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SHiP Colloquium | CERN | 9 November 2017

and Lepton Flavour Violation

Theory of Lepton Number
Neutrinoless double beta decay

\[ \Delta L_e = 2, \Delta L_\mu = 0, \Delta L = 2 \]

Lepton Number Violation + Lepton Flavour Violation

Lepton Flavour Violation

\[ \Delta L_e = 1, \Delta L_\mu = -1, \Delta L = 0 \]

Lepton Number Violation

Conversion in nuclei

Neutrinoless double beta decay
Neutrinoless double beta decay

\[ \Delta L_e = 2, \Delta L_\mu = 0, \Delta L_\tau = 2 \]

Lepton Number Violation + Lepton flavour Violation

\[ \Delta L_e = 1, \Delta L_\mu = 1, \Delta L_\tau = 2 \]

Conversion in nuclei

Lepton Flavour Violation

\[ \Delta L_e = 1, \Delta L_\mu = -1, \Delta L_\tau = 0 \]

Lepton Flavour Violation

Neutrino Oscillations

Nobelprize.org

Lepton Number Violation

\[ 2 = 0, \Delta L_\tau = 2 \]

Double beta decay

Neutrinoless

\[ \nu \rightarrow e, \nu \rightarrow \mu \]
Two possibilities to define neutrino mass:

1.Dirac mass analogous to other fermions but with $\mathcal{m}_\nu \approx 10^{-12}$ couplings to Higgs

2.Majorana mass, using only a left-handed neutrino
Neutrino interaction eigenstates different from mass eigenstates

- CP Violation? Sign of $\Delta m_{23}$? Octant of $\theta_{23}$? Sterile Neutrino?
- Experimental unknowns and anomalies
- Current errors ~ 1 - 10%

Era of neutrino precision physics

Neutrino flavour can change through propagation

Neutrino interaction eigenstates different from mass eigenstates

$\nu_i = U_\alpha i \nu_\alpha$

$\nu_i = e^{-i E_i t} - p_i x$

$\mathcal{P}_\alpha \rightarrow \beta = \sin^2 2\theta \sin^2 \frac{1.27 \Delta m^2}{E/\text{GeV}}$
Impact on flavour models (Girardi, 14)

- DUNE sensitivity to mass ordering (Marone et al., '15)
- JUNO sensitivity to mass ordering (Marrone et al., '15)

CP violating phase

- DUNE sensitivity to CP violation (Frandsen et al., '15)
- Normal Hierarchy
- Inverted Hierarchy

Neutrino Oscillations
Single beta decay

\[ (A,Z) \rightarrow (A,Z+1) + e^- + \bar{v}_e \]

Allowed double beta (2\(\nu\beta\)) decay

\[ (A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{v}_e \]

Neutrinoless double beta (0\(\nu\beta\)) decay

\[ (A,Z) \rightarrow (A,Z+2) + 2e^- \]

Violation of lepton number

Mediated by Majorana neutrinos

\[ 0\nu\beta+\beta^+ \: (A,Z) \rightarrow (A,Z-2) + 2e^+ \]

\[ 0\nu\beta+EC: (A,Z) + e^- \rightarrow (A,Z-2) + e^+ \]

\[ 0\nuEC: (A,Z) + 2e^- \rightarrow (A,Z-2)^* \]

Majoron-assisted 0\(\nu\beta\) decay

\[ (A,Z) \rightarrow (A,Z+2) + 2e^- + n \]

Variants
\[
\text{Leptonic phase space}\quad G_0 \nu
\]

\[
T_{1/2} \approx \frac{\frac{1}{2}}{10^{25}\text{yr}} \approx \frac{|m_{\beta\beta}|^2}{G_F Q^5}
\]

\[
|W_{\nu_0} G_0 \nu | \approx \frac{1}{2} / T_{1/2} \approx \frac{1}{100}\text{MeV} \approx b
\]
\[ T_{1/2} \propto \frac{1}{m_{\beta\beta}} \left( \frac{\Lambda^2}{|G^{\nu}|^2} \right) \approx \frac{T_{1/2}}{10^{25} \text{yr}} \]

\[ T_{1/2} \approx \frac{2}{4} \text{MeV} \]

\[ m_{\beta\beta} \approx 10^{-25} \text{yr} \]

\[ T_{1/2} \propto m_{\beta\beta}^2 \]

\[ Q \approx \frac{2}{4} Q \]

\[ Z_{\beta\beta} \approx \frac{1}{4} \sum_{i=1}^{3} U_{e i}^2 \]
For NH possible accidental cancellation phases unknown Majorana uncertainy from

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

\[ \epsilon_{\beta\beta} m_{\beta\beta} = c_{12} c_{13} m_{\nu_1} + s_{12} c_{13} m_{\nu_2} + s_{12} s_{13} m_{\nu_3} \]

Effective [\( \nu_{\beta\beta} \) Mass

Degenerate Regime

Uncertainty from KAMLAND-ZEN upper limit

Dell'Oro, Marcocci, Vissani, Viel (2016)
Effective 0νββ Mass

Future


Uncertainty from

Accidental cancellation phases

For NH possible

Uncertainty from unknown Majorana

\[ \left( \frac{Z}{2\phi} \right) \sin^2(2\theta_{21}) \sin^2 \frac{\Delta m^2_{\text{sol}} \ell}{4E} \int m \right] \]

\[ m_{\text{eff}} = |m_{\text{0νββ}}| \]

\[ m_{\text{0νββ}} = \sum_{i,j} \sum_{\nu} m_{\nu} \rho_{\nu} \}

Future surveys
Experimental Sensitivity

Over $P_{\nu}$ light Neutrinos
Hadronic current

\[ J_{\mu} q = g V_{\gamma} \mu + i g M^2 m N \sigma_{\mu\nu} q - g P_{\gamma} \mu \]

\[ M_{0\nu} = g A^2 M_{GT} - g V^2 g^2 A^2 M_{F} + M_T \]

Nuclear Matrix Element \( M_{0\nu} \)

Many-body problem

\[ \left( \sum_{W} W \frac{\alpha}{2} - C_{\gamma} \right) \frac{\alpha}{2} = M_{0\nu} \]

Between nuclear models

Factor 2 - 3 uncertainty

\[ n b_s \lambda d \theta - n \lambda \lambda d \theta + \frac{2 m}{M} d \theta = (b)_{d} \]

Nuclear Matrix Elements

\[ \eta b_s \lambda d \theta - \eta \lambda \lambda d \theta = (b)_{d} \]
Axial-vector coupling $g_A$

\[ (\gamma_\mu W + \frac{\gamma_\mu g}{A^6} - \frac{\gamma_\mu W}{A^6}) M_{\nu}^{\infty} = 0 W \]

Quenching of $g_A$ Possible causes:
- Short-comeing of models
- Genuine effect or reduction of sensitivity if applicable to $0\nu\beta\beta$
- Comparison of single $\beta$ and $2\nu\beta\beta$ decay with theory
- Free nucleon: $g_A \approx 1.27$
- Genuene effect or short-comeing of models?
Axial–vector coupling \( g^A \)

\[
\begin{aligned}
(\nu \! \! \rightarrow e^+ v)^\nu \! \! \rightarrow e^+ v = M_0 \bar{\nu}^A \nu^A M_0
\end{aligned}
\]
Nuclear matrix element

Axial-vector coupling $g^A$

Free nucleon: $g^A \approx 1.27$
Comparison of single $\beta$
Comparison of single $2\nu\beta\beta$ decay with theory:
$g^A \approx 0.6 - 0.8$

If applicable to $0\nu\beta\beta$,
Reduction of sensitivity
Genuine effect or
Short-comings of models?

Quenching of $g^A$
Plethora of New Physics scenarios

\[ e_ne_u_u_d_0nbb_{T_1} - 1_{T_2} = \epsilon_{NP2} \sum_{NP0} G_{NP0} M_{NP0}^2 \]

Left-Right Symmetry

\[ T/L = \frac{G_{W0}^d M^N P}{\epsilon^2} \]

New Physics and OVPB

Extra Dimensions

Majorons

Leptoquarks

R-Parity Violating SUSY
Plethora of New Physics scenarios

Neutrinos still Majorana

Left–Right Symmetry

Extra Dimensions

Lepothearks

Majorons

Violating SUSY R-Parity

\[ T^0_{12} = \epsilon_{NP} \gamma T^0_{0NP} M_{NP} \]

Plentoria of New Physics scenarios

New Physics and OVP
Examples in Left–Right Symmetry

New Physics and \( \nu \bar{b}g \)}
Examples in Left-Right Symmetry

\[ \frac{\langle I(V) \rangle_{\text{1 TeV}}}{10^{-8}} \approx 3 \times \frac{\eta^2}{m_{\nu}^2} \left( \sum_{i=1}^{3} \epsilon_i \right) \]

Modified angular and energy distribution of emitted electrons (Doi et al., '83; Ali et al., '06)

New Physics and Ovbg

\[ \frac{dN}{d\eta} \approx \frac{dN}{d\eta_0} \]

the TeV scale

Ovbg probes
Example of Left–Right Symmetry

(Mohapatra, Senjanovic, 75)

Oybg vs LHC
Effective operator for Majorana neutrino mass

Seesaw Mechanism

Only dimension-5 operator beyond SM

Effective operator for Majorana neutrino mass

Neutrino Mass Models
Neutrino masses

Radiative Generation via Loops

Alternative to Seesaw, e.g. Babu-Zee model (Zee '85, Babu '88)

Effective operator for Majorana neutrino mass

Only dimension-5 operator beyond SM
Correct light neutrino masses for TeV scale heavy neutrinos

- Seesaw Mechanism with TeV scale heavy neutrinos
- Standard Seesaw with small Yukawa couplings
- Seesaw Mechanism with TeV scale heavy neutrinos
- Decouple $\nu$LNV from heavy neutrino mass
- CLFV remains small
- "Bent" Seesaw mechanisms
- CLFV remains small
- Standard Seesaw with small Yukawa couplings
- Potentially large CLFV
- In the limit $\mu \rightarrow 0$, no LNV but CLFV

$\begin{pmatrix}
\eta & W & 0 \\
W & \eta & \langle H \rangle^{\lambda} \\
0 & \langle H \rangle^{\lambda} & 0
\end{pmatrix} = \mathcal{M}$

Example

$M_{\nu} = 10^2$ GeV

$M_{\nu} = 10^3$ GeV

$\langle H \rangle = 10^2$ GeV

$\langle H \rangle = 10^3$ GeV

$\mu \rightarrow 0$

$\nu$LNV

Heavy Sterile Neutrinos
Constraints on coupling to leptons

\[ V_{lN} \]

Neutrinoless Double Beta Decay

\[ \text{GERDA} \]

\[ \text{Z Decays} \]

\[ \text{SHiP} \]

\[ K^+ \rightarrow e^+ \nu \]

Peak Searches in Meson Decays

\[ \text{Belle} \]

\[ m K^+ \rightarrow e^+ \nu \]

Beam Dump Experiments

\[ \text{LBNE} \]

\[ \text{e.g. PS191, CHARM} \]

\[ \text{LB} \]

\[ \text{LEP: L3, Delphi} \]

\[ \text{FCC-ee} \]

\[ \text{FFD, Dev, Pilaftsis} \]

NJP 17 (2015) 7, 075019

Electroweak Precision Tests

\[ \text{EWPD: Fit of electroweak precision observables,} \]

\[ \text{lepton universality observables} \]

LNV Meson Decays

\[ \text{SHiP} \]

\[ \text{LB} \]

\[ \text{N} \]

\[ \text{Majarana} \]

Universal for pure decays

CERDA

\[ \text{Decay} \]

\[ \text{Neutrinoless Double Beta} \]

\[ \text{Constraints on coupling} \]

\[ |V_{lN}| \]

Heavy Sterile Neutrinos
CLFV in the Seesaw Mechanism

- Light neutrino exchange: negligible due to small neutrino masses
- Heavy neutrino exchange: sizable for TeV scale heavy neutrinos and large LR mixing $V_{LR} \approx 10^{-2}$

\[ \text{BR}(\mu \rightarrow e\gamma) \approx \frac{3\alpha}{3\pi} \approx 4 \times 10^{-3} \]

Neutrino mixing $V_{LR} \approx 10^{-2}$

- Heavy neutrino exchange
- Light neutrino exchange

CLFV in the Seesaw Mechanism

Heavy Sterile Neutrinos
Neutrino flavour mixing radiatively induces slepton flavour mixing (Borzumati, Masiero '86).

Correlation between slepton and neutrino flavour mixing induces observable charged LFV rates despite high scale Seesaw $M^{\nu}_{\tau} \approx 10^{14}$ GeV.

Neutrino flavour mixing radiatively

Esteves et al., '11
Classic Example: High-Scale Leptogenesis

- Generation via heavy neutrino decays
- Competition with LNV washout processes
- Conversion to baryon asymmetry at $T \approx 100 \text{ GeV}$

What if we observe lepton number violating processes in $0\nu\beta\gamma$?

\[
\eta_B \equiv n_B - n_{\bar{B}} = (6.20 \pm 0.15) \times 10^{-10}
\]

- Observed asymmetry
- EW sphaleron processes at $T \approx 100 \text{ GeV}$
- Conversion to baryon asymmetry
- Competition with LNV washout processes
- Generation via heavy neutrino decays

Baron Asymmetric

Generation and 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.

Effective washout $\Gamma_\text{LW} \gg 1$ corresponds to highly effective washout $\Gamma_\text{LHC} \gg 1$ can falsify high-scale baryogenesis scenarios.

Observation of lepton asymmetry washout in the early Universe can falsify high-scale baryogenesis scenarios.

LNV and LFV

Barion Asymmetry Washout

Lepton Asymmetry Washout
Neutrinos much lighter than other fermions

LNV and LFV are crucial probes for BSM physics

Strong Synergy with LHC+LFV searches

LHC can deep-probe anatomy of neutrino mass generation

Test mechanisms and scale of neutrino mass generation

Observation of LNV+LFV would strongly constrain baryogenesis

How is lepton number/flavour approximately protected

High scale, small couplings, symmetry?

Neutrinoless double beta decay

Strong Synergy with LHC+LFV searches

Exclusion $\leftrightarrow$ Dirac $\uparrow$? Fine-tuned SM?

Discovery $\leftrightarrow$ Majorana $\uparrow$ Physics near GUT scale? LNV $\uparrow$ TeV?

Neutrinos much lighter than other fermions

Conclusions