The State of the $\nu$ Mass Spectrum

Morgan Wascko
Imperial College London
Outline

- Introduction
- Discovery
  - Oscillation measurements
- Absolute scale of mass
  - Beta decay endpoint
  - Cosmology
- Nature of neutrino mass
  - Double beta decay
- Summary

<table>
<thead>
<tr>
<th>Mass (eV)</th>
<th>ν1</th>
<th>ν2</th>
<th>ν3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.009</td>
<td>solar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>atmospheric</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Flavor key:

- νe
- νμ
- ντ
"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do."

— Wolfgang Pauli (1930)
"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do."

— Wolfgang Pauli (1930)
νs in Standard Model

- Electrically Neutral
- Colorless
- Massless
- Flavors don’t mix
Why $\nu$ mass is difficult

- Usual techniques
  - Mass reconstruction
  - Spectrometry
- Cannot directly measure $\nu$ mass eigenstates!
- Must resort to indirect techniques

*Phys Rev. Lett. 33, 1406 (1974)*
Why $\nu$ mass is difficult

- Usual techniques
- Mass reconstruction
- Spectrometry

- Cannot directly measure $\nu$ mass eigenstates!
- Must resort to indirect techniques

$e^{-} \rightarrow e^{+}$

*Phys Rev. Lett. 33, 1406 (1974)*
Why $\nu$ mass is difficult

- Usual techniques
  - Mass reconstruction
  - Spectrometry
- Cannot directly measure $\nu$ mass eigenstates!
- Must resort to indirect techniques

Discovery of Neutrino Mass

Super Kamiokande
First hints

- Solar Neutrino Problem
  PRL 20 1205 (1968)

- Atmospheric Muon Neutrino Deficit
  PRD 18 2239 (1978)
Neutrino Oscillation

if neutrinos have mass...

A neutrino that is produced as a $\nu_\mu$

- (e.g. $\pi^+ \rightarrow \mu^+ \nu_\mu$)

might some time later be observed as a $\nu_e$

- (e.g. $\nu_e \, n \rightarrow e^- \, p$)

Pontecorvo, Maki, Nakagawa, Sakata
Neutrino Oscillation

\[
\left( \begin{array}{c} \nu_{\mu} \\ \nu_e \end{array} \right) = \left( \begin{array}{cc} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{array} \right) \left( \begin{array}{c} \nu_1 \\ \nu_2 \end{array} \right)
\]

- Consider only two types of neutrinos
- If weak states differ from mass states
  - i.e. \((\nu_{\mu}, \nu_e) \neq (\nu_1, \nu_2)\)
- Then weak states are mixtures of mass states

\[
\left| \nu_\mu(t) \right> = -\sin \theta \left| \nu_1 \right> e^{-iE_1 t} + \cos \theta \left| \nu_2 \right> e^{-iE_2 t}
\]

- Probability to find \(\nu_e\) when you started with \(\nu_\mu\)

\[
P_{osc}(\nu_\mu \rightarrow \nu_e) = \left| \left< \nu_e | \nu_\mu(t) \right> \right|^2
\]
2 fundamental parameters
- $\Delta m_{12}^2 (= m_1^2 - m_2^2) \leftrightarrow$ period
- $\theta_{12} \leftrightarrow$ magnitude

2 experimental parameters
- $L =$ distance travelled
- $E =$ neutrino energy

Tune $L$ & $E$ for $\Delta m^2$ range, uncertainties determine $\theta$ sensitivity

Neutrino disappearance and appearance

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2(1.27\Delta m_{12}^2 \frac{L}{E})$$
2 fundamental parameters

- $\Delta m^2_{12} (=m_1^2-m_2^2) \leftrightarrow$ period
- $\theta_{12} \leftrightarrow$ magnitude

2 experimental parameters

- $L =$ distance travelled
- $E =$ neutrino energy

Tune $L$ & $E$ for $\Delta m^2$ range, uncertainties determine $\theta$ sensitivity

Neutrino disappearance and appearance

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{12} \sin^2 (1.27\Delta m^2_{12} \frac{L}{E})$$
2 fundamental parameters
- $\Delta m_{12}^2 (=m_1^2-m_2^2) \leftrightarrow \text{period}$
- $\theta_{12} \leftrightarrow \text{magnitude}$

2 experimental parameters
- $L = \text{distance travelled}$
- $E = \text{neutrino energy}$

Tune $L$ and $E$ for $\Delta m^2$ range, uncertainties determine $\theta$ sensitivity

Neutrino disappearance and appearance

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2 \left(1.27 \Delta m_{12}^2 \frac{L}{E}\right)$$
$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2 (1.27 \Delta m^2_{12} \frac{L}{E})$

- 2 fundamental parameters
  - $\Delta m^2_{12} (=m_1^2-m_2^2)$ ↔ period
  - $\theta_{12}$ ↔ magnitude

- 2 experimental parameters
  - $L$ = distance travelled
  - $E$ = neutrino energy

- Tune $L$ & $E$ for $\Delta m^2$ range, uncertainties determine $\theta$ sensitivity

- Neutrino disappearance and appearance
\[ P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2 (1.27\Delta m_{12}^2 \frac{L}{E}) \]

- 2 fundamental parameters
  - \( \Delta m_{12}^2 (=m_1^2-m_2^2) \leftrightarrow \) period
  - \( \theta_{12} \leftrightarrow \) magnitude

- 2 experimental parameters
  - \( L = \) distance travelled
  - \( E = \) neutrino energy

- Tune \( L & E \) for \( \Delta m^2 \) range, uncertainties determine \( \theta \) sensitivity
- Neutrino disappearance and appearance

\( \nu_\mu \rightarrow \nu_\mu \)

\( \nu_\mu \rightarrow \nu_e \)
• 2 fundamental parameters
  • $\Delta m^2_{12} (=m_1^2-m_2^2) \leftrightarrow$ period
  • $\theta_{12} \leftrightarrow$ magnitude

• 2 experimental parameters
  • $L =$ distance travelled
  • $E =$ neutrino energy

• Tune $L$ & $E$ for $\Delta m^2$ range, uncertainties determine $\theta$ sensitivity

• Neutrino disappearance and appearance

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2 (1.27\Delta m^2_{12} \frac{L}{E})$$
- 2 fundamental parameters
  - $\Delta m_{12}^2 (= m_1^2 - m_2^2) \leftrightarrow$ period
  - $\theta_{12} \leftrightarrow$ magnitude

- 2 experimental parameters
  - $L =$ distance travelled
  - $E =$ neutrino energy

- Tune $L$ & $E$ for $\Delta m^2$ range, uncertainties determine $\theta$ sensitivity

- Neutrino disappearance and appearance

\[
P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2 (1.27\Delta m_{12}^2 \frac{L}{E})
\]
Discovery

- Super-Kamiokande @ Neutrino 98

• Difference in observed atmospheric muon neutrino fluxes
  • Depending on zenith angle!
  • $5 \times 10^{-4} \text{ eV}^2 < \Delta m^2 < 6 \times 10^{-3} \text{ eV}^2$

PRL 81, 1562 (1998)
Solving Solar Problem

- Sensitive to all flavors
- CC and NC channels
- Neutrinos transform flavor!
- Electron flux = 30% of total neutrino flux
- $\Delta m^2 = 4.6^{+2.8}_{-1.1} \times 10^{-5}$ eV$^2$

$\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.301 \pm 0.033$ (total)

See T. Vahle’s talk for more information on mixing
**Confirmation**

- Need same L/E to probe same $\Delta m^2$ region as atmospheric
- Confirmed with accelerator neutrinos
  - K2K and MINOS
  - $\Delta m^2 = 2.43 \pm 0.13 \times 10^{-3} \text{ eV}^2$

$\nu_\mu + N \rightarrow \mu + X$

**K2K:** PRL 98, 081802 (2005)
**MINOS:** PRL 101, 131802 (2008)
Confirmation

- Need same L/E to probe same $\Delta m^2$ region as atmospheric
- Confirmed with accelerator neutrinos
  - K2K and MINOS
  - $\Delta m^2 = 2.43\pm0.13 \times 10^{-3}$ eV$^2$

$\nu_\mu + N \rightarrow \mu + X$

Confirming Solar

- Solar oscillation confirmed with reactor antineutrinos
- KamLAND experiment sensitive to antineutrinos from several reactors
  - Similar mixing angle
  - \( \Delta m^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5} \text{ eV}^2 \)

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

*PRL 100, 221803 (2008)*
Confirming Solar

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

- Solar oscillation confirmed with reactor antineutrinos
- KamLAND experiment sensitive to antineutrinos from several reactors
  - Similar mixing angle
  - \( \Delta m^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5} \text{ eV}^2 \)

*PRL 100, 221803 (2008)*
\[ |\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle \]

Mass Spectrum

Mass (eV)

\[ \nu \]
\[ \nu \]
\[ \nu \]

\[ 0.05 \] atmospheric
\[ 0.009 \] solar

flavor key:

\[ \nu_e \nu_\mu \nu_\tau \]
Open Questions

- What is the mass hierarchy?
- What is the absolute mass scale?
- What is the nature of neutrino mass?
  - Dirac or Majorana?
- Answers important for theories about origins of neutrino mass
  - Relations to flavor? GUTs?
- Cosmological and astrophysical implications
Absolute Scale of Neutrino Mass
Beta decay endpoint

- Sensitive to $<m_\beta> = \sqrt{\sum |U_{ei}|^2 m_i^2}$
Tritium has short half life but high Q value (18.6 keV)

Previous measurements

- Troitsk: $m_\beta < 2.05$ eV (95% CL)
- Mainz: $m_\beta < 2.3$ eV (95% CL)

Source = $^3$H
KATRIN

- Powerful T² source (1.7×10¹¹ Bq!)
- Pre-spectrometer removes all βs with no mν information (10⁷ reduction!)
- Excellent energy resolution (0.93 eV)
- Sensitivity: mβ < 200 meV (90% CL) (1000 days)
- Discovery potential: mβ = 350 meV (5σ)

The ultimate tritium decay experiment

http://www-ik.fzk.de/tritium/
Physics Reach

Assuming normal hierarchy

$m_i$, eV/c^2

$\Delta m_{23}^2$

$\nu_{atm}$

$\Delta m_{12}^2$

$\nu_{sol}$

LMA

$m_1$, eV/c^2

$m_3$ ($\sim 55$ meV/c^2)

$m_2$ ($\sim 8$ meV/c^2)

Hierarchical $\nu$ masses

Mainz & Troitsk

KATRIN

Quasidegenerate $\nu$ masses

Rhenium Decay

Bolometers

Source = $^{187}$Re

- Rhenium has long half life and low Q value (2.47 keV)
- MIBETA (AgReO4); MANU (metallic Re)
- $m_\beta < 15.0$ eV (90% CL)

When in presence of decays to excited states, the calorimeter measures both the electron and the de-excitation energy.

- high energy resolution
  - differential spectrum: $dN/dE$

$PRL \ 91, \ 161802 \ (2003)$

$MARE \ Proposal$
MARE

New collaboration: MANU + MIBETA + US groups

- Phase 1: Improve by factor 10
  - \( m_\beta < 2 \text{ eV} \)
  - \( 10^{10} \beta \text{ decays} \)
  - Exploring detector options
- Phase 2: Another factor 10
  - \( m_\beta < 0.2 \text{ eV} \)
  - \( 10^{14} \beta \text{ decays} \)
  - R&D for new detector technology
    - Magnetic micro-calorimeter with SQUID readout
- Goal: 2015

Scalable technology
Cosmology

- $m_\nu$ can be inferred from cosmological data + cosmological assumptions
  - $\sum m_i < (0.17 - 0.32) \text{ eV}$

- Degeneracies between some parameters
  - $H_0$ and $m_\nu$

- Best approach:
  - Observe neutrino mass, then use as cosmological input
The Nature of Neutrino Mass

CUORE

NEMO3

SNO+
Double Beta Decay

- Can happen if single $\beta$ decay is energetically forbidden
- $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu$
- If $\nu = \bar{\nu}$, then can have $0\nu\beta\beta$ decay
- $(A,Z) \rightarrow (A,Z+2) + 2e^-$
- Best way to search for Majorana particles

$1/\tau = G(Q,Z) |M|^2 <m_{\beta\beta}>^2$

$m_{\beta\beta} = \sum |U_{ei}|^2 m_i^2 \varepsilon_i$
## Experimental techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Nuclei</th>
<th>Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolometers</td>
<td>$^{130}$Te</td>
<td>CUORICINO $\rightarrow$ CUORE</td>
</tr>
<tr>
<td>Semiconductors</td>
<td>$^{76}$Ge</td>
<td>Heidelberg-Moscow, GERDA, MAJORANA, COBRA</td>
</tr>
<tr>
<td>Scintillators</td>
<td>$^{48}$Ca, $^{116}$Cd, $^{150}$Nd</td>
<td>MOON, CANDLES, ELEGANT, KIEV, SNO+</td>
</tr>
<tr>
<td>Xenon</td>
<td>$^{136}$Xe</td>
<td>EXO, XMASS, NEXT</td>
</tr>
<tr>
<td>Tracker/Calo</td>
<td>Ca, Cd, $^{100}$Mo, Nd, Se, Te, $^{96}$Zr</td>
<td>NEMO3 $\rightarrow$ SuperNEMO</td>
</tr>
</tbody>
</table>

More detailed info in Session D.10 Sat 3:30 pm, Governor’s Square
# Current Limits

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Nucleus</th>
<th>Mass Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUORICINO</td>
<td>$^{130}$Te</td>
<td>$m_{\beta\beta} &lt; (0.2-0.68)$ eV</td>
</tr>
<tr>
<td>NEMO3</td>
<td>$^{100}$Mo</td>
<td>$m_{\beta\beta} &lt; (0.8-1.3)$ eV</td>
</tr>
<tr>
<td>NEMO3</td>
<td>$^{82}$Se</td>
<td>$m_{\beta\beta} &lt; (1.4-2.2)$ eV</td>
</tr>
<tr>
<td>ELEGANT V</td>
<td>$^{100}$Mo</td>
<td>$m_{\beta\beta} &lt; 1.7$ eV</td>
</tr>
<tr>
<td>NEMO3</td>
<td>$^{150}$Nd</td>
<td>$m_{\beta\beta} &lt; (1.7-2.4)$ eV</td>
</tr>
<tr>
<td>NEMO3</td>
<td>$^{96}$Zr</td>
<td>$m_{\beta\beta} &lt; (7.4-20.1)$ eV</td>
</tr>
<tr>
<td>NEMO3</td>
<td>$^{48}$Ca</td>
<td>$m_{\beta\beta} &lt; 29.6$ eV</td>
</tr>
</tbody>
</table>

*Ranges due to nuclear matrix elements*
Future Mass reach

Not a complete list!

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Nucleus</th>
<th>Mass Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>GERDA</td>
<td>⁷⁶Ge</td>
<td>$m_\nu &lt; 0.11\text{-}0.27\text{ eV}$</td>
</tr>
<tr>
<td>MAJORANA</td>
<td>⁷⁶Ge</td>
<td>$m_\nu &lt; 0.12\text{ eV}$</td>
</tr>
<tr>
<td>NEXT</td>
<td>¹³⁶Xe</td>
<td>$m_\nu &lt; 0.06\text{ eV}$</td>
</tr>
<tr>
<td>SNO+</td>
<td>¹⁵⁰Nd</td>
<td>$m_\nu &lt; 0.04\text{ eV}$</td>
</tr>
<tr>
<td>CUORE</td>
<td>¹³⁰Te</td>
<td>$m_\nu &lt; (0.014\text{-}0.047)\text{ eV}$</td>
</tr>
<tr>
<td>SuperNEMO</td>
<td>⁸²Se or ¹⁵⁰Nd</td>
<td>$m_\nu &lt; (0.04\text{-}0.11)\text{ eV}$</td>
</tr>
<tr>
<td>EXO</td>
<td>¹³⁶Xe</td>
<td>$m_\nu &lt; (0.005\text{-}0.007)\text{ eV}$</td>
</tr>
</tbody>
</table>
Observation?

- In 2001, a subgroup of the Heidelberg-Moscow experiment ($^{76}\text{Ge}$) released a discovery claim.
- Somewhat controversial.
- $T_{1/2}^{0\nu} = 1.2 \times 10^{25}$ y
- $m_{\beta\beta} = 440$ meV (4.2$\sigma$)

Observation?

• In 2001, a subgroup of the Heidelberg-Moscow experiment (\(^{76}\)Ge) released a discovery claim

• Somewhat controversial

• \(T_{1/2}^{0\nu} = 1.2 \times 10^{25} \text{ y}\)

• \(m_{\beta\beta} = 440 \text{ meV (4.2}\sigma)\)
Mass Reach


see Engel’s talk in session Q.2, Monday 10:45 in Plaza D
All planned experiments can test the 440 meV claim.

- DISCOVERY CLAIM REGION
  - GERDA II
  - Majorana (30 kg, 3 yr)
  - SuperNEMO (~2016)
  - NEXT (100 kg, 10 yr)
  - SNO+ (10 years, enriched)
  - CUORE (5 year, low background)
  - EXO (1-10 ton w/ Ba tagging)

see Engel’s talk in session Q.2, Monday 10:45 in Plaza D
Summary: Open Questions

- Neutrinos have mass!
- Moving from discovery to precision era
- What is the mass hierarchy?
- What is the absolute scale?
- Are they Majorana or Dirac?
- Why are they so small?

Worldwide program of experiments to answer these!
Thank you!

Denver Skyline
Sign of $\Delta m^2$

- $\Delta m^2_{ij} = m_i^2 - m_j^2$
- Solar experiments explained by MSW (matter) effects
  - Resonant enhancement of oscillation $\Rightarrow$ sun emits $\nu_2$
  - $m_2 > m_1$
- No such information (yet) for $\Delta m^2_{23}$
  - Need to observe matter effects in $\theta_{13}$ measurement $\nu$ and $\bar{\nu}$ to sort that out
  - NOvA + T2K + Reactors

See T. Vahle’s talk for more information