Neutrino Physics with Reactors

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Workshop for Neutrino Programs with facilities in Japan, J-Parc, Aug. 5, 2015
Reactor Neutrinos

- Discovery of neutrino in 1956
- Small $\theta_{13}$ in 1990s
- Limit on neutrino magnetic moment
- Observation of reactor $\bar{\nu}_e$ disappearance in 2003
- Discovery of non-zero $\theta_{13}$ in 2012
- Mass hierarchy and precision measurements
- Sterile neutrinos, Magnetic moment, …

Reactor Neutrinos

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Outline

- Measuring $\theta_{13}$ and $\Delta m^2_{ee}$
  - Daya Bay
  - Double Chooz
  - RENO

- Determining Mass Hierarchy & precision measurement of $\theta_{12}$, $\Delta m^2_{21}$ and $\Delta m^2_{31}$
  - JUNO
  - RENO-50

- Search for sterile neutrinos
- Measuring reactor neutrino flux and spectrum
- Search for abnormal magnetic moment
- Summary
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, ~180\(\mu\)s) or Gd (8 MeV, ~30\(\mu\)s)**

0.1% Gd by weight

Near site: ~thousands IBD/day
Far site: ~hundreds IBD/day
Measuring $\theta_{13}$ and $\Delta m^2_{ee}$
- Daya Bay
- Double Chooz
- RENO
The Daya Bay Experiment

- 6 reactor cores, 17.4 MWth
- Relative measurement
  - 2 near sites, 1 far site
- Multiple detector modules
- Good cosmic shielding
  - 250 m.w.e @ near sites
  - 860 m.w.e @ far site
- Redundancy
Double Chooz

Daya Bay

Double Chooz

Chooz Reactors
4.27GW_th x 2 cores

Near Detector
L = 400m
10m^3 target
120m.w.e.
2013 ~

Far Detector
L = 1050m
10m^3 target
300m.w.e.
April 2011 ~
Double Chooz Near Site

- the second detector was inaugurated on September 25, 2014

Fill this summer ➔
Neutrinos in September/October

Buffer closed
main tank to be closed this week
RENO

16t, 120 MWE

Near Detector

6 cores
16.5 GW

Daya Bay

RENO

Double Chooz

Far Detector

16t, 450 MWE
Double Chooz

- 2011.4-2013.1 (460 days). No near site data until 2014.9
- Used spectrum analysis for both nGd & nH events
- Used Reactor-off data to directly measure backgrounds
- New analysis ➞ less background and uncertainties, better flux prediction($^{238}$U), better energy reconstruction, ...

### Reactor Rate Modulation

- Background rate: 1.38 $^{+0.14}_{-0.16}$ day$^{-1}$
- $\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$ (stat+sys)
- DC-III (n-Gd) Preliminary

### Data
- $\chi^2$/doF = 54/7
- Best fit $\chi^2$/doF = 4.2/6

### Observations
- Expected rate (day$^{-1}$)
- Observed rate (day$^{-1}$)

### Flux Prediction
- R+S: $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$, BG rate: 1.38 ± 0.14 day$^{-1}$
- RRM: $\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$, BG rate: 1.56 ± 0.17 day$^{-1}$
- RRM (no BG constraint): $\sin^2 2\theta_{13} = 0.060 ± 0.039$, BG rate: 0.93 ± 0.40 day$^{-1}$
RENO

- 2011.8-2013.12 (800 days)
- Also reactor rate modulation analysis
- Shape analysis is on the way
- Reduced systematics but worsened by $^{252}$Cf contamination

$\sin^2 2\theta_{13} = 0.090 \pm 0.008\text{(stat.)} \pm 0.008\text{(syst.)}$

- 5 years of data:
  1. Rate-only: $\pm 7\%$
     - stat. error: $\pm 0.008 \rightarrow \pm 0.005$
     - syst. error: $\pm 0.010 \rightarrow \pm 0.005$
  2. Rate+shape: $\pm 5\%$

Rate+shape (5 % precision)
Daya Bay

- 2011.12-2013.11 (621 days)
- Detailed and precise corrections for E non-linearity
- Continue to improve: reduced backgrounds and systematics
- Rate + Shape analysis for nGd events
- Rate analysis for nH events

Relative energy scale difference: <0.2%  Non-linearity uncertainty 1%

0.5%  2%

C. Zhang, Neutrino14 & W. Wang, ICHEP14
Daya Bay Results

\[ \sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005} \]

\[ |\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3} \text{eV}^2 \]

\[ \chi^2/NDF = 134.7/146 \]

\[ \Delta (\sin^2 2\theta_{13})/\sin^2 2\theta_{13} \sim 6\% \]

\[ \Rightarrow \text{best among all mixing angles} \]

\[ \Delta (\Delta m^2_{ee})/\Delta m^2_{ee} \sim 5\% \]

\[ \Rightarrow \text{similar to that of MINOS} \]

arXiv: 1505.03456

nGd rate+shape

nH rate

\[ \sin^2 2\theta_{13} = 0.083 \pm 0.018 \]
Systematics at Daya Bay

- Side-by-side calibration: Multiple detectors at near sites

AD1/AD2 (6+8AD data)
Expected: 0.982
Measured: 0.981 ± 0.004

AD3/AD8 (8AD data)
Expected: 1.012
Measured: 1.019 ± 0.004

J.Zhao, Nufact14
**Backgrounds at DC**

- **Major backgrounds for reactor exp.**
  - Cosmogenic neutron/isotopes: $^8$He/$^9$Li and fast neutron
  - Ambient radioactivity: accidental coincidence

- **Direct measurement of backgrounds:**
  - 7 events in 7.24 days
  - $12.9^{+3.1}_{-1.4}$ expected
  - Tension @ ~ 2σ → no room for unknown backgrounds

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![Graph showing neutrino rate vs. day^(-1) with DC-III (n-Gd) Preliminary data, expected v rate, and measured candidates rate.](image-url)
Remarkable Improvements on $\theta_{13}$

Uncertainty reduced significantly $\rightarrow$ now 6%, will be 3% in 2017.

For accelerator experiments assuming $\delta_{CP}=0$, $\theta_{23}=45^\circ$

Jetter, Tau2014

Y.F. Wang, Nufact2014
Future Prospects

- Precision still dominated by statistics
- Continue to improve systematics
- Precision expected:
  - Daya Bay:
    - $\Delta(\sin^2 2\theta_{13}) \sim 0.003 \implies \sim 3\%$
    - $\Delta(\Delta m^2_{ee}) \sim 0.07 \implies \sim 3\%$
  - RENO: ~5%
  - Double Chooz: ~10%
Determining Mass Hierarchy

Precision measurement of $\theta_{12}$, $\Delta m^2_{21}$ and $\Delta m^2_{31}$

⇒ JUNO

⇒ RENO-50
Determine MH with Reactors

Precision energy spectrum measurement interference between $P_{31}$ and $P_{32}$

$\phi$: Relative measurement

Further improvement with $\Delta m^2_{\mu\mu}$ measurement from accelerator exp.

$\Delta m^2_{ee}$: Absolute measurement

\[ P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32} \]
\[ P_{21} = \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) \]
\[ P_{31} = \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) \]
\[ P_{32} = \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32}) \]

\[ \frac{1}{2} \sin^2 2\theta_{13} \left[ 1 - \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}} \cos(2|\Delta_{ee}| \pm \phi) \right] \]

- A fixed definition $\Delta m^2_{ee}$
- And an energy related phase shift $\phi$
# JUNO for Mass Hierarchy

<table>
<thead>
<tr>
<th>NPP</th>
<th>Daya Bay</th>
<th>Huizhou</th>
<th>Lufeng</th>
<th>Yangjiang</th>
<th>Taishan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status</td>
<td>Operational</td>
<td>Planned</td>
<td>Planned</td>
<td>Under construction</td>
<td>Under construction</td>
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<tr>
<td>Power</td>
<td>17.4 GW</td>
<td>17.4 GW</td>
<td>17.4 GW</td>
<td>17.4 GW</td>
<td>18.4 GW</td>
</tr>
</tbody>
</table>

by 2020: 26.6 GW

Overburden ~ 700 m

Kaiping, Jiang Men city, Guangdong Province

Daya Bay ~60 km JUNO

Overburden ~ 700 m

Kaiping, Jiang Men city, Guangdong Province

Daya Bay ~60 km JUNO

2.5 h drive

Distance to Reactor (m)

<table>
<thead>
<tr>
<th>Cores</th>
<th>YJ-C1</th>
<th>YJ-C2</th>
<th>YJ-C3</th>
<th>YJ-C4</th>
<th>YJ-C5</th>
<th>YJ-C6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (GW)</td>
<td>2.9</td>
<td>2.9</td>
<td>2.9</td>
<td>2.9</td>
<td>2.9</td>
<td>2.9</td>
</tr>
<tr>
<td>Baseline (km)</td>
<td>52.75</td>
<td>52.84</td>
<td>52.42</td>
<td>52.51</td>
<td>52.12</td>
<td>52.21</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cores</th>
<th>TS-C1</th>
<th>TS-C2</th>
<th>TS-C3</th>
<th>TS-C4</th>
<th>DYB</th>
<th>HZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (GW)</td>
<td>4.6</td>
<td>4.6</td>
<td>4.6</td>
<td>4.6</td>
<td>17.4</td>
<td>17.4</td>
</tr>
<tr>
<td>Baseline (km)</td>
<td>52.76</td>
<td>52.63</td>
<td>52.32</td>
<td>52.20</td>
<td>215</td>
<td>265</td>
</tr>
</tbody>
</table>
**JUNO Physics**

- JUNO has been approved in Feb. 2013. ~ 300 M$.
- is a multiple-purpose neutrino 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 neutrino
  - Geoneutrino
  - Solar neutrino
  - Atmospheric neutrino
  - Exotic searches

*Neutrino Physics at JUNO, arXiv:1507.05613*
High-precision, Giant LS detector

- Muon tracker
- Steel Tank
- Acrylic tank: \( \Phi \sim 35.4 \) m
- Stainless Steel tank: \( \Phi \sim 39.0 \) m
- VETO PMTs coverage: \( \sim 77\% \)
- \( \sim 18000 \) 20” PMTs
- \( \sim 20 \) kt water
- \( \sim 6 \) kt MO
- \( \sim 1500 \) 20” VETO PMTs

JUNO

Muon tracker

Energy resolution vs rec_energy

\[ \sigma_E = 0.18\% + \frac{2.57\%}{\sqrt{E(\text{MeV})}} \]

- 77\% photocathode coverage
- PMT QE from 35\%
- Attenuation length of 20 m
  \( \Rightarrow \) abs. 60 m + Rayl. scatt. 30 m

<table>
<thead>
<tr>
<th></th>
<th>KamLAND</th>
<th>BOREXINO</th>
<th>JUNO</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS 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>
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Sensitivity on MH

**JUNO** MH sensitivity with 6 years' data:

<table>
<thead>
<tr>
<th>Statistics only</th>
<th>Relative Meas.</th>
<th>Use absolute $\Delta m^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Realistic case</td>
<td>3$\sigma$</td>
<td>4$\sigma$</td>
</tr>
</tbody>
</table>

| Ideal | Core distr. | Shape | B/S (stat.) | B/S (shape) | $|\Delta m_{\mu\mu}^2|$ |
|-------|-------------|-------|------------|-------------|-----------------|
| Size  | 52.5 km     | Real  | 1%         | 4.5%        | 0.3%            | 1%              |
| $\Delta \chi^2_{\text{MH}}$ | +16 | -4 | -1 | -0.5 | -0.1 | +8 |
Precision Measurements

Probing the unitarity of \( U_{PMNS} \) to \(~1\%\) more precise than CKM matrix elements!

<table>
<thead>
<tr>
<th></th>
<th>Statistics</th>
<th>+BG</th>
<th>+1% b2b</th>
<th>+1% EScale</th>
<th>+1% EnonL</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sin^2 \theta_{12} )</td>
<td>0.54%</td>
<td>0.67%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Delta m_{21}^2 )</td>
<td>0.24%</td>
<td>0.59%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Delta m_{ee}^2 )</td>
<td>0.27%</td>
<td>0.44%</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Correlation among parameters

0.16%\( \rightarrow \)0.24%

0.16%\( \rightarrow \)0.27%

0.39%\( \rightarrow \)0.54%

E resolution
Current Status & Brief Schedule

- **Ground breaking in Jan. 2015**
  - 500 m slope tunnel excavated out of 1340 m
  - 75 m vertical shaft excavated out of 611 m
- **Central detector using acrylic**
- **International Collaboration formed w/ 380 members from 55 institutions in 12 countries/regions**

**Schedule:**
- Civil preparation: 2013-2014
- Civil construction: 2014-2017
- Detector component production: 2016-2017
- PMT production: 2016-2019
- Detector assembly & installation: 2018-2019
- Filling & data taking: 2020
**RENO-50**

- An underground detector consisting of 18 kton ultra-low-radioactivity liquid scintillator & 15,000 20” PMTs, at 50 km away from the Hanbit (Yonggwang) nuclear power plant
- **Goals:**
  - Precision meas. of $\theta_{12}$ and $\Delta m^2_{21}$
  - Determination of mass hierarchy
  - Study neutrinos from reactors, (the Sun), the Earth, Supernova, and any possible stellar objects
- **Budget:** $100M for 6 year (Civil engineering: $15M, Detector: $85M)
- **Schedule**
  - 2014-2019: Facility and detector construction
  - 2020~ Operation
RENO-50

18 kton LS Detector
~47 km from YG reactors

Mt. Guemseong (450 m)
~900 m.w.e. overburden
J-PARC neutrino beam

Dr. Okamura & Prof. Hagiwara

- Detection of J-PARC beam: ~200 events/year
Complementary MH Determination

\[ \Delta m^2_{31} \text{ and } \Delta m^2_{32} \]

Interference (\( \phi \))

\[ \Delta m^2_{ee} \text{ and } \Delta m^2_{\mu\mu} \]

difference

Matter Effect

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**Reactors**
- **JUNO**: approved, data in 2020, 3-4\( \sigma \) in 6 years.
- **RENO-50**: R&D

**Atmospheric**
- **INO**: approved, data in 2019-2020, 3\( \sigma \) in 10 years
- **PINGU**: planned, data in 2021, 3\( \sigma \) in 4 years
- **ORCA**: planned, data in 2020, 3\( \sigma \) in 4 years
- **Hyper-K**: planned, data in 2025?

**Accelerator**
- **NOvA**: operation, 1/3 chance at 95\% CL
- **DUNE**: 10 kton from 2024, 40 kton from 2027, >5\( \sigma \) for all CPs
Reactor Anomaly

- Short baseline experiment observed deficit comparing to an improved flux model (Huber+Mueller) (Mention et al.)
- Daya Bay measurement of absolute Flux
  - Data/(Huber+Mueller): $0.947 \pm 0.022$
  - Data/(ILL+Vogel): $0.992 \pm 0.023$
  - Consistent with others
Future Reactor Exp. for Sterile Neutrino

- Different technologies: (Gd, Li, B) (seg.)(movable)(2 det.)
- Most have sensitivity $0.02\sim0.03 \Delta m^{2}\sim1eV^2$ @90\% CL
Example: PROSPECT

- **Li-LS**
- **4-5% energy resolution**
- **U-235 spectrum**
More Examples: NEOS, Neutrino-4

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<tbody>
<tr>
<td>Detector Construction &amp; Commissioning &amp; Installation on site</td>
<td>Reactor Overhaul Maintenance</td>
<td>Reactor On</td>
</tr>
<tr>
<td></td>
<td>Reactor Off data</td>
<td>Reactor On Data</td>
</tr>
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NEOS
0.5 y
95% CL

**Neutrino-4**

90% CL

- Reactor (Rate+Shape) + Gallium (Rate)

No-oscillation hypothesis disfavored at 3.6σ

- Neutrino-4, waiting for filling
Search for Light Sterile Neutrinos

- Precise reactor neutrino spectrum from Daya Bay near site can test the sterile neutrino hypothesis
- ~400 m baseline is not ideal for the reactor anomaly $\rightarrow$ much better exclusion in 0.001-0.1 eV$^2$ region

Measurement by shape distortion

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \sim 1 - \cos^4 \theta_{14} \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{ee}^2 L}{4E_{\nu}} \right) - \sin^2 2\theta_{14} \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E_{\nu}} \right)$

Daya Bay: PRL113, 141802, 2014
5 MeV Bump on Reactor Spectrum

- Significance ~ 4 $\sigma$
- Events are reactor power related & time independent
- Events are IBD-like:  
  $\Rightarrow$ Disfavors unexpected backgrounds
- No effect to $\theta_{13}$ at DYB, RENO; under control at DC

All three experiments

DC, Neutrino 2014

RENO, Neutrino 2014

Daya Bay, ICHEP2014

Jetter, Tau2014
Absolute Reactor Flux and Spectrum

Absolute neutrino spectrum

- Unfolded from the positron spectrum after non-linearity correction. Most precise reactor spectrum.
- Unfolding bias 0.5% between 2.2-6.5 MeV

e+ spectrum uncertainty 0.9% @3.5 MeV

Data
Huber+Mueller (full unc.)
Huber+Mueller (react. unc.)
ILL+Vogel

Spectrum normalized to the prediction for shape only comparison
Gas TPC detector at ~20 m from a reactor (J. Cao, L.J. Wen)

- v-e scattering
- High energy precision ( <3%/sqrt(E) )

Major motivation: high precision reactor neutrino spectrum

- Input for JUNO. Daya Bay energy resolution 8%, JUNO 3%

Other motivations:

- The weak mixing angle \( \theta_w \)
- Abnormal magnetic moment
- Sterile neutrino

MUNU exp:

\[ \mu_v < 0.9 \times 10^{-10} \mu_B \]

CF\(_4\), T > 700 keV

PLB 615(2005)153
Summary

- Significant improvement on $\sin^2 2\theta_{13}$ precision from the Daya Bay, Double Chooz and RENO experiments.
- Ultimate precision of $\sin^2 2\theta_{13}$ will reach ~ 3-4%.
- A precision measurement of the absolute neutrino flux and spectrum from Daya Bay.
- A bump around 5 MeV observed by all three experiments.
- Reactor Anomaly may have a definite answer before 2020.
- Reactor neutrinos will play important roles on:
  - Mass hierarchy
  - Precision measurement of 3/6 mixing parameters up to < ~1% level $\Rightarrow$ unitarity test of the mixing matrix
  - Sterile neutrinos
  - Other Neutrino properties
Thanks !