Models of neutrino Majorana masses

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Outline

1. Desirability of neutrino Majorana mass
    - Why have Majorana mass at all
    - Implications of Majorana mass
2. Bottom-up models: SM gauge group with new particles
    - Right handed neutrinos: Type I seesaw
    - Higgs triplet: Type II seesaw
    - Radiative mass models
3. Top-down models: SM extensions / GUTs
    - Spontaneous $B - L$ violation
    - Grand unified theories: SU(5), SO(10)
    - Left-right symmetry, Supersymmetry
4. $0\nu\beta\beta$ without neutrino Majorana mass
    - Majorana mass may not be directly needed
5. Concluding remarks

Outline

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Dirac vs. Majorana mass

- Dirac mass term: $\mathcal{L}_{\rm Yukawa} = m_D \overline{\psi}_L \psi_R$
- Antiparticles: $\psi^c \equiv \gamma_0 C \psi^*$
  (C: charge conjugation operator)
- If neutrinos are their own antiparticles, $\psi^c = e^{i\theta}\psi$
- Majorana mass term: $\mathcal{L}_M = m_M \overline{\nu_L^c} \nu_L$
- ν_R not needed, but lepton number violated !

Why not have just Dirac mass ?

- Fine tuning in Yukawa couplings needed to get small neutrino masses
- Lepton number is an “accidental symmetry” of the SM, no fundamental principle (e.g. the gauge principle) prevents it
- A guiding principle of gauge theories: anything that is not forbidden by a symmetry should be allowed
- Once right handed neutrinos are involved, Majorana mass term for them is possible, and should be taken into account

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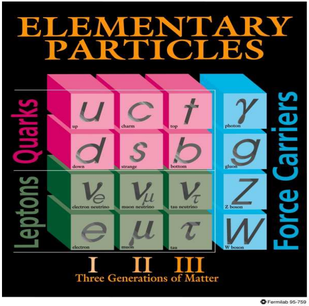
Implications of Majorana mass

- Lepton number violating processs: as yet unobserved
- "Forbidden" processes like $\nu_\mu N \to \mu^+\ell^+\ell^- X$, $\mu^- e^+ \to \mu^+ e^-$ possible at colliders
- New particles like the Majoron predicted for a class of models
- Heavy Majorana neutrinos may play an important role in Baryogenesis

Outline

The standard model gauge group: $SU(2)_L \times U(1)_Y$



- $U_L : (2, 1/3)$, $D_L : (2, 1/3)$
- $U_R : (1, 4/3)$, $D_R : (1, -2/3)$
- $\nu_L : (2, -1)$, $e_L^- : (2, -1)$
- $e_R^- : (1, -2)$
- $\Phi : (2, 1)$

- Only possible mass terms: $\overline{U}_L \Phi^c U_R$, $\overline{D}_L \Phi D_R$, $\overline{e}_L \Phi e_R$
- No mass term for neutrinos

Outline

Mass terms with right handed neutrinos

- ν_R : $(0,0)$
- Possible neutrino mass term: $\overline{\nu_L}\Phi^c\nu_R \Rightarrow m_D\overline{\nu_L}\nu_R$
- However, also possible to have $M_R\overline{\nu_R^c}\nu_R$: mass for right handed neutrinos
- M_R can be very heavy: no symmetry to keep it light
- $-\mathcal{L}_m = \frac{1}{2}\begin{pmatrix}\overline{\nu_L} & \overline{\nu_R^c}\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D & M_R\end{pmatrix}\begin{pmatrix}\nu_L^c \\ \nu_R\end{pmatrix} + h.c.$
- Both eigenvectors Majorana particles
- $m_D \ll M \Rightarrow$ Eigenvalues: $m_1 \approx -\frac{m_D^2}{M_R}$ and $m_2 \approx M_R$
- Seesaw mechanism ! $M_R \Uparrow m_1 \Downarrow$

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Type I seesaw for multiple generations

- m_D and M_R are now matrices:
  $-\mathcal{L}_m = \frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$
- m_1 and m_2 to be treated as matrices:
  $m_1 \approx m_D M_R^{-1} m_D^T$ and $m_2 \approx M_R$
- If $m_D \sim m_{\rm Quarks}$, values of $m_\nu \lesssim 1$ eV can be obtained if $M_R \gtrsim 10^9$–10^{12} GeV
- Two consequences:
  - light neutrino masses for low energy neutrino data
  - heavy Majorana neutrinos for leptogenesis
- Quark masses hierarchical $\Rightarrow$ neutrino masses hierarchical

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Majorana mass for left-handed neutrinos

- $m_L \overline{\nu_L} \nu_L^c$ forbidden by $SU(2)_L \times U(1)$:
  $\overline{\nu_L} \nu_L^c \sim (2,1) \times (2,1) = (1,2) + (3,2)$
- If a Higgs triplet $\Delta \equiv \begin{pmatrix} \Delta_0 \\ \Delta_- \\ \Delta_{--} \end{pmatrix} : (3,-2)$ exists, then

$$-\mathcal{L}_m = \sum_{\ell,\ell'} \frac{f_{\ell,\ell'}}{\sqrt{2}} \overline{\nu_{\ell L}} (\tau \cdot \Delta) \nu^c_{\ell' L} \qquad \text{possible}$$

- $\langle \Delta_0 \rangle$ also affects M_W and M_Z
- Measurements of $\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = \frac{1+2(\langle \Delta_0 \rangle / \langle \Phi_0 \rangle)^2}{1+4(\langle \Delta_0 \rangle / \langle \Phi_0 \rangle)^2}$
  restricts $\langle \Delta_0 \rangle / \langle \Phi_0 \rangle < 0.07$

Type II seesaw

- With $m_L \equiv f_{\ell\ell'} \langle \Delta_0 \rangle / \sqrt{2}$,

$$-\mathcal{L}_m = \frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} m_L & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

- $m_1 \approx m_L - m_D M_R^{-1} m_D^T$ and $m_2 \approx M_R$
- The same two consequences as Type I seesaw:
    - light neutrino masses for low energy neutrino data
    - heavy Majorana neutrinos for leptogenesis
- Quasi-degenerate neutrino masses now possible naturally

Baryogenesis through leptogenesis

- Decays of heavy Majorana neutrinos, e.g. $\nu_R \to \nu_L \Phi$, may violate CP symmetry
- Decay rate $\Gamma \ll H$ (the Hubble expansion rate) $\Rightarrow$ Nonequilibrium in $\nu_R \leftrightarrow \nu_L \Phi$ and its charge conjugate process during the early universe
- Sakharov conditions satisfied $\Rightarrow$ lepton asymmetry may be generated (Leptogenesis !)
- Lepton asymmetry can be partly converted to baryon asymmetry via sphalerons (non-perturbative process) during the electroweak phase transition
- Matter-antimatter asymmetry generated (Baryogenesis !)

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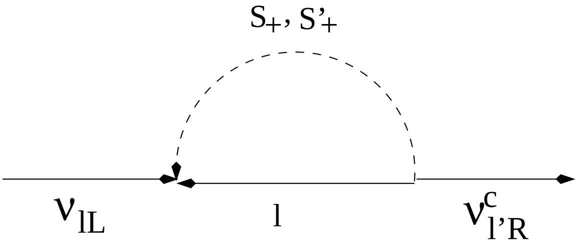
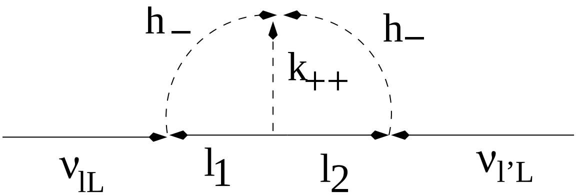
Zee model

- $\overline{\nu_L}\nu_L^c \sim (2,1) \times (2,1) = (1,2) + (3,2)$
- Can form an invariant with h_- : $(1,-2)$
- A consistent model needs 2 Higgses, Φ and Φ'
- Neutrino mass through loop diagram: (S_+, S'_+ are some combination of Φ_+, Φ'_+ and h_+)



Babu's model: $h_{-}(1,-2)$ and $k_{++}(1,4)$



- Both h_{+} and k_{++} carry two units of $B-L$ charge
- k_{++} : $(1,4)$ neutralises $\overline{l_L^c} l_L$: $(1,-4)$

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Spontaneous $B - L$ violation

- Majorana mass implies broken $B - L$ symmetry
- Breaking possible explicitly through, e.g., $M_R \overline{\nu_R^c} \nu_R$
- Alternatively, coupling $\overline{\nu_R^c} S \nu_R$,
  "Higgs" S with lepton number (or $B - L$ charge) of -2
- S may get a vacuum expectation value by spontaneous symmetry breaking, which breaks $B - L$
- $\Rightarrow$ A massless Goldstone boson, the "Majoron" J
- Limits on J through the processes
  $\mu \to e + J$, $\gamma + e \to e + J$
- Stringent limits from cooling rates of stars
- One or more Majorons may also be emitted in $0\nu\beta\beta$

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GUTs: symmetry breaking through Higgses

- Larger gauge groups at the high scale are broken by Higgses getting vacuum expectation values
- If Higgses break $B - L$, Majorana masses generated
- $SU(5) \to SU(3)_C \times SU(2)_L \times U(1)_Y$ through a 15-dim Higgs S_{ij}, with S_{55} getting a vev
- $\mathcal{L}_{\rm Yuk} = f \overline{\psi_i} \psi_j S^{ij}$, Higgs potential $V = \mu_S H_i H_j S^{ij}$
- $SO(10) \to SU(4)_C \times SU(2)_L \times SU(2)_R$
  $\to SU(3)_C \times SU(2)_L \times U(1)$
  through H (10 dim) or Δ (126-dim) Higgs
- For all fermions, $\mathcal{L}_{\rm Yuk} = h_{ab}\psi_a\psi_b H + f_{ab}\psi_a\psi_b\overline{\Delta}$
- depending on whether h_{ab} or f_{ab} dominate, diferent relations between quark and lepton masses

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Left-right symmetric model

- $G_{\rm weak} = SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- $Q = I_{3L} + I_{3R} + (B-L)/2$
- $SU(2)_R$ broken, $SU(2)_L$ unbroken $\Rightarrow \Delta I_{3R} = \Delta(B-L)/2$
- Type II Seesaw mechanism possible, with $H(2,1)$ and $\Delta(3,-2)$
- Can give rise to $\mu^- \to e^- e^- e^+$, $\mu^- \to e^- \nu_e \bar{\nu}_\mu$, $\mu^+ e^- \to \mu^- e^+$
- Constraints on the coupling $\sim 10^{-3} G_F$

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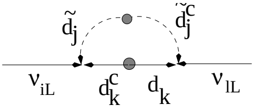
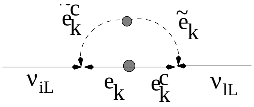
Supersymmetric models

- SUSY: a superpartner for each particle, boson $\leftrightarrow$ fermion
- R-parity: $R = (-1)^{3(B-L)+2S}$
  +1 for particles, -1 for superpartners
- R-parity conserving MSSM: no neutrino mass
- R parity violation: soft SUSY breaking superpotential
  $W = \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda'' U^c_i D^c_j D^c_k$
  First two terms violate R parity





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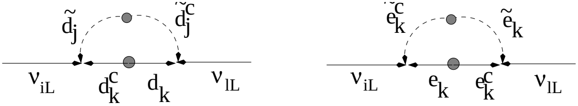

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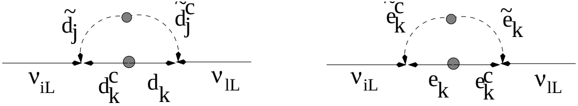

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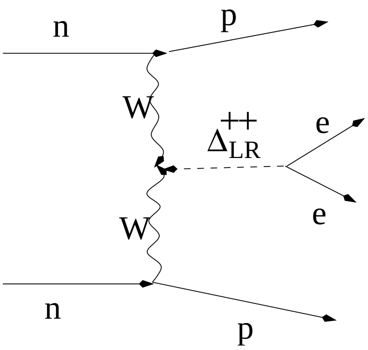
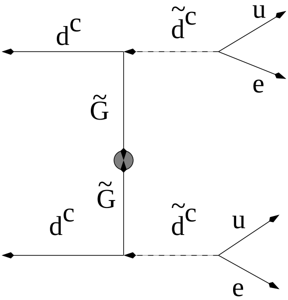
Left-right symmetric model

Mediation by doubly charged Higgs

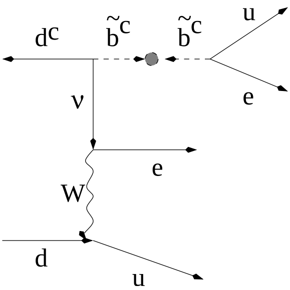


Supersymmetry

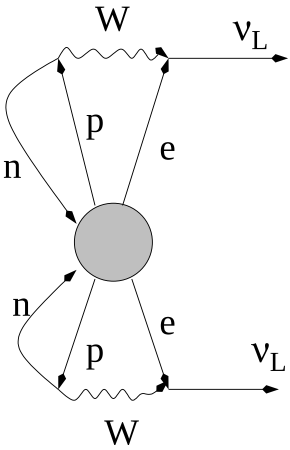
R-parity violation



Joint vector-scalar exchange



$0\nu\beta\beta$ induces Majorana neutrino mass



- "Blob" corresponds to effective $0\nu\beta\beta$ process

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Concluding remarks

- Neutrino Majorana mass: a viable possibility
- Test of lepton number violation
- Mass generation connected to physics at the high scale
  - Seesaw mechanisms
  - Radiative mass generation
  - GUTs / LR symmetric models / SUSY models
- Spontaneous $B - L$ breaking models predict Majoron
- Leptogenesis possible through heavy Majorana neutrinos
- Though $0\nu\beta\beta$ happens at $\sim$ MeV, probes physics at very high scales: 10^{12} GeV
- $0\nu\beta\beta$ is a strong evidence for neutrino Majorana mass: other sources may give rise to $0\nu\beta\beta$, but then they also induce a Majorana neutrino mass.

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