The Profound Implications of Neutrinoless Double Beta Decay

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Neutrinoless Double Beta Decay $[0\nu\beta\beta]$

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, $\nu_L$, and its charge-conjugate, $\nu_L^c$, we can build a Left-Handed Majorana mass term —

$$m_L \overline{\nu}_L \nu_L^c \quad \xrightarrow{\text{Majorana} \text{ masses mix } \nu \text{ and } \overline{\nu}} \quad (\overline{\nu})_R \times \nu_L$$

Majorana masses mix $\nu$ and $\overline{\nu}$, 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 \( f \leftrightarrow \bar{f} \).

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

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

Majorana \( \nu \) masses cannot come from \( H_{SM} \bar{\nu}_L \nu_R \), the \( \nu \) analogue of the Higgs coupling that leads to the \( q \) and \( \ell \) masses, and the progenitor of a *Dirac* \( \nu \) mass term.
Possible progenitors of Majorana mass terms:

- $H_{\text{SM}} H_{\text{SM}} \nu^c_L \nu_L$
- $H_{IW} = 1 \nu^c_L \nu_L$
- $m_R \nu^c_R \nu_R$

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 \rightarrow $ A Majorana mass term
Does $\overline{\nu} = \nu$?
What Is the Question?

For each \textit{mass eigenstate} \( \nu_i \), and \textit{given helicity} \( h \), does —

\begin{itemize}
  \item \( \overline{\nu}_i(h) = \nu_i(h) \) \quad (\text{Majorana neutrinos})
\end{itemize}

or

\begin{itemize}
  \item \( \overline{\nu}_i(h) \neq \nu_i(h) \) \quad (\text{Dirac neutrinos})
\end{itemize}

Equivalently, do neutrinos have \textit{Majorana masses}? If they do, then the mass eigenstates are \textit{Majorana neutrinos}. 
The objects $\nu_L$ and $\nu_L^c$ in $m_L \bar{\nu}_L \nu_L^c$ are not the mass eigenstates, but just the neutrinos in terms of which the model is constructed.

$m_L \bar{\nu}_L \nu_L^c$ induces $\nu_L \leftrightarrow \nu_L^c$ mixing.

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

$$K_{S,L} \equiv (K^0 \pm \bar{K}^0)/\sqrt{2}.$$  \(K_{S,L} = K_{S,L}^c\).

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

$$\nu_i = \nu_L + \nu_L^c = \text{“} \nu + \bar{\nu} \text{”}.$$  $\bar{\nu}_i = \nu_i$. 

### Why Majorana Masses $\rightarrow$ Majorana Neutrinos
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

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

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

**Left-handed**

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

- Makes $\ell^-$
- Doesn’t interact
When \( \overline{\nu} = \nu \)

We have only 2 mass-degenerate states:

\[ \overline{\nu} \quad \nu \]
\[ \nu \quad \nu \]

This collection of 2 states is a Majorana neutrino.
The SM $\ell\nu W$ interaction is —

$$L_{SM} = -\frac{g}{\sqrt{2}} \left( \ell_L \gamma^\lambda \nu_{LW} L - \bar{\nu}_L \gamma^\lambda \ell_{LW} + \bar{\nu}_L \gamma^\lambda \ell_{LW}^+ \right)$$

*Left-handed*

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

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

\[ \nu \quad \leftarrow \quad \text{makes } \ell^- \]

\[ \nu \quad \rightarrow \quad \text{makes } \ell^+ \]
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 $m_\nu m_N \sim m_D^2 \sim m_q^2$. See-Saw Relation
The See-Saw Mechanism

Very heavy neutrino \rightarrow N

\nu \rightarrow \{ \text{Familiar light neutrino} \}

\{ \text{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??

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

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 $n_B = n_{\overline{B}}$ \rightarrow $n_B \gg n_{\overline{B}}$?
Sakharov: $n_B = n_{\bar{B}} \quad \rightarrow \quad n_B \gg n_{\bar{B}} \quad \text{requires CP.}$

The CP in the quark mixing matrix, seen in B and K decays, leads to much too small a $B-\bar{B}$ asymmetry.

If quark CP cannot generate the observed $B-\bar{B}$ 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 $\nu$, are Majorana particles. Thus, an $N$ can decay into $\ell^-$ or $\ell^+$. 

$\mathcal{CP}$ is expected in these decays.

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

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

This produces a universe with unequal numbers of leptons and antileptons.
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 $0\nu\beta\beta$ would be evidence in favor of the See-Saw, hence of Leptogenesis.

(Other evidence for Leptogenesis would come from the observation of $\mathcal{CP}$ in neutrino oscillation.)
— 0νββ —

A Closer Look
We anticipate that $0\nu\beta\beta$ is dominated by a diagram with Standard Model vertices:

\[
\sum_i U_{ei} \overline{\nu}_i \rightarrow W^- \rightarrow \nu_i U_{ei} \rightarrow e^-
\]

Then —

\[\text{Amp}[0\nu\beta\beta] \propto \left| \sum m_i U_{ei}^2 \right| \equiv m_{\beta\beta}\]
Why $\text{Amp}[0\nu\beta\beta]$ Is $\propto$ 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 $0\nu\beta\beta$ can only come from \textit{Majorana neutrino masses}, such as —

$$m_L (\bar{\nu}_L^c \nu_L + \bar{\nu}_L \nu_L^c)$$
How Large is $m_{\beta\beta}$, and What Would We Learn By Measuring It?

Talk by Serguey Petcov this afternoon.
A non-zero signal for $0\nu\beta\beta$ would be a tremendously important discovery.

Good luck in finding it!