Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay

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Reactor Antineutrino

>99.9% antineutrinos are the fission products of $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$

$O(10^{20})$ fissions / second

~6 antineutrinos / fission

Most powerful man-made neutrino source
Reactor Antineutrino Anomaly
Missing Reactor Antineutrinos?

\[
R_{DYB} = 0.946 \pm 0.020 \text{ (exp.)}
\]
\[
R_{ALL} = 0.943 \pm 0.08 \text{ (exp.)} \pm 0.023 \text{ (model)}
\]

Daya Bay is consistent with past reactor anti-nu experiments. Huber-Mueller model over-estimated the flux by \(~6\%)
6 x 2.9 GWth
Antineutrino Detectors (ADs)

**Inverse ß-decay (IBD)**

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

\[ n + ^x Gd \rightarrow ^{x+1} Gd + \gamma \]

**Prompt positron**
Carries antineutrino energy
\[ E_{e^+} \approx E_\nu - 0.8 \text{ MeV} \]

**Delayed neutron capture**
~30 µs for 0.1% Gd
Allows tagging a high purity sample of antineutrinos

*Example: Daya Bay Detector*
Daya Bay: Largest Sample of $\bar{\nu}_e$ Interactions

Daya Bay @ EPS 2017
Sterile neutrino search, X. Qian (talk)
Oscillation results, M.C. Chu (poster)
Lorentz Violation search, A. Higuera (poster)
Cosmogentic neutron production, J. Cheng (poster)

mid-2015: ~2.2M candidates at the near sites
Evolution of Reactor $\bar{\nu}_e$ Flux

- Fuel composition evolves over time
- Expected more anti-$\nu$ produced from $^{235}\text{U}$ fission chain than $^{239}\text{Pu}$
  \[ \Rightarrow \text{Changes in anti-$\nu$ flux} \]

**Effective fission fraction ($F_i$)**

Weighted by power ($W$), survival probability ($p$), baseline ($L$) over 6 reactor cores

\[
F_i(t) = \sum_{r=1}^{6} \frac{W_{th,r}(t) \bar{p}_r f_{i,r}(t)}{L_r^2 \bar{E}_r(t)} \Bigg/ \sum_{r=1}^{6} \frac{W_{th,r}(t) \bar{p}_r}{L_r^2 \bar{E}_r(t)}
\]

- Binned in 8 groups
Daya Bay Results

Unambiguous Fuel-dependent Variation (at 10 s.d.)

Absolute flux prediction is 5.4% higher.
Daya Bay Results
Flux Evolution (cont.)

Daya Bay
\[ \frac{d\sigma}{dF_{239}} = -1.86 \pm 0.18 \]

Huber-Mueller Model
\[ \frac{d\sigma}{dF_{239}} = -2.46 \pm 0.06 \]

[units: \(10^{-43} \text{ cm}^2 / \text{fission}\)]

- total flux prediction is 5.4% higher
- predicted magnitude of fuel-dependent variation is 7.8% higher too
Daya Bay Results
Fits to Individual Isotopes $^{235}\text{U} & ^{239}\text{Pu}$

Assume loose (10\%) uncertainties on sub-dominant $^{238}\text{U} & ^{241}\text{Pu}$
(central values taken from Huber-Mueller model)

Daya Bay
$\sigma_{235} = 6.17 \pm 0.17$
$\sigma_{239} = 4.27 \pm 0.26$

Huber-Mueller model
$\sigma_{235} = 6.69 \pm 0.15$
$\sigma_{239} = 4.36 \pm 0.11$

Overestimated contribution from $^{235}\text{U}$?
Possible explanations to the reactor antineutrino anomaly:

1. solely incorrect prediction on $^{235}$U
   - favored by Daya Bay data with (2-side) p-value 0.68
2. solely incorrect prediction on $^{239}$Pu
   - disfavored at 3.2σ C.L.
3. equal deficit on all isotopes
   - disfavored at 2.8σ C.L.

Daya Bay results suggest an overestimation of antineutrino flux from $^{235}$U in reactor models.
Daya Bay Results
Evolution of Energy Spectrum

- Same analysis in 4 different energy bins
- Energy-dependent evolution is observed
  - change in spectral shape as fuel composition evolves
- first unambiguous measurements of this behavior
  - excluded no spectral change hypothesis by 5.1σ
Daya Bay Results

How about the spectral discrepancy?

No major indication that ‘bump’ data-model discrepancy comes from a particular isotope.
Conclusions

- Daya Bay observed unambiguous flux and energy spectrum variations w.r.t. fuel composition evolution
- Daya Bay data suggests an overestimation antineutrino flux from 235U in reactor models
  - might explain the reactor antineutrino anomaly
- Improvements in systematic uncertainties (e.g. detection efficiency) and increase in statistics could further strengthen the claim