Reactor antineutrino fluxes: status and challenges

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Neutrinos from fission

\[ N = 50 \]

\[ N = 82 \]

\[ Z = 50 \]

\[ ^{235}\text{U} \]

\[ ^{239}\text{Pu} \]

stable

fission yield

8E-5 0.004 0.008
### β-branches

<table>
<thead>
<tr>
<th>I(β)</th>
<th>Logft</th>
<th>100% I(β)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0005 6.38</td>
<td>(1,2+)</td>
<td>6143.4</td>
</tr>
<tr>
<td>0.0063 6.58</td>
<td>(1,2+)</td>
<td>5838.3</td>
</tr>
<tr>
<td>0.0040 7.04</td>
<td>(1,2+)</td>
<td>5625.6</td>
</tr>
<tr>
<td>0.0130 6.77</td>
<td>(1,2+)</td>
<td>5408</td>
</tr>
<tr>
<td>0.0110 7.43</td>
<td>(1,2+)</td>
<td>5196.6</td>
</tr>
<tr>
<td>0.0110 7.60</td>
<td>(1,2+)</td>
<td>5196.6</td>
</tr>
<tr>
<td>0.013 7.70</td>
<td>(1,2+)</td>
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</tr>
<tr>
<td>0.012 8.07</td>
<td>(1,2+)</td>
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</tr>
<tr>
<td>0.081 7.37</td>
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<td>0.041 7.92</td>
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<tr>
<td>0.043 9.72</td>
<td>(1,2+)</td>
<td>5196.6</td>
</tr>
<tr>
<td>0.44 8.97</td>
<td>(1,2+)</td>
<td>5196.6</td>
</tr>
<tr>
<td>1.26 8.97</td>
<td>(1,2+)</td>
<td>5196.6</td>
</tr>
<tr>
<td>95.5 5.591</td>
<td>(1,2+)</td>
<td>5196.6</td>
</tr>
</tbody>
</table>

\[ Q_{\text{gs}} = 7896 \text{ keV} \]
$\beta$-spectrum from fission

$^{235}\text{U}$ foil inside the High Flux Reactor at ILL

Electron spectroscopy with a magnetic spectrometer

Same method used for $^{239}\text{Pu}$ and $^{241}\text{Pu}$

For $^{238}\text{U}$ recent measurement by Haag et al., 2013

**Virtual branches**

1 – fit an allowed $\beta$-spectrum with free normalization $\eta$ and endpoint energy $E_0$ the last $s$ data points
2 – delete the last $s$ data points
3 – subtract the fitted spectrum from the data
4 – goto 1

Invert each virtual branch using energy conservation into a neutrino spectrum and add them all. 

*e.g.* Vogel, 2007
Corrections to $\beta$-shape

There are numerous correction to the $\beta$-spectrum

Many of these correction can be accurately computed for a allowed decays.
Reactor antineutrino fluxes

Shift with respect to ILL results, due to
a) different effective nuclear charge distribution
b) branch-by-branch application of shape corrections

Mueller et al., 2011; Huber 2011
In Mueller et al. 2011 an attempt was made to compute the neutrino spectrum from fission yields and information on individual $\beta$ decay branches from databases.
A priori calculations

Updated $\beta$-feeding functions from total absorption $\gamma$ spectroscopy (safe from pandemonium) for the isotopes: $^{102,104,105,106,107}\text{Tc}$, $^{105}\text{Mo}$ and $^{102}\text{Nb}$

The calculation for $^{238}\text{U}$ agrees within 10% with measurement of Haag et al.

Still a 10-20% discrepancy with the measured total $\beta$-spectra.

Fallot et al., 2012
Forbidden decays

Hayes et al., 2013 point out that in forbidden decays a mixture of different operators are involved.

Large source of uncertainty.
Forbidden decays

$e, \bar{\nu}$ final state can form a singlet or triplet spin state $J=0$ or $J=1$

Allowed:
s-wave emission ($l = 0$)

Forbidden:
p-wave emission ($l = 1$) or $l > 1$

Significant dependence on nuclear structure in forbidden decays $\rightarrow$ large uncertainties!
Recent neutrino measurements

In Daya Bay, RENO and Double Chooz, the distance is such that all sterile oscillations are averaged away – no confusion between nuclear physics and new physics.

The statistics in the Daya Bay near detectors is around 1 million events.

In combination, this should provide a good test of our ability to compute reactor fluxes.
The 5 MeV bump

- Seen by all three reactor experiments
- Tracks reactor power
- Seems independent of burn-up
Explanations?

Direct summation of latest ENSDF database with allowed beta-spectrum shape Sonzogni et al., 2016

This direct summation, as all other direct summations, does not agree with the Schreckenbach measurement.
What happened?

Fission yield data has been suspected previously Hayes et al. 2015 and this what Sonzogni et al., 2016 found:

Who is the odd-one-out?

Fission yields for germanium-86 wrong in ENDF/B but not in JEFF.
Uranium-238?

Hayes and Vogel, 2016 point out that fast neutron fission of $^{238}$U could be responsible for the bump

If true, NO bump should be seen a reactors running on HEU (nearly pure $^{235}$U).
Neutron spectrum?

Hayes and Vogel, 2016 point also out that the neutron spectrum is important.

If true, NO bump should be seen a reactors running on HEU (nearly pure $^{235}$U).
A coincidence?

Based on JEFF fission yields and using ENSDF spin-parity assignments

If true, bump should be about the same in all reactors.
Different reactors

Optimistic flux errors (per isotope) from Huber, 2011 and bump put by hand to match Daya Bay result.

![Graph showing MOX3 - true bump in U-238 and Bump in Pu-239 with data points and fitted curves.]

<table>
<thead>
<tr>
<th>Fit/True</th>
<th>$^{235}$U</th>
<th>$^{238}$U</th>
<th>$^{239}$Pu</th>
<th>$^{241}$Pu</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{235}$U</td>
<td>-</td>
<td>&gt; 4</td>
<td>&gt; 4</td>
<td>&gt; 4</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>&gt; 4</td>
<td>-</td>
<td>3.8</td>
<td>0.6</td>
</tr>
<tr>
<td>$^{239}$Pu</td>
<td>&gt; 4</td>
<td>3.7</td>
<td>-</td>
<td>&gt; 4</td>
</tr>
<tr>
<td>$^{241}$Pu</td>
<td>&gt; 4</td>
<td>0.7</td>
<td>&gt; 4</td>
<td>-</td>
</tr>
</tbody>
</table>

Requires good statistics: 5 ton, 40% efficient, 1 year data taking.

Huber, 2016, see also Buck et al., 2015
Summary

Reactors are complex neutrino sources – our current understanding from conversion calculations is at the 5% level.

Massive amounts of data go into direct calculations – details matter and experimental programs (TAGS) underway to improve crucial beta-decay information.

New neutrino data will have to have systematics around 1% or better to make a real difference.

The bump is amenable to experiments, but requires good statistics and the right reactor.

The Daya Bay data set will remain a benchmark which we need to exploit to its fullest.
Questions?