The Nature and Magnitude of Neutrino Mass

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Outline

- What we know
  Our current knowledge regarding neutrino masses.

- What we do not know
  Open questions related to neutrino masses.

- Why we need to know
  Implications on the Standard Model of Particle physics.

- What is being done to know
  1. Direct mass measurements - The KATRIN experiment
  2. Neutrinoless double beta decays - The EXO experiments.

- Summary
What we know

- Neutrino flavor eigenstates are linear superpositions of non-degenerate mass eigenstates.
- Neutrinos are massive and extremely light. Courtesy data from solar (Homestake, SNO), atmospheric (Super-Kamiokande), reactor (KamLAND, Daya Bay) and beam (MINOS, K2K, Super-K, T2K) neutrinos oscillation experiments.
- Oscillation data sensitive to squared mass differences, $\Delta m^2$ and mixing matrix parameters, $U_{ij}$.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best Fit ± 1σ</th>
<th>2σ Range</th>
<th>3σ Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2_{21} \left[ 10^{-5} \text{eV}^2 \right]$</td>
<td>$7.60^{+0.19}_{-0.18}$</td>
<td>7.26–7.99</td>
<td>7.11–8.18</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m^2_{31}</td>
<td>\left[ 10^{-3} \text{eV}^2 \right]$ (NH)</td>
<td>$2.48^{+0.05}_{-0.07}$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m^2_{31}</td>
<td>\left[ 10^{-3} \text{eV}^2 \right]$ (IH)</td>
<td>$2.38^{+0.05}_{-0.06}$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}/10^{-1}$</td>
<td>$3.23 \pm 0.16$</td>
<td>2.92–3.57</td>
<td>2.78–3.75</td>
</tr>
<tr>
<td>$\theta_{12}/^\circ$</td>
<td>$34.6 \pm 1.0$</td>
<td>32.7–36.7</td>
<td>31.8–37.8</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}/10^{-1}$ (NH)</td>
<td>$5.67^{+0.32}_{-1.24}$</td>
<td>4.14–6.23</td>
<td>3.93–6.43</td>
</tr>
<tr>
<td>$\theta_{23}/^\circ$</td>
<td>$48.9^{+1.8}_{-7.2}$</td>
<td>40.0–52.1</td>
<td>38.8–53.3</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}/10^{-1}$ (IH)</td>
<td>$5.73^{+0.25}_{-0.39}$</td>
<td>4.35–6.21</td>
<td>4.03–6.40</td>
</tr>
<tr>
<td>$\theta_{23}/^\circ$</td>
<td>$49.2^{+1.5}_{-2.3}$</td>
<td>41.3–52.0</td>
<td>39.4–53.1</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}/10^{-2}$ (NH)</td>
<td>$2.26 \pm 0.12$</td>
<td>2.02–2.50</td>
<td>1.90–2.62</td>
</tr>
<tr>
<td>$\theta_{13}/^\circ$</td>
<td>$8.8^{+0.3}_{-0.2}$</td>
<td>8.2–9.1</td>
<td>7.9–9.3</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}/10^{-2}$ (IH)</td>
<td>$2.29 \pm 0.12$</td>
<td>2.05–2.52</td>
<td>1.93–2.65</td>
</tr>
<tr>
<td>$\theta_{13}/^\circ$</td>
<td>$8.7 \pm 0.2$</td>
<td>8.2–9.1</td>
<td>8.0–9.4</td>
</tr>
<tr>
<td>$\delta/\pi$ (NH)</td>
<td>$1.41^{+0.55}_{-0.40}$</td>
<td>0.0–2.0</td>
<td>0.0–2.0</td>
</tr>
<tr>
<td>$\delta/^\circ$</td>
<td>$254^{+9.9}_{-7.2}$</td>
<td>0–360</td>
<td>0–360</td>
</tr>
<tr>
<td>$\delta/\pi$ (IH)</td>
<td>$1.48 \pm 0.31$</td>
<td>0.00–0.09 &amp; 0.86–2.0</td>
<td>0.0–2.0</td>
</tr>
<tr>
<td>$\delta/^\circ$</td>
<td>$266 \pm 56$</td>
<td>0–16 &amp; 155–360</td>
<td>0–360</td>
</tr>
</tbody>
</table>

What we do not know

- The absolute neutrino masses.
- The nature of neutrino masses - Dirac or Majorana.
- The mechanism for small masses.
- The neutrino mass hierarchy - NH, IH or QD.

Neutrino masses as a function of the lightest mass.
Implications of neutrino mass on the Standard Model

- Neutrino masses ⇒ Standard Model is incomplete. Augmentation of particle content required.
- SM requires RH neutrinos and unnaturally small Higgs-Yukawa couplings to incorporate Dirac neutrino masses.
- Motivates theories beyond the Standard Model - extra dimensions, supersymmetry, GUTs, see-saw mechanisms etc.

Two ambiguities to be addressed in this talk.
1. What is the absolute mass scale?
2. What is the nature of neutrino mass? Dirac or Majorana?
Attempts at measuring the absolute mass scale

Three kinds of experiments are sensitive to the absolute masses of neutrinos.

- **Cosmology:** Sensitive to the sum of the three neutrino mass eigenstates, for example, $\sum m(\nu_i) < 0.66\text{eV}$ (from the Planck Collaboration) [2]

- **Neutrinoless double beta decay ($0\nu\beta\beta$):** Forbidden in the SM and depends on Majorana nature of neutrinos.

\[
\Gamma_{0\nu\beta\beta} \propto \left| \sum U_{ei}^2 m(\nu_i) \right|^2 = m^2_{ee}
\]

- **Direct mass measurements:** Purely based on kinematics (energy-momentum conservation) without further assumptions.
  1. Time of flight method.
  2. Precision investigation of weak decays - most sensitive and model-independent method to determine neutrino mass.

I will discuss the second method here.
Principle

- Electron spectrum in nuclear $\beta$-decay

\[ \mathcal{N}(A, Z) \rightarrow \mathcal{N}(A, Z + 1) + e^- + \bar{\nu}_e \]

is investigated near the end-point, $T_{e,\text{max}} = Q_\beta$ for $m(\nu_e) = 0$ and $T_{e,\text{max}} = Q_\beta - m(\nu_e)$ for $m(\nu_e) \neq 0$

- Neutrinos are non-relativistic at the end-point.
- Neutrino mass is calculated from $E^2 = p^2 + m^2$ relation.

The problem in measured the end-point - very few events near the end-point. An order of magnitude calculation [6] for the relative number of events occurring in an energy interval $\Delta T$ below the end-point is

\[ \frac{n(\Delta T)}{n} \propto \left( \frac{\Delta T}{Q_\beta} \right)^3 \]

- Desirable to have $Q_\beta$ as low as possible. $Q_\beta = 18.6$ keV for Tritium is one of the lowest among all $\beta$-emitters.
Characterization

- Information about $m(\nu_e)$ found by the distortion of Kurie plot near end-point, where

$$K(T) = \sqrt{\frac{d\Gamma/dT}{\frac{G_F^2 m_e^5}{2\pi^2} \cos^2 \theta_C |\mathcal{M}|^2 F(Z, Z_e) E_e p_e}}$$

$$= \left[ (Q_\beta - T) \sqrt{(Q_\beta - T)^2 - m^2(\nu_e)} \right]^{1/2}$$
The KATRIN experiment
The KATRIN experiment

- The Karlsruhe Tritium Neutrino (KATRIN) experiment is a next-gen direct neutrino mass experiment.
- Collaboration with groups from institutions all over the world.
- The experiment is housed at Tritium Laboratory, Karlsruhe (TLK) at KIT’s North Site.
- Scientific goals
  1. Designed to improve the $m(\nu_e)$ sensitivity from present 2 eV to 200 meV at 90% CL [$m(\nu_e) < 2.3\text{eV}$, Mainz and $m(\nu_e) < 2.5\text{eV}$, Troitsk].
  2. Discovery potential of a neutrino mass of 0.35 eV at $5\sigma$ significance and 0.30 eV at $3\sigma$ significance.
  3. Analyzing interval 30 eV below end-point.
Components

The KATRIN has the following components:
1. Windowless Gaseous Tritium Source (WGTS)
2. Transport Section having differential (DPS) and cryogenic (CPS) pumping sections
3. Pre-spectrometer, main spectrometer
4. Detector.

The most important parts are the energy filters in the pre- and main spectrometers.
MAC-E-Filter

- Magnetic Adiabatic Collimation with an electrostatic filter (MAC-E) combines high luminosity at low background and high energy resolution.
Two superconducting solenoids produce a magnetic guiding field.

$\beta$-electrons from source magnetically guided in a cyclotron motion into the forward hemisphere $\rightarrow$ accepted solid angle of nearly $2\pi$.

$\mathbf{B}$ decreases smoothly by several orders of magnitude keeping the magnetic moment

$$\mu = \frac{E_\perp}{B} = \text{constant}$$

Broad beam of electrons flying almost parallel to the magnetic field lines.

Energetically analyzed by applying an electrostatic barrier with cylindrical electrodes. Relative sharpness given by

$$\frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}}$$
Attempts at determining the nature of neutrino mass
Neutrinoless double beta decay

- Most promising way to find Majorana nature of neutrinos.
- Majorana imposition breaks matter-antimatter distinction i.e
  \[ \nu = \nu^C = C\bar{\nu}^T \] [Majorana condition]
- Possible for neutrino because of electrical charge neutrality.

\[ \mathcal{N}(A, Z) \rightarrow \mathcal{N}(A, Z + 2) + 2e^- \]

Forbidden in the SM due to lepton number violation.
- $\beta\beta$ decay observed only if the corresponding $\beta$-decay is energetically forbidden or strongly suppressed due to spin.
- The $\nu\nu\beta\beta$ and $0\nu\beta\beta$ decays are distinguished by the $\beta$-energy spectra- the former being a continuous distribution and the latter a line at Q-value.
Why neutrinos should be massive and Majorana for $0\nu\beta\beta$

- In the SM, $0\nu\beta\beta$ is not allowed due to particle-antiparticle mismatch and helicity mismatch.
- For Majorana neutrinos, $\nu_e = \bar{\nu}_e$. Upper leptonic vertex can emit a neutrino with $-ve$ helicity with relative amplitude $m(\nu_e)/E_e$ which is absorbed by the lower leptonic vertex with relative amplitude unity ($+ve$ helicity).
The EXO experiment

The EXO-200 Collaboration

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Carleton University, Ottawa ON, Canada - V. Basque, M. Dunford, K. Graham, C. Hargrove, R. Killick, T. Koffas, P. Leonard, C. Licciardi, M.P. Rozo, D. Sinclair
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Drexel University, Philadelphia PA, USA - M.J. Dolinski, J.K. Gaison, M.J. Jewell, Y.H. Lin, E. Smith, Y.-R. Yen
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University of Illinois, Urbana-Champaign IL, USA - D. Beck, M. Coon, J. Ling, M. Tarka, J. Walton, L. Yang
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University of California, Irvine, Irvine CA, USA - M. Moe
Laurentian University, Sudbury ON, Canada - B. Cleveland, A. Der Mecobian-Kahzakan, J. Farine, B. Mong, U. Wichoski
University of Maryland, College Park MD, USA - C. Davis, C. Hall
University of Massachusetts, Amherst MA, USA - J. Abdollahi, T. Daniels, S. Johnston, K. Kumar, A. Pocar, D. Shy
University of Seoul, South Korea - D.S. Leonard
Technical University of Munich, Garching, Germany - W. Feldmeier, P. Fierlinger, M. Marino
TRIUMF, Vancouver BC, Canada - J. Dilling, R. Krucken, F. Retiere, V. Strickland
Looking for $0\nu\beta\beta$ in Xe-136. It has two parts

1. EXO-200: A 200-kg prototype currently operating at Waste Isolation Pilot Plant (WIPP).
2. nEXO (next EXO): A tonne-scale experiment using Xe-136. Extensive R and D going on to design the detector and develop Ba-tagging techniques.
Mode of operation

- Detector has a back to back Time Projection Chamber (TPC) with high efficiency UV light detection.
- When a particle deposits energy in the liquid xenon, it ionizes the xenon atoms, knocking electrons off.
- Electrons liberated during ionization drift towards wire grids (anode).
- Recombination of Xe-atoms with $\text{e}^-$ and consequent de-excitation to ground states releases UV light.
- Photons are recorded using a multidiode array of large area avalanche photodiodes.
- The time between the light signal (nearly instantaneously) and the ionization signal (takes microsecond due to drift) allows to reconstruct the full 3D location of the event when combined with the 2D position from the wire grids. [5]
Experimental results

- First $\nu\nu\beta\beta$ decay observed in Xe-136 using EXO-2011.
- No signature of $0\nu\beta\beta$ observed yet.
- Date analysis gives $T_{1/2} > 1.6 \times 10^{25}$ yrs at 90 % CL for $0\nu\beta\beta$ decay of Xe-136.
- The $m(\nu_e)$ mass limit obtained using nuclear shell model, interacting boson model, RQRPA and QRPA-2 is 140-380 meV. [5]
Summary

Present mass regimes of the direct mass measurements and $0\nu\beta\beta$-decay experiments [3] [6]
KATRIN will investigate the entire parameter space of QD neutrino masses.

The ultimate challenge in $\beta$-spectroscopy is to push the $\nu$-mass sensitivity to the lowest values possible ($\approx 4 \times 10^{-3}$ eV).

The EXO collaboration is planning a detector using 5 tonnes of Xe, that would allow a very substantial advance in the sensitivity to a Majorana neutrino mass. Only by comparing high precision results from direct mass measurements and $0\nu\beta\beta$ searches, we can obtain the complete picture of $\nu$-masses to assess the unique role of neutrinos in particle physics and cosmology. [4]
“Without experimentalists, theorists tend to drift”....
“Without theorists, experimentalists tend to falter”

T.D Lee

Thank you!!!