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Reactor flux and spectrum measurements with the Daya Bay full data set

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This talk reports reactor flux and spectrum measurements with the Daya Bay full data set, 34% increase in statistics compared to the previous results. Using detector data spanning effective ^{239}Pu fission fractions F_{239} from 0.25 to 0.35, Daya Bay measures an average IBD yield and a fuel-dependent variation in IBD yield, $d\sigma/dF_{239}$. In addition, the yields and prompt spectra of the two dominant isotopes, ^{235}U and ^{239}Pu, are extracted. Using SVD unfolding techniques, the $\bar{\nu}_e$ spectra are estimated from the prompt spectra of ^{235}U, ^{239}Pu, and the total measurement, thereby providing a model-independent reactor $\bar{\nu}_e$ spectrum prediction for the other reactor $\bar{\nu}_e$ experiments.

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1. Introduction

Nuclear reactors are pure and powerful sources of $\bar{\nu}_e$ and have played an important role in neutrino physics. The reactor $\bar{\nu}_e$ are mainly generated from fissions of four isotopes: ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu. Each fission of these four isotopes produces a different flux and energy spectrum of $\bar{\nu}_e$. Fissions of other isotopes contribute less than 0.3%. With the operation of the reactor, the fission fractions of 4 isotopes change, leading to the change of flux and spectrum of $\bar{\nu}_e$ emitted by the reactor, and this is called the evolution of the flux and energy spectrum of the reactor.

Inverse beta decay (IBD) often used to detect reactor $\bar{\nu}_e$, using the positrons and neutrons produced by the reaction as prompt and delayed signals to pair. The positrons preserve most of the energy information of the incoming $\bar{\nu}_e$, which allows us to study the energy spectrum of the $\bar{\nu}_e$ using the spectrum of the prompt signal.

The flux measurements have confirmed 6% deficit [1] of the reactor $\bar{\nu}_e$ compared to the Huber[2]-Mueller[3] (HM) model, which is known as the "reactor antineutrino anomaly"(RAA), and the spectra measurements confirmed a "5 MeV bump" compared to the HM model and SM2018[4] model. The Daya Bay extracted the yields of ^{235}U and ^{239}Pu[5], which indicates that most of the deficit of flux comes from ^{235}U. The measurement at Kurchatov Institute[6] (KI) also supports this view. However, there is currently no model that can describe the anomaly of the energy spectrum. Precision measurements are essential to investigate the origins of RAA and provide crucial inputs to future reactor $\bar{\nu}_e$ experiments. For example, JUNO experiments aimed at determination of neutrino mass ordering at the medium baseline.

The Daya Bay experiment, consisting of 8 antineutrino detectors (ADs) deployed in 2 near sites and 1 far site, detects $\bar{\nu}_e$ from 6 commercial reactors. The experiment operated for 3158 days from 2011 to 2020 and accumulated about 4.7 million IBD candidates based on neutron captured on Gd (n-Gd) at 4 near detectors. The statistic of full data set has increased by 34% compared to the previous publication(1958 days)[7].

2. Flux Evolution and Extraction

The weekly power and fission fraction information are provided by nuclear power plant. To describe the fraction of fission isotopes expected in detectors, we can define effective fission fraction:

$$F_i = \sum_{r=1}^{6} \frac{W_{th,r} f_{i,r}}{L_r^2 \sum_i f_{i,r} e_i} / \sum_{r=1}^{6} \frac{W_{th,r}}{L_r^2 \sum_i f_{i,r} e_i} \tag{1}$$

The data of 4 near ADs are divided into 20 groups according to the effective fission fraction. IBD yield can be considered as a linear function of fission fraction of ^{239}Pu as shown in Eq.2. In this equation, the slope $d\sigma_f/df_{239}$ can be fitted as free parameters.

$$\sigma_f = \bar{\sigma}_f + \frac{d\sigma_f}{df_{239}}(F_{239} - \bar{F}_{239}) \tag{2}$$

Use 1958-day data, which have been published[8], Daya Bay experiment report the average flux and spectrum, as well as their evolution with ^{239}Pu fission fraction. And the measurements are compared the SM2018 model and the HM model. The measured average flux and spectrum, as well

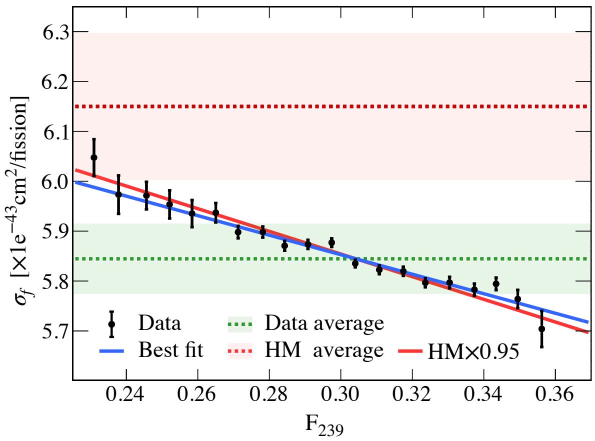

Figure 1: Yield as a function of effective fission fraction of ^{239}Pu, as well as the comparison with the HM model.

as their evolution with the ^{239}Pu isotopic fraction, are inconsistent with the predictions of the HM model. In contrast, the SM2018 model is shown to agree with the average flux and its evolution but fails to describe the energy spectrum.

Full data set result is shown in Fig.1, $d\sigma_f/df_{239} = -1.96 \pm 0.13$ and $\bar{\sigma} = 5.84 \pm 0.07$, unit is $10^{-43} cm^2/fission$. The uncertainty of slope is dominated by statistical uncertainty, while that of $\bar{\sigma}$ is dominated by detection efficiency. For the yield result, there is a 5% deficit compared to the HM model. For the slope result, it is between the HM model -2.46 and SM2018 model -1.82. Compared to the previously published results[5] (1230 days) of Daya Bay, the slope has slightly decreased within the error range.

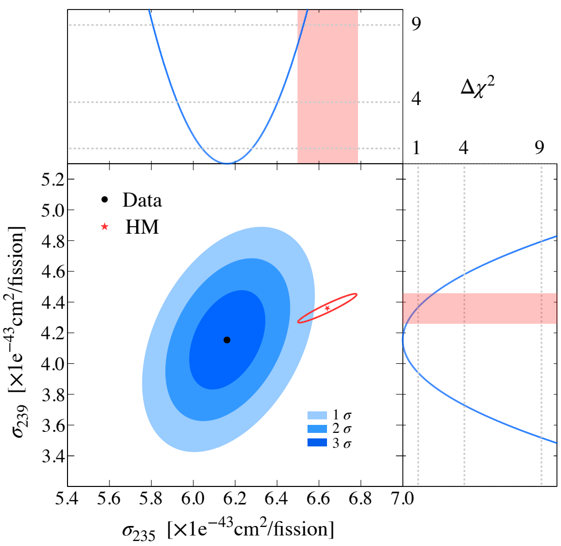

Figure 2: Yield extraction of ^{235}U and ^{239}Pu, as well as the comparison with the HM model.

The yields of ^{238}U and ^{241}Pu are constrained by the HM model, 10% uncertainty for both, and the yield of ^{235}U and ^{239}Pu can be extracted by the evolutionary data, as shown in Fig.2. The results are $\sigma_{235} = 6.16 \pm 0.12$ and $\sigma_{239} = 4.16 \pm 0.21$, the unit is $10^{-43} cm^2/fission$. Compare with the results of 1958 days result[7], the values of σ_{235} and σ_{239} are 1% larger and 4% smaller, and the accuracy is improved by 25% and 19%, respectively. Compared to the HM model, σ_{235} has a deficit of 7.0% (3σ) and σ_{239} has a deficit of 4.2% (1σ).

3. Spectra Analysis

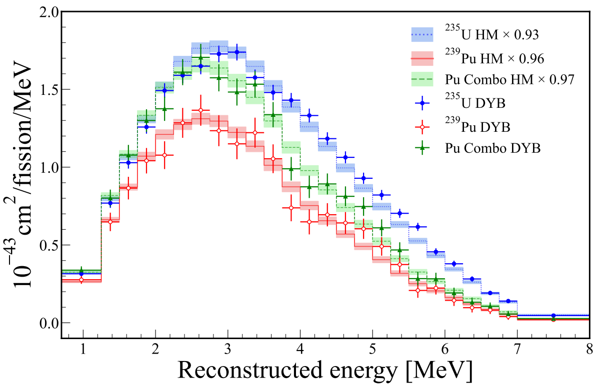

Figure 3: Extracted reconstructed energy spectra of ^{235}U, ^{239}Pu and Pu combo, as well as the comparison with the HM model.

The total reconstructed energy spectrum of prompt signal can be obtained using the full data set, after subtracting the background and spent nuclear fuel and non-equilibrium effects. The uncertainty of reconstructed energy spectra caused by systematic uncertainties is estimated by using MC method. The accuracy between 2 and 5 MeV is about 1.4%. Using the sliding window method, the time window of 4 to 6 MeV is calculated, and the shape discrepancy compared with the HM is greater than 5σ. The reason for this discrepancy is not yet explained.

Using a method similar to yield extraction, we can extract the reconstructed energy spectra of ^{235}U and ^{239}Pu by constraining the spectra of ^{238}U and ^{241}Pu. For ^{238}U and ^{241}Pu, we adopted a conservative approach to magnify the original uncertainties of the HM model. The extracted spectra results are shown in the Fig.3, along with the normalized the HM model. The precisions in 2 to 5MeV are 3% and 8% for ^{235}U and ^{239}Pu, respectively. In terms of a shape-only comparison, the Daya Bay ^{235}U and ^{239}Pu spectra differ the HM model with a bump around 5 MeV. The significances w.r.t the HM model are 4σ and 1σ for ^{235}U and ^{239}Pu, respectively, indicating that the data consist with "5 MeV bump" in both spectra, more significantly with ^{235}U.

In low-enriched uranium (LEU) reactor, the fissile isotopes ^{239}Pu are mainly produced by the neutron captured by ^{238}U and a succession of two radioactive beta decays, and ^{241}Pu mainly produced by neutron captured on ^{239}Pu. As a result, the correlation between the f_{239} and f_{241} in most LEU nuclear power reactors are similar, and the correlation can be described by $f_{241} = k \times f_{239}$. The value of k is 0.185 by fitting the effective fission fraction of ^{239}Pu and ^{241}Pu. Pu combo spectra can be defined as: $S_{PuCombo} = S_{Pu239} + 0.185 \times S_{Pu241}$, the result is shown in Fig.3. Replacing

^{239}Pu with Pu combo can significantly reduces the impact of ^{241}Pu, and the relative uncertainty of Pu combo is reduced by 30% relative to ^{239}Pu.

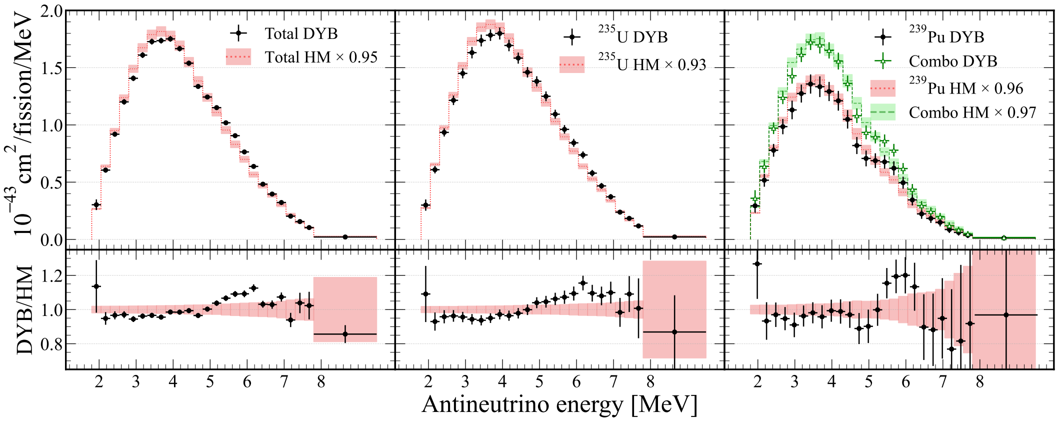

Figure 4: Unfolded spectra of total, ^{235}U, ^{239}Pu and Pu combo, as well as the comparison with the HM model.

The SVD regularization method[9] is adopted to unfold the total, ^{235}U and ^{239}Pu together, which is achieved by minimizing the following χ^2,

$$\chi^2 = (\boldsymbol{S} - \boldsymbol{R}\boldsymbol{S}^\nu)^T \boldsymbol{V}^{-1} (\boldsymbol{S} - \boldsymbol{R}\boldsymbol{S}^\nu) + \tau (\boldsymbol{C}\boldsymbol{S}^\nu)^T (\boldsymbol{C}\boldsymbol{S}^\nu) . \tag{3}$$

$\boldsymbol{S}$ is composed of the three reconstructed energy spectra, $\boldsymbol{s_f}$, $\boldsymbol{s_{235}}$ and $\boldsymbol{s_{239}}$, and $\boldsymbol{S}^\nu$ is composed of the corresponding neutrino energy spectra, $\boldsymbol{s}^\nu_{\boldsymbol{f}}$, $\boldsymbol{s}^\nu_{\boldsymbol{235}}$ and $\boldsymbol{s}^\nu_{\boldsymbol{239}}$. $\boldsymbol{V}$ is the covariance matrix of the three reconstructed energy spectra. $\boldsymbol{R}$ is the response matrix, which contain the conversion relation between reconstructed energy and neutrino energy. $\boldsymbol{C}$ is composed of three second-order derivative matrices arranged diagonally, through which the smoothness of each individual spectrum is imposed. τ is the regularization strength optimized by achieving minimal Mean Squared Error (MSE) between data and model. This method can provide a proper treatment on the shape correlation between different spectra and the unfolding result is shown in Fig.4.

4. Summary

This talk reports the precision measurements of reactor flux and spectrum based of the Daya Bay full data set. Based on the n-Gd samples, we obtained the average yield and energy spectrum of reactor $\bar{\nu}_e$, and extract the yield and spectra of ^{235}U and ^{239}Pu from the total yield and spectra according to the evolution data. At last, the measured three reconstructed energy spectra are unfolded to neutrino energy spectra with the aid of the SVD regularization. For the first time, several spectra are unfolded together to consider the correlations among different spectra. This analysis provides a precision data-driven input for future reactor $\bar{\nu}_e$ studies.

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