Reactor Experiment for Neutrino Oscillation

9 Institutions and 40 Physicists

Chonnam National University
Dongshin University
Gwangju Institute of Science and Technology
Gyeongsang National University
Korea Advanced Institute of Science and Technology
Kyungpook National University
Seoul National University
Seoyeong University
Sungkyunkwan University

- Start of project: 2006
- The first reactor experiment running with both near and far detectors since August 2011

South Korea
Yonggwang
RENO Experimental Setup

Near Detector
(120 m.w.e)

Hanbit Nuclear Power Plant Complex
6 Reactor array
2.8GW$_{th}$/reactor

Far Detector
(450 m.w.e)
Two identical (near and far) detectors

- Target (Gd-loaded LS) 16 tons
- Gamma catcher (LS) 29 tons
- Buffer (Mineral oil) 64 tons
- Veto (Water) 353 tons
Inverse Beta Decay

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

\[ E_{\nu}^{thr} = \frac{(m_n + m_p)^2 - m_p^2}{2m_p} = 1.806 \text{ MeV} \]

\[ E_{\text{prompt}} = K.E. (e^+) + 2 \times (0.511) \text{ MeV} \]

\[ \approx E_{\nu} - 0.78 \text{ MeV} \]
Recent Results from RENO

- “Fuel-composition dependent reactor antineutrino yield at RENO”

- “Observation of Reactor Antineutrino Disappearance Using Delayed Neutron Capture on Hydrogen at RENO”
  JHEP04 (2020) 029
  - Update of 1500 days data
  - The first $\theta_{13}$ measurement in n-H channel
  \[ \rightarrow \text{see poster session #56 by Dr. Eunhyang Kwon} \]

- “Search for Sub-eV Sterile Neutrino at RENO”
  \[ \rightarrow \text{see poster session #128 by Dr. Jiwoong Seo} \]

- Updated analysis of 2900 days (Aug. 2011 – Feb. 2020) of RENO data
  - 2200 Days results published at PRL121 (2018) 20, 201801
  - Update on Reactor Antineutrino Anomaly (RAA)
  - Update on $\theta_{13}$ and $\Delta m^2$ from n-Gd channel
  - Update on 5 MeV excess (finer bin measurement)
  \[ \rightarrow \text{see poster session #62 by Dr. DongHa Lee} \]
Measured Spectra of IBD Prompt Signal

RENO 2900 days (2200 + 700 days) : Aug. 2011 — Feb. 2020
- Clear excess at 5MeV compared to the Huber-Mueller prediction

Near detector live time: 2509 days
# IBD candidates: 989,736
Background rate: 2.26 ± 0.05 %
5 MeV excess rate: 2.50 ± 0.06 %

Far detector live time: 2908 days
# IBD candidates: 120,383
Background rate: 4.77 ± 0.19 %
5 MeV excess rate: 2.26 ± 0.18 %
Observed IBD Rate VS Thermal Power

Near

Observed IBD rate rate (/day)

Far

Observed IBD rate rate (/day)

Near

Observed / Expected ratio

Far

Observed / Expected ratio

0.9387 ± 0.0017

0.9368 ± 0.0050

Expected IBD rate (/day)

Expected IBD rate (/day)
5 MeV Excess VS Thermal Power

Near

Far

2.722 ± 0.082 %

2.416 ± 0.223 %
Fuel Dependence of the Fractional 5 MeV Excess (2900 Days)

\[ 2.5124 \pm 0.0609 \]

\[ \Delta \chi^2 = 10.33 (3.21\sigma) \]

\[ 2 = 10^{0.33 (3.21\sigma)} \]

Preliminary
Reactor Antineutrino Anomaly (RAA)

\[ R = 0.940 \pm 0.001(\text{stat.}) \pm 0.020(\text{sys.}) \text{ for H-M model} \]

IBD yield: \( \bar{y}_f = 5.8303 \pm 0.1249(\times 10^{-43} \text{ cm}^2/\text{fission}) \)

Data / Prediction: \( R = 0.983 \pm 0.001(\text{stat.}) \pm 0.021(\text{sys.}) \text{ for ILL+Vogel model} \)

Average fission fraction:
\[
\bar{F}_{235} : \bar{F}_{238} : \bar{F}_{239} : \bar{F}_{241} = 0.571 : 0.073 : 0.300 : 0.056
\]
Far to Near Prompt Spectra Shape Comparison

- Energy dependent disappearance of reactor antineutrinos

![Graph showing energy dependent disappearance of reactor antineutrinos](image-url)

- Preliminary data
Neutrino Oscillation: $\theta_{13}$ and $\Delta m^2_{ee}$

RENO 2900 days (Aug. 2011 — Feb. 2020)

\[ \sin^2 2\theta_{13} = 0.0892 \pm 0.0044 \text{(stat.)} \pm 0.0045 \text{(sys.)} \pm 7.0\% \]

\[ |\Delta m^2_{ee}| = 2.74 \pm 0.10 \text{(stat.)} \pm 0.06 \text{(sys.)} (\times 10^{-3} \text{eV}^2) \pm 4.4\% \]
Neutrino Oscillation: $\theta_{13}$ and $\Delta m^2_{32}$

This Result, RENO
RENO nH
PDG 2019
Daya Bay
Daya Bay nH
Double Chooz

This Result, RENO
PDG 2019
Daya Bay
T2K
MINOS
NOvA
Neutrino Oscillation: L/E Dependence

\[
P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2 \left(1.27\Delta m^2_{ee} \frac{L}{E_\nu}\right)
\]

\[
\sin^2 2\theta_{13} = 0.0892 \pm 0.0044\,(stat.) \pm 0.0045\,(sys.)
\]

\[
|\Delta m^2_{ee}| = 2.74 \pm 0.10\,(stat.) \pm 0.06\,(sys.) \times 10^{-3}\,\text{eV}^2
\]

Yoo-2020-06-25 @ Neutrino 2020 for RENO Collaboration

Preliminary
RENO 1500-Days Data n-H Analysis Results

Prompt signal

$\bar{\nu}_e \rightarrow p$

$e^-$

$\gamma$

$E_\gamma = 2.2\text{MeV}$

Delayed signal

$p$

$p$

Near : $\tau = 208.7 \pm 1.5 \mu s$

Far : $\tau = 210.0 \pm 4.3 \mu s$

Events / 4 $\mu$s

Neutron Capture Time($\mu$s)

Near

Far

Data

Fit

Events / 4 $\mu$s

Delayed Energy (MeV)

0.5

1

1.5

2

2.5

3

0.01

0.02

0.03

0.04

0.05

0.06

0.07

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**Neutrino Oscillation from n-H Data**

**Independent measurement of $\sin^2 2\theta_{13}$ using 1500 live days n-H data**

\[
\sin^2 2\theta_{13} = 0.086 \pm 0.008\text{(stat.)} \pm 0.014\text{(sys.)}
\]

(using PDG input: $|\Delta m^2_{ee}| = 2.562 \times 10^{-3} \text{eV}^2$)
(3+1) Neutrino Model

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2 \left( 1.27\Delta m^2_{31} \frac{L}{E_\nu} \right) - \sin^2 2\theta_{14} \sin^2 \left( 1.27\Delta m^2_{41} \frac{L}{E_\nu} \right) \]
RENO Sterile Neutrino Search

2200 Days of RENO Data

![Graph showing data and expected values for neutrino energy spectrum with different mass squares and mixing angles.]

- $\Delta m^2_{41} = 5 \times 10^{-2}$ eV$^2$
- $\Delta m^2_{41} = 5 \times 10^{-3}$ eV$^2$
- $\Delta m^2_{41} = 1 \times 10^{-3}$ eV$^2$
- $\sin^2 2\theta_{14} = 0.1$ assumed

Measured / Expected from Near

- Data
- Uncertainty of 3ν prediction

arXiv: 2006.07782 (posted on 14th June 2020)
RENO Sterile Neutrino Search

RENO 2200 days

arXiv: 2006.07782 (posted on 14th June 2020)
Summary

- Report updated results using **RENO 2900 days data**
- Precision measurement of $\theta_{13}$ and $|\Delta m_{ee}|$
- Absolute reactor neutrino flux: $R = 94.0\pm2.0\ %$ (for HM)
- Correlation between 5 MeV excess and $^{235}$U fission (3.2$\sigma$ C.L.)

**RENO Poster Presentations in Neutrino 2020**

1. **DongHa Lee**, “Updated results on reactor antineutrino oscillation amplitude and frequency for 2900 days at RENO” *(poster #62)*
2. **Jiwoong Seo**, “Search for Sterile Neutrinos at RENO” *(poster #128)*
3. **Eunhyang Kwan**, “$\theta_{13}$ measurement using data with neutron capture on hydrogen at RENO” *(poster #56)*
Backup Slides
RENO 2900-Days Daily IBD Rate

Near

Far

Preliminary

2200 days

700 days

IBD Rate [day]

Observed

Expected (with oscillation)

Date [yy/mm/dd]
RENO Fuel Fraction in the Reactor Core

Near Preliminary

\[ F_{235} \]

\[ F_i \]

\[ F_{235}, F_{238}, F_{239}, F_{241} \]
Identical yield  \( \overline{y}_f = 5.8303 \pm 0.0063 \times 10^{-43} \text{ cm}^2/\text{fission} \)

Null fuel dependence ruled out by 7.7\( \sigma \)
$y_{235} = 6.155^{+0.183}_{-0.178} \times 10^{-43} \text{ cm}^2/\text{fission}$

$y_{239} = 4.142^{+0.250}_{-0.245} \times 10^{-43} \text{ cm}^2/\text{fission}$
RENO 1500-Days Data n-H Analysis Results

![Graph showing results for different experiments]

- RENO (n-H)
- PDG (2018)
- RENO (n-Gd)
- Daya Bay
- Double Chooz
- T2K

$\sin^2 2\theta_{13}$
Independent measurement of $\sin^2 2\theta_{13}$ using 1500 live days n-H data

$$\sin^2 2\theta_{13} = 0.086 \pm 0.008^{\text{(stat.)}} \pm 0.014^{\text{(sys.)}}$$

$$|\Delta m_{ee}^2| = 2.562 \times 10^{-3} \text{ eV}^2$$
RENO Sterile Neutrino Search (Additional Plots)

![Graph 1: RENO sterile neutrino search Rate only (2200 days)]

![Graph 2: RENO sterile neutrino search Spectrum (2200 days)]

This results

- RENO 95% C.L.
- RENO 90% C.L.
- DayaBay 95% C.L. (2016)
- DayaBay FC 90% C.L. (2020)