Unit 6:
The Absolute Neutrino Mass

- Experimental Bounds
- Direct Measurements
- Dirac and Majorana Neutrinos
- Double Beta Decay Experiments

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What we have learnt from mixing: neutrino mass lower bound

• Weak eigenstates $\nu_e$, $\nu_\mu$, $\nu_\tau$ superposition of mass eigenstates $\nu_1$, $\nu_2$, $\nu_3$ numbered in increasing order of $\nu_e$ content, given by $|U_{ei}|^2$ (shown in red in figure)

$\nu_1 \sim 70\% \nu_e$, $\nu_2 \sim 30\% \nu_e$, $\nu_3 \sim 2.5\% \nu_e$

- What is the absolute value of neutrino masses?

Neutrino oscillation experiments can measure only mass differences. However note that $\Delta m^2_{atm} \sim 2.5 \times 10^{-3} \text{ eV}^2$

$\Rightarrow$ at least one neutrino with mass $> \sqrt[2]{\Delta m^2_{23}} \sim 50 \text{ meV}$

Is it $m_2$ or $m_3$? Depends on the mass hierarchy!
Understanding the mass “hierarchy”

Direct **upper bounds** on neutrino mass:

\[
\begin{align*}
  m_{\nu_e} &< 2 \text{ eV} \quad \text{from } \beta\text{-decay (95\%CL)} \\
  m_{\nu_\mu} &< 0.19 \text{ MeV} \quad \text{from } \pi \rightarrow \mu \nu \ (90\% \text{ CL}) \\
  m_{\nu_\tau} &< 18.2 \text{ MeV} \quad \text{from } \tau \text{ decays (95\%CL)}
\end{align*}
\]

We know now that flavor eigenstates do not coincide with mass eigenstates, so these are bounds on the “effective” mass:

\[
m^2_{\text{eff}}(\nu_\alpha) = \sum_{i=1,3} |U_{\alpha i}|^2 m^2(\nu_i)
\]

If the mass hierarchy is “inverted” \(\nu_e\) is effectively heavier than \(\nu_\mu\) and \(\nu_\tau\)!
Even more significant is the absolute scale.
Massive neutrinos affect both the evolution of Universe and the growth of structures on small scales.

In general: cosmological constraint much tighter than direct constraints but rely on theoretical models and important assumptions. Systematic uncertainties hard to quantify.

The upper bound would be somewhat worse if you also allowed, for example, the curvature of the universe to vary, and/or the dark energy equation of state, and/or including e.g. an axion component. Perhaps with current data that error would go up by around a factor 2. [Jo Dunkley, private communication]

For a recent discussion see PhysRevD.90.063516
Direct Mass Measurement in $\beta$ decay

- Neutrino mass modifies the shape of the electron spectrum.
- Challenge: determination of shape and absolute energy in the few eV below the endpoint energy $E_0=18.57$ keV with $O(1\text{eV})$ precision or better. Needs excellent control of resolution, absolute scale and background.
- Current limit $m(\nu_e) < 2.2$ eV (95% CL) by “Mainz” experiment.

Tritium $\beta$-decay and the neutrino rest mass

$^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e$

- Neutrino mass modifies the shape of the electron spectrum.

![Graph showing electron spectrum](graph.png)
The KATRIN Experiment

(KArlsruhe TRItium Neutrino experiment, location: Forschungszentrum Karlsruhe)

Improve $m_\nu$ by x10 (2.2 $\rightarrow$ 0.2 eV)
- Stronger Tritium source (x80)
- Longer measuring period (100 $\rightarrow$ 1000 days)
- Better spectrometer ($\Delta E=0.93$eV)
- Smaller systematics, reduced energy losses

- Katrin aim to improve upper bound by an order of magnitude (0.2 eV)
- Based on special type of spectrometer: MAC-E-Filters (Magnetic Adiabatic Collimation combined with an Electrostatic Filter)
- A pre-spectrometer is required to remove all electrons but a fraction of $10^{-7}$ at the highest energies (to minimize the background due to trapped electrons)
- The detector at the end counts electrons. High energy and position resolution to suppress the background. Semiconductor technology employed.

First tritium data in 2017
MAC-E Filter

- The spectrometer acts as an integrating high-energy pass filter with a resolution $\Delta E/E = B_{\text{min}}/B_{\text{max}}$.

Principle:
- Two superconducting solenoids
- Electrons guided magnetically on a cyclotron motion around the magnetic field lines into the spectrometer
- In the center the magnetic field drops. Cyclotron motion transformed adiabatically into longitudinal motion.
- Electrons isotropically emitted at the source transformed in a broad beam of electrons flying almost parallel to field lines and run against an electrostatic potential formed by a system of cylindrical electrodes
- Only electrons with enough energy to pass the electrostatic barrier are reaccelerated and collimated onto a detector.
- Varying the electrostatic retarding potential allows to measure the beta spectrum in an integrating mode.
Neutrino mass: physics beyond the SM

• The Big Question: Why are neutrinos so much lighter than other fermions?
• Majorana neutrinos and See-Saw Mechanism introduced in extensions of the Standard Model provide an answer
Dirac and Majorana neutrino

**Is the neutrino its own antiparticle?** If so, neutrinos are Majorana particles (from Ettore Majorana who first introduced the idea in 1937)

- Charged particles cannot coincide with anti-particle (ex electron different from positron). Different electric charge (which is conserved)
- Neutron is different from anti-neutron (different baryonic number)
- $\pi^0$ is a boson and is its own antiparticle!

Lesson: particle/anti particle distinction corresponds to a symmetry of the theory or, in other words, some conserved quantum number

If neutrinos ($L = -1$) are Dirac particles they are distinct from their anti-particle ($L = 1$) and leptonic number is conserved

If neutrinos are Majorana particles

$$\nu = \nu^c$$

and leptonic number is violated.

In experimental terms: if, for a given momentum and helicity, neutrinos and anti-neutrinos have identical interactions with matter, neutrinos are Majorana particles.
Why we do not know if $\nu=\bar{\nu}$

- Available neutrinos are always polarised: we observe only left-handed neutrinos and right-handed anti-neutrinos, as a result we are not able to compare the interaction with matter of neutrinos and antineutrinos of the same helicity. Is the different interaction due to different polarisation or real distinction between neutrinos and anti-neutrinos?

- Ex: $\pi^+ \rightarrow \mu^+ \nu_{\mu}$ produces a left-handed neutral particle
  
  \[
  \nu_{\mu} N \rightarrow \mu^- X \quad \text{Observed}
  \]
  
  \[
  \nu_{\mu} N \rightarrow \mu^+ X \quad \text{NOT Observed}
  \]

  $\pi^- \rightarrow \mu^- \bar{\nu}_{\mu}$ produces a right-handed neutral particle

  \[
  \bar{\nu}_{\mu} N \rightarrow \mu^- X \quad \text{NOT Observed}
  \]
  
  \[
  \bar{\nu}_{\mu} N \rightarrow \mu^+ X \quad \text{Observed}
  \]

  is $\nu_{\mu}$ different from $\bar{\nu}_{\mu}$ or is the different charge of the lepton produced in the two cases due to the different polarization?

  To distinguish the two cases we should reverse the helicity (how? For example boost to a frame which moves faster than neutrino), which is not possible if neutrino is massless $\Rightarrow$ For massless neutrinos the distinction between Majorana and Dirac disappears
Dirac neutrino mass

General mass term in the Lagrangian for field $\psi$

$m\psi \overline{\psi}$ where $\overline{\psi} = \psi^{+} \gamma^{0}$

given $\psi_{L,R} = \frac{1}{2} (1 \mp \gamma^{5}) \psi$

$\overline{\psi}_{L,R} = \frac{1}{2} \psi (1 \pm \gamma^{5})$

$\overline{\psi} \psi = \overline{\psi}_{L} \psi_{R} + \overline{\psi}_{R} \psi_{L}$

$\Rightarrow$ In order to introduce a DIRAC mass term we need right-handed neutrinos and left-handed antineutrinos (which in the Standard Model are absent). So if neutrinos are massive DIRAC particles there must be 4 different states ($2 \times$ HELICITY)

Within the simplest extension of the SM (no changes in the Higgs sector)
neutrino mass would be given by $m_{\nu} = g_{\nu} v / \sqrt{2}$

in analogy with electron mass, $m_{e} = g_{e} v / \sqrt{2}$ where $<h^{0}> = v / \sqrt{2}$

Small mass $g_{e} > 5 \times 10^{5} g_{\nu}$

Why would the relative couplings be so different?
Majorana mass terms

- If $\nu$ and $\bar{\nu}$ are different helicity states of the same particle, the most generic mass term in the Lagrangian can contain lepton number violating combinations

$$\begin{pmatrix} \bar{\phi} & \Phi \end{pmatrix} \begin{pmatrix} M_L & m \\ m & M_R \end{pmatrix} \begin{pmatrix} \phi \\ \Phi \end{pmatrix}$$

The off-diagonal elements $m$ give rise to lepton-number conserving Dirac mass terms and the $M_{L,R}$ terms on the diagonal to lepton-number violating Majorana mass terms

In general for Majorana neutrino we will have both Dirac and Majorana mass terms in the Lagrangian

$$\phi = (\psi^c_L + \psi_L)/\sqrt{2}$$
$$\Phi = (\psi^c_R + \psi_R)/\sqrt{2}$$
See-saw mechanism

- To enforce the gauge symmetry of the SM, it is required that $M_L = 0$ (hep-ph/0310238). This is called Type I see-saw, where also $M_R$ is very large and $m \approx$ mass charge lepton

\[
\begin{pmatrix}
0 & m_
u \\
m_
u & M
\end{pmatrix}
\]

The diagonalization of this matrix gives rise to the mass eigenstates (2 for each neutrino flavour):

- $m_{\text{light}} \approx m_
u^2 / M$ mostly LH
- $m_{\text{heavy}} \approx M$ mostly RH and not observed because too massive
Double $\beta$ Decay

- **Double $\beta$ decay**
  \[(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e\]
  Allowed in the SM
  observed for nuclei which do not undergo $\beta$ decay (energetically forbidden)

- **Neutrino-less double $\beta$ decay**
  \[(A,Z) \rightarrow (A,Z+2) + 2e^-\]
  Hypothetical $L$ violating process not allowed in the SM

The emitted antineutrino does not have neither the correct helicity nor the correct leptonic number to be absorbed at the second vertex

\[0\nu\beta\beta\]

\[0\nu\beta\beta\ (in\ the\ hypothesis\ of\ neutrino\ exchange)\]

\[
\begin{cases}
m(\nu) \neq 0 & \text{since helicity has to flip} \\
\nu = \bar{\nu} & \\
\end{cases}
\]
Decay rate and mass

Decay rates are given by: \( 1/\tau = G(Q_{\beta\beta,Z}) |M^{0\nu}|^2 <m_\nu>^2 \)

- \( G(Q_{\beta\beta,Z}) \) is the phase space integral
- \( |M^{0\nu}| \) is the nuclear matrix element (known to factor 2 or 3, source of large uncertainties)
- \( <m_\nu>^2 = |\sum U_{ei}^2 m_i|^2 \)

Note that the effective mass measured in 0\( \nu \) decay (noted as \( m_{ee} \) in the y axis of the plot) is different from the effective mass measured in \( \beta \) decay

\( <m_\nu>^2 = \sum |U_{ei}|^2 m_i^2 \)
Energy spectrum for $2\beta$ decays

- Sum of 2 electron energy allow to separate $0\nu\beta\beta$ and $2\nu\beta\beta$
- Excellent energy resolution required (few keV at 1-2 MeV)
- Very Low background:
  - Underground lab
  - High radio-purity of all materials
  - Background rejection in the signal reconstruction (shape analysis)
- Big source (O(100 Kg) now; 1t in the future)

0ν peak width depends on detector resolution

$2\nu\beta\beta$ is ultimate, irreducible background
Double-$\beta$ decay experiments

2 experimental approaches:

- **Source = detector**
  - Bolometry and calorimetry
    - ✓ good energy resolution
    - ✓ large detector mass

- **Source ≠ detector**
  - Tracking
    - ✓ good topological reconstruction
    - ✓ different isotopes as source allow to circumvent theoretical errors in nuclear matrix calculations
Choice of $\beta\beta$ isotope

Phase-space factor for all $\beta\beta$ emitters with $Q>2\text{MeV}$

$G^{0\nu} \propto Q^5$

$\Rightarrow$ Considered only isotopes with $Q>2\text{MeV}$:

$\Rightarrow$ Only 11

Other important considerations:

• background control (better above $\sim3\text{MeV}$)
• $\beta\beta2\nu$ decay rate (preferred slow decaying isotopes, intrinsic bkg)
• Well-understood nuclear physics
Germanium Experiments

• Why Germanium?
  – $^{76}\text{Ge}$ $2\nu 2\beta$ decay
  – Excellent energy resolution of Ge semiconductor diodes
  – Well-proven technology

• Longest running exp: Heidelberg-Moscow 13 years at Gran Sasso (1990-2003) used about 10 Kg (86% enriched) $^{76}\text{Ge}$ diodes

No $0\nu 2\beta$ signal observed
$T_{1/2} > 1.9 \times 10^{25}$ yr (90% CL)

$\Rightarrow m_\nu < 0.4$ eV

A double-$\beta$ decay evidence?

Analysis of the $^{76}$Ge data by a sub-group of the HM Collaboration (Klapdor-Kleingrothaus et al, PLB 586,198,2004)

4$\sigma$ effect claimed

$T^{0\nu}_{1/2} = (0.69 - 4.18) \times 10^{25}$ y

$\langle m_{\nu} \rangle = (0.17 - 0.63)$ eV

Critics:

- low statistical significance of signal
- Unknown extra-peak at 2030 keV with similar significance
- Larger energy window checks?
Re-analysis of same data (2006)

1995-2003 data new re-analysis:
SSE selection by MC & ANN
6.4$\sigma$ signal
7.05 ± 1.11 events
2.23$^{+0.44}_{-0.31}$ 10$^{25}$ years / 0.32±0.03 eV


Not confirmed and essentially ruled out by current more sensitive experiments
Magnetic + tracking detector + calorimeter
- tracking for background rejection (drift cells)
- calorimetry for energy resolution (plastic scintillators+PMT)
- multiple isotopes for systematics ($^{100}$Mo, $^{82}$Se, $^{130}$Te, $^{116}$Cd,..)
10 Kg distributed in thin source foils

Tag and measures all components of backgrounds: $\alpha$, $\gamma$, $e^-$, $e^+$
0νββ decay: Nemo3 latest results [Waters, Nu2016]

- Closed to the best limits from other experiments, with only 7kg of isotope.

\[ T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{24} \text{ yr (90\% C.L.)} \]
\[ \langle m_\nu \rangle < 0.3 - 0.6 \text{ eV} \]

- Expected (observed) half-life limit is 11\% (34\%) better than using E_{TOT} alone.
**Compilation of current results**

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Experiment</th>
<th>Exposure (kg \cdot year)</th>
<th>$T^{0\nu}_{1/2}$ limit (yr) 90%CL</th>
<th>$&lt;m_{\beta\beta}&gt;$ (eV)</th>
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</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>ELEGANT VI</td>
<td>0.025</td>
<td>$&gt;5.8 \times 10^{22}$</td>
<td>$&lt;3.5-22$</td>
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<tr>
<td>$^{76}$Ge</td>
<td>Heidelberg-Moscow</td>
<td>35.5</td>
<td>$&gt;1.9 \times 10^{25}$</td>
<td>$&lt;0.2-0.32^*$</td>
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<td>GERDA</td>
<td>34.36</td>
<td>$&gt;5.2 \times 10^{25}$</td>
<td>$&lt;0.16-0.26$</td>
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<tr>
<td>$^{82}$Se</td>
<td>NEMO-3</td>
<td>4.2</td>
<td>$&gt;3.2 \times 10^{23}$</td>
<td>$&lt;0.8-1.4$</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>NEMO-3</td>
<td>0.031</td>
<td>$&gt;9.2 \times 10^{21}$</td>
<td>$&lt;9.3-13.7$</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>NEMO-3</td>
<td>31.2</td>
<td>$&gt;1.0 \times 10^{24}$</td>
<td>$&lt;0.4-0.7$</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>Solotvina</td>
<td>0.14</td>
<td>$&gt;1.7 \times 10^{23}$</td>
<td>$&lt;1.2-2.2$</td>
</tr>
<tr>
<td>$^{128}$Te</td>
<td>Geochemical</td>
<td>–</td>
<td>$&gt;7.7 \times 10^{24}$</td>
<td>$&lt;0.7-1.2$</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>CUORICINO</td>
<td>19.75</td>
<td>$&gt;2.8 \times 10^{24}$</td>
<td>$&lt;0.44-0.81$</td>
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<tr>
<td>$^{136}$Xe</td>
<td>KamLAND-Zen</td>
<td>150</td>
<td>$&gt;11 \times 10^{25}$</td>
<td>$&lt;0.06-0.16$</td>
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<tr>
<td></td>
<td>EXO-200</td>
<td>100</td>
<td>$&gt;1.1 \times 10^{25}$</td>
<td>$&lt;0.19-0.45$</td>
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<tr>
<td>$^{150}$Nd</td>
<td>NEMO-3</td>
<td>0.093</td>
<td>$&gt;1.8 \times 10^{22}$</td>
<td>$&lt;4.0-6.3$</td>
</tr>
</tbody>
</table>

*part of the group claims a finite value

“Klapdor’s claim” strongly disfavoured
\(\beta\beta\)-decay New Experiments
(a selection)

Calorimeters

GERDA (GE-76)  
CUORE (TeO2)  
KamLAND-ZEN (Xe-136+LS)  
SNO+ (Te + LS)

Xe-TPC’s

EXO (Xe-136)LXe  
NEXT (Xe-136)HPXe  
Also PandaX

Tracking Calorimeter

SuperNEMO \((^{82}\text{Se})\)
Kamland-ZEN

~400 Kg $^{136}$Xe loaded liquid scintillator in a mini-balloon inside ultra-low background KAMLAND detector

Kamland2-Zen with 1000kg enriched Xe in preparation
Better energy resolution and background rejection
Aiming at full coverage of IH year

Phase-2 data (Neutrino 2016)

No excess over background

KamLAND-Zen
Half-life limit (@90% C.L.)
- Phase 1: $T_{1/2}^{0\nu} > 1.9 \times 10^{25}$ yr
- Phase 2: $T_{1/2}^{0\nu} > 9.2 \times 10^{25}$ yr
- Combined: $T_{1/2}^{0\nu} > 1.07 \times 10^{26}$ yr
Plan to fill SNO vessel with 780t of liquid scintillator loaded with Tellurium

- 34% natural abundance of $^{130}$Te
  - Can load high amount of natural isotope (~4tons)
  - Relatively inexpensive compared to enriched isotopes
- Low 2νββ decay (100 times smaller than $^{150}$Nd)
From NEMO to SuperNEMO

<table>
<thead>
<tr>
<th></th>
<th>NEMO-3</th>
<th>SuperNEMO</th>
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<tbody>
<tr>
<td>Mass</td>
<td>7 kg</td>
<td>100 kg</td>
</tr>
<tr>
<td>Isotopes</td>
<td>$^{100}$Mo</td>
<td>$^{82}$Se</td>
</tr>
<tr>
<td></td>
<td>7 isotopes</td>
<td>$^{150}$Nd, $^{48}$Ca</td>
</tr>
<tr>
<td>Foil density</td>
<td>60 mg/cm²</td>
<td>40 mg/cm²</td>
</tr>
<tr>
<td>Energy resolution ($\sigma$</td>
<td>FWHM)</td>
<td></td>
</tr>
<tr>
<td>@ 1 MeV</td>
<td>6.3</td>
<td>15 %</td>
</tr>
<tr>
<td>@ 3 MeV</td>
<td>3.4</td>
<td>8 %</td>
</tr>
<tr>
<td>Radon in tracker</td>
<td>$A(^{222}$Rn)</td>
<td>$\sim 5.0$ mBq/m$^3$</td>
</tr>
<tr>
<td>Sources contaminations</td>
<td>$A(^{208}$Tl)</td>
<td>$\sim 100$ $\mu$Bq/kg</td>
</tr>
<tr>
<td></td>
<td>$A(^{214}$Bi)</td>
<td>60 - 300 $\mu$Bq/kg</td>
</tr>
<tr>
<td>Detector</td>
<td>tracking cells</td>
<td>6180</td>
</tr>
<tr>
<td></td>
<td>calo blocks</td>
<td>1940</td>
</tr>
<tr>
<td>Sensitivity (90 % CL)</td>
<td>$T_{1/2}^{0\nu}$</td>
<td>$&gt; 1.1 \times 10^{24}$ y</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>m_{\beta\beta}</td>
</tr>
</tbody>
</table>

SuperNEMO demonstrator module with 7 kg of $^{82}$Se (53 mg/cm$^2$) is under construction Near completion
Future sensitivity of $0\nu2\beta$ experiments

- **AIM:** 10-20 meV sensitivity
  - DISCOVERY if mass HIERARCHY is inverted
- **What is it required?**
  - Different experiments with different isotopes
  - Reduce nuclear matrix elements uncertainties
  - Improve all parameters determining sensitivity

10 meV are very challenging:
factor 10 in neutrino mass => factor $10^4$ in $M \times t/ (Bkg \times \Delta E)$!
Need new ideas to reach < 10 meV
Summary

Single beta decay

\[ m_\nu = \sqrt{\sum |U_{ei}|^2 m_i^2} \]

KATRIN \[ m_\nu < 2.3 \text{ eV} \rightarrow m_\nu < 0.2 \text{ eV} \]

Double beta decay

\[ |\langle m_\nu \rangle| = |\sum U_{ei}^2 m_i| \]

Unique tool to study neutrino nature (DIRAC/Majorana)

Experiments have reached a sensitivity at the top of the inverted hierarchy region

Future generation aims to improve the limit by factor 10 and probe the inverted mass-hierarchy region

New ideas needed to go below 10 meV and probe normal hierarchy region