Latest Results on Reactor Antineutrino Disappearance at Daya Bay

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On behalf of the Daya Bay Collaboration

Yale, September 30, 2013
Reactor Neutrinos

2008 - Precision measurement of $\Delta m_{12}^2$. Evidence for oscillation

2003 - First observation of reactor antineutrino disappearance

1995 - Nobel Prize to Fred Reines at UC Irvine

1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe

1956 - First observation of (anti)neutrinos

Past Reactor Experiments
- Hanford
- Savannah River
- ILL, France
- Bugey, France
- Rovno, Russia
- Goesgen, Switzerland
- Krasnoyark, Russia
- Palo Verde
- Chooz, France

55 years of liquid scintillator detectors a story of varying baselines...
Reactor Antineutrinos

**Source**

$\bar{\nu}_e$ from $\beta$-decays of n-rich fission products

> 99.9% of $\nu_e$ are produced by fissions in $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$

**Detecion**

inverse beta decay

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

mean energy of $\bar{\nu}_e$: 3.6 MeV

only disappearance experiments possible

From Bemporad, Gratta and Vogel

observed spectrum

calculated reactor spectrum

pure $\bar{\nu}_e$ source
Observation of Reactor $\bar{\nu}_e$ Disappearance

Karsten Heeger, Yale University

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KamLAND 2003

55 reactors

mean, flux-weighted reactor distance ~ 180km

1kt liquid scintillator detector

Reactor Neutrino Physics 1956-2003

Reactor Antineutrinos at KamLAND

KamLAND 2007-2010

Evidence for spectral distortion

KamLAND has measured $\Delta m_{12}^2$ to ~2.8%

Direct evidence for oscillation

KamLAND → $\Delta m_{12}^2$
SNO → $\theta_{12}$

L_0=180km

KamLAND 2010
Recent Observations

- atmospheric $\nu_\mu$ and $\bar{\nu}_\mu$ disappear most likely to $\nu_\tau$ (SK, MINOS)
- accelerator $\nu_\mu$ and $\bar{\nu}_\mu$ disappear at $L \sim 250$, 700 km (K2K, T2K, MINOS)
- some accelerator $\nu_\mu$ appear as $\nu_\mu$ at $L \sim 250$, 700 km (T2K, MINOS)
- solar $\nu_e$ convert to $\nu_\mu/\nu_\tau$ (Cl, Ga, SK, SNO, Borexino)
- reactor $\bar{\nu}_e$ disappear at $L \sim 200$ km (KamLAND)
- reactor $\nu_e$ disappear at $L \sim 1$ km (DC, Daya Bay RENO)

$$P_{i \rightarrow i} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

Experiments have demonstrated vacuum oscillation L/E pattern
**Neutrino Oscillation**

**Neutrino Oscillation Imply Neutrino Mass**

mass eigenstates ≠ flavor eigenstates

\[ |\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle \]

flavor composition of neutrinos changes as they propagate

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \left| \langle \nu_\beta | \nu_\alpha(L) \rangle \right|^2
\]

\[
= \delta_{\alpha\beta} - 4 \sum_{i,j} \Re(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2[1.27 \Delta m^2_{ij} L/E] \\
+ 2 \sum_{i,j} \Im(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2[2.54 \Delta m^2_{ij} L/E]
\]

2-neutrino case

\[
P_{i\rightarrow j} = \sin^2 2\theta \sin^2 \left( 1.27 \Delta m^2 L/E \right)
\]

energy and baseline dependent osc frequency depends on $\Delta m^2$
amplitude depends on $\theta$
Measurement of Fundamental Parameters

Mass Splittings

\[ m^2 \]

- \( m_1^2 \) to \( m_2^2 \)
- \( m_2^2 \) to \( m_3^2 \)
- \( m_3^2 \) to \( m_1^2 \)

- \( \Delta m^2 \) (10^{-3} eV^2)

- Normal
- Inverted

\( \Delta m^2 / (10^{-3} eV^2) \)

\( \sin^2(2\theta) \)

KamLAND 2010

MINOS Nu2012
Neutrino Oscillation - Before 2011

Mixing Angles

\[ U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \]

\( U_{\text{MNSP}} \) Matrix

Maki, Nakagawa, Sakata, Pontecorvo

\[
\begin{bmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{bmatrix}
\begin{bmatrix}
\cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\
0 & 1 & 0 \\
-e^{i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13}
\end{bmatrix}
\begin{bmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 \\
0 & e^{i\alpha/2} & 0 \\
0 & 0 & e^{i\alpha/2 + i\beta}
\end{bmatrix}
\]

atmospheric, K2K
reactor and accelerator
SNO, solar SK, KamLAND
\( 0\nu\beta\beta \)

\[ \sin^2 \theta_{23} = 0.50 \pm 0.07 \]
\[ \sin^2 \theta_{13} = 0.318 \pm 0.019 \]
\[ \sin^2 \theta_{12} = 0.019 \pm 0.016 \]

small? zero?
maximal?
large, but not maximal!
Reactor Neutrino Oscillation Experiments

Measure (non)-1/r² behavior of $\bar{\nu}_e$ interaction rate

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E_v}\right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E_v}\right)$$

for 3 active $\nu$, two different oscillation length scales: $\Delta m_{21}^2, \Delta m_{23}^2$

$\Delta m_{21}^2 \sim 7.6 \times 10^{-5} \text{ eV}^2$

$\Delta m_{23}^2 \sim 2.4 \times 10^{-3} \text{ eV}^2$

$L/E \rightarrow \Delta m^2$  

amplitude of oscillation $\rightarrow \theta$
Measuring $\theta_{13}$ with Reactor Experiments

**Near-Far Concept**

- $V_e$ near
- $V_{e,x}$ distance $L \approx 1.5$ km
- $V_{e,x}$ far

**Absolute Reactor Flux**
Largest uncertainty in previous measurements

**Relative Measurement**
Removes absolute uncertainties!

First proposed by L. A. Mikaelyan and V.V. Sinev, Phys. Atomic Nucl. 63 1002 (2000)

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

- far/near $\overline{V}_e$ ratio
- target mass
- distances
- efficiency
- oscillation deficit
Daya Bay Nuclear Power Plant

A Powerful Neutrino Source

- Among the top 5 most powerful reactor complexes in the world, producing 17.4 GW$_{th}$ (6 x 2.95 GW$_{th}$)
- All 6 reactors are in commercial operation
- Adjacent to mountains; convenient to construct tunnels and underground labs with sufficient overburden to suppress cosmic rays

Reactors produce $\sim 2 \times 10^{20}$ antineutrinos/sec/GW
An International Effort

Asia (21)
Beijing Normal Univ., CGNPG, CIAE, Dongguan Polytechnic, ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

Europe (2)
Charles University, JINR Dubna

North America (17)
Brookhaven Natl Lab, CalTech, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Rensselaer Polytechnic, Siena College, UC Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

230 Collaborators from 40 Institutions
Daya Bay Experiment Layout

- Daya Bay Experiment Layout
- 6 reactor cores
- 3 experimental halls
- 6 (8) detectors

<table>
<thead>
<tr>
<th>Overburden</th>
<th>$R_\mu$</th>
<th>$E_\mu$</th>
<th>D1,2</th>
<th>L1,2</th>
<th>L3,4</th>
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<td>EH1</td>
<td>250</td>
<td>1.27</td>
<td>57</td>
<td>364</td>
<td>857</td>
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<tr>
<td>EH2</td>
<td>265</td>
<td>0.95</td>
<td>58</td>
<td>1348</td>
<td>480</td>
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<tr>
<td>EH3</td>
<td>860</td>
<td>0.056</td>
<td>137</td>
<td>1912</td>
<td>1540</td>
</tr>
</tbody>
</table>

Karsten Heeger, Yale University

Yale, September 30, 2013
Daya Bay Experiment Layout

Hall 3: began 3 AD operation on Dec. 24, 2011

Hall 2: began 1 AD operation on Nov. 5, 2011

Hall 1: began 2 AD operation on Sep. 23, 2011
Daya Bay Detectors

6 “functionally identical” detectors
Gd-LS defines target volume, no position cut

Dual tagging systems: 2.5 meter water shield and RPCs

_target mass: 20 ton per AD
_photosensors: 192 8”-PMTs
_energy resolution: \((7.5 / \sqrt{E} + 0.9)\)%

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

Two-zone ultrapure water Cherenkov detector
_multiple detectors allow comparison and cross-checks

Karsten Heeger, Yale University

Yale, September 30, 2013
Antineutrino Detector Assembly

detector assembly in pairs
Detector Filling and Target Mass Measurement

ISO tank on load cells

detector in scintillator hall

coriolis flow meters

Target mass determination error ± 3kg out of 20,000

<0.03% during data taking period

Detectors are filled from same reservoirs “in-pairs” within < 2 weeks.
Automated Calibration System

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

Three axes: center, edge of target, middle of gamma catcher

Top view

3 sources in each robot, including:
- 10 Hz $^{68}$Ge (0 KE $e^+ = 2\times0.511$ MeV $\gamma$'s)
- 0.75 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 time calibration

Temporary special calibration sources:
$\gamma$: $^{137}$Cs (0.662 MeV), $^{54}$Mn (0.835 MeV), $^{40}$K (1.461 MeV)
$n$: $^{241}$Am-$^{9}$Be, $^{239}$Pu-$^{13}$C
Antineutrino Candidates (Inverse Beta Decay)

Prompt + Delayed Selection

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

Uncertainty in relative \(E_d\) efficiency (0.12\%) between detectors is largest systematic.

Prompt Energy Signal

![Prompt Energy Distribution](image)

Delayed Energy Signal

![Delayed Energy Distribution](image)
Antineutrino Candidates Selection

Antineutrino interactions cleanly separated from backgrounds

(1) Reject spontaneous PMT light emission ("flashers")
(2) Prompt positron: 0.7 MeV < Ep < 12 MeV
(3) Delayed neutron: 6.0 MeV < Ed < 12 MeV
(4) Neutron capture time: 1 μs < t < 200 μs
(5) Muon veto:
   - Water pool muon (>12 hit PMTs): Reject [-2μs; 600μs]
   - AD muon (>3000 photoelectrons): Reject [-2 μs; 1400μs]
   - AD shower muon (>3×10^5 p.e.): Reject [-2 μs; 0.4s]
(6) Multiplicity:
   - No additional prompt-like signal 400μs before delayed neutron
   - No additional delayed-like signal 200μs after delayed neutron
Analyzed Data Sets

Two detector comparison
[1202.6181]
- 90 days of data, Daya Bay near only
- NIM A **685** (2012), 78-97

First oscillation analysis
[1203:1669]
- 55 days of data, 6 ADs near+far
- PRL **108** (2012), 171803

Improved oscillation analysis
[1210.6327]
- 139 days of data, 6 ADs near+far
- CP C **37** (2013), 011001

Spectral Analysis
- 217 days complete 6 AD period
- 55% more statistics than CPC result
Side-by-Side Comparison in Near Hall

ratio of neutrino events in AD1 and AD2
expected: 0.981
measured: 0.987 ± 0.008 (stat) ± 0.003

ratio is not 1 because of baseline difference

Daya Bay Initial Results

March 2012  Based on 55 days of data with 6 ADs, discovered disappearance of reactor $\bar{\nu}_e$ at short baseline.  [PRL 108, 171803]

June 2012  Obtained the most precise value of $\theta_{13}$:

$$\sin^2 2\theta_{13} > 0$$

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005$$  [CPC 37, 011001]
A Top-10 Breakthrough of 2012

TALENs, and another genome-editing tool called meganucleases is that they must be reengineered for each new DNA target. These proteins have two parts: the DNA targeting sequence and the DNA-cutting section. The new technology substitutes RNA—which is simpler to make than a piece of a protein—for the DNA targeting section. It also makes use of a bacterial protein called Cas9, which is part of a natural bacterial defense system called CRISPR, to do the cutting.

Researchers have shown in a test-tube that they can combine these two RNAs into a single one that both matches the DNA target and holds Cas9 in place. Using this system, they were able to cut specific target DNA, demonstrating the potential of Cas9 to work like TALENs. Now, those researchers are trying this approach in organisms other than bacteria, and other genome engineers are quite excited about their prospects, suggesting that it may one day challenge zinc finger nucleases and TALENs as the core genome engineering technology.

CRASH PROJECT OPENS A DOOR IN NEUTRINO PHYSICS

Sometimes it’s not the result itself so much as the promise it holds that matters most. This year, physicists measured the last parameter describing how elusive particles called neutrinos morph into one another as they zip along at near-light speed. And the result suggests that in the coming decades neutrino physics will be every bit as rich as physicists had hoped—and may even help explain how the universe evolved to contain so much matter and so little antimatter.

Born in certain nuclear interactions, neutrinos come in three types or flavors that change into one another in so-called neutrino oscillations. The rates and extents to which the flavors mix depend on six parameters: the three differences between the neutrinos’ masses, and three “mixing angles.” In March, the 250 researchers with the Daya Bay Reactor Neutrino Experiment in China reported that last unknown parameter, the mixing angle known as $\theta_{13}$, (pronounced “theta one three”), equals 8.8°; give or take 0.8°.

The result itself is remarkable, as it’s not every year that physicists measure a new fundamental parameter. The real excitement, however, stems from the result’s broader implications. The measurement proves that all three mixing angles are greater than zero. That fact, in turn, implies that the oscillations of antineutrinos might differ from those of neutrinos, something that would not be possible had $\theta_{13}$ equaled zero.

That’s a big deal. Such a difference would

That was fast! Construction of China’s Daya Bay Reactor Neutrino Experiment began in 2007. With 2 months’ worth of data, it scooped competitors in Japan, France, Korea, and the United States.
Spectral Information

Rate-only Analysis:  

\[
\frac{N_{\text{far}}}{N_{\text{near}}} = \frac{N_{\text{protons, far}}}{N_{\text{protons, near}}} \frac{L_{\text{near}}^2}{L_{\text{far}}^2} \frac{\epsilon_{\text{far}}}{\epsilon_{\text{near}}} \int_{E_{\text{min}}}^{E_{\text{max}}} dE \frac{P_{\text{surv}}(E, L_{\text{far}}; \theta_{13}, \Delta m_{ee}^2)}{P_{\text{surv}}(E, L_{\text{near}}; \theta_{13}, \Delta m_{ee}^2)} \sigma(E) \Phi(E)
\]

Advantages: Fewer systematic uncertainties  
Disadvantages: Less sensitive, Unable to constrain $\Delta m_{ee}^2$

Rate + Spectrum Analysis:  

\[
\frac{dN_{\text{far}}}{dE} = \frac{N_{\text{protons, far}}}{N_{\text{protons, near}}} \frac{L_{\text{near}}^2}{L_{\text{far}}^2} \frac{\epsilon_{\text{far}}}{\epsilon_{\text{near}}} P_{\text{surv}}(E, L_{\text{far}}; \theta_{13}, \Delta m_{ee}^2) \sigma(E) \Phi(E)
\]

Advantages: Each energy bin is an independent oscillation measurement, $\Delta m_{ee}^2$  
Disadvantages: Requires detailed understanding of detector energy response.
Stable and Consistent Energy Response

After calibration, achieve energy response that is **stable to ~0.1%** in all detectors, with a **total relative uncertainty of 0.35%** between detectors.

Spallation $n$Gd capture peak vs. time (after all calibration)

Relative energy peaks in all detectors (after calibration)
Calibration: Detector Uniformity

Measure uniformity with sources placed along three axes and spallation nGd events.

Example: $^{60}$Co

3 sources along 3 axes

After first-order correction, energy is more uniform.

Energy response varies across detector...
...but still consistent between detectors.

~% level residual non-uniformities
Energy Response Model

Model maps true energy $E_{\text{true}}$ to reconstructed kinetic energy $E_{\text{rec}}$

- Minimal impact on oscillation measurement
- Crucial for measurement of reactor spectra
Energy loss in acrylic causes small distortion of energy spectrum

If antineutrino interacts in or near acrylic vessel, a portion of the kinetic energy of inverse beta positrons will not be detected.

Annihilation gammas with longer range can also deposit energy in the vessels.

Generated 2D distortion matrix from MC to correct predicted positron energy spectrum.

Uncertainties from varying acrylic vessel thicknesses and MC statistics incorporated into analysis.
Karsten Heeger, Yale University

Yale, September 30, 2013

Scintillator Response Model

Electron response

2 parameterizations to model quenching effects and Cherenkov radiation:

1) 3-parameter purely empirical model:

\[ \frac{E_{\text{vis}}}{E_{\text{true}}} = \frac{1 + p_3 \cdot E_{\text{true}}}{1 + p_1 \cdot e^{-p_2 \cdot E_{\text{true}}}} \]

2) Semi-emp. model based on Birks' law:

\[ \frac{E_{\text{vis}}}{E_{\text{true}}} = f_q(E_{\text{true}}; k_B) + k_C \cdot f_C(E_{\text{true}}) \]

\[ k_B: \text{ Birks' constant} \]

\[ k_C: \text{ Cherenkov contribution} \]

Gammas + positrons

- Gammas connected to electron model through MC:

\[ E_{\text{vis}}^\gamma = \int E_{\text{vis}}^{e^-} \left( E_{\text{true}}^{e^-} \right) \cdot \frac{dN}{dE} \left( E_{\text{true}}^{e^-} \right) dE_{\text{true}}^{e^-} \]

- Positrons connected to electron model through MC:

\[ E_{\text{vis}}^{e^+} = E_{\text{vis}}^{e^-} + 2 \cdot E_{\text{vis}}^\gamma (0.511 \text{ MeV}) \]

Simulation of individual $e^-, e^+$ energies due to gamma interaction in scintillator.

\[ \gamma \]

\[ \gamma \]

\[ n \text{ capture on H} \]

\[ n \text{ capture on C} \]

\[ 60\text{Co} \]

Energy of primary $e^+/e^-$ [MeV]
Electronics does not fully capture late secondary hits
- Slow scintillation component missed at high energies
- Charge collection efficiency decreases with visible light

PMT readout electronics introduces additional biases

- Effective model as a function of total visible energy
- 2 empirical parameterizations: exponential and quadratic
- Total effective non-linearity $f$ from both scintillation and electronics effects:

$$f = \frac{E_{\text{rec}}}{E_{\text{true}}} = \frac{E_{\text{rec}}}{E_{\text{vis}}} \cdot \frac{E_{\text{vis}}}{E_{\text{true}}}$$

1. Electronics non-linearity
2. Scintillator non-linearity

Time Since First Hit [ns]  
Secondary Hit Charge Collection Eff.

Single Channel MC Simulation
Energy Resolution Model

Functional form:

\[ \frac{\sigma_E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}} \]

Contributions from:
- \( a \): Spacial/temp. resolution (\( \propto E \))
- \( b \): Photon statistics (\( \propto \sqrt{E} \))
- \( c \): Dark noise (const:)

Calibrated primarily using monoenergetic gamma sources

- Radioactive calibration sources placed at the detector center
- Additional data from IBD and spallation neutrons, uniformly distributed in LS
- Alpha source data used to cross-check result
  - Larger uncertainties due to different response from electronics
Constraining the Non-Linearity Parameters

Full detector calibration data
1. Monoenergetic gamma lines from various sources
   - Radioactive calibration sources, employed regularly: $^{68}$Ge, $^{60}$Co, $^{241}$Am-$^{13}$C
     and during special calibration periods: $^{137}$Cs, $^{54}$Mn, $^{40}$K, $^{241}$Am-$^{9}$Be, Pu-$^{13}$C
   - Singles and correlated spectra in regular physics runs ($^{40}$K, $^{208}$Tl, n capture on H)
2. Continuous spectrum from $^{12}$B produced by muon spallation inside the scintillator

Standalone measurements
- Scintillator quenching measurements using neutron beams and Compton e⁻
- Calibration of readout electronics with flash ADC
Energy Response Model

Constraints

Use calibration gamma sources and continuous $^{12}$B spectrum to constrain energy model parameters

Positron Energy Response

multiple models are constructed with different data and parameter constraints

conservatively combine 5 minimal correlated energy models
### Uncertainty Summary

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<thead>
<tr>
<th>Detector</th>
<th>Efficiency</th>
<th>Correlated</th>
<th>Uncorrelated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Protons</td>
<td>99.98%</td>
<td>0.47%</td>
<td>0.03%</td>
</tr>
<tr>
<td>Flasher cut</td>
<td>99.98%</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Delayed energy cut</td>
<td>90.9%</td>
<td>0.6%</td>
<td>0.12%</td>
</tr>
<tr>
<td>Prompt energy cut</td>
<td>99.88%</td>
<td>0.10%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Multiplicity cut</td>
<td>100.0%</td>
<td>0.02%</td>
<td>&lt;0.01%</td>
</tr>
<tr>
<td>Capture time cut</td>
<td>98.6%</td>
<td>0.12%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Gd capture ratio</td>
<td>83.8%</td>
<td>0.8%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Spill-in</td>
<td>105.0%</td>
<td>1.5%</td>
<td>0.02%</td>
</tr>
<tr>
<td>Livetime</td>
<td>100.0%</td>
<td>0.002%</td>
<td>&lt;0.01%</td>
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<tr>
<td>Combined</td>
<td>78.8%</td>
<td>1.9%</td>
<td>0.2%</td>
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**Reactor**

<table>
<thead>
<tr>
<th>Correlated</th>
<th>Uncorrelated</th>
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<tbody>
<tr>
<td>Energy/fission</td>
<td>Power</td>
</tr>
<tr>
<td>$\bar{\nu}_e$/fission</td>
<td>Fission fraction</td>
</tr>
<tr>
<td>3%</td>
<td>0.6%</td>
</tr>
<tr>
<td>0.2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Combined</td>
<td>0.3%</td>
</tr>
<tr>
<td>3%</td>
<td>0.8%</td>
</tr>
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</table>

For near/far oscillation, only uncorrelated uncertainties are used.

Largest systematics are smaller than far site statistics (~0.5%).

Influence of uncorrelated reactor systematics reduced by far vs. near measurement.
Accidental Background

Two uncorrelated signals can accidentally mimic an antineutrino signal.

Accidental B/S is 4% (1.5%) of far (near) signal.

Accidental background be accurately modeled using uncorrelated signals in data. ➔ Negligible uncertainty in background rate or spectra.
**Background: β-n decay**

**β-n decay:**
- Prompt: β-decay
- Delayed: neutron capture

- Generated by cosmic rays
- Long-lived
- Mimic antineutrino signal

\[ ^9\text{Li}: \tau_{\frac{1}{2}} = 178 \text{ ms}, \ Q = 13.6 \text{ MeV} \]

\[ ^8\text{He}: \tau_{\frac{1}{2}} = 119 \text{ ms}, \ Q = 10.6 \text{ MeV} \]

This background is directly measured by fitting the distribution of IBD candidates vs. time since last muon.

Analysis muon veto cuts control B/S to ~0.3±0.1%.

---

**9Li / 8He Decay**

- Generated by cosmic rays
- Long-lived
- Mimic antineutrino signal

\[ ^9\text{Li} / ^8\text{He} \]

uncorrelated

\[ ^9\text{Li}/^8\text{He} \]

Time since muon [ms]
Shape for $^9\text{Li}$ and $^8\text{He}$ is predicted from a simulation benchmarked with external data and which accounts for all daughter particles.

Uncertainty in shape is conservatively accounted for by varying the $^9\text{Li}/(^9\text{Li}+^8\text{He})$ ratio, as well as the parameters of the detector response model.
Background: Fast neutrons

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

Analysis muon veto cuts control B/S to 0.06% (0.1%) of far (near) signal.

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

Validate with fast-n events tagged by muon veto.
## Signal and Background Summary

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<tr>
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<th>Near Halls</th>
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<th>Far Hall</th>
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<tbody>
<tr>
<td></td>
<td>AD 1</td>
<td>AD 2</td>
<td>AD 3</td>
<td>AD 4</td>
</tr>
<tr>
<td>IBD candidates</td>
<td>101290</td>
<td>102519</td>
<td>92912</td>
<td>13964</td>
</tr>
<tr>
<td>DAQ live time (days)</td>
<td>191.001</td>
<td></td>
<td>189.645</td>
<td>189.779</td>
</tr>
<tr>
<td>Efficiency $e_\mu \cdot e_m$</td>
<td>0.7957</td>
<td>0.7927</td>
<td>0.8282</td>
<td>0.9577</td>
</tr>
<tr>
<td>Accidentals (per day)*</td>
<td>9.54±0.03</td>
<td>9.36±0.03</td>
<td>7.44±0.02</td>
<td>2.96±0.01</td>
</tr>
<tr>
<td>Fast-neutron (per day)*</td>
<td>0.92±0.46</td>
<td></td>
<td>0.62±0.31</td>
<td></td>
</tr>
<tr>
<td>$^9$Li/$^8$He (per day)*</td>
<td>2.40±0.86</td>
<td></td>
<td>1.2±0.63</td>
<td></td>
</tr>
<tr>
<td>Am-C corr. (per day)*</td>
<td></td>
<td></td>
<td>0.26±0.12</td>
<td></td>
</tr>
<tr>
<td>$^{13}$C$^{16}$O backgr. (per 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>
</tr>
<tr>
<td>IBD rate (per day)*</td>
<td>653.30±2.31</td>
<td>664.15±2.33</td>
<td>581.97±2.07</td>
<td>73.31±0.66</td>
</tr>
</tbody>
</table>

*Background and IBD rates were corrected for the efficiency of the muon veto and multiplicity cuts $e_\mu \cdot e_m$.

**Collected more than 300k antineutrino interactions**

- Consistent rates for side-by-side detectors
- Uncertainties still dominated by statistics
Antineutrino Rate vs Time

Detected rate strongly correlated with reactor flux expectations

- Predicted rate assumes no oscillation
- Absolute normalization determined by fit to data
- Normalization within a few percent of expectations
Prompt IBD Spectra

Daya Bay Near Hall

Ling Ao Near Hall

Far Hall

Spectral distortion consistent with oscillation

- Both background and predicted no oscillation spectrum determined by best fit
- Errors statistical only

Shape distortion from energy losses in acrylic
Towards a Precision Reactor Spectrum

Reines 1959

Goesgen 1986

KamLAND 2010

Daya Bay (> 300,000 events)
Strong confirmation of oscillation-interpretation of observed $\bar{\nu}_e$ deficit

<table>
<thead>
<tr>
<th>Normal MH $\Delta m^2_{32}$ [10$^{-3}$eV$^2$]</th>
<th>Inverted MH $\Delta m^2_{32}$ [10$^{-3}$eV$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>From Daya Bay $\Delta m^2_{ee}$</td>
<td>$2.54^{+0.19}_{-0.20}$</td>
</tr>
<tr>
<td>From MINOS $\Delta m^2_{\mu\mu}$</td>
<td>$2.37^{+0.09}_{-0.09}$</td>
</tr>
<tr>
<td></td>
<td>$-2.64^{+0.19}_{-0.20}$</td>
</tr>
<tr>
<td></td>
<td>$-2.41^{+0.11}_{-0.09}$</td>
</tr>
</tbody>
</table>

A. Radovic, DPF2013
Pure Spectral Analysis

\[ \sin^2 2\theta_{13} = 0.108 \pm 0.028 \]
\[ |\Delta m_{ee}^2| = 2.55^{+0.21}_{-0.18} \cdot 10^{-3} \text{eV}^2 \]
\[ \chi^2/N_{\text{DoF}} = 161.2/148 \]

\[ \theta_{13} = 0 \text{ can be excluded at } > 3\sigma \text{ from spectral information alone} \]

For each AD, total event prediction fixed to observed data:

1. \( \theta_{13} \) free-floating: \( \chi^2/N_{\text{DoF}} = 161.2/148 \)
2. \( \theta_{13} = 0 \): \( \chi^2/N_{\text{DoF}} = 178.5/146 \)

\[ \Delta \chi^2/N_{\text{DoF}} = 17.3/2, \text{ corresponding to } p = 1.75 \cdot 10^{-4} \]
A Comment on $\Delta m^2$

Short-baseline reactor experiments insensitive to neutrino mass hierarchy. Cannot discriminate two frequencies contributing to oscillation: $\Delta m_{31}^2$, $\Delta m_{32}^2$

One effective oscillation frequency is measured:

$$P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{ee}^2 L}{4E} \right) - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E} \right)$$

Result can be easily related to actual mass splitting, based on true hierarchy:

$$|\Delta m_{ee}^2| \approx |\Delta m_{32}^2| \pm 5.21 \times 10^{-5} \text{eV}^2$$

+: Normal Hierarchy

 -: Inverted Hierarchy

Hierarchy discrimination requires $\sim$2% precision on both $\Delta m_{ee}^2$ and $\Delta m_{\mu\mu}^2$
L/E Oscillation

Energy and Baseline Dependence of Oscillation Effect

now
L/E Oscillation

Energy and Baseline Dependence of Oscillation Effect

in FY17
Global Comparison of $\theta_{13}$ Measurements

![Graph showing global comparison of $\theta_{13}$ measurements]

- Best Fit + 68% C.L.
- Accelerator Experiments
  - Normal Hierarchy
  - Inverted Hierarchy
- Reactor Experiments
  - Rate only
  - Rate+Spectral
  - $n$-Gd
  - $n$-H

[Data points for different experiments and years (2011, 2012, 2013) with corresponding sin$^22\theta_{13}$ values]
Installation of Final Antineutrino Detectors

Full Volume Calibration
Daya Bay Future

Improved precision on oscillation parameters

- Statistics contribute 73% (65%) to total uncertainty in $\sin^2 2\theta_{13}$ ($|\Delta m^2_{ee}|$)
- Major systematics:
  - $\theta_{13}$: Relative + absolute energy, and relative efficiencies
  - $|\Delta m^2_{ee}|$: Relative energy model, relative efficiencies, and backgrounds
- Precision of mass splitting measurement closing in on results from $\mu$ flavor sector

Measure absolute reactor neutrino flux and spectrum
Cosmogenic Backgrounds
Supernova Neutrinos
Neutrino Anomalies

Anomalies in 3-v interpretation of global oscillation data

- LSND ($\nu_e$ appearance)
- MiniBoone ($\nu_e$ appearance)
- Ga anomaly
- Reactor anomaly ($\bar{\nu}_e$ disappearance)

Cosmology suggests higher radiation density

$N_{\text{eff}} > 3$

new oscillation signal requires $\Delta m^2 \sim O(1\text{eV}^2)$ and $\sin^2 2\theta > 10^{-3}$

systematics or experimental effect? $\Rightarrow$ need to test effects
Reactor Fluxes and “Anomaly”

Reactor $\theta_{13}$ experiments cannot directly search for short-baseline oscillations

3+1 neutrino oscillation

Average $= 0.943 \pm 0.023$ ($\chi^2=19.6/19$)

New flux prediction

at $\sim 1$km reactor $\theta_{13}$ experiments probe overall suppression

Precision measurement of spectral shape can reveal new physics independent of normalization
Summary

For > 60 years reactor experiments have played an important role in neutrino physics, in both discoveries and precision measurements.

Reactors are flavor pure sources of $\overline{\nu}_e$.

Current reactor experiments ($L \sim 1-2\text{km}$) provide precision data on $\theta_{13}$, and reactor antineutrino spectra.

The Daya Bay Experiment has reported the first direct measurement of the short-distance electron antineutrino oscillation frequency:

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \times 10^{-3}\text{eV}^2$$

The measurement has also produced the most precise estimate of the mixing angle:

$$\sin^2(2\theta_{13}) = 0.090^{+0.008}_{-0.009}$$

There is more to come... stay tuned!
End