Search for the Neutrino Mixing Angle $\theta_{13}$

with non-accelerator experiments

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University of Wisconsin

APS April Meeting, Jacksonville, Florida
Discovery Era in Neutrino Physics: 1998 - Present

- Neutrinos are not massless
- **Evidence** for neutrino flavor conversion $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$
- Experimental results show that neutrinos oscillate

$\Delta m_{ij}^2$ measured and confirmed.
Constraints on Neutrino Mixing Angles from Solar, Atmospheric, And Reactor Experiments

SNO

KamLAND

Constraints on Neutrino Mixing Angles from Solar, Atmospheric, And Reactor Experiments

SNO

KamLAND

SK

SK

APS April Meeting, Jack
Neutrino Mixing

$U_{MNSP}$ Matrix
Maki, Nakagawa, Sakata, Pontecorvo

$$U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix} = \begin{pmatrix}
0.8 & 0.5 & U_{e3} \\
0.4 & 0.6 & 0.7 \\
0.4 & 0.6 & 0.7
\end{pmatrix}$$

$\Delta m^2, [\text{eV}^2]$ = \begin{array}{c}
10^{-5} \\
10^{-6}
\end{array}$

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

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

$\theta_{23} = \sim 45^\circ$ $\theta_{13} = \ ?$ $\theta_{12} \sim 32^\circ$
Neutrino Oscillation Search with Reactor Antineutrinos

Oscillation Searches at Chooz + Palo Verde:

Distance: 1km

\( \bar{\nu}_e \rightarrow \bar{\nu}_x \)

\( \sim 3000 \) events in 335 days

2.7% uncertainty

Absolute measurement with 1 detector
Current Knowledge of $\theta_{13}$

Direct search at Chooz and Palo Verde

At $\Delta m_{31}^2 = 2.5 \times 10^{-3} \, \text{eV}^2$, $\sin^2 2\theta_{13} < 0.15$

Global analysis of solar+other data

Ref: hep-ex/0604011

SK 3-flavor oscillation analysis

Matter enhancement separates the 1-2 and 1-3 oscillation effects in solar and reactor neutrinos
Experiment & Theory

Global Fit

\[ \sin^2 2\theta_{13} = 0.04 \]
\[ \sin^2 2\theta_{13} < 0.11 \text{ (90\% CL)} \]

Theory

<table>
<thead>
<tr>
<th>Model(s)</th>
<th>Refs.</th>
<th>( \sin^2 2\theta_{13} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimal SO(10)</td>
<td>[22]</td>
<td>0.13</td>
</tr>
<tr>
<td>Orbifold SO(10)</td>
<td>[23]</td>
<td>0.04</td>
</tr>
<tr>
<td>SO(10) + Flavor symmetry</td>
<td>[24]</td>
<td>( 1.2 \cdot 10^{-6} )</td>
</tr>
<tr>
<td></td>
<td>[25]</td>
<td>( 7.8 \cdot 10^{-4} )</td>
</tr>
<tr>
<td></td>
<td>[26-28]</td>
<td>( 0.01 \ldots 0.04 )</td>
</tr>
<tr>
<td></td>
<td>[29-31]</td>
<td>( 0.09 \ldots 0.18 )</td>
</tr>
<tr>
<td>SO(10) + Texture</td>
<td>[32]</td>
<td>( 4 \cdot 10^{-4} \ldots 0.01 )</td>
</tr>
<tr>
<td></td>
<td>[33]</td>
<td>0.04</td>
</tr>
<tr>
<td>SU(2)_L \times SU(2)_R \times SU(4)_c</td>
<td>[34]</td>
<td>0.09</td>
</tr>
<tr>
<td>Flavor symmetries</td>
<td>[35-37]</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>[38-40]</td>
<td>( \leq 0.004 )</td>
</tr>
<tr>
<td></td>
<td>[41-43]</td>
<td>( 10^{-4} \ldots 0.02 )</td>
</tr>
<tr>
<td></td>
<td>[40,44-47]</td>
<td>( 0.04 \ldots 0.15 )</td>
</tr>
<tr>
<td>Textures</td>
<td>[48]</td>
<td>( 4 \cdot 10^{-4} \ldots 0.01 )</td>
</tr>
<tr>
<td></td>
<td>[49-52]</td>
<td>( 0.03 \ldots 0.15 )</td>
</tr>
<tr>
<td>3 \times 2 see-saw</td>
<td>[53]</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>[54]</td>
<td>( 0.02 ) (n.h.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \geq 1.6 \cdot 10^{-4} ) (i.h.)</td>
</tr>
<tr>
<td>Anarchy</td>
<td>[55]</td>
<td>( &gt; 0.04 )</td>
</tr>
<tr>
<td>Renormalization group enhancement</td>
<td>[56]</td>
<td>0.03 \ldots 0.04</td>
</tr>
<tr>
<td>M-Theory model</td>
<td>[57]</td>
<td>( 10^{-4} )</td>
</tr>
</tbody>
</table>

we don't know \( \theta_{13} \) ...

Ref: FNAL proton driver report, hep-ex/0509019

April Meeting, Jacksonville, April 16, 2007
\[ P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = -16s_{12}c_{12}s_{13}^2c_{13}s_{23}c_{23} \]

\[ \sin \delta \sin \left( \frac{\Delta m_{12}^2}{4E} L \right) \sin \left( \frac{\Delta m_{13}^2}{4E} L \right) \sin \left( \frac{\Delta m_{23}^2}{4E} L \right) \]

\[ \Rightarrow \]

Is there \( \mu-\tau \) symmetry in neutrino mixing? Can we use \( \nu \) to search for CP?
\[ \theta_{13} \] and Nuclear Astrophysics

neutrino oscillation effects on supernova light-element synthesis

understanding the origin of matter (vs antimatter)

Leptogenesis

*Fukugita, Yanagida, 1986*

- Out-of-equilibrium L-violating decays of heavy Majorana neutrinos leading to L asymmetry but leaving B unchanged. \( B_L - L_L \) is conserved.

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astr-ph/0606042
Measuring $\theta_{13}$

**Method 1: Accelerator Experiments**

$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}^2 L}{4 E_\nu} + \ldots$$

- appearance experiment $\nu_\mu \rightarrow \nu_e$
- measurement of $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_e$ yields $\theta_{13}, \delta_{CP}$
- baseline $O(100-1000 \text{ km})$, matter effects present

**Method 2: Reactor Neutrino Oscillation Experiment**

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

- disappearance experiment $\bar{\nu}_e \rightarrow \bar{\nu}_e$
- look for rate deviations from $1/r^2$ and spectral distortions
- observation of oscillation signature with 2 or multiple detectors
- baseline $O(1 \text{ km})$, no matter effects
\( \theta_{13} \) from Reactor and Accelerator Experiments

**Reactor** (\( \bar{\nu}_e \) disappearance)

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

- Clean measurement of \( \theta_{13} \)
- No matter effects

**Accelerator** (\( \nu_e \) appearance)

\[
P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31} \\
+ 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin \Delta_{31} [\cos \Delta_{32} \cos \delta] \\
+ 4c_{13}^2 s_{12}^2 [c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta] \sin^2 \Delta_{21} \\
- 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2) \frac{aL}{4E_\nu} \sin \Delta_{31} \left[ \cos \Delta_{32} - \frac{\sin \Delta_{31}}{\Delta_{31}} \right].
\]

- \( \sin^2 2\theta_{13} \) is missing key parameter for any measurement of \( \delta_{\text{CP}} \)

Karsten Heeger, Univ. of Wisconsin  
APS April Meeting, Jacksonville, April 16, 2007
Resolving the $\theta_{23}$ Parameter Ambiguity

Super-K, T2K $\nu_\mu$ disappearance $\theta_{23} = 45\pm9^\circ$

NOvA, T2K $\nu_e$ appearance experiments measure $P[\nu_\mu \rightarrow \nu_e]$

Ref: hep-ph/0601258
Branch Point: $\sin^2 2\theta_{13} < 0.01$

for techniques to measure CP violation ...

→ **U13.00001**: Summary of the US long Baseline Neutrino Experiment Study, Milind Diwan

→ **U13.00004**: Analysis of a Proposed Long Baseline Neutrino Oscillation Experiment, Christine Lewis
A High Precision Measurement of $\theta_{13}$ with Reactor Neutrinos

Search for $\theta_{13}$ in new oscillation experiment

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

Small-amplitude oscillation due to $\theta_{13}$ integrated over $E$

Large-amplitude oscillation due to $\theta_{12}$
Principle of Relative Measurement

Measure ratio of interaction rates in detector (+shape)

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

Measured Ratio of Rates
Detector Mass Ratio, H/C
Detector Efficiency Ratio
\[ \sin^2 2\theta_{13} \]
Concept of Reactor $\theta_{13}$ Experiment

- relative measurement between detectors at different distances
- cancel source (reactor) systematics
  → need “identical detectors” at near and far site

Detectors will never be “identical” but we can understand, measure, and control

- relative target mass & composition to < 0.30% (0.10%)
- relative antineutrino detection efficiency to < 0.25% (0.15%)

...between pairs of detectors.

Daya Bay baseline (target)
Reactor $\theta_{13}$ Experiment at Krasnoyarsk, Russia

Original ideal, first proposed at Neutrino2000

Krasnoyarsk
- underground reactor
- detector locations determined by infrastructure

Ref: Marteyamov et al, hep-ex/0211070
Ratio of Measured to Expected $\bar{\nu}_e$ Flux

Expected precision in Daya Bay to reach $\sin^2 2\theta_{13} < 0.01$

Ref: KamLAND, Daya Bay, McKeown
Double Chooz and Daya Bay have strong international collaborations. Ready to start construction.
Double Chooz

10.2 tons detectors
8.4 GW$_{th}$ reactor power
300 mwe overburden at far site
60 mwe overburden at near site

near detector completion in ~ 2009

$\sigma_{sys} = 2.5\%$

$\sigma_{sys} = 0.6\%$
Powerful $\nu_e$ Source:
Multiple reactor cores.
(at present 4 units with 11.6 $GW_{th}$, in 2011 6 units with 17.4 $GW_{th}$)

Shielding from Cosmic Rays:
Up to 1000 mwe overburden nearby.
Adjacent to mountain.

http://dayawane.ihep.ac.cn/
Daya Bay Site

Far Site
1600 m from Ling Ao
2000 m from Daya Bay
Overburden: 350 m

Daya Bay Near
360 m from Daya Bay
Overburden: 97 m

Ling Ao Near
500 m from Ling Ao
Overburden: 98 m

Ling Ao II
(under construction)

error from multiple cores
4 reactors: 0.087%
6 reactors: 0.126%
Detecting Reactor $\bar{\nu}_e$

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

0.3 b

$\rightarrow + p \rightarrow D + \gamma$ (2.2 MeV)

(DELAYED)

49,000 b

$\rightarrow + Gd \rightarrow Gd^*$

$\rightarrow Gd + \gamma$'s (8 MeV)

(DELAYED)

Coincidence signal allows background suppression

0.1% Gadolinium-Liquid Scintillator

- Proton-rich target
- Easily identifiable n-capture signal above radioactive backgrounds
- Short capture time ($\tau \sim 28 \mu s$)
- Good light yield

$^{155}$Gd $\Sigma \gamma = 7.93$ MeV

$^{157}$Gd $\Sigma \gamma = 8.53$ MeV

Other Gd isotopes with high abundance have very small neutron capture cross sections

Karsten Heeger, Univ. Wisconsin

Daya Bay CD-1 Review, April 10, 2007
Baseline Design of Detector and Halls

multiple 3-zone antineutrino detectors

muon detectors
- water pool and Cherenkov counter
- RPC on top for tracking muons
Event Rates and Signal

Antineutrino Interaction Rates
(events/day per 20 ton module)

Daya Bay near site 960
Ling Ao near site ~760
Far site 90

Prompt Energy Signal

Reconstructed Positron Energy Spectrum

Energy 88465
Mean 3.576
RMS 1.462
Underflow 0
Overflow 0

Statistics comparable to single detector in far hall

Delayed Energy Signal

reconstructed neutron (delayed) capture energy spectrum

entries: 75959
energy: 6 MeV
mean: 7
RMS: 2.22
underflow: 0
overflow: 3
Design, R&D, and Prototyping for Daya Bay

Completing design of civil infrastructure

Gd-LS R&D in US and China

Detector Prototypes at IHEP and in Hong Kong

Acrylic Vessel R&D
## Detector-related Uncertainties

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Chooz (absolute)</th>
<th>Daya Bay (relative)</th>
<th>Goal w/Swapping</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Baseline</td>
<td>Goal</td>
</tr>
<tr>
<td># protons</td>
<td>0.8</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Detector Efficiency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy cuts</td>
<td>0.8</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Position cuts</td>
<td>0.32</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Time cuts</td>
<td>0.4</td>
<td>0.1</td>
<td>0.03</td>
</tr>
<tr>
<td>H/Gd ratio</td>
<td>1.0</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>n multiplicity</td>
<td>0.5</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Trigger</td>
<td>0</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Live time</td>
<td>0</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Total detector-related uncertainty</td>
<td>1.7%</td>
<td>0.38%</td>
<td>0.18%</td>
</tr>
</tbody>
</table>

Baseline: currently achievable relative uncertainty without R&D
Goal: expected relative uncertainty after R&D

for relative measurement between detectors at near and far sites
### Daya Bay Background Summary

<table>
<thead>
<tr>
<th></th>
<th>Daya Bay site</th>
<th>Ling Ao site</th>
<th>Far site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidental/signal</td>
<td>&lt;0.2%</td>
<td>&lt;0.2%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Fast n / signal</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>$^9$Li-$^8$He / signal</td>
<td>0.3%</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

- B/S ~ same for near and far sites
- constrained by measurements to required precision
- input to sensitivity calculations (assume 100% uncertainty)
Daya Bay Sensitivity & Milestones

• Reactor-related systematics: 0.09% (4 cores)
  0.13% (6 cores)
• Relative detector systematics: 0.38% (baseline)
• Backgrounds will be measured: < 0.2%

• Apr ‘07 completed DOE CD-1 review
• Jul ‘07 start civil construction
• Oct ‘08 delivery of Gd-LS to Daya Bay
• Aug-Dec ‘08 assembly of first detector pair
• May ‘09 start data taking at near site
• Mar ‘10 start data taking at near+far sites

→ U13.00005: The Daya Bay Reactor Neutrino Experiment
Mary Bishai
## Proposed Reactor $\theta_{13}$ Neutrino Experiments

<table>
<thead>
<tr>
<th>Location</th>
<th>Thermal Power (GW)</th>
<th>Distances Near/Far (m)</th>
<th>Depth Near/Far (mwe)</th>
<th>Target Mass (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Angra</strong>&lt;br&gt;proposed</td>
<td>Brazil</td>
<td>4.1</td>
<td>300/1500</td>
<td>250/2000</td>
</tr>
<tr>
<td><strong>Daya Bay</strong>&lt;br&gt;construction start in '07</td>
<td>China</td>
<td>11.6&lt;br&gt;17.4 after 2010</td>
<td>360(500)/1750&lt;br&gt;360(500)/1750</td>
<td>260/910</td>
</tr>
<tr>
<td><strong>Double-CHOOZ</strong>&lt;br&gt;under construction</td>
<td>France</td>
<td>8.7</td>
<td>150/1067&lt;br&gt;150/1067</td>
<td>60/300</td>
</tr>
<tr>
<td><strong>RENO</strong>&lt;br&gt;R&amp;D</td>
<td>Korea</td>
<td>17.3</td>
<td>150/1500&lt;br&gt;150/1500</td>
<td>230/675</td>
</tr>
</tbody>
</table>

*experiments that are underway*
\[ \sin^2 2\theta_{13} \] Sensitivity Limits

Ref: FNAL proton driver report, hep-ex/0509019

Daya Bay
DChooz
CHOOZ & Solar excluded
now 2010-12

Statistics limit
Systematics limit

Ref: FNAL proton driver report, hep-ex/0509019

Karsten Heeger, Univ. of Wisconsin
APS April Meeting, Jacksonville, April 16, 2007
Neutrino Physics at Reactors

Past Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France
Reactors in Japan

1956
First observation of neutrinos

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

1995
Nobel Prize to Fred Reines at UC Irvine

2002
Discovery of reactor antineutrino oscillation

Next step
High-precision measurement of $\theta_{13}$
...open door for CP violation searches