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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 ^{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 allows for an anomaly. 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 IBD cross section and the antineutrino flux per fission, was fitted with a linear dependence on F_{239} as [1],

$$\sigma_f(F_{239}) = \overline{\sigma}_f + \frac{d\sigma_f}{dF_{239}}\left(F_{239} - \overline{F}_{239}\right), \tag{1}$$

where $\overline{\sigma}_f$ is the average IBD yield, $\overline{F}_{239}$ 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: $\overline{\sigma}_f = (5.9 \pm 0.13) \times 10^{-43}$ cm^2/fission, $\frac{d\sigma_f}{dF_{239}} = (-1.86 \pm 0.18) \times 10^{-43}$ cm^2/fission, and $\overline{F}_i = (0.571, 0.076, 0.299, 0.054)$ for i=(^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu).

These DB results confirm the "reactor neutrino anomaly" [2, 3], in that the measured value of $\overline{\sigma}_f$ 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 $\frac{d\sigma_f}{dF_{239}} = (-2.46 \pm 0.06) \times 10^{-43}$ cm^2/fission differs from DB's measured value by 3.1 σ. The H-M ratio $\overline{\sigma}_f / \frac{d\sigma_f}{dF_{239}}$ does not agree with experiment and is incompatible with the IBD deficit being the same for all four actinides by 2.6 σ. DB's experimentally deduced IBD yields for ^{235}U and ^{239}Pu are $\sigma_{235} = (6.17 \pm 0.17)^{-43}$ 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. The maximum uncertainty in this ratio is obtained if we assume that σ_{235} is independent of σ_{239}, which gives an uncertainty of $\pm$0.097. Using the correlation between σ_{235} and σ_{239} implied by the ellipse in Fig. 3 of ref. [1], we find an uncertainty in the the $\sigma_{235}/\sigma_{239}$ ratio of 0.06. By comparison, the Huber model ratio is 1.534$\pm$ 0.05 if we assume σ_{235} and σ_{239} are independent or 1.534$\pm$ 0.025 if we take the correlations from Fig. 3 of ref. [1] into account. 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, σ_{235}, is 7.8% larger than that deduced by DB, while the model IBD yield for ^{239}Pu, σ_{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.

TABLE I: The individual IBD cross sections σ_{235} and σ_{239} change by a few percent when the assumptions in fitting the ILL aggregate beta spectra are changed. In particular, the inclusion of forbidden transitions and alternate treatments of Z_{eff} tends to reduce the magnitude of the IBD cross sections, thus reducing the significance of the reactor neutrino anomaly. But the ratio $\sigma_{235}/\sigma_{239}$ always remains close to 1.53

	all allowed $Z_{\rm eff}^{\rm Huber}$	all allowed $Z_{\rm eff}$	allow.+forbid. $Z_{\rm eff}$	allow.+forbid. $(Z^2_{\rm eff})^{1/2}$
^{235}U	6.69	6.58	6.47	6.48
^{239}Pu	4.36	4.3	4.22	4.23
ratio	1.534	1.530	1.533	1.532

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

Varying all of the assumptions in fitting the aggregate fission beta spectra for ^{235}U and ^{239}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 with Huber's quadratic prescription for $Z_{\rm eff}$, (2) all transitions are allowed and $Z_{\rm eff} = \Sigma Y_{c_i} Z_i/\Sigma Y_{c_i}$, (3) transitions can be either allowed or forbidden and $Z_{\rm eff} = \Sigma Y_{c_i} Z_i/\Sigma Y_{c_i}$, and (4) transitions can be either allowed or forbidden and $Z_{\rm eff} = \sqrt{\Sigma Y_{c_i} Z_i^2/\Sigma Y_{c_i}}$. Here Y_{c_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 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}U/^{239}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 of the uncertainties associated with the summation spectra. In general, determining the uncertainty on the database summation spectra is a very difficult task. It would involve evaluating the uncertainty and correlations between the hundreds of input data that go into the database predictions for the antineutrino spectra, including possible systematic effects. As a first attempt, we simply added the quoted uncertainties for all fission fragments in quadrature, and found a resulting uncertainty that is unrealistically low, being about 2%. One important issue affecting the uncertainty in the summation $\sigma_{235}/\sigma_{239}$ ratio is the fact that about 4% of the predicted ^{235}U electron spectra and 7% of the ^{239}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. The quoted [16] uncertainty on the Kawano spectra is 50%. However, scaling the theoretical contributions to the total antineutrino spectra up or down by 50% can lead to some inconsistencies. For example, the theoretical spectra can not be increased so as to exceed the known maximum Q-value for β-decay for any given nucleus. In addition, many of the nuclei involve decay by both neutron emission and β-decay, and the Kawano analysis takes the neutron decay branches into account. The intention of the present work is *not* to present new predictions, including realistic uncertainties, for the antineutrino spectra. Rather, it is to present a database prediction as a *counter example* to the H-M predictions, in order to show that the Daya Bay evolution data by themselves cannot be used to rule out sterile neutrinos. We suggest that an approximately 5% uncertainty be associated with the summation spectra for ^{235}U, ^{239}Pu and ^{241}Pu, while the uncertainty on the summation spectrum for ^{238}U is probably closer to 10%.

The database predictions presented here differ from, mostly being larger than, the summation contributions found by Mueller *et al.*. This is because the latter predictions only included nuclei whose β decay properties were known

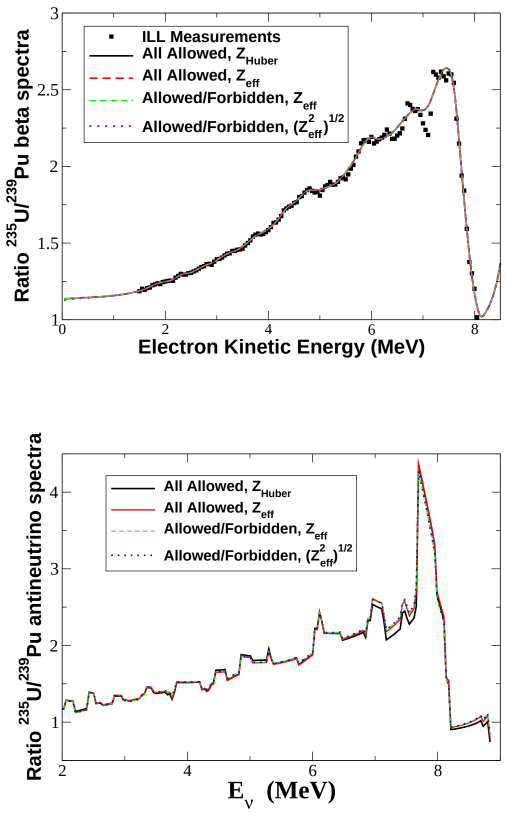

FIG. 1: (top)The ratio of the ^{235}U and ^{239}Pu beta spectra. The data are from [6], and the curves are the ratios obtained by fitting the individual ^{235}U and ^{239}Pu data, using different assumptions. The different assumptions are explained in the text. Excellent fits were obtained in all cases. (bottom)The ratio of the antineutrino spectra resulting from the fits. We note that the jagged structures largely reflect the fact that the fits only require about 25 endpoints; these effects are normally smoothed in published expected spectra.

from experiment. An additional difference comes from the fact that the present work uses the JEFF-3.1 fission yields, while Mueller *et al.* used the England and Rider [17] fission yield evaluations.

The current summation method prediction for $\frac{d\sigma_f}{dF_9}$, which also involves ^{238}U and ^{241}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}U, ^{239}Pu and ^{241}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}U, the uncertainty in the antineutrino spectrum is larger because ^{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 $\frac{1}{S_j}\frac{dS_j}{dF_{239}}$, where j denotes four prompt energy intervals E_p^j, (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^j:

$$S_j(F_{239}) = \overline{S}_j + \frac{dS_j}{dF_{239}}(F_{239} - \overline{F}_{239})\ . \tag{2}$$

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.

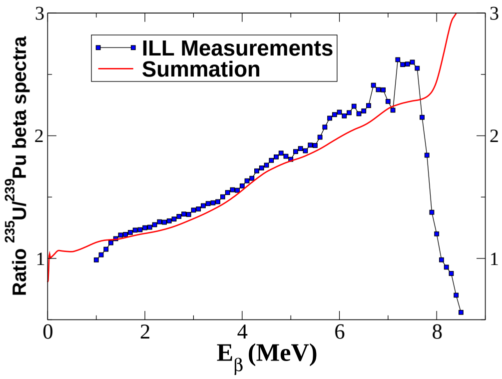

FIG. 2: The ratio of the ^{235}U to ^{239}Pu aggregate beta spectra as a function of the kinetic energy of the electron, for the Schreckenbach *et al.* [6] measurement (squares), and the summation method (curve).

	DB^a	Summation	H-M^b
$\overline{\sigma}_f(10^{-43}\text{cm}^2)$	5.9± 0.13	6.11	6.22±0.14
$\frac{d\sigma_f}{dF_{239}}(10^{-43}\text{cm}^2)$	-1.86± 0.18	-2.05	-2.46±0.06
σ_5 (10^{-43}cm^2)	6.17± 0.17	6.49	6.69±0.15
σ_9 (10^{-43}cm^2)	4.27± 0.26	4.49	4.36±0.11
σ_8 (10^{-43}cm^2)	10.1±1.0	10.2	10.1±1.0
σ_4 (10^{-43}cm^2)	6.04±0.6	6.4	6.04±0.6
σ_5/σ_9	1.445±0.097	1.445	1.53± 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 σ_8 and σ_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. Uncertainties in the database predictions are very difficult to estimate, and, thus, the difference between the summation IBD yields and those deduced by Daya Bay are not necessarily significant.

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 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}U contribute approximately equally to the summation anomaly. But we note that ^{238}U does not evolve with the rest of the fuel, and its summation antineutrino spectrum is at least 10% uncertain. The summation anomaly observed in the present work is unlikely to be statistically significant, and 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}U and ^{239}Pu would also be very valuable in determining whether there is a problem with the $\sigma_{235}/\sigma_{239}$ ratio.

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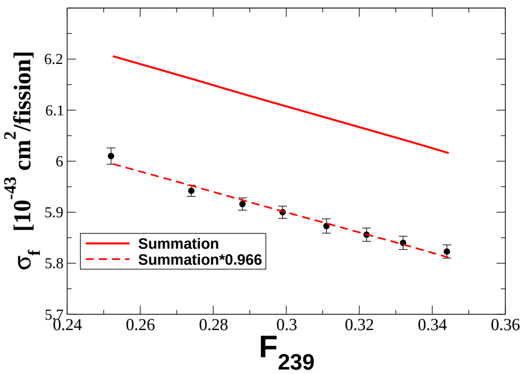

FIG. 3: The IBD yield per fission as a function of the fraction of fissions from ^{239}Pu. The data are from Daya Bay [1], while the straight (dashed) curves are the absolute (renormalized) predictions from the summation calculations. The slope of the summation predictions for the change in the the IBD yield with F_{239} is in agreement with experiment, but the absolute value of the predicted IBD yield is 3.5% high.

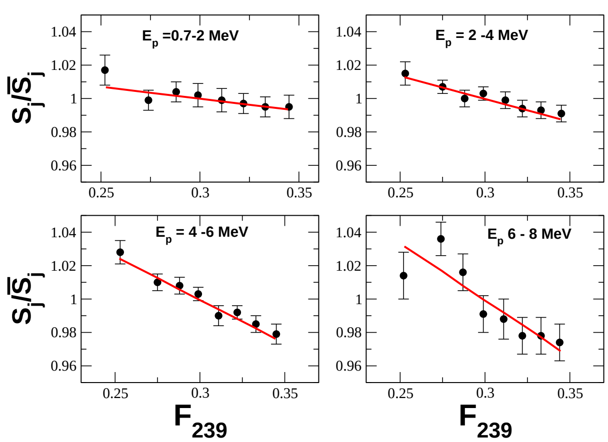

FIG. 4: The variation of the IBD yield in four prompt energy ranges. The data are from [1], while the straight lines are the predictions of the summation method. The summation predictions for $\overline{S}^{-1} dS_j/dF_{239}$ are (-0.143, -0.273, -0.521, -0.678) for j=1-4, to be compared with the experimental values of (-0.16±0.07, -0.23±0.04, -0.49±0.05, -0.69±0.12).

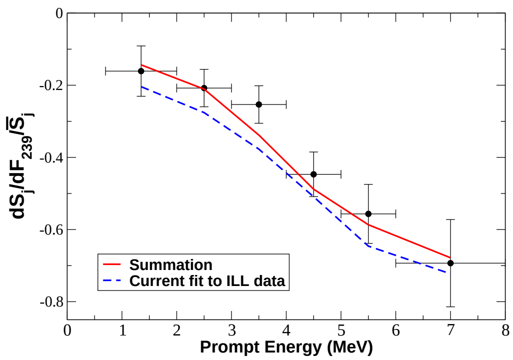

FIG. 5: The variation of the IBD yield for different prompt energy ranges. The data are from [1], the solid line is the prediction of the summation method, while the dashed line is obtained from converting the ILL data to antineutrino spectra and using the database for ^{238}U.

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