Neutrinoless Double Beta Decay and Neutrino Mass — A Point of Principle

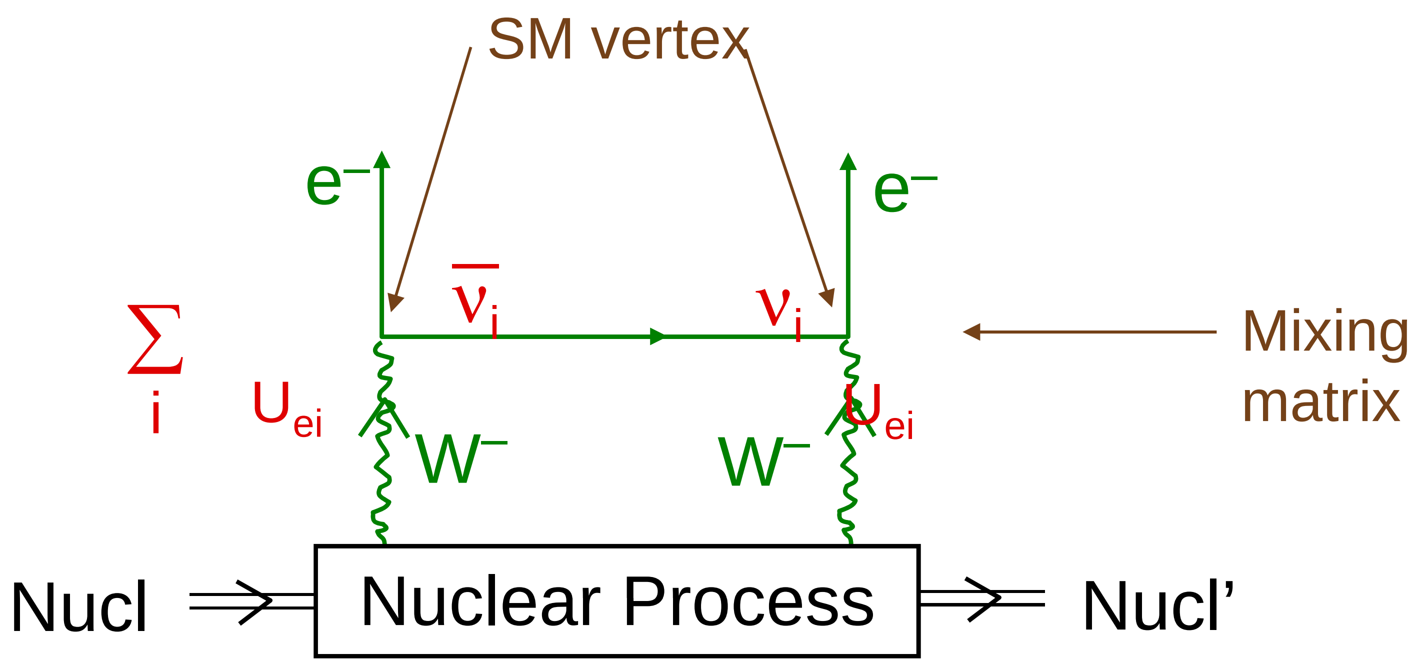
Neutrinoless Double Beta Decay [$0\nu\beta\beta$]

This is the promising approach to testing whether neutrinos are their own antiparticles.

It will be sought with greatly increased sensitivity.

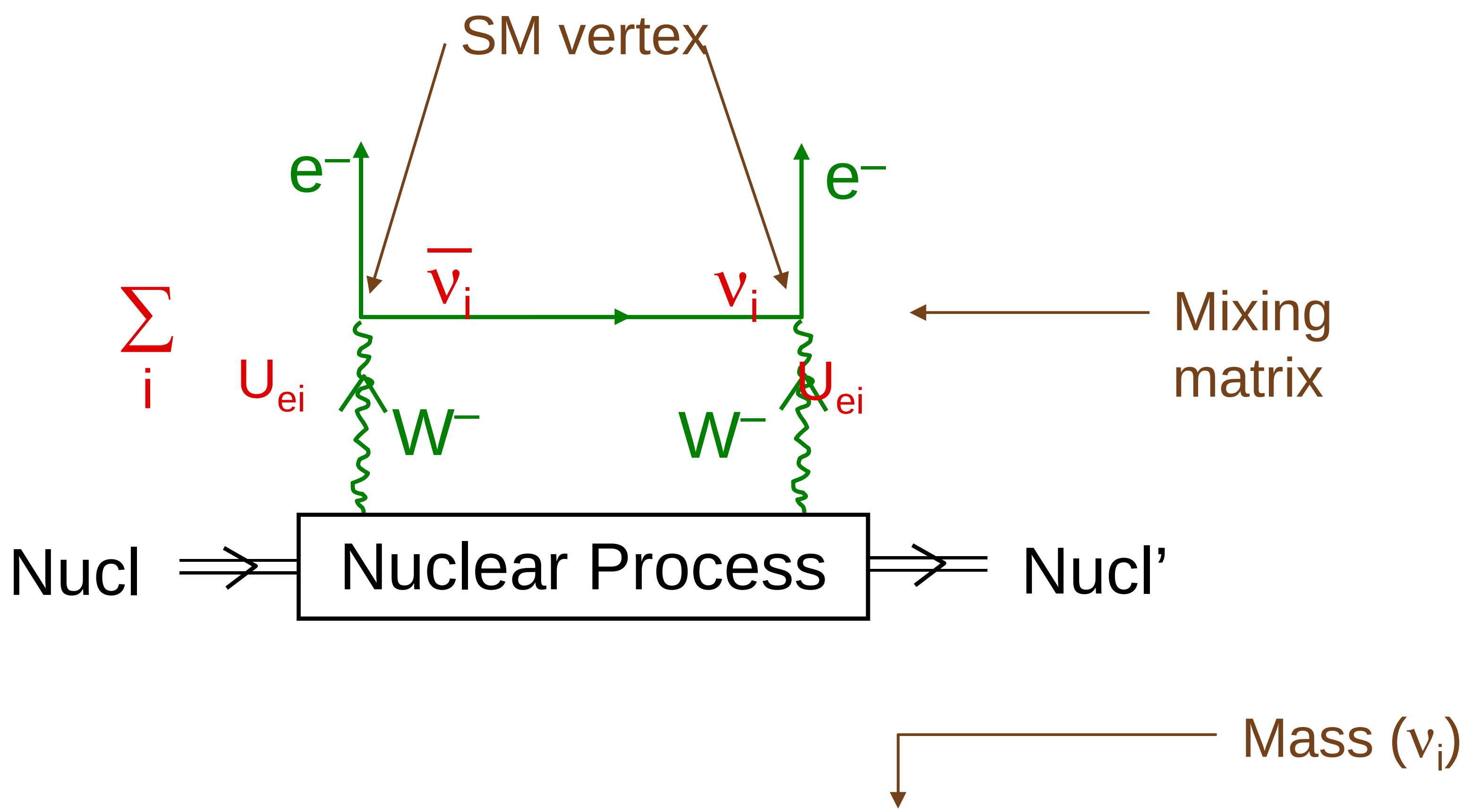
To estimate the sensitivity required —

we assume that 0νββ is dominated by a diagram with Standard Model vertices:



— Down the Garden Path —

In —



the $\bar{\nu}_i$ is emitted [RH + O{m_i/E}LH].

Thus, Amp [ν_i contribution] $\propto m_i$

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

The Trap

This makes it look as if $0\nu\beta\beta$ needs ν mass only because of a helicity mismatch.

Suppose we had a parity-conserving world, that treats right-handed and left-handed particles in the same way.

Couldn't we then have $0\nu\beta\beta$ without any ν mass?

No!

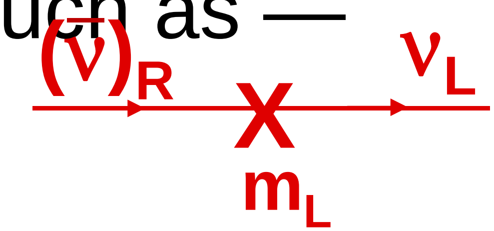
ν mass is still required.

Why?

— manifestly does not conserve L.

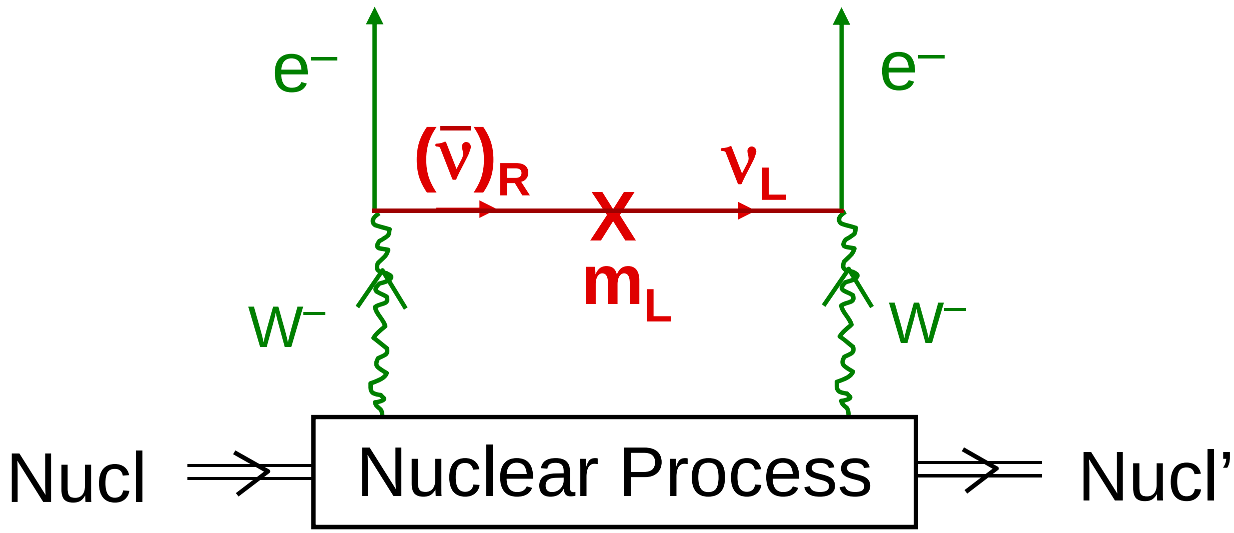
But the Standard Model (SM) weak interactions *do* conserve L. Absent any non-SM L-violating interactions, the $\Delta L = 2$ of $0\nu\beta\beta$ can only come from *Majorana neutrino masses*, such as —

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



Assuming Standard Model vertices, $0\nu\beta\beta$ is

—



The Majorana neutrino mass term plays two roles:

1) Violate L

2) Flip handedness

It will be needed for (1) even when not needed for (2)

A Parity-Conserving Toy-Model Illustration

Suppose there is only one generation.

Suppose the W couples to the electron and neutrino via a parity-conserving vector current:

$$-L_W = \frac{g}{\sqrt{2}} W_\lambda^- \overline{e} \gamma^\lambda \nu + \text{h.c.} = \frac{g}{\sqrt{2}} W_\lambda^- \left(\overline{e_L} \gamma^\lambda \nu_L + \overline{e_R} \gamma^\lambda \nu_R \right) + \text{h.c.}$$

Suppose the neutrino mass term is also $L \Leftrightarrow R$ invariant:

$$-L_M = \frac{1}{2} m_M \left(\overline{\nu_L^c} \nu_L + \overline{\nu_R^c} \nu_R \right) + m_D \overline{\nu_R} \nu_L + \text{h.c.}$$

We take $m_{M,D}$ real, $m_M > m_D$, and neglect the electron mass.

The neutrino mass eigenstates are the two Majorana particles —

$$\nu_2 = \frac{1}{\sqrt{2}}\left[(\nu_L + \nu_R) + (\nu_L + \nu_R)^c\right], \text{ with mass } m_2 = m_M + m_D \,,$$

and

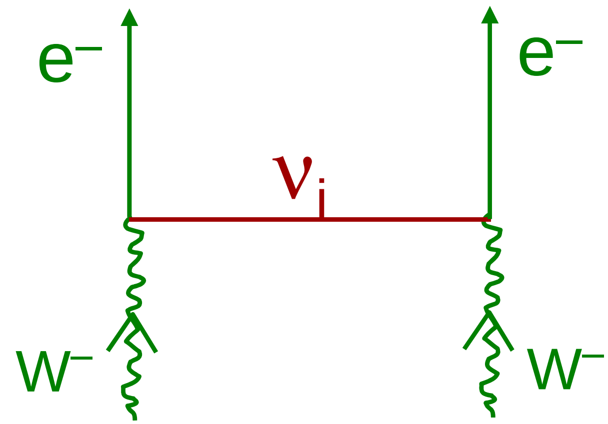
$$\nu_1 = \frac{1}{\sqrt{2}}\left[(\nu_L - \nu_R) + (\nu_L - \nu_R)^c\right], \text{ with mass } m_1 = m_M - m_D \,.$$

In terms of them —

$$-L_W = \frac{g}{\sqrt{2}} W_\lambda^- \left[\overline{e_L}\gamma^\lambda \frac{1}{\sqrt{2}}(\nu_{2L} + \nu_{1L}) + \overline{e_R}\gamma^\lambda \frac{1}{\sqrt{2}}(\nu_{2R} - \nu_{1R})\right] + \text{h.c.}$$

Consider now the particle-physics part of $0\nu\beta\beta$ —

$$\sum_{i=1,2}$$



If the electrons both emerge Left-Handed (LH), only the LH leptonic currents contribute.

For this final state, one finds that the amplitude, A_{LL}, obeys —

$$A_{LL} \propto \frac{m_2}{q^2 - m_2^2} + \frac{m_1}{q^2 - m_1^2} \cong \frac{m_2 + m_1}{q^2} = \frac{2m_M}{q^2}$$

The amplitude is proportional to the Majorana ν mass

Similarly, if both electrons emerge right-handed, the amplitude, A_{RR}, obeys —

$$A_{RR} \propto \frac{2m_M}{q^2}$$

If the electrons emerge with opposite handedness, both the LH and RH currents are involved, and one finds that the amplitude, A_{LR}, obeys —

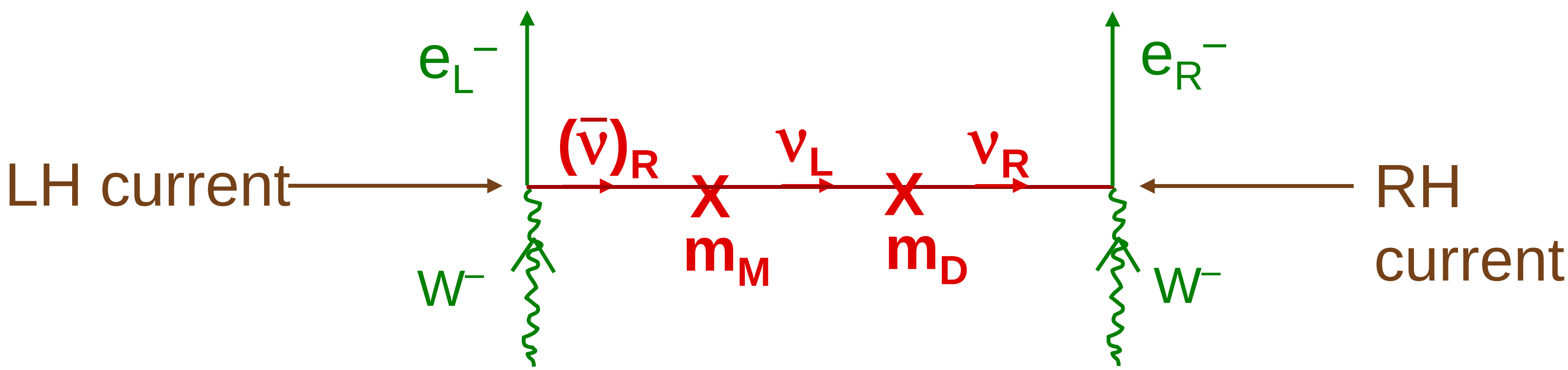
$$A_{LR} \propto i\not{q}\left(\frac{1}{q^2 - m_2^2} - \frac{1}{q^2 - m_1^2}\right) \cong i\not{q}\left(\frac{m_2^2 - m_1^2}{\left(q^2\right)^2}\right) = \frac{i\not{q}}{\left(q^2\right)^2} 4 m_M m_D$$

The amplitude is proportional to the Majorana ν mass m_M.

Why A_{LR} is also proportional to the Dirac mass m_D:

{ BK, Petcov, and Rosen; Enqvist, Maalampi, and Mursula }

The process is —



Two flips of handedness are needed.

Summary

Absent L-nonconserving interactions from beyond the Standard Model, $0\nu\beta\beta$ requires Majorana neutrino mass.

This mass is needed to introduce L-nonconservation, even if it is not needed for any other reason.