Analysis of the Daya Bay Reactor Antineutrino Flux Changes with Fuel Burnup

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We investigate the recent Daya Bay results on the changes in the antineutrino flux and spectrum with the burnup of the reactor fuel. We find that the discrepancy between current model predictions and the Daya Bay results can be traced to the original measured \( \frac{^{235}U}{^{239}Pu} \) ratio of the fission beta spectra that were used as a base for the expected antineutrino fluxes. An analysis of the antineutrino spectra that is based on a summation over all fission fragment beta-decays, using nuclear database input, explains all of the features seen in the Daya Bay evolution data. However, this summation method still predicts an anomaly. Thus, we conclude that there is currently not enough information to use the antineutrino flux changes to rule out the possible existence of sterile neutrinos.

Recent results from the Daya Bay (DB) reactor neutrino experiment \([1]\) show significant change in the emitted antineutrino flux with the evolution of the reactor fuel. Over the course of 1230 days, the fuel evolved such that the fraction of fissions from \( ^{239}Pu \) increased from 25\% to 35\%, while those from \( ^{235}U \) decreased from 63\% to 51\%. Over the same period, the fraction from \( ^{238}U \) remained approximately constant at 7.6\%, while the \( ^{241}Pu \) fraction increased from 4\% to 8\%. The dependence of antineutrino flux on the fuel evolution was measured \([1]\) by the change in the yield from the inverse beta decay (IBD) reaction \( \nu + p \rightarrow e^+ + n \) with the variation in the \( ^{239}Pu \) fission fraction, \( F_{239} \). The IBD yield, which is an integral over energy of the product of the DB cross section and the antineutrino flux per fission, was fitted with a linear dependence on \( F_{239} \) as \([1]\),

\[
\sigma_f(F_{239}) = \sigma_f + \frac{d\sigma_f}{dF_{239}} (F_{239} - F_{239}) , \tag{1}
\]

where \( \sigma_f \) is the average IBD yield, \( F_{239} \) is the average \( ^{239}Pu \) fission fraction, and \( \frac{d\sigma_f}{dF_{239}} \) is the change of the IBD yield per unit \( ^{239}Pu \) fission fraction. The values reported by Daya Bay are: \( \sigma_f = (5.9 \pm 0.13) \times 10^{-43} \) cm\(^2\)/fission, \( \frac{d\sigma_f}{dF_{239}} = (-1.86 \pm 0.18) \times 10^{-43} \) cm\(^2\)/fission, and \( F_{239} = (0.571, 0.076, 0.299, 0.054) \) for \( i = (^{235}U, ^{239}U, ^{239}Pu, ^{241}Pu) \).

These DB results confirm the “reactor neutrino anomaly” \([2,3]\), in that the measured value of \( \sigma_f \) is about 5.1\% below that predicted by the model spectra of Huber and Mueller (H-M) \([4,5]\). However, the new DB results question the origin of this anomaly because the magnitude of the anomaly varies with the fuel evolution. The variation in the size of the anomaly with the fuel evolution results from the fact that the H-M value for \( \frac{d\sigma_f}{dF_{239}} \) does not agree with experiment and is incompatible with the IBD deficit being the same for all four actinides by 2.6\%. DB’s experimentally deduced IBD yields for \( ^{235}U \) and \( ^{239}Pu \) are \( \sigma_{235} = (6.17 \pm 0.17) \times 10^{-43} \) cm\(^2\)/fission and \( \sigma_{239} = (4.27 \pm 0.26) \times 10^{-43} \) cm\(^2\)/fission, respectively, corresponding to a \( \sigma_{235}/\sigma_{239} \) ratio of 1.445\pm0.097. By comparison, the Huber model ratio is 1.534\pm0.05. The DB analysis \([1]\) suggests that the anomaly arises almost entirely from \( ^{235}U \), and that the Huber prediction \([4]\) for IBD yield for \( ^{235}U \), \( \sigma_{235} \), is 7.8\% larger than that deduced by DB, while the model IBD yield for \( ^{239}Pu \), \( \sigma_{239} \), is in reasonable agreement with experiment.

The purpose of the present work is to point out that (1) the Huber prediction for \( \sigma_{235}/\sigma_{239} \) is strongly constrained by the original measured aggregate beta spectra of Schreckenbach et al. \([6]\) that Huber converted to antineutrino spectra, and (2) a nuclear database analysis, involving a summation over all beta-decay transitions that make up the aggregate antineutrino spectra, provides a reasonable description of all of the evolution data, but still predicts an anomaly. Thus, it is difficult to draw a conclusion about the existence of sterile neutrinos from evolution data alone.

The experimental aggregate beta spectra were obtained in the 1980’s \([6]\) at the Institute Laue-Langevin (ILL). To investigate the origin of the Huber \( \sigma_{235}/\sigma_{239} \) ratio, we refitted the ILL beta decay spectra, varying many of the assumptions that go into such a fit. The spectra were fitted assuming different combinations of allowed and first forbidden beta transitions, ranging from...
TABLE I: The individual IBD cross sections $\sigma_{235}$ and $\sigma_{239}$ change by a few percent when the assumptions in fitting the ILL aggregate beta spectra are changed. But the ratio $\sigma_{235}/\sigma_{239}$ always remains close to 1.53.

|        | all allowed | all allowed | allow.+forbid. | allow.+forbid. | $\left(Z_{\text{eff}}^2\right)^{1/2}$ |
|--------|-------------|-------------|----------------|----------------|--------------------------------------|
| $^{235}\text{U}$ | 6.69        | 6.58        | 6.47           | 6.48           |                                      |
| $^{239}\text{Pu}$ | 4.36        | 4.3         | 4.22           | 4.23           |                                      |
| ratio  | 1.534       | 1.530       | 1.533          | 1.532          |                                      |

all allowed to 40% first forbidden. The procedure and parameterization that we employed is described in [7]. Only 25 or so transitions are required to fit the integral beta spectra. Thus, in order to calculate the the Fermi function and its finite size correction, a choice must be made to assign a $Z_{\text{eff}}$ and $A_{\text{eff}}$ to these effective transitions. These choices of $Z_{\text{eff}}$ and $A_{\text{eff}}$ and the related endpoint energies introduce uncertainty into the fit, with a corresponding uncertainty in the antineutrino spectra. Thus, in fitting the spectra the prescriptions for $Z_{\text{eff}}$ and $A_{\text{eff}}$ were also varied. The relative importance of the different approximations used in deriving antineutrino spectra is summarized in [8].

Varying all of the assumptions in fitting the aggregate fission beta spectra for $^{235}\text{U}$ and $^{239}\text{Pu}$ led to variations in the corresponding antineutrino spectra that differed at the few percent level. However, in all cases the ratio of the antineutrino spectra and IBD yield ratio varied only slightly, with $\sigma_{235}/\sigma_{239}$ remaining close to 1.53, Fig. 1 and Table 1. In this figure and table we show results for four sets of assumptions: (1) all transitions are allowed and Huber’s quadratic prescription for $Z_{\text{eff}}$, (2) all transitions are allowed and $Z_{\text{eff}} = \sum Y_i Z_i/\Sigma Y_i$, (3) transitions can be either allowed or forbidden and $Z_{\text{eff}} = \sum Y_i Z_i^2/\Sigma Y_i$, and (4) transitions can be either allowed or forbidden and $Z_{\text{eff}} = \sqrt{\sum Y_i Z_i^2/\Sigma Y_i}$. Here $Y_i$ are the cumulative fission yields for the fission fragments ($Z_i, A_i$). We find that, for all sets of assumptions that we checked, the fits to the Schreckenbach beta spectra result in an IBD yield ratio with $\sigma_{235}/\sigma_{239}$ that is about 6% higher than the DB result.

An alternate procedure for investigating the $\sigma_{235}/\sigma_{239}$ ratio is to employ the so-called summation method using the nuclear database libraries for the cumulative fission yields and beta decay spectra. In this work we have used the JEFF-3.1 cumulative fission yields [9] in combination with a preliminary version of the ENDF/B-VIII.0 decay data sub-library [10] as described in Ref. [13]. ENDF/B fission yields were not used due to the compatibility issues discussed in Ref. [14]. For most of the energy interval, 2-7 MeV, these summation calculations predict a smaller $^{235}\text{U}/^{239}\text{Pu}$ beta spectra ratio, see Fig. 2, leading to an IBD antineutrino yield ratio equal to 1.46. However, it is difficult to draw any conclusions from this fact because about 4% of the predicted $^{235}\text{U}$ electron spectra and 7% of the $^{239}\text{Pu}$ predicted electron spectra originate from nuclei whose decays are quite uncertain. In such cases the theoretical spectra of Kawano et al. [15] were used. In addition, the uncertainty on the database summation spectra was not estimated because correlation matrices for fission yields are not available. The summation method prediction for $\frac{d\sigma}{dE}$, which also involves $^{238}\text{U}$ and $^{241}\text{Pu}$, is in closer agreement with the Daya Bay result than the H-M model, Table 2 and Fig. 3. However, the DB and summation results differ in detail. In particular, the summation predictions for the IBD cross section for $^{235}\text{U}$, $^{239}\text{Pu}$ and $^{241}\text{Pu}$ are all about 5% higher than the Daya Bay values. Thus, all three actinides contribute approximately equally to the summation anomaly. In the case of $^{238}\text{U}$, the uncertainty in the antineutrino spectrum is larger because...
\[ \sigma_f(10^{-43} \text{cm}^2) = 5.9 \pm 0.13 \quad \text{Summation} \quad 6.11 \quad \text{H-M}^6 \]
\[ \frac{d\sigma}{dF_{239}}(10^{-43} \text{cm}^2) = -1.86 \pm 0.18 \quad -2.05 \quad -2.46 \pm 0.06 \]
\[ \sigma_5 (10^{-43} \text{cm}^2) = 6.17 \pm 0.17 \quad 6.49 \quad 6.69 \pm 0.15 \]
\[ \sigma_9 (10^{-43} \text{cm}^2) = 4.27 \pm 0.26 \quad 4.49 \quad 4.36 \pm 0.11 \]
\[ \sigma_8 (10^{-43} \text{cm}^2) = 10.1 \pm 1.0 \quad 10.2 \quad 10.1 \pm 1.0 \]
\[ \sigma_4 (10^{-43} \text{cm}^2) = 6.04 \pm 0.6 \quad 6.4 \quad 6.04 \pm 0.6 \]
\[ \sigma_5/\sigma_9 = 1.445 \pm 0.097 \quad 1.445 \quad 1.53 \pm 0.05 \]

TABLE II: The IBD average yields, the variation with the $^{239}$Pu content of the fuel, and the contributions from individual actinides. $^a$The DB values for $\sigma_8$ and $\sigma_4$ were assumed. $^b$The uncertainties quoted for the H-M model are those used by the DB collaboration. A more direct comparison between the summation predictions and experimental IBD yield data is shown in Fig. 3.5.

$^{238}$U involves fast (as opposed to thermal) fission yields. In addition, $F_{238}$ does not change significantly with the fuel evolution.

The Daya Bay collaboration also observed a change in the shape of antineutrino spectrum over the course of the reactor fuel evolution. This is defined as $S_j$, where $j$ denotes four prompt energy intervals $E_p$ (0.7-2 MeV, 2-4 MeV, 4-6 MeV, and 6-8 MeV), with $E_p = E_\nu + 0.8$ MeV. $S_j$ is the corresponding partial contribution to the IBD yield in the energy range $E_p$:

$$S_j(F_{239}) = \overline{S}_j + \frac{dS_j}{dF_{239}}(F_{239} - \overline{F}_{239}).$$

The summation predictions, along with the DB measurements are shown in Fig. 4, where good agreement is seen. A comparison to the change in the IBD spectrum with $F_{239}$ for six prompt energy ranges is shown in Fig.5. In this figure we show both the summation predictions and one of our conversions of the ILL data, using assumption (2) of Fig. 1. The current fit to ILL leads to a change in the IBD spectrum that is very similar to the Huber model, while the summation predictions are closer to experiment.

The Daya Bay collaboration concluded that the expected Huber model $^{235}$U spectrum is too high in magnitude, while that for $^{239}$Pu is consistent with the DB
FIG. 5: The variation of the IBD yield for different prompt energy ranges. The data are from [1], the solid line is the prediction of the summation method, while the dashed line is obtained from converting the ILL data to antineutrino spectra and using the database for $^{238}\text{U}$.

data. This raises the question whether the measured changes in IBD yield and spectrum are consistent with a sterile neutrino explanation of the reactor neutrino anomaly. The present analysis suggests that there is currently insufficient evidence to draw any conclusions on this issue. As we have shown, an analysis based on the summation method explains all of the features seen in the evolution data, but it predicts an average IBD yield that is 3.5% higher than observed. All actinides except $^{238}\text{U}$ contribute approximately equally to the summation anomaly. But we note that $^{238}\text{U}$ does not evolve with the rest of the fuel, and its summation antineutrino spectrum is at least 10% uncertain. Resolving the issue of the existence of sterile neutrinos requires new very short baseline neutrino experiments. A re-measurement of the aggregate fission beta spectra of $^{235}\text{U}$ and $^{239}\text{Pu}$ would also be very valuable in determining whether there is a problem with the $\sigma_{235}/\sigma_{239}$ ratio.

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