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Improved determination of the ^{235}U and ^{239}Pu reactor antineutrino cross sections per fission

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We present the results of a combined fit of the reactor antineutrino rates and the Daya Bay measurement of $\sigma_{f,235}$ and $\sigma_{f,239}$. The combined fit leads to a better determination of the two cross sections per fission: $\sigma_{f,235} = 6.29 \pm 0.08$ and $\sigma_{f,239} = 4.24 \pm 0.21$ in units of 10^{-43} cm^2/fission, with respective uncertainties of about 1.2% and 4.9%. Since the respective deviations from the theoretical cross sections per fission are 2.5σ and 0.7σ, we conclude that, if the reactor antineutrino anomaly is not due to active-sterile neutrino oscillations, it is likely that it can be solved with a revaluation of the ^{235}U reactor antineutrino flux. However, the ^{238}U, ^{239}Pu, and ^{241}Pu fluxes, which have larger uncertainties, could also be significantly different from the theoretical predictions.

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The flux of electron antineutrinos produced in nuclear reactors is generated by the β decays of the fission products of ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu. The 2011 recalculation [1,2] of the four fluxes led to the discovery of the reactor antineutrino anomaly [3], which is a deficit of the rate of electron antineutrinos measured in several reactor neutrino experiments. There are two known possible explanations of the reactor antineutrino anomaly: (1) a miscalculation of one or more of the four electron antineutrino fluxes [4,5] and (2) active-sterile neutrino oscillations (see Ref. [6] and references therein). In this paper, we consider the first possibility and we present an improvement of the results presented in Refs. [4,5] on the determination of the cross sections per fission $\sigma_{f,235}$ and $\sigma_{f,239}$, which are, respectively, the integrals of the products of the ^{235}U and ^{239}Pu electron antineutrino fluxes and the detection cross section [see Eq. (8) of Ref. [3]].

The cross section per fission $\sigma_{f,235}$ of the ^{235}U electron antineutrino flux was determined in Ref. [4] with a fit of the reactor rates by taking into account the different fuel compositions. Recently the Daya Bay Collaboration presented a determination of $\sigma_{f,235}$ and $\sigma_{f,239}$ obtained by measuring the correlations between the reactor core fuel evolution and the changes in the reactor antineutrino flux and energy spectrum [5]. In this paper we present a combined fit of the reactor rates and the Daya Bay measurement of $\sigma_{f,235}$ and $\sigma_{f,239}$ which leads to a better determination of both cross sections per fission.

In the analysis of the reactor rates, we consider the theoretical ratios [4]

$$R_a^{\text{th}} = \frac{\sum_k f_k^a r_k \sigma_{f,k}^{\text{SH}}}{\sum_k f_k^a \sigma_{f,k}^{\text{SH}}}, \tag{1}$$

where f_k^a is the antineutrino flux fraction from the fission of the isotope with atomic mass k and the coefficient r_k is the corresponding correction of the theoretical cross section per fission $\sigma_{f,k}^{\text{SH}}$ which is needed to fit the data ($k = 235$, 238, 239, 241, denotes, respectively, the ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu electron antineutrino fluxes). The theoretical cross sections per fission $\sigma_{f,k}^{\text{SH}}$ are the Saclay + Huber (SH) [2,3] cross sections per fission listed in Table 1 of Ref. [4]. The index a labels the reactor neutrino experiments listed in Table 1 of Ref. [6]: Bugey-4 [7], Rovno91 [8], Bugey-3 [9], Gosgen [10], ILL [11,12], Krasnoyarsk87 [13], Krasnoyarsk94 [14,15], Rovno88 [16], SRP [17], Nucifer [18], Chooz [19], Palo Verde [20], Daya Bay [21], RENO [22], and Double Chooz [23].

We analyze the data of the reactor rates with the least-squares statistic

$$\chi^2_{\text{R}} = \sum_{a,b} (R_a^{\text{th}} - R_a^{\text{exp}})(V_{\text{R}}^{-1})_{ab}(R_b^{\text{th}} - R_b^{\text{exp}}) + \sum_{k=238,241} \left(\frac{1-r_k}{\Delta r_k}\right)^2, \tag{2}$$

where R_a^{exp} are the measured reactor rates listed in Table 1 of Ref. [6] and V_{R} is the covariance matrix constructed with the corresponding uncertainties. The second term in Eq. (2) serves to keep under control the variation of the rates of the minor fissionable isotopes ^{238}U and ^{241}Pu, which are not well determined by the fit [4]. We consider $\Delta r_{238} = 15\%$ and $\Delta r_{241} = 10\%$, which are significantly larger than the nominal theoretical uncertainties (respectively, 8.15% and 2.15% [2,3]) and the 5% estimate in Ref. [24].

The fit of the data gives $(\chi^2_{\text{R}})_{\text{min}} = 17.7$ with 22 degrees of freedom, which correspond to an excellent 72% goodness of fit. Figure 1 shows the marginal $\Delta\chi^2_{\text{R}} = \chi^2_{\text{R}} - (\chi^2_{\text{R}})_{\text{min}}$ for the coefficients r_k of the four antineutrino fluxes, for which we obtain

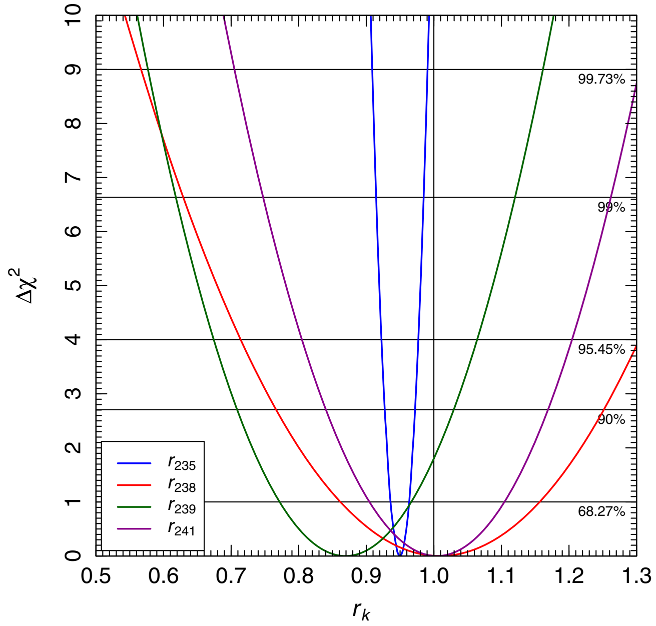

FIG. 1. Marginal $\Delta\chi^2_{\rm R} = \chi^2_{\rm R} - (\chi^2_{\rm R})_{\rm min}$ for the coefficients r_k of the four antineutrino fluxes obtained from the fit of the reactor rates.

$$r_{235} = 0.950 \pm 0.014, \tag{3}$$

$$r_{238} = 1.009 \pm 0.147, \tag{4}$$

$$r_{239} = 0.869 \pm 0.097, \tag{5}$$

$$r_{241} = 1.005 \pm 0.100. \tag{6}$$

These values and Fig. 1 are different from the corresponding ones in Ref. [4], because of the different second term in Eq. (2) with respect to that in Eq. (8) of Ref. [4], which constrained all the r_k's. The best-fit values and uncertainties of $\sigma_{f,235}$ and $\sigma_{f,239}$ are given in the second column of Table I. The value of $\sigma_{f,235}$ is determined by the fit with a precision of about 1.4% and differs from the theoretical value $\sigma^{\rm SH}_{f,235}$ by 2.0σ. This confirms the necessity of a revaluation of the theoretical value of $\sigma_{f,235}$ found in Ref. [4]. The value of $\sigma_{f,239}$ is also determined by the fit, but with the worse precision of about 11.2%, which renders it compatible with the theoretical value $\sigma^{\rm SH}_{f,239}$ within 1.3σ.

TABLE I. Comparison of the theoretical Saclay + Huber (SH) values of the cross sections per fission $\sigma_{f,235}$ and $\sigma_{f,239}$ with those obtained from the fit of the reactor rates, from the Daya Bay data [5], and from the combined fit. The units are 10^{-43} cm^2/fission.

	SH	Reactor Rates	Daya Bay	Combined
$\sigma_{f,235}$	6.69 ± 0.14	6.35 ± 0.09	6.17 ± 0.17	6.29 ± 0.08
$\sigma_{f,239}$	4.40 ± 0.11	3.82 ± 0.43	4.27 ± 0.26	4.24 ± 0.21

In order to take into account the Daya Bay measurement of $\sigma_{f,235}$ and $\sigma_{f,239}$ [5], we consider the least-squares statistic

$$\chi^2_{\rm tot} = \tilde{\chi}^2_{\rm R} + \sum_{k,j=235,239} (\sigma^{\rm th}_{f,k} - \sigma^{\rm DB}_{f,k})(V^{-1}_{\rm DB})_{kj}(\sigma^{\rm th}_{f,j} - \sigma^{\rm DB}_{f,j}), \tag{7}$$

where $\tilde{\chi}^2_{\rm R}$ is given by Eq. (2) without considering the Daya Bay rate [21], in order to avoid considering the Daya Bay data twice. The cross sections per fission $\sigma^{\rm DB}_{f,235}$ and $\sigma^{\rm DB}_{f,239}$ are those measured in Daya Bay [5] and listed in the third column of Table I. We obtained the Daya Bay covariance matrix $V_{\rm DB}$ with a Gaussian approximation of the χ^2 distribution in Fig. 3 of Ref. [5]. The theoretical cross sections per fission $\sigma^{\rm th}_{f,k}$ are given by

$$\sigma^{\rm th}_{f,k} = r_k \sigma^{\rm SH}_{f,k}, \tag{8}$$

with the same coefficients r_k that are present in the definition of $R^{\rm th}_a$ in Eq. (1).

The minimization of $\chi^2_{\rm tot}$ gives $(\chi^2_{\rm tot})_{\rm min} = 19.5$ with 23 degrees of freedom, which correspond to a 67% goodness of fit, which is practically as good as that obtained in the analysis of the reactor rates with $\chi^2_{\rm R}$ in Eq. (2). Figure 2 shows the marginal $\Delta\chi^2_{\rm tot} = \chi^2_{\rm tot} - (\chi^2_{\rm tot})_{\rm min}$ for the coefficients r_k of the four antineutrino fluxes, for which we obtain

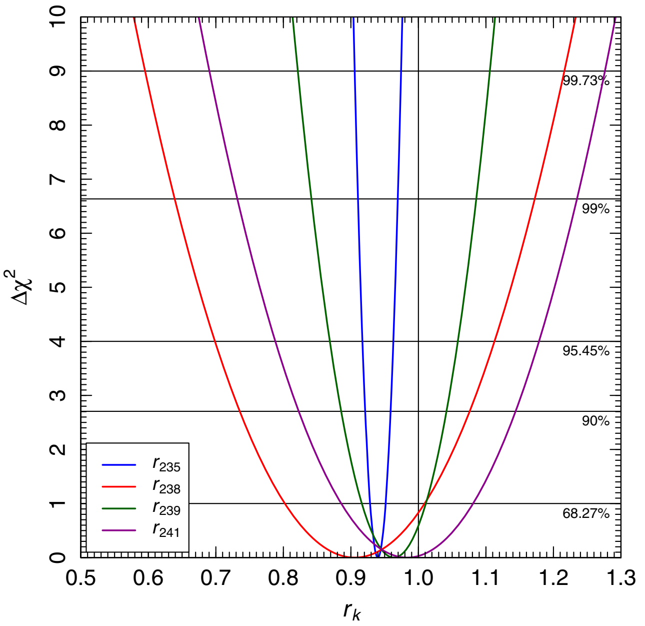

FIG. 2. Marginal $\Delta\chi^2_{\rm tot} = \chi^2_{\rm tot} - (\chi^2_{\rm tot})_{\rm min}$ for the coefficients r_k of the four antineutrino fluxes obtained from the fit of the reactor rates and the Daya Bay measurement of $\sigma_{f,235}$ and $\sigma_{f,239}$ [5].

$$r_{235} = 0.940 \pm 0.011, \tag{9}$$

$$r_{238} = 0.906 \pm 0.103, \tag{10}$$

$$r_{239} = 0.964 \pm 0.047, \tag{11}$$

$$r_{241} = 0.983 \pm 0.097. \tag{12}$$

The corresponding best-fit values and uncertainties of $\sigma_{f,235}$ and $\sigma_{f,239}$ are given in the fourth column of Table I. The value of $\sigma_{f,235}$ is determined by the fit with a precision which is slightly better than that obtained from the fit of the reactor rates, and significantly better than the precision of the Daya Bay measurement [5]. The combined fit results in a substantial improvement of the precision of the determination of $\sigma_{f,239}$ with respect to the fit of the reactor rates alone: the value of $\sigma_{f,239}$ is determined with a precision of about 4.9%, which is also better than that of the Daya Bay measurement [5]. Since the deviation from the theoretical value $\sigma^{\mathrm{SH}}_{f,239}$ is only of 0.7σ, there is no compelling necessity of a revaluation of its theoretical value.

Figure 3 shows the correlation between the determinations of $\sigma_{f,235}$ and $\sigma_{f,239}$. The values of $\sigma_{f,235}$ and $\sigma_{f,239}$ obtained from the fit of the reactor rates are slightly anticorrelated, whereas the Daya Bay values are significantly correlated and have a larger uncertainty for $\sigma_{f,235}$ and smaller uncertainty for $\sigma_{f,239}$. The combined fit results in an allowed region with practically uncorrelated values of $\sigma_{f,235}$ and $\sigma_{f,239}$ and significantly smaller uncertainties.

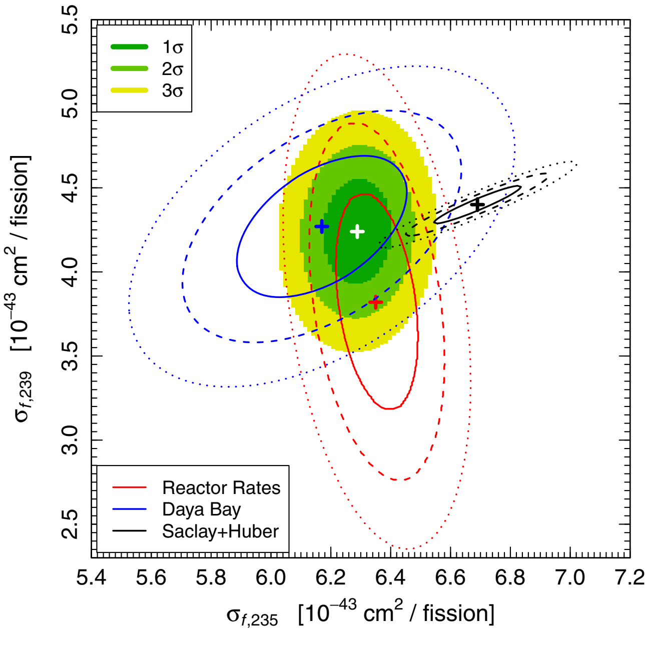

FIG. 3. Allowed regions in the $\sigma_{f,235} - \sigma_{f,239}$ plane obtained from the combined fit of the reactor rates and the Daya Bay measurement of $\sigma_{f,235}$ and $\sigma_{f,239}$ [5]. The red, blue, and black curves enclose, respectively, the allowed regions obtained from the fit of the reactor rates, the allowed regions corresponding to the Daya Bay measurement of $\sigma_{f,235}$ and $\sigma_{f,239}$ [5], and the theoretical Saclay + Huber allowed regions at 1σ (solid), 2σ (dashed), and 3σ (dotted). The best-fit points are indicated by crosses.

The 2.5σ deviation of $\sigma_{f,235}$ from the theoretical Saclay + Huber [2,3] cross sections per fission confirms the indications obtained in Refs. [4,5] that the reactor antineutrino anomaly is most probably mainly due to the ^{235}U electron antineutrino flux (if is not due to active-sterile neutrino oscillations). This possibility may be connected with a ^{235}U origin of the 5 MeV bump of the reactor antineutrino spectrum measured in the RENO [25,26], Double Chooz [27], Daya Bay [21], and NEOS [28] experiments, as indicated by the analysis in Ref. [29] and by the hint of a correlation in the RENO experiment [22]. The new reactor experiments PROSPECT [30], SoLid [31], and STEREO [32] which are in preparation for the search of short-baseline neutrino oscillations with highly enriched ^{235}U research reactors, will improve the determination of the ^{235}U electron antineutrino flux.

Since the ^{238}U and ^{241}Pu fuel composition in power reactors is small (see Table 1 of Ref. [6]), the antineutrino data do not give precise information on the corresponding cross sections per fission. From Fig. 2 one can see that $r_{238} = 0.906 \pm 0.103$ and $r_{241} = 0.983 \pm 0.097$. Hence, there is an indication that $\sigma_{f,238}$ may be substantially smaller than the theoretical $\sigma^{\mathrm{SH}}_{f,238}$ value, but the discrepancy is less than 1σ. On the other hand, the fit favors a value of $\sigma_{f,241}$ close to the theoretical $\sigma^{\mathrm{SH}}_{f,241}$ value, but the uncertainty is large.

The calculations of the ^{235}U, ^{239}Pu, and ^{241}Pu antineutrino fluxes were performed through the inversion of the corresponding electron spectra measured at ILL in the 80's [33,34]. A possible explanation of the discrepancy between the calculated and measured values of $\sigma_{f,235}$ alone could be some unknown systematic error in the measurement of the ^{235}U electron spectrum which was not present in the measurements of the ^{239}Pu and ^{241}Pu electron spectra. It is clear that it would be very important to check these measurements with new experiments.

In conclusion, we performed a combined fit of the reactor antineutrino rates [4] and the recent Daya Bay measurement of $\sigma_{f,235}$ and $\sigma_{f,239}$ [5]. The combined fit leads to the better determination of $\sigma_{f,235}$ and $\sigma_{f,239}$ in Table I, with respective uncertainties of about 1.2% and 4.9%. The respective deviations from the theoretical Saclay + Huber [2,3] cross sections per fission are 2.5σ and 0.7σ. Therefore, we confirm the conclusion already reached in Refs. [4,5] that the ^{235}U reactor antineutrino flux is the most probable main contributor to the reactor antineutrino anomaly [3] if the anomaly is not due to active-sterile neutrino oscillations. However, also the ^{239}Pu flux, which is constrained by the cross section per fission in Table I, and the ^{238}U and ^{241}Pu fluxes, for which the data do not provide stringent constraints, could be significantly different from the theoretical predictions. Let us finally emphasize that the knowledge of the reactor antineutrino fluxes is useful not only for applications in fundamental physics research, but also for practical applications as antineutrino monitoring of reactors (see Refs. [35–37]).

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