Results from Reactor Neutrino Experiments

Soo-Bong Kim (KNRC, Seoul National University)

“Tsukuba Global Science Week (TGSW2017), Tsukuba, Sep. 25-27, 2017”
Neutirno Oscillation

Bruno Pontecorvo
(1913 - 1993)

1946: Proposal of neutrino detection using $^{37}$Cl
1957: Proposal of neutrino transformation
(neutrino $\leftrightarrow$ antineutrino)
1967/69: Proposal of neutrino flavor oscillation
1998: Neutrino oscillation
Neutrino Mixing Angles

Atmospheric Neutrino Oscillation

$\theta_{23}$

$\sim 45^\circ$ (1998)
Super-K; K2K

Solar Neutrino Oscillation

$\theta_{12}$

$34^\circ$ (2001)
SNO, Super-K; KamLAND

Reactor Neutrino Oscillation

$\theta_{13}$

$9^\circ$ (2012)
Daya Bay, RENO
Double Chooz + T2K (2011)

“Neutrino has mass”

“Established three-flavor mixing framework”

2015 Nobel Prize

2017 Pontecorvo Prize
Definitive measurement of the last, smallest neutrino mixing angle $\theta_{13}$ based on the disappearance of reactor electron antineutrinos

→ Open a new window for determining
   (1) CP violating phase, and
   (2) neutrino mass ordering without a neutrino factory

For example, Hyper-Kamiokande(+ KNO), DUNE, JUNO, PINGU, INO, ….
$\theta_{13}$ Impacts for Future Experiments

- Reactor
  - JUNO
- Accelerator
  - DUNE
- MO & $\delta_{CP}$
- Atmosphere
  - RENO-50
  - INO
  - PINGU
  - ORCA

MO = Mass Ordering
Neutrino Physics with Reactor

1956 Discovery of (anti)neutrino

2003 Observation of reactor neutrino oscillation ($\theta_{12}$ & $\Delta m_{21}^2$)

2012 Measurement of the smallest mixing angle $\theta_{13}$
Reactor Neutrinos

- Cost-free, intense, low-energy & well-known neutrino source!

\[ \sim 5 \times 10^{20} \nu/\text{sec} \]
Reactor $\theta_{13}$ Experiments

- RENO at Yonggwang, Korea
- Daya Bay at Daya Bay, China
- Double Chooz at Chooz, France
$\theta_{13}$ Reactor Neutrino Detectors
Comparisons of Reactor $\theta_{13}$ Experiments

**Baselines**

- Double Chooz
- RENO
- Daya Bay

**Target (ton)**

- Double Chooz
- RENO
- Daya Bay

**Reactor Thermal Power (GW$_{th}$)**

- Daya Bay
- RENO
- Double Chooz

**Manpower**

- Daya Bay
- RENO
- Double Chooz
### First $\theta_{13}$ measurements in 2012

<table>
<thead>
<tr>
<th></th>
<th>Double Chooz</th>
<th>Daya Bay</th>
<th>RENO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2(2\theta_{13})$</td>
<td>0.086</td>
<td>0.092</td>
<td>0.113</td>
</tr>
<tr>
<td>Stat. error</td>
<td>0.041</td>
<td>0.016</td>
<td>0.013 (220 days)</td>
</tr>
<tr>
<td></td>
<td>(101 days)</td>
<td>(49 days)</td>
<td></td>
</tr>
<tr>
<td>Syst. error</td>
<td>0.030</td>
<td>0.005 (MC driven)</td>
<td>0.019</td>
</tr>
<tr>
<td></td>
<td>(flux uncert.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Significance</td>
<td>1.7 $\sigma$</td>
<td>5.2 $\sigma$</td>
<td>4.9 $\sigma$</td>
</tr>
</tbody>
</table>

~ 5 years ago

- 1 month
- 2 weeks
RENO Collaboration

Reactor Experiment for Neutrino Oscillation

(7 institutions and 40 physicists)
- Chonnam National University
- Dongshin University
- GIST
- Kyungpook National University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

- Total cost : $10M
- Start of project : 2006
- The first experiment running with both near & far detectors from Aug. 2011

YongGwang (靈光)：
**The RENO Detector**

- **Target**: 16.5 ton Gd-LS  
  (R=1.4m, H=3.2m)
- **Gamma Catcher**:  
  30 ton LS  
  (R=2.0m, H=4.4m)
- **Buffer**: 65 ton *mineral oil*  
  (R=2.7m, H=5.8m)
- **Veto**: 350 ton *water*  
  (R=4.2m, H=8.8m)

-- 354 ID 10 “PMTs
-- 67 OD 10” PMTs
Detection of Reactor Antineutrinos

Schematics:
- **Inverse beta decay:**
  \[ \bar{\nu}_e + p \rightarrow e^+ + n \]

- **Prompt signal (e\textsuperscript{+}):** 1 MeV 2\( \gamma \)'s + e\textsuperscript{+} kinetic energy (E = 1~10 MeV)
- **Delayed signal (n):** 8 MeV \( \gamma \)'s from neutron's capture by Gd or H
  - Gd capture or H capture
  - \(~200 \mu s\)
  - \(~2.2 \text{ MeV}\)

**Details:**
- Prompt signal (e\textsuperscript{+}) : 1 MeV 2\( \gamma \)'s + e\textsuperscript{+} kinetic energy (E = 1~10 MeV)
- Delayed signal (n) : 8 MeV \( \gamma \)'s from neutron’s capture by Gd or H
  - \(~30 \mu s\) or \(~200 \mu s\)
Coincidence of prompt and delayed signals

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]  (delayed signal)

Prompt signal

Delayed signal

n-Gd IBD

n-H IBD

\(~30\ \mu s\)

\(~200\ \mu s\)
**Backgrounds**

- **Accidental coincidence** between prompt and delayed signals
- **Fast neutrons** produced by muons, from surrounding rocks and inside detector (n scattering: prompt, n capture: delayed)
- $^9\text{Li}/^8\text{He} \beta$-n followers produced by cosmic muon spallation
New Results from RENO

- Observation of energy dependent disappearance of reactor neutrinos to measure $\Delta m_{ee}^2$ and $\theta_{13}$ using ~1500 days of data (Aug. 2011 ~ Sep. 2015)

- Measurement of absolute reactor neutrino flux using 1500 days

- Observation of an excess at ~5 MeV in reactor neutrino spectrum using ~1500 days of data
Data taking began on Aug. 1, 2011 with both near and far detectors.
(DAQ efficiency : ~95%)

A (220 days) : First $\theta_{13}$ result
PRL 108, 191802 (2012)

B (403 days) : Improved $\theta_{13}$ result
NuTel 2013, TAUP 2013, WIN 2013

C (500 days) : First $|\Delta m_{ee}^2|$ result
Rate+shape analysis ($\theta_{13}$ and $|\Delta m_{ee}^2|$)
PRL 116, 211801 (2016)
submitted to PRD (arXiv:1610.04326)

D (1500 days) : New results
Delayed Signals from Neutron Capture by Gd

**Near**
\[\tau = 26.16 \pm 0.09\]

**Far**
\[\tau = 26.09 \pm 0.28\]
Identical Performance of Near and Far Detectors

Spectra of Delayed Signals Using $^{252}\text{Cf}$ Source
Reduction of background rates & uncertainties

Allows precise measurements of $\sin^2 2\theta_{13}$ and $\Delta m_{ee}^2$

- **Accidentals**: Additional cuts and improved flashing-PMT removal algorithms
- **Cosmogenic $^9Li/^8He** : Optimized muon veto criteria
- **$^{252}Cf$ contamination**: Improved multiple-neutron removal algorithms

Measured Spectra of IBD Prompt Signal

RENO’s observation of 5 MeV excess

Clear excess at 5 MeV
Correlation of 5 MeV Excess with Reactor Power

The 5 MeV excess has a clear correlation with reactor thermal power!

The 5 MeV excess comes from reactors!
Correlation of 5 MeV excess with $^{235}\text{U}$ isotope fraction

$^{235}\text{U}$ fraction corresponds to freshness of reactor fuel

\[ y = a \times x + b \]

\[ \Delta \chi^2 = 1.174 \]

P-value = 0.240

<table>
<thead>
<tr>
<th>Fit function</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y = a$</td>
<td>1.407</td>
</tr>
<tr>
<td>$y = a \times x + b$</td>
<td>0.233</td>
</tr>
</tbody>
</table>

Preliminary \( \text{(Beginning of reactor cycle)} \)

RENO 1500 days \( \text{(End of reactor cycle)} \)
R (data/prediction) = 0.946 ± 0.021 (1500 days)

- The flux prediction is with Huber + Mueller model
- Flux weighted baseline at near: 411 m

Deficit of observed reactor neutrino fluxes relative to the prediction (Huber + Mueller model) indicates an overestimated flux or possible oscillation to sterile neutrinos.
Far/Near Shape Analysis

Energy-dependent disappearance of reactor antineutrinos

\[ \sin^2 2\theta_{13} = 0.086 \pm 0.006 \text{(stat.)} \pm 0.005 \text{(syst.)} \quad (\pm 9 \%) \]

\[ \Delta m_{ee}^2 = 2.61^{+0.15}_{-0.16} \text{(stat.)}^{+0.09}_{-0.09} \text{(syst.)} \times 10^{-3} \text{eV}^2 \quad (\pm 7 \%) \]
Allowed regions in $|\Delta m_{ee}^2|$ and $\sin^2 2\theta_{13}$
Observed L/E Dependent Oscillation

\[ P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{ee}^2 L}{4E_{\nu}} \right) \]
Summary of $\theta_{13}$ results from reactors compared to accelerator experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\sin^2 2\theta_{13}$</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daya Bay</td>
<td>0.0841 ± 0.0033</td>
<td></td>
</tr>
<tr>
<td>RENO</td>
<td>0.082 ± 0.010</td>
<td></td>
</tr>
<tr>
<td>D-CHOOZ</td>
<td>0.111 ± 0.018</td>
<td></td>
</tr>
<tr>
<td>T2K NH</td>
<td></td>
<td>0.140 ± 0.038</td>
</tr>
<tr>
<td>T2K IH</td>
<td></td>
<td>0.170 ± 0.045</td>
</tr>
<tr>
<td>MINOS NH</td>
<td></td>
<td>0.051 ± 0.038</td>
</tr>
<tr>
<td>MINOS IH</td>
<td></td>
<td>0.093 ± 0.054</td>
</tr>
</tbody>
</table>
More precise measurement of $\theta_{13}$ and $|\Delta m_{ee}^2|$

PRL 116, 211801 (2016), Submitted to PRD (arXiv:1610.04326)

<table>
<thead>
<tr>
<th>500 days</th>
<th>Mean</th>
<th>Stat.</th>
<th>Sys.</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 2\theta_{13}$</td>
<td>0.082</td>
<td>+0.009 -0.009</td>
<td>+0.006 -0.006</td>
<td>12 %</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{ee}^2</td>
<td>(x10^{-3} eV^2)$</td>
<td>2.62</td>
<td>+0.21 -0.23</td>
</tr>
</tbody>
</table>

New results (preliminary)

<table>
<thead>
<tr>
<th>1500 days</th>
<th>Mean</th>
<th>Stat.</th>
<th>Sys.</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 2\theta_{13}$</td>
<td>0.086</td>
<td>+0.006 -0.006</td>
<td>+0.005 -0.005</td>
<td>9 %</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{ee}^2</td>
<td>(x10^{-3} eV^2)$</td>
<td>2.61</td>
<td>+0.15 -0.16</td>
</tr>
</tbody>
</table>

Systematic errors are reduced due to background reduction and larger statistics of control samples.
RENO : Plan and Prospects

Plan for RENO data taking

<table>
<thead>
<tr>
<th>Year</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

RENO data will be taken for 2 more years from now and it will take 3 additional years for the analysis.

Possible extension of additional 2~3 years

According to our recent study, the systematic error of $|\Delta m_{ee}^2|$ is smaller than the statistical error.

$\sin^2 2\theta_{13}$ and $|\Delta m_{ee}^2|$ will approach to ~6% precision (our design goal).

<table>
<thead>
<tr>
<th>500 days Measured</th>
<th>1500 days Measured (preliminary)</th>
<th>~3000 days Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 2\theta_{13}$</td>
<td>12 %</td>
<td>9 %</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{ee}^2</td>
<td>$</td>
</tr>
</tbody>
</table>
$\theta_{13}$ & $|\Delta m^2_{ee}|$ in Daya Bay

**Neutrino 2016**

1230 days data

$$P = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{1.267 \Delta m^2_{21} L}{E}$$

$$- \sin^2 2\theta_{13} \sin^2 \frac{1.267 \Delta m^2_{ee} L}{E}.$$

$\sin^2 2\theta_{13} = [8.41 \pm 0.27 \text{(stat.)} \pm 0.19 \text{(syst.)}] \times 10^{-2}$

$|\Delta m^2_{ee}| = [2.50 \pm 0.06 \text{(stat.)} \pm 0.06 \text{(syst.)}] \times 10^{-3} \text{eV}^2$

$\chi^2/\text{NDF} = 232.6/263$

**Last publication:**

P. R. L. 115, 111802 (2015)
\[ \sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029} \]

Assuming \( \Delta m^2_{31} = 2.44^{+0.09}_{-0.10} \times 10^{-3} \text{eV}^2 \) → MINOS result

468 days

\( \theta_{13} \): Double Chooz

JHEP 10 (2014) 086
### Future Prospects on $\theta_{13}$

<table>
<thead>
<tr>
<th></th>
<th>Double Chooz</th>
<th>RENO</th>
<th>Daya Bay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>3 yrs Near&amp;Far</td>
<td>5 yrs</td>
<td>6 yrs</td>
</tr>
<tr>
<td>$\Delta(\sin^2(2\theta_{13}))$</td>
<td>~10 %</td>
<td>~5 %</td>
<td>~3 %</td>
</tr>
<tr>
<td>$\Delta(</td>
<td>m^2_{ee}</td>
<td>)$</td>
<td>-</td>
</tr>
</tbody>
</table>

![Graph showing uncertainty of $\sin^22\theta_{13}$](image)

J. Cao @TAUP2015
Summary

- More precise measurements of $\theta_{13}$ and $\Delta m_{ee}^2$ using energy dependent disappearance of reactor neutrinos

$$\sin^2 2\theta_{13} = 0.086 \pm 0.006{\text{(stat)}} \pm 0.005{\text{(syst)}} \pm 0.008 \quad 9\% \text{ precision}$$

$$|\Delta m_{ee}^2| = 2.61^{+0.15}_{-0.16}(\text{stat.})^{+0.09}_{-0.09}(\text{syst.})(\times 10^{-3} \text{ eV}^2) \pm 0.18 \quad 7\% \text{ precision}$$

- Measured absolute reactor neutrino flux: $R = 0.946 \pm 0.021$

- Observed an excess at 5 MeV in reactor neutrino spectrum

- $\sin^2(2\theta_{13})$ and $\Delta m_{ee}^2$ to 6% accuracy after 2 more years data taking

- Additional 2~3 years of data taking under consideration to improve $\Delta m_{ee}^2$ accuracy
Thanks for your attention!
Reactor Neutrino Oscillations

Oscillations observed as a deficit of anti-neutrinos

The position of the minimum is defined by $\Delta m^2_{ee}$

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$

$\simeq 1 - \sin^2 2\theta_{13} \sin^2 (\Delta_{ee}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$

$\Delta_{ij} \equiv 1.267 \Delta m^2_{ij} L / E$

$\Delta m^2_{ee} \equiv \cos^2 \theta_{12} \Delta m^2_{31} + \sin^2 \theta_{12} \Delta m^2_{32}$

$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21 \times 10^{-5} \text{eV}^2$

$\cos^2 \theta_{12} |\Delta m^2_{21}|$

H. Nunokawa et al, PRD72 013009(2005)
Energy Calibration from $\gamma$-ray Sources

- Non-linear response of the scintillation energy is calibrated using $\gamma$-ray sources.
- The visible energy from $\gamma$-ray is corrected to its corresponding positron energy.

Fit function: $E_{\text{vis}}/E_{\text{true}} = a - b/(1 - \exp(-cE_{\text{true}} - d))$