Observation of Electron Antineutrino Disappearance at Daya Bay

Karsten M. Heeger, University of Wisconsin

on behalf of the Daya Bay collaboration

EWNP Symposium, March 8, 2012
Neutrino Physics at Reactors

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

Next - Discovery and precision measurement of $\theta_{13}$

55 years of liquid scintillator detectors a story of varying baselines...
Neutrino Oscillation

Mixing Angles & Mass Splittings

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

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

\[ U_{\text{MNSP}} \text{ Matrix} \]
Maki, Nakagawa, Sakata, Pontecorvo

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

atmospheric, K2K
reactor and accelerator
SNO, solar SK, KamLAND
\[ 0_{\nu}\beta\beta \]

Schwetz et al
updated as of 2010
Neutrino Oscillation

Mixing Angles

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

UMNSP Matrix
Maki, Nakagawa, Sakata, Pontecorvo

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

atmospheric, K2K
reactor and accelerator
SNO, solar SK, KamLAND

\[
\sin^2 \theta_{23} = 0.50_{-0.06}^{+0.07}
\]

\[
\sin^2 \theta_{13} = 0.013_{-0.009}^{+0.013}
\]

\[
\sin^2 \theta_{12} = 0.318_{-0.016}^{+0.019}
\]

maximal? small? zero? large, but not maximal!
Recent Indications for $\theta_{13}$

T2K $\quad 0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$

$\theta_{13}=0$ disfavored @ 2.5$\sigma$

MINOS $\quad 2 \sin^2 (\theta_{23}) \sin^2 (2\theta_{13}) = 0.041^{+0.047}_{-0.031}$

$\theta_{13}=0$ disfavored @ 89% C.L.

Double Chooz $\quad \sin^2 (2\theta_{13})=0.086$

$\pm 0.041$(stat) $\pm 0.030$(syst)

a precision experiment is needed
Oscillation Experiments with Reactors

Looking for non-1/r² behavior of $\bar{\nu}_e$ interaction rate

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m^2_{31} L}{4E_\nu} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m^2_{21} L}{4E_\nu} \right)$$

L/E oscillation effect provides measurement of $\Delta m^2$

Amplitude of oscillation provides measurement of $\theta$

for 3 active neutrinos, can study oscillation with two different oscillation length scales: $\Delta m^2_{12}, \Delta m^2_{13}$

$\Delta m^2_{12} \sim 7.6 \times 10^{-5} \text{ eV}^2$

$\Delta m^2_{13} \sim 2.4 \times 10^{-3} \text{ eV}^2$
Measuring $\theta_{13}$ with Reactor Experiments

Near-Far Concept

$\bar{\nu}_e, \bar{\nu}_e, \bar{\nu}_e, \bar{\nu}_e$

distance $L \sim 1.5$ km

\[
P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E}
\]

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EWNP Symposium, March 8, 2012
Measuring $\theta_{13}$ with Reactor Experiments

**Near-Far Concept**

- $\bar{\nu}_e$ near
- $\bar{\nu}_{e,x}$ far
- Distance $L \sim 1.5$ km

**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 $\bar{\nu}_e$ ratio
- target mass
- distances
- efficiency
- oscillation deficit
Daya Bay - A Powerful Neutrino Source

- Among the top 5 most powerful reactor complexes in the world, producing 17.4 GW\textsubscript{th} (6 \times 2.95 GW\textsubscript{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
Daya Bay Experiment Layout

6 antineutrino detectors in 3 underground experimental halls

<table>
<thead>
<tr>
<th></th>
<th>Overburden</th>
<th>$R_\mu$</th>
<th>$E_\mu$</th>
<th>D1.2</th>
<th>L1.2</th>
<th>L3.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>EH1</td>
<td>250</td>
<td>1.27</td>
<td>57</td>
<td>364</td>
<td>857</td>
<td>1307</td>
</tr>
<tr>
<td>EH2</td>
<td>265</td>
<td>0.95</td>
<td>58</td>
<td>1348</td>
<td>480</td>
<td>528</td>
</tr>
<tr>
<td>EH3</td>
<td>860</td>
<td>0.056</td>
<td>137</td>
<td>1912</td>
<td>1540</td>
<td>1548</td>
</tr>
</tbody>
</table>

outer and inner water shields (IWS and OWS)

RPCs

自動化校正ユニット (ACU)

antineutrino detectors (AD)

AD Gd-LS target

concrete

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Reactor-Detector Distance 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

Negligible reactor flux uncertainty (<0.02%) from precise survey.

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

distances
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\]

distances
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 Antineutrino Detectors

6 “functionally identical”, 3-zone detectors reduces systematic uncertainties

total detector mass: ~ 110t
inner: 20 tons Gd-doped LS (d=3m)
mid: 20 tons LS (d=4m)
outer: 40 tons mineral oil buffer (d=5m)

photosensors: 192 8”-PMTs
energy resolution: \((7.5 / \sqrt{E} + 0.9)\)%

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

detector assembly in pairs
6 ADs operational, AD7,8 in assembly
Liquid Scintillator Hall
Detector Filling and Target Mass Measurement

ISO tank on load cells

detector in scintillator hall

coriolis flow meters

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Relative</th>
<th>Absolute</th>
</tr>
</thead>
<tbody>
<tr>
<td>protons/kg</td>
<td>neg.</td>
<td>0.47%</td>
</tr>
<tr>
<td>Density (kg/L)</td>
<td>neg.</td>
<td>neg.</td>
</tr>
<tr>
<td>Total mass</td>
<td>0.015%</td>
<td>0.015%</td>
</tr>
<tr>
<td>Overflow tank geometry</td>
<td>0.0066%</td>
<td>0.0066%</td>
</tr>
<tr>
<td>Overflow sensor calibration</td>
<td>0.0043%</td>
<td>0.0043%</td>
</tr>
<tr>
<td>Bellows Capacity</td>
<td>0.0025%</td>
<td>0.0025%</td>
</tr>
<tr>
<td>Target mass</td>
<td>0.017%</td>
<td>0.017%</td>
</tr>
<tr>
<td>Target protons</td>
<td>0.017%</td>
<td>0.47%</td>
</tr>
</tbody>
</table>

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.
Antineutrino Detector Installation - Near Hall
Daya Bay Antineutrino Detection

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

0.3 b \quad \rightarrow + p \rightarrow D + \gamma \ (2.2 \text{ MeV}) \quad \text{(delayed)}

49,000 b \quad \rightarrow + \text{Gd} \rightarrow \text{Gd}^* \rightarrow \text{Gd} + \gamma's \ (8 \text{ MeV}) \ (\text{delayed})

prompt+delayed coincidence provides distinctive signature

**Prompt positron:** carries antineutrino energy

$$E_{e^+} \approx E_\nu - 0.8 \text{ MeV}$$

**Delayed neutron capture:** tags antineutrino signal

Prompt Energy Signal

![Prompt Energy Signal Graph]

Delayed Energy Signal

![Delayed Energy Signal Graph]
Automated Calibration System

3 Automatic 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 $e^+ = 2 \times 0.511$ 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
Data Period

Two Detector Side-by-Side Comparison
- Side-by-side comparison of 2 detectors
- Demonstrated detector systematics better than requirements.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass measurement relative precision</td>
<td>0.02%</td>
</tr>
<tr>
<td>Flasher cut</td>
<td>0.01%</td>
</tr>
<tr>
<td>Efficiency of neutron energy cut</td>
<td>0.11%</td>
</tr>
<tr>
<td>Efficiency of e⁺ threshold cut</td>
<td>0.01%</td>
</tr>
<tr>
<td>Efficiency of multiplicity cut</td>
<td>&lt; 0.01%</td>
</tr>
<tr>
<td>Efficiency of capture time cuts</td>
<td>0.01%</td>
</tr>
<tr>
<td>Relative precision on H/Gd ratio</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>Relative uncertainty of spill-in/out</td>
<td>0.02%</td>
</tr>
<tr>
<td>Livetime precision</td>
<td>&lt; 0.01%</td>
</tr>
<tr>
<td>Total detector-related uncertainty</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

Table 4: Detector-related relative uncertainty of Daya Bay evaluated with the 1st pair of ADs in the Daya Bay Near Hall.

Daya Bay Collab.  
Data Period

Two Detector Side-by-Side Comparison
- Side-by-side comparison of 2 detectors
- Demonstrated detector systematics better than requirements.

Daya Bay Collab.

Current Oscillation Analysis
- All 3 halls (6 ADs) operating
- DAQ uptime: >97%
- Antineutrino data: ~89%

Daya Bay Collab.
http://dayawane.ihep.ac.cn/
Trigger Performance

Trigger Thresholds
- AD: > 45 PMTs (digital trigger)
  > 0.4 MeV (analog trigger)
- Inner Water Veto: > 6 PMTs
- Outer Water Veto: > 7 PMTs
- RPC: ¾ layers in module

Trigger Efficiency
- No measurable inefficiency > 0.7 MeV
- Minimum energy expected for prompt antineutrino signal is ~0.9 MeV.
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**

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

\[
\text{Quadrant} = \frac{Q3}{Q2+Q4}
\]

MaxQ = maxQ/sumQ

Inefficiency to antineutrinos signal:
0.024% ± 0.006%(stat)
Contamination: < 0.01%
Singles Spectrum

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

spectrum after muon cuts

Daya Bay Collab.
Calibration driven by uncertainty in relative detector efficiency

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

Selection of Prompt + Delayed
- 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 MeV in -200 μs to 200 μs of IBD.

Selection driven by uncertainty in relative detector efficiency

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

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

Consistent IBD capture time measured in all detectors

Capture time cut: 1μs to 200μs

Relative detector efficiency estimated within 0.01% by considering possible variations in Gd concentration.

Capture time in each detector constrains H/Gd capture ratio

Measurement of Am-C source neutron capture time distributions constrain uncertainty in relative H/Gd capture efficiency to < 0.1% between detectors.

Karsten Heeger, Univ. of Wisconsin

EWNP Symposium, March 8, 2012
Background: Accidentals

Two single signals can accidentally mimic an antineutrino (IBD) signal.

Rate and spectrum can be accurately predicted from singles data.

Multiple analyses/methods estimate consistent rates.

<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>Accidental rate (/day)</td>
<td>9.82±0.06</td>
<td>9.88±0.06</td>
<td>7.67±0.05</td>
<td>3.29±0.03</td>
<td>3.33±0.03</td>
<td>3.12±0.03</td>
</tr>
<tr>
<td>B/S</td>
<td>1.37%</td>
<td>1.38%</td>
<td>1.44%</td>
<td>4.58%</td>
<td>4.77%</td>
<td>4.43%</td>
</tr>
</tbody>
</table>
Background: β-n decay

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

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

$^9\text{Li}$: $\tau_{1/2} = 178$ ms, $Q = 13.6$ MeV
$^8\text{He}$: $\tau_{1/2} = 119$ ms, $Q = 10.6$ MeV

fit with known decay times for $^8\text{He}/^9\text{Li}$

Analysis muon veto cuts control B/S to $\sim 0.4 \pm 0.2\%$. 

$E_\mu > 4$ GeV (visible)
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.
### Daya Bay Data Set Summary

<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><strong>Antineutrino candidates</strong></td>
<td>28935</td>
<td>28975</td>
<td>22466</td>
<td>3528</td>
<td>3436</td>
<td>3452</td>
</tr>
<tr>
<td><strong>DAQ live time (day)</strong></td>
<td>49.5530</td>
<td>49.4971</td>
<td>48.9473</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Veto time (day)</strong></td>
<td>8.7418</td>
<td>8.9109</td>
<td>7.0389</td>
<td>0.8785</td>
<td>0.8800</td>
<td>0.8952</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>0.8019</td>
<td>0.7989</td>
<td>0.8363</td>
<td>0.9547</td>
<td>0.9543</td>
<td>0.9538</td>
</tr>
<tr>
<td><strong>Accidentals (/day)</strong></td>
<td>9.82±0.06</td>
<td>9.88±0.06</td>
<td>7.67±0.05</td>
<td>3.29±0.03</td>
<td>3.33±0.03</td>
<td>3.12±0.03</td>
</tr>
<tr>
<td><strong>Fast neutron (/day)</strong></td>
<td>0.84±0.28</td>
<td>0.84±0.28</td>
<td>0.74±0.44</td>
<td>0.04±0.04</td>
<td>0.04±0.04</td>
<td>0.04±0.04</td>
</tr>
<tr>
<td><strong>$^{8}$He/$^{9}$Li (/day)</strong></td>
<td>3.1±1.6</td>
<td>1.8±1.1</td>
<td>0.16±0.11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Am-C corr. (/day)</strong></td>
<td>0.2±0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>$^{13}$C($\alpha$, n)$^{16}$O (/day)</strong></td>
<td>0.04±0.02</td>
<td>0.04±0.02</td>
<td>0.035±0.02</td>
<td>0.03±0.02</td>
<td>0.03±0.02</td>
<td>0.03±0.02</td>
</tr>
<tr>
<td><strong>Antineutrino rate (/day)</strong></td>
<td>714.17±4.58</td>
<td>717.86±4.60</td>
<td>532.29±3.82</td>
<td>71.78±1.29</td>
<td>69.80±1.28</td>
<td>70.39±1.28</td>
</tr>
</tbody>
</table>

consistent rates for side-by-side detectors
uncertainty dominated by statistics
Reactor Flux Expectation

Antineutrino flux is estimated for each reactor core

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

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
Antineutrino Rate vs. Time

Detected rate strongly correlated with reactor flux expectations.

Predicted Rate: (in figure)
- Assumes no oscillation.
- Normalization is determined by fit to data.
- Absolute normalization is within a few percent of expectations.
Prompt Positron Spectra

Near Halls

**EH1**
- **Signal**
- **Accidentals**
- **Lithium-9**
- **$^{241}\text{Am-}^{13}\text{C}$**
- **Fast n**
- **$(\alpha, n)$**

57910 signal candidates

**EH2**
- **Signal**
- **Accidentals**
- **Lithium-9**
- **$^{241}\text{Am-}^{13}\text{C}$**
- **Fast n**
- **$(\alpha, n)$**

22466 signal candidates

Far Hall

**EH3**
- **Signal**
- **Accidentals**
- **Lithium-9**
- **$^{241}\text{Am-}^{13}\text{C}$**
- **Fast n**
- **$(\alpha, n)$**

10416 signal candidates

High-statistics reactor antineutrino spectra. B/S ratio is 2% (5%) at far (near) sites.
Uncertainty Summary

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

Largest systematics are smaller than far site statistics (~1%)

Influence of uncorrelated reactor systematics reduced (~1/20) by far vs. near measurement.
Far vs. Near Comparison

Compare measured rates and spectra

$$R = \frac{Far_{measured}}{Far_{expected}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_iM_3)}$$

$M_n$ 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 (~6%).

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.

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

$\sin^2 2\theta_{13} = 0$ excluded at 5.2$\sigma$

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.
Daya Bay has made an unambiguous observation of electron-antineutrino disappearance at ~2km and measured a far/near ratio of

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

Interpretation of disappearance as neutrino oscillation rules out \(\sin^2 2\theta_{13} = 0\) at 5.2\(\sigma\)

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

Daya Bay precision surpasses all existing measurements. Expect more statistics and improvements in analysis.

paper submitted to PRL, available at http://dayawane.ihep.ac.cn/

Assembly of last two detector pair underway. Installation this summer.
Daya Bay Collaboration

An International Effort

Asia (20)
IHEP, Beijing Normal Univ., Chengdu Univ. of Sci and Tech, CGNPG, CIAE, Dongguan Polytech, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

North America (16)

Europe (3)
Charles Univ., Dubna, Kurchatov Inst.

228 collaborators