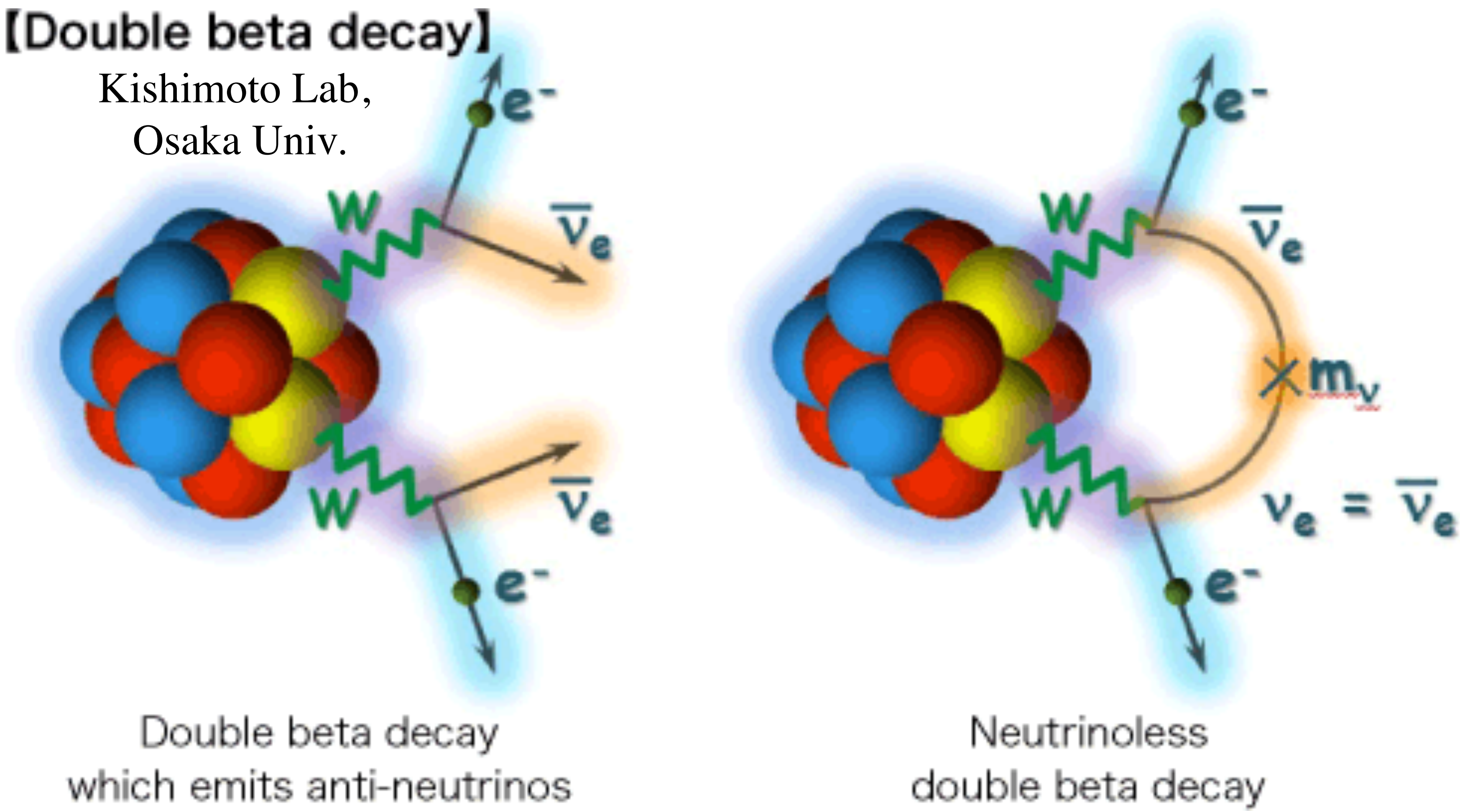


The Nature of Neutrinos, and the Origin of Their Masses

Boris Kayser, Solvay Workshop, November 2017

Three Related Open Questions

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

What is the origin of the neutrino masses?

Is conservation of the lepton number
$L \equiv$ #(Leptons) – #(Antileptons) violated?

What is the origin of the neutrino masses?

The discovery and study of the ***Higgs boson*** at the LHC has provided strong evidence that the ***quarks*** and ***charged leptons*** derive their masses from a coupling to the ***Higgs field***.

But most theorists strongly suspect that the origin of the neutrino masses is different from the origin of the masses of all other known particles.

The Standard-Model (SM) ***Higgs field*** is probably still involved, but there is probably something more — something way outside the SM —

Majorana masses.

What Majorana Masses Are

For simplicity, let us treat a world with just one flavor, and correspondingly, just one neutrino mass eigenstate.

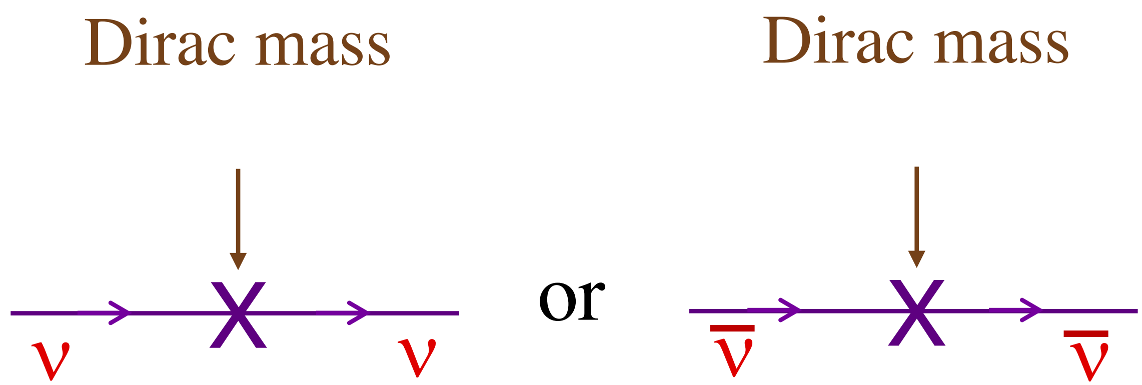
We start with underlying neutrino states ν and $\bar{\nu}$ that are distinct from each other, like other familiar fermions, and are not the mass eigenstate.

We will have to see what the mass eigenstate is later.

We can have two types of masses:

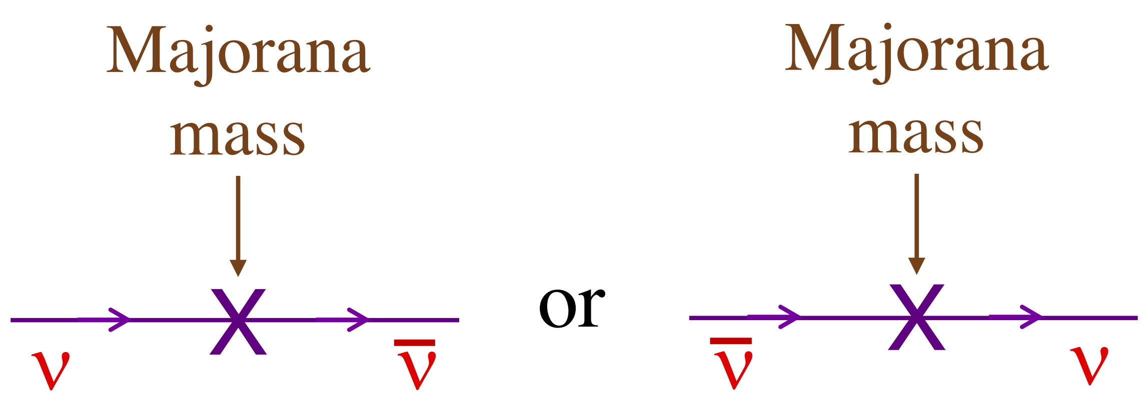
Dirac Mass

A Dirac mass has the effect:



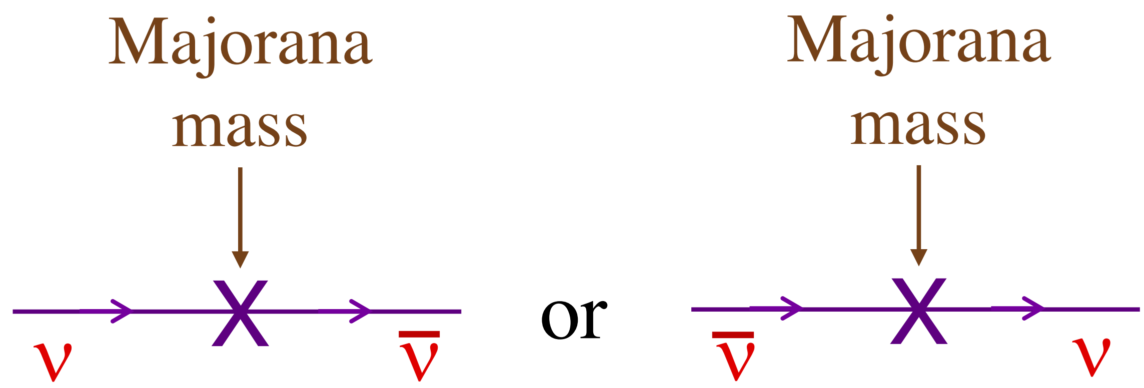
Majorana Mass

A Majorana mass has the effect:



Majorana Masses and Lepton Number Non-Conservation

A Majorana mass has the effect:



Majorana masses mix ν and $\bar{\nu}$, so they do not conserve the Lepton Number L.

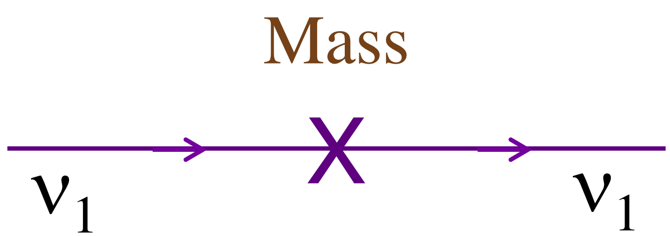
The SM weak interactions conserve L ($\nu \rightarrow e^-$; $\bar{\nu} \rightarrow e^+$).

Let us assume there are no significant non-SM interactions that violate L.

Then any violation of L must come from Majorana neutrino masses, and thus will be suppressed by m_ν/E_ν.

The Mass Eigenstate When There Are Majorana Masses

For the neutrino mass eigenstate "ν_1" the action of its mass must be —

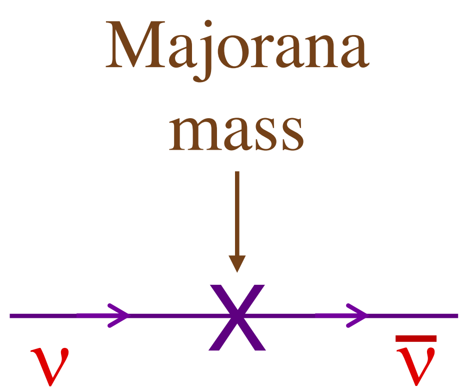


The mass eigenstate must be sent back into itself:

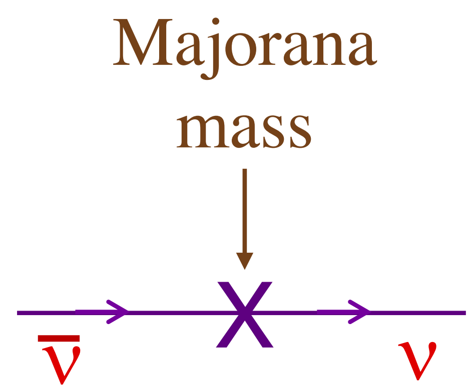
$$H|\nu_1\rangle = m_1|\nu_1\rangle$$

Recall that —

A ***Majorana*** mass has the effect:



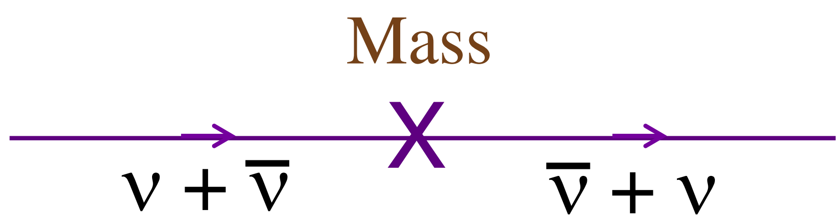
or



Then the mass eigenstate neutrino ν_1 must be —

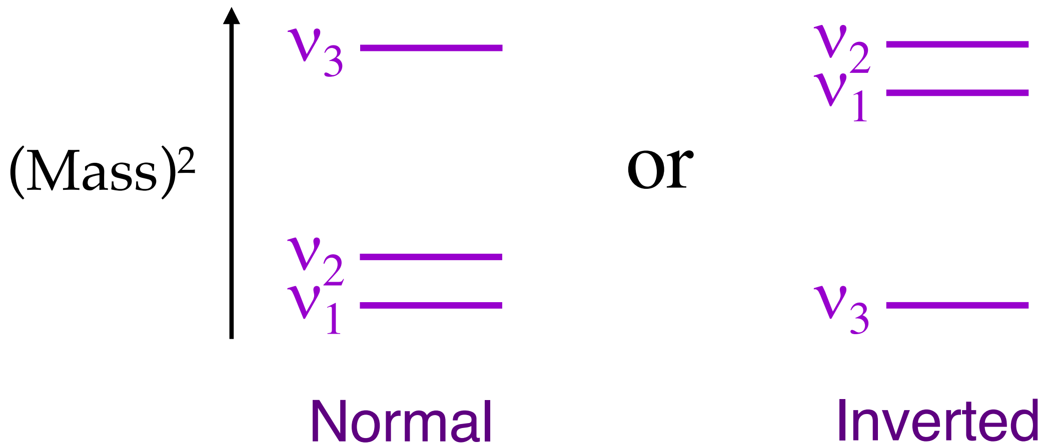
$$\nu_1 = \nu + \bar{\nu} \ ,$$

since this is the neutrino that the Majorana mass term sends back into itself, as required for any mass eigenstate particle:



When the underlying mass is a Majorana mass, the mass eigenstate will be its own antiparticle.

The Real World, With
$\geqq$ 3 Mass Eigenstates



Terminology

With ν_i one of the mass eigenstates, with helicity h,

if $\overline{\nu_i}(h) = \nu_i(h)$ *Majorana neutrino*

if $\overline{\nu_i}(h) \neq \nu_i(h)$ *Dirac neutrino*

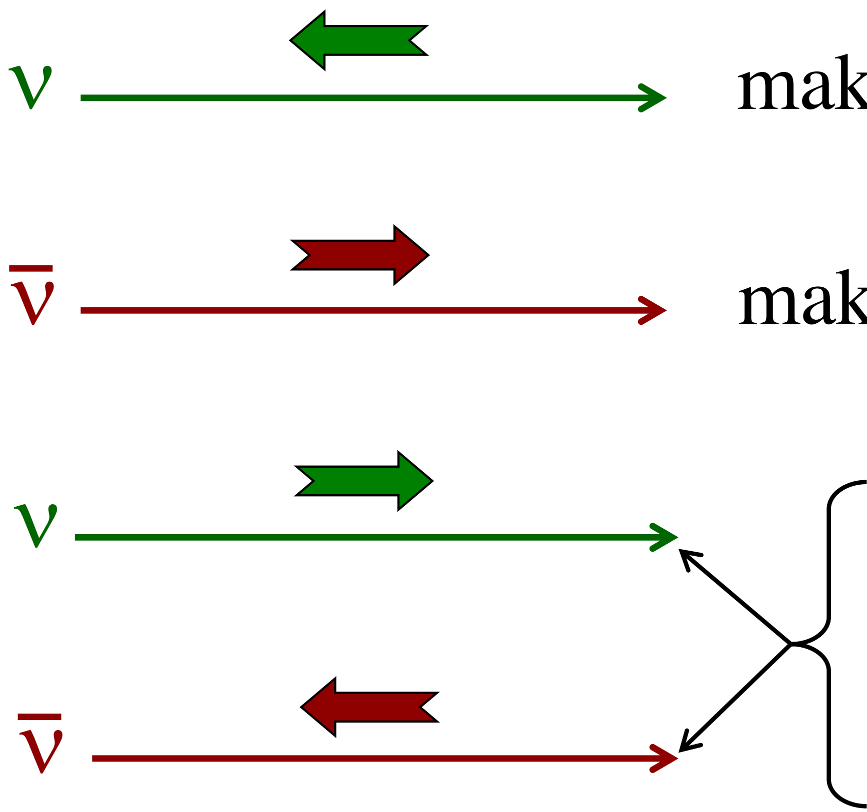
In the real world of several mass eigenstates, if the underlying neutrino masses are *Majorana masses*, then all the mass eigenstates are *Majorana neutrinos*.

If, in addition to *Majorana masses*, there are also *Dirac masses*, the mass eigenstates are still *Majorana neutrinos*.

The SM Interactions of Dirac, and Especially Majorana, Neutrino Mass Eigenstates

SM Interactions Of A Dirac Neutrino

We have 4 mass-degenerate states:

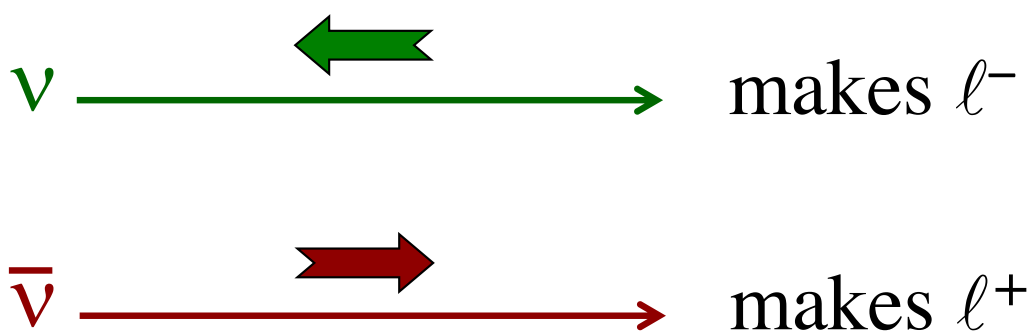


		Conserved L
ν	makes ℓ^-	+1
$\bar{\nu}$	makes ℓ^+	–1

These states, *when Ultra Rel.*, do not interact.
(The weak interaction is Left Handed.)

SM Interactions Of An *Ultra-Relativistic* Majorana Neutrino

We have only 2 mass-degenerate states:



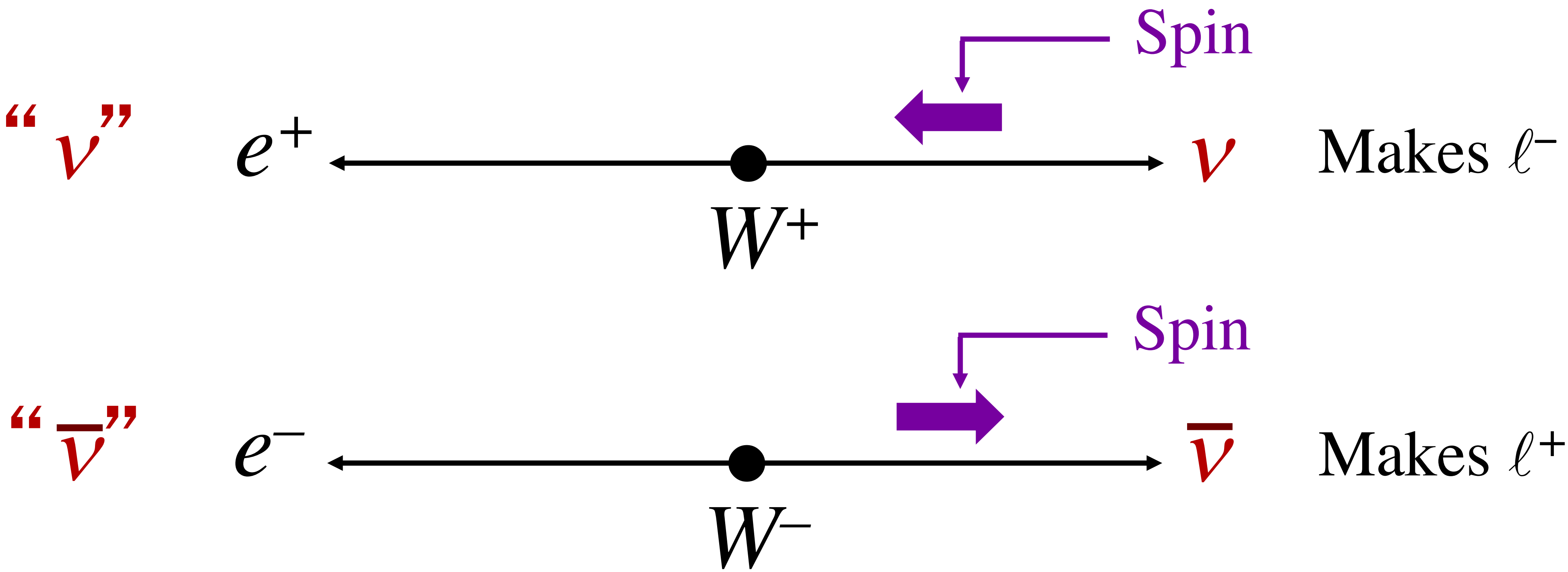
The SM weak interactions violate *parity*.

(They can tell *Left* from *Right*.)

An incoming left-handed neutral lepton makes ℓ^-.

An incoming right-handed neutral lepton makes ℓ^+.

Note: " ν " and " $\bar{\nu}$ " are ***produced*** with opposite helicity.



The SM weak interactions violate ***Parity***.

Particles with left-handed and right-handed helicity can behave differently.

For ***ultra-relativistic Majorana*** neutrinos,
helicity is a "substitute" for lepton number.

Majorana neutrinos almost always behave
indistiguishably from Dirac neutrinos.

However, for ***non-relativistic*** neutrinos,
there can be a big difference between the behavior
of Majorana neutrinos and Dirac neutrinos,
as we will see later.

To Determine Whether Majorana Masses Occur in Nature, So That $\bar{\nu} = \nu$

The Promising Approach — Seek

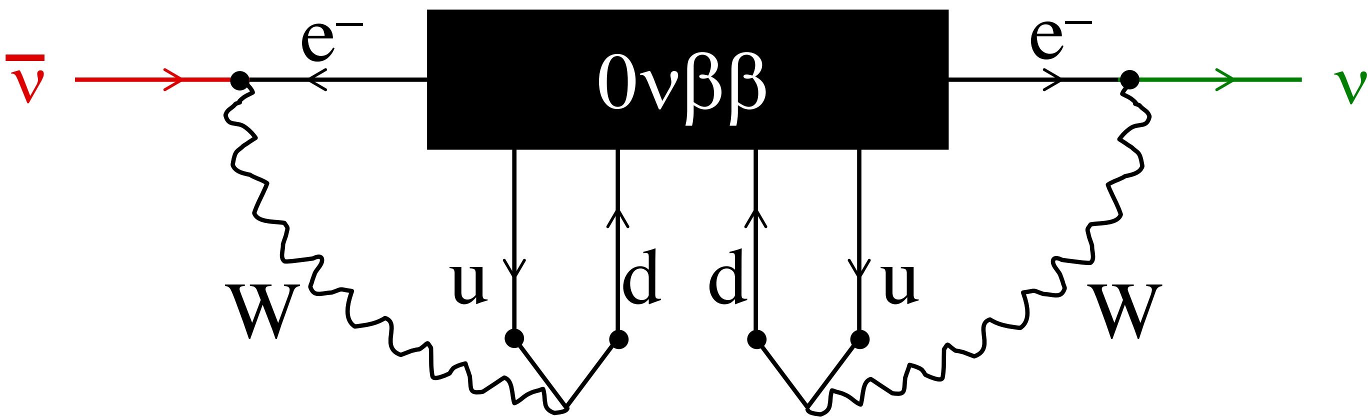
Neutrinoless Double Beta Decay [$0\nu\beta\beta$]

Observation at any non-zero level would imply —

- Lepton number L is not conserved ($\Delta L = 2$)
- Neutrinos have Majorana masses
- Neutrinos are Majorana particles (self-conjugate)

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

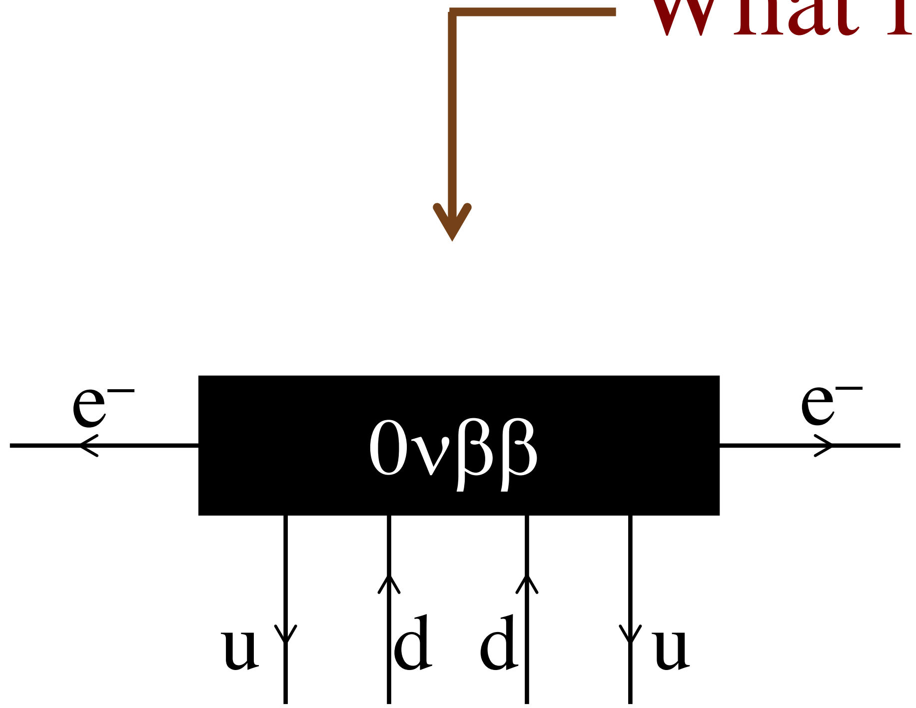
(Schechter and Valle)



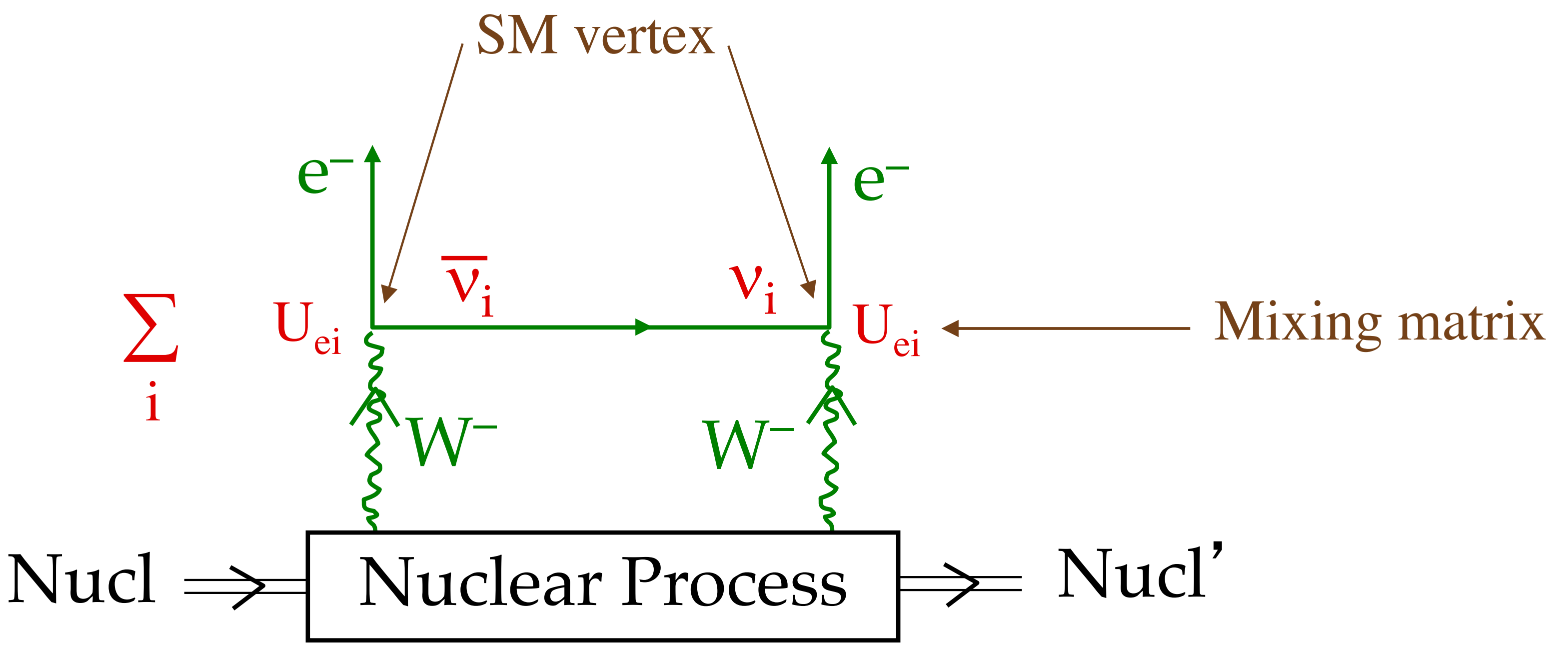
$\bar{\nu} \rightarrow \nu$: A (tiny) Majorana mass term

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

What is inside?



We anticipate that 0νββ is dominated by a diagram with light neutrino exchange and Standard Model vertices:



Then –

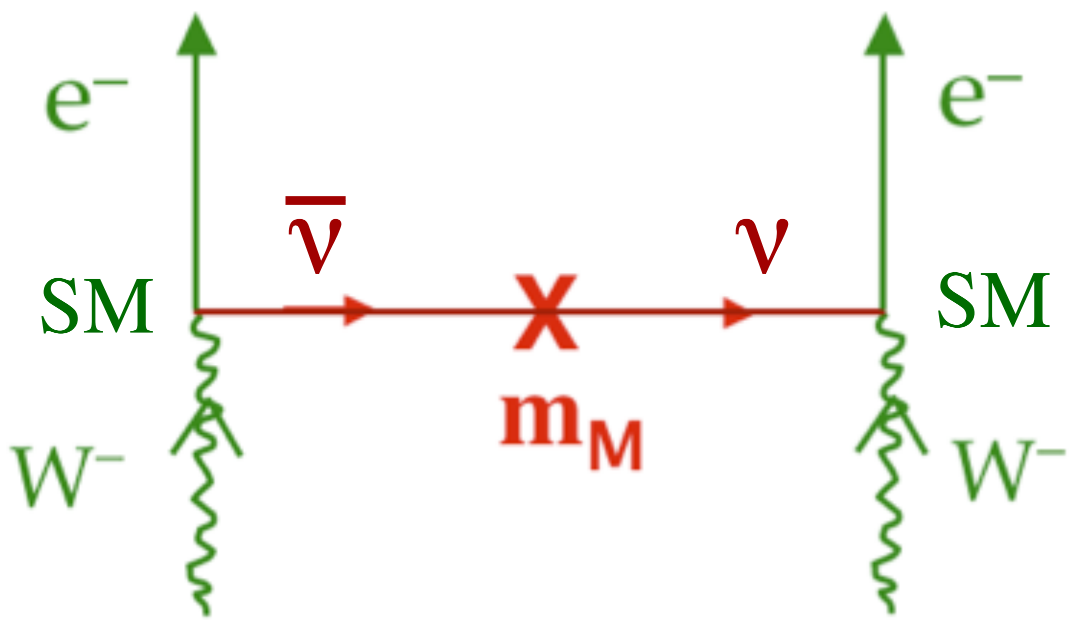
Mass (ν_i)

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

Why the neutrino mass is involved

$0\nu\beta\beta$ has $\Delta L = 2$. This ΔL must come from a ***Majorana mass***, since the SM interactions conserve L.

Viewed as a perturbation in a small Majorana mass m_M, what happens is —



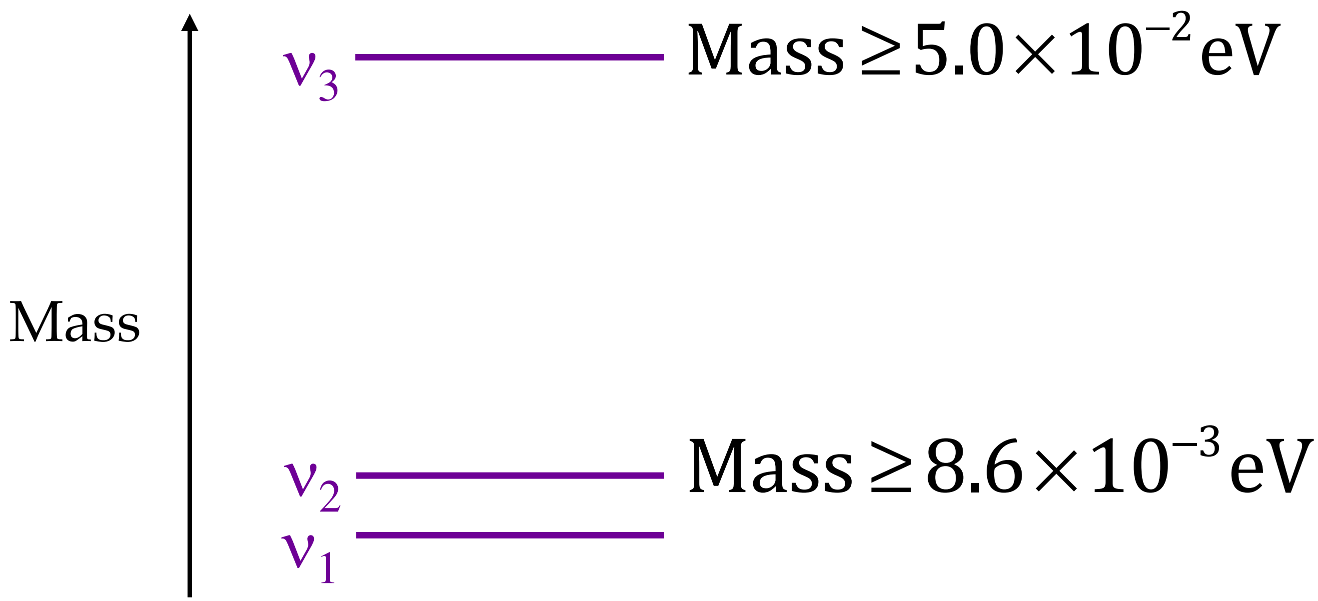
When Neutrinos Are Non-Relativistic

With thanks for discussions to Petr Vogel, Baha Balantekin, and Amol Patwardhan.

Many, and perhaps all, of the neutrinos produced in the Big Bang are non-relativistic today.

These neutrinos are currently at $kT = 1.7 \times 10^{-4}\,\text{eV}$.

From the mass-squared splittings measured in neutrino oscillation experiments, we know that if the mass ordering is *Normal* —



If the ordering is *Inverted*, $\text{Mass}(\nu_1 \text{ and } \nu_2) \geq 5.0 \times 10^{-2}\,\text{eV}$.

There are hopes of detecting the Big Bang relic neutrinos via their ***capture on tritium***.

(PTOLEMY)

Tritium β decay: $^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \overline{\nu}_i$; $i = 1, 2$, or 3

$$E_e \leq \left(m_H - m_{He}\right) - m_{\nu_i}$$

Capture of a very non-relativistic relic ν_i on tritium:

$$\nu_i + {}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^-$$

$$E_e = \left(m_H - m_{He}\right) + m_{\nu_i}$$

The challenge: Demonstrate there are electrons with energies slightly beyond the decay endpoint.

How Does the Capture Rate Depend on the Majorana or Dirac Nature of the Relic Neutrinos?

1. ***How the current populations of the various non-relativistic neutrino spin states compare in the two cases.***

The neutrinos are highly relativistic when they are produced in the early universe, so the rate of production of each helicity state is the same in the Dirac and Majorana cases.

After decoupling, the neutrinos free stream, and as they cool to being nearly at rest, helicity just becomes a spin direction.

<u>If Majorana</u>

At decoupling $\nu \big\downarrow \uparrow \quad \bar{\nu} \big\downarrow \downarrow$ Equally abundant

At earth, after expansion $\nu(\uparrow) \quad \bar{\nu}(\downarrow) \quad \nu(\downarrow) \quad \bar{\nu}(\uparrow)$

At decoupling $\nu \big\uparrow \downarrow \quad \bar{\nu} \big\uparrow \uparrow$

The total number of particles per unit volume is the same in the two cases, equally distributed among the four sub-populations. In the Dirac case, half of the particles cannot create an <u>electron</u> on ^3H.

2. How the cross sections for capture on ^3H compare in the two cases.

For the two sub-populations that are neutrinos (not antineutrinos) in both cases, we have for either case —

$$\text{Amplitude}\left(\nu + {}^3\text{H} \rightarrow {}^3\text{He} + e^-\right) \propto \bar{u}_e \gamma^\lambda \left(1 - \gamma_5\right) u_\nu J_\lambda^{\text{Hadronic}}$$

Causes no suppression for neutrinos nearly at rest

No Dirac-Majorana distinction.

For the two sub-populations that are antineutrinos in the Dirac case —

$$\text{Amplitude}\left(\bar{\nu} + {}^3\text{H} \rightarrow {}^3\text{He} + e^-\right) = 0$$

But in the Majorana case, these two sub-populations contribute the same as the other two.

For a given total density of non-relativistic relic neutrinos here at the earth, the capture rate on tritium is twice as big if neutrinos are Majorana particles as it is if they are Dirac particles.

(Long, Lunardini, Sabancilar; B. K.)

(See also Lazauskas, Vogel, Volpe)

This illustrates that when neutrinos are non-relativistic, their Majorana or Dirac nature can make a big difference.

Actually using capture of the relic neutrinos on tritium to determine whether neutrinos are Majorana or Dirac particles would face very daunting obstacles:

- One must observe the process. This has not been done yet. Huge background from ^{3}H β decay.
- One must know the ***local*** (not universe-average) density of relic neutrinos.
  Estimates differ by orders of magnitude.
- If one of the three neutrino mass eigenstates is still relativistic today, two thirds of the captures could become indistinguishable from β decays.

But if this approach to determining the Majorana or Dirac nature of neutrinos could be made to work…….

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

What is the origin of the neutrino masses?

Is conservation of the lepton number
$L \equiv$ #(Leptons) – #(Antileptons) violated?

We look forward to learning the answers!