Lepton Number violating Decays: Theoretical and experimental Challenges

Manfred Lindner

Knoxville, TN, July 29-31, 2016
Neutrino Masses: New Physics...

**Simplest possibility:** assume 3 right handed singlets \( (1_L) \)

\[
\begin{align*}
\nu_L \ g_N \ & \nu_R \\
\nu_R \ & \nu_R \\
\langle \phi \rangle = & \nu
\end{align*}
\]

\( \mathcal{L} \)

- Majorana mass = scales
- lepton number violation

+9+ new ingredients: \( \Rightarrow \) SM+

6x6 block mass matrix

block diagonalization

\( M_R \) heavy \( \Rightarrow \) 3 light \( \nu \)'s

Or: **add scalar triplets** \( (3_L) \)

or **fermionic** 1\(_L\) or 3\(_L\)

\( \Rightarrow \) left-handed Majorana mass term:

\[
\begin{pmatrix}
\nu_L \\
\nu_R \\
\nu_R \\
\nu_R
\end{pmatrix}
\]

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

\[
\begin{pmatrix}
\nu_L \\
\nu^c_L
\end{pmatrix}
\]

\( M_LLL^c \)
Both $\nu_R$ and new singlets / triplets:

$\Rightarrow$ see-saw type II, III

$$m_\nu = M_L - m_D M_R^{-1} m_D^T$$

Higher dimensional operators: $d=5, \ldots$

Radiative neutrino mass generation

SUSY, extra dimensions, \ldots

$\Rightarrow$ neutrino masses can/may solve two of the SM problems:

- see-saw $\Rightarrow$ leptogenesis as best explanation of BAU
- keV sterile neutrinos as excellent warm dark matter candidate
even for $\nu_R \Rightarrow$ BSM physics $\leftrightarrow$ often connections to LFV, LHC, DM
Majorana Masses well motivated

⇒ Lepton Number Violation

⇒ Neutrinoless Double Beta Decay

Warning:

1) All we know is two $\Delta m^2$ and three mixing angles, no CP phase (yet)
   ⇒ uncertainties and unknown parameters in 3 flavour picture
   ⇒ which mass mechanism? how many right-handed fields? …???
2) Be careful about the reverse reasoning…: $0\nu\beta\beta$ ⇒ Majorana…
The Standard Picture of Double Beta Decay

$2\nu\beta\beta$ decay seen for diff. isotopes (Kirsten,…)
$T^{1/2} = O(10^{18} - 10^{21} \text{ years}) \Rightarrow \text{up to } 10^{11} \otimes T_{\text{Universe}}$

$0\nu\beta\beta$ decay

$2\nu\beta\beta$ decay

T$^{1/2} > O(10^{25} \text{y})$

- observe $2\nu\beta\beta$
- look for $0\nu\beta\beta$ signal at $Q_{\beta\beta}$
- large amount of $^{76}\text{Ge}$ nuclei
- extreme low backgrounds!

$\Rightarrow$ signal = Majorana mass
Special nuclei:
• single $\beta$ decay energetically forbidden
• double $\beta$ decay allowed

$Q_{\beta\beta} = 2039$ keV

Odd-odd
Even-even

Important: Isotopes with forbidden single $\beta$ decay

$^{76}$Ge: Only double $\beta$ decay $\rightarrow$ SM: $2\nu + 2e^-$ *OR* $2e^-$

Further double beta isotopes…
\( m_{ee} : \text{The Effective Neutrino Mass} \)

\[
m_{ee} = |m_{ee}^{(1)}| + |m_{ee}^{(2)}| \cdot e^{i\Phi_2} + |m_{ee}^{(3)}| \cdot e^{i\Phi_3}
\]

- \( |m_{ee}^{(1)}| = |U_{e1}|^2 m_1 \)
- \( |m_{ee}^{(2)}| = |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2} \)
- \( |m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2} \)

**Comments:**
- two cases: NH and IH
- includes current exp. errors
  - some improvements
  - missing: CP phases, NH/IH
  - picture complete?
- NMEs → unavoidable theory errors
- Lower bound for IH:
  \[
  \frac{1}{\sqrt{\Delta m^2_{A} c^2_{13} \cos 2\theta_{12}}} \Rightarrow \sqrt{\Delta m_{31}^2} \geq \frac{m_{0}}{1-t_{13}^2-2s_{13}^2 t_{13}}
  \]
  ↔ fully test IH case: \( \sim \) few meV

ML, Merle, Rodejohann
Recently: New results from
- KamLAND-Zen
- GERDA-II
- Majorana demonstrator

⇒ reaching IH !?

⇒ new projects to cover IH
- big, expensive, long-term…
- log scale plot
- uncertainties, other information

⇒ how robust? other opportunities?
Robustness #1: Improved $\nu$ parameters

neutrino parameter measurements $\rightarrow$ improved precision

$\Rightarrow$ positive: better know lower bound for IH
$\Rightarrow$ negative: IH may be excluded in a few years
The absolute Neutrino Mass

- Waiting for KATRIN ➔ data taking to start 2016/2017 ➔ factor 10 improvement to ~ 0.2 eV ➔ and then? PROJECT 8 and other developments…

- Cosmology and the sum of neutrino masses:

  \[
  \begin{align*}
  \text{NH: } & 0.06 \text{ eV} \\
  \text{IH: } & 0.12 \text{ eV} \\
  \Sigma(m_i) & \leq 0.14...0.20 \text{ eV}
  \end{align*}
  \]

  ➔ IH seems to become a bit disfavoured by cosmology ➔ the same (weak) trend seems to appear in global oscillation fits

  ➔ if real ➔ very important for $0\nu\beta\beta$ experiments
Robustness #2: NMEs
For a Majorana mass $\Delta L=2$ process

2 Neutrons (in one nucleus) $\Rightarrow$ 2 protons + 2 electrons $\iff (Z,N) \Rightarrow (Z+2,N)$

$\Rightarrow$ 2$^{\text{nd}}$ order weak process $\Rightarrow$ extremely rare….

transition time $O(10^{25} \text{ Jahre})$ $\iff \mathcal{T}_{\text{Universum}} = 1.3 \times 10^{10} \text{ Jahre}$

$\Rightarrow$ reasonable rate $\Rightarrow$ large amount of some special isotope

$\Rightarrow$ rare $\Rightarrow$ enormous suppression of all sort of backgrounds

$\Rightarrow$ non-perturbative problem: nuclei are bound states!
NME’s: Relating Lifetimes & Neutrino Masses

\[ \frac{1}{\tau} = G(Q, Z) |M_{\text{nucl}}|^2 <m_{ee}>^2 \]

rate of $0\nu\beta\beta$

nuclear matrix elements:

- virtual excitations of intermediate states

\[ 0^+ + 1^+ + 2^- \]

nuclear matrix elements:

\[
\begin{align*}
\text{phase space} & \quad \text{nuclear matrix elements} & \quad \text{effective Majorana neutrino mass} \\
\text{rate of } 0\nu\beta\beta & \quad \text{virtual excitations of intermediate states} & \quad \text{effective Majorana neutrino mass}
\end{align*}
\]

progress in TH errors

- which NME is correct?
- but: what is a $1\sigma$ theory error?
- experimental cross-checks of TH!

M. Lindner, MPIK
Robustness #3: $g_A$ quenching?
Quenching

Half-life: \[ T_{1/2}^{-1} = m_{\beta\beta}^2 G^{0\nu} g_A^4 |M^{0\nu}|^2 \]

Axial-vector coupling \( g_A \):
- Free nucleon: \( g_A \approx 1.27 \)
- Comparison of \( \beta \) and \( 2\nu\beta\beta \) decay with theory: \( g_A \approx 0.6 - 0.8 \)
- Needs further studies
- If applicable to \( 0\nu\beta\beta \)
  - reduced of sensitivity
  - potentially big impact: \( (g_A)^4 \)
Robustness #4: Beyond minimal Szenario
More general: L Violating Processes

**SM**

$2\nu\beta\beta$

**BSM**

$T^{1/2} > O(10^{25} y)$

$0\nu\beta\beta$

...interpretation changes:

Search unchanged…

$0\nu\beta\beta$ decay

$2\nu\beta\beta$ decay
Other Double Beta Decay Processes

Standard Model:

\[ \nu_{\beta\beta} \rightarrow 2 \text{ electrons} + 2 \text{ neutrinos} \]

Majorana \( \nu \)-masses or other \( \Delta L=2 \) physics:

\[ \nu_{\beta\beta} \rightarrow 2 \text{ electrons} \]

- Majorana neutrino masses \( \leftrightarrow \) Dirac?
- SM + Higgs triplet
- SUSY
- Important connections to LHC and LFV ...
- Sub eV Majorana mass \( \leftrightarrow \) TeV scale physics
Interference of $\Delta L=2$ Operators

Usually
\[
(T_{1/2}^{0\nu})^{-1} = \left(\frac{|m_{0\nu}/m_e|}{m_e}\right)^2 |\mathcal{M}_{}^{0\nu}|^2 G^{0\nu}.
\]

with interferences
\[
(T_{1/2}^{0\nu})^{-1} = |m_{0\nu}/m_e M_{}^{0\nu} + \epsilon m_e M_{}^{\epsilon}(M_{}^{0\nu})^{-1}|^2 \frac{G_{int}}{m_e^2} \\
= |(m_{0\nu}/m_e M_{}^{0\nu} + \epsilon m_e M_{}^{\epsilon}(M_{}^{0\nu})^{-1})M_{}^{0\nu}|^2 \frac{G_{int}}{m_e^2} \\
= |m_{int}/m_e|^2 |M_{}^{0\nu}|^2 \frac{G_{int}}{m_e^2},
\]

\[G_{int} = \epsilon m_e M_{}^{\epsilon}\]

= overall phase space factor
\[\leftrightarrow\] determined by parameters of new physics

\[m_{int} = m_{0\nu}/m_e M_{}^{0\nu} + \epsilon m_e M_{}^{\epsilon}(M_{}^{0\nu})^{-1} \equiv m_{0\nu}/m_e + m_\epsilon.\]

\[m_\epsilon \sim (\Lambda_{new})^{-5}\]

\[m_{0\nu}/m_e = 1 \text{ eV} \leftrightarrow \Lambda_{new} \sim \text{TeV}\]
**Extreme Cases**

$m_{ee}$ from Majorana neutrinos only and no other $\Delta L=2$ physics

$m_\epsilon$ from other $\Delta L=2$ physics with Dirac neutrino masses

and anything in-between
interferences
growing $m_\epsilon$ for fixed $0\nu\beta\beta$
\rightarrow shifts of masses, mixings and CP phases
\rightarrow destroys ability to extract Majorana phases
\rightarrow sensitivity to TeV
The Schechter-Valle Theorem induced Mass

- any $\Delta L = 2$ operator which leads to $0\nu\beta\beta$ decay induces via loops a Majorana mass $\Rightarrow$ must $\nu$'s be Majorana?
- assume a $0\nu\beta\beta$ signal $\Rightarrow$ how big is the induced mass?

4 loops $\Rightarrow$ $\delta m_\nu = 5 \times 10^{-28}$ eV $\Rightarrow$ extremely tiny (academic)
$\Rightarrow$ cannot explain observed $\nu$ masses and splittings
$\Rightarrow$ explicit Dirac neutrino mass operators required

Extreme possibility:
- $0\nu\beta\beta = L$ violation = other BSM physics
- neutrino masses = Dirac (plus very tiny correction)
CON: Cosmology / BBN
→ how many light sterile \( \nu \)'s allowed? (thermalized? LAU? …)
+/- how many \( \sigma \)'s required? +/- systematics (H\( \leftrightarrow \)N\(_{\text{eff}}\))
→ pushing it: at most 1,2 steriles …

PRO: Various hints for sterile neutrinos
Reactor anomaly, LSND, MiniBooNE, MINOS, Gallex…
→ hints for light sterile \( \nu \)'s? → not all; one would be enough
→ new and better data / experiments are needed
Sterile neutrinos solve problems:
- keV sterile \( \nu \) is an excellent warm dark matter candidate
- avoid small scale crisis of CDM
- leptogenesis as explanation of BAU
- TeV-ish sterile \( \nu \)'s improve overall EW fits!

theory: natural explanation for light sterile \( \nu \)'s with small mixings
Light sterile $\nu$’s $\Rightarrow$ modified See-Saw

Grimus, Lavoura; Hettmansperger, ML, Rodejohann; ...

The usual see-saw equations are an approximation:

$\tilde{m}_\nu = -m_D^T M_R^{-1} m_D$
$\tilde{M}_R = M_R$

$\rightarrow$ ‘expansion’ in $m_D/M_R$
$\rightarrow$ OK if all elements of $m_D << \min(\text{eigenvalues of } M_R)$

Important corrections to usual see-saw relations if
- $M_R @\text{TeV scale} \leftrightarrow m_D/M_R$ makes relevant corrections
- light sterile neutrinos $\leftrightarrow$ some small eigenvalues of $M_R$

$\Rightarrow$ two ways to go:
1) ‘boundary shifting’
2) NLO and NNLO terms in see-saw expansion
Boundary Shifting

\[
\mathcal{M}_\nu = \begin{pmatrix}
0 & m^{e\mu}_L & m^{e\tau}_L \\
m^{e\mu}_L & 0 & 0 \\
m^{e\tau}_L & 0 & 0 \\
m^{e1}_D & 0 & 0 \\
0 & m^{\mu2}_D & m^{\tau2}_D \\
0 & m^{\mu3}_D & m^{\tau3}_D \\
\end{pmatrix}
\begin{pmatrix}
m^{e1}_D & 0 & 0 \\
0 & m^{\mu2}_D & m^{\mu3}_D \\
0 & m^{\tau2}_D & m^{\tau3}_D \\
\end{pmatrix}
= \begin{pmatrix}
(4x4) & (2x4) \\
(4x2) & (2x2)
\end{pmatrix}
\]

\[
\text{det}(M_{ij}) = 0 \implies M_1 = 0
\]

- Use standard type II see-saw relation for 4x4, 2x4, 4x2 and 2x2 matrices
- ~ expansion
Define: \[ A \equiv m_D m_D^\dagger (M_R^*)^{-1} \quad X \equiv A + A^T \]

\[
\tilde{m}_\nu = -m_D^T M_R^{-1} m_D + \frac{1}{2} m_D^T M_R^{-1} X M_R^{-1} m_D
\]

\[
\tilde{M}_R = M_R + \frac{1}{2} (A + A^T)
\]

\[
\tilde{m}_\nu^{\text{NNLO}} = \frac{1}{2} m_D^T M_R^{-1} \left[ \frac{1}{4} A M_R^{-1} A + \frac{1}{4} A^T M_R^{-1} A^T + \frac{1}{2} A^T M_R^{-1} A + \frac{1}{2} (M_R^*)^{-1} A^* A^T
\]

\[+ \frac{1}{2} A A^\dagger (M_R^*)^{-1} + A A^* (M_R^*)^{-1} + (M_R^*)^{-1} A^\dagger A^T \right] M_R^{-1} m_D,
\]

\[
\tilde{M}_R^{\text{NNLO}} = -\frac{1}{2} \left[ A A^* (M_R^*)^{-1} + (M_R^*)^{-1} A^\dagger A^T + \frac{1}{4} A M_R^{-1} A + \frac{1}{4} A^T M_R^{-1} A^T \right].
\]

\(\Rightarrow 0\nu\beta\beta\) effective neutrino mass modified by the existence of light sterile neutrinos

Hettmansperger, ML, Rodejohann: double, inverse, linear, singular see-saw, … other cases
Recently: New results...

Plot assumes
- certain NMEs
- vanilla 3 flavour
- pure Majorana mass
- \( g_A = 1.27 \)
- no other L violation

IH getting less likely from cosmology and global fits

Experimental effort: Opportunity ↔ cost, time, ... risks
The experimental Challenge
Sensitivity & Background (for a Majorana Mass)

\[ (T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z) \left| M_{0\nu} \right|^2 m_{\beta\beta}^2 \]

\[ m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right| \]

**without background**

\[ N = \log 2 \cdot \frac{N_A}{W} \cdot \varepsilon \cdot \frac{M \cdot t}{T_{1/2}^{0\nu}} \]

- \( N_A \) = Avogadro’s number
- \( W \) = atomic weight of isotope
- \( \varepsilon \) = signal detection efficiency
- \( M \) = isotope mass
- \( t \) = data taking time

\[ m_{\beta\beta} = \sqrt[4]{\frac{N}{\varepsilon M t}} \]

**with background**

\[ N' = N + N_{\text{background}} \]

\[ m_{\beta\beta} = K_2 \cdot \sqrt{1/\varepsilon} \left( \frac{c \, \Delta E}{M t} \right)^{1/4} \]

- \( c = \text{cts/keV/kg/yr} \)
- \( \Delta E = \text{ROI} \)

M. Lindner, MPIK
Two Directions

with background

\[ N' = N + N_{\text{background}} \]

\[ m_{\beta\beta} = K_2 \sqrt{\frac{1}{\varepsilon}} \left( \frac{c \Delta E}{Mt} \right)^{1/4} \]

\( c = \text{cts/keV/kg/yr} ; \Delta E = \text{ROI} \)

biggest possible mass \( M \)
\( \rightarrow \) less energy resolution
\( \rightarrow \) nearby background lines?
\( \rightarrow \) LS, …

smallest resolution \( \Delta E \)
\( \rightarrow \) less mass for sensitivity
\( \rightarrow \) less risk for unknown bgd
\( \rightarrow \) Ge, …

in common:
- minimize background level \( c \)
- long running times \( \leftrightarrow \) stability
- expensive

Question: Affordable path to large \( m \), excellent \( \Delta E \), low bckgd?
GERDA (and Majorana): Lowest $\Delta E$

The required background level:

typical material 30Bq/kg $\sim 10^{12}$ cts/ton/year

GERDA-I
100-1000 cts/keV/ton/year

$\times$ 100
1-10 cts/keV/ton/year

$0.01-0.1$ cts/keV/ton/year

$0.001-0.01$ cts/keV/ton/year

$\Rightarrow$ how low can it become?
The Fight against Background

Extreme rare reaction (T>10^{25} years >> age of Universe)
Magnitude 1 decay/kg/year
Environment ~ 30Bq/kg = 10^9 /kg/year \(\Rightarrow\) 3000/person/second

- avoid single \(\beta\) decay \(\Leftarrow\rightarrow\) suitable isotopes
- avoiding / suppression of environmental radioactivity

- in the 0\(\nu\)\(\beta\)\(\beta\) detector material
  - ultra clean (production, handling)
  - puls form analysis (identify & reject background)

- in the detector parts (e.g. holders, signal amplifiers)
  - lowest amount of material
  - ultra pure materials (selection; environment = O(100Bq/kg) \(\Leftarrow\rightarrow\) \(\mu\)Bq/kg)
  - extremely helpful: \(^{76}\)Ge source = detector (a big Ge diode)

- in the environment
  - ultra clean room (clean room, …)
  - avoid Radon (decay of U, Th in the environment \(\Rightarrow\) \(^{222}\)Rn-gas)
  - avoid cosmogenic activation (new isotopes \(\Rightarrow\) go underground)
  - avoid cosmogenic myons, neutrons \(\Rightarrow\) go underground
\( \gamma \) and Rn Screening Facilities

- \( \gamma \)-screening stations (1mBq/kg) @MPIK underground lab
- 4 GEMPIs (10\( \mu \)Bq/kg) @LNGS
- New: GIOVE (50\( \mu \)Bq/kg) @MPIK
- extensive task for GERDA and other experiments (XENON, ...)

\( Rn \) Screening Facilities \( \leftrightarrow \) \(^{222}\)Rn emanation:

Gas counting systems (LNGS, MPIK)
sensitivity = few atoms/probe
- typ. sensitivity: few \( \mu \)Bq/m\(^2\)

ICPMS: ...
**Extreme Radiopurity Requirements**

- Materials have unavoidably impurities of unstable elements
  - select cleanest raw materials
  - screening
- Processing can clean materials, but also introduce new impurities
  - careful planning & screening
- Transport and activation
  - go underground
- Rn emanation from U and Th in all materials → Rn222 decays…
  - …
- …

Further improvements are very challenging and there are limitations
GERDA Phase I achievement

EPJ C74 (2014) 2764

- various identified backgrounds
- excellent energy resolution
  ➔ tiny ROI (green band)
  ➔ eliminates many backgrounds
  ➔ unprecedented BI

➔ background index (BI) after pulse shape discrimination

\[
BI = 1.0(1) \times 10^{-2} \frac{\text{counts}}{\text{keV kg yr}}
\]
GERDA Phase II

- add more new BEGe detectors ➔ ~factor 2 in $^{76}$Ge mass
- add active veto (light instrumentation) ➔ improved background suppression
  ➔ BI goal: 10-3 counts/(keV kg yr)
- ➔ go for O(100-200kg*yr) exposure

unexpected 42K background
Light Instrumentation for Phase II

transparent nylon cylinder coated with wave length shifter \(\Rightarrow\) avoid drifting of 42K in field

\(\Rightarrow\) phase II: first results
LI works nicely: $^{228}\text{Th}$ Suppression

GERDA preliminary May 2015

2$^{28}$Th calibration run
- anti-coincidence cut (AC)
- AC + PSD
- AC + LAr veto
- AC + LAr veto + PSD

count/s/5 keV

detectors:
4/C, 1/D, 79C, 02B, 35B

energy [keV]

energy [keV]
GERDA Phase II first Results

- DEP events used as proxy for $0\nu\beta\beta$
- signal efficiency: $87.3 \pm 0.9\%$
- $2\nu\beta\beta$ acceptance: $85.4^{+1.9}_{-0.8}\%$

![Graph showing energy distribution and different cuts](image_url)
GERDA Phase II first Results

BEGe, 5.826 kg yr
- before PSD + LAr
- after LAr
- after LAr + PSD

background region

<table>
<thead>
<tr>
<th>Description</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>total # counts in background region</td>
<td>25</td>
</tr>
<tr>
<td>after LAr</td>
<td>7</td>
</tr>
<tr>
<td>after PSD</td>
<td>5</td>
</tr>
<tr>
<td>after LAr + PSD</td>
<td>1</td>
</tr>
</tbody>
</table>

after PSD + LAr veto

\[ BI = 0.7^{+1.1}_{-0.5} \times 10^{-3} \frac{counts}{keV \cdot kg \cdot yr} \]

after PSD + LAr veto
no events left at \( Q_{\beta\beta} \)
Going to huge Detectors…

Limit setting

Testing IH
\[ \Rightarrow 17 \text{ meV} \]
\[ \Rightarrow \sim 10^{28} \text{y} \]

Effort:
- \[ 1 \text{ty} = 200 \text{kg} \times 5 \text{y} \]
- \[ 10 \text{ty} = 1 \text{t} \times 10 \text{y} \]

enrichment lead time:
\[ O(100) \text{ kg/y} \]

\[ \Rightarrow \text{bgd for ton?} \]
\[ \Rightarrow \text{by then the MH should be known and may be NH…} \]
The Value of small $\Delta E$

expected bg from interpolation: 5.1 events w/o PSD
2.5 events with PSD
Good energy resolution is important $\Rightarrow$ less mass, avoids unknown backgrounds $\Rightarrow$ $0\nu\beta\beta$ experiments with big mass and less resolution may see H.O. nuclear lines!
Summary

- Lepton number violation is a very important topic!
- Goes beyond neutrino masses
- Very big new \(0\nu\beta\beta\) experiments \(\rightarrow\) search for L-violation
  - ... are very hard (ultra low background)
  - ... and expensive (large quantities of very special material)
  - ... will take many years (complexity, R&D)
  - ... while expectations will change:
- LHC results/limits \(\leftrightarrow\) ν mass terms (SUSY, \(W_R\), nothing)
- Sterile neutrinos may be confirmed
- The mass hierarchy will be known
- Other L-violation?
- Nuclear physics uncertainties
  - the few meV goal
  - Is uncertain and very hard to reach