"Reactor neutrino oscillation" and "Development of liquid scintillators for the neutrino experiments"

RENO = Reactor Experiment for Neutrino Oscillation
(On behalf of RENO Collaboration)

K.K. Joo
Chonnam National University
March 17, 2015

Yonsei Particle Theory Seminar @ Yonsei University
Outline

1st part (physics)

RENO & RENO-50
- Recent result of $\theta_{13}$ from RENO
- Future project RENO-50

2nd part (R&D)

Liquid scintillators
- Technology for metal-loaded liquid scintillators
- Water-based liquid scintillator (WbLS)
Quick Overview

- Results with ~800 days of data sample
- New measured value of $\theta_{13}$ from rate-only analysis (Neutrino 2014)
- Shape analysis in progress: finalizing the result now!
- Results of reactor neutrinos with neutron capture on H (Significant improvement since Neutrino 2014)
Neutrino Oscillation

Neutrino: elementary particle

Three types of neutrinos exist & mixing among them

Oscillation parameters

$$\begin{pmatrix}
\theta_{12} \\
\theta_{23} \\
\theta_{13}
\end{pmatrix}$$

Trying to measure precisely

Neutrino:

- Elementary particle

- Oscillation
  - Reactor Antineutrino Oscillation
  - Neutrino Oscillation

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{1.27 \Delta m_{13}^2 L}{E_\nu} \right)$$

Daya Bay

RENO

Double Chooz
### Neutrino Mixing Parameters

**Matrix Components:**
- 3 Angles \( \theta_{12}; \theta_{13}; \theta_{23} \)
- 1 CP phase \( \delta \)
- 2 Mass differences

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{-i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

- Initial measurement done
- Precise measurement under way

\[\theta_{23} \approx \theta_{\text{atm}} \approx 45^\circ\]
Large and maximal mixing!

- In 1962 Z. Maki, M. Nakagawa, and S. Sakata considered neutrino **flavor** oscillations: neutrinos of different flavors can be transformed to each other.

\[\theta_{12} \approx \theta_{\text{sol}} \approx 32^\circ\]
Reduction of reactor neutrinos due to oscillations

\[ \sin^2 2\theta_{13} = 0.10 \]

\[ \theta_{12} = 34^\circ, \quad \Delta m_{21}^2 = 7.9 \times 10^{-5} \text{eV}^2, \quad \Delta m_{31}^2 = 2.5 \times 10^{-3} \text{eV}^2 \]

- \[ \sin^2 2\theta_{13} > 0.01 \] with 10 t \(\cdot\) 14 GW \(\cdot\) 3 yr \(\sim\) 400 t \(\cdot\) GW \(\cdot\) yr
  (400 t \(\cdot\) GW \(\cdot\) yr: a 10(40) ton far detector and a 14(3.5) GW reactor in 3 years)
Experimental Method of $\theta_{13}$ Measurement

Oscillations observed as a deficit of anti-neutrinos

The position of the minimum is defined by $\Delta m_{13}^2 (\sim \Delta m_{23}^2)$

Experimentally, find the disappearance of $\bar{\nu}_e$ fluxes due to neutrino oscillation as a function of energy using multiple, identical detectors to reduce the systematic errors in 1% level.

$$P(\nu_e \rightarrow \nu_e) \approx 1 - \cos^4 \theta_{13} \sin^2 2 \theta_{12} \sin^2 \left( \frac{1.27 \Delta m_{12}^2 L}{E_\nu} \right) - \sin^2 2 \theta_{13} \sin^2 \left( \frac{1.27 \Delta m_{13}^2 L}{E_\nu} \right)$$

Distance

1200 to 1800 meters

Probabilité $\nu_e$

1.0

Flux before oscillation observed here

$\sin^2 2 \theta_{13}$
RENO Collaboration

11 institutions and 40 physicists in Korea

- Chonbuk National University
- Chonnam National University
- Chung-Ang University
- Dongshin University
- GIST
- Gyeongsang National University
- Kyungpook National University
- Sejong University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

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

YongGwang (靈光):

Reactor Experiment for Neutrino Oscillation
Located in the west coast of southern part of Korea
~300 km from Incheon international airport
6 reactors are lined up in roughly equal distances and span ~1.3 km
Total average thermal output ~16.7GW\(_{th}\) (2\(^{nd}\) largest in the world)

YongGwang (靈光): = glorious [splendid] light (~spirited)
New name: Hanbit
YongGwang Nuclear Power Plant

Google Satellite View of Experimental Site

Near Detector
- 70m high

Reactors
- 200m high
- 300m high

Far Detector
- 1,380m
- 290m

YongGwang Nuclear Power Plant

(RENO) 

\[ \theta_{13} \]

\[ V_e \leftrightarrow V_{\mu} \]

\[ V_e \leftrightarrow V_{\tau} \]

Korea Neutrino Research Center (KNIRC)

(110 m.w.e.) Near Detector
(450 m.w.e.) Far Detector
**RENO Detector**

### RENO Detector Components

- **Target**: 140 Acrylic (10mm) + Gd (0.1%) + LS, Mass: 15.4 tons
- **Gamma Catcher**: 60 Acrylic (15mm) LS, Mass: 27.5 tons
- **Buffer**: 70 SUS (5mm) Mineral oil, Mass: 59.2 tons
- **Veto**: 150 Steel (15mm) water, Mass: 354.7 tons

#### Detector Details:

- **Inner PMTs**: 354 10” PMTs
  - Solid angle coverage = ~14%
- **Outer PMTs**: ~ 67 10” PMTs

**Total Mass**: ~460 tons
### Reactor θ₁³ Experiments

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Location</th>
<th>Thermal Power (GW)</th>
<th>Flux Weighted Baselines Near/Far (m)</th>
<th>Depth Near/Far (mwe)</th>
<th>Target Mass (tons)</th>
<th>Statistics per year (GW·ton·yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double Chooz</td>
<td>France</td>
<td>8.5</td>
<td>[410/1050]</td>
<td>120/300</td>
<td>8.6/8.6</td>
<td>73</td>
</tr>
<tr>
<td>RENO</td>
<td>Korea</td>
<td>16.7</td>
<td>409/1444</td>
<td>120/450</td>
<td>16/16</td>
<td>267</td>
</tr>
<tr>
<td>Daya Bay</td>
<td>China</td>
<td>17.4</td>
<td>470(576)/1648</td>
<td>250/860</td>
<td>40×2/80</td>
<td>1392</td>
</tr>
</tbody>
</table>
The Daya Bay Experiment

- Measuring neutrino mixing angle $\theta_{13}$
- 6 reactor cores, 17.4 GW$_{th}$
- Relative measurement
  - 2 near sites, 1 far site
- Multiple LS detector modules
  - 20 ton target, 110 ton total weight
- Good cosmic shielding
  - 250 (860) m.w.e @ near (far) sites
The Double Chooz Experiment

Near Detector
L=400 m
Depth = 115 m.w.e.
(under construction)

Far Detector
L=1050 m
Depth = 300 m.w.e.
(collecting data since April 2011)

Chooz-B Reactors
$2 \times 4.25 \text{ GW}_{\text{th}}$
Finishing the Detector Installation (2011.1)

- Neutrino Target (Gd + LS)
- Gamma Cather (LS)
- Buffer (Mineral Oil)
- VETO (Water)
Detection of Reactor Antineutrinos

- Use inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$) reaction process
- Prompt part:
  - subsequent annihilation of the positron to two 0.511MeV $\gamma$
- Delayed part:
  - neutron is captured
    - $\sim 200\mu s$ w/o Gd
    - $\sim 30\mu s$ w/ Gd
  - Gd has largest n absorption cross section & emits high energy $\gamma$
- Signal from neutron capture
  - $\sim 2.2$MeV w/o Gd
  - $\sim 8$MeV w/ Gd
- Measure prompt signal & delayed signal
- “Delayed coincidence” reduces backgrounds drastically
Signal: IBD Pair

Prompt signal (S1)

- n-Gd IBD
- ~30 µs

Delayed signal (S2)

- n-H IBD
- ~200 µs

Suppresses background a lot!
Recipe of Liquid Scintillator

<table>
<thead>
<tr>
<th>Aromatic Solvent &amp; Flour</th>
<th>WLS</th>
<th>Gd–compound</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAB</td>
<td>PPO + Bis–MSB</td>
<td>0.1% Gd+TMHA (trimethylhexanoic acid)</td>
</tr>
</tbody>
</table>

- High Light Yield: not likely Mineral oil (MO)
- replace MO and even Pseudocume (PC)
- Good transparency (better than PC)
- High flash point: 147°C (PC: 48°C)
- Environmentally friendly (PC: toxic)
- Components well known (MO: not well known)
- Domestically available: Isu Chemical Ltd.

Solvent-solvent extraction method

\[
\begin{align*}
\text{RCOOH} + \text{NH}_3 \cdot \text{H}_2\text{O} & \rightarrow \text{RCOONH}_4 + \text{H}_2\text{O} \\
3\text{RCOONH}_4(aq) + \text{GdCl}_3(aq) & \rightarrow \text{Gd}((\text{RCOO})_3 + 3\text{NH}_4\text{Cl}
\end{align*}
\]

0.1% Gd compounds with CBX (Carboxylic acids; R-COOH)

- CBX: TMHA (trimethylhexanoic acid)
Liquid Production System (2010. 11~2011. 3)
Data Acquisition System

- 24 channel PMT input to ADC/TDC
- 0.1pC, 0.52nsec resolution
- ~2500pC/ch large dynamic range
- No dead time (w/o hardware trigger)
- Fast data transfer via Ethernet R/W

From SK electronics group
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 (~800 days): New $\theta_{13}$ result  
Shape+rate analysis (in progress)  

Total observed reactor neutrino events as of today: ~1.5M (Near), ~0.15M (Far)  
Absolute reactor neutrino flux measurement in progress  
[reactor anomaly & sterile neutrinos]

Now
IBD Event Selection

- Reject flashers and external gamma rays: \( \frac{Q_{\text{max}}}{Q_{\text{tot}}} < 0.03 \)

- Muon veto cuts: reject events after the following muons
  1. 1 ms after an ID muon with \( E > 70 \) MeV, or with \( 20 < E < 70 \) MeV and OD NHIT > 50
  2. 10 ms after an ID muon with \( E > 1.5 \) GeV

- Coincidence between prompt and delayed signals in 100 \( \mu s \)
  - \( E_{\text{prompt}} \): 0.7 \( \sim \) 12.0 MeV, \( E_{\text{delayed}} \): 6.0 \( \sim \) 12.0 MeV
  - coincidence: 2 \( \mu s < \Delta t_{e+n} < 100 \) \( \mu s \)

- Multiplicity cut: reject pairs if there is a trigger in the preceding 100 ms window
Signature of Reactor Neutrino Event (IBD)

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

- **Prompt signal (e\(^+\))**: 1 MeV 2\(\gamma\)'s + e\(^+\) kinetic energy (E = 1\text{~}10 \text{ MeV})
- **Delayed signal (n)**: 8 MeV \(\gamma\)'s from neutron's capture by Gd
  
  \(~26 \mu s (0.1\% \text{ Gd}) \text{ in LS}\)

**Observed spectra for Prompt Signal**

\[ \Delta m^2_{12} = 7.6 \times 10^{-5} \]
\[ \sin^2(2\theta_{12}) = 0.8556 \]
\[ \Delta m^2_{13} = 2.32 \times 10^{-3} \]
\[ \sin^2(2\theta_{13}) = 0.113 \]
Observed Spectra for Delayed Signal ($n$ captured by Gd)

**Near**

- IBD delayed signal
- Neutron Capture Time by Gd
  - $\tau = 26.16 \pm 0.09$

**Far**

- IBD delayed signal
- Neutron Capture Time by Gd
  - $\tau = 26.09 \pm 0.28$
IBD Candidate Event

A candidate for a neutron captured by Gd

Near: Run 666, Event 59351041

ID Qmax: 369
ID NHits: 343
ID Qsum: 26385
(1MeV ~ 3300 ADC)

OD NHits: 0
OD Qsum: 0
**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

---

**Accidentals**

**Fast neutrons**

$^9\text{Li}/^8\text{He}$ $\beta$-n followers
Background Events

Event time (S1, S2) is not satisfied

Veto hit exists
Backgrounds

After Neutrino 2014, $Q_{\text{max}}/Q_{\text{tot}}$ cut: 0.03 $\rightarrow$ 0.04

- allow more accidentals to increase acceptance of signal and minimize any bias to the spectral shape

<table>
<thead>
<tr>
<th>Backgrounds ( /day)</th>
<th>Near</th>
<th>Far</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidentals</td>
<td>$1.82\pm0.11$ $\rightarrow$ $4.45\pm0.01$</td>
<td>$0.36\pm0.01$ $\rightarrow$ $0.89\pm0.01$</td>
</tr>
<tr>
<td>Fast Neutron</td>
<td>$2.67\pm0.08$ $\rightarrow$ $2.21\pm0.03$</td>
<td>$0.56\pm0.02$ $\rightarrow$ $0.49\pm0.01$</td>
</tr>
<tr>
<td>Li/He</td>
<td>$9.18\pm0.67$ $\rightarrow$ $11.64\pm1.04$</td>
<td>$2.07\pm0.21$ $\rightarrow$ $2.12\pm0.22$</td>
</tr>
<tr>
<td>Cf contamination</td>
<td>$0.45\pm0.07$ $\rightarrow$ $0.31\pm0.05$</td>
<td>$3.17\pm0.28$ $\rightarrow$ $2.01\pm0.26$</td>
</tr>
<tr>
<td>Total</td>
<td>$14.18\pm0.69$ $\rightarrow$ $18.61\pm1.04$</td>
<td>$6.17\pm0.35$ $\rightarrow$ $5.49\pm0.34$</td>
</tr>
</tbody>
</table>

Fraction to total IBD: 3.1 % (Near) 8.1% (Far)
Measured Spectra of IBD Prompt Signal

Near Live time = 761.11 days
# of IBD candidate = 457,176
# of background = 14,165 (3.1 %)

Bkg.: 3.1 %

Far Live time = 794.72 days
# of IBD candidate = 53,632
# of background = 4366 (8.1 %)

Bkg.: 8.1 %
- Reactor neutrino flux

\[
\Phi(E_\nu) = \frac{P_{th}}{\sum_{\text{isotopes}} f_i \cdot E_i} \sum_{i} f_i \cdot \phi_i(E_\nu)
\]

- \( P_{th} \): Reactor thermal power provided by the YG nuclear power plant
- \( f_i \): Fission fraction of each isotope determined by reactor core simulation of Westinghouse ANC
- \( \phi_i(E_\nu) \): Neutrino spectrum of each fission isotope
  
  [* P. Huber, Phys. Rev. C84, 024617 (2011)
- \( E_i \): Energy released per fission
  

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>James</th>
<th>Kopeikin</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{235}\text{U})</td>
<td>201.7±0.6</td>
<td>201.92±0.46</td>
</tr>
<tr>
<td>(^{238}\text{U})</td>
<td>205.0±0.9</td>
<td>205.52±0.96</td>
</tr>
<tr>
<td>(^{239}\text{Pu})</td>
<td>210.0±0.9</td>
<td>209.99±0.60</td>
</tr>
<tr>
<td>(^{241}\text{Pu})</td>
<td>212.4±1.0</td>
<td>213.60±0.65</td>
</tr>
</tbody>
</table>

- Graph showing fractions of fission rate vs. days.
Observed Daily Averaged IBD Rate

- Good agreement with observed rate and prediction.
- Accurate measurement of thermal power by reactor neutrinos.
New $\theta_{13}$ Measurement by Rate-only Analysis

(Preliminary)

$$\sin^2 2\theta_{13} = 0.101 \pm 0.008\text{(stat.)} \pm 0.010\text{(syst.)}$$

<table>
<thead>
<tr>
<th>Uncertainties (%)</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics (near)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(far)</td>
<td>(0.15%)</td>
<td>(0.43%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isotope fraction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.28%)</td>
<td></td>
</tr>
<tr>
<td>Thermal power</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.20%)</td>
</tr>
<tr>
<td>Detection efficiency</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.20%)</td>
</tr>
<tr>
<td>Backgrounds (near)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.21%)</td>
</tr>
<tr>
<td>(far)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.50%)</td>
</tr>
</tbody>
</table>

$$\sin^2 2\theta_{13} = 0.113 \pm 0.023 \rightarrow 0.100 \pm 0.016 \rightarrow 0.101 \pm 0.013$$

4.9 $\sigma$ (Neutrino 2012)

6.3 $\sigma$ (TAUP/WIN 2013)

7.8 $\sigma$ (Neutrino 2014)
**Motivation:**

1. Independent measurement of $\theta_{13}$ value.
2. Consistency and systematic check on reactor neutrinos.

* RENO’s low accidental background makes it possible to perform n-H analysis.

-- low radioactivity PMT
-- successful purification of LS and detector materials.
IBD Sample with n-H

**preliminary**

**n-H IBD Event Vertex Distribution**

<table>
<thead>
<tr>
<th></th>
<th>Near</th>
<th>Far</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live time(day)</td>
<td>379.663</td>
<td>384.473</td>
</tr>
<tr>
<td>IBD Candidate</td>
<td>249,799</td>
<td>54,277</td>
</tr>
<tr>
<td>IBD( /day)</td>
<td>619.916</td>
<td>67.823</td>
</tr>
<tr>
<td>Accidental ( /day)</td>
<td>25.16±0.42</td>
<td>68.90±0.35</td>
</tr>
<tr>
<td>Fast Neutron( /day)</td>
<td>5.62±0.30</td>
<td>1.30±0.08</td>
</tr>
<tr>
<td>LiHe( /day)</td>
<td>9.87±1.48</td>
<td>3.19±0.37</td>
</tr>
</tbody>
</table>

S.H. Seo

Nantes, 2015
Results from n-H IBD sample

Very preliminary
Rate-only result

(B data set, ~400 days)

\[ \sin^2 2\theta_{13} = 0.103 \pm 0.014 \text{(stat.)} \pm 0.014 \text{(syst.)} \]

(Neutrino 2014) \[ \sin^2 2\theta_{13} = 0.095 \pm 0.015 \text{(stat.)} \pm 0.025 \text{(syst.)} \]

\[ \leftarrow \text{Removed a soft neutron background} \] and reduced the uncertainty of the accidental background

\[ \sin^2 2\theta_{13} = \theta \sin^2 \theta \]

\[ \sin 13 \]

preliminary

preliminary

Near Detector

Far Detector
$\sin^2 2\theta_{13} = 0.101 \pm 0.008\, (\text{stat.}) \pm 0.010\, (\text{syst.})$

- 5 years of data: $\pm 7\%$
  - stat. error: $\pm 0.008 \rightarrow \pm 0.005$
  - syst. error: $\pm 0.010 \rightarrow \pm 0.005$
  - shape information $\rightarrow \pm 5\%$
A Brief History of $\theta_{13}$ from Reactor Experiments

<table>
<thead>
<tr>
<th>Year</th>
<th>Experiment</th>
<th>Days</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>DC</td>
<td>97</td>
<td>[1112.6353]</td>
</tr>
<tr>
<td></td>
<td>R+S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>DB</td>
<td>49</td>
<td>[1203.1669]</td>
</tr>
<tr>
<td></td>
<td>RENO</td>
<td>222</td>
<td>[1204.0626]</td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>228</td>
<td>[1207.6632]</td>
</tr>
<tr>
<td></td>
<td>R+S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>DB</td>
<td>139</td>
<td>[1210.6327]</td>
</tr>
<tr>
<td></td>
<td>RENO</td>
<td>403</td>
<td>[NuTel2013]</td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>n-H</td>
<td>[1301.2948]</td>
</tr>
<tr>
<td></td>
<td>R+S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>DB</td>
<td>190</td>
<td>[1310.6732]</td>
</tr>
<tr>
<td></td>
<td>RENO</td>
<td>403</td>
<td>[TAUP2013]</td>
</tr>
<tr>
<td></td>
<td>DC</td>
<td>469</td>
<td>[ν 2014]</td>
</tr>
<tr>
<td></td>
<td>DB</td>
<td>563</td>
<td>[ν 2014]</td>
</tr>
<tr>
<td></td>
<td>RENO</td>
<td>795</td>
<td>[ν 2014]</td>
</tr>
<tr>
<td></td>
<td>RENO</td>
<td>384</td>
<td>[ν 2014]</td>
</tr>
<tr>
<td></td>
<td>RENO</td>
<td>n-H</td>
<td>[NOW 2014]</td>
</tr>
</tbody>
</table>
Summary

- New measurement of $\theta_{13}$ by rate-only analysis
  \[ \sin^2 2\theta_{13} = 0.101 \pm 0.008\text{(stat)} \pm 0.010\text{(syst)} \] (preliminary)

- Shape analysis for $\Delta m^2$ is being finalized… (stay tuned)

- First result on n-H IBD analysis
  \[ \sin^2 2\theta_{13} = 0.103 \pm 0.014\text{(stat)} \pm 0.014\text{(syst)} \] (very preliminary)

- $\sin^2(2\theta_{13})$ to 7% accuracy within 3 years
RENO-50
**Overview of RENO-50**

- **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**: - Determination of neutrino mass hierarchy
  - High-precision measurement of $\theta_{12}$, $\Delta m^2_{21}$ and $\Delta m^2_{31}$
  - Study neutrinos from reactors, the Sun, the Earth, Supernova, and any possible stellar objects

- **Budget**: $100M for 6 year construction
  (Civil engineering: $15M, Detector: $85M)

- **Schedule**: 2015 ~ 2020: Facility and detector construction
  2021 ~: Operation and experiment
Reactor Neutrino Oscillations

\[ P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{ee}^2 L}{4E} \right) - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E} \right) \]

Short Baseline

Long Baseline

\[ \left| \Delta m_{ee}^2 \right| \simeq \left| \Delta m_{32}^2 \right| \pm 5.21 \times 10^{-5} \text{eV}^2 \]

\[ \cos^2 \theta_{12} \left| \Delta m_{21}^2 \right| \]

+: Normal Hierarchy

-: Inverted Hierarchy

[Nunokawa & Parke (2005)]
Far Detector
Near Detector

RENO-50
18 kton LS Detector
~47 km from YG reactors
Mt. Guemseong (450 m)
~900 m.w.e. overburden
Mt. GuemSeong
Altitude: 450 m

RENO-50 Candidate Site

~ 47km
Reactor Neutrino Oscillations at 50 km

Neutrino mass hierarchy (sign of $\Delta m^2_{31}$) + precise values of $\theta_{12}$, $\Delta m^2_{21}$ & $\Delta m^2_{31}$
3% energy resolution essential for distinguishing the oscillation effects between normal and inverted mass hierarchies.
18 ktons ultra-low-radioactivity Liquid Scintillation Detector
### Technical Challenges

<table>
<thead>
<tr>
<th></th>
<th>KamLAND</th>
<th>RENO-50</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LS mass</strong></td>
<td>~1 kt</td>
<td>18 kt</td>
</tr>
<tr>
<td><strong>Energy resolution</strong></td>
<td>6.5%/\sqrt{E}</td>
<td>3%/\sqrt{E}</td>
</tr>
<tr>
<td><strong>Light yield</strong></td>
<td>500 p.e./MeV</td>
<td>&gt;1000 p.e./MeV</td>
</tr>
<tr>
<td><strong>LS attenuation length</strong></td>
<td>~16 m</td>
<td>~25 m</td>
</tr>
</tbody>
</table>

- High transparency LS : 15 m → 25 m (purification & better PPO)
- Large photocathode coverage : 34% → 67% (15,000 20” PMT)
- High QE PMT : 20% → 35% (Hamamatsu 20” HQE PMT)
- High light yield LS : ×1.5 (1.5 g/ℓ PPO → 5 g/ℓ PPO)
MC Simulation of RENO-50

- PMT arrangement scheme.
  - Barrel: 50 raw * 200 column
  - Top & Bottom: 2500 PMTs for each region

- Target: Acrylic, 30m*30m
- Buffer: Stainless-Steel, 32m*32m
- Veto: Concrete, 37m*37m

• R&D with optimization of detector design by a MC study

• Increase of photosensitive area up to ~60% using 15,000 20” PMTs to maximize the light collection
RENO-50 PMT Arrangement

Top & Bottom

55 cm

Barrel

60 cm

57 cm
High QE PMTs

- Use of high, 35%, quantum efficiency PMTs in development

Hamamatsu HQE PMT, R12860

Venetian blind type (Super-K) vs. Box and line type (New for 20-inch)
# LS Purification Scheme

- Develop efficient methods for mass purification of radioactivity in LS

## Table

<table>
<thead>
<tr>
<th>Radio-isotopes</th>
<th>Source</th>
<th>Typical concentration</th>
<th>Required concentration</th>
<th>Strategy for reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{14}$C</td>
<td>Cosmogenic bombardment of $^{14}$N</td>
<td>$^{14}$C/$^{12}$C $\leq 10^{-12}$</td>
<td>$^{14}$C/$^{12}$C $\leq 10^{-18}$</td>
<td>Use of LAB from petroleum derivative (old carbon)</td>
</tr>
<tr>
<td>$^{7}$Be</td>
<td>Cosmogenic bombardment of $^{12}$C</td>
<td>$3 \times 10^{-2}$ Bq/t-carbon</td>
<td>$&lt; 10^{-6}$ Bq/t-carbon</td>
<td>Distillation, or underground storage of scintillator</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>Dust or surface contamination</td>
<td>$2 \times 10^{-5}$ g/g-dust</td>
<td>$&lt; 10^{-16}$ g/g LAB</td>
<td>Water extraction +Distillation +Filtration +pH control</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>Dust or surface contamination</td>
<td>$2 \times 10^{-5}$ g/g-dust</td>
<td>$&lt; 10^{-16}$ g/g in LAB</td>
<td>Water extraction</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>Dust or contamination in fluor</td>
<td>$2 \times 10^{-6}$ g/g-dust</td>
<td>$&lt; 10^{-13}$ g/g in LAB &lt; $10^{-11}$ g/g in fluor</td>
<td>Water extraction</td>
</tr>
<tr>
<td>$^{222}$Rn</td>
<td>Air and emanation from material</td>
<td>100 Rn atom/t-LAB</td>
<td>1 Rn atom/t-LAB</td>
<td>Nitrogen stripping</td>
</tr>
</tbody>
</table>

*From a Borexino paper*
- Develop a test purification facility of ~5 ton LS and build a water shield tank of scintillation detector to measure radioactivity in LS

- **Water extraction**: removal of polar and charged impurities
- **Vacuum distillation**: removal of radioactive and chemical impurities
- **Filtration with a 0.05 mm Teflon filter**: removal of particulates
  (* suspended dust particles that may contain U, Th and K)
- **Nitrogen stripping**: removal of water and dissolved noble gases of Kr

---

**Test facility of Borexino**

### RENO-50 vs. KamLAND

<table>
<thead>
<tr>
<th></th>
<th>Oscillation Reduction</th>
<th>Reactor Neutrino Flux</th>
<th>Detector Size</th>
<th>Syst. Error on ν Flux</th>
<th>Error on sin²θ₁₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>RENO-50 (50 km)</td>
<td>80%</td>
<td>13×6×ϕ₀ [6 reactors]</td>
<td>18 kton</td>
<td>~ 0.3%</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>KamLAND (180 km)</td>
<td>40%</td>
<td>0.6×55×ϕ₀ [55 reactors]</td>
<td>1 kton</td>
<td>3%</td>
<td>5.4%</td>
</tr>
<tr>
<td>Figure of Merit</td>
<td>×2</td>
<td>×2.4</td>
<td>×18</td>
<td>×10</td>
<td></td>
</tr>
</tbody>
</table>

\[(50 \text{ km} / 180 \text{ km})^2 \approx 13\]

**Observed Reactor Neutrino Rate**
- RENO-50: ~ 15 events/day
- KamLAND: ~ 1 event /day

**Determination of mass ordering:**
\[\sim 3\sigma \text{ with 5 year data}\]
Leptons

Neutrino Mixing

\[
\sin^2(2\theta_{12}) = 0.857 \pm 0.024 \quad (\pm 2.8\%)
\]
\[
\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5} \text{ eV}^2 \quad (\pm 2.7\%)
\]
\[
\sin^2(2\theta_{23}) > 0.95 \quad (\pm 3.1\%)
\]
\[
\Delta m^2_{32} = (2.32^{+0.12}_{-0.08}) \times 10^{-3} \text{ eV}^2 \quad (+5.2-3.4\%)
\]
\[
\sin^2(2\theta_{13}) = 0.098 \pm 0.013 \quad (\pm 13.3\%)
\]

\[
\sin^2 \theta_{12} = 0.312 \pm 0.017 \quad (\pm 5.4\%)
\]

\[
\frac{\Delta m^2_{21}}{|\Delta m^2_{31(32)}|} \approx 0.03
\]

- Precise measurement of $\theta_{12}$, $\Delta m^2_{21}$ and $\Delta m^2_{32}$

\[
\frac{\delta \sin^2 \theta_{12}}{\sin^2 \theta_{12}} < 1.0\%(1\sigma) \quad (\leftarrow 5.4\%)
\]
\[
\frac{\delta \Delta m^2_{21}}{\Delta m^2_{21}} < 1.0\%(1\sigma) \quad (\leftarrow 2.7\%)
\]
\[
\frac{\delta \Delta m^2_{32}}{\Delta m^2_{32}} < 1.0\%(1\sigma) \quad (\leftarrow 5.2\%)
\]
Additional Physics with RENO-50

- **Neutrino burst from a Supernova in our Galaxy**
  - ~5,600 events (@8 kpc) (* NC tag from 15 MeV deexcitation $\gamma$)
  - A long-term neutrino telescope

- **Geo-neutrinos**: ~1,000 geo-neutrinos for 5 years
  - Study the heat generation mechanism inside the Earth

- **Solar neutrinos**: with ultra low radioacitivity
  - MSW effect on neutrino oscillation
  - Probe the center of the Sun and test the solar models

- **Detection of J-PARC beam**: ~200 events/year

- **Neutrinoless double beta decay search**: possible modification like KamLAND-Zen
Schedule

- **2015**: Group organization
  - Detector simulation & design
  - Geological survey

- **2016 ~ 2017**: Civil engineering for tunnel excavation
  - Underground facility ready
  - Structure design
  - PMT evaluation and order,
  - Preparation for electronics, HV, DAQ & software tools,
  - R&D for liquid scintillator and purification

- **2018 ~ 2020**: Detector construction

- **2021 ~**: Data taking & analysis
Summary

- Longer baseline (~50 km) reactor experiments is under pursuit to determine the mass hierarchy in $3\sigma$ for 5 years of data-taking, and to perform high-precision (<1%) measurements of $\theta_{12}$, $\Delta m^2_{21}$, & $\Delta m^2_{31}$.

- Domestic and international workshops held in 2013 to discuss the feasibility and physics opportunities.

- An R&D funding (US $ 2M in next 3 years) will be given by the Samsung Science & Technology Foundation.

- SNU & CNU start doing various R&D works

- A proposal have been submitted to obtain full funding.

Thanks for your attention!
RENO can be used as near detector for RENO-50. → Reduces systematic error of nu flux.

While Daya Bay II can not use Daya Bay detector as near detector. → To reduce neutrino interference effect from other reactors.

Li, Cao, Wang, Zhan: arXiv: 1303.6733
<table>
<thead>
<tr>
<th></th>
<th>Osc. Reduct.</th>
<th>Reactor $\nu$ Flux</th>
<th>Detector Size</th>
<th>Sys. Error (Flux)</th>
<th>Error of Mixing param</th>
</tr>
</thead>
<tbody>
<tr>
<td>KamLAND (180 km)</td>
<td>40 %</td>
<td>53</td>
<td>1 kton</td>
<td>3 %</td>
<td>$\sin^2(2\theta_{12})$: 5.4 %</td>
</tr>
<tr>
<td>RENO-50 (47 km)</td>
<td>77 %</td>
<td>6 * 14.7</td>
<td>18 kton</td>
<td>~0.3 %</td>
<td>&lt; 0.4 %</td>
</tr>
<tr>
<td>Daya Bay II (58 km)</td>
<td>85 %</td>
<td>X * 9.6</td>
<td>20 kton</td>
<td>3 %</td>
<td>&lt; 0.4 %</td>
</tr>
</tbody>
</table>
$\theta_{13}$ from Reactor and Accelerator Experiments

First hint of $\delta_{CP}$ combining Reactor and Accelerator data

Best overlap is for Normal hierarchy & $\delta_{CP} = -\pi/2$

Is Nature very kind to us? Are we very lucky? Is CP violated maximally?

Strong motivation for anti-neutrino runs and precise measurements of $\theta_{13}$

Courtesy C. Walter (T2K Collaboration) Talk at Neutrino 2014
Expected Energy Resolution

PMT coverage: 67% (15,000 20” PMTs)
- Attenuation length: 25 m
- QE: 35%