Observation of Electron Anti-neutrino Disappearance at Daya Bay

Yifang Wang
Institute of High Energy Physics
CERN, March 20, 2012
Outline

- Introduction
- Data set & quality control
- Calibration and Event reconstruction
- Event selection
- Backgrounds & uncertainties
- Efficiencies & systematic errors
- Expectation
- Results of neutrino oscillation
- Summary

F.P. An et al., Daya Bay Coll., “Observation of electron anti-neutrino disappearance at Daya Bay”, arXiv:1203.1669[hep-ex], submitted to PRL
Neutrinos & Neutrino Oscillation

- Fundamental building blocks of matter:
  \[
  \begin{pmatrix}
  e & \mu & \tau \\
  v_e & v_\mu & v_\tau
  \end{pmatrix}
  \begin{pmatrix}
  u & c & t \\
  d & s & b
  \end{pmatrix}
  \]

- Neutrino mass: the central issue of neutrino physics
  - Tiny mass but huge amount
  - Influence to Cosmology: evolution, large scale structure, ...
  - Only evidence beyond the Standard Model

- Neutrino oscillation: a great method to probe the mass

Oscillation probability:

\[ P(v_e \to v_\mu) = \sin^2(2\theta) \sin^2(1.27\Delta m^2 L/E) \]
Daya Bay: for a New Type of Oscillation

- **Goal**: search for a new oscillation $\theta_{13}$

$\theta_{12}$ solar neutrino oscillation

$\theta_{23}$ atmospheric neutrino oscillation

- **Neutrino mixing matrix**:

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Unknown mixing parameters: $\theta_{13}$, $\delta$ + 2 Majorana phases

Need sizable $\theta_{13}$ for the $\delta$ measurement
Two ways to measure $\theta_{13}$

Reactor experiments:

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 (1.27\Delta m^2_{13} L/E) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 (1.27\Delta m^2_{12} L/E)$$

Long baseline accelerator experiments:

$$P_{\mu e} \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 (1.27\Delta m^2_{23} L/E) + \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 (1.27\Delta m^2_{12} L/E) - A(\rho) \cos^2 \theta_{13} \sin \theta_{13} \sin(\delta)$$

At reactors:

- Clean signal, no cross talk with $\delta$ and matter effects
- Relatively cheap compared to accelerator based experiments
- Provides the direction to the future of neutrino physics
**Direct Searches in the Past**

- **Palo Verde & Chooz: no signal**
  \[
  \sin^2 \theta_{13} < 0.15 \quad @ \quad 90\% \text{ C.L.}
  \]
  if \( \Delta m^2_{23} = 0.0024 \text{ eV}^2 \)

- **T2K: 2.5 \( \sigma \) over bkg**
  \[
  0.03 < \sin^2 \theta_{13} < 0.28 \quad @ \quad 90\% \text{ C.L. for NH}
  \]
  \[
  0.04 < \sin^2 \theta_{13} < 0.34 \quad @ \quad 90\% \text{ C.L. for IH}
  \]

- **Minos: 1.7 \( \sigma \) over bkg**
  \[
  0 < \sin^2 \theta_{13} < 0.12 \quad @ \quad 90\% \text{ C.L. NH}
  \]
  \[
  0 < \sin^2 \theta_{13} < 0.19 \quad @ \quad 90\% \text{ C.L. IH}
  \]

- **Double Chooz: 1.7 \( \sigma \)**
  \[
  \sin^2 \theta_{13} = 0.086 \pm 0.041(\text{stat}) \pm 0.030(\text{sys})
  \]
Reactor Experiment: comparing observed/expected neutrinos

Precision of past exp.
- Reactor power: ~1%
- Spectrum: ~0.3%
- Fission rate: 2%
- Backgrounds: ~1-3%
- Target mass: ~1-2%
- Efficiency: ~2-3%

Our design goal: a precision of ~0.4%

- 2 near sites, 1 far site

Multiple AD modules at each site to reduce Uncorr. Syst. Err.

- Far: 4 modules, near: 2 modules

Multiple muon detectors to reduce veto eff. uncertainties

- Water Cherenkov: 2 layers
- RPC: 4 layers at the top + telescopes
Underground Labs

<table>
<thead>
<tr>
<th></th>
<th>Overburden (MWE)</th>
<th>( R_\mu ) (Hz/m²)</th>
<th>( E_\mu ) (GeV)</th>
<th>D1,2 (m)</th>
<th>L1,2 (m)</th>
<th>L3,4 (m)</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>
Anti-neutrino Detector (AD)

- Three zones modular structure:
  I. Target: Gd-loaded scintillator
  II. γ-catcher: normal scintillator
  III. Buffer shielding: oil

- 192 8” PMTs/module

- Two optical reflectors at the top and the bottom, Photocathode coverage increased from 5.6% to 12%

- Resolution (%)

  - AD1
  - AD2
  - Gc
  - n H-capture (spallation)
  - Co
  - n Gd-capture (AmC, IBD, spallation)

  \[ \frac{7.5}{\sqrt{E_{\text{rec}}(\text{MeV})}} + 0.9\% \]

- ~ 163 PE/MeV

- Target: 20 t, 1.6m
- γ-catcher: 20t, 45cm
- Buffer: 40t, 45cm
- Total weight: ~110 t
Neutrino Detection: Gd-loaded Liquid Scintillator

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

Neutrino Event: coincidence in time, space and energy

\[ \tau \approx 28 \mu s (0.1\% \text{ Gd}) \]

\[ n + p \rightarrow d + \gamma \ (2.2 \text{ MeV}) \]

\[ n + \text{Gd} \rightarrow \text{Gd}^* + \gamma \ (8 \text{ MeV}) \]

Neutrino energy:

\[ E_{\bar{\nu}} \approx (T_{e^+}) + T_n + (M_n - M_p) + m_{e^+} \]

10-40 keV, 1.8 MeV: Threshold
Gd-loaded Liquid Scintillator

- Liquid production, QA, storage and filling at Hall 5
  - 185t Gd-LS, ~180t LS, ~320t oil
- LAB+Gd (TMHA)$^3$+PPO+BisMSB
- Stable over time
  - Light yield: ~163 PE/MeV
Automatic Calibration System

◆ Three Z axis:
  ➞ One at the center
    ✓ For time evolution, energy scale, non-linearity…
  ➞ One at the edge
    ✓ For efficiency, space response
  ➞ One in the γ-catcher
    ✓ For efficiency, space response

◆ 3 sources for each z axis:
  ➞ LED
    ✓ for $T_0$, gain and relative QE
  ➞ $^{68}$Ge (2×0.511 MeV γ’s)
    ✓ for positron threshold & non-linearity…
  ➞ $^{241}$Am-$^{13}$C + $^{60}$Co (1.17+1.33 MeV γ’s)
    ✓ For neutron capture time, …
    ✓ For energy scale, response function, …

◆ Once every week:
  ➞ 3 axis, 5 points in Z, 3 sources
Muon Veto Detector

- **RPCs**
  - 4 layers/module
  - 54 modules/near hall, 81 modules/far hall
  - 2 telescope modules/hall

- **Water Cerenkov detector**
  - Two layers, separated by Tyvek/PE/Tyvek film
  - 288 8” PMTs for near halls; 384 8” PMTs for the far hall

- **Water processing**
  - High purity de-ionized water in pools also for shielding
  - First stage water production in hall 4
  - Local water re-circulation & purification

Two active cosmic-muon veto’s
- Water Cerenkov: Eff. > 97%
- RPC Muon tracker: Eff. > 88%
Two ADs Installed in Hall 1
Hall 1(two ADs) Started the Operation on Aug. 15, 2011
One AD installed in Hall 2
Physics Data Taking Started on Nov. 5, 2011
Three ADs installed in Hall 3
Physics Data Taking Started on Dec.24, 2011
Trigger Performance

- Threshold for a hit:
  - AD & pool: \( \frac{1}{4} \) PE

- Trigger thresholds:
  - AD: \( N_{\text{HIT}} = 45 \), \( E_{\text{tot}} = \sim 0.4 \text{ MeV} \)
  - Inner pool: \( N_{\text{HIT}} = 6 \)
  - Outer pool: \( N_{\text{HIT}} = 7 \) (8 for far hall)
  - RPC: 3/4 layers in each module

- Trigger rate (EH1)
  - AD singles rate:
    - >0.4MeV, \( \sim 280\text{Hz} \)
    - >0.7MeV, \( \sim 60\text{Hz} \)
  - Inner pool rate: \( \sim 170\text{Hz} \)
  - Outer pool rate: \( \sim 230\text{Hz} \)
Data Set

- Dec. 24, 2011 - Feb. 17, 2012, 55 days
- Data volume: 15TB
- DAQ eff. ~ 97%
- Eff. for physics: ~ 89%
Flashers: Imperfect PMTs

- Spontaneous light emission by PMT
- ~5% of PMT, 5% of event
- Rejection: pattern of fired PMTs
  - Topology: a hot PMT + near-by PMTs and opposite PMTs

\[ \log_{10} \left( \frac{Q_3}{Q_1} \right)^2 + \left( \frac{\text{MaxQ}}{0.45} \right)^2 < 0 \]

Quadrant = \(Q_3/(Q_2+Q_4)\)
MaxQ = maxQ/sumQ

Inefficiency to neutrinos: 0.024% ± 0.006% (stat)
Contamination: < 0.01%

2012/3/20
Single Rate: Understood

- **Design:** ~50Hz above 1 MeV
- **Data:** ~60Hz above 0.7 MeV, ~40Hz above 1 MeV

- From sample purity and MC simulation, each of the following component contribute to singles
  - ~ 5 Hz from SSV
  - ~ 10 Hz from LS
  - ~ 25 Hz from PMT
  - ~ 5 Hz from rock

- All numbers are consistent
**Event Reconstruction: PMT Calibration**

- PMT gains from low-intensity LED:
  - PMT HV is set for a gain of \(1 \times 10^7\)
  - Gain stability depends on environments such as temperature
    - All three halls are kept in a temperature within ±1 °C

![SPE peaks for AD1/AD2](image)

![Fit to one PMT SPE distribution](image)
Event Reconstruction: Energy Calibration

- PMT gain calibration ➔ No. of PEs in an AD
- $^{60}$Co at the center ➔ raw energies,
  ➔ time dependence corrected
  ➔ different for different ADs
- $^{60}$Co at different R & Z to obtain the correction function, $f(R,Z) = f_1(R) \times f_2(Z)$
  ➔ space dependence corrected
  ➔ same for all the ADs

- ~% level residual non-uniformities
Event Reconstruction: Energy Calibration

- Correct for energy non-linearity: normalize to neutron capture peak
- Energy uncertainty among 6 ADs (uncorrelated):
  - Relative difference between ADs is better than 0.5%
  - Uncertainties from time-variation, non-linearity, non-uniformity… are also within 0.5%

Uniformity at different location

Peak energy of different sources
An Alternative Method

- Using spallation neutrons in each space grid to calibrate the energy response
- Neutrons from neutrinos can then be reconstructed correctly
- Consistent with methods within 0.5%

Residual non-uniformities

Energy of spallation neutron

Uniformity of energy response
**Event Signature and Backgrounds**

- **Signature:** \[ \bar{\nu}_e + p \rightarrow e^+ + n \]
  - **Prompt:** \( e^+ \), 1-10 MeV,
  - **Delayed:** \( n \), 2.2 MeV@H, 8 MeV @ Gd
  - **Capture time:** 28 \( \mu s \) in 0.1\% Gd-LS

- **Backgrounds**
  - **Uncorrelated:** random coincidence of \( \gamma \gamma \), \( \gamma n \) or \( nn \)
    - \( \gamma \) from U/Th/K/Rn/Co… in LS, SS, PMT, Rock, …
    - \( n \) from \( \alpha-n \), \( \mu \)-capture, \( \mu \)-spallation in LS, water & rock
  - **Correlated:**
    - Fast neutrons: prompt—\( n \) scattering, delayed—\( n \) capture
    - \( ^8\text{He}/^9\text{Li} \): prompt—\( \beta \) decay, delayed—\( n \) capture
    - Am-C source: prompt—\( \gamma \) rays, delayed—\( n \) capture
    - \( \alpha-n: \) \( ^{13}\text{C}(\alpha,n)^{16}\text{O} \)
Neutrino Event Selection

- Pre-selection
  - Reject Flashers
  - Reject Triggers within (-2 μs, 200 μs) to a tagged water pool muon

- Neutrino event selection
  - Multiplicity cut
    - Prompt-delayed pairs within a time interval of 200 μs
    - No triggers $E > 0.7$ MeV before the prompt signal and after the delayed signal by 200 μs
  - Muon veto
    - $1s$ after an AD shower muon
    - $1ms$ after an AD muon
    - $0.6ms$ after an WP muon
    - $0.7$ MeV $< E_{\text{prompt}} < 12.0$ MeV
    - $6.0$ MeV $< E_{\text{delayed}} < 12.0$ MeV
    - $1μs < Δt_{e^-n} < 200μs$
Selected Signal Events: Good Agreement with MC

- Prompt energy distribution
- Delayed energy distribution
- Time interval distribution
- Distance distribution

2012/3/20
Accidental Backgrounds

Simple calculation:

\[ N_{\text{accBkg}} = \sum_i N^i_{\text{n-like singles}} \left( 1 - e^{-\frac{R^i_{e^{+}-\text{like triggers}}}{200\mu s}} \right) \pm \frac{N_{\text{accBkg}}}{\sqrt{\sum_i N^i_{\text{n-like singles}}}} \]

<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>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>

2012/3/20
Cross Check: Outside the space and time window

- Prompt-delayed distance distribution. Check the fraction of prompt-delayed pair with distance $>2m$
- Off-window coincidence $\rightarrow$ ‘measure’ the accidental background
- Results in agreement within 1%.

Uncertainty: $<1\%$
Fast Neutrons

- Look at the prompt energy spectrum above 12 MeV, to estimate backgrounds in the region of [0.7 MeV, 12 MeV]:
  - A fit to the spectrum in the region of [12 MeV, 80 MeV] extrapolate to [0.7 MeV, 12 MeV]
  - Difference of the fitting function, 0th-order or 1st-order polynomial, gives systematic uncertainties
Cross Check: sum up all the sources

- **Fast neutrons from water pools**
  - Obtain the rate and energy spectrum of fast neutrons by tagged muons in water pool. Consistent with MC simulation.
  - Estimate the untagged fast neutron by using water pool inefficiency

- **Fast neutrons from nearby rock**
  - Estimated based on MC simulation

<table>
<thead>
<tr>
<th></th>
<th>Fast neutron (event/day)</th>
<th>Cross checks(event/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD1</td>
<td>0.84 ± 0.28</td>
<td>0.6 ± 0.4</td>
</tr>
<tr>
<td>AD2</td>
<td>0.84 ± 0.28</td>
<td>0.6 ± 0.4</td>
</tr>
<tr>
<td>AD3</td>
<td>0.74 ± 0.44</td>
<td>0.6 ± 0.4</td>
</tr>
<tr>
<td>AD4</td>
<td>0.04 ± 0.04</td>
<td>0.04 ± 0.04</td>
</tr>
<tr>
<td>AD5</td>
<td>0.04 ± 0.04</td>
<td>0.04 ± 0.04</td>
</tr>
<tr>
<td>AD6</td>
<td>0.04 ± 0.04</td>
<td>0.04 ± 0.04</td>
</tr>
</tbody>
</table>

Results are consistent
Backgrounds – $^8$He/$^9$Li

- Cosmic $\mu$ produced $^9$Li/$^8$He in LS
  - $\beta$-decay + neutron emitter
  - $\tau(^8\text{He}/^9\text{Li}) = 171.7\text{ms}/257.2\text{ms}
  - $^8$He/$^9$Li, $\text{Br(n)} = 12\%/48\%$, $^9$Li dominant
  - Production rate follow $E_\mu^{0.74}$ power law

- Measurement:
  - Time-since-last-muon fit
    $$f(t) = B/\lambda \cdot e^{-t/\lambda} + S/T \cdot e^{-t/T}$$
    - Improve the precision by reducing the muon rate:
      - Select only muons with an energy deposit $>1.8\text{MeV}$ within a [10us, 200us] window
      - Issue: possible inefficiency of $^9$Li
    - Results w/ and w/o the reduction is studied

NIM A564 (2006)471
Measurement in EH1+EH2 & Prediction in EH3

- Measurement in EH1/EH2 with good precision, but EH3 suffers from poor statistics
- Results w/ and w/o the muon reduction consistent within 10%
- Correlated $^9$Li production ($E_\mu^{0.74}$ power law) allow us to further constraint $^9$Li yield in EH3
- Cross check: Energy spectrum consistent with expectation
241Am-13C Backgrounds

- **Uncorrelated backgrounds:**
  \[ R = 50 \text{ Hz} \times 200 \mu\text{s} \times R_{n\text{-like}} \text{(events/day/AD)} \]
  - \( R_{n\text{-like}} \) Measured to be \(~230\)/day/AD, in consistent with MC Simulation
  - \( R \) is not a negligible amount, particularly at the far site (\( B/S \sim 3.17\% \))
  - Measured precisely together with all the other uncorrelated backgrounds

- **Correlated backgrounds:**
  - Neutron inelastic scattering with \(^{56}\text{Fe} + \text{neutron capture on}^{57}\text{Fe} \)
  - Simulation shows that correlated background is 0.2 events/day/AD, corresponding to a \( B/S \) ratio of 0.03\% at near site, 0.3\% at far site

*Uncertainty: 100\%*
Backgrounds from $^{13}$C($\alpha$,n)$^{16}$O

- Identify $\alpha$ sources: $^{238}$U, $^{232}$Th, $^{227}$Ac, $^{210}$Po,…
- Determine $\alpha$ rate from cascade decays
- Calculate backgrounds from $\alpha$ rate + ($\alpha$,n) cross sections

<table>
<thead>
<tr>
<th>Components</th>
<th>Total $\alpha$ rate</th>
<th>BG rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region A: Acc. Coincidence of $^{210}$Po &amp; $^{210}$Po</td>
<td>$^{210}$Po:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10Hz at EH1</td>
<td>0.02/day at EH1</td>
</tr>
<tr>
<td></td>
<td>8Hz at EH2</td>
<td>0.015/day at EH2</td>
</tr>
<tr>
<td></td>
<td>6Hz at EH3</td>
<td>0.01/day at EH3</td>
</tr>
<tr>
<td>Region B: Acc. Coincidence of $^{210}$Po &amp; $^{40}$K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Region C: Acc. Coincidence of $^{40}$K &amp; $^{210}$Po</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Region D: Acc. Coincidence of $^{208}$Tl &amp; $^{210}$Po</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Region E: Cascade decay in $^{227}$Ac chain</td>
<td>1.4 Bq</td>
<td>0.01/day</td>
</tr>
<tr>
<td>Region F: Cascade decay in $^{238}$U chain</td>
<td>0.07Bq</td>
<td>0.001/day</td>
</tr>
<tr>
<td>Region G: Cascade decay in $^{232}$Th chain</td>
<td>1.2Bq</td>
<td>0.01/day</td>
</tr>
</tbody>
</table>

Uncertainty: 50%
# Signals and Backgrounds

<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>Neutrino candidates</td>
<td>28935</td>
<td>28975</td>
<td>22466</td>
<td>3528</td>
<td>3436</td>
<td>3452</td>
</tr>
<tr>
<td>DAQ live time (day)</td>
<td>49.5530</td>
<td>49.4971</td>
<td>48.9473</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Veto time (day)</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>Efficiency $\varepsilon_{\mu} \cdot \varepsilon_{m}$</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>Accidental (/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>Fast neutron (/day)</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>$^8\text{He}/^9\text{Li}$ (/day)</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>Am-C corr. (/day)</td>
<td></td>
<td></td>
<td></td>
<td>0.2±0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{13}\text{C}(\alpha, n)^{16}\text{O}$ background (/day)</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>Neutrino rate (/day)</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>
Signal + Background Spectrum

**EH1**
- **57910 signal candidates**

**EH2**
- **22466 signal candidates**

**EH3**
- **10416 signal candidates**

<table>
<thead>
<tr>
<th>Component</th>
<th>B/S @EH1/2</th>
<th>B/S @EH3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidentals</td>
<td>~1.4%</td>
<td>~4.5%</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>~0.1%</td>
<td>~0.06%</td>
</tr>
<tr>
<td>$^8$He/$^9$Li</td>
<td>~0.4%</td>
<td>~0.2%</td>
</tr>
<tr>
<td>Am-C</td>
<td>~0.03%</td>
<td>~0.3%</td>
</tr>
<tr>
<td>$\alpha$-n</td>
<td>~0.01%</td>
<td>~0.04%</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td><strong>1.5%</strong></td>
<td><strong>4.7%</strong></td>
</tr>
</tbody>
</table>
Energy Cuts Efficiency and Systematics

- **Delayed energy cut** $E_n > 6$ MeV
  - Energy scale uncertainty $0.5\%$
  - Efficiency uncertainty $\sim 0.12\%$

- **Prompt energy cut** $E_p > 0.7$ MeV
  - Energy scale uncertainty $2\%$
  - Efficiency uncertainty $\sim 0.01\%$

The inefficiency mainly comes from edges

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<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>
</tbody>
</table>
**Spill-in effect and Systematics**

- Neutrons generated in acrylic and LS can spill into Gd-LS and be captured on Gd.
- Simulation shows that Gd capture is increased by 5%.
- The relative differences in acrylic vessel thickness, acrylic density and liquid density are modeled in MC.

### Results Table

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Spill-in</td>
<td>105.0%</td>
<td>1.5%</td>
<td>0.02%</td>
</tr>
</tbody>
</table>
Muon Veto and Multiplicity Cut

- **Muon veto**
  - Total veto time is the sum of all the veto time windows
  - Temporal overlap is taken into account

- **Multiplicity cut**
  - Efficiency $= \varepsilon_1 \times \varepsilon_2 \times \varepsilon_3$

- **Total efficiency**
  - Uncertainty coming mainly from the average neutron capture time. It is correlated.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.02%</td>
<td>&lt; 0.01%</td>
</tr>
</tbody>
</table>

Efficiency is AD dependent, see page 38

2012/3/20

$1s$ after an AD shower mu
$1ms$ after an AD mu
$0.6ms$ after an WP mu

Prompt-delayed pairs within 200 μs
No triggers before the prompt and after the delayed signal by 200 μs

$1\mu s < \Delta e^+ - n < 200\mu s$
Gd Capture Fraction: H/Gd and Systematics

- Uncertainty is large if takes simply the ratio of area
- Relative Gd content variation 0.1% → evaluated from neutron capture time
- Geometry effect on spill-in/out 0.02% → relative differences in acrylic thickness, acrylic density and liquid density are modeled in MC

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gd capture ratio</td>
<td>83.8%</td>
<td>0.8%</td>
<td>&lt;0.1%</td>
</tr>
</tbody>
</table>

Neutron capture time from Am-C
Time Correlation Cut: $1 \mu s < \Delta t_{e^-n} < 200 \mu s$

- Uncertainty comes from Gd concentration difference and possible trigger time walk effect (assuming 20ns)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>98.6%</td>
<td>0.12%</td>
<td>0.01%</td>
</tr>
</tbody>
</table>

2012/3/20
Livetime

- **Synchronization of 3 Halls**
  - Divide data taking time into one-hour slices
  - Discard data in a whole slice if not all 3 halls are running

- **Uncertainty**
  - Comes from the case when electronics buffer is full.
  - This estimated to be less than 0.0025%, by either blocked trigger ratio or accumulating all buffer full periods.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Livetime</td>
<td>100 %</td>
<td>0.002 %</td>
</tr>
</tbody>
</table>
Alternative Analysis

- Using an alternative energy calibration algorithm based on spallation neutron peak
- Different neutrino selection criteria
  - Muon cut: 0.4s after an AD shower muon (different shower muon threshold), 1.4ms after an AD muon, 0.6ms after a WP muon
  - A different multiplicity cut
- Results: consistent within statistical errors
Side-by-side Comparison

- **Expected ratio of neutrino events:** $R(\text{AD1}/\text{AD2}) = 0.981$
  - The ratio is not 1 because of target mass, baseline, etc.
- **Measured ratio:** $0.987 \pm 0.008(\text{stat}) \pm 0.003(\text{syst})$

This final check shows that systematic errors are under control.
Predictions

- Baseline
- Target mass
- Reactor neutrino flux

- These three predictions are blinded before we fix our analysis cuts and procedures
- They are opened on Feb. 29, 2012
- The physics paper is submitted to PRL on March 7, 2012
Baseline

- Survey:
  - Methods: GPS, Total Station, laser tracker, level instruments, …
  - Results are compared with design values, and NPP coordinates
  - Data processed by three independent software
- Results: sum of all the difference less than 28 mm
- Uncertainty of the fission center from reactor simulation:
  - 2 cm horizontally
  - 20 cm vertically
- The combined baseline error is 35 mm, corresponding to a negligible reactor flux uncertainty (<0.02%)
Target Mass & No. of Protons

- Target mass during the filling measured by the load cell, precision ~ 3kg $\Rightarrow$ 0.015%
- Checked by Coriolis flow meters, precision ~ 0.1%
- Actually target mass:
  \[ M_{\text{target}} = M_{\text{fill}} - M_{\text{overflow}} - M_{\text{bellow}} \]
- $M_{\text{overflow}}$ and $M_{\text{bellow}}$ are determined by geometry
- $M_{\text{overflow}}$ is monitored by sensors

### Target Mass Variation

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Relative</th>
<th>Absolute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free protons/Kg</td>
<td>neg.</td>
<td>0.47%</td>
</tr>
<tr>
<td>Density</td>
<td>neg.</td>
<td>0.0002%</td>
</tr>
<tr>
<td>Total mass</td>
<td>0.015%</td>
<td>0.015%</td>
</tr>
<tr>
<td>Bellows</td>
<td>0.0025%</td>
<td>0.0025</td>
</tr>
<tr>
<td>Overflow tank</td>
<td>0.02%</td>
<td>0.02%</td>
</tr>
<tr>
<td>Total</td>
<td>0.03%</td>
<td>0.47%</td>
</tr>
</tbody>
</table>
Reactor Neutrinos

- Reactor neutrino spectrum
  
  \[ S(E_\nu) = \frac{W_{\text{th}}}{\sum_i (f_i/F_e) e_i} \sum_i (f_i/F) S_i(E_\nu) \]

- Thermal power, \( W_{\text{th}} \), measured by KIT system, calibrated by KME method

- Fission fraction, \( f_i \), determined by reactor core simulation

- Neutrino spectrum of fission isotopes \( S_i(E_\nu) \) from measurements

- Energy released per fission \( e_i \)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>( E_{f,i} ), MeV/fission</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{235}\text{U})</td>
<td>201.92 ± 0.46</td>
</tr>
<tr>
<td>(^{238}\text{U})</td>
<td>205.52 ± 0.96</td>
</tr>
<tr>
<td>(^{239}\text{Pu})</td>
<td>209.99 ± 0.60</td>
</tr>
<tr>
<td>(^{241}\text{Pu})</td>
<td>213.60 ± 0.65</td>
</tr>
</tbody>
</table>


Reactor

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

Relative measurement \( \Rightarrow \) independent from the neutrino spectrum prediction
Three halls taking data synchronously allows near-far cancellation of reactor related uncertainties.

Rate changes reflect the reactor on/off.

Predictions are absolute, multiplied by a normalization factor from the fitting.
### Complete Efficiency and Systematics

<table>
<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>99.88%</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>98.6%</td>
<td>0.12%</td>
<td>&lt;0.01%</td>
</tr>
<tr>
<td>Capture time cut</td>
<td>83.8%</td>
<td>0.8%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Gd capture ratio</td>
<td>105.0%</td>
<td>1.5%</td>
<td>0.02%</td>
</tr>
<tr>
<td>Spill-in</td>
<td>100.0%</td>
<td>0.002%</td>
<td>&lt;0.01%</td>
</tr>
<tr>
<td>Livetime</td>
<td>78.8%</td>
<td>1.9%</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

**TDR:** (0.18 - 0.38) %

### Reactor

<table>
<thead>
<tr>
<th>Correlated</th>
<th>Uncorrelated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy/fission</td>
<td>Power</td>
</tr>
<tr>
<td>0.2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>(\bar{\nu_e}/\text{fission})</td>
<td>Fission fraction</td>
</tr>
<tr>
<td>3%</td>
<td>0.6%</td>
</tr>
<tr>
<td></td>
<td>Spent fuel</td>
</tr>
<tr>
<td></td>
<td>0.3%</td>
</tr>
<tr>
<td>Combined</td>
<td>Combined</td>
</tr>
<tr>
<td>3%</td>
<td>0.8%</td>
</tr>
</tbody>
</table>
Using near to predict far:

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

\[ M_i = \frac{1 - B_i^{\text{acc}} - B_i^{\text{Neutron}} - B_i^{\text{\alpha-Li/8He}} - B_i^{\text{AmC}} - B_i^{\text{\alpha-n}}}{\epsilon_i^{\mu} \epsilon_i^{\text{multi}} \text{Mass}_i} \]

Determination of \( \alpha, \beta \):
1) Set \( R=1 \) if no oscillation
2) Minimize the residual reactor uncertainty

**Observed:** 9901 neutrinos at far site,
**Prediction:** 10530 neutrinos if no oscillation

\[ R = 0.940 \pm 0.011 \text{ (stat)} \pm 0.004 \text{ (syst)} \]
\( \chi^2 \) Analysis

\[
\chi^2 = \sum_{i=1}^{N} \frac{(O_i - E_i)^2}{E_i}
\]

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

\[
\chi^2 / \text{NDF} = 4.26 / 4
\]

5.2 \( \sigma \) for non-zero \( \theta_{13} \)
Future plan

- Assembly of AD7 and AD8 is underway now, to be completed before summer
- Current data taking will continue until the summer
- Summer activities:
  - Installation of AD7 & AD8
  - Detector calibration
- Re-start data taking after summer
The Daya Bay Collaboration

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

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

Asia (20)
IHEP, Beijing Normal Univ., Chengdu Univ.
of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. Univ., 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.

~250 Collaborators
Summary

- Electron anti-neutrino disappearance is observed at Daya Bay,

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

- together with a spectral distortion

- A new type of neutrino oscillation is thus discovered

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

\[ \chi^2/NDF = 4.26/4 \]

5.2 \(\sigma\) for non-zero \(\theta_{13}\)