

Reactor antineutrino anomaly in light of recent flux model refinements

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We study the status of the reactor antineutrino anomaly in light of recent reactor flux models obtained with the conversion and summation methods. We present a new improved calculation of the inverse beta decay yields of the standard Huber-Mueller model and those of the new models. We show that the reactor rates and the fuel evolution data are consistent with the predictions of the Kurchatov Institute conversion model and with those of the Estienne-Fallot summation model, leading to a plausible robust demise of the reactor antineutrino anomaly. We show that the results of several goodness of fit tests favor the Kurchatov Institute and Estienne-Fallot models over other models that we considered. The data-driven isotopic inverse beta decay yields can also be obtained from global fits of the experimental rate and evolution data, which provide an anomaly-free model for the prediction of future experiments.

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1. Introduction

Reactor antineutrinos have been widely used to study the fundamental properties of neutrinos, which are mainly from beta decays of neutron-rich fission fragments generated by the heavy fissionable isotopes ^{235}U , ^{238}U , ^{239}Pu , and ^{241}Pu . In 2011 improved calculations by Mueller *et al.* [1] and Huber [2] (HM model) predicted reactor antineutrino fluxes which are about 5% larger than the fluxes measured in several short-baseline reactor neutrino experiments. This discrepancy is known as the “reactor antineutrino anomaly” (RAA) [3].

There are two basic methods to predict reactor antineutrino fluxes: the summation method and the conversion method [4]. The summation method is based on fission and decay information provided by the nuclear databases. The conversion method utilizes virtual branches to convert measured β spectra to corresponding antineutrino spectra. The converted ^{235}U , ^{239}Pu , and ^{241}Pu antineutrino spectra are based on the measurement at the Institut Laue-Langevin (ILL) in the 1980’s [5]. The converted ^{238}U antineutrino spectrum can be obtained based on the measured β spectrum at FRM II in Garching in 2013 [6]. In addition to the HM model, we consider other three conversion models: HKSS [7], KI [8] and HKSS-KI models, and one summation model: EF [9] model.

Our updated calculation of inverse beta decay (IBD) yields in all models is presented in Section 2, and then the methods of analysis are introduced as well. Our results of the fits of reactor rates and evolution data are also shown in Section 3. In Section 4, we discuss which the best-fit model is. Furthermore, model independent fluxes are demonstrated in Section 5. At last, we will summarize our conclusions.

2. Model predictions and method of analysis

The event rates are usually expressed as a physical quantity called “cross section per fission” $\sigma_{f,a}$ also known as “inverse beta decay yield”:

$$\sigma_{f,a} = \sum_i f_i^a \sigma_i, \quad \text{with} \quad \sigma_i = \int_{E_{\nu}^{\text{thr}}}^{E_{\nu}^{\text{max}}} dE_{\nu} \Phi_i(E_{\nu}) \sigma_{\text{IBD}}(E_{\nu}) \quad (1)$$

where a is the experiment label, σ_i is the IBD yield for the fissionable isotope i , and f_i^a is the effective fission fraction of the isotope i . $\Phi_i(E_{\nu})$ is the neutrino flux generated by the fissionable isotope i , and $\sigma_{\text{IBD}}(E_{\nu})$ is the IBD cross section considered as the Strumia and Vissani cross section [10] including radiative corrections with PDG2020 [11] here. The neutrino energy is integrated from $E_{\nu}^{\text{thr}} = 1.806 \text{ MeV}$ to $E_{\nu}^{\text{max}} = 10 \text{ MeV}$ using the EF model high-energy spectra with 100% uncertainties. The off-equilibrium corrections are also taken into account, which is based on Table VII of Ref. [1] assuming the 450 days approximation of the spectrum at equilibrium. Our updated results of IBD yields for these five models are shown in Table III in Ref. [12].

A χ^2 function based on Wilks’ theorem is usually applied to analyze the reactor antineutrino data. There are three main approaches when choosing different methods to deal with systematic theoretical uncertainties: **(A)** consider a covariance matrix with experimental and theoretical uncertainties added in quadrature [3]; **(B)** calculate the fit results considering only the experimental

uncertainties and add by hand a global theoretical uncertainty [13]; (C) take into account the theoretical uncertainties with appropriate pull terms [14], which is chosen in this work:

$$\chi^2 = \sum_{a,b} \left(\sigma_{f,a}^{\text{exp}} - R_{\text{NP}}^a \sigma_{f,a}^{\text{th}} \right) (V^{\text{exp}})_{ab}^{-1} \left(\sigma_{f,b}^{\text{exp}} - R_{\text{NP}}^b \sigma_{f,b}^{\text{th}} \right) + \sum_{i,j} (r_i - 1) \left(\tilde{V}^{\text{mod}} \right)_{ij}^{-1} (r_j - 1), \quad (2)$$

$$\sigma_{f,a}^{\text{th}} = \sum_i r_i f_i^a \sigma_i^{\text{mod}}. \quad (3)$$

Here σ_i^{mod} denotes the IBD yield of the antineutrino flux generated by the fissionable isotope i and $\tilde{V}_{ij}^{\text{mod}} = V_{ij}^{\text{mod}} / (\sigma_i^{\text{mod}} \sigma_j^{\text{mod}})$, where V^{mod} is the covariance matrix. The coefficient R_{NP}^a is a possible suppression factor of the IBD yield in the experiment a .

3. Fit of reactor rates and reactor fuel evolution data

In this section, we firstly consider the reactor rates listed in Table IV of Ref. [12], and the results are presented in Table 1. For HM model, the fit of reactor rates $\bar{R}_{\text{HM}} = 0.936_{-0.023}^{+0.024}$, which indicates a RAA with 2.5σ .

Model	Rates		Evolution		Rates + Evolution	
	\bar{R}_{mod}	RAA	\bar{R}_{mod}	RAA	\bar{R}_{mod}	RAA
HM	$0.936_{-0.023}^{+0.024}$	2.5σ	$0.933_{-0.024}^{+0.025}$	2.6σ	$0.930_{-0.023}^{+0.024}$	2.8σ
EF	$0.960_{-0.031}^{+0.033}$	1.2σ	$0.975_{-0.030}^{+0.032}$	0.8σ	$0.975_{-0.030}^{+0.032}$	0.8σ
HKSS	$0.925_{-0.023}^{+0.025}$	2.9σ	$0.925_{-0.024}^{+0.026}$	2.8σ	$0.922_{-0.023}^{+0.024}$	3.0σ
KI	$0.975_{-0.021}^{+0.022}$	1.1σ	$0.973_{-0.022}^{+0.023}$	1.2σ	0.970 ± 0.021	1.4σ
HKSS-KI	$0.964_{-0.022}^{+0.023}$	1.5σ	$0.955_{-0.023}^{+0.024}$	1.9σ	$0.960_{-0.021}^{+0.022}$	1.8σ

Table 1: Average ratio \bar{R}_{mod} obtained from the least-squares analysis of the reactor rates in Table IV of Ref. [12] and of the Daya Bay and RENO evolution data.

There is practically no RAA for the EF model, since \bar{R}_{EF} differs from unity by only 1.2σ . Also the KI corrections lead to the practical disappearance of RAA, especially without the HKSS corrections. However, as for the 5 MeV bump, it is not fitted well by any of the models.

To compare these flux evolution data with the different model predictions, we fit the evolution data with a linear function describing the IBD yield as a function of f_{239} :

$$\sigma_{f,a}^{\text{lin}} = \bar{\sigma}_f + \frac{d\sigma_f}{df_{239}} (f_{239}^a - \bar{f}_{239}), \quad (4)$$

where $\bar{\sigma}_f$ is the average IBD yield and $d\sigma_f/df_{239}$ is the change in the IBD yield. The discrepancies of $d\sigma_f/df_{239}$ are 3.5σ and 3.6σ for the HM model and HKSS model, respectively. However, other models give consistent values of $\bar{\sigma}_f$ and $d\sigma_f/df_{239}$.

Then, we further fit the evolution data and the combined data using Eq. 2 as done to reactor rates. In Table 1, the inclusion of the evolution data confirms the existence of a reactor antineutrino anomaly for the HM (2.8σ) and HKSS (3.0σ) models and the absence of the anomaly for the EF model (only 0.8σ). For KI and HKSS-KI models, the resulting 1.4σ (KI) and 1.8σ (HKSS-KI) are still too small to claim an anomaly.

4. Best-fit reactor flux model

In this section we apply goodness of fit tests to the reactor rates to select which the best-fit model is. Table VI in Ref. [12] shows that the standard χ^2 goodness of fit test rejects none of the five models if we consider the usual minimum p -value of 5% corresponding to a confidence level of 95%. However, the χ^2 test is only sensitive to the sizes not the signs of the deviations. Then, we applied the following tests: sign, Kolmogorov-Smirnov (KS), Cramer-von Mises (CVM), Anderson-Darling (AD), Z_K , Z_C , and Z_A tests, which are sensitive to the sign and size of the deviations of the transformed data with respect to the standard Gaussian distribution.

Since the EF and KI models are preferred by different tests and sets of data, it is fair to consider both as favorite. Therefore, we conclude that the KI model is the best among the conversion models and the only summation model that we considered, the EF model, is practically equally good.

5. Model independent fluxes

The nuclear reactors of reactor antineutrino experiments can be divided into two categories: the commercial reactors mainly composited with ^{235}U and ^{239}Pu (LEU); and the research reactors with practically pure ^{235}U (HEU). Based on the intrinsic reactor fuel burnup relation, there is a quasi-linear relationship between the fission fractions of ^{241}Pu and ^{239}Pu in LEU reactors $f_{241} = k \cdot f_{239}$, where f_{239} and f_{241} are the fission fractions of ^{239}Pu and ^{241}Pu , respectively, where k is the fitting linear coefficient from reactor rates or evolution data, and we always use the value from the combined data with $k = 0.177$. Therefore, the IBD yield for a certain LEU reactor antineutrino experiment can be expressed as

$$\sigma_{f,a} = f_{235}^a \cdot \sigma_{235} + f_{238}^a \cdot \sigma_{238} + f_{239}^a \cdot \sigma_{\text{Pu}} + \Delta f^a \cdot \sigma_{241}, \quad (5)$$

where $\sigma_{\text{Pu}} = \sigma_{239} + k \cdot \sigma_{241}$ is the combined isotopic IBD yield of Pu's, and $\Delta f^a = f_{241}^a - k \cdot f_{239}^a$ is the residual fission fraction of ^{241}Pu .

In Ref. [15], we have demonstrated the robustness of the isotopic IBD yields for ^{235}U , ^{238}U and Pu's and are going to propose the following data-driven model for the isotopic IBD yields:

$$\begin{cases} \sigma_{235} = (6.37 \pm 0.08) \times 10^{-43} \text{ cm}^2/\text{fission} \\ \sigma_{238} = (6.63 \pm 1.30) \times 10^{-43} \text{ cm}^2/\text{fission} \\ \sigma_{\text{Pu}} = (5.64 \pm 0.20) \times 10^{-43} \text{ cm}^2/\text{fission}, \end{cases} \quad (6)$$

where σ_i 's ($i = 235, 238,$ and Pu) are from the fits of all reactor data (i.e., evolution data + reactor rates) based on the residual ^{241}Pu correction from σ_{241}^{HM} .

The model-independent isotopic IBD yields can be adopted to predict the IBD yield of a future reactor antineutrino experiment with typical fission fractions. We can estimate the predicted IBD yields of a future experiment with $(^{235}\text{U} : ^{238}\text{U} : ^{239}\text{Pu} : ^{241}\text{Pu}) = (0.577 : 0.076 : 0.295 : 0.052)$:

$$\sigma_f = [5.84 \pm (0.04)_{\text{MI}} \pm (0.0004)_{\text{HM}}] \times 10^{-43} \text{ cm}^2/\text{fission} \quad (0.7\% \text{ precision}), \quad (7)$$

where the first and second terms represent the uncertainties originating from model-independent (MI) isotopic IBD yields and the HM model input of σ_{241} , respectively. A comparison of the

predicted IBD yields using both the model-independent method and theoretical flux models is illustrated in Figure 1. From this comparison, we conclude that the model-independent method has the best precision among all the models, which is because the data-driven isotopic IBD yields have a specific form of the correlation matrix, resulting in sizable cancellations between different isotopic contributions. Note that the model-independent method predicts a smaller IBD yield than the HM and HKSS models, free from the reactor antineutrino anomaly.

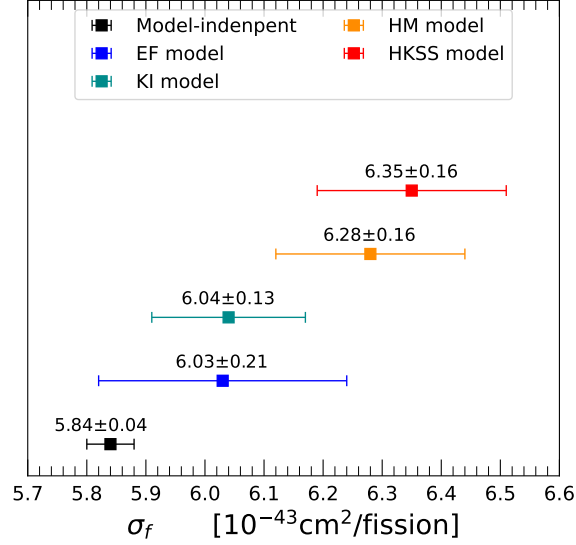


Figure 1: Predicted IBD yields for a future reactor experiment with both the model independent IBD yields and theoretical flux models in Ref. [12]. The IBD yields are given in units of [$10^{-43} \text{ cm}^2/\text{fission}$].

6. Summary and conclusions

In Ref. [12] we revisited the reactor antineutrino anomaly based on the recent reactor antineutrino flux calculations. We first performed an improved calculation of the IBD yields of five reactor antineutrino flux models in Section 2. Then, in Section 3, based on the proper statistical method for the analysis, we calculated the suppression of the reactor antineutrino flux predicted by the 5 models by fitting the measured rates listed in Table IV of Ref. [12]. We found there is practically no anomaly for the EF, KI, and HKSS-KI models. The addition of the Daya Bay and RENO evolution data confirms these conclusions. In Section 4, we further explored the question of which is the best-fit model by applying several goodness of fit tests. We can consider EF as the best summation model and KI as the best conversion model, leaving the decision of a clear preference between the two models to future studies with more data. In Ref. [15], we obtained a model-independent reactor isotopic cross sections per fission from the global fits of the reactor antineutrino data. With the implicit quasi-linear relationship between the fission fractions of ^{239}Pu and ^{241}Pu , the IBD yields of ^{235}U , ^{238}U , and Pu's can be properly constrained in the global fits. We also proposed a model-independent method to calculate the expected IBD yield of future reactor experiments, in which better than 1% accuracy can be achieved for those using typical commercial reactors.

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