Double Beta Decay and Lepton Number Violation

\[ \Delta L \neq 0 \]
Why are Neutrino Masses so small?

if neutrinos acquire their mass by coupling to the Higgs, in the same way as the charged leptons, why should the coupling be so different?
Neutrino Mass

SM massterms: \( m \left( \bar{e}_L e_R + \bar{e}_R^c e_L^c \right) \)

\[
\psi_L \quad m \quad \psi_R
\]

particle \quad particle

no \( \nu_R \) or \( \nu_L^c \) in standard model

\( \Rightarrow \) no \( V \)-massterm

\( \Rightarrow \) add \( \nu_R \) , \( \nu_L^c \)

\[
\begin{align*}
N_L &= \begin{pmatrix} \nu_L \\ \nu_L^c \end{pmatrix} \\
N_R &= \begin{pmatrix} \nu_R \\ \nu_R^c \end{pmatrix}
\end{align*}
\]

( active sterile)

two degenerate mass-eigenvalues \( m_D \)

Dirac

\[ \nu_L \quad \nu_L^c \quad
\nu_R \quad \nu_R^c \]

\[ \nu_D \neq \nu_D^c \]

Majorana

\[ \nu_{M,L} = \nu_L + \nu_L^c \]

\[ \nu_{M,R} = \nu_R^c + \nu_R \]

\[ \nu_M = \nu_M^c \]
Majorana Neutrino

\[ \nu_M = \nu_M^c \]

\[
\begin{align*}
\psi_L & \quad m \quad \psi_R \\
\text{particle} & \quad \text{particle} \\
\end{align*}
\]

\[
m_D \bar{\nu}_L \nu_R + m_D \bar{\nu}_L^c \nu_R^c \\
= \bar{N}_L \left( \begin{array}{cc} M_L & m_D \\ m_D & M_R \end{array} \right) N_R \\
\]

\[
N_L = \begin{pmatrix} \nu_L \\ \nu_C_L \end{pmatrix} \\
N_R = \begin{pmatrix} \nu_C_R \\ \nu_R \end{pmatrix} \\
\]

Mass-eigenvalues split

\[
\nu_{M,L} = \nu_L + \nu_L^c \\
\nu_{M,R} = \nu_R^c + \nu_R \\
\nu_M = \nu_M^c \\
\]

Majorana
Majorana Neutrino

\[ \nu_M = \nu_M^c \]

\[
\begin{pmatrix}
0 & m_D \\
m_D & M_R
\end{pmatrix}
\]

- \( m_D \) normal Fermion-mass
- \( M_R \approx \) higher scale (GUT ?)

\[
m_1 = \frac{m_D^2}{M_R}
\]
mostly left-handed, active

\[
m_2 = M_R
\]
mostly right-handed, sterile

\[
\Rightarrow \quad \nu \quad \text{we know}
\]

\[
to \ get \quad m_1 \sim \text{meV} \quad M_R \sim 10^{15} \text{eV}
\]

Majorana

\[
\nu_{M,L} = \nu_L + \nu_L^c
\]

\[
\nu_{M,R} = \nu_R^c + \nu_R
\]

\[
\nu_M = \nu_M^c
\]
Majorana Neutrino

\[ \nu_M = \nu_M^c \]

\[ \nu \] has no charge \( \Rightarrow \) can be Majorana-particle
\[ \Rightarrow \] can explain small \( \nu \) – mass (even with normal \( m_D \))

*Neutrino is a normal Fermion, it just happened to have no charge*

\( \Rightarrow \) heavy right handed partner
\( \Rightarrow \) decays in early Universe \( \Delta L \neq 0 \)
\( \Rightarrow \) creates Matter - Antimatter imbalance

**Majorana**

\[ \nu_{M,L} = \nu_L + \nu_{L}^c \]
\[ \nu_{M,R} = \nu_{R}^c + \nu_R \]

\[ \nu_M = \nu_M^c \]
Majorana Neutrino

$\nu_M = \nu_M^c$

$\nu$ has no charge $\Rightarrow$ can be Majorana-particle
$\Rightarrow$ can explain small $\nu$ – mass (even with normal $m_D$)

*Neutrino is a normal Fermion, it just happened to have no charge*

$\Rightarrow$ heavy right handed partner
$\Rightarrow$ decays in early Universe $\Delta L \neq 0$
$\Rightarrow$ creates Matter - Antimatter imbalance

$\nu_M = \nu_M^c$
$\Delta L \neq 0$

CP violation in $\nu$-sector

$\Rightarrow$ Us! Matter in the Universe
Search for Neutrino-less Double Beta Decay

ΔL ≠ 0

easiest but not easy way to see
if ν are Majorana-type

⇒ checks
Majorana character
⇒ very sensitive to m_ν
Sensitivity

\[ 1 / T_{1/2} = G \cdot \text{NME}^2 \cdot m_{\beta\beta}^2 \]

phase space \( \sim Q^5 \)

no favored isotope considering spread of nuclear matrix elements and \( Q \)-values

NME extremely important to get \( m_{\beta\beta}^2 \)

large mass \( [kg_{\text{isotope}}] \)

low background in ROI \( [cts / FWHM t_{\text{isotope yr}}] \)

\( \Delta L \neq 0 \)
Sensitivity

effective neutrino mass

\[ \frac{1}{T_{1/2}^{0\nu}} = G \cdot \text{NME}^2 \cdot m_{\beta\beta} \]

phase space \( \sim Q^5 \)
nuclear matrix element

sensitivity on \( T_{1/2}^{0\nu} \)

mid term: \textbf{a few} \( 10^{26} \) yrs \( (m_{\beta\beta} \sim 40-100 \text{ meV}) \)
long term: \textbf{a few} \( 10^{27} \) yrs \( (m_{\beta\beta} \sim 10-20 \text{ meV}) \)

large mass
[\text{kg}_{\text{isotope}}]

low background in ROI
[\text{cts} / \text{FWHM} t_{\text{isotope yr}}]
Double Beta Decay and Lepton Number Violation $\Delta L \neq 0$

easiest but not easy way to see if $\nu$ are Majorana-type

mid term: a few $10^{26}$ yrs ($m_{\beta\beta} \sim 40$-100 meV)
long term: a few $10^{27}$ yrs ($m_{\beta\beta} \sim 10$-20 meV)

sensitivity on $T_{1/2}^{0\nu}$

via $\nu$ exchange

$1 / T_{1/2}^{0\nu} = G \cdot NME^2 \cdot m_{\beta\beta}^2$

phase space nuclear matrix element
Double Beta Decay and Lepton Number Violation $\Delta L \neq 0$

The easiest but not easy way to see if $\nu$ are Majorana-type involves double beta decay ($2\nu\beta\beta$) via $\nu$ exchange.

- **Sensitivity on $T_{1/2}^{0\nu}$**
  - Mid term: a few $10^{26}$ yrs ($m_{\beta\beta} \sim 40-100$ meV)
  - Long term: a few $10^{27}$ yrs ($m_{\beta\beta} \sim 10-20$ meV)

The effective neutrino mass is given by

$$\frac{1}{T_{1/2}^{0\nu}} = G \cdot NME^2 \cdot m_{\beta\beta}^2$$

where $G$ is the coupling constant, $NME$ is the nuclear matrix element, and $m_{\beta\beta}$ is the mass of the neutrino.

The graph shows the dependence of $m_{\beta\beta}$ on $m_{\text{light}}$ with sensitivity at 17 meV.
Double Beta Decay and Lepton Number Violation $\Delta L \neq 0$

- $\nu$ are Majorana-type
- $\Delta L \neq 0$ is the key, not so much $m_{\beta\beta}$

mid term: a few $10^{26}$ yrs ($m_{\beta\beta} \sim 40$-100 meV)
long term: a few $10^{27}$ yrs ($m_{\beta\beta} \sim 10$-20 meV)

sensitivity on $T_{1/2}^{0\nu}$

other $\Delta L \neq 0$ processes

LR symmetry

heavy $W_R$ and $N_R$ exchange

$\beta\beta$ searches complementary and competitive

arXiv:1509.00423v1
### Search for Neutrino-less Double Beta Decay

\( \Delta L \neq 0 \)

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<th>Ge detectors</th>
<th>very good ( \Delta E ) (narrow ROI)</th>
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<th>CdZnTe detectors</th>
<th>larger variety of isotopes, new techniques</th>
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<td>COBRA</td>
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| cryo bolometers Te              |                                          |
|---------------------------------|                                          |
| CUORE                            |                                          |

| cryo + light Te, Mo             |                                          |
|---------------------------------|                                          |
| Cupid, AMoRe                    |                                          |

competetive limits running in preparation R&D and future projects
liquid Xenon TPC enriched in $^{136}\text{Xe}$ (80.6 %), charge and light detection

WIPP New Mexico USA

$\Delta E \sim 70$ keV FWHM

self shielding, multi site recognition

EXO 200: 170 kg$_{\text{isotope}}$ total / 80 kg$_{\text{isotope}}$ active volume

results:

234 kg·yr exposure

sensitivity $5.0 \cdot 10^{25}$ yr

$T_{1/2}^{0\nu\beta\beta} > 3.5 \cdot 10^{25}$ yr

background in ROI

170 / FWHM · t$_{\text{isotope}}$ · yr

PRL 120 072701 (2018)
liquid Xenon single TPC

5000 kg enriched IXe

expected to be at SNOLAB

improved performance:
  energy and position resolution ….

R&D on Ba-tagging

goal $T_{1/2}^{0
\nu\beta} > 9.2 \cdot 10^{27}$ yr exclusion
  $5.7 \cdot 10^{27}$ yr discovery

background in ROI
  $\sim 0.6 / \text{FWHM} \cdot \text{isotope} \cdot \text{yr}$

arXiv 1710.05075
Liquid Scintillator - KamLAND-Zen

3 m diam. ballon: **liquid scintillator** loaded with enriched Xenon inserted into KamLAND

$\Delta E \sim 250$ keV FWHM

**results:** 383 kg Xe / 110 kg$_{\text{isotope}}$ in FV

$\sim 600$ kg·yr

$T_{1/2}^{0\nu\beta\beta} > 10.7 \cdot 10^{25}$ yr

sensitivity $5.6 \cdot 10^{25}$ yr

background in ROI $\sim 60 / \text{FWHM} \cdot t_{\text{isotope}} \cdot \text{yr}$

PRL 117 082503 (2016)
Liquid Scintillator - SNO+

infrastructure at SNOLAB

Phase I:
acrylic vessel filled with LS
+ 4000 kg of nat-Te
(~30% Te-130)

LS filling 2019
Te loading 2020

sensitivity goal $T_{1/2}^{0
\nu
\beta} > 1.9 \cdot 10^{26}$ yr

Phase II: more Te, better FWHM

THEIA project: 50 kton water-based liquid scintillator
solar-ν will be dominant background
Calorimetry at mK temperature in natural TeO$_2$ crystals $^{130}$Te (30%)

CUORE 750 kg TeO$_2$ (206 kg $^{130}$Te)
988 crystals

**results 2019:**
369.9 kg·yr (103 kg·yr $^{130}$Te)
$\Delta E \sim 8$ keV FWHM

$$ T^{0\nu\beta\beta}_{1/2} > 2.3 \cdot 10^{25} \text{ yr} $$

background in ROI
$\sim 450 \text{ / FWHM} \cdot t_{\text{isotope}} \cdot \text{yr}$

**goals:**
goal sensitivity
$$ T^{0\nu\beta\beta}_{1/2} > 9.5 \cdot 10^{25} \text{ yr} $$

background
$\sim 180 \text{ / FWHM} \cdot t_{\text{isotope}} \cdot \text{yr}$

potential upgrade with calorimetry + light
CUORE $\Rightarrow$ CUPID
**Scintillating bolometers**

**AMORE** @ Yangyang UGL Korea

**goal**

sensitivity $T_{1/2}^{0\nu\beta\beta} > 3 \cdot 10^{26}$ yr for $^{100}$Mo 250kg·yr exposure

**AMORE-Pilot results**

2kg CaMoO$_4$, 0,3 kg·yrs exposure still very high background

$T_{1/2}^{0\nu\beta\beta} > 9,5 \cdot 10^{22}$ yr

**CANDLES** @ Kamioka / Japan

$^{48}$Ca highest Q-value 4,27MeV, lowest abundance 0,187%

305 kg CaF scintillator detectors in liquid scintillator

result from 131 days

$T_{1/2}^{0\nu\beta\beta} > 6,2 \cdot 10^{22}$ yr

working on scintillating bolometers first demonstration results
Ge detectors
Cu/Pb shielding

Sanford Lab, USA
44.1 kg $^{76}\text{Ge}$ (88%) running

results
26 kg·yr

$T_{1/2}^{0\nu\beta\beta} > 2.7 \times 10^{25}$ yr

background in ROI
18 / FWHM·$t_{\text{isotope}}$·yr

PRC 100 025501 (2019)
GERDA

\[ \Delta L \neq 0 \]

\[ \Delta E \sim 3\text{keV FWHM} \]

LAr veto combines
selfshielding / veto of liquid noble gas
high resolution of Ge detectors
pulse shape discrimination
multi site and surface event recognition

GERDA Phase II
started Dec 2015
35,6 kg enr. Ge (86%)
goals:
- 100 kgyr
- sensitivity $> 10^{26}$ yr
- bkg 3 / FWHM t yr
GERDA combines advantages
- active shielding of liquid noble gas
- high energy resolution of Ge detectors
GERDA

\[ \Delta L \neq 0 \]
pulse shape discrimination
multi site and surface event recognition

i) $\beta\beta$ decay is localized (pointlike) – single site event

ii) signal generation mostly when charges reach region close to small electrode

iii) different drift times for multi site events => slower signal rise

iv) $\alpha$ decays at unprotected contact surface show very fast rise
- 97% of events between 600-1300keV are $2\nu\beta\beta$
- Background 250 times lower compared to Heidelberg-Moscow Exp. (~10y)

pulse shape discrimination
- single site / multi site
  ⇒ $\gamma$ lines supressed by ~ 6
- surface / bulk
  ⇒ all $\alpha$ (surface) events removed
GERDA results

82.4 kg·yr total exposure

background in ROI

$4 / \text{FWHM} \cdot t_{\text{isotope}} \cdot \text{yr}$

sensitivity $11 \cdot 10^{25} \text{yr}$

$T_{1/2}^{0\nu\beta\beta} > 9 \cdot 10^{25} \text{yr}$

background free $0\nu\beta\beta$ experiment → potential for discovery (up to $\sim 10^{26} \text{yr}$)

makes sense to grow larger (background goal for LEGEND 200 almost reached)
new collaboration formed LEGEND
Majorana + GERDA members + others

use GERDA concept and staged approach to 1000kg

⇒ one worldwide collaboration on $^{76}$Ge

LEGEND 200: first 200kg in GERDA setup @ Gran Sasso

- starting 2021
- $^{76}$Ge available for 190kg of detectors
- funded by NSF, INFN, MPI, BMBF

sensitivity $> 10^{27}$ yr

LEGEND 1000: 1000kg phase depends on US down selection process

sensitivity $> 10^{28}$ yr
Search for Neutrinoless Double Beta Decay

ΔL ≠ 0

Search for Neutrinoless Double Beta Decay

50% chance for 3σ discovery

1t for 3yr

1t for 17yr

low background essential for discovery potential

background free regime

\[ T_{1/2} \sim \text{exposure} \]
Summary

- search for double beta decay highly motivated:
  \( \Delta L \neq 0 \), Majorana \( \nu \), lightness of \( \nu \)-mass, Leptogenesis

  next experiments explore range up to
  \( T_{1/2} < 10^{27} \) yr mid term
  \( T_{1/2} < 10^{28} \) yr long term

  \( \Rightarrow \) chance for discovery of \( \Delta L \neq 0 \)

- field is very active and competitive,
  variety of approaches and technologies

\[ \Delta L = 0 \]