Observation of Electron Antineutrino Disappearance at Daya Bay

Karsten M. Heeger, University of Wisconsin

on behalf of the Daya Bay collaboration

FNAL, March 23, 2012
Reactor Neutrino Physics

**1956** - First observation of (anti)neutrinos

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

**1995** - Nobel Prize to Fred Reines at UC Irvine

**2003** - First observation of reactor antineutrino disappearance

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

**2008** - Precision measurement of $\theta_{13}$

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

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...
Non-Accelerator Neutrino Discoveries

1968  Ray Davis detects 1/3 of expected solar neutrinos.  
      (Nobel prize in 2002)

1998  SuperK reports evidence for oscillation of atmospheric neutrinos.

2001/2002  SNO finds evidence for solar $\nu_e$ flavor change.

2003  KamLAND discovers disappearance of reactor $\bar{\nu}_e$

2007  Borexino detection of $^7\text{Be}$ solar neutrinos
Accelerator Neutrino Oscillation Studies

- precision measurements of $\nu$ oscillation
- indications of $\nu_e$ appearance
- anomalies
...
... + much more
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

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

\[ = \delta_{\alpha\beta} - 4 \sum_{i > j} \Re(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2[1.27 \Delta m_{ij}^2 L/E] \]

\[ + 2 \sum_{i > j} \Im(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2[2.54 \Delta m_{ij}^2 L/E] \]

2-neutrino case

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

energy and baseline dependent
osc frequency depends on \( \Delta m^2 \)
amplitude depends on \( \theta \)
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 
\(0\nu\beta\beta\)
Neutrino Oscillation

Mixing Angles & Mass Splittings

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

\[
U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
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\end{pmatrix} = \begin{pmatrix}
0.8 & 0.5 & U_{e3} \\
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\end{pmatrix}
\]

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

atmospheric, K2K

reactor and accelerator

SNO, solar SK, KamLAND

0νββ
Neutrino Oscillation

Mixing Angles

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Maki, Nakagawa, Sakata, Pontecorvo

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

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

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

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

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

Mixing Angles

\[
U = \begin{pmatrix}
  U_{e1} & U_{e2} & U_{e3} \\
  U_{\mu1} & U_{\mu2} & U_{\mu3} \\
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\[U_{\text{MNSP}} \text{ Matrix} \quad \text{Maki, Nakagawa, Sakata, Pontecorvo}\]

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

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

atmospheric, K2K \quad \text{reactor and accelerator} \quad \text{SNO, solar SK, KamLAND} \quad 0\nu\beta\beta

Quarks \quad \text{vs.} \quad \text{Leptons}
Recent Indications for $\theta_{13}$

**T2K**

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

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

**MINOS**

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

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

**Double Chooz**

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

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

no result $>2.5\sigma$ from $\theta_{13}=0$

a precision experiment is needed
Oscillation Experiments with Reactors

Looking for non-$1/r^2$ behavior of $\nu_e$ interaction rate

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

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: $\Delta m_{12}^2, \Delta m_{13}^2$

$\Delta m_{12}^2 \approx 7.6 \times 10^{-5} \text{ eV}^2$

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

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32}L}{4E}$$
Measuring $\theta_{13}$ with Reactor Experiments

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
Reactor Antineutrinos

Source

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

\[ ^{235}\text{U}:^{238}\text{U}:^{239}\text{Pu}:^{241}\text{Pu} = 0.570: 0.078: 0.0295: 0.057 \]

~ 200 MeV per fission

~ 6 $\bar{\nu}_e$ per fission

~ $2 \times 10^{20}$ $\bar{\nu}_e$/GW$_{th}$-sec

Detection

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
Daya Bay - A Powerful Neutrino Source

- Among the top 5 most powerful reactor complexes in the world, producing 17.4 GW\textsubscript{th} (6 x 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>Layer</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>

RPCs
AD Gd-LS target
automated calibration units (ACU)
concrete
outer and inner water shields (IWS and OWS)
antineutrino detectors (AD)
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

Karsten Heeger, Univ. of Wisconsin
FNAL, March 23, 2012
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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” detectors reduces systematics
Gd-LS defines target volume, no position cut

photomultipliers
steel tank
radial shield
outer acrylic tank
inner acrylic tank

optical reflectors at top/bottom of cylinder

Gd-doped liquid scintillator

liquid scintillator γ-catcher

mineral oil

5 m

inner: 20 tons Gd-doped LS (d=3m)
mid: 20 tons LS (d=4m)
outer: 40 tons mineral oil buffer (d=5m)

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 <0.25% uncertainty

Two-zone ultrapure water Cherenkov detector
Antineutrino Detector Assembly

detector assembly in pairs
6 ADs operational, AD7,8 in assembly
Liquid Scintillator Hall

LAB + Gd (0.1%) + PPO (3 g/L) + bis-MSB (15 mg/L)
Number of protons: $$(7.169\pm0.034) \times 10^{25}$$ p per kg

185-ton Gd-LS + 196-ton LS production

Multi-stage purifications yield optical improvement and U/Th removal

Gd-loaded liquid scintillator shows good stability with time

A 1-m apparatus yielded attenuation length of $\sim 15$ m @ 430 nm.
Detector Filling and Target Mass Measurement

Detectors are filled from same reservoirs "in-pairs" within < 2 weeks.

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

<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>

Detectors are filled from same reservoirs "in-pairs" within < 2 weeks.
Antineutrino Detector Installation - Near Hall
Antineutrino Detector Installation - Far Hall
Daya Bay Antineutrino Detection

prompt+delayed coincidence provides distinctive signature

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

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}) \quad (\text{delayed})

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

**Delayed neutron capture**: tags antineutrino signal, above radioactive background

**Prompt Energy Signal**

**Delayed Energy Signal**
Automated Calibration System

Automatic calibration units (ACUs) on each detector
- routine weekly source deployment: 3 sources, 3 vertical axes, 5 points along z
- 3 axes: center, edge of target, middle of gamma catcher

3 sources for each z axis on a turntable
- $^{68}\text{Ge}$ (0 KE $e^+$ = 2×0.511 MeV γ’s), 10 Hz
- $^{241}\text{Am-13C}$ neutron source (3.5 MeV n without γ), 0.5 Hz + $^{60}\text{Co}$ gamma source (1.173+1.332 MeV γ), 100 Hz
- LED diffuser ball (500 Hz) for $T_0$ and gain

position accuracy < 5 mm
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.

Data Periods

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.
Data Analysis Approach

Blinded Information

- True target mass
- True baselines from detectors to reactors
- True reactor flux history

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

far/near $\bar{\nu}_e$ ratio  target mass  distances  efficiency  oscillation deficit

Multiple Independent Analyses

- Common data set
- Independent analysis cross-check results before unblinding
- Different
  - Energy Calibration / Reconstruction
  - Antineutrino Candidate Selection / Efficiency Estimation
  - Background Estimation
  - $\theta_{13}$ Rate Analysis

Only results from one analysis are presented here
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

$\log_{10} \left( \frac{\text{Quadrant}^2 + \left( \frac{\text{MaxQ}}{0.45} \right)^2}{\text{MaxQ}/\text{sumQ}} \right) < 0$

Quadrant = Q3/(Q2+Q4)
MaxQ = maxQ/sumQ

Inefficiency to antineutrinos signal: 0.024% ± 0.006%(stat)
Contamination: < 0.01%
Uncorrelated signals dominated by low-energy radioactivity

Spectrum
after muon cuts

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

Sources
Stainless Steel: U/Th chains
PMTs: $^{40}\text{K}$, U/Th chains
Scintillator: Radon/U/Th chains

Task: Select antineutrinos
~800 IBD events/AD/day at near AD,
~80 IBD events/AD/day at far AD

\[
A = 2 \times \frac{AD_1 - AD_2}{AD_1 + AD_2}
\]
Calibration

PMT charge vs. time

Energy Calibration

Energy vs. position

**Energy scale vs. Time**

Detector tests

**Energy resolution**

- AD1
- AD2

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

- Ge
- n H-capture (spallation)
- Co
- n Gd-capture (AmC, IBD, spallation)
Antineutrino (IBD) Selection

Prompt + Delayed Selection  \( \bar{\nu}_e + p \rightarrow e^+ + n \)

- 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 \( \mu s \) to 200 \( \mu s \) of IBD.

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 in each detector constrains H/Gd capture ratio

Capture time cut: 1µs to 200µs

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

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

Accidentals: Two uncorrelated events ‘accidentally’ passing the cuts and mimic IBD event.

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

Correlated events mimic IBD events

- prompt: β-decay
- delayed: neutron capture

\[ ^9\text{Li} \rightarrow ^{\text{Be}} + e^- + \bar{\nu}_e \rightarrow n + 2\alpha \]

Generated by cosmic rays, long-lived

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

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

\(^9\text{Li}/^8\text{He}, \text{Br}(n) = 48\% / 12\%, ^9\text{Li} \text{ dominant} \)

Example of the fit

Fit with known decay times for \(^8\text{He}/^9\text{Li} \)

Analysis muon veto cuts control B/S to

\sim 0.4\% (0.2\%) of far (near) signal.
Background: Fast neutrons

Correlated events mimic IBD events

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: 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.
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) – Po – Pb

$^{210}$Po: spectrum fitting

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

<table>
<thead>
<tr>
<th>Example alpha rate in AD1</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)%
Background: $^{241}\text{Am-^{13}C}$ neutrons

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

Simulate neutron capture position

mimick IBD if both $\gamma$ enter scintillating region

Constrain far site B/S to $0.3 \pm 0.3\%$:
- Measure uncorrelated gamma rays from ACU in data
- Estimate ratio of correlated/uncorrelated rate using simulation/MC
- Assume 100% uncertainty from simulation
## 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>DAQ live time (day)</td>
<td>49.5530</td>
<td></td>
<td>49.4971</td>
<td></td>
<td>48.9473</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</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>Accidentals (/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></td>
<td>1.8±1.1</td>
<td></td>
<td>0.16±0.11</td>
<td></td>
</tr>
<tr>
<td>Am-C corr. (/day)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.2±0.2</td>
</tr>
<tr>
<td>$^{13}\text{C}(\alpha, n)^{16}\text{O}$ (/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><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>

rates /day/AD consistent rates for side-by-side detectors uncertainty dominated by statistics
IBD Prompt Event Locations

x-y Location
IBD Prompt Event Locations

z-R² Location
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.

- EH1:
  - D2 off
  - D2 on

- EH2:
  - L3 on
  - L2 off
  - L2 on
  - L1 off

- EH3:
  - Predicted
  - Measured

Karsten Heeger, Univ. of Wisconsin
FNAL, March 23, 2012
High-statistics reactor antineutrino spectra. B/S ratio is 2% (5%) at far (near) sites.
### Uncertainty Summary

#### Detector

<table>
<thead>
<tr>
<th></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></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>
</tr>
<tr>
<td>Combined</td>
<td>78.8%</td>
<td>1.9%</td>
<td>0.2%</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>Fission fraction 0.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spent fuel 0.3%</td>
</tr>
<tr>
<td>Combined</td>
<td>3%</td>
<td>Combined 0.8%</td>
</tr>
</tbody>
</table>

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

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

Influence of uncorrelated reactor systematics (0.8%) is reduced to 0.04% detector systematics uncertainty by far vs near measurement.
Rate Analysis

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

Uses standard $\chi^2$ approach.

$\chi^2$/NDF=4.26/4

Far vs. near relative measurement.

[Absolute rate is not constrained.]

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

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

$\sin^2 2\theta_{13} = 0$ excluded at 5.2\(\sigma\)
Spectrum Shape

Compare far/near measured rates and spectra

\[ R = \frac{F_{\text{ar,measured}}}{F_{\text{ar,expected}}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_iM_3)} \]

- \( M_n \) 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.
Global $\theta_{13}$ Situation

Daya Bay precision surpasses existing estimates.

Expect more statistics and further improvements in analysis.
Daya Bay has measured
\[ \sin^2 2\theta_{13} = 0.092 \pm 0.016 \text{ (stat)} \pm 0.005 \text{ (syst)} \]
which implies
\[ \theta_{13} = 8.8^\circ \]
We don’t know yet what this tells us.

Example of theoretical prediction in the literature,
e.g. texture zero matrices by Fritzsch,
arXiv:1203.4406

\[
U = \begin{pmatrix}
s_\nu s_\tau c + c_\nu c_\tau e^{-i\varphi} & s_\nu c_\tau c - c_\nu s_\tau e^{-i\varphi} & s_\nu s \\
c_\nu s_\tau c - s_\nu c_\tau e^{-i\varphi} & c_\nu c_\tau c + s_\nu s_\tau e^{-i\varphi} & c_\nu s \\
-s_\nu s & -c_\nu s & c
\end{pmatrix} P_\nu
\]
\[ \tan \theta_i \simeq \sqrt{m_e/m_\mu} \]
\[ \theta_{13} \simeq 8.9^\circ \]

Theorists can now validate models against measured mixing angle...
$\theta_{13}$ and the Experimental Neutrino Program

The measurement of $\theta_{13}$ opens an exciting future. Experimentalists have a decade+ of work ahead of them.
Summary

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\( \sigma \)

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

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

Assembly of last two detectors underway. Installation this summer/fall.
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 (2)
Charles Univ., Dubna

~230 collaborators