Reactor antineutrino anomaly in light of recent flux model refinements

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Online Event
Outline

• Motivation
• New calculation of IBD yield
• Method of analysis
• Fit of reactor rates
• Fit of reactor fuel evolution data
• Best-fit model
• Summary
Part 1: Motivation
Motivation

• Reactor antineutrino anomaly

Reactor experiments data → test RAA for different models.

- Huber-Mueller model

- Estienne-Fallot summation model

- Hayen-Kostensalo-Severijns-Suhonen model

- Recent Kurchatov Institute measurements
  - arXiv:2103.01684

Models

Reactor data

- Reactor rates data (27)
  - 80s-90s, 2000s
  - Recent Prospect & STEREO

- Fuel evolution data (8+8)
  - Daya Bay
  - RENO

mean averaged ratio: \( \bar{R} = 0.943 \pm 0.024 \)
Part 2: New calculation of IBD yield
Reactor flux models

- Theoretical reactor antineutrino spectra
  - Conversion method
    Measured $\beta$ spectra $\rightarrow$ neutrino spectra
  - Summation method
    Sum all the decay branches

- Huber-Mueller model
  - $^{235}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$: ILL $\beta$ spectrum $\rightarrow$ neutrino spectrum
  - $^{238}\text{U}$: sum all $\beta$ decay branches
  - Allowed approximation

- HKSS model
  - Forbidden transition contribution

Partially explain “5 MeV bump”:

- Measured $\beta$ spectra $\rightarrow$ neutrino spectra
- Sum all the decay branches

How to convert ILL into neutrino spectra


database
Reactor flux models

- **Kurchatov Institute model:**  
  - $^{235}\text{U}$ HM model + KI measurement  
  - $^{238}\text{U}$ conversion spectrum + KI measurement  
  - Pu spectra: same with HM model

- **HKSS-KI model:**  
  - $^{235}\text{U}$ HKSS model + KI measurement  
  - $^{238}\text{U}$ and Pu: same with HKSS model

With the assumption of the unchanged $^{239}\text{Pu}$ comparing with ILL  

**KI measurement:** Reduction of $^{235}\text{U}$!

The Kurchatov Institute measurement (open circles) directly measured the ratio of $^{235}\text{U}$ beta spectrum and $^{239}\text{Pu}$ beta spectrum, which is lower than HM model (closed circles) in most region.

*arXiv:2103.01684*  

*Phys. Atom. Nucl. 84, no.1, 1-10 (2021)*
Reactor flux models


- **Estienne-Fallot summation model**
  - Summation method
  - Nuclear database + Pandemonium-free data

**Model considered in this work**

- Conversion model
- RAA
- Forbidden transition
- HKSS model
- Partially explain “5 MeV bump”.
- Summation model
- EF model
- The event rate is only 1.9% deviation from Daya Bay.

**ILL measurement** (measured $\beta$ spectra)

**KI measurement** (measured $\beta$ spectra)
Updated IBD yields

- IBD yield $\sigma_f \sigma_{f,a} = \sum_i f_i^a \sigma_i$, $i = 235, 238, 239, \text{and} 241 \text{ for } ^{235}\text{U}, ^{238}\text{U}^\text{Pu} \text{ and } ^{241}\text{Pu}$.

- The individual IBD yield $\sigma_i$

\[ \sigma_i = \int_{E_{\text{min}}}^{E_{\text{max}}} dE \frac{\Phi(E)}{\sigma_{\text{IBD}}(E)} \]

1. IBD cross section: *Phys. Rev. D60, 053003 (1999)*
   - 1st-order Vogel-Beacom IBD cross section w/ PDG 2020

   0th-order cross section
   \[ \sigma_{\text{tot}}^{(0)} = \frac{2\pi^2}{m_e^5} \frac{E_e^{(0)} p_e^{(0)}}{f_{\text{p.s.}}^R \tau_n} \]

   0th-order
   \[ E_e^{(0)} = E_\nu - \Delta, \quad \Delta = M_n - M_p \]

   1st-order
   \[ E_e^{(1)} = E_e^{(0)} \left[ 1 - \frac{E_\nu}{M} (1 - v_e^{(0)} \cos \theta) \right] - \frac{y^2}{M} \]
   \[ y^2 = \frac{(\Delta^2 - m_e^2)}{2} \]

2. Integral energy regions

- Neutron lifetime $\tau_n = 879.4s$
- Phase space factor $f_{\text{p.s.}}^R = 1.7152$

A historical perspective of values of neutron lifetime $\tau_n$

0th and 1st order IBD cross section
Updated IBD yields

• The individual IBD yield $\sigma_i$
  1. IBD cross section \cite{PhysRevD60,053003(1999)}
  2. Integral energy regions (1.8→10.0 MeV)
    • Low energy region (1.8 → 8.0 MeV)
      extrapolate and interpolate with the original spectra.
    • High energy region approximation (8.0 → 10.0 MeV)
      EF summation model spectra with a very conservative 100% uncertainty.

original IBD yields

\begin{center}
\begin{tabular}{l|cccc}
Model & $\sigma_{235}$ & $\sigma_{238}$ & $\sigma_{239}$ & $\sigma_{241}$ \\
\hline
HM & 6.69 ± 0.14 & 10.10 ± 0.82 & 4.40 ± 0.11 & 6.03 ± 0.13 \\
EF & 6.28 ± 0.31 & 10.14 ± 1.01 & 4.42 ± 0.22 & 6.23 ± 0.31 \\
HKSS & 6.74 ± 0.17 & 10.33 ± 0.85 & 4.43 ± 0.13 & 6.07 ± 0.16 \\
KI & 6.27 ± 0.13 & 9.34 ± 0.47 & 4.33 ± 0.11 & 6.01 ± 0.13 \\
\end{tabular}
\end{center}

our selected IBD yields input

\begin{center}
\begin{tabular}{l|cccc}
Model & $\sigma_{235}$ & $\sigma_{238}$ & $\sigma_{239}$ & $\sigma_{241}$ \\
\hline
HM & 6.62 ± 0.16 & 10.09 ± 0.82 & 4.34 ± 0.13 & 6.02 ± 0.16 \\
EF & 6.23 ± 0.31 & 10.07 ± 1.00 & 4.37 ± 0.22 & 6.17 ± 0.31 \\
HKSS & 6.70 ± 0.17 & 10.19 ± 0.84 & 4.39 ± 0.13 & 6.09 ± 0.16 \\
KI & 6.29 ± 0.13 & 9.44 ± 0.48 & 4.34 ± 0.13 & 6.02 ± 0.16 \\
HKSS-KI & 6.36 ± 0.13 & 10.19 ± 0.84 & 4.39 ± 0.13 & 6.09 ± 0.16 \\
\end{tabular}
\end{center}

Small contribution above 8 MeV: 0.3% for $^{235}$U, 0.9% for $^{238}$U, 0.2% for $^{239}$Pu, 0.3% for $^{241}$Pu.
Part 3:
Method of analysis
LSM with Wilks’ theorem

How to treat the systematic theoretical uncertainties in the least-squares function.

Method A  

A covariance matrix with experimental and theoretical uncertainties added in quadrature.

\[ \chi^2 = \sum_{a,b} \left( \sigma_{f,a}^{\text{exp}} - R_{NP}^a \sigma_{f,a}^{\text{th}} \right) \left( V^{\text{tot}} \right)^{-1}_{ab} \left( \sigma_{f,b}^{\text{exp}} - R_{NP}^b \sigma_{f,b}^{\text{th}} \right) \]

\[ V^{\text{tot}} = V^{\text{exp}} + V^{\text{th}} \]

\[ \sigma_{f,a}^{\text{th}} = \sum_i f_i^a \sigma_i^{\text{mod}}. \]

A strongly-correlated theoretical matrix derived from the covariance matrix \( V_{ij}^{\text{mod}} \) among \(^{235}\text{U}, ^{238}\text{U}, ^{239}\text{Pu}, \) and \(^{241}\text{Pu} \)

The method A will suffer the PPP!

Peelle’s Pertinent Puzzle

strongly correlated data

the best-fit average can be lower than most of the data

non-intuitive

- improper combination of experimental and theoretical matrices
- truncation of data space

\[ x_1 \]

\[ x_2 \]

\[ \bar{x} \]

20% normalization error

10% individual error
**LSM with Wilks’ theorem**

**Method B**  
*Phys. Rev. D87, 073018 (2013)*  
Calculate the fit results considering only the experimental uncertainties and add by hand a global theoretical uncertainty to the final result.

\[
\chi^2 = \sum_{a,b} \left( \sigma_{f,a}^{\exp} - R_{NP}\sigma_{f,a}^{th} \right) (V^{\exp})^{-1}_{ab} \left( \sigma_{f,b}^{\exp} - R_{NP}\sigma_{f,b}^{th} \right) 
\]

**Method C**  
Consider the theoretical uncertainties with appropriate **pull terms**  

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

\[
\sigma_{f,a}^{th} = \sum_i r_i f_i^a \sigma_{i}^{\text{mod}}. \quad \tilde{V}_{i,j}^{\text{mod}} = V_{i,j}^{\text{mod}}/(\sigma_{i}^{\text{mod}} \sigma_{j}^{\text{mod}}) 
\]

PPP is avoided by decoupling the minimization of **physical parameters** from the minimization of pull coefficients!
Part 4: Fit of reactor rates & evolution data
Fit of reactor rates

**HM model**

<table>
<thead>
<tr>
<th>Original HM IBD yield</th>
<th>Updated HM IBD yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.69 ± 0.14</td>
<td>6.62 ± 0.16</td>
</tr>
<tr>
<td>10.10 ± 0.82</td>
<td>10.09 ± 0.82</td>
</tr>
<tr>
<td>4.40 ± 0.11</td>
<td>4.34 ± 0.13</td>
</tr>
<tr>
<td>6.03 ± 0.13</td>
<td>6.02 ± 0.13</td>
</tr>
</tbody>
</table>

Our work

**Work in 2017**

RAA: 2.8 $\sigma$

0.934 ± 0.024

w/ method C

**Work in 2021**

RAA: 2.5 $\sigma$

0.940 ± 0.024

w/ method C

RAA: 2.3 $\sigma$

0.943 ± 0.024

w/ new IBD yields

RAA: 2.8 $\sigma$ (2017) $\rightarrow$ 1.9 $\sigma$ (2021)
Fit of reactor rates

These 3 models give RAA less than 1 σ . (No anomaly)
Fit of reactor fuel evolution data

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

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

The HM and HKSS models are disfavored by the evolution data

- 3.1 $\sigma$ for HM model
- 3.2 $\sigma$ for HKSS model
- EF, KI and HKSS-KI models give values of $\overline{\sigma}_f$ and $d\sigma_f/df_{239}$ that agree with the fit of the evolution data within the uncertainties.

When using RENO data, we have the similar results.
Part 5: Best-fit model
Statistic test

- $\chi^2$ test: only shows the size of deviation not show the sign
  rejects none of the five models

$$x_{a}^{\text{mod}} = \sum_{b} (V_{\text{tot}})^{-1/2} \left( \sigma_{f,b}^{\exp} - \sigma_{f,b}^{\text{mod}} \right)$$

Shapiro-Wilk test

sign test

positive or negative deviations

Kolmogorov-Smirnov test

Cramer-von Mises test

Anderson-Darling test

$Z_K, Z_C, Z_A$ test

more powerful, based on likelihood ratio

CDF for reactor rates and evolution data

Statistic test

$p$-value = 0.05 $\rightarrow$ confidence level 95%

rates + evolution data

<table>
<thead>
<tr>
<th>Test</th>
<th>HM</th>
<th>EF</th>
<th>HKSS</th>
<th>KI</th>
<th>HKSS-KI</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$</td>
<td>0.21</td>
<td>0.46</td>
<td>0.14</td>
<td>0.78</td>
<td>0.60</td>
</tr>
<tr>
<td>SW</td>
<td>0.37</td>
<td>0.28</td>
<td>0.38</td>
<td>0.69</td>
<td>0.58</td>
</tr>
<tr>
<td>sign</td>
<td>0.03</td>
<td>0.38</td>
<td>0.01</td>
<td>0.38</td>
<td>0.38</td>
</tr>
<tr>
<td>KS</td>
<td>0.08</td>
<td>0.81</td>
<td>0.04</td>
<td>0.82</td>
<td>0.56</td>
</tr>
<tr>
<td>CVM</td>
<td>0.06</td>
<td>0.78</td>
<td>0.03</td>
<td>0.76</td>
<td>0.47</td>
</tr>
<tr>
<td>AD</td>
<td>0.07</td>
<td>0.72</td>
<td>0.03</td>
<td>0.76</td>
<td>0.47</td>
</tr>
<tr>
<td>$Z_K$</td>
<td>0.001</td>
<td>0.22</td>
<td>0.0002</td>
<td>0.15</td>
<td>0.03</td>
</tr>
<tr>
<td>$Z_C$</td>
<td>0.11</td>
<td>0.60</td>
<td>0.04</td>
<td>0.86</td>
<td>0.62</td>
</tr>
<tr>
<td>$Z_A$</td>
<td>0.14</td>
<td>0.44</td>
<td>0.06</td>
<td>0.77</td>
<td>0.40</td>
</tr>
</tbody>
</table>

EF model is the best summation model; KI model is the best conversion model.
Part 6:
Summary
Summary

• Updated IBD yields including high energy regions.

• Comparison of different fitting method
  With improved fitting method (Method C), the RAA seems smaller for all models (for HM, $2.5\sigma \rightarrow 1.9\sigma$) avoiding the PPP successfully.

• As for the best-fit model, EF model is the best summation model, and KI model is the best conversion model.

• The KI measurement can pull down the rate deficit, which implies the reactor antineutrino anomaly might be caused by mis-normalization in ILL measurements. (need other experiments to confirm)

• Shape anomaly (“5 MeV Bump”) is still not solved.
Thanks!
Backup
Oscillation

HM

KI

$\Delta m^2_{41}$

$\sin^2 2\theta_{ee}$

$[\text{eV}^2]$
Oscillation

Reactor Rates – 3σ
- Bugey-4 (1994)
- Rovno91 (1991)
- Rovno88 (1988)
- Bugey-3 (1995)
- Gosgen (1986)
- ILL (1995)
- Krasnoyarsk (1987–99)
- SRP (1996)
- Nucler (2016)
- STEREO (2020)
- Chocz (1999)
- Palo Verde (2001)
- Daya Bay (2018)
- RENO (2018)
- Double Chooz (2016)

Combined 1σ
- 1σ
- 2σ
- 3σ

Combined
- Combined