Latest Results on Reactor Neutrino Experiments

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Outline

• Reactor neutrinos
  – Neutrino flux and detection
  – Neutrino oscillation

• Measurement of $\theta_{13}$
  – Current experiments
  – Results

• Measurement of reactor neutrino flux
  – Reactor neutrino rate anomaly
  – Reactor neutrino spectrum deviation
Reactor neutrino flux

- Pure electron antineutrinos $\bar{\nu}_e$
- $2 \times 10^{20} \ \bar{\nu}_e$/second/GW\textsubscript{th}
- Produced by fission products from four major isotopes: $^{235}$U, $^{238}$U, $^{239}$Pu, and $^{241}$Pu
- $\sim 6 \ \bar{\nu}_e$ per fission
Neutrino detection

Detect neutrino via inverse beta decay (IBD)

\[ \bar{\nu}_e + p \rightarrow e^+ + n \text{ (prompt)} \]
\[ \rightarrow + p \rightarrow D + \gamma \text{ (2.2 MeV delayed)} \]
\[ \rightarrow + \text{Gd} \rightarrow \text{Gd}^* \rightarrow \text{Gd} + \gamma's \text{ (8 MeV delayed)} \]

Prompt signal: a proxy of neutrino energy
Delayed signal: a tag of neutrino event
Reactor neutrino oscillation

- $\bar{\nu}_e \rightarrow \bar{\nu}_e$ disappearance
- No dependence on CP phase and $\theta_{23}$
- 2-km oscillation: $\theta_{13}$ and $\Delta m^2_{ee}$
- 50-km oscillation: $\theta_{12}$ and $\Delta m^2_{21}$
- JUNO can observe both $\Delta m^2_{ee}$ and $\Delta m^2_{21}$ driven oscillations, and is sensitivity to neutrino mass ordering (talk by Monica Sisti)
Glorious history

• Discovery of neutrinos by Clyde L. Cowan and Frederick Reines in 1956
• First confirmation of solar neutrino oscillation by KamLAND in 2002
• Observation of non-zero $\theta_{13}$ at Daya Bay, RENO, Double Chooz in 2012
Measurement of $\theta_{13}$
Current experiments

Daya Bay

RENO

Double Chooz
Experiment layout

- Common feature: near/far relative measurement
Detector design

- Common three-zone design: GdLS – LS – Buffer

<table>
<thead>
<tr>
<th>Design</th>
<th>AD PMTs</th>
<th>Energy resolution</th>
<th>Muon PMTs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double Chooz</td>
<td>390 x 10&quot;</td>
<td>6% at 1 MeV</td>
<td>78 x 8&quot;</td>
</tr>
<tr>
<td>RENO</td>
<td>354 x 10&quot;</td>
<td>7% at 1 MeV</td>
<td>67 x 10&quot;</td>
</tr>
<tr>
<td>Daya Bay</td>
<td>192 x 8&quot;</td>
<td>8% at 1 MeV</td>
<td>288 x 8&quot; (near)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>388 x 8&quot; (far)</td>
</tr>
</tbody>
</table>
Near/far identical detector

- Near/far: reduce neutrino flux uncertainty
- Identical detector: cancel detection efficiency uncertainty

\[
\frac{N_f}{N_n} = \left( \frac{N_{p,f}}{N_{p,n}} \right) \left( \frac{L_n}{L_f} \right)^2 \left( \frac{\varepsilon_f}{\varepsilon_n} \right) \left( \frac{P_{\text{sur}}(E, L_f)}{P_{\text{sur}}(E, L_n)} \right)
\]

- Unique feature in Daya Bay: side-by-side detectors ➔ Verification of identical detectors: side-by-side detectors observe ‘equal’ number of neutrinos (with correction of baseline difference).

![Graph showing ratio of e- rates with observed and expected ratios for different configurations.](image)
Discovery of non-zero $\theta_{13}$

Double Chooz
with only a far detector
(Nov. 2011)

Daya Bay
(March 2012)

RENO
(April 2012)

$\sin^2 2\theta_{13} = 0.086 \pm 0.041 \text{ (stat)}$
$\pm 0.030 \text{ (syst)}$

$\sin^2 2\theta_{13} = 0.092 \pm 0.016 \text{ (stat.)}$
$\pm 0.005 \text{ (syst.)}$

$\sin^2 2\theta_{13} = 0.103 \pm 0.013 \text{ (stat.)}$
$\pm 0.011 \text{ (syst.)}$
1958-Day results of Daya Bay

- World-leading results: $\sin^2 2\theta_{13}$ uncertainty is 3.4% and $|\Delta m^2_{ee}|$ uncertainty is 2.8%
- Statistical uncertainty contributes 60% for $\sin^2 2\theta_{13}$ and 50% for $|\Delta m^2_{ee}|$

\[\sin^2 2\theta_{13} = 0.0856 \pm 0.0029\]
\[\Delta m^2_{ee} = (2.522^{+0.068}_{-0.070}) \times 10^{-3} \text{ eV}^2\]
\[\Delta m^2_{32} = (2.47 \pm 0.07) \times 10^{-3} \text{ eV}^2 \text{ (NO)}\]
\[\Delta m^2_{32} = (-2.58 \pm 0.07) \times 10^{-3} \text{ eV}^2 \text{ (IO)}\]

Latest results of Double Chooz and RENO

- Double Chooz
  \[ \sin^2 2\theta_{13} = 0.105 \pm 0.014 \]

- RENO
  \[ \sin^2 2\theta_{13} = 0.0896 \pm 0.0067 \]
  \[ |\Delta m^2_{ee}| = 2.68 \pm 0.14 \times 10^{-3} \text{ eV}^2 \]

<table>
<thead>
<tr>
<th>Data sample in latest results</th>
<th>Near detectors</th>
<th>Far detectors</th>
<th>B/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daya Bay</td>
<td>3.5 million</td>
<td>0.5 million</td>
<td>~ 2%</td>
</tr>
<tr>
<td>RENO</td>
<td>0.85 million</td>
<td>0.1 million</td>
<td>~ 5%</td>
</tr>
<tr>
<td>Double Chooz</td>
<td>0.21 million</td>
<td>0.09 million</td>
<td>~ 9%</td>
</tr>
</tbody>
</table>
\[ \sin^2 2\theta_{13} \text{ precision} \]

- Best precision at Daya Bay
- Still dominated by statistics
- Great success and rapid improvement on the precision: 20% \( \rightarrow \) 3.4% from 2012 to 2019
- Measured \( \Delta m^2_{31} \) with spectral information
  - Comparable precision with T2K/MINOS
- More data taking
  - Daya Bay: 2011-2020
  - Double Chooz: 2011-2017
  - RENO: 2011-2021(?)
- Ultimate precision: 3% from Daya Bay
Measurement of reactor neutrino flux
Reactor antineutrino anomaly

- New prediction of reactor neutrino flux in 2011: Huber-Mueller model
- Reactor Antineutrino Anomaly (RAA), *PRD 83 (2011) 073006*
  - Observation/prediction = 0.943, a 6% deficit.
- Possible reasons
  - Sterile neutrinos?
  - Incorrect model prediction? (uncertainty underestimated?)
Neutrino flux measurement

- Near/far relative measurements in oscillation cancel the flux uncertainty.
- The observed number of IBD events in near detectors yields absolute measurement of neutrino flux.
- Uncertainty dominated by detection efficiency.
- Both Daya Bay and RENO confirmed the deficit in RAA.

Daya Bay: Data/Huber-Mueller = 0.952 ± 0.014(exp.) ± 0.023 (model)

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Correlated</td>
</tr>
<tr>
<td>Target protons</td>
<td>-</td>
</tr>
<tr>
<td>Flasher cut</td>
<td>99.98%</td>
</tr>
<tr>
<td>Prompt Energy cut</td>
<td>99.8%</td>
</tr>
<tr>
<td>Multiplicity cut</td>
<td>-</td>
</tr>
<tr>
<td>Capture time cut</td>
<td>98.7%</td>
</tr>
<tr>
<td>Delayed neutron cut</td>
<td>81.48%</td>
</tr>
<tr>
<td>Live time</td>
<td>-</td>
</tr>
<tr>
<td>Combined</td>
<td>80.2%</td>
</tr>
</tbody>
</table>
Spectrum measurement

- Absolute spectral shape is **NOT** consistent with the prediction. A bump is observed in 4-6 MeV of the prompt energy.

Daya Bay: PRL 123 (2019) no.11, 111801

Also observed at Double Chooz, NEOS
Reactor Fuel Evolution in Daya Bay

- Which isotope(s) is (are) responsible for anomalies: \(^{235}\text{U}, ^{239}\text{Pu}, ^{238}\text{U},\) and \(^{241}\text{Pu}\)
- IBD yield depends on \(F_{^{239}}\), negative slope
- \(^{235}\text{U}\) is the main contributor to the reactor flux anomaly

PRL 118, 251801 (2017)

\(^{235}\text{U}: 74\% \rightarrow 45\%
^{239}\text{Pu}: 16\% \rightarrow 38\%\)
Reactor Fuel Evolution in RENO

- Similar conclusions observed in RENO
  - Negative (positive) slope of IBD yield vs. $F_{239}$ ($F_{235}$) is observed
  - Larger $^{235}$U deficit than $^{239}$Pu

\[
\frac{y_{235}}{y_{239}} = 6.15 \pm 0.19 \text{ (2.8\sigma deficit)}
\]
\[
\frac{y_{239}}{y_{235}} = 4.18 \pm 0.26 \text{ (0.8\sigma deficit)}
\]

PRL 122 (2019) no.23, 232501
Spectrum Evolution in Daya Bay

- Antineutrino spectrum depends on fission fraction

Results in
PRL 118 251801 (2017)

Observed spectrum evolution in a coarse binning
Extracted $^{235}\text{U}$ and $^{239}\text{Pu}$ Spectra

- **IBD yield comparison**
  - $^{235}\text{U}$: data/prediction = 0.92 ± 0.023(exp.) ± 0.021(model)
  - $^{239}\text{Pu}$: data/prediction = 0.99 ± 0.057(exp.) ± 0.025(model)

- First measurement of $^{235}\text{U}$ spectrum in commercial reactors
- First measurement of $^{239}\text{Pu}$ spectrum
- Spectral shape comparison after normalizing the model
  - Similar bump excess for $^{235}\text{U}$ and $^{239}\text{Pu}$ in 4—6 MeV
  - Significance of local deviations: 4σ for $^{235}\text{U}$, only 1.2σ for $^{239}\text{Pu}$ due to larger uncertainty

Daya Bay: PRL 123 (2019) no.11, 111801
Bump or Deficit?

• Compare the spectrum without normalization for $^{235}\text{U}$
  
  – The 8% deficit of $^{235}\text{U}$ depends on the energy
  
  – 11% deficit below 4 MeV (4σ) for $^{235}\text{U}$ spectrum $\Rightarrow$ 8% overall rate deficit
Sterile neutrinos?

- Reactor Antineutrino Anomaly
- LSND anomaly: excess of events in neutrino beam, similar results in MiniBooNE.
- Gallium anomaly: deficit of $\nu_e$ at meter level

Search for light (1 eV$^2$) sterile neutrinos, details in other talks at this conference

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reactor Power/Fuel</th>
<th>Overburden (mwe)</th>
<th>Detection Material</th>
<th>Segmentation</th>
<th>Optical Readout</th>
<th>Particle ID Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>DANSS (Russia)</td>
<td>3000 MW LEU fuel</td>
<td>~50</td>
<td>Inhomogeneous PS &amp; Gd sheets</td>
<td>2D, ~5mm</td>
<td>WLS fibers.</td>
<td>Topology only</td>
</tr>
<tr>
<td>NEOS (South Korea)</td>
<td>2800 MW LEU fuel</td>
<td>~20</td>
<td>Homogeneous Gd-doped LS</td>
<td>none</td>
<td>Direct double ended PMT</td>
<td>recoil PSD only</td>
</tr>
<tr>
<td>nuLat (USA)</td>
<td>40 MW $^{235}$U fuel</td>
<td>few</td>
<td>Homogeneous $^6$Li doped PS</td>
<td>Quasi-3D, 5cm, 3-axis Opt. Latt</td>
<td>Direct PMT</td>
<td>Topology, recoil &amp; capture PSD</td>
</tr>
<tr>
<td>Neutrino4 (Russia)</td>
<td>100 MW $^{235}$U fuel</td>
<td>~10</td>
<td>Homogeneous Gd-doped LS</td>
<td>2D, ~10cm</td>
<td>Direct single ended PMT</td>
<td>Topology only</td>
</tr>
<tr>
<td>PROSPECT (USA)</td>
<td>85 MW $^{235}$U fuel</td>
<td>few</td>
<td>Homogeneous $^6$Li-doped LS</td>
<td>2D, 15cm</td>
<td>Direct double ended PMT</td>
<td>Topology, recoil &amp; capture PSD</td>
</tr>
<tr>
<td>SoLiD (UK Fr Bel US)</td>
<td>72 MW $^{235}$U fuel</td>
<td>~10</td>
<td>Inhomogeneous $^6$LiZnS &amp; PS</td>
<td>Quasi-3D, 5cm multiplex</td>
<td>WLS fibers</td>
<td>topology, capture PSD</td>
</tr>
<tr>
<td>Chandler (USA)</td>
<td>72 MW $^{235}$U fuel</td>
<td>~10</td>
<td>Inhomogeneous $^6$LiZnS &amp; PS</td>
<td>Quasi-3D, 5cm, 2-axis Opt. Latt</td>
<td>Direct PMT/ WLS Scint.</td>
<td>topology, capture PSD</td>
</tr>
<tr>
<td>Stereo (France)</td>
<td>57 MW $^{235}$U fuel</td>
<td>~15</td>
<td>Homogeneous Gd-doped LS</td>
<td>1D, 25cm</td>
<td>Direct single ended PMT</td>
<td>recoil PSD</td>
</tr>
</tbody>
</table>

Table from Nathaniel Bowden @ Neutrino 2016
Sterile neutrino search in ~km experiments

- Multiple-baseline in Daya Bay has potential in search for sterile neutrinos
- Improved sensitivity when combined with accelerator experiments
- Reject the regions (< 2 eV^2) in LSND and two global fit results with 99% C.L.

Daya Bay, Nufact 2019

RENO, AAP 2019

Daya Bay + MINOS, Nufact 2019
Summary

• Great success and rapid progress in the measurement of $\sin^2 2\theta_{13}$ with $\sim$km reactor neutrino experiments
  – Ultimate precision on $\sin^2 2\theta_{13}$ to reach 3%

• Anomalies observed both in the reactor neutrino rate and spectrum suggest problems in the model predictions.

• Experiments to search for sterile neutrinos at 10s meter baselines are active.

• JUNO with goal to determine the neutrino mass ordering is under construction, and is expected to take data in 2021.
Thanks