Neutrinoless Double Beta Decay Overview

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Dirac vs Majorana

- Origin of neutrino masses beyond the Standard Model
- Two possibilities to define neutrino mass

Dirac mass analogous to other fermions but with \( \frac{m_\nu}{\Lambda_{EW}} \approx 10^{-12} \) couplings to Higgs

Majorana mass, using only a left-handed neutrino → Lepton Number Violation
Beta decays

- Single beta decay
  \[(A, Z) \rightarrow (A, Z + 1) + e^- + \bar{\nu}_e\]

- Allowed double beta (2\(\nu\)\(\beta\beta\)) decay
  \[(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e\]

- Neutrinoless double beta (0\(\nu\)\(\beta\beta\)) decay
  \[(A, Z) \rightarrow (A, Z + 2) + 2e^-\]
  - Violation of lepton number
  - Mediated by Majorana neutrinos
  - Variants
    - 0\(\nu\)\(\beta^+\beta^+\): \[(A, Z) \rightarrow (A, Z - 2) + 2e^+\]
    - 0\(\nu\)\(\beta^+\)EC: \[(A, Z) + e^- \rightarrow (A, Z - 2) + e^+\]
    - 0\(\nu\)ECEC: \[(A, Z) + 2e^- \rightarrow (A, Z - 2)^*\]

- Majoron-aided 0\(\nu\)\(\beta\beta\) decay
  \[(A, Z) \rightarrow (A, Z + 2) + 2e^- + n\chi\]
0νββ

- Half-life
  \[ T_{1/2}^{-1} = |m_{ββ}|^2 G^{0ν} |M^{0ν}|^2 \]

- Particle Physics
  - Leptonic phase space \( G^{0ν} \)
  - Nuclear transition matrix element \( M^{0ν} \)

- Atomic Physics
  - Nuclear transition matrix element \( M^{0ν} \)

- Nuclear Physics
  - Nuclear transition matrix element \( M^{0ν} \)

\[ Q \approx 2–4 \text{ MeV} \]

\[ T_{1/2}^{-1} \propto \left( \frac{|m_{ββ}|^2}{q^4} \right) G_F^4 Q^5 \]

\[ \frac{10^{25} \text{yr}}{T_{1/2}} \approx \left( \frac{|m_{ββ}|}{eV} \right)^2 \]
Three Active Neutrinos

- Effective $0\nu\beta\beta$ Mass

$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}}$$

- Degenerate Regime

$$|m_{\beta\beta}| = m_{\nu} \sqrt{1 - \sin^2(2\theta_{12})\sin^2\left(\frac{\phi_{12}}{2}\right)}$$

- Uncertainty from unknown Majorana phases

- Accidental cancellation for NH possible

KamLAND–Zen upper limit
Three Active Neutrinos

- Experimental Sensitivity

Agostini, Benato, Detwiler
arXiv:1705.02996
Light Sterile Neutrinos

- **Effective $0\nu\beta\beta$ Mass**

\[ m_{\beta\beta} = c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i(\phi_{13} - 2\delta)} + s_{14}^2 m_{\nu_4} e^{i\phi_{14}} + \cdots \]

- **Dependence on new mass, mixing, phase**

Heavy Sterile Neutrinos

- with mass larger than \( \approx 100 \text{ MeV} \)

\[
\mathcal{A}_{\mu\nu}^{\text{lep}} = \frac{1}{4} \sum_{i=1}^{3} V_{ei}^2 \gamma_\mu (1 + \gamma_5) \frac{\not{q} + M_{N_i}}{q^2 - M_{N_i}^2} \gamma_\nu (1 - \gamma_5) \approx \frac{-\gamma_\mu (1 + \gamma_5) \gamma_\nu}{4} \sum_{i=1}^{3} \frac{V_{ei}^2}{M_{N_i}} \left( \frac{1}{M_N} \right)_{\beta\beta}
\]

- Nuclear matrix elements change
  - Short-range operator
- Many other probes

\[
\mathcal{A}_{\mu\nu}^{\text{lep}} = \frac{1}{4} \sum_{i=1}^{3} V_{ei}^2 \gamma_\mu (1 + \gamma_5) \frac{\not{q} + M_{N_i}}{q^2 - M_{N_i}^2} \gamma_\nu (1 - \gamma_5) \approx \frac{-\gamma_\mu (1 + \gamma_5) \gamma_\nu}{4} \sum_{i=1}^{3} \frac{V_{ei}^2}{M_{N_i}} \left( \frac{1}{M_N} \right)_{\beta\beta}
\]
Nuclear Matrix Elements

- Hadronic current

\[ J^\mu (q) = g_V \gamma^\mu - g_A \gamma^\mu \gamma^5 + \frac{ig_M}{2m_N} \sigma^{\mu\nu} q_\nu - g_P \gamma^5 q^\mu \]

- Nuclear Matrix Element \( M^{0\nu} \)

\[ M^{0\nu} = g_A^2 \left( M_{GT} - \frac{g_V^2}{g_A^2} M_F + M_T \right) \]

- Many-body problem
- Factor 2 – 3 uncertainty between nuclear models

Menendez, arXiv:1605.05059

Iwata et al., Phys. Rev. Lett. 116, 112502
Nuclear Matrix Elements

- Heavy Neutrino Exchange
  - NMEs less uncertain?
  - Talk by J. Menendez at INT Seattle

Menendez to be submitted
Song et al. PRC95 (2017) 024305
Quenching of $g_A$?

- **Nuclear matrix element**
  \[
  M^{0\nu} = g_A^2 \left( M_{GT} - \frac{g_V^2}{g_A^2} M_F + M_T \right)
  \]

- **Axial–vector coupling $g_A$**
  - Free nucleon: $g_A \approx 1.27$
  - Comparison of $\beta$ and $2\nu\beta\beta$ decay with theory: $g_A \approx 0.6–0.8$
  - If applicable to $0\nu\beta\beta$, reduction of sensitivity
  - Genuine effect or short-coming of models?

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**Iachello '16**

\[
M^{0\nu} = g_A^2 \left( M_{GT} - \frac{g_V^2}{g_A^2} M_F + M_T \right)
\]
Quenching of $g_A$?

- Comparison with measured single beta / electron capture rates
  - Fit of model parameters $g_A$ and $g_{pp}^i$ (per even–even isotope)

$$\log ft = \log_{10}(f_0 t_{1/2}[s]) = \log_{10}\left(\frac{6147}{B_{GT}}\right)$$

$$B_{GT} = \frac{g_A^2}{2J + 1} |M_{GT}(g_{pp}, g_{ph})|^2$$

*FFD, Suhonen, Phys. Rev. C 94 (2016) 5, 055501*
Quenching of $g_A$?

- Comparison with measured single beta / electron capture rates
  - Fit of model parameters $g_A$ and $g_{pp}^i$ (per even–even isotope)
  - Taking into account all isotopes
  - Comparison with $2\nu\beta\beta$
  - Quenching of $g_A$ (mass number dependent), including large errors

FFD, Suhonen, Phys. Rev. C 94 (2016) 5, 055501
Quenching of $g_A$?

- Single beta / EC / $2\nu\beta\beta$
  analysis relevant for $0\nu\beta\beta$?
Quenching of $g_A$?

- Single beta / EC / $2\nu\beta\beta$ analysis relevant for $0\nu\beta\beta$?

**Unclear!**

- Processes different at nucleon level
- Probing different transitions
- Incorporate more experimental information
  - Higher, forbidden beta decays
  - Charge exchange reactions
  - Muon capture
Quenching of $g_A$?

- Single beta / EC / $2\nu\beta\beta$ analysis relevant for $0\nu\beta\beta$?
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New Physics and $0\nu\beta\beta$

- Plethora of New Physics scenarios

\[ T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} |M_{NP}^{0\nu}|^2 \]

Left–Right Symmetry

R–Parity Violating SUSY

Extra Dimensions

Majorons

Leptoquarks

...
New Physics and $0\nu\beta\beta$

- Plethora of New Physics scenarios

\[ T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^0 |M_{NP}^{0\nu}|^2 \]

- Neutrinos still Majorana

Extra Dimensions

- Majorons
- Leptoquarks

...
New Physics and 0νββ

- Examples in Left–Right Symmetry

- 0νββ probes the TeV scale

\[ T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} |M_{NP}^{0\nu}|^2 \]

\[ \epsilon_{V-A}^{V+A} = \sum_{i=1}^{3} U_{ei} W_{ei} \tan \zeta_W \approx 10^{-9} \left( \frac{\Lambda}{10 \text{ TeV}} \right)^3 \]

\[ \epsilon_{3}^{RRz} = \sum_{i=1}^{3} V_{ei}^2 \frac{m_p}{m_N} \frac{m_W^4}{m_W^4} \frac{1}{m_N m_W^4} \approx 10^{-8} \left( \frac{\Lambda}{1 \text{ TeV}} \right)^5 \]
New Physics and $0\nu\beta\beta$

- Examples in Left–Right Symmetry

$$T_{1/2}^{-1} = \epsilon_{NP}^{2} G_{NP}^{0\nu} |M_{NP}^{0\nu}|^2$$

- $0\nu\beta\beta$ probes the TeV scale

$$\epsilon_{3}^{RRZ} = \sum_{i=1}^{3} V_{ei}^2 \frac{m_p}{m_{W}} \frac{m_{W}}{m_{W}} \approx 10^{-8} \quad \frac{(\Lambda/1 \text{ TeV})^5}{(\Lambda/1 \text{ TeV})^5}$$

Modified angular and energy distribution of emitted electrons

(Doi et al. '83; Ali et al. '06)

Angular and energy distribution of emitted electrons
(Doi et al. '83; Ali et al. '06; Arnold et al. '10; FFD, Jackson, Nasteva, Söldner–Rembold '10)

\[
\frac{d\Gamma}{dE_{e_1} dE_{e_2} d\cos \theta} = \frac{\Gamma}{2} (1 - k(E_{e_1}, E_{e_2}) \cos \theta), \quad -1 < k < 1
\]

- Linear in $\cos \theta$
- $k(E_{e_1}, E_{e_2})$ depends on $0\nu\beta\beta$ mechanism
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- Linear in \( \cos \theta \)
- \( k(E_{e_1}, E_{e_2}) \) depends on \( 0\nu\beta\beta \) mechanism

Comparison of \( 0\nu\beta\beta \) in multiple isotopes
(FFD, Päs PRL 2007, Meroni et al. 2013)
- Depends on \( 0\nu\beta\beta \) mechanism
- Independent of details of new physics
  (if one mechanism dominates)

\[
\frac{T_{1/2}(X)}{T_{1/2}(Y)} = \frac{G(Y)|M(Y)|^2}{G(X)|M(X)|^2}
\]
Example of Left–Right Symmetry
(Mohapatra, Senjanovic '75)

Example of Left–Right Symmetry
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- Correlation of contributions, e.g.
  Seesaw II dominance with $m_{\nu} \propto M_N$
Quadruple $0\nu\beta\beta\beta$

- $(A, Z) \rightarrow (A, Z + 4) + 4e^-$
- Possible for new physics violating lepton number $\Delta L = 4$
  

- Dirac neutrinos despite lepton number violation
- Challenging to probe

\[
\frac{T_{1/2}^{0\nu4\beta}}{T_{1/2}^{2\nu2\beta}} \approx 10^{46} \left( \frac{\Lambda}{\text{TeV}} \right)^4 > 120 \text{ NEMO-3}
\]
Baryon Asymmetry Generation and Washout

- **Classic Example: High-Scale Leptogenesis**
  - Generation via heavy neutrino decays
  - Competition with LNV washout processes
  - Conversion to baryon asymmetry
    - EW sphaleron processes at $T \approx 100 \text{ GeV}$
    - Observed asymmetry
      \[
      \eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.20 \pm 0.15) \times 10^{-10}
      \]

- **What if we observe lepton number violating processes in $0\nu\beta$?**
Baryon Asymmetry
Lepton Asymmetry Washout

- Compare $0\nu\beta\beta$ rate with lepton asymmetry washout in the early Universe
- Observation of lepton number violation
  - gives information at what temperatures operators are in equilibrium
  - corresponds to highly effective washout $\Gamma_w/H \gg 1$
  - can falsify high-scale baryogenesis scenarios

[Graph and diagram showing $0\nu\beta\beta$ and LFV decay rates with temperature $T$ on the y-axis and operators $O_5, O_7, O_9, O_{11}, O_{\nu\gamma}, O_{\tau\gamma}, O_{\mu\equiv\nu\gamma}$ on the x-axis.]
Conclusion

- Neutrinos much lighter than other fermions
  - Dirac or Majorana? Lepton Number Violation?
  - Mechanism of neutrino mass generation? At what scale?

- $0\nu\beta\beta$ is crucial probe for BSM physics
  - Discovery $\rightarrow$ Majorana $\nu$ $\rightarrow$ Physics near GUT scale? LNV @ TeV?
  - Exclusion $\rightarrow$ Dirac $\nu$? $\rightarrow$ Fine-tuned SM?

- Challenging nuclear physics
  - Effort to calculate NMEs from first principles
  - Quenching (if any) needs to be understood quantitatively

- Strong Synergy with LHC+LFV searches
  - LHC can deep-probe anatomy of $0\nu\beta\beta$ LNV operators
  - Observation of LNV+LFV would strongly constrain baryogenesis