r_{235}$ is sharply determined by the data:

$$r_{235} = 0.950 \pm 0.014 \Rightarrow \sigma_{\text{f,235}} = r_{235}\sigma_{\text{f,235}}^{\text{SH}} = (6.35 \pm 0.09) \times 10^{-43} \text{ cm}^2/\text{fission.} \quad (4)$$

This value of the $^{235}$U cross section per fission must be compared with the calculated value in Table 1: $\sigma_{\text{f,235}}^{\text{SH}} = (6.69 \pm 0.14) \times 10^{-43} \text{ cm}^2/\text{fission}$. The value of $\sigma_{\text{f,235}}$ obtained from the fit has an uncertainty that is smaller than the uncertainty of $\sigma_{\text{f,235}}^{\text{SH}}$. Adding the two uncertainties quadratically, there is a discrepancy of 2.0$\sigma$ between the two values.

However, one can question the reliability of the calculation above by noting that the large deviations from unity of the best-fit values $r_{239}^{\text{bf}} = 0.118$ and $r_{241}^{\text{bf}} = 3.490$, are excessive for a physical explanation. In order to restrict the values of $r_{238}$, $r_{239}$, and $r_{241}$ to reasonable intervals around unity, we use the least-squares function

$$\tilde{\chi}^2 = \chi^2 + \sum_k \left( \frac{1 - r_k}{\Delta r_k} \right)^2. \quad (5)$$

Taking into account the 5% uncertainty of the reactor neutrino flux recently advocated in Refs. [30–32], we consider $\Delta r_{235} = \Delta r_{239} = \Delta r_{241} = 0.05$, and we slightly increase the large uncertainty of $r_{238}$ in Table 1 by considering $\Delta r_{238} = 0.1$. The results of the fit are shown in
Fig. 1(b). One can see that the values of all the ratios are now in a reasonable range around unity:

\[ r_{235} = 0.946 \pm 0.012, \quad r_{238} = 0.908 \pm 0.077, \quad r_{239} = 0.956 \pm 0.041, \quad r_{241} = 0.990 \pm 0.049. \]  

The values of \( r_{238}, r_{239}, \) and \( r_{241} \) have still large uncertainties and they are compatible with unity. For \( r_{235} \) we obtain a result similar to that in Eq. (4), but more reliable, because of the more reasonable values of \( r_{238}, r_{239}, \) and \( r_{241} \). In this case, for \( \sigma_{f,235} \) we obtain

\[ \sigma_{f,235} = (6.33 \pm 0.08) \times 10^{-43} \text{ cm}^2/\text{fission}. \]  

There is now a discrepancy of 2.2σ with the calculated value \( \sigma_{f,235}^{SH} \) in Table 1.

In conclusion, we obtained the reliable precise determination in Eq. (7) of the \( ^{235}\text{U} \) cross section per fission which is more precise than the calculated value and differs from it by 2.2σ. Hence, if the reactor neutrino anomaly is due to a miscalculation of the antineutrino fluxes, it is very likely that at least the calculation of the \( ^{235}\text{U} \) flux must be revised.

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