Measurement of $\theta_{13}$

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Disclaimer

I am a member of the Daya Bay Collaboration.

Results from the Double Chooz and RENO collaborations are collected from previous publications or presentations. My apologies if I do not present their latest results or misinterpret them.
Physics Motivation

The small but finite neutrino rest mass predicts oscillation phenomena which can be utilized to measure mixing angles and mass differences. One of the mixing angles, $\theta_{13}$, is intimately connected to leptonic CP violation which may be related to the matter-antimatter asymmetry of the universe.
Neutrino Oscillation

Neutrinos change flavor (e,μ,τ) with time

**Principle:** Mass eigenstates ≠ Interaction (flavor) eigenstates

\[
P_{\nu_e \rightarrow \nu_e} (t) = \left| \langle \nu_e (0) | \nu_e (t) \rangle \right|^2 = \left| \sum_{j=1}^{3} \langle \nu_j (0) | U_{e j}^* \sum_{i=1}^{3} e^{i E_i t} U_{i e} \nu_i (0) \rangle \right|^2
\]

**Physical Parameters:** (chosen by nature)

\(\theta_{ij}\): (appear in U)

3 angles between mass/flavor eigenstates set oscillation amplitude

\(\Delta m_{ij}^2\): (appear in \(E_i - E_j\) as a function of \(p\))

Differences in 3 neutrino masses determine oscillation frequency (distance)

**First Evidence of Oscillation:**
Davis detects 1/3 expected solar neutrinos (1968)

We want to know all \(\theta\) and \(\Delta m^2\)
Many recent measurements of neutrino oscillation

\[ c_{ij} \equiv \cos \theta_{ij} \text{ and } s_{ij} \equiv \sin \theta_{ij} \]

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

\[ \theta_{23} \approx 45^\circ \]
Atmospheric \( \nu \) Accelerator \( \nu \)

\[ \theta_{13} < 10^\circ \]
Short-Baseline Reactor \( \nu \) Accelerator \( \nu \)

\[ \theta_{12} \approx 35^\circ \]
Solar \( \nu \) Long-Baseline Reactor \( \nu \)

\[ \theta_{13}: \text{ Only angle not yet firmly observed. It is the gateway to leptonic CP violation } \delta \]
What is the rest mass of neutrinos?

Which is the right mass hierarchy?

Mass Hierarchy of Neutrinos

Normal

Inverted

What is the rest mass of neutrinos?
Neutrino Survival Probability

Neutrino survival probability depends on mixing angles and time (baseline)

\[ P_{\nu_e \rightarrow \nu_e}(t) = \left| \langle \nu_e(0) | \nu_e(t) \rangle \right|^2 = \sum_{j=1}^{3} \langle \nu_j(0) | U_{ej}^* \sum_{i=1}^{3} e^{iE_i t} U_{ie} | \nu_i(0) \rangle \right|^2 \]

\[ P_{\nu_e \rightarrow \nu_e} = (c_{13} c_{12})^2 (c_{13} c_{12})^2 + (c_{13} s_{12})^2 (c_{13} s_{12})^2 (c_{13} s_{12})^2 + (s_{13})^2 (s_{13})^2 \]

\[ + (c_{13} s_{12})^2 (c_{13} c_{12})^2 2 \cos \left( \frac{\Delta m_{21}^2 t}{2p} \right) + (s_{13})^2 (c_{13} c_{12})^2 2 \cos \left( \frac{\Delta m_{31}^2 t}{2p} \right) \]

\[ + (s_{13})^2 (c_{13} s_{12})^2 2 \cos \left( \frac{\Delta m_{32}^2 t}{2p} \right) \]

\[ P_{\nu_e \rightarrow \nu_e} \approx 1 - \sin^2 2 \theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) - \cos^4 \theta_{13} \sin^2 2 \theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E} \right) \]
Reactor Neutrino Oscillation

$\theta_{13}$ revealed by a deficit of reactor antineutrinos at $\sim 2$ km.

\[ P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E_\nu} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E_\nu} \right) \]
Early Hints of non-zero $\theta_{13}$

2011 has given many hints:


**Double CHOOZ**: Y. Abe et al., arXiv:1112.6353

Appearance of $\nu_e$ in $\nu_\mu$ accelerator beam

Double Chooz reported improved single detector measurement.

Summary of $\theta_{13}$ measurements before Daya Bay

No result $>2.5\sigma$ from $\theta_{13} = 0$ as of March 7, 2012
Design principles of Reactor-based experiments

In order to measure the potentially small $\theta_{13}$ to levels of 0.01 for $\sin^2 2\theta_{13}$, the experiments were designed to measure relative quantities with multiple functionally identical detectors, paying detailed attention to background rejection and control.
Relative Measurement

Absolute Reactor Flux:
Largest uncertainty in previous measurements (~ 3%)

Relative Measurement:
Removes absolute uncertainties!

Far/Near $\nu_e$ Ratio

\[ \frac{N_f}{N_n} = \left( \frac{N_{p,f}}{N_{p,n}} \right) \left( \frac{L_n}{L_f} \right)^2 \left( \frac{\epsilon_f}{\epsilon_n} \right) \left[ \frac{P_{\text{sur}}(E, L_f)}{P_{\text{sur}}(E, L_n)} \right] \]

Detector Target Mass

Detector efficiency

Distances from reactor

Oscillation deficit

Baseline [km]
Detection Method

Inverse β-decay (IBD):

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]
\[ n + {}^x\text{Gd} \rightarrow {}^{x+1}\text{Gd} + \gamma \]

Prompt positron:
Carries antineutrino energy,
\[ E_{e^+} \approx E_\nu - 0.8 \text{ MeV} \]

Delayed neutron capture:
Efficiently tags antineutrino signal

Prompt + Delayed coincidence provides distinctive signature
The $\bar{\nu}_e$ energy spectrum

$\nu_e + p \rightarrow n + e^+$
cross section
$(\sim 10^{-42} \text{ cm}^2)$

Calculated reactor $\bar{\nu}_e$ spectrum

Neutrinos with $E < 1.8$ MeV are not detected
### Brief summary of $\theta_{13}$ reactor experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Daya Bay</th>
<th>Double Chooz</th>
<th>RENO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of reactors &amp; total power</td>
<td>3 (17.4 GW)</td>
<td>2 (9.4 GW)</td>
<td>6 (16.5 GW)</td>
</tr>
<tr>
<td>Reactor configuration</td>
<td>3</td>
<td>2</td>
<td>6 inline</td>
</tr>
<tr>
<td>Detector configuration</td>
<td>2 N +1 F</td>
<td>1 N +1 F</td>
<td>1 N +1 F</td>
</tr>
<tr>
<td>Baseline (meter)</td>
<td>(364, 480, 1912)</td>
<td>(400, 1050)</td>
<td>(290, 1380)</td>
</tr>
<tr>
<td>Overburden (mwe)</td>
<td>(280, 300, 880)</td>
<td>(120, 300)</td>
<td>(110, 450)</td>
</tr>
<tr>
<td>Detector medium</td>
<td>Gd-doped liquid scintillator (GdLS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detector geometry</td>
<td>Concentric cylinders of GdLS, $\gamma$-catcher and Oil buffer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target mass (ton)</td>
<td>(40, 40, 80)</td>
<td>(10, 10)</td>
<td>(16.5, 16.5)</td>
</tr>
<tr>
<td>Outer shield</td>
<td>2.5 m water</td>
<td>0.50 m of LS + 0.15 m of Steel</td>
<td>1.5 of water</td>
</tr>
<tr>
<td>Muon veto</td>
<td>Water Cerenkov + RPC Cover</td>
<td>LS + Scintillator Strip Cover</td>
<td>Water Cerenkov</td>
</tr>
</tbody>
</table>
The Daya Bay Neutrino Experiment

A large international collaboration of about 230 members was formed to build and deploy eight modules, each with 20-t target mass, inside a mountain next to the Daya Bay Nuclear Power Plant Complex, 4 in two near halls and 4 in the far hall at distances of about 2km.
Daya Bay: An Ideal Location

17.4 GW (thermal) reactor power adjacent to mountains.

Mountains shield detectors from cosmic ray backgrounds

Reactors produce $\sim 2 \times 10^{20}$ antineutrinos / s / GW
The Daya Bay Collaboration

~ 230 collaborators, 37 institutions

Europe (2) (~10)
- Charles University, Czech Republic,
- JINR, Dubna, Russia

North America (16) (~100)
- BNL, Caltech, Illinois Inst. Tech., Iowa State Univ., LBNL, Princeton, RPI, Siena,
- UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Illinois-Urbana-Champaign, Univ. of Wisconsin-Madison,
- Virginia Tech., William and Mary

Asia (19) (~140)
- Beijing Normal Univ., Chengdu Univ.
Experiment Layout

Overburden: ~860 mwe
Weighted baseline: ~1650 m

Overburden: ~265 mwe
Weighted baseline: ~500 m

Overburden: ~250 mwe
Weighted baseline: ~360 m
The Daya Bay Detector

**ADs surrounded by > 2.5-meter thick two-section water shield and RPCs**

- Antineutrino detectors (ADs) are concentric acrylic tanks filled with liquid scintillator or mineral oil
- Inner and outer water shields are instrumented with
  - 288 8” PMTs in each near hall
  - 384 8” PMTs in Far Hall
- 4-layer RPC modules above pool
  - 54 modules in each near hall
  - 81 modules in Far Hall
Antineutrino Detectors

6 ‘functionally identical’ detectors:
Reduce systematic uncertainties

\[
\frac{N_f}{N_n} = \left( \frac{N_{p,f}}{N_{p,n}} \right) \left( \frac{L_n}{L_f} \right)^2 \left( \frac{\epsilon_f}{\epsilon_n} \right) \left[ \frac{P_{\text{sur}}(E, L_f)}{P_{\text{sur}}(E, L_n)} \right]
\]

3 nested cylinders:
Inner: 20 tons Gd-doped LS (d=3m)
Mid: 20 tons LS (d=4m)
Outer: 40 tons mineral oil buffer (d=5m)

Each detector:
192 8-inch Photomultipliers
Reflectors at top/bottom of cylinder
Provides (7.5 / √E + 0.9)% energy resolution
Antineutrino IBD Event Selection

Use IBD Prompt + Delayed correlated signal to select antineutrinos

Selection:
- Reject Flashers
- Prompt Positron: $0.7 \text{ MeV} < E_p < 12 \text{ MeV}$
- Delayed Neutron: $6.0 \text{ MeV} < E_d < 12 \text{ MeV}$
- Capture time: $1 \mu s < \Delta t < 200 \mu s$
- Muon Veto:
  Pool Muon: Reject 0.6ms
  AD Muon (>20 MeV): Reject 1ms
  AD Shower Muon (>2.5GeV): Reject 1s
- Multiplicity:
  No other signal $> 0.7 \text{ MeV}$
  in $\pm 200 \mu s$ of IBD.

$$\frac{N_f}{N_n} = \left( \frac{N_p,f}{N_p,n} \right) \left( \frac{L_n}{L_f} \right)^2 \left( \frac{\epsilon_f}{\epsilon_n} \right) \left[ \frac{P_{\text{sur}}(E,L_f)}{P_{\text{sur}}(E,L_n)} \right]$$
PMT Light Emission (Flashing)

**Flashing PMTs:**
- Instrumental background from ~5% of PMTs
- ‘Shines’ light to opposite side of detector
- Easily discriminated from normal signals

Relative PMT charge

FID = \log_{10} \left[ \left( \frac{\text{Quadrant}}{1.0} \right)^2 + \left( \frac{\text{MaxQ}}{0.45} \right)^2 \right] < 0

Quadrant = \frac{Q3}{Q2+Q4}
MaxQ = \text{maxQ} / \text{sumQ}

Inefficiency to antineutrinos signal: 0.024% ± 0.006%(stat)
Contamination: < 0.01%
Prompt/Delayed Energy

Clear separation of antineutrino events from most other signals

Uncertainty in relative $E_d$ efficiency (0.12%) between detectors is largest systematic.
Capture Time

Consistent IBD capture time measured in all detectors

Relative detector efficiency estimated within 0.02% by considering possible variations in Gd concentration.

Simulation contains no background (deviates from data at >150 μs)
Calibration driven by uncertainty in relative detector efficiency

\[ \frac{N_f}{N_n} = \left( \frac{N_{p,f}}{N_{p,n}} \right) \left( \frac{L_n}{L_f} \right)^2 \left( \frac{\epsilon_f}{\epsilon_n} \right) \frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)} \]

PMT gain vs. time

Energy vs. time

Energy vs. position

60Co at center
Uncorrelated signals dominated by low-energy radioactivity

**Measured Rates:**
~65 Hz in each detector
(>0.7 MeV)

**Sources:**
Stainless Steel: U/Th chains
PMTs: $^{40}$K, U/Th chains
Scintillator: Radon/U/Th chains
Accidental Background

- Calculation:
  - Random coincidence of neutron-like singles and prompt signals

- Cross check:
  - Prompt-delayed distance distribution. Check the fraction of prompt-delayed with distance >2m.

Accidental background rates (per day), muon veto and multiplicity cut eff corrected

<table>
<thead>
<tr>
<th></th>
<th>AD1</th>
<th>AD2</th>
<th>AD3</th>
<th>AD4</th>
<th>AD5</th>
<th>AD6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidents (per day)</td>
<td>9.73 ± 0.10</td>
<td>9.61 ± 0.10</td>
<td>7.55 ± 0.08</td>
<td>3.05 ± 0.04</td>
<td>3.04 ± 0.04</td>
<td>2.93 ± 0.03</td>
</tr>
</tbody>
</table>
**Fast neutron Background**

**Fast Neutrons:**
Energetic neutrons produced by cosmic rays (inside and outside of muon veto system)

**Mimics antineutrino (IBD) signal:**
- Prompt: Neutron collides/stops in target
- Delayed: Neutron captures on Gd

**Background uncertainties**
are 0.3% (0.2%) in far (near) halls.

Constrain fast-n rate using IBD-like signals in 10-50 MeV

Validate with fast-n events tagged by muon veto.
**β-n decay Background**

- Generated by cosmic rays
- Long-lived
- Mimic antineutrino signal
- Estimate $^9\text{Li}$ rate using time-correlation with muon

**β-n decay:**
- Prompt: $\beta$-decay
- Delayed: neutron capture

$^9\text{Li}$: $\tau_{1/2} = 178$ ms, $Q = 13.6$ MeV

$^8\text{He}$: $\tau_{1/2} = 119$ ms, $Q = 10.6$ MeV

Analysis muon veto cuts control B/S to $\sim 0.4\pm0.2\%$. 

$E_\mu > 4$ GeV (visible)
Summary of Backgrounds

<table>
<thead>
<tr>
<th></th>
<th>Near Halls</th>
<th>Far Hall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B/S %</td>
<td>σB/S %</td>
</tr>
<tr>
<td>Accidentals</td>
<td>1.5</td>
<td>0.02</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>0.12</td>
<td>0.05</td>
</tr>
<tr>
<td>$^9\text{Li}/^8\text{He}$</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>$^{241}\text{Am}-^{13}\text{C}$</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>$^{13}\text{C}(\alpha, n)^{16}\text{O}$</td>
<td>0.01</td>
<td>0.006</td>
</tr>
</tbody>
</table>

Total backgrounds are **5% (2%)** in far (near) halls.
# Data Set Summary

> 200k antineutrino interactions!

<table>
<thead>
<tr>
<th></th>
<th>AD1</th>
<th>AD2</th>
<th>AD3</th>
<th>AD4</th>
<th>AD5</th>
<th>AD6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antineutrino candidates</td>
<td>69121</td>
<td>69714</td>
<td>66473</td>
<td>9788</td>
<td>9669</td>
<td>9452</td>
</tr>
<tr>
<td>DAQ live time (day)</td>
<td>127.5470</td>
<td>127.3763</td>
<td>126.2646</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.8015</td>
<td>0.7986</td>
<td>0.8364</td>
<td>0.9555</td>
<td>0.9552</td>
<td>0.9547</td>
</tr>
<tr>
<td>Accidentals (/day)</td>
<td>9.73 ± 0.10</td>
<td>9.61 ± 0.10</td>
<td>7.55 ± 0.08</td>
<td>3.05 ± 0.04</td>
<td>3.04 ± 0.04</td>
<td>2.93 ± 0.03</td>
</tr>
<tr>
<td>Fast neutron (/day)</td>
<td>0.77 ± 0.24</td>
<td>0.77 ± 0.24</td>
<td>0.58 ± 0.33</td>
<td>0.05 ± 0.02</td>
<td>0.05 ± 0.02</td>
<td>0.05 ± 0.02</td>
</tr>
<tr>
<td>$^8\text{He}/^9\text{Li}$ (/day)</td>
<td>2.9 ± 1.5</td>
<td>2.0 ± 1.1</td>
<td></td>
<td>0.22 ± 0.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Am-C corr. (/day)</td>
<td></td>
<td></td>
<td></td>
<td>0.2 ± 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{13}\text{C}(\alpha, \text{n})^{16}\text{O}$ (/day)</td>
<td>0.08 ± 0.04</td>
<td>0.07 ± 0.04</td>
<td>0.05 ± 0.03</td>
<td>0.04 ± 0.02</td>
<td>0.04 ± 0.02</td>
<td>0.04 ± 0.02</td>
</tr>
<tr>
<td>Antineutrino rate (/day)</td>
<td><strong>662.47 ± 3.00</strong></td>
<td><strong>670.87 ± 3.01</strong></td>
<td><strong>613.53 ± 2.69</strong></td>
<td><strong>77.57 ± 0.85</strong></td>
<td><strong>76.62 ± 0.85</strong></td>
<td><strong>74.97 ± 0.84</strong></td>
</tr>
</tbody>
</table>

Consistent rates for side-by-side detectors

Uncertainty currently dominated by statistics
Detected rate strongly correlated with reactor flux expectations.

Predicted Rate:
- Normalization is determined by data fit.
- Absolute normalization is within a few percent of expectations.
Far vs. Near Comparison

Compare the far/near measured rates and spectra

$$R = \frac{\text{Far}_{\text{measured}}}{\text{Far}_{\text{expected}}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6} (\alpha_i (M_1 + M_2) + \beta_i M_3)}$$

$M_n$ are the measured rates in each detector. Weights $\alpha_i, \beta_i$ are determined from baselines and reactor fluxes.

$$R = 0.940 \pm 0.011 \text{ (stat)} \pm 0.004 \text{ (syst)}$$

Clear observation of far site deficit.

Spectral distortion consistent with oscillation.*

* Caveat: Spectral systematics not fully studied; $\theta_{13}$ value from shape analysis is not recommended.
Rate Analysis

Estimate $\theta_{13}$ using measured rates in each detector.

$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \text{ (stat)} \pm 0.005 \text{ (syst)}$

Most precise measurement of $\sin^2 2\theta_{13}$ to date.

Uses standard $\chi^2$ approach.

Far vs. near relative measurement. [Absolute rate is not constrained.]

Consistent results obtained by independent analyses, different reactor flux models.
RENO

A collaboration of about 40 members from 12 Korean institutions. The antineutrinos are from 6 reactors on a straight line. There are 1 far and 1 near detectors, 16.5 tons of Gd-loaded liquid scintillator each, both located inside a mountain.
RENO Collaboration

(12 institutions and 40 physicists)

- Chonbuk National University
- Chonnam National University
- Chung-Ang University
- Dongshin University
- Gyeongsang National University
- Kyungpook National University
- Pusan National University
- Sejong University
- Seokyeong 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
RENO Experiment

Reactors: 6 x 2.8 GW$_{th}$

Detectors: Near and Far
Each 16.5 t Gd loaded scintillator
Reno Daily IBD Rate
RENO (NuTel 2013 Seon-Hee Seo)

**Reactor Antineutrino Disappearance**

![Graph showing reactor antineutrino disappearance](image)

\[
R = \frac{\Phi^{\text{Far}}_{\text{observed}}}{\Phi^{\text{Far}}_{\text{expected}}} = 0.929 \pm 0.006(\text{stat.}) \pm 0.009(\text{syst.})
\]

- A clear deficit in rate (7 % reduction)
- Consistent with neutrino oscillation in the spectral distortion

**preliminary**
Double Chooz

A large international collaboration of about 200 members. Both far and near detectors are 10 m$^3$ of Gd-loaded liquid scintillator. The far detector was completed in April 2011, while the near detector is still under construction with expected completion date in 2013.
Double Chooz collaboration

Brazil
CBPF
UNICAMP
UFABC

France
APC
CEA/DSM/
IRFU:
SPP
SPhN
SEDI
SIS
SENAC
CNRS/IN2P3:
Subatech
IPHC

Germany
EKU Tübingen
MPIK
Heidelberg
RWTH Aachen
TU München
U. Hamburg

Japan
Tohoku U.
Tokyo Inst. Tech.
Tokyo Metro. U.
Niigata U.
Kobe U.
Tohoku Gakuin U.
Hiroshima Inst. Tech.

Russia
INR RAS
IPC RAS
RRC
Kurchatov

Spain
CIEMAT-
Madrid

USA
U. Alabama
ANL
U. Chicago
Columbia U.
UCDavis
Drexel U.
IIT
KSU
LLNL
MIT
U. Notre Dame
U. Tennessee

Spokesperson:
H. de Kerret (IN2P3)

Project Manager:
Ch. Veyssière (CEA-Saclay)

Web Site:
www.doublechooz.org/
Double Chooz experiment

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 Daily IBD Rate

Two reactors on (60%)
One reactors on (40%)
Two reactors off (1 day)
two independent measurements of $\theta_{13}$

**Gd-IBD**

- ~8250 IBDs (with BG)
- ~227 days
- $X^2$/dof: 42.1/35

**H-IBD**

- 36284 IBDs (with BG)
- ~240 days
- $X^2$/dof: 38.9/30

---

rate+shape analysis $\rightarrow$ clear $\theta_{13}$ E/L pattern & BG constrains

**DC-II(Gd):** $\sin^2(2\theta_{13}) = 0.109 \pm 0.04$ [0.030$^{\text{stat}}$$\pm$0.025$syst$]

**DC-II(H):** $\sin^2(2\theta_{13}) = 0.097 \pm 0.05$ [0.034$^{\text{stat}}$$\pm$0.034$syst$]

---

@ Nu2012 (Jun. 2012)

@ APC (Dec. 2012)
Summary of $\theta_{13}$ results

Reactor-based neutrino experiments have measured $\theta_{13}$ to a precision better than the other 2 angles. Continuation of current measurements will begin to constrain the unitarity of the 3-flavor paradigm of neutrinos, and provide help to CP violation measurements.
Current $\theta_{13}$ Landscape

[5] Daya Bay:
\[ \sin^2 2\theta_{13} = 0.092 \pm 0.016 \text{ (stat)} \pm 0.005 \text{ (syst)} \]

[6] RENO:
\[ \sin^2 2\theta_{13} = 0.113 \pm 0.013 \text{ (stat)} \pm 0.019 \text{ (syst)} \]

[8] Double Chooz:
\[ \sin^2 2\theta_{13} = 0.109 \pm 0.030 \text{ (stat)} \pm 0.025 \text{ (syst)} \]

[9] Daya Bay:
Chinese Physics C, 37, 011001 (2013)
\[ \sin^2 2\theta_{13} = 0.089 \pm 0.010 \text{ (stat)} \pm 0.005 \text{ (syst)} \]
Backup

Some backup slides
Non-zero measurements of $\theta_{13}$

**Daya Bay:**

\[ \sin^2 2\theta_{13} = 0.092 \pm 0.016 \text{ (stat)} \pm 0.005 \text{ (syst)} \]

*Result announced simultaneous by all collaborating institutions on March 8, 2012*

**RENO:**

\[ \sin^2 2\theta_{13} = 0.113 \pm 0.013 \text{ (stat)} \pm 0.019 \text{ (syst)} \]
Background: $^{13}$C(α,n)$^{16}$O

Potential alpha source:

$^{238}$U, $^{232}$Th, $^{235}$U, $^{210}$Po:

Each of them are measured in-situ:

U&Th: cascading decay of

Bi(or Rn) $\rightarrow$ Po $\rightarrow$ Pb

$^{210}$Po: spectrum fitting

Combining (α,n) cross-section, correlated background rate is determined.

Example alpha rate in AD1

<table>
<thead>
<tr>
<th></th>
<th>$^{238}$U</th>
<th>$^{232}$Th</th>
<th>$^{235}$U</th>
<th>$^{210}$Po</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bq</td>
<td>0.05</td>
<td>1.2</td>
<td>1.4</td>
<td>10</td>
</tr>
</tbody>
</table>

Near Site: 0.04+/-0.02 per day, B/S (0.006 ± 0.004) %

Far Site: 0.03+/-0.02 per day, B/S (0.04 ± 0.02) %
Reactor Flux Expectation

Antineutrino flux is estimated for each reactor core

Flux estimated using:

\[ S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F_e) \cdot \sum_i (f_i/F)S_i(E_\nu)} \]

Reactor operators provide:
- Thermal power data: \( W_{th} \)
- Relative isotope fission fractions: \( f_i \)

Energy released per fission: \( e_i \)

Antineutrino spectra per fission: \( S_i(E_\nu) \)
P. Huber, Phys. Rev. C84, 024617 (2011)

Flux model has negligible impact on far vs. near oscillation measurement
Accidental Background (Method II)

- An alternative method
  - Off-window fits with two choices of windows
- Based on the difference between two methods, the systematic error is below 1%. No systematic error is assigned to the accidental background.

Comparison of accidental rates (per day) among different methods

<table>
<thead>
<tr>
<th></th>
<th>EH1-AD1</th>
<th>EH1-AD2</th>
<th>EH2-AD1</th>
<th>EH3-AD1</th>
<th>EH3-AD2</th>
<th>EH3-AD3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical</td>
<td>9.73 ± 0.03</td>
<td>9.61 ± 0.03</td>
<td>7.55 ± 0.03</td>
<td>3.05 ± 0.02</td>
<td>3.04 ± 0.02</td>
<td>2.93 ± 0.02</td>
</tr>
<tr>
<td>Off-window1</td>
<td>9.69 ± 0.03</td>
<td>9.59 ± 0.03</td>
<td>7.54 ± 0.03</td>
<td>3.06 ± 0.02</td>
<td>3.03 ± 0.02</td>
<td>2.95 ± 0.02</td>
</tr>
<tr>
<td>Rel. diff.</td>
<td>-0.4%</td>
<td>-0.5%</td>
<td>-0.2%</td>
<td>0.2%</td>
<td>-0.2%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Off-window2</td>
<td>9.77 ± 0.05</td>
<td>9.66 ± 0.05</td>
<td>7.61 ± 0.04</td>
<td>3.05 ± 0.02</td>
<td>3.02 ± 0.02</td>
<td>2.94 ± 0.02</td>
</tr>
<tr>
<td>Rel. diff.</td>
<td>0.4%</td>
<td>0.5%</td>
<td>0.8%</td>
<td>0.0%</td>
<td>-0.6%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>
The RPC muon detector

Resistive Plate Chambers (RPCs) are placed above the water pools to detect muons entering the pool with high efficiency. The RPC system, combined with the water pool instrumented as a Cerenkov detector, will allow us to measure muon-induced background to reach the ultimate sensitivity.
Streamers are formed in the gas gap between two resistive electrodes with a gas gain of \(~ 10^9\).

The Daya Bay RPCs are made from Bakelite with resistivity controlled to \(0.5 - 2.5 \times 10^{12} \Omega.\text{cm.}\)

The gas mixture is Argon, R134a, Isobutane and a trace amount of SF6.

The signal is read out from outside using strips at a threshold of 40 mV.
RPC installation

RPC modules in SAB

RPC supporting structure

Gas system

Fully installed RPC
Detector Filling

ISO tank on load cells

Detector target filled from GdLS in ISO tank.

Load cells measure 20 ton target mass to 3 kg (0.015%)

3 fluids filled simultaneously, with heights matched to minimize stress on acrylic vessels
- Gadolinium-doped Liquid Scintillator (GdLS)
- Liquid Scintillator (LS)
- Mineral Oil (MO)
Automated Calibration System

3 Automated calibration ‘robots’ (ACUs) on each detector

Top view

3 sources for each z axis on a turntable (position accuracy < 5 mm):

- 10 Hz $^{68}$Ge (0 KE $e^+ = 2\times0.511$ MeV $\gamma$’s)
- 0.5 Hz $^{241}$Am-$^{13}$C neutron source (3.5 MeV n without $\gamma$) + 100 Hz $^{60}$Co gamma source (1.173+1.332 MeV $\gamma$)
- LED diffuser ball (500 Hz) for $T_0$ and gain
Muon Tagging System

Dual tagging systems: 2.5 meter thick two-section water shield and RPCs

- Outer layer of water veto (on sides and bottom) is 1m thick, inner layer >1.5m. Water extends 2.5m above ADs
  - 288 8” PMTs in each near hall
  - 384 8” PMTs in Far Hall
- 4-layer RPC modules above pool
  - 54 modules in each near hall
  - 81 modules in Far Hall
- Goal efficiency: > 99.5% with uncertainty <0.25%
The Daya Bay RPC Modules

- The Daya Bay RPC Modules are 2 m x 2 m
- There are 4 layers of bare RPCs, each with 1 readout plane, inside an Al box
- There are 2 x and 2 y 25-cm wide strips per module
- The spatial resolution is about 8 cm per coordinate
- There are 54 modules each in EH1 and EH2, and 81 in EH3.
- The RPCs are triggered by having 3 out of 4 layers hit per module
- The muon detection efficiency based on RPCs alone is > 95%.
Data acquisition and analysis

Antineutrino interactions are selected based on their characteristic time sequence of a prompt signal followed by delayed energetic neutron capture signal by Gadolinium. Relative detection efficiencies are known to high precision via calibration and Monte Carlo simulation.
**Multiplicity**

Ensure exactly one prompt-delayed coincidence

\[ \varepsilon_1 = e^{-R \cdot 200 \mu s} \]

- If \( T_s \geq 200 \mu s \)
  \[ \varepsilon_{3a} = 1 - R \cdot 200 \mu s \cdot \left(1 - \frac{100 \mu s}{\Delta T_s}\right) \]
- If \( T_s < 200 \mu s \)
  \[ \varepsilon_{3b} = 1 - R \cdot \frac{T_s}{2} \]

1 \( \mu s < \Delta e^+ - n < 200 \mu s \)

\[ \varepsilon_2 = 1 - R \cdot \overline{t_{cap}} \]

Uncorrelated background and IBD signals result in ambiguous prompt, delayed signals.

-> Reject all IBD with >2 triggers above 0.7 MeV in -200\( \mu s \) to +200\( \mu s \).

Introduces \( \sim 2.5\% \) IBD inefficiency, with negligible uncertainty.
Current $\theta_{13}$ Landscape

- KamLAND + SOLAR
  - Original Flux
  - Reevaluated Flux
  - T2K

- MINOS
  - Normal Hierarchy
  - Inverted Hierarchy

- Double Chooz

- Daya Bay (2012-03)

- RENO (2012-04)

- Double Chooz (2012-07)

- Double Chooz nH (2013-01)

- T2K Update (2013-04)

- RENO (Prelim. 2013-03)

- Daya Bay (2012-10)
Trigger Perf

Trigger Thresholds:
- AD: >45 PMTs (digital trigger)
  >0.4 MeV (analog trigger)
- Inner Water Veto: > 6 PMTs
- Outer Water Veto: >7 PMTs
- RPC: 3/4 layers in module

Trigger Efficiency:
- No measureable inefficiency >0.7 MeV
- Minimum energy expected for prompt antineutrino signal is ~0.9 MeV.
Background

Background rates are determined from data whenever possible or from data and simulation.
Result

The efficiency-corrected background-subtracted yields at the far hall are compared to predictions from those of near halls. A 6.0 % deficit at the far site was observed. Our analysis with the increased statistics (2.5 X) showed that $\theta_{13}$ is large and consistent with our RPL result.
Negligible reactor flux uncertainty (<0.02%) from precise survey.

Detailed Survey:
- GPS above ground
- Total Station underground
- Final precision: 28mm

Validation:
- Three independent calculations
- Cross-check survey
- Consistent with reactor plant and design plans
The Daya Bay Detector

Eight neutrino detectors, each holding 20 tons of liquid scintillator doped with Gadolinium, are deployed to measure the energy and time of antineutrino interactions electronically. The detectors are submerged in water to shield them from ambient radioactivity background. Active muon detectors are installed to veto residual cosmic muons which can produce cosmogenic background.
Summary

- With 2.5x more data, the Daya Bay reactor neutrino experiment measures a far/near antineutrino deficit at ~2 km:

  \[ R = 0.944 \pm 0.007 \text{ (stat)} \pm 0.003 \text{ (syst)} \]

  \[ \text{[PRL value: } R = 0.940 \pm 0.011 \text{ (stat)} \pm 0.004 \text{ (syst)}] \]

- Interpretation of disappearance as neutrino oscillation yields:

  \[ \sin^2 2\theta_{13} = 0.089 \pm 0.010 \text{ (stat)} \pm 0.005 \text{ (syst)} \]

  \[ \text{[PRL value: } \sin^2 2\theta_{13} = 0.092 \pm 0.016 \text{ (stat)} \pm 0.005 \text{ (syst)}] \]

- Installation of final two antineutrino detectors this year

  Gateway to Leptonic CP violation wide open!

Stay tuned for more results from Daya Bay
A. Two Detector Comparison: arXiv:1202:6181  
- Side-by-side comparison of 2 detectors in Hall 1  
- Demonstrated detector systematics better than requirements.  
- To be published in Nucl. Inst. and Meth.

- All 3 halls (6 ADs) operating  
- First observation of $\bar{\nu}_e$ disappearance  

C. This Update:  
- More than 2.5x the previous data set
Inverse beta decay has a distinctive signature

Inverse $\beta$-decay (IBD):

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

$$n + ^{x} Gd \rightarrow ^{x+1} Gd + \gamma$$

Prompt positron:
Carries antineutrino energy
$$E_{e^+} \approx E_\nu - 0.8 \text{ MeV}$$

Delayed neutron capture:
Efficiently tags antineutrino signal

Prompt + Delayed coincidence provides distinctive signature
Detectors are optimized for inverse beta decay observation

- **Outer $\mu$-Veto (OV)**
- **$\nu$-Target (NT)**
  - Gd-doped Liquid-Scintillator
- **$\gamma$-Catcher (GC)**
  - Liquid-Scintillator
- **Light Buffer**
  - Oil (negligible scintillation)
- **Inner $\mu$-Veto (IV)**
- **Inert $\gamma$-Shield**
  - 15cm of steel (around all detector)
observed vs expected rate...

next: plot observed vs expected IBD rate per day

Anatael Cabrera @NuTel 2013
Experiment Layout

6 Antineutrino Detectors (ADs) in 3 underground halls.

<table>
<thead>
<tr>
<th></th>
<th>Overburden</th>
<th>$R_\mu$</th>
<th>$E_\mu$</th>
<th>D1,D2</th>
<th>L1,L2</th>
<th>L3,L4</th>
</tr>
</thead>
<tbody>
<tr>
<td>EH1</td>
<td>280</td>
<td>1.27</td>
<td>57</td>
<td>364</td>
<td>857</td>
<td>1307</td>
</tr>
<tr>
<td>EH2</td>
<td>300</td>
<td>0.95</td>
<td>58</td>
<td>1348</td>
<td>480</td>
<td>528</td>
</tr>
<tr>
<td>EH3</td>
<td>880</td>
<td>0.056</td>
<td>137</td>
<td>1912</td>
<td>1540</td>
<td>1548</td>
</tr>
</tbody>
</table>

TABLE I. Overburden (m.w.e), muon rate $R_\mu$ (Hz/m²), and average muon energy $E_\mu$ (GeV) of the three EHs, and the distances (m) to the reactor pairs.
For near/far oscillation, only uncorrelated uncertainties are used.

Largest systematics are smaller than far site statistics (~1%)
High-statistics reactor antineutrino spectra.

B/S ratio is 5% (2%) at far (near) sites.
Background: \(^{241}\text{Am-}^{13}\text{C}\) neutrons

Weak (0.5Hz) neutron source in ACU can mimic IBD via inelastic scattering and capture on iron.

Simulated neutron capture position

Constrain far site B/S to 0.3 ± 0.3%:
- Measure uncorrelated gamma rays from ACU in data
- Estimate ratio of correlated/uncorrelated rate using simulation
- Assume 100% uncertainty from simulation