Reactor Neutrino Experiments and Anomalies

Jun Cao
Institute of High Energy Physics

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Content

- Reactor neutrino flux and spectrum
  - Rate anomaly
  - Spectrum anomaly
  - More?
- Measuring $\theta_{13}$ and $\Delta m^2_{ee}$
  - Daya Bay, Double Chooz, RENO
- JUNO status
  - Mass hierarchy & precision measurement of $\theta_{12}$, $\Delta m^2_{21}$ and $\Delta m^2_{31}$ with reactor
Reactor Neutrinos

Discovery of $\nu$

1953, Hanford, 0.3 ton
1956, Savannah River, 4.2 ton

Mass Hierarchy, Precision meas.
2020, JUNO, 20,000 ton

Non-zero $\theta_{13}$

Early searches for oscillation
1980 Savannah, YES
1980 ILL, NO
1984 Bugey, YES
1986 Gosgen, NO
1995 Bugey-3, NO

Reactor $\nu$ spectra $\sim 2\%$

1997, CHOOZ, 8 ton
2000, Palo Verde, 12 ton

$\sin^2 2\theta_{13} < 0.15$

2012,
Daya Bay, 160 ton
Double Chooz, 16 ton
RENO, 32 ton

Mass Hierarchy, Precision meas.
2020, JUNO, 20,000 ton

Non-zero $\theta_{13}$

Very short baseline exp. for sterile $\nu$

2002, KamLAND, 1000 ton
Reactor Neutrino Flux

- Neutrinos from subsequent $\beta$-decays of fission fragments.
- PWR (Pressurized Water Reactor) as example. 
  (3-5)% U-235 enrichment. Other is U-238.

\[ S(E_\nu) = \sum_i f_i S_i(E_\nu) \]

- U-235 depletion
- Pu-239 breeding

Isotope evolution

Neutrino spectra, ILL

More neutrinos from a U-235 fission than Pu-239

Visible spectrum,
Spectra of Isotopes

- **Ab initio:** Nuclear database, Σ fragments, Σ chains, Σ branches → 10% uncertainty (e.g. Vogel et al., PRC24, 1543 (1981)).

- **Conversion:** ILL measured the β-spectra → convert to neutrino spectra
  - ILL spectra: Use spectra of 30 virtual (allowed) decays, fit amplitude and endpoints (ILL-Vogel spectra)
  - Mueller: 90% ab initio + 10% fit → rate anomaly
  - Huber: fit w/ improved nuclear effects (Huber-Mueller spectra)

K. Schreckenbach et al. PLB118, 162 (1985)
A.A. Hahn et al. PLB160, 325 (1985)

Shape verified by Bugey-3 data
Normalization by Bugey-4, 1.6%
- ILL spectra agree w/ data
- 2011, Huber-Mueller spectra higher than data by 6%
- Sterile neutrino?

G. Mention et al.  
Phys. Rev. D83 (2011) 073006
Daya Bay, Double Chooz, RENO for $\theta_{13}$

- Daya Bay
- Double Chooz
- RENO for $\theta_{13}$

- 8.5 GW$_{th}$
- 17.4 GW$_{th}$
- 16.8 GW$_{th}$

- 8t
- 40t
- 40t
- 80t

- 1050 m
- 365 m
- 490 m
- 1650 m

- 290 m
- 1380 m

- 16t
- 16t
## Very Short Baseline Exps.

- Different technologies: (Gd, Li, B) (seg.)(movable)(2 det.)
- Most have sensitivity $0.02 \sim 0.03 \, @\Delta m \sim 1\,eV^2 \, @90\%CL$

<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>

Talk by Nathaniel Bowden @NEUTRINO2016
Detecting Reactor Antineutrino

- $\nu$-e scattering
- Inverse beta decay (IBD)

**Prompt signal**

$$ e^+ + e^- \rightarrow 2\gamma $$

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

**Delayed signal, Capture on H (2.2 MeV, $\sim$180$\mu$s) or Gd (8 MeV, $\sim$30$\mu$s)**

$$ E(\bar{\nu}_e) = E_{\text{prompt}} + Q - m_e $$

$$ \sim E_{\text{prompt}} + 0.8 \text{ MeV} $$

**Graphs:**
- Reconstructed neutron (delayed) capture energy spectrum
- Energy vs. Reaction Energy (MeV)
- Prompt vs. Delayed energy [MeV]

Capture on H

Capture on Gd

0.1% Gd

0.1% Gd
**Daya Bay Absolute Rate Measurement**

Data/(Huber+Mueller): 0.946 ± 0.020

Past global average: 0.942 ± 0.009

Data/(ILL+Vogel): 0.992 ± 0.021

Chin. Phys. C41, 013002 (2017)

Special calibration in Jan. 2017

Stay tuned
Daya Bay Fuel Evolution

- Combined fit for major fission isotopes $^{235}\text{U}$ and $^{239}\text{Pu}$

- $\sigma_{235}$ is 7.8% lower than Huber-Mueller model (2.7% meas. uncertainty)

- $\sigma_{239}$ is consistent with the prediction (6% meas. uncertainty)

- 2.8$\sigma$ disfavor equal deficit (H-M model & sterile hypothesis)

**PRL118, 251801 (2017)**
Published June 19, 2017

Talk by David Martinez in Neutrino session
Reactor Anomaly (Spectrum)

- 5 MeV Bump
- Not due to energy non-linearity
- Not due to sterile $\nu$
- Possibly due to forbidden decays (PRL112: 2021501; PRL114:012502)

Talk by T. Sogo-Bezerra in neutrino session

Unfolding the reactor neutrino spectrum

- Between 1.5 and 7 MeV: 1.0% at 3.5 MeV, 6.7% at 7 MeV
- Above 7 MeV it is larger than 10%.

New prediction besides *ab initio* method and conversion method

W/ the direct measurement, spectra uncertainty comes mainly from energy non-linearity uncertainty (do not double counting): 1% energy scale → 10% uncertainty in spectrum.

Aim at 1% for JUNO → next page
Precision Spectrum with Gas TPC

- How to reach 1% spectrum uncertainty?
- Improving Daya Bay (Stay tuned)
  - Electronics non-linearity
    - 192 channels Flash ADC for AD1. Data taking completed.
  - Liquid scintillator non-linearity
    - Replaced LS in AD1 for JUNO R&D
      - Consequence: Daya Bay from 8 AD to 7 AD since Dec. 2016
    - Testing detector responses with 13 different LS configurations
      (PPO from 0.5g/L to 4g/L, bis-MSB from 0.1-15 mg/L)
      - Building precision Monte Carlo
  - Relative meas. to cancel non-linearity btwn Daya Bay and JUNO
- Other experiments, like PROSPECT (4.5% energy resolution)
- Gas TPC detector at ~20 m from a reactor (Prototyping at IHEP)
  - ν-e scattering
  - High energy resolution (1%/\sqrt{E}, Daya Bay 8%, JUNO 3%)
  - Other motivations: θw, abnormal magnetic moment (to 10^{-12})
\[ \sin^2 2\theta_{13} = [8.41 \pm 0.33] \times 10^{-2} \]

NH: \( \Delta m^2_{32} = [2.45 \pm 0.08] \times 10^{-3} \text{ eV}^2 \)

IH: \( \Delta m^2_{32} = [-2.55 \pm 0.08] \times 10^{-3} \text{ eV}^2 \)

1230 days

PRD 95, 072006 (2017)
Global Comparison

- **DYB**: running to 2020, 3% precision (1.5x stat. in 2018 summer)
- **RENO**: operation funding secured until 2019.2
- **Double Chooz**: at least Jan. 2018
The JUNO Experiment


- 20 kton LS detector
- 3% energy resolution
- 700 m underground
- Rich physics possibilities
  - Reactor neutrino for Mass hierarchy and precision measurement of oscillation parameters
  - Supernovae, DSNB
  - Geo-neutrino
  - Solar neutrino
  - Proton decay
  - Exotic searches

- [http://juno.ihep.ac.cn](http://juno.ihep.ac.cn)

Talks by A. Cabrera (general), H. Li (SN), M. Grassi (sPMT) in neutrino session.
Sensitivity w/ Reactor nu

![Graph showing sensitivity with reactor neutrinos with different prior assumptions and experiment percentages.](image)

<table>
<thead>
<tr>
<th></th>
<th>KamLAND</th>
<th>BOREXINO</th>
<th>JUNO</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
<td>1 kt</td>
<td>0.5 kt</td>
<td>20 kt</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>6%/$\sqrt{E}$</td>
<td>5%/$\sqrt{E}$</td>
<td>3%/$\sqrt{E}$</td>
</tr>
<tr>
<td>Light yield</td>
<td>250 p.e./MeV</td>
<td>511 p.e./MeV</td>
<td>1200 p.e./MeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Statistics</th>
<th>w/ sys.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.54%</td>
</tr>
<tr>
<td>$\Delta m^2_{21}$</td>
<td>0.24%</td>
</tr>
<tr>
<td>$\Delta m^2_{ee}$</td>
<td>0.27%</td>
</tr>
</tbody>
</table>
JUNO Location/Collaboration

71 Institutions, 533 collaborators

- China (32), Thailand (3), Pakistan, Armenia
- Italy (8), Germany (7), France (6), Russia (3), Belgium, Czech, Finland, Slovakia
- Brazil (2), Chile (2), USA (2)
Central detector

Top Tracker (OPERA TT)

Calibration

Water Cherenkov

Electronics

Filling + Overflow

Acrylic Sphere: ID35.4m

Steel Latticed Shell: ID40.1m

Acrylic Sphere: ID: 35.4m
Thickness: 120mm

SSLS: ID: 40.1m
OD: 41.1m

Water pool
ID: 43.5m
Height: 44m
Water Depth: 43.5m

JUNO Detector

Pool ID: 43.5m

Pool Depth: 44m

Acrylic sphere (contracted): 18,000 20” PMT (contracted: Hamamatsu 5K NNVT 15 K)

25,000 3” PMT (contracted: HZCT)

~2000 20” PMT

Water Cherenkov

SS latticed shell
JUNO Progress and Schedule

Ground breaking in Jan. 2015
- slope tunnel done (1265 m)
- vertical shaft done (575 m)
- Delayed by unexpected water

Schedule:
- Detector assembly & installation: 2018-2019
- Filling & data taking: 2020
- Delayed by ~1 year
Central Detector + Muon Detector

- Acrylic sphere: ID 35.4m, thickness: 120mm, >200 pieces of panels bonded on site. 600 t
- Stainless steel: ID 40.1m, OD 41.1m, divided into 30 longitudes and 23 layers, 600 t

Water Čerenkov detector
- ~2000 20” PMT
- 35 kton ultrapure water

Top tracker
- Re-using the OPERA’s Target Tracker. Arrived in China
LS Pilot plant

- Purified 20 ton LAB to test the overall design of the purification system at Daya Bay. Replaced the target LS in one detector
  - Optimization of recipe, Study of radioactivity background
- Target:
  - Optical: >20m A.L @430nm
  - Radio-purity: $10^{-15}$ g/g (U, Th)

Distillation system
Steam stripping system
Water extraction
Ultra-pure nitrogen

LAB storage tank
$\text{Al}_2\text{O}_3$ column
20-inch PMT

- Contracts were signed in 2015
  - 15k MCP-PMT (75%) from NNVT
  - 5k Dynode (25%) from Hamamatsu

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>unit</th>
<th>MCP-PMT (NNVT)</th>
<th>R12860 (Hamamatsu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection Efficiency (QE<em>CE</em>area)</td>
<td>%</td>
<td>27%, &gt; 24%</td>
<td>27%, &gt; 24%</td>
</tr>
<tr>
<td>P/V of SPE</td>
<td></td>
<td>3.5, &gt; 2.8</td>
<td>3, &gt; 2.5</td>
</tr>
<tr>
<td>TTS on the top point</td>
<td>ns</td>
<td>~12, &lt; 15</td>
<td>2.7, &lt; 3.5</td>
</tr>
<tr>
<td>Rise time/ Fall time</td>
<td>ns</td>
<td>R<del>2, F</del>12</td>
<td>R<del>5, F</del>9</td>
</tr>
<tr>
<td>Anode Dark Count</td>
<td>Hz</td>
<td>20K, &lt; 30K</td>
<td>10K, &lt; 50K</td>
</tr>
<tr>
<td>After Pulse Rate</td>
<td>%</td>
<td>1, &lt;2</td>
<td>10, &lt; 15</td>
</tr>
<tr>
<td>Radioactivity of glass</td>
<td>ppb</td>
<td>238U:50</td>
<td>238U:400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>232Th:50</td>
<td>232Th:400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40K: 20</td>
<td>40K: 40</td>
</tr>
</tbody>
</table>

- MCP-PMT: 648 tubes, 28% D.E.
- Dynode-PMT: 960 tubes, 27% D.E.

Warehouse near JUNO
Received 1600 PMTs

Mass testing equip from Germany
Small PMT

- 25,000 3-inch PMTs, contracted to HZC (China)
- Work together with the 20-in PMT as a double calorimetry
  - Increase photon statistics by 3%
  - Measure energy via “photon counting”, control systematics
  - muon tracking, supernova detection …
Summary

- Ultimate precision of $\sin^2 2\theta_{13}$ will reach $\sim 3\%$.
- Flux and spectrum anomalies are also interesting.
  - Fuel evolution shows deficit from U-235
- Systematics improvements of DYB expected with special calibration, FADC, LS replacement.
- Major progresses in JUNO construction
  - 35.4-meter acrylic sphere
  - Super-transparent liquid scintillator (>20m)
  - High DE PMTs (27%)

Thanks!