The Profound Implications of Neutrinoless Double Beta Decay

Boris Kayser
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Neutrinoless Double Beta Decay [0νββ]

Cannot occur in the Standard Model

Observation at any level would imply —

- Lepton number L is not conserved
- Neutrinos have *Majorana masses* — masses with a different origin than the quark and charged lepton masses
- Neutrinos are their own antiparticles

Observation of $0\nu\beta\beta$ would be evidence in favor of —

- The See-Saw model of the origin of neutrino mass

- Leptogenesis as the origin of the baryon-antibaryon asymmetry of the universe

What does all this mean?

Why is it interesting?

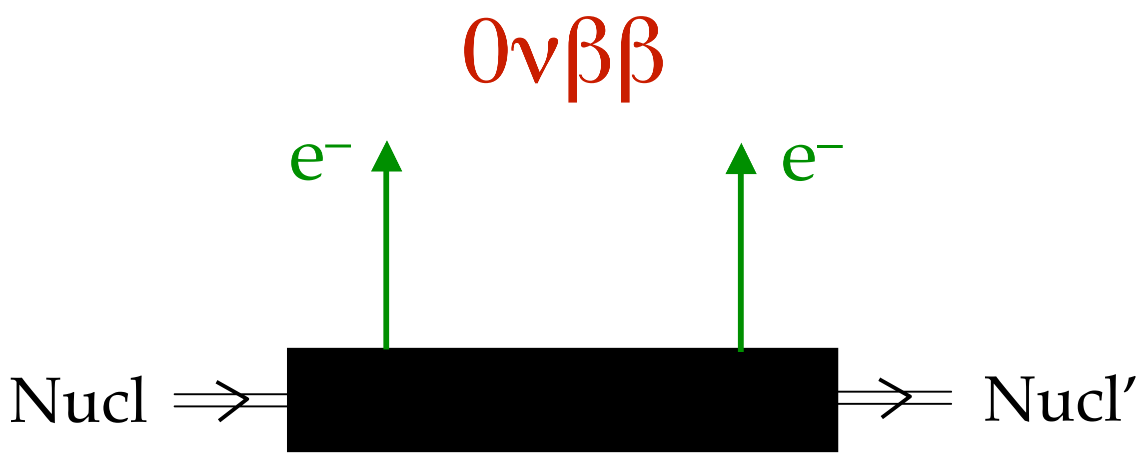
Nonconservation of Lepton Number L

The Lepton Number L is defined by —

$$L(\nu) = L(\ell^-) = -L(\bar{\nu}) = -L(\ell^+) = 1$$

This is the quantum number that distinguishes antileptons from leptons.

It is the leptonic analogue of the Baryon Number B, which distinguishes antibaryons from baryons.



Clearly does not conserve L: $\Delta L = 2$.

Non-perturbative ***Sphaleron*** processes in the Standard Model (SM) do not conserve L.

But Sphaleron processes can only change L by a multiple of 3.

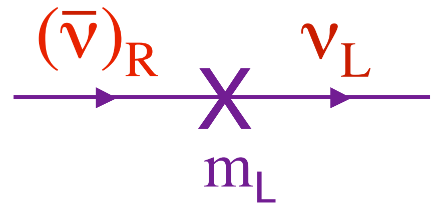
2 is not a multiple of 3.

The $\Delta L = 2$ of $0\nu\beta\beta$ is outside the SM.

Majorana Masses

Out of, say, a left-handed neutrino field, ν_L, and its charge-conjugate, $\nu_L{}^c$, we can build a Left-Handed Majorana mass term —

$$m_L \overline{\nu_L}\, \nu_L{}^c$$



Majorana masses mix ν and $\bar{\nu}$, so they do not conserve the Lepton Number L, changing it by $\Delta L = 2$, precisely what is needed for $0\nu\beta\beta$.

A Majorana mass for any fermion f causes f $\leftrightarrow$ $\bar{\text{f}}$.

Quark and *charged-lepton* Majorana masses are forbidden by electric charge conservation.

Neutrino **Majorana masses would make the neutrinos *very* distinctive.**

SM Higgs

Majorana ν masses cannot come from $H_{SM}\bar{\nu}_L\nu_R$, the ν analogue of the Higgs coupling that leads to the q and ℓ masses, and the progenitor of a *Dirac* ν mass term.

Possible progenitors of Majorana mass terms:

$$H_{SM} H_{SM} \overline{\nu_L^c} \nu_L, \quad H_{I_W=1} \overline{\nu_L^c} \nu_L, \quad m_R \overline{\nu_R^c} \nu_R$$

Not renormalizable

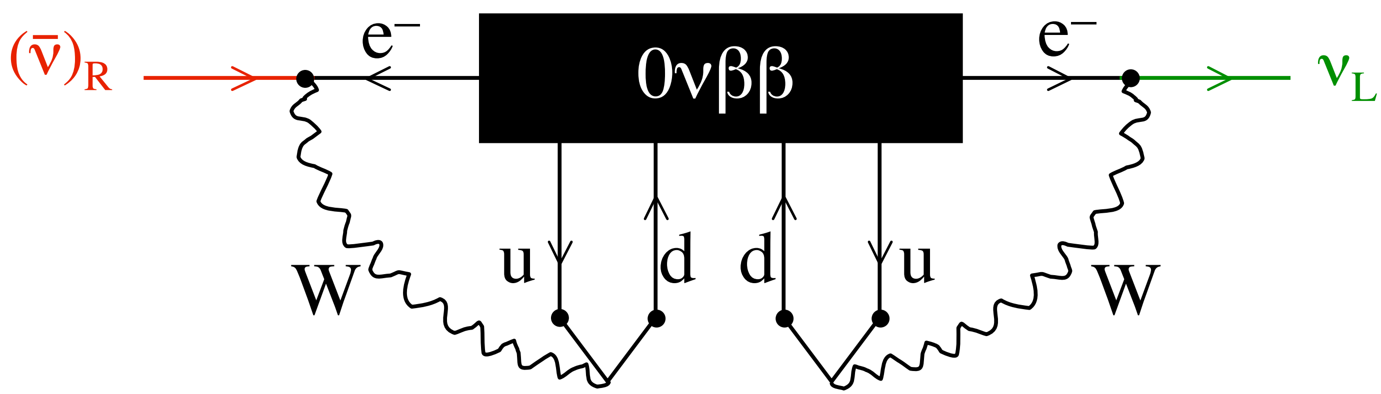
This Higgs not in SM

No Higgs

Majorana neutrino masses must have a different origin than the masses of quarks and charged leptons.

Whatever diagrams cause $0\nu\beta\beta$, its observation would imply the existence of a Majorana mass term:

(Schechter and Valle)



$(\bar{\nu})_R \rightarrow \nu_L$: A (tiny) Majorana mass term

$\therefore$ $0\nu\beta\beta$ ⟹ A Majorana mass term

Does $\bar{\nu} = \nu$?

What Is the Question?

For each ***mass eigenstate*** ν_i , and ***given helicty*** h***,*** does —

- $\overline{\nu_i}(h) = \nu_i(h)$ (Majorana neutrinos)

or

- $\overline{\nu_i}(h) \neq \nu_i(h)$ (Dirac neutrinos) ?

Equivalently, do neutrinos have *Majorana masses*? If they do, then the mass eigenstates are *Majorana neutrinos*.

Why Majorana Masses ⟹ Majorana Neutrinos

The objects ν_L and $\nu_L{}^c$ in $m_L \overline{\nu_L}\, \nu_L{}^c$ are not the mass eigenstates, but just the neutrinos in terms of which the model is constructed.

$m_L \overline{\nu_L}\, \nu_L{}^c$ induces $\nu_L \leftrightarrow \nu_L{}^c$ mixing.

As a result of $K^0 \longleftrightarrow \overline{K^0}$ mixing, the neutral K mass eigenstates are —

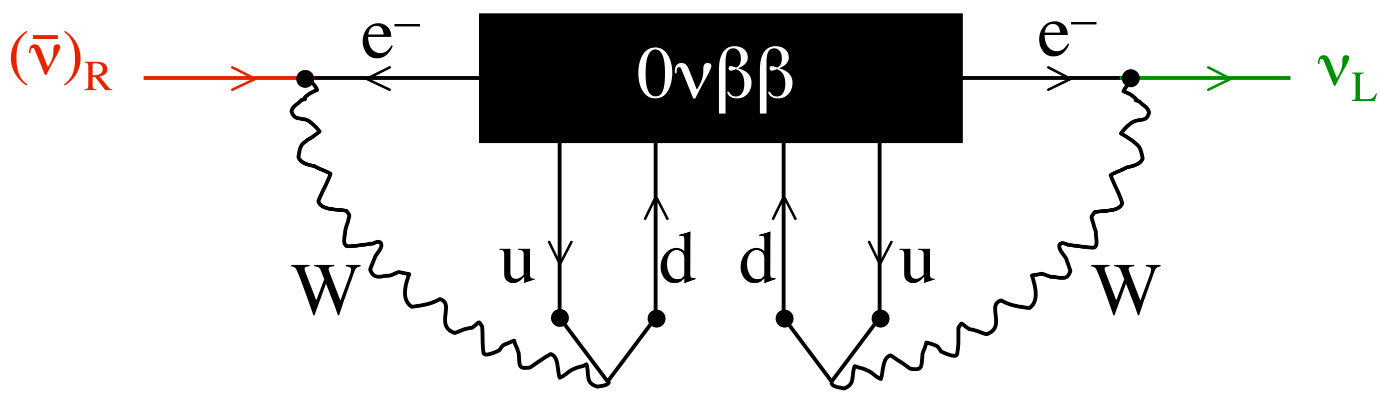
$$K_{S,L} \cong (K^0 \pm \overline{K^0})/\sqrt{2}\,. \qquad \overline{K_{S,L}} = K_{S,L}\,.$$

As a result of $\nu_L \leftrightarrow \nu_L{}^c$ mixing, the neutrino mass eigenstate is —

$$\nu_i = \nu_L + \nu_L{}^c = \text{“}\, \nu + \overline{\nu}\, \text{”}. \quad \overline{\nu_i} = \nu_i\,.$$

Whatever diagrams cause $0\nu\beta\beta$, its observation would imply the existence of a Majorana mass term:

(Schechter and Valle)



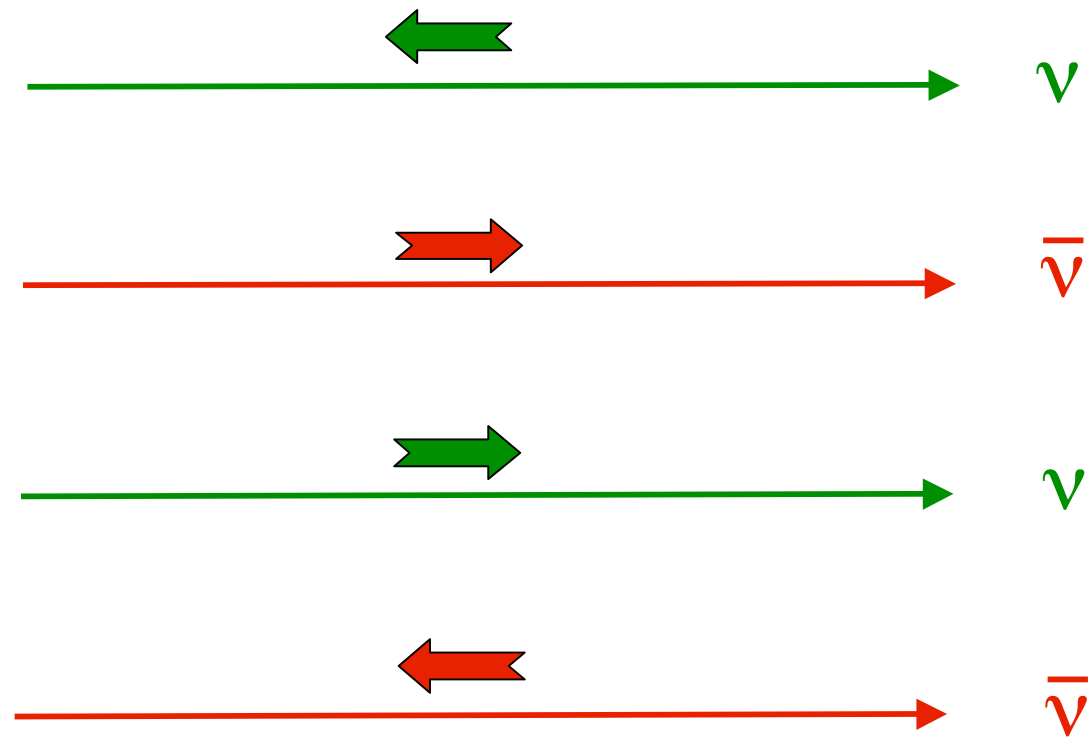
$(\bar{\nu})_R \rightarrow \nu_L$: A (tiny) Majorana mass term

$\therefore$ $0\nu\beta\beta$ ➡ $\bar{\nu}_i = \nu_i$

The Nature of Majorana Neutrinos

When $\bar{\nu} \neq \nu$

We have 4 mass-degenerate states:



This collection of 4 states is a Dirac neutrino plus its antineutrino.

The SM $\ell\nu W$ interaction, which conserves L, is —

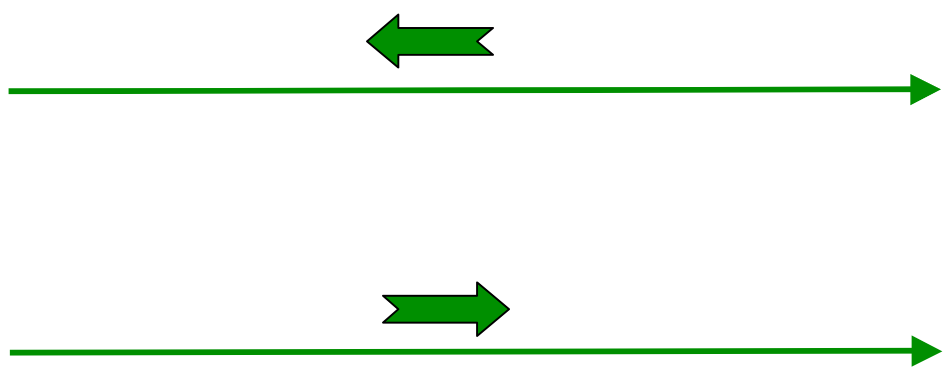
Left-handed

$$L_{SM} = -\frac{g}{\sqrt{2}}\left(\bar{\ell}_L \gamma^\lambda \nu_L W_\lambda^{-} + \bar{\nu}_L \gamma^\lambda \ell_L W_\lambda^{+}\right)$$

Absorbs right-handed $\bar{\nu}$

When $\bar{\nu} \neq \nu$

ν

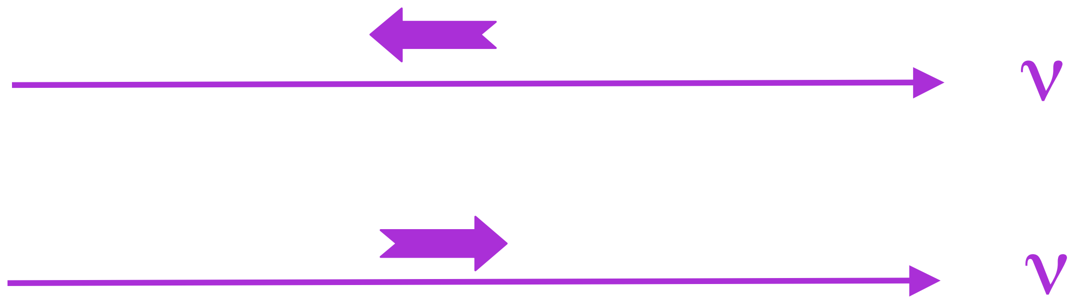


makes ℓ^-

ν doesn't interact

When $\bar{\nu} = \nu$

We have only 2 mass-degenerate states:



This collection of 2 states is a Majorana neutrino.

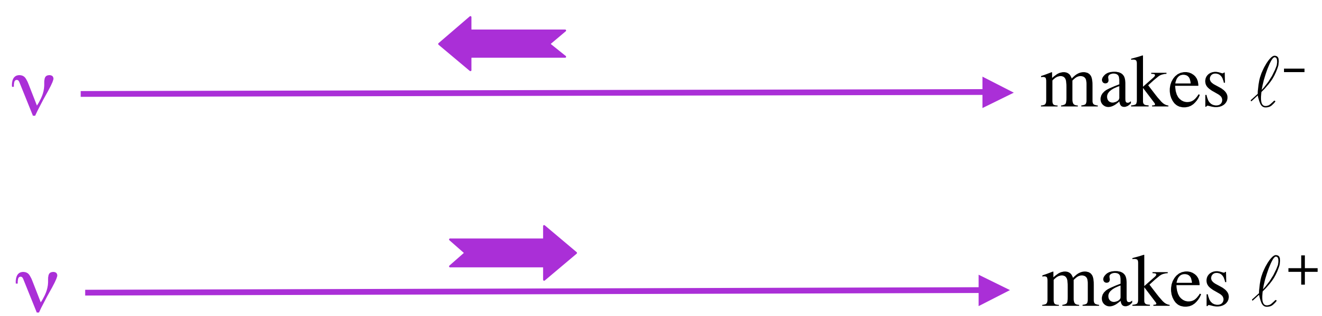
The SM $\ell\nu W$ interaction is —

Left-handed

$$L_{SM} = -\frac{g}{\sqrt{2}}\left(\bar{\ell}_L \gamma^\lambda \nu_L W_\lambda^- + \bar{\nu}_L \gamma^\lambda \ell_L W_\lambda^+\right)$$

Absorbs right-handed $\bar{\nu} = \nu$

When $\bar{\nu} = \nu$

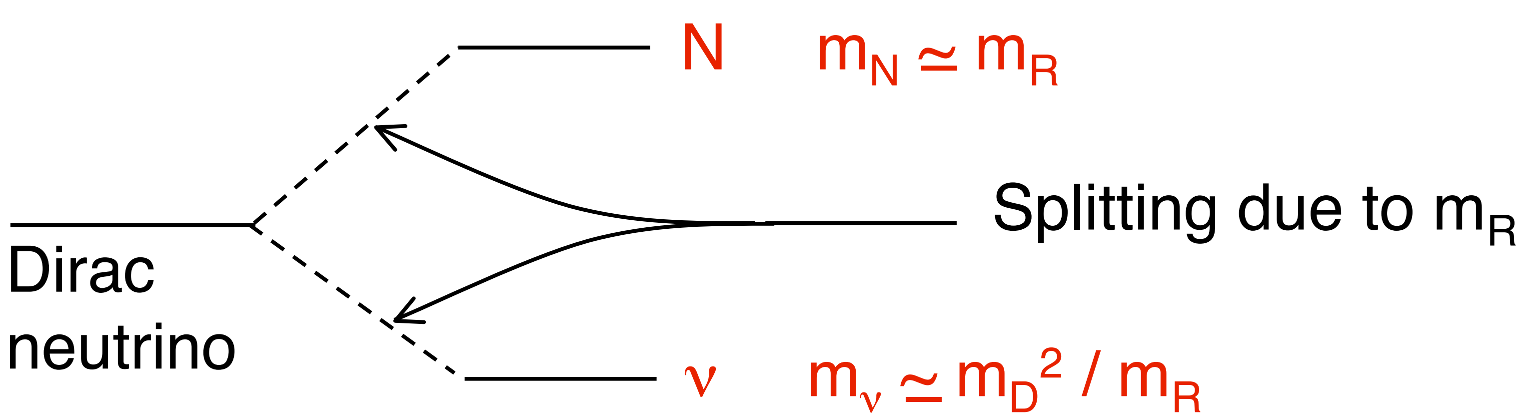


The See-Saw

The See-Saw Mechanism — A Summary —

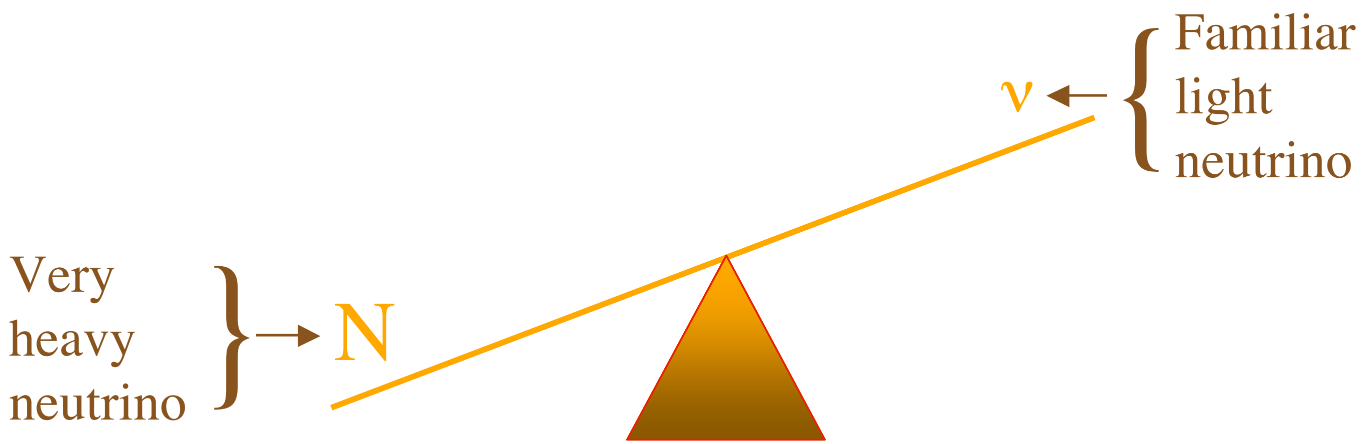
The most popular explanation of why neutrinos are so light.

There is both a large RH Majorana mass m_R and a much smaller Dirac mass $m_D \sim m_{q\ or\ l}$. m_R splits the Dirac neutrino.



Note that $m_\nu m_N \sim m_D^2 \sim m_{q\ or\ l}^2$. ***See-Saw Relation***

The See-Saw Mechanism



Yanagida;
Gell-Mann, Ramond, Slansky;
Mohapatra, Senjanovic;
Minkowski

Predictions of the See-Saw

- Each $\bar{\nu}_i = \nu_i$ (Majorana neutrinos)
- The light neutrinos have heavy partners N_i

How heavy??

$$m_N \sim \frac{m^2_{top}}{m_\nu} \sim \frac{m^2_{top}}{0.05 \text{ eV}} \sim 10^{15} \text{ GeV}$$

Near the GUT scale.

Coincidence??


Are we descended
from the heavy
See-Saw partner
neutrinos?

The Challenge —
A Cosmic Broken Symmetry

The universe contains baryons,
but essentially no antibaryons.

Standard cosmology: Any initial baryon – antibaryon asymmetry would have been erased.

How did $n_B = n_{\overline{B}}$ ⇒ $n_B >> n_{\overline{B}}$?

Sakharov: $n_B = n_{\overline{B}}$ ⇨ $n_B >> n_{\overline{B}}$ requires $\not{CP}$.

The $\not{CP}$ in the quark mixing matrix,
seen in B and K decays, leads to
much too small a B–$\overline{B}$ asymmetry.

If ***quark*** $\not{CP}$ cannot generate
the observed B–$\overline{B}$ asymmetry,
can some scenario involving ***leptons*** do it?

The candidate scenario: *Leptogenesis*,
an outgrowth of the *See-Saw* ***picture***.

(Fukugita, Yanagida)

Leptogenesis — Step 1

The heavy neutrinos N would have been made in the hot Big Bang.

The heavy neutrinos N, like the light ones ν, are Majorana particles. Thus, an N can decay into ℓ^- or ℓ^+.
$\not{CP}$ is expected in these decays.

Then, in the early universe, we would have had different rates for the CP-mirror-image decays –

$$N \rightarrow \ell^- + H^+ \quad \text{and} \quad N \rightarrow \ell^+ + H^-$$

Standard-Model Higgs

This produces a universe with unequal numbers of leptons and antileptons.

Leptogenesis — Step 2

The Standard-Model ***Sphaleron*** process,
which does not conserve Baryon Number B,
or Lepton Number L, but does conserve $B - L$, acts.

$$B_i = 0$$
$$L_i \neq 0$$

→ Sphaleron Process →

$$B_f \cong -\frac{1}{3} L_i$$
$$L_f \cong \frac{2}{3} L_i \cong -2 B_f$$

Initial state from N decays

Final state

There is now a *Baryon Asymmetry*.

Evidence for the See-Saw and for Leptogenesis

By confirming the existence of Majorana masses
and the Majorana character of neutrinos —

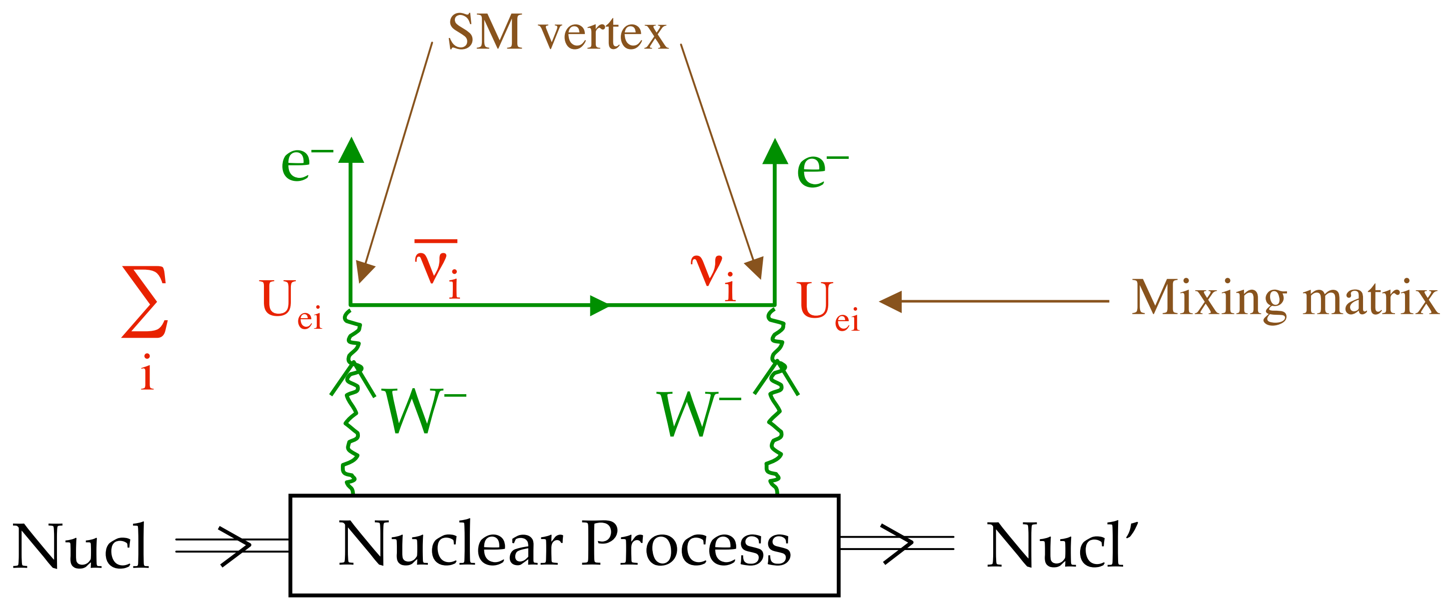
— the observation of **0νββ** would be evidence in favor of the *See-Saw*, hence of *Leptogenesis*.

(Other evidence for *Leptogenesis* would come from the observation of ~~CP~~ in neutrino oscillation.)

— $0\nu\beta\beta$ —

A Closer Look

We anticipate that 0νββ is dominated by a diagram with Standard Model vertices:



Then —

Mass (ν_i)

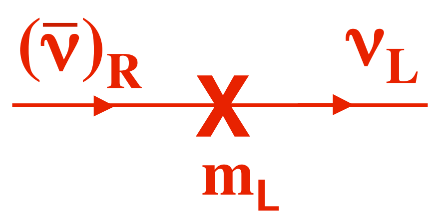
$$\mathrm{Amp}[0\nu\beta\beta] \propto \left| \sum m_i U_{ei}^2 \right| \equiv m_{\beta\beta}$$

Why Amp[0νββ] Is ∝ Neutrino Mass

— manifestly does not conserve L.

But the Standard Model (SM) weak interactions *do* conserve L. Absent any non-SM L-violating interactions, the $\Delta L = 2$ of 0νββ can only come from *Majorana neutrino masses*, such as —

$$m_L(\overline{\nu_L{}^c}\,\nu_L + \overline{\nu_L}\,\nu_L{}^c)$$



How Large is $m_{\beta\beta}$, and What Would We Learn By Measuring It?

Talk by **Serguey Petcov** this afternoon.

Summary

A non-zero signal for $0\nu\beta\beta$ would be a tremendously important discovery.

Good luck in finding it!