Dirac vs Majorana Neutrinos

Dirac neutrinos:

\[ L_{\text{mass}} = m_D \bar{\nu}\nu = m_D \left( \bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L \right) \]

\[ m_D \bar{\nu}_R \nu_L \quad \nu_L \quad \nu_R \quad m_D \]

chirality flip

Do not interact if neutrinos are highly relativistic.

\[ \nu \quad \bar{\nu} \]

makes \( \ell^- \)

makes \( \ell^+ \)
Majorana neutrinos:

\[ \nu^C_L = C \nu^T_L \] is a right handed field

\[ \nu = \nu_L + \nu^C_L \] is a self-conjugated state:

\[ \nu = \bar{\nu} \]

\[ L_{\text{mass}} = \frac{1}{2} m_L \left( \bar{\nu}^C \nu + \bar{\nu} \nu^C \right) \]

\[ = \frac{1}{2} m_L \left( \bar{\nu}^C_L \nu_L + \bar{\nu}_L \nu^C_L \right) \]

\[ m_L \bar{\nu}_L \nu^C_L \]

lepton number violating

\[ \nu \quad \text{makes } \ell^- \]

\[ \nu \quad \text{makes } \ell^+ \]
Neutrino Masses

\[ (0.05 \text{ eV})^2 \]

\[ (0.01 \text{ eV})^2 \]
## Neutrino Mass Constraints

### Experimental Bounds:
- "Elektron-Neutrino": $m < 2.2 \text{ eV}$ (Mainz, Troitsk)
- "Muon-Neutrino": $m < 170 \text{ keV}$
- "Tau-Neutrino": $m < 15.5 \text{ MeV}$

<table>
<thead>
<tr>
<th>Tool</th>
<th>Cosmology CMB + LSS + ...</th>
<th>Neutrinoless double $\beta$-decay</th>
<th>$\beta$-decay endpoint and EC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observable</td>
<td>$\sum m_{\nu} = \sum_{i=1}^{3} m_i$</td>
<td>$\langle m_{\beta\beta} \rangle = \left</td>
<td>\sum_{j=1}^{3} U_{ej}^2 m_j e^{i\alpha_j} \right</td>
</tr>
<tr>
<td>Present upper limit</td>
<td>0.15 – 1 eV</td>
<td>0.2 – 0.4 eV</td>
<td>2 eV</td>
</tr>
<tr>
<td>Potential</td>
<td>20 – 50 meV</td>
<td>20 – 50 meV</td>
<td>200 meV</td>
</tr>
<tr>
<td>Model dependence</td>
<td>Multi-parameter cosmological model</td>
<td>- Majorana vs. Dirac phase cancellations possible - nucl. matrix elements</td>
<td>Direct, only kinematics; no cancellations in incoherent sum</td>
</tr>
</tbody>
</table>

Relic neutrino density: $336 \, \nu \, \text{cm}^3$
Neutrino Mass Measurement

\[ \frac{d\Gamma}{dE} = C \cdot F(Z, E) \cdot p(E + m_e) \cdot (E_0 - E) \sum_i |U_{ei}|^2 \cdot \sqrt{(E_0 - E)^2 - m^2(\nu_i)} \]

Key requirements:
- high-activity source
- low-endpoint β emitter (\(^3\text{H}\)) or EC isotope (\(^{163}\text{Ho}\))
- excellent energy resolution (MAC-E filter or calorimeter)

„Direct“ kinematic measurement

spectral distortion measures
“effective” mass square:

\[ m^2(\nu_e) := \sum_i |U_{ei}|^2 \cdot m_i^2 \]
MAC-E Filter - Principle

Electrostatic spectrometer:

\[ q \cdot \vec{E} \quad U \quad q \cdot \vec{E} \]

Solenoid

\[ \vec{B} \]

No electron flux for:  \[ E_{kin} = e \cdot U_{max} \]
Adiabatic variation of B-field leads to alignment of momentum vector.
KATRIN = Karlsruhe Tritium Neutrino Exp.

Goal: measure neutrino mass with sensitivity of 0.2 eV (90%CL)

~ 70 m

Windowless Gaseous Tritium Source

- tritium $\beta$-decay
- decay rate: $10^{11}$ 1/s
- $T_2$ pressure: $10^{-3}$ to $10^{-6}$ mbar

Differential and Cryogenic Pumping sections

- $\beta$-electron transport
- tritium retention (factor $>10^{14}$)

Pre-Spectrometer

- energy analysis of $\beta$-electrons
- resolution 0.93 eV @ 18.6 keV
- pressure $<10^{-10}$ mbar
- counting of transmitted $\beta$-electrons
  $<1e/\text{s}$

Main Spectrometer

Detector
Journey of KATRIN
Looks good on paper, but ...
After 3 years:

sensitivity (90% CL)
$m(\nu) < 0.2$ eV

discovery potential
$m(\nu) = 0.35$ eV ($5\sigma$)

Starts now!
Holmium Electron Capture

$^{163}\text{Ho} \rightarrow ^{163}\text{Dy}^* + \nu_e$

Low $Q_{EC} \sim 2.8$ keV and $T_{1/2} \sim 4570$ years

Challenges:
- production & purification of isotope $^{163}\text{Ho}$
- incorporation of $^{163}\text{Ho}$ into high-resolution detectors
- operation & readout of large calorimeter arrays
- detailed understanding of calorimetric spectrum (nuclear & atomic physics + detector response)

How to measure 2.8 keV w/ high precision?

Dy = Dysprosium
Micro Calorimeters: MMCs

**MMC:** metallic magnetic calorimeters with paramagnetic sensor Au:Er

\[ \delta T \text{ in absorber from EC-decay} \Rightarrow \text{change in magnetization } M \text{ of sensor} \]

signal: \[ \delta \Phi_s \sim \frac{\partial M}{\partial T} \cdot \Delta T \sim \frac{\partial M}{\partial T} \cdot \frac{1}{C_{\text{tot}}} \cdot \delta E \]

thermometers micro-calorimeters with transition edge sensor (TES)

\[ \delta T \text{ in absorber from EC-decay} \Rightarrow \text{change in temperature } T \text{ and} \\
\text{resistance } R \text{ of thermistor} \]

signal: current change measured by SQUID array

L. Gastaldo
C. Enss
MMC technology: ECHO

Uni Heidelberg:
C. Enss, L. Gastaldo
Mass parabola from Weizsäcker formula

Normal $\beta$-decay energetically forbidden for $^{74}$Ge. Double $\beta$-decay allowed: even-even nuclei.
Neutrinoless Double Beta Decay

Allowed in SM, $\Delta L=0$

Half-life: $T_{1/2}^{2\nu} \sim (10^{18} - 10^{24})$ yr

$T_{1/2}^{2\nu}(^{76}\text{Ge}) = (1.93 \pm 0.10) \cdot 10^{21}$ yr

Allowed only if neutrinos are Majorana particles
Helicities – Mass dependence

\[ \bar{\nu}_R = \nu_L^c = \nu^\uparrow + \epsilon \cdot \nu^\downarrow \]

\[ \nu_L = \nu^\downarrow + \epsilon \cdot \nu^\uparrow \]

\[ \epsilon \sim O \left( \frac{m_\nu}{2E_\nu} \right) \]

i.e. no \( 0\nu2\beta \) für vanishing \( m_\nu \)

\[ \rightarrow \text{Probability to observe } 0\nu2\beta \]

is suppressed by \( (m_\nu / 2E_\nu)^2 \)

If the flavor state \( \nu_e \) is a mixture of mass states:

\[ \Gamma(0\nu2\beta) \sim \frac{\sum U_{ei}^2 m_i}{E_\nu^2} \sim \left( m_{\beta\beta} \right)^2 \]

with \( \sum U_{ei}^2 m_i = \left( m_{\beta\beta} \right) \)
Resolve mass hierarchy

\[
\left( T_{1/2}^{0\nu} \right)^{-1} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2
\]

- \( G^{0\nu}(Q, Z) \) = Phase Space integral
- \( |M^{0\nu}|^2 \) = nuclear matrix element
- \( \langle m_{\beta\beta} \rangle^2 = \sum_i U_{ei}^2 m_i \) = effective \( \nu \) mass
- \( U_{ei} \) = PMNS mixing matrix elements
Germanium $^{76}\text{Ge}$:
• Candidate for 2$\beta$ decay
• Same decay and detector material
• Germanium detectors have excellent energy resolution: FWHM $\sim 1.5 \times 10^{-3}$
• Enrichment of $^{76}\text{Ge}$ up to 86%

Source = Detector

Ge diode w/ reverse biasing
GERDA Experiment

- Located in Hall A at Laboratori Nazionali del Gran Sasso of INFN
- 3800 mwe overburden ($\mu$ flux $\sim 1 \text{ m}^{-2}\text{h}^{-1}$)
- Array of bare Ge detectors 86% enriched in $^{76}$Ge directly inserted in liquid argon (LAr)

<table>
<thead>
<tr>
<th>Material</th>
<th>$^{208}$TI Activity [μBq/Kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock, concrete</td>
<td>3000000</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>$\sim 5000$</td>
</tr>
<tr>
<td>Cu (NOSV), Pb</td>
<td>$&lt; 20$</td>
</tr>
<tr>
<td>Purified water</td>
<td>$&lt; 1$</td>
</tr>
<tr>
<td>LN$_2$, LAr</td>
<td>$\sim 0$</td>
</tr>
</tbody>
</table>
Gerda Construction

Copper shield

Vacuum-insulated double wall stainless steel cryostat
**GERDA Results**

*Phys. Rev. Lett. 111 (2013) 122503*

**Total livetime:** 492.3 days  
**Exposure:** 21.6 kg·yr

**Pulse shape discrimination**

<table>
<thead>
<tr>
<th>Pulse Shape Discrimination</th>
<th>Dataset</th>
<th>Obs.</th>
<th>Exp. bkg</th>
</tr>
</thead>
<tbody>
<tr>
<td>no</td>
<td>Golden</td>
<td>5</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>Silver</td>
<td>1</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>BEGe</td>
<td>1</td>
<td>1.0</td>
</tr>
<tr>
<td>yes</td>
<td>Golden</td>
<td>2</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Silver</td>
<td>1</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>BEGe</td>
<td>0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**GERDA Phase II**

- Expected background at $Q_{\beta\beta}$: $10^{-3}$ counts/(keV·kg·yr)
- Expected sensitivity: $T_{1/2}^{0\nu} \sim 1.4 \cdot 10^{26}$ yr, $m_{\beta\beta} \sim 0.1$ eV

**Limit on effective neutrino mass**

\[ T_{1/2}^{0\nu} > 2.1 \cdot 10^{25} \text{ yr} \]

@90% C.L.

\[ m_{\beta\beta} < 0.2\text{-}0.4 \text{ eV} \text{ (90\% C.L.)} \]
FIG. 2 (color online). Limits (90% C.L.) on $T_{1/2}^{0\nu}$ of $^{76}\text{Ge}$ (this work) and $^{136}\text{Xe}$ [14,15] compared with the signal claim for $^{76}\text{Ge}$ of Ref. [11] (68% C.L. band). The lines in the shaded gray band are the predictions for the correlation of the half-lives in $^{136}\text{Xe}$ and in $^{76}\text{Ge}$ according to different NME calculations [27,28,33–37]. The selection of calculations and the labels are taken from Ref. [29].

Heidelberg-Moscow Experiment

Ruled out

Fig. 17. The total sum spectrum of all five detectors (in total 10.96 kg enriched in $^{76}\text{Ge}$), for the period November 1990–May 2003 (71.7 kg year) in the range 2000–2060 keV and its fit (see Section 3.2).

- $0.34-2.03 \times 10^{25}$ y (3 sigma)
- Best fit $1.19 \times 10^{25}$ y
- $m_{ee} = 0.1-0.9$ eV
- best fit 0.44 eV
$T_{0\nu} > 6.6 \times 10^{24}$ yr
$m_{\beta\beta} < 210 - 590$ meV

July 2017, preliminary
Constraints on mass hierarchy