Probing Neutrino Mass and Mixing with Non-Accelerator Experiments

Karsten M. Heeger
University of Wisconsin

Yale University, March 1, 2010
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Why neutrinos?
330 neutrinos per cm$^3$.
0.5 proton and one billion photons per cm$^3$.

One billion more neutrinos than protons.

Big-Bang neutrinos are as numerous as the Big-Bang photons.

“neutrinos are the most abundant particles in the Universe besides photons”
“neutrinos are the most abundant particles in the Universe besides photons”
Heavy Elements: 0.03%

Ghostly Neutrinos: ~0.3%

Dark Energy: 70%

Dark Matter: 25%

Matter in the Universe

Stars: 0.5%

Free Hydrogen and Helium: 4%

neutrinos are highly abundant but with little mass

$\sum m_\nu \quad 0.0006 < \Omega_\nu < 0.015$
Neutrinos and Mass

"why is the neutrino mass so small?"
Neutrinos and the Early Universe

at $T \sim 1$ MeV ($\sim 1$ sec)
neutrinos decouple
relic neutrino spectrum left over

at $T < 100$ keV
deuterium formation, followed by BBN

at $T < 1$ eV (380,000 yrs)
photons decouple, cannot break up atoms
no more free charges to scatter photons
Universe becomes transparent

$n+p \leftrightarrow d+\gamma$

$p+e^- \leftrightarrow H+\gamma$
Neutrinos and the Structure of the Universe

“neutrinos have influenced the large and small-scale structure of the Universe”
Neutrinos and Supernovae

“without neutrinos dying stars would not explode”

“neutrinos helped cook the light elements in the Universe”
Neutrinos and Baryon Asymmetry

“neutrinos might explain the matter-antimatter asymmetry”

Leptogenesis

Fukugita, Yanagida, 1986

Sakharov, 1967

1. baryon number violation
2. violation of C and CP
3. departure from thermal equilibrium
Neutrinos and the Universe

very early universe | big bang nucleosynthesis | CMB | late time structure formation

matter-antimatter ratio | CMB | large-scale structure
Neutrinos from the Big Bang  \(~330\) neutrinos per \(\text{cm}^3\)

- Supernova Neutrinos
- Atmospheric Neutrinos
- Geo Neutrinos
- Accelerator & Reactor Neutrinos
- Solar Neutrinos

High Energy Cosmic Neutrinos
Neutrino Energies

Big-Bang neutrinos ~ 0.0004 eV

Neutrinos from the Sun < 20 MeV depending of their origin.

Atmospheric neutrinos ~ GeV

Antineutrinos from nuclear reactors < 10.0 MeV

Neutrinos from accelerators up to GeV ($10^9$ eV)
The Experimental Quest
Postulate of the Neutrino

Chadwick, 1914

\[ N \rightarrow N' + e^- \text{ some nuclei emit electrons!} \]

Reines and Cowan, 1956

"Observation of the Free Antineutrino"

\[ \nu_e + p \rightarrow e^+ + n \]
Neutrinos in the Standard Model

Discovery of $\nu_\mu$ and $\nu_\tau$

Accelerator studies of $\nu$

The Standard Model

- 3$\nu$ flavors
- upper limits on $m_\nu$ from kinematic studies.
- massless $\nu$ (ad hoc assumption in Standard Model)
Birth of Neutrino Astrophysics

1938  Bethe & Critchfield

\[ p + p \rightarrow ^2H + e^+ + \nu_e \]

1947  Pontecorvo, 1949 Alvarez

propose neutrino detection through

\[ ^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^- \]

1960’s  Ray Davis builds chlorine detector.

John Bahcall, generates first solar model calculations and \(\nu\) flux predictions.

“…to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars…” (Bahcall, 1964)
A Decade of Discoveries

1998 - Super-Kamiokande
atmospheric and solar neutrinos

2001/2002 - Sudbury Neutrino Observatory
solar neutrinos

2003-2008 - KamLAND
reactor antineutrinos

Borexino
solar neutrinos
Atmospheric Neutrino Studies

Earth

Cosmic ray (proton)

E_{\nu} \sim 0.5 - 5 \text{ GeV}
L_{\text{down}} \sim 100 \text{ km}
L_{\text{up}} \sim 10,000 \text{ km}

2 muon neutrinos
1 electron neutrino

R' = (\mu/e)_{\text{DATA}} / (\mu/e)_{\text{MC}}

No osc.
Atmospheric Neutrino Oscillations

1998

Δm^2 = 2.5 \times 10^{-3} \text{eV}^2 \neq 0 \rightarrow \text{at least 1 } m_\nu \neq 0

Mixing angle is large (\theta \sim 45°)

evidence for ν_\mu disappearance:
zenith-angle dependence

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Solar Neutrino Problem: Too few $\nu_e$ observed from the Sun.

Even with all solar neutrino fluxes as free parameters, cannot reproduce the data. $P_{\text{MSM}} < 1.7\%$ at 95% CL

KMH, Robertson PRL 77:3270 (1996)

Model-independent evidence for solar $\nu_e$ flavor change
Solar Neutrino Measurements with SNO

Neutral-Current \( \nu_e + \nu_\mu + \nu_\tau \)

Charged-Current \( \nu_e \)

Elastic Scattering \( \nu_e + 0.15 (\nu_\mu + \nu_\tau) \)

solar neutrino measurements at SNO

Total \(^{8}\text{B}\) neutrino flux

Neutrinos interact with matter in Sun and Earth (MSW effect)
Neutrino Oscillation

Neutrino Mass and Mixing

\[
|\nu_a\rangle = \cos \theta |\nu_1\rangle - \sin \theta |\nu_2\rangle
\]
\[
|\nu_b\rangle = \sin \theta |\nu_1\rangle + \cos \theta |\nu_2\rangle
\]

Mass States

\[
\begin{pmatrix}
|\nu_1\rangle \\
|\nu_2\rangle
\end{pmatrix}
\]

Weak States

\[
\begin{pmatrix}
|\nu_e\rangle \\
|\nu_\mu\rangle
\end{pmatrix} = \begin{pmatrix}
\cos \theta & \sin \theta \\
2 \sin \theta & \cos \theta
\end{pmatrix}
\]

Time Evolution

there are at least 3 states...

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

Pontecorvo, 1968
Neutrino Mixing and Flavor Oscillation

\[ \nu_\mu \leftrightarrow \nu_\tau \]
\[ \nu_e \leftrightarrow \nu_\mu, \nu_\tau \]

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Oscillation Searches with Reactor Antineutrinos

- $\bar{\nu}_e$ from n-rich fission products
- detection via inverse beta decay
- measure flux and energy spectrum

Chooz

8.5GW power
1 km baseline

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

5 ton target

~3000 events
335 days

No evidence for oscillation, absolute measurement with 1 detector
Oscillation Searches with Reactor Antineutrinos

- $\bar{\nu}_e$ from n-rich fission products
- detection via inverse beta decay
- measure flux and energy spectrum

Chooz

8.5GW power
1 km baseline

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

5 ton target

2008 MINOS result:
$|\Delta m_{23}^2| = 2.43 \pm 0.13 \times 10^{-3} \text{eV}^2$

No evidence for oscillation, absolute measurement with 1 detector
Measuring Reactor Antineutrinos with KamLAND

Japanese Reactors

Kashiwazaki
Takahama
Ohi

55 reactors

KamLAND

Reactor Antineutrinos

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

$\sim 200$ MeV per fission

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

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

reactor $\bar{\nu}$ flux at KamLAND

$\sim 6 \times 10^6$/cm$^2$/sec
KamLAND 2003: First Direct Evidence for Reactor $\bar{\nu}_e$ Disappearance

Reactor Neutrino Physics 1956-2003

- ILL
- Savannah River
- Bugey
- Rovno
- Goesgen
- Krasnoyarsk
- Palo Verde
- Chooz
- KamLAND

- Observed $\bar{\nu}_e$: 54 events
- No-Oscillation: $86.8 \pm 5.6$ events
- Background: $1 \pm 1$ events
- Livetime: 162.1 ton-yr

Mean, flux-weighted reactor distance $\sim 180$ km
KamLAND 2008: Precision Measurement of Oscillation

Prompt event energy spectrum for $\bar{\nu}_e$

- KamLAND data
- no oscillation
- best-fit osci.
- accidental
- $^{13}\text{C} (\alpha, n) ^{16}\text{O}$
- best-fit Geo $\bar{\nu}_e$
- best-fit osci. + BG
- + best-fit Geo $\bar{\nu}_e$

number of events
- expected: $2179 \pm 89$ (syst)
- observed: $1609$
- bkgd: $276 \pm 23.5$

significance of disappearance (with 2.6 MeV threshold): $8.5\sigma$
- no-osc $\chi^2$/ndf=63.9/17
- best-fit $\chi^2$/ndf=21/16 (18% C.L.)

systematic uncertainties:
- fiducial volume reduced from 4.7% $\rightarrow$ 1.8%
- total systematics: 4.1%

<table>
<thead>
<tr>
<th>$\Delta m^2_{21}$</th>
<th>Detector-related (%)</th>
<th>Reactor-related (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy scale</td>
<td>1.9</td>
<td>$\bar{\nu}_e$-spectra [7]</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td>1.8</td>
<td>$\bar{\nu}_e$-spectra</td>
</tr>
<tr>
<td>Energy threshold</td>
<td>1.5</td>
<td>Reactor power</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.6</td>
<td>Fuel composition</td>
</tr>
<tr>
<td>Cross section</td>
<td>0.2</td>
<td>Long-lived nuclei</td>
</tr>
</tbody>
</table>

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KamLAND 2008: Precision Measurement of Oscillation

L/E Dependence

- Data - BG - Geo $\bar{\nu}_e$
- Expectation based on osci. parameters determined by KamLAND

$\Delta m^2_{21}$ (eV$^2$)

$\tan^2 \theta_{12}$

$L_0=180 \text{ km}$


KamLAND+solar
(combined under assumption of CPT invariance)

$\tan^2 \Theta = 0.47 \pm 0.06$

$\Delta m^2 = 7.59 \pm 0.21 \times 10^{-5} \text{ eV}^2$
KamLAND and Solar Neutrino Fits

KamLAND and solar best fit values are not quite the same.

solar $\nu$ versus reactor $\overline{\nu}$

CPT-violation? Other new physics?

What do we know?
Neutrino Oscillation

Mixing Angles

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

\[
U_{\text{MNSP}} \text{ Matrix}
\]
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

$0\nu\beta\beta$

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Yale University, March 1, 2010
Neutrino Oscillation

Mixing Angles

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

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\begin{pmatrix}
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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}
\]

\[
\begin{align*}
\theta_{23} &= 45.0^{+4.0}_{-3.5} \\
\theta_{13} &< 7.2^{+2.0}_{-2.8} \\
\sin^2 \theta_{13} &< 0.056 \\
\theta_{12} &= 33.5^{+1.3}_{-1.0}
\end{align*}
\]

large, but not maximal! small!

maximal?

because of small \(\sin^2 2\theta_{13}\), solar & atmospheric \(\nu\) oscillations almost decouple
**Neutrino Oscillation**

**Mixing Angles**

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

**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**  **$0\nu\beta\beta$**

\[
\theta_{23} = 45.0^{+4.0}_{-3.5} \\
\theta_{13} < 7.2^{+2.0}_{-2.8} \\
\sin^2 \theta_{13} < 0.056 \\
\text{90\% C.L.}
\]

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

Mass Splitting

KamLAND provides most precise value of $\Delta m_{12}^2$ (~2.8%)
What we don’t know ...
Neutrino Particle Properties - Open Questions

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

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

- Is there $\mu$–$\tau$ symmetry in neutrino mixing?
- Is there leptonic CPV?
- Do neutrinos have Majorana mass?
- What is mass hierarchy?
- What is the absolute mass scale?
Neutrino Particle Properties - Open Questions

- Reactor experiment to measure $\theta_{13}$
- Search for $0\nu\beta\beta$

Questions:
- Is there $\mu-\tau$ symmetry in neutrino mixing?
- Is there leptonic CPV?
- Do neutrinos have Majorana mass?
- What is mass hierarchy?
- What is the absolute mass scale?
\( \theta_{13} \) from Global Fits

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

Current best limit
\( \sin^2 2\theta_{13} < 0.11 \) @90% CL

\( \sin^2 2\theta_{13} \sim 0.06-0.08? \)

Fogli, et al., arXiv:0905:3549

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Theoretical Predictions for $\theta_{13}$

\[ \sin^2 2\theta_{13} \approx 4 \sin^2 \theta_{13} \]

Albright et al.

arXiv:0911.2437

Parke, Mar 2009
Reactor and Accelerator Experiments

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

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

- disappearance experiment $\bar{\nu}_e \rightarrow \bar{\nu}_e$
- low-energy neutrinos (MeV)
- no matter effects, baseline $O(1 \text{ km})$

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

$$P(\nu_\mu \rightarrow \nu_e) = 4 c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31}$$

$$+ 8 c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin \Delta_{31} [\cos \Delta_{32} \cos \delta - \sin \Delta_{32} \sin \delta] \sin \Delta_{21}$$

$$- 8 c_{13}^2 s_{13}^2 s_{23}^2 s_{12} \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$$

$$+ 4 c_{13}^2 s_{12} [c_{12}^2 c_{23} + s_{12}^2 s_{23}^2 s_{13} - 2 c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta] \sin^2 \Delta_{21}$$

$$- 8 c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2) \frac{aL}{4E_\nu} \sin \Delta_{31} \left[ \cos \Delta_{32} - \frac{\sin \Delta_{31}}{\Delta_{31}} \right].$$

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

mass hierarchy
CP violation
matter
Precision Measurement of $\theta_{13}$ with Reactor Antineutrinos

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

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

Daya Bay Reactors:
Powerful $\bar{\nu}_e$ source, multiple cores
11.6 GW$_{th}$ now, 17.4 GW$_{th}$ in 2011

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

Large-amplitude oscillation due to $\theta_{12}$
Concept of Reactor $\theta_{13}$ Experiments

Measure ratio of interaction rates in multiple detectors

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

- Measured Ratio of Rates
- Detector Mass Ratio, H/C
- Detector Efficiency Ratio
- $\sin^2 2\theta_{13}$

$V_e$

Distance $L \sim 1.5 \text{ km}$
## Reactor $\theta_{13}$ Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Thermal Power (GW)</th>
<th>Distances Near/Far (m)</th>
<th>Depth Near/Far (mwe)</th>
<th>Target Mass (tons)</th>
<th>Start Date</th>
<th>Sensitivity @2.5x10^{-3} eV^2 90% CL, 3 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double-CHOZ (France)</td>
<td>8.6</td>
<td>410/1050</td>
<td>115/300</td>
<td>8.8/8.8</td>
<td>4/2010, 2011</td>
<td>0.032</td>
</tr>
<tr>
<td>RENO (So. Korea)</td>
<td>17.3</td>
<td>290/1380</td>
<td>120/450</td>
<td>16/16</td>
<td>9/2010</td>
<td>0.02</td>
</tr>
<tr>
<td>Daya Bay (China)</td>
<td>17.4</td>
<td>363(481) / 1985(1613)</td>
<td>260/910</td>
<td>40(×2) / 80</td>
<td>2011</td>
<td>0.008</td>
</tr>
</tbody>
</table>
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Yale University, March 1, 2010

Daya Bay, China
http://dayawane.ihep.ac.cn/

far detector
near detector
experimental hall

PMTs
RPCs
water pool
muon veto system

antineutrino detectors
multiple detectors per site
cross-check efficiency
Civil Construction Progress
Daya Bay Antineutrino Detectors

- 8 "identical", 3-zone detectors
- no position reconstruction, no fiducial cut

- target mass: 20t per detector
- detector mass: ~110t
- photosensors: 192 PMTs
- energy resolution: $12\%/\sqrt{E}$

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

Signal and Event Rates

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

- 0.3 b \[ + p \rightarrow D + \gamma \text{ (2.2 MeV)} \text{ (delayed)} \]
- 49,000 b \[ + \text{Gd} \rightarrow \text{Gd}^* \rightarrow \text{Gd} + \gamma's \text{ (8 MeV)} \text{ (delayed)} \]

Daya Bay near site \hspace{1cm} 840
Ling Ao near site \hspace{1cm} 760
Far site \hspace{1cm} 90

\textit{events/day per 20 ton module}

Prompt Energy Signal

<table>
<thead>
<tr>
<th>Energy</th>
<th>Events</th>
<th>Mean</th>
<th>RMS</th>
<th>Underflow</th>
<th>Overflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MeV</td>
<td>86485</td>
<td>3.576</td>
<td>1.462</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Delayed Energy Signal

<table>
<thead>
<tr>
<th>Energy</th>
<th>EnergyRecon</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 MeV</td>
<td></td>
<td>75959</td>
<td>7</td>
<td>2.22</td>
</tr>
<tr>
<td>10 MeV</td>
<td></td>
<td></td>
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</tbody>
</table>

Reconstructed Positron Energy Spectrum

Reconstructed neutron (delayed) capture energy spectrum
Systematic Uncertainties

Detector-Related Uncertainties

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Chooz (absolute)</th>
<th>Daya Bay (relative)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Baseline Goal Goal w/ Swapping</td>
</tr>
<tr>
<td># protons</td>
<td>0.8</td>
<td>0.3 0.1 0.006</td>
</tr>
<tr>
<td>Detector Energy cuts</td>
<td>0.8</td>
<td>0.2 0.1 0.1</td>
</tr>
<tr>
<td>Efficiency Position cuts</td>
<td>0.32</td>
<td>0.0 0.0 0.0</td>
</tr>
<tr>
<td>Time cuts</td>
<td>0.4</td>
<td>0.1 0.03 0.03</td>
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<tr>
<td>H/Gd ratio</td>
<td>1.0</td>
<td>0.1 0.1 0.0</td>
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<td>n multiplicity</td>
<td>0.5</td>
<td>0.05 0.05 0.05</td>
</tr>
<tr>
<td>Trigger</td>
<td>0</td>
<td>0.01 0.01 0.01</td>
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<tr>
<td>Live time</td>
<td>0</td>
<td>&lt;0.01 &lt;0.01 &lt;0.01</td>
</tr>
</tbody>
</table>
| Total detector-related uncertainty | 1.7% | 0.38% 0.18% 0.12% |}

\(O(0.2-0.3\%)\) precision for relative measurement between detectors at near and far sites

Ref: Daya Bay TDR
Antineutrino Detector Assembly
Antineutrino Detector Dry Run

one calibration system

one PMT ladder

Cosmic rays (Cerenkov in acrylic)

LED Flasher

Events/bin

charge [photon-electrons]
$\sin^2(2\theta_{13}) < 0.01$ @ 90% CL in 3 years of data taking

$\Delta m^2 = 2.5 \times 10^{-3} eV^2$

$\sin^2 2\theta_{13} < 0.01$ @ 90% CL in 3 years of data taking

Most sensitive reactor $\theta_{13}$ experiment under construction.

2010 start data taking with near site
2011 start data taking with full exp.
Search for $\theta_{13}$: A Possible Scenario

- Precision measurement at $\sin^2 2\theta_{13} < 0.01$ by Daya Bay

- First hint of $\theta_{13}$ by Double Chooz possible if $\theta_{13}$ large

- Early measurement of $\theta_{13}$ will help make decision on future long-baseline experiments

- Precision measurement of $\theta_{13}$ for unambiguous discovery and combined analysis with T2K and NOvA

Ref: Huber et al.
Neutrino Mass and Particle Nature

What is the absolute mass scale?
What is the mass hierarchy?

Are neutrinos their own antiparticles?

\[ \Delta m_{\text{atm}}^2 \rightarrow m_\nu > 0.045 \text{ eV} \]
Neutrinoless Double Beta Decay: $0\nu\beta\beta$

**2ν mode:** conventional 2nd order process in nuclear physics

\[
\Gamma_{2\nu} = G_{2\nu} |M_{2\nu}|^2
\]

G are phase space factors

**0ν mode:** hypothetical process only if $M_\nu \neq 0$ AND $\nu = \bar{\nu}$

\[
\Gamma_{0\nu} = G_{0\nu} |M_{0\nu}|^2 \left\langle m_{\beta\beta} \right\rangle^2
\]

$G_{0\nu} \sim Q^5$

**0νββ** would imply
- lepton number non-conservation
- Majorana nature of neutrinos

**0νββ** may allow us to determine
- effective neutrino mass
CUORE: Cryogenic Underground Observatory for Rare Events will be a tightly packed array of 988 bolometers with mass of ~ 200 kg of $^{130}$Te

- Operated at Gran Sasso laboratory
- Special cryostat built w/ selected materials
- Cryogen-free dilution refrigerator operated at ~ 10mK
- Shielded by several lead shields

19 Cuoricino-like towers with 13 planes of 4 crystals each
TeO$_2$ Bolometers

For $E = 1$ MeV: $\Delta T = E/C \approx 0.1$ mK

Signal size: 1 mV

Voltage signal $\propto$ energy deposited

Time constant: $\tau = C/G = 0.5$ s

Energy resolution: $\sim 5$-10 keV at 2.5 MeV
Search for $0\nu\beta\beta$ in $^{130}\text{Te}$

Experimental Signature of $0\nu\beta\beta$
- peak at the transition Q-value
- enlarged by detector resolution
- over unavoidable $2\nu\beta\beta$ background

$Q(^{130}\text{Te}) = 2530.3 \pm 2$ keV

Cuoricino summed spectrum energy = key event signature
single tower

44 5x5x5 cm³
and 18 3x3x6 cm³
TeO₂ crystals

detector mass: 40.7 kg

¹³⁰Te mass: 11 kg

operated at LNGS from 2005 to 2008

Updated CUORICINO Result
- Use new more accurate Q-value
- Updated statistics through Jan 2008
  (total exposure ~ 18 yr*kg ¹³⁰Te):

\[ T_{1/2} (90\% \text{ C.L.}) \geq 2.9 \times 10^{24} \text{ yr} \]
CUORE Detector Calibration System

Energy Calibration of 988 Bolometers

- **motion system:**
  - insertion and extraction of sources in and out of cryostat

- **guide tubes:**
  - no straight vertical access

- **source strings:**
  - move under own weight in guide tubes

- **source locations**

- **top view of detector array with source positions**

- **insertion of 12 γ sources that move under own weight**
Sensitivity to $<m_{\beta\beta}>$

- Solar: $5 \times 10^{-5}$ eV$^2$
- Atmospheric: $3 \times 10^{-3}$ eV$^2$

**Diagram:**
- 99% CL (1 dof)
- 76Ge-claim (best fit value)
- Normal
- Inverted
- Degenerate
- Excluded by CUORICINO at 90% C.L.
From Cuoricino to CUORE

Sensitivities

**Cuoricino** (2003-2008)
\[ <m_{\beta\beta} > < 350-720 \text{ meV} \ (90\% \ CL) \]

**CUORE-0** (2010-2012)
- single CUORE tower
- \[ <m_{\beta\beta} > < 170-350 \text{ meV} \ (1\sigma) \]

**CUORE** (2012 - ....)
- \[ <m_{\beta\beta} > < 47-87 \text{ meV} \ (1\sigma) \]

End of 2010    start of CUORE-0
End of 2012    start of CUORE
Advanced Bolometers
- active background rejection (surface sensitive detector or scintillating bolometers)
- enriched bolometric detectors
- other isotopes

**Surface sensitive bolometers**

**Other isotopes**
Tested bolometrically, as good as TeO$_2$
CaF$_2$, Ge, PbMoO$_4$, CdWO$_4$

**Isotopic enrichment of $^{130}$Te**
- up to 3x more sensitive
- no change to CUORE cryostat
Beyond CUORE - Future Opportunities

Next 10-15 years?

CUORE enriched
- bkg: $10^{-2}$ counts/keV/kg/yr
- 80% $^{130}$Te enrichment
- 5 year live time
- $<m_{\beta\beta}> < 27 - 57$ meV (1σ)

SuperCUORE w/ scintillating ZnSe
- bkg: $10^{-4}$ counts/keV/kg/yr
- 95% $^{82}$Se enrichment
- CUORE-size, 5 year live time
- $<m_{\beta\beta}> < 11 - 23$ meV (1σ)
## Future of Neutrino Mass Measurements

<table>
<thead>
<tr>
<th>Methods</th>
<th>Present Sensitivity</th>
<th>Future Sensitivity (next 10 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cosmology</strong></td>
<td>0.5-1 eV</td>
<td>0.05 eV</td>
</tr>
<tr>
<td>(model-dependent)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>0νββ</strong></td>
<td>0.5 eV</td>
<td>0.05 eV</td>
</tr>
<tr>
<td>(nuclear matrix element)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Weak Decay Kinematics</strong></td>
<td>2.2 eV</td>
<td>0.2 eV</td>
</tr>
<tr>
<td>(direct)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Workshop at INT Seattle, Feb 2010**

Summary and Conclusions

• Atmospheric, solar and reactor experiments were key to the discovery of neutrino mass and oscillation in the past decade (1998-2008).

• Reactor experiments are essential in probing neutrino mixing:
  - KamLAND discovered reactor $\nu_e$ oscillation, made a precise measurement of $\Delta m^2_{12}$.
  - Double-CHOOZ, RENO, and Daya Bay will make precision measurements of $\theta_{13}$ in 2010-14, with Daya Bay reaching $\sin^22\theta_{13} < 0.01$. The measurement of $\sin^22\theta_{13} > 0.01$ is a prerequisite for the search of leptonic CP violation.

• Search for $0\nu\beta\beta$ is the only method to establish the Majorana nature of neutrinos. If observed, we have discovered lepton number violation!

Acknowledgements

SNO, KamLAND, Daya Bay and CUORE collaborations
Neutrino Oscillation with 3ν

Atmospheric $\nu_\mu$ is lost ($>10\sigma$), converted mostly likely to $\nu_\tau$ ($>99\%$CL) (SK, MACRO)

Solar $\nu_e$ is converted to either $\nu_\mu$ or $\nu_\tau$ ($>5\sigma$) (SN)

- Solar & atmospheric $\nu$ oscillations easily accommodated within three generations
- $\sin^2 2\theta_{23}$ near maximal, $\Delta m^2_{\text{atm}} \sim 3 \times 10^{-3}\text{eV}^2$
- $\sin^2 2\theta_{12}$ large, $\Delta m^2_{\text{solar}} \sim 3\text{–}30 \times 10^{-5}\text{eV}^2$?
- $\sin^2 2\theta_{13} < 0.05$ from CHOOZ, Palo Verde
- Because of small $\sin^2 2\theta_{13}$, solar & atmospheric $\nu$ oscillations almost decouple
$\theta_{13}$ from Global Fits
Daya Bay Antineutrino Detectors

3-Zone Design
no position reconstruction, no fiducial cut for event identification

Gd-LS
(20 tons)

= 5m (tunnel limitations)

Oil buffer (MO) thickness
> 15cm buffer between PMT and OAV

Gamma catcher (LS) thickness
thickness = 42.3 cm
det. efficiency > 91.5%
Detector Top/Bottom Reflectors

specular reflectors consist of ESR® high reflectivity film on acrylic panels

reflector flattens detector response

<table>
<thead>
<tr>
<th>total pe</th>
<th>without reflector</th>
<th>with reflector</th>
</tr>
</thead>
<tbody>
<tr>
<td>z (cm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>250-200</td>
<td>150-100-50</td>
<td>200-150-100</td>
</tr>
<tr>
<td>150-100</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>100-50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Karsten Heeger, Univ. of Wisconsin
Yale University, March 1, 2010
**Antineutrino Detector Response**

**Detector Uniformity**

- **along radial R direction**
  - Gd-LS boundary
  - GEANT4-based simulations
  - idealized 3-zone detector plus reflectors
  - developing realistic geometry in simulations

- **along vertical symmetry axis (z-direction)**
  - Gd-LS boundary
  - GEANT4-based simulations
  - idealized 3-zone detector plus reflectors
  - developing realistic geometry in simulations

- **Entries**
  - 23784
  - Mean 1.985
  - Median 121.2
  - 11294
  - Mean .001
  - Median 10.7
Detector Calibration

- Automated calibration system
  → Routine weekly deployment of sources

- LED light sources
  → Monitoring optical properties

- $e^+$ and $n$ radioactive sources (=fixed energy)
  → Energy calibration

- $^{68}$Ge source
- Am-C + $^{60}$Co source
- LED diffuser ball

Tagged cosmogenic background (free)
→ Fixed energy and time

$\sigma/E = 0.5\%$ per pixel requires:
1 day (near), 10 days (far)
Energy Calibration and Efficiencies

Prompt Energy Signal

Reconstructed Positron Energy Spectrum

<table>
<thead>
<tr>
<th>Energy</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
<th>Underflow</th>
<th>Overflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MeV</td>
<td>88485</td>
<td>3.576</td>
<td>1.482</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8 MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6 MeV cut for prompt positrons: >99%, uncertainty negligible

Delayed Energy Signal

νe + p → e+ + n

Reconstructed neutron (delayed) capture energy spectrum

<table>
<thead>
<tr>
<th>EnergyRecon</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
<th>Underflow</th>
<th>Overflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 MeV</td>
<td>75959</td>
<td>7</td>
<td>2.22</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>10 MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6 MeV threshold: n capture signals at 8 and 2.2 MeV (n source, spallation)

6 MeV cut for delayed neutrons: 91.5%, uncertainty 0.22% assuming 1% energy uncertainty

e+ threshold: stopped positron signal using 68Ge source (2x0.511 MeV)
e+ energy scale: 2.2 MeV neutron capture signal (n source, spallation)
**Muon Veto System**

**RPCs:** muon detect efficiency 98.6% and ~0.5m spatial resolution.

**Two-layer water pool:** 962 PMTs, >2.5m water shield for neutron background, ~0.5m spatial resolution.

Daya Bay veto system provides a combined muon detection efficiency > 99.5%.
Daya Bay Background Summary

<table>
<thead>
<tr>
<th></th>
<th>DYB site</th>
<th>LA site</th>
<th>far site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antineutrino rate (/day/module)</td>
<td>840</td>
<td>760</td>
<td>90</td>
</tr>
<tr>
<td>Natural radiation (Hz)</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;50</td>
</tr>
<tr>
<td>Single neutron (/day/module)</td>
<td>18</td>
<td>12</td>
<td>1.5</td>
</tr>
<tr>
<td>$\beta$-emission isotopes (/day/module)</td>
<td>210</td>
<td>141</td>
<td>14.6</td>
</tr>
<tr>
<td>Accidental/Signal</td>
<td>&lt;0.2%</td>
<td>&lt;0.2%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Fast neutron/Signal</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>$^8\text{He}^9\text{Li}/Signal$</td>
<td>0.3%</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

 backgrounds from beta-delayed neutron emission isotopes $^8\text{He}$ and $^9\text{Li}$ will have to be measured and subtracted

Karsten Heeger, Univ. of
Antineutrino Detector Event Distributions

Geant4-based simulations

\( R^2 \) distribution of neutron production point

Gd-LS

spill out

LS

\( R^2 \) distribution of neutron capture position

\( \sim 12\% / E^{1/2} \)

reconstructed energy resolution

\( \chi^2/\text{ndf} \)

335.0 / 7

P1 11.77

Energy (MeV)
Detection Efficiencies

Prompt $e^+$ Signal

1 MeV cut for prompt positrons: >99%, uncertainty negligible

Delayed $n$ Signal

6 MeV cut for delayed neutrons: 91.5%, uncertainty 0.22% assuming 1% energy uncertainty

Geant4-based simulations
Detector Filling & Target Mass Measurement

- 200-ton Gd-LS reservoir
- ISO Gd-LS weighing tank
- Pump stations
- Filling platform with clean room
- Detector
- Load cell accuracy < 0.02%
- Coriolis mass flowmeters < 0.1%
- 20-ton ISO tank
- Pump stations
- Filling "pairs" of detectors
- LS Gd-LS MO
Daya Bay experiment uses 185 ton 0.1% gadolinium-loaded liquid scintillator (Gd-LS). Gd-TMHA + LAB + 3g/L PPO + 15mg/L bis-MSB

Gd-LS will be produced in multiple batches but mixed in reservoir on-site, to ensure identical detectors.

4-ton test batch production in March 2009.

Gd-LS stability in 4-ton test
Gd-Liquid Scintillator - 185t Production

GdCl₃ + TMHA

Gd-TMHA

- chemical purification and precision control
- A 4-t batch per day; 5 days per week

0.5% Gd-LAB mix

1. sit 24 hrs to drain the aqueous phase
2. add LAB for dissolution

LAB+PPO (30g/L)+ bis-MSB (150mg/L), 0.4t

0.1% Gd-LS, 4t

1. transfer to clearance tank via filtration to sit 72 hrs for clearance
2. drain the residual water

LAB, 2.8t

0.5% Gd-LAB clear, 0.8t

QC

filtration/QC

QC/QA

40-t Storage Tank

A 4-t batch per day; 5 days per week
Neutrino Mass and Particle Nature

Search for $0
\nu\beta\beta$  Do neutrinos have Majorana mass?

What is mass hierarchy?

What is the absolute mass scale?

$\Delta m^2_{\text{atm}} \quad m_\nu > 0.045$ eV
Mixing with 3+? neutrinos?

example: θ_{13} and θ_{14} driven oscillation

see also Double Chooz talks in session H12
Atmospheric Neutrino Oscillations

MINOS Collaboration
PRL, 221804 (2008)

Figure 2. Determination of the leading "atmospheric" oscillation parameters from the interplay of data from artificial and natural neutrino sources. We show χ²-profiles and allowed regions at 90% and 99.73% CL (2 dof) for atmospheric and MINOS, as well as the 99.73% CL region for the combined analysis (including also K2K). The dot, star and diamond indicate the best fit points of atmospheric data, MINOS and global data, respectively. We minimise with respect to ∆m²_{21}, θ_{12} and θ_{13}, including always solar, KamLAND, and CHOOZ data.

Exposure used in the latest version of Ref. [8] by about 34%. The latest data confirm the energy dependent disappearance of ν_µ, showing significantly less events than expected in the case of no oscillations in the energy range ≲ 6 GeV, whereas the high energy part of the spectrum is consistent with the no oscillation expectation. We include this result in our analysis by fitting the event spectrum given in Fig. 2 of Ref. [9]. Current MINOS data largely supersedes the pioneering K2K measurement [27] which by now gives only a very minor contribution to the ∆m²_{31} measurement.

We combine the long-baseline accelerator data with atmospheric neutrino measurements from Super-Kamiokande [28], using the results of Ref. [8], see references therein for details. In this analysis sub-leading effects of ∆m²_{21} in atmospheric data are neglected, but effects of θ_{13} are included, in a similar spirit as in Ref. [29].
Oscillation Interpretation of Solar Neutrino Data

→ observe vacuum-matter transition as evidence for matter-enhanced MSW oscillations
Solar Neutrino Measurements with Borexino

Detection of $^7$Be Solar Neutrinos

- $^7$Be solar neutrinos expected

Borexino collaboration arXive: 0708.2251, 0808.2868

0.862 MeV $^7$Be solar neutrinos

observed $47 \pm 7_{\text{stat}} \pm 12_{\text{syst}}$ cts/(day-100ton)
expected $49 \pm 4$
no-oscillation $75 \pm 4$
Oscillation Interpretation of Solar Neutrino Data

vacuum-matter transition in solar neutrino oscillation

with present errors Borexino plays no significant role in the determination of neutrino oscillation parameters

the observed value for \( P_{ee} \) coincides with the prediction at the best-fit point

Escrihuele et al. arXiv: 0907.2630
Borexino arXiv: 0808.2868

\[
\frac{P_{7Be}}{P_{8B}} = 1.60 \pm 0.33
\]
CUORE Sensitivity

If Klapdor is right...
\[ m_\nu \sim 0.45 \text{ eV} \]

If no signal,
\[ 1\sigma \text{ limit: } T^{1/2} = 2 \times 10^{26} \text{ y} \]

Assumptions
- Klapdor \( <m> \) & matrix element for Te-130
- \( T^{1/2} = 2.5 \times 10^{24} \text{ y} \) (this is the current Cuoricino limit)
- Background: 0.01 c/keV/kg/year, resolution: 5 keV FWHM, 5 years of running
- Conservative scaling of \( ^{60}\text{Co} \) and \( ^{208}\text{Tl} \) peaks
### Sensitivity of Future Bolometric Experiments

#### Sensitivities at 1\(\sigma\) after 5 years of livetime

<table>
<thead>
<tr>
<th>Configuration</th>
<th>bkg ([c/keV/kg/y])</th>
<th>(T_{1/2}) (1\sigma) sens ([10^{26} \text{ y}])</th>
<th>(m_\nu) (1\sigma) sens ([\text{meV}])</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Result</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cuoricino</td>
<td>0.18</td>
<td>0.029 (90%CL)</td>
<td>350-720 (90%CL)</td>
</tr>
<tr>
<td><strong>Construction</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cuoricino + CUORE-0</td>
<td>0.06</td>
<td>0.12* (90%CL)</td>
<td>170-350* (90%CL)</td>
</tr>
<tr>
<td>CUORE baseline</td>
<td>0.01</td>
<td>2.0</td>
<td>42-87</td>
</tr>
<tr>
<td><strong>R&amp;D</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LUCIFER (ZnSe 95% enrich)</td>
<td>0.001</td>
<td>2.7</td>
<td>42-89</td>
</tr>
<tr>
<td>CUORE 80% enriched</td>
<td>0.01</td>
<td>4.7</td>
<td>27-57</td>
</tr>
<tr>
<td>CUORE enriched w/ TeO(_2) SSB</td>
<td>0.001</td>
<td>14</td>
<td>16-33</td>
</tr>
<tr>
<td>CdWO(_4) enriched 1000crystals</td>
<td>0.001</td>
<td>8</td>
<td>21-29</td>
</tr>
<tr>
<td>ZnSe enriched 1000crystals</td>
<td>1e-4</td>
<td>41</td>
<td>11-23</td>
</tr>
</tbody>
</table>

EXO 1 ton w/ Ba\(^+\) tagging: \(<m_{\bar{\nu}p}> < 12 - 25\ \text{meV} \ (1\sigma)\)

Majorana/GERDA 1-ton: \(<m_{\bar{\nu}p}> < 15 - 38\ \text{meV} \ (1\sigma)\)

* after 2 years live time

Summary and Conclusions

• In the next 5-10 years low-energy ν experiments may provide key insight into the nature of neutrino mass and mixing.

• Reactor experiments (e.g. Daya Bay) will determine the future of long-baseline ν oscillation experiments. The measurement of $\sin^2 2\theta_{13} > 0.01$ is a prerequisite for the search of leptonic CPV.

• Search for $0\nu\beta\beta$ is the only method to establish the Majorana nature of neutrinos. If observed, we know the mass hierarchy and can infer the mass scale.

Acknowledgements

SNO, KamLAND, Daya Bay and CUORE collaborations
The Open Questions

• Are ν’s Dirac or Majorana particles?
• What are the absolute ν masses?
• What is the ordering of ν mass states?
• Is there CP violation for neutrinos?

Non-accelerator experiments were key in discovering neutrino mass and oscillations in the past decade (1998-2008)

A Strategy for the Next Decade

• ν mass, scale, hierarchy: towards a ton-scale detector for the determination of the fundamental nature and mass of neutrinos (→ CUORE, Majorana)
• direct ν mass: R&D on bolometer, tritium trapping,... (→ MARE)
• CP, ν mass hierarchy: a megaton-scale detector for the search for proton decay, for neutrino astrophysics, and for the investigation of neutrino properties (→ DUSEL LBL)

stay tuned ....