Neutrino Oscillations and Interactions

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University of Wisconsin

NSAC workshop, August 10, 2012
Neutrino Discoveries - A Success Story

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

2012 Daya Bay, RENO, DC measure $\theta_{13}$
Accelerator Neutrino Oscillation Studies

- precision measurements
- indications of $\nu_e$ appearance
- anomalies
... + much more
Neutrino Oscillation

Neutrino flavor change occurs if neutrinos have mass and leptons mix.

\[ |\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle \]

Mixing matrix

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

Mass eigenstates

Experiments study flavor conversion as a function of energy, distance and determine mixing angle and mass splitting.

2-neutrino case, vacuum

\[ P_{i\rightarrow i} = \sin^2 2\theta \sin^2 \left( 1.27 \Delta m^2 \frac{L}{E} \right) \]
From Anomalies to Precision Oscillation Physics

solar neutrino problem

oscillation searches

precision measurements

http://hitoshi.berkeley.edu/neutrino
From 2-v to 3-v Oscillation Picture

atmospheric/beam neutrinos

\( \theta_{23}, \Delta m^2_{23} \)

solar/reactor neutrinos

\( \theta_{12}, \Delta m^2_{12} \)

\[ |\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \]

3-flavor picture needed

http://hitoshi.berkeley.edu/neutrino
Neutrino Observations

By 2012 we now have a suite of data ....

- atmospheric $\nu_\mu$ and $\bar{\nu}_\mu$ disappear most likely to $\nu_\tau$ (SK, MINOS)
- accelerator $\nu_\mu$ and $\bar{\nu}_\mu$ disappear at $L \sim 250, 700$ km (K2K, T2K, MINOS)
- some accelerator $\nu_\mu$ appear as $\nu_\mu$ at $L \sim 250, 700$ km (T2K, MINOS)
- solar $\nu_e$ convert to $\nu_\mu/\nu_\tau$ (Cl, Ga, SK, SNO, Borexino)
- reactor $\bar{\nu}_e$ disappear at $L \sim 200$ km (KamLAND)
- reactor $\nu_e$ disappear at $L \sim 1$ km (DC, Daya Bay RENO)

Vacuum oscillation L/E pattern

![Graphs showing data and predictions for neutrino oscillations](image-url)
Neutrino Observations

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MSW conversion in Sun

![Graph showing MSW conversion in Sun]
Neutrino Observations

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Determining Oscillation Parameters

<table>
<thead>
<tr>
<th>Solar Experiments</th>
<th>Reactor LBL (KamLAND)</th>
<th>Reactor MBL (Daya-Bay, Reno, D-Chooz)</th>
<th>Atmospheric Experiments</th>
<th>Accelerator LBL $\nu_\mu$ Disapp (Minos)</th>
<th>Accelerator LBL $\nu_e$ App (Minos, T2K)</th>
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<tbody>
<tr>
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<td></td>
<td>$\to \theta_{12}$</td>
<td>$\to \theta_{23}$</td>
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<td>$\to \Delta m^2_{21}$</td>
<td>$\to \Delta m^2_{atm}$</td>
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<td>$\theta_{13}$</td>
<td>$\theta_{13}, \theta_{23}$</td>
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<td>$\Delta m^2_{atm}, \theta_{13}, \delta_{cp}$</td>
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<td>$\theta_{13}, \theta_{23}$</td>
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</tbody>
</table>

Gonzalez-Garcia et al, ICHEP2012
Neutrino Oscillation

Mixing Angles & Mass Splittings

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

Maki, Nakagawa, Sakata, Pontecorvo

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

\[
\left| \nu_\alpha \right\rangle = \sum_i U_{\alpha i}^* \left| \nu_i \right\rangle
\]

\[ \theta_{23} = 40.4^\circ \pm 0.8^\circ \]

\[ \theta_{13} = 8.7^\circ \pm 0.45^\circ \]

\[ \theta_{12} = 32.4^\circ \pm 0.8^\circ \]

maximal?

not so small

large, but not maximal!

All three neutrino mixing angles are now known!
Neutrino Oscillation

Mixing Angles & Mass Splittings

\[ U_{\text{MNSP}} \text{ Matrix} \]
\[ \text{Maki, Nakagawa, Sakata, Pontecorvo} \]
\[ U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{r1} & U_{r2} & U_{r3} \end{pmatrix} \]
\[ |\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \]

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

\[ |U|_{\text{LEP}(3\sigma)} = \begin{pmatrix}
0.795 & 0.841 & 0.517 & 0.584 & 0.141 & 0.179 \\
0.213 & 0.543 & 0.425 & 0.728 & 0.575 & 0.802 \\
0.213 & 0.541 & 0.411 & 0.720 & 0.576 & 0.802
\end{pmatrix} \]
Neutrino Oscillation

Mixing Angles & Mass Splittings

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}$$

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

- (1 0 0)
- (0 cos θ_{23} sin θ_{23})
- (0 -sin θ_{23} cos θ_{23})

Cl

atmospheric, K2K

reactor and accelerator

SNO, solar SK, KamLAND

$0\nu\beta\beta$

Gonzalez-Garcia et al, ICHEP2012

Global (with ATM)

Cl

sin^2 θ_{13}

tan^2 θ_{23}

Δm^2_{atm} [10^{-3} eV^2]

Δm^2_{sol} [10^{-5} eV^2]
Neutrino Oscillation

Mixing Angles & Mass Splittings

\[ U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \]

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

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

Gonzalez-Garcia et al, ICHEP2012

Karsten Heeger, Univ. of Wisconsin  
NSAC workshop, August 10, 2012
Neutrino Oscillation

Mass Splittings

KamLAND has measured $\Delta m_{12}^2$ to $\sim 2.8\%$

MINOS Nu2012

KamLAND, PRL 100, 221803 (2008)
Neutrino Oscillation

Mass Splittings

\[ \Delta m_{21}^2 = 7.5 \pm 0.19 \ (\pm 0.59) \times 10^{-5} \text{ eV}^2 \]
\[ \Delta m_{31}^2 (N) = 2.45^{+0.067}_{-0.071} \ (\pm 0.22) \times 10^{-3} \text{ eV}^2 \]
\[ |\Delta m_{32}^2| (I) = 2.43 \pm 0.068 \ (\pm 0.22) \times 10^{-3} \text{ eV}^2 \]
Neutrino Oscillation

3-ν Global Analyses in 2012

preference for $\theta_{23}$ in first octant, difficult to say much about hierarchy
most interesting question for global analyses: $\theta_{23}$ octant and $\delta_{CP}$

$1\sigma$ preference for $\theta \sim \pi$

enhances interference oscillation terms and gives extra electron appearance for atmospheric events $O(\text{GeV})$, part of SK electron excess

Ref: Fogli et al 1205.5254 and Nu2012
Neutrino Anomalies

Anomalies in 3-ν interpretation of global neutrino oscillation data

- LSND ($\bar{\nu}_e$ appearance)
- MiniBoone ($\bar{\nu}_e$ appearance)
- Ga anomaly
- $N_{\text{eff}}$ in cosmology
- Short-baseline reactor anomaly ($\bar{\nu}_e$ disappearance)

If new oscillation signal, requires $\Delta m^2 \sim O(1\text{eV}^2)$ and $\sin^2 2\theta > 10^{-3}$

Systematics or experimental effects?

→ Need to test each experimental effect
Beyond 3ν - Sterile Neutrinos?

Anomalies

Are $\nu_e \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_e$ consistent?

strong tension if all three are combined, tension also in 3+2 fit
Neutrino Mass

Mass Measurements

Masses of Neutrinos, Leptons, Quarks

neutrinos

d
s
b
u

charged leptons

e
μ
τ

quarks

energy/mass

Fig: Wilkerson, Nu2012

Fig: Murayama
Neutrino Mass and Mixing

Fig: NRC NP2010, Robertson
Neutrinos - Open Questions

The Origin of Mass
- Why are neutrinos so light?
- Do neutrinos have Majorana mass?
- What is the absolute mass scale?
- Normal or inverted mass ordering?
- Are there more than 3 $\nu$?

The Flavor Puzzle
- Why is lepton mixing so different from quarks?
- CP violation?
- $\theta_{23}$ octant?
Neutrino Sources and Energies

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

**Antineutrinos from nuclear reactors**  $< 10.0$ MeV

**Atmospheric neutrinos**  $\sim$ GeV

**Neutrinos from accelerators**  up to GeV ($10^9$ eV)
**Neutrino Sources, Flavors, Environment**

**Solar Neutrinos**
- Pure $\nu_e$
- Matter effects, large distances

\[
p + p \rightarrow ^2\text{H} + e^+ + \nu_e \\
p + e^- + p \rightarrow ^2\text{H} + \nu_e  \\
^2\text{H} + p \rightarrow ^3\text{He} + \gamma \\
^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p \\
^3\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu_1 \\
^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \\
^7\text{Be} + e^- \rightarrow ^7\text{Li} + \gamma + \nu_e \\
^7\text{Li} + p \rightarrow \alpha + \alpha \\
^7\text{Be} + p \rightarrow ^8\text{B} + \gamma \\
^8\text{B} \rightarrow ^8\text{Be}^* + e^+ + \nu_e
\]

**Reactor Neutrinos**
- Pure $\bar{\nu}_e$
- A vacuum environment

**Nuclear $\beta$-decays**
- Pure $\bar{\nu}_e$
- Nucleus as a laboratory

**Supernova Neutrinos**
- $\nu_e, \bar{\nu}_e, \nu_x$ (all species)
- Extreme densities
Neutrino Sources, Flavors, Environment

Atmospheric Neutrinos
\( \nu_\mu, \bar{\nu}_\mu, \nu_e \)
long baselines, Earth effects

Accelerator Neutrinos
\( \nu_\mu \) (with some \( \nu_e \) contamination)
long baselines, Earth effects

**Cosmic Ray**

- Air nucleus
- \( \pi^+ \)
- Pions
- Electron
- \( \nu_\mu \), \( \bar{\nu}_\mu \), \( \nu_e \)
- 2 muon neutrinos
- 1 electron neutrino

**Neutrino Factory**

- Proton Driver
- Accelerator
- Target
- Front End
- Acceleration
- \( \mu \) Storage Ring
-Muon Collider

**Miniboone Collaboration**

**Muon Collider**

- Proton Driver
- Accelerator
- Decay Cherenkov
- Phase Rotator
- Acceleration
- Collider Ring

**High Energy Physics**
Oscillation Experiments

reactor ($\bar{\nu}_e$ disappearance)

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

- disappearance experiment $\nu_e \rightarrow \bar{\nu}_e$
- rate deviations from $1/r^2$ and spectral distortions
- baseline $O(1 \text{ km})$, no matter effects

accelerator ($\nu_e$ appearance)

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

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

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

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

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

- appearance experiment $\nu_\mu \rightarrow \nu_e$
- baseline $O(100 -1000 \text{ km})$, matter effects present

complementary approaches to understand all aspects of $\nu$ oscillation
Beta Decay Spectra

Precision Studies of the Energy Spectrum

\[ \frac{dN}{dT} = \frac{G_F \cos \theta_C}{2\pi^3} |M_{\text{nuc}}|^2 F(Z, T)(T + m)(T^2 + 2mT)^{1/2}(T_0 - T) \sum_{i} |U_{ei}|^2 [(T_0 - T)^2 - m_i^2]^{1/2} \]

For \( m_1 \gtrsim 100 \text{ eV} \) and no sterile neutrinos, the beta spectrum simplifies to an “effective mass”

\[ m_\beta = \left[ \sum_{i} |U_{ei}|^2 m_i^2 \right]^{1/2} \]
Neutrinoless Double Beta Decay: $0\nu\beta\beta$

2ν mode: conventional 2\textsuperscript{nd} 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 $M_\nu \neq 0 \text{ AND } \nu = \bar{\nu}$

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

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

$0\nu\beta\beta$ would imply
- lepton number non-conservation
- Majorana nature of neutrinos

$0\nu\beta\beta$ may allow us to determine
- effective neutrino mass
Neutrinos in Astrophysics: Supernovae

neutrinos from SN 1987A confirmed the basic SN model, 99% of energy emitted in neutrinos over 10s of sec but what mechanism mediates explosion?

various kinds of oscillations: vacuum, MSW, collective (non-linear, v-v scattering) in high v density

\[
\begin{align*}
e^- p & \leftrightarrow \nu_e n \\
e^+ n & \leftrightarrow \bar{\nu}_e p \\
e^- e^+ & \leftrightarrow \nu_i \bar{\nu}_i \\
N N & \leftrightarrow \nu_i \bar{\nu}_i \\
\tilde{\gamma} & \leftrightarrow \nu_i \bar{\nu}_i
\end{align*}
\]
What have we accomplished since 2007?

What’s next?
Observation of Reactor $\bar{\nu}$ Oscillation with KamLAND

Reactors in Japan

Kamioka

KamLAND

55 reactors

mean, flux-weighted reactor distance ~ 180km

1kt liquid scintillator detector
Observation of Reactor $\bar{\nu}$ Oscillation with KamLAND

Calibrating fiducial volume for reduced systematics in target mass

<table>
<thead>
<tr>
<th>$\Delta m_{21}^2$</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>Event rate</td>
<td></td>
<td>Reactor power</td>
</tr>
<tr>
<td>Energy threshold</td>
<td>1.5</td>
<td>Fuel composition</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.6</td>
<td>Long-lived nuclei</td>
</tr>
<tr>
<td>Cross section</td>
<td>0.2</td>
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</tr>
</tbody>
</table>

fiducial volume and reactor flux important for precision reactor experiments
Observation of Reactor $\bar{\nu}$ Oscillation with KamLAND

Reactor Antineutrino Spectrum

KamLAND has measured $\Delta m_{12}^2$ to $\sim$2.8%

Direct Evidence for Oscillation

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

KamLAND, Phys.Rev. D83 (2011) 052002

\[ L_0 = 180\text{km} \]
Oscillation Experiments with Reactors

Measure (non)-1/r² behavior of $\overline{\nu}_e$ interaction rate

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

$L/E \rightarrow \Delta m^2$

amplitude of oscillation $\rightarrow \theta$

for 3 active $\nu$, two different oscillation length scales: $\Delta m_{12}^2, \Delta m_{23}^2$

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

$\Delta m_{23}^2 \sim 2.4 \times 10^{-3} \text{ eV}^2$

$\Delta m_{23}^2 \approx \Delta m_{13}^2$
Measuring $\theta_{13}$ with Reactor Experiments

**Near-Far Concept**

- **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)

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

- far/near $\overline{v}_e$ ratio
- target mass
- distances
- efficiency
- oscillation deficit
Karsten Heeger, Univ. of Wisconsin

**Daya Bay**

- 6 reactor cores
- 3 experimental halls
- 6 detectors (2 still under construction)
Daya Bay Reactor Antineutrino Studies

Observation of Electron Antineutrino Disappearance over 1-2km

<table>
<thead>
<tr>
<th>Weighted Baseline [km]</th>
<th>Expected</th>
<th>Detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.9</td>
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<td>0.2</td>
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<td>1.1</td>
</tr>
<tr>
<td>2.0</td>
<td>1.0</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Far vs. near relative measurement

\( \sin^2 \theta_{13} = 0.089 \pm 0.010 \text{ (stat)} \pm 0.005 \text{ (syst)} \)

Most precise measurement of \( \sin^2 \theta_{13} \) to date.

Precision Reactor Spectrum

> 200,000 events at near site

Ref: Daya Bay, Nu2012
Other Reactor $\theta_{13}$ Experiments

Double Chooz

![Double Chooz Experiment Graph]

- Preliminary

Rate only: $\sin^2 2\theta_{13} = 0.170 \pm 0.035 \text{(stat)} \pm 0.040 \text{(syst)}$

Rate+Shape: $\sin^2 2\theta_{13} = 0.109 \pm 0.030 \text{(stat)} \pm 0.025 \text{(syst)}$

Ref: Ishitsuka, Neutrino2012

RENO

![RENO Experiment Graph]

$\sin^2 2\theta_{13} = 0.113 \pm 0.013 \text{(stat)} \pm 0.019 \text{(syst)}$

PRL, 108 (2012) 191802
Reactor Flux Predictions

Reactor Anomaly: Beyond 3ν?

2011νₑ flux predictions
- new reactor antineutrino spectra
- re-analysis of 19 short-baseline reactor results
- neutron lifetime correction, off-equilibrium effects

Adapted from Schwetz Neutrino2012

Average = 0.943 ± 0.023 (χ²=19.6/19)

net 3% upward shift in energy averaged fluxes

deficit from flux normalization problem or from additional oscillation at L~O(1-10m)?

nuclear physics or new physics?
neutron and near-surface backgrounds are key issues
Solar Neutrino Measurements

Detection of pep neutrinos

- pep rate for 100 t target: $3.1 \pm 0.6 \text{(stat)} \pm 0.3 \text{(sys)} \text{ cpd}$

Measurement of $^7$Be Flux

- $^7$Be rate for 100 t target: $46.0 \pm 1.5 \text{ (stat)} \pm 1.5 \text{ (sys)} \text{ cpd}$

Limit on CNO rate

$< 7.1 \text{ cpd}/100 \text{ t}$

8B Flux (SNO LETA + combined)

3.5MeV thresholds achieved in SNO & SK first direct extraction of $\nu_e$ survival probability
Probing vacuum/matter transition

Near future (2012-2015)

- Improve $^7\text{Be}$, $^8\text{B}$ → test of MSW
- Confirm pep at >$3\sigma$ and reduce error
- Improve upper limit on CNO → probe metallicity
- Attempt direct pp measurement
Recent Results in the Search for $0\nu\beta\beta$

2$\nu\beta\beta$ Measurements

\[ T_{2\nu \frac{1}{2}} = 2.23 \pm 0.017 \text{(stat)} \pm 0.22 \text{(sys)} \times 10^{21} \text{ y} \]
\[ \langle m_{\beta\beta} \rangle < 140–380 \text{ meV (90\% C.L.)} \]

see Piepke’s talk

KamLAND, 2011

\[ T_{2\nu \frac{1}{2}} = 2.38 \pm 0.02 \text{(stat)} \pm 0.14 \text{(syst)} \times 10^{21} \text{ years} \]
Recent Results in the Search for $0\nu\beta\beta$

Limits on $0\nu\beta\beta$

Cuoricino, 2010

$T_{0\nu1/2} > 2.8 \times 10^{24}$ y at 90% C.L.

$m_{\beta\beta} < 0.3 – 0.7$ eV

$T_{0\nu1/2} > 1.6 \times 10^{25}$ y

$\langle m_{\beta\beta} \rangle < 140–380$ meV (90% C.L.)
Preparations for the Next $0\nu\beta\beta$ Search

Majorana Demonstrator

Three Phases

- Prototype cryostat (2 strings, $^{nat}\text{Ge}$) **(End 2012)**
  
  1st order of $^{enr}\text{Ge}$ (20 kg) on hand. 2nd order in process. Refinement/processing facility in Oak Ridge (via NSF) has completed testing with $^{nat}\text{Ge}$.

- Cryostat 1 (3 strings $^{enr}\text{Ge}$ & 4 strings $^{nat}\text{Ge}$) **(Fall 2013)**

- Cryostat 2 (up to 7 strings $^{enr}\text{Ge}$) **(Fall 2014)**

SNO+

dissolve $^{nat}\text{Nd}$ salt in liquid scintillator

CUORE-0/CUORE

CUORE-0 is being cooled down
CUORE under construction

see Poon’s talk

see Klein’s talk

see Kolomensky’s talk
Theoretical Progress

Nuclear Matrix Elements for $0\nu\beta\beta$

$$\left[ T_{1/2}^{0\nu\beta\beta} (0^+ \rightarrow 0^+) \right]^{-1} = G_{0\nu} \left| M_{0\nu} \right|^2 \left| f_b (m_e U_{ei}) \right|^2$$

Beyond the standard model
(Particle physics)

Phase-space factor
(Atomic physics)

Matrix elements
(Nuclear physics)

Using the values of $g_{A,\text{eff}}$ extracted from $2\nu\beta\beta$ one can make “absolute” predictions for $0\nu\beta\beta$ life-times.

<table>
<thead>
<tr>
<th>Decay</th>
<th>IBM-2 rem.</th>
<th>ISM rem.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{28}\text{Ca} \rightarrow ^{28}\text{Ti}$</td>
<td>22.887</td>
<td>89.243</td>
</tr>
<tr>
<td>$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$</td>
<td>46.416</td>
<td>69.1217</td>
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<tr>
<td>$^{85}\text{Se} \rightarrow ^{85}\text{Kr}$</td>
<td>17.627</td>
<td>18.4572</td>
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<tr>
<td>$^{96}\text{Zr} \rightarrow ^{96}\text{Mo}$</td>
<td>29.546</td>
<td>18.4572</td>
</tr>
<tr>
<td>$^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$</td>
<td>18.137</td>
<td>18.4572</td>
</tr>
<tr>
<td>$^{118}\text{Pd} \rightarrow ^{118}\text{Cd}$</td>
<td>68.640</td>
<td>18.4572</td>
</tr>
<tr>
<td>$^{116}\text{Cd} \rightarrow ^{116}\text{Sn}$</td>
<td>35.050</td>
<td>18.4572</td>
</tr>
<tr>
<td>$^{124}\text{Sn} \rightarrow ^{124}\text{Te}$</td>
<td>42.922</td>
<td>27.003</td>
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<tr>
<td>$^{128}\text{Te} \rightarrow ^{128}\text{Xe}$</td>
<td>413.792</td>
<td>344.356</td>
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<tr>
<td>$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$</td>
<td>21.445</td>
<td>17.601</td>
</tr>
<tr>
<td>$^{132}\text{Xe} \rightarrow ^{132}\text{Ba}$</td>
<td>31.785</td>
<td>25.260</td>
</tr>
<tr>
<td>$^{140}\text{Nd} \rightarrow ^{140}\text{Sm}$</td>
<td>145.971</td>
<td>25.260</td>
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<tr>
<td>$^{150}\text{Nd} \rightarrow ^{150}\text{Sm}$</td>
<td>16.400</td>
<td>25.260</td>
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<tr>
<td>$^{154}\text{Sm} \rightarrow ^{154}\text{Gd}$</td>
<td>300.019</td>
<td>25.260</td>
</tr>
<tr>
<td>$^{160}\text{Gd} \rightarrow ^{160}\text{Dy}$</td>
<td>46.557</td>
<td>25.260</td>
</tr>
<tr>
<td>$^{198}\text{Pt} \rightarrow ^{198}\text{Hg}$</td>
<td>259.526</td>
<td>25.260</td>
</tr>
</tbody>
</table>

IBM-2 from J. Barea and F. Iachello, Phys. Rev. C 79, 044301 (2009) and to be published.

Ref: Iachello, NDM2012
Theoretical Progress

Neutrino Mixing Models

- Survey of 63 $\nu$ mass models in 2006 (Albright, M-C Chen, hep-ph/0608136)

Predictions of All 63 Models

Only 7 got it right!

Gonzalez-Garcia et al, ICHEP2012
Theoretical Progress

Antineutrino Emission from Nuclear Reactors

Recently the reactor $\bar{\nu}_e$ fluxes have been recalculated


Re-evaluations find higher fluxes by about 3.5%

Ref: Mention et al, 1101.2755 (2012 upd)
Long-Term Scientific Questions in 3-ν Framework

- $0νββ$
  - towards a 1-ton experiment
  - confirm/measure with different nuclei
- absolute neutrino mass
  - KATRIN operations
  - confirm/improve with Project 8 or ECHO?
- Mass hierarchy
- $δ_{CP}$
- precision solar spectroscopy
(Sun as a calibrated source of neutrinos)

If neutrino anomalies are confirmed and evidence for sterile neutrinos....
Next-Generation 0νββ Experiments

Techniques

Calorimeter
- Ge diode $\varepsilon, \Delta E \quad {^{76}}\text{Ge}$
- Bolometers $\varepsilon, \Delta E \quad ^{130}\text{Te}, ^{82}\text{Se}, ^{100}\text{Mo}$
- Liquid Xe $\varepsilon, M \quad (N_{\text{Bckg}}) \quad ^{136}\text{Xe}$
- Scintillator $\varepsilon, M \quad ^{136}\text{Xe}, ^{48}\text{Ca}, ^{150}\text{Nd}, ^{100}\text{Mo}$
- KamLAND-Zen CANDLES SNO+ Borexino CdWO4 AMoRE
- Tracker
- Tracko-calor $N_{\text{Bckg}}, \text{isotopes} \quad ^{82}\text{Se} (^{150}\text{Nd}, ^{48}\text{Ca})$
- Pixellized CdZnTe $\varepsilon, N_{\text{Bckg}} \quad ^{116}\text{Cd}$
- TPC $\varepsilon, N_{\text{Bckg}} \quad ^{136}\text{Xe}, ^{150}\text{Nd}$

MTD EXO-gas NEXT

SuperNEMO

COBRA

Isotopes

- $^{116}\text{Cd}$
- $^{76}\text{Ge}$
- $^{82}\text{Se}$
- $^{136}\text{Xe}$
- $^{100}\text{Mo}$
- $^{130}\text{Te}$
- $^{48}\text{Ca}$
- $^{150}\text{Nd}$

- many R&D efforts
- few options scale for a 1-ton experiment
- improvements of backgrounds needed, active background discrimination helpful

Fig: Piquemal, Nu2012

see S. Elliott’s talk
Next-Generation 0νββ Experiments

Sensitivity Goals

- **Isotope mass**
  - ~ 10 kg (200 – 400 kg $^{136}$Xe) 2012
  - ~ 100 kg 2015
  - ~ 1000 kg

- **Required background level in the ROI**
  - 100 – 1000 cts/yr/ton
  - 1 – 10 cts/yr/ton
  - 0.1 – 1 cts/yr/ton

- **Deep location important**

- **Not all isotopes or detectors scale to 1-ton experiment**

- **See S. Elliott’s talk**

- **Fig: deepscience.org**
Towards an Absolute Neutrino Mass Measurement

**KATRIN**
under construction, expected data taking in 2015

tritium decay  electron transport  tritium reduction  energy analysis

EC on $^{163}$Ho
R&D

Project 8
R&D

low-temperature metallic magnetic calorimeters to study both $^{187}$Re and $^{163}$Ho.

KATRIN under construction, expected data taking in 2015


measure $\beta$-frequency proof of principle underway

$\omega = \frac{qB}{\gamma m} \equiv \frac{\omega_c}{\gamma}$
Reactor Neutrinos and Mass Hierarchy

Daya Bay II (and RENO 50km)

Determine mass hierarchy from precision measurements of $|\Delta m^2_{31}|$ and $|\Delta m^2_{32}|$

$$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$$

NH: $|\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$

IH: $|\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$

$\Delta m^2_{21}$ is only 3% of $|\Delta m^2_{32}|$

Mass Hierarchy Sensitivity

50k events, 3 years $\rightarrow$ 96%
100k events $\rightarrow$ 3σ

must understand energy scale non-linearity at fraction of %

Qian et al. arXiv: 1208.1551
**Precision Solar Spectroscopy**

Solar Neutrino Physics Topics

- **exclusive, precision measurement of pp flux**
  Test luminosity constraint

- **exclusive precision measurement of CNO flux**
  Resolve solar metallicity

- improved measurement of pep flux
  Probe vacuum-matter transition region
  Search for new physics and/or confirm MSW

- Low-energy 8B measurement with LS detectors
  Probe transition region, search for predicted upturn

---

**With luminosity constraint:**

\[
\phi_{\text{measured}}^{(pp)} = (1.02 \pm 0.02 \pm 0.01) \phi_{\text{theory}}^{(pp)}
\]

\[
\phi_{\text{measured}}^{(8B)} = (0.88 \pm 0.04 \pm 0.23) \phi_{\text{theory}}^{(8B)}
\]

\[
\phi_{\text{measured}}^{(7Be)} = (0.91^{+0.24}_{-0.62} \pm 0.11) \phi_{\text{theory}}^{(7Be)}
\]

**Without constraint:**

\[ L_v/L_\odot \text{ known to 20-40%} \]

testing L integrates over a lot of new physics
Neutrino science is international

many experiments require some kind of underground location
US neutrino physicists worldwide

US physicists engaged in many experiments overseas
many collaborations are truly international

Fig: deepscience.org

see B. Plaster’s talk
recent discoveries in neutrino physics from international collaborations
- US leads $0\nu\beta\beta$ and acc experiments
- partners in reactor and $0\nu\beta\beta$ experiments
- participates in $\beta$-decay, solar and atm experiments
Summary

Neutrino experiments have been enormously successful.

Neutrino experiments address questions about the origin of mass and the flavor puzzle. Important for understanding physics beyond the SM.

Broad current and near-term program. Big questions require planning beyond 2020.

Nuclear physicists play a key role in neutrino science.

Recent discoveries enabled by international collaborations.

Thanks to many colleagues for slides, materials, and discussions.