Particle Physics – Neutrino Mass Generation via the See-Saw Mechanism

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Outline

Neutrino Mass Terms: Dirac and Majorana

- **Standard Model (SM)** neutrinos are massless [1].
- Introduce right-handed neutrino fields N_R to generate masses.
- Allows for both **Dirac** and **Majorana** mass terms.

Mass Terms in the Lagrangian

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}\begin{pmatrix}\overline{\nu_L} & \overline{N_R^c}\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D^T & M_R\end{pmatrix}\begin{pmatrix}\nu_L^c \\ N_R\end{pmatrix} + \text{h.c.}$$

- $m_D = Y_\nu \langle H \rangle$: Dirac mass matrix.
- M_R: Majorana mass matrix [2].

Origin of Mass Terms

Dirac Mass Term (m_D):

- Couples ν_L with N_R.
- Arises from Yukawa interactions after Higgs VEV.

Majorana Mass Term (M_R):

- Involves only N_R.
- Can be at a very high scale (GUT scale) [3, 4].

See-Saw Mechanism Approximation

- Assume $M_R \gg m_D$ [5].
- Neutrino mass matrix:

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

- Effective light neutrino mass:

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

Implications of the See-Saw Mechanism

- Light neutrino masses are suppressed by large M_R.
- Explains why neutrino masses are much smaller than other fermions.
- Heavy neutrinos (N) have masses $\sim M_R$.

Baryon Asymmetry of the Universe (BAU)

- Observed matter-antimatter imbalance.
- **Leptogenesis** provides a possible explanation [6].
- Heavy N_R decay generates lepton asymmetry.

Mechanism of Leptogenesis

1. Decay of heavy neutrinos: $N_R \to \ell + H$.
2. CP violation in decay rates.
3. Out-of-equilibrium decays (Sakharov conditions).
4. Sphaleron processes convert L asymmetry to B asymmetry.

Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

- Lepton number violating process.
- Observation would confirm Majorana nature of neutrinos [7].
- Experiments: GERDA, KamLAND-Zen, EXO-200.

Precision Measurements

- Determination of neutrino mass hierarchy and absolute mass scale.
- Experiments: KATRIN [8], NOvA, DUNE.
- Could provide hints supporting the see-saw mechanism.

Lepton Flavor Violation (LFV) Processes

- Processes like $\mu \to e\gamma$, $\mu \to 3e$.
- Induced by heavy N_R through loop diagrams [9].
- Experiments: MEG [10], Mu3e, COMET.

Direct Production at Colliders

- Production of heavy N_R via $pp \to \ell N_R$.
- Challenging due to high M_R scale.
- Accessible if N_R are lighter (TeV scale) [11].

Conclusion

- See-saw mechanism explains small neutrino masses.
- Provides framework for leptogenesis and BAU.
- Experimental efforts are crucial to validate the mechanism.

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