Three?
Why Three?

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ICISE
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We know there are ***at least*** 3 neutrinos.

Are there more?

Why are there at least 3?

More generally —

Why are there 3 generations of quarks and leptons?

After all, we humans and all ordinary matter are made of just the quarks and electrons of the 1st generation.

An Incorrect Argument

1. Our existence depends on the universe containing matter but essentially no antimatter.
2. This matter-antimatter asymmetry depends on there having been CP violation in the early universe.
3. CP violation among the quarks requires at least 3 generations. (Kobayashi and Maskawa)
4. Presumably, this is also true for CP violation among the leptons.
5. Therefore, there must be at least 3 generations, or we would not be here.

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X Presumably, this is also true for CP violation among the leptons.

X Therefore, there must be at least 3 generations, or we would not be here.

Leptogenesis is a counterexample.

Leptogenesis explains the matter-antimatter asymmetry of the universe in terms of CP violation in the decays of ***heavy*** Majorana (self-conjugate) neutral leptons N_i that lived briefly in the early universe.

(Talks by Pasquale di Bari and Juraj Klaric)

(Thanks to Jessica Turner for illuminating discussions)

The hypothesis that these N_i exist is motivated by the See-Saw model, which adds them to the Standard-Model (SM) particles, enlarging the leptonic sector.

In the straightforward (type I) See-Saw model,

Large Majorana masses

Charge conjugate

SM lepton doublet

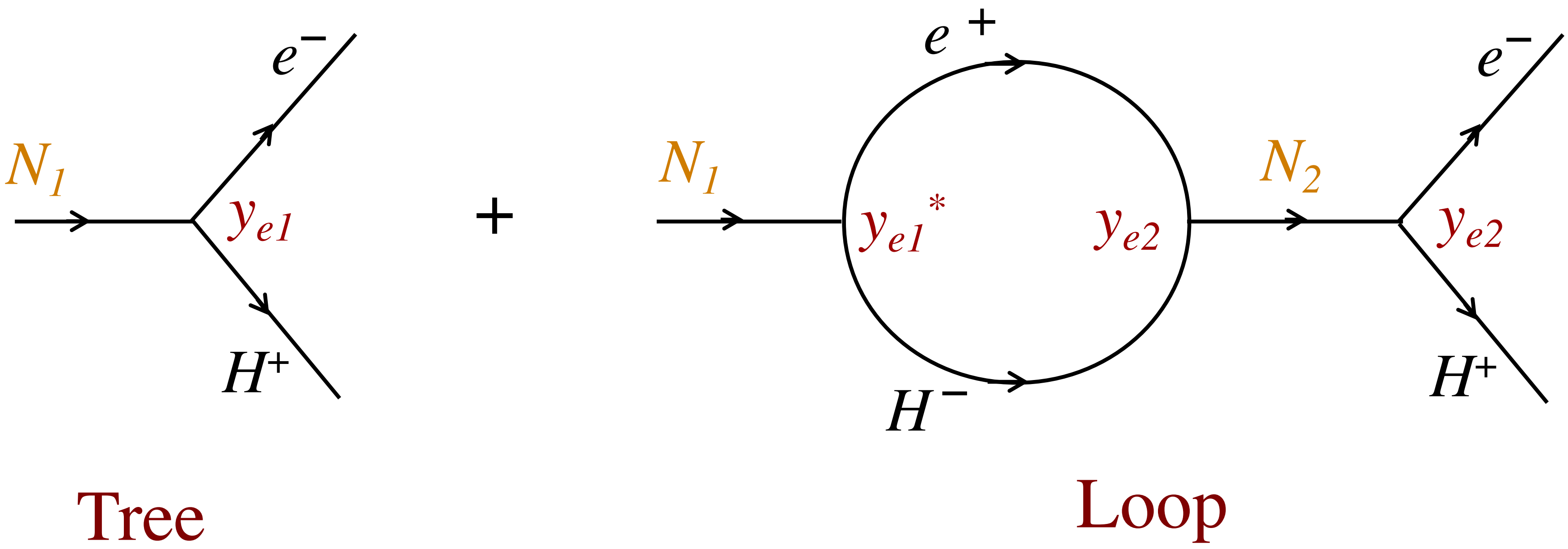
$$\mathcal{L}_{new} = -\frac{1}{2}\sum_i m_{N_i}\,\overline{N_i^c}\,N_i + \sum_{\substack{\alpha=e,\mu,\tau \\ i}} y_{\alpha i}\left[\bar{\nu}_\alpha \overline{H^0} - \bar{\ell}_\alpha H^-\right]N_i + h.c.$$

SM Higgs doublet

Yukawa coupling matrix

Note: In the early universe, before $\langle H^0 \rangle_0$ turned on, and the charged Higgs particles were absorbed by the W bosons, they were physical particles themselves.

An example of CP violation with only 1 SM lepton generation



$$\Gamma\left(N_1 \rightarrow e^- + H^+\right) = \left| y_{e1} K_{Tree} + y_{e1}^* y_{e2} y_{e2} K_{Loop} \right|^2$$

Kinematical factors

$$\Gamma\left(N_1 \to e^- + H^+\right) = \left| y_{e1} K_{Tree} + y_{e1}^* y_{e2} y_{e2} K_{Loop} \right|^2$$

When we go to the CP-mirror-image decay, $N_1 \to e^+ + H^-$, all the coupling constants get complex conjugated, but the kinematical factors do not change.

From Hermiticity of H

$$\Gamma\left(N_1 \to e^+ + H^-\right) = \left| y_{e1}^* K_{Tree} + y_{e1} y_{e2}^* y_{e2}^* K_{Loop} \right|^2$$

Then —

$$\boxed{\begin{aligned} &\Gamma\left(N_1 \to e^- + H^+\right) - \Gamma\left(N_1 \to e^+ + H^-\right) \\ &= 4\,\mathrm{Im}\left(\left(y_{e1}^*\right)^2 \left(y_{e2}\right)^2\right) \mathrm{Im}\left(K_{Tree} K_{Loop}^*\right) \end{aligned}}$$

This produces a matter-antimatter ($e^- - e^+$) asymmetry.

It requires **<u>2</u>** $\boldsymbol{N_i}$, but only **<u>1</u>** SM generation.

So why are there <u>3</u> Standard-Model generations????????

Is it crucial, for something important, to have <u>3</u> generations???

Are There More Than 3 Neutrinos?

The neutrinos beyond 3 need not be associated with SM generations.

We know they do not couple to the SM Z (or W) boson.

(Talk by Monica Pepe Altarelli)

Hence, we call them ***"sterile"***.

But if they exist, they presumably couple to ***something***.

➡ ***New particles besides the new neutrinos, and new interactions.***

There could be sterile neutrinos at any mass scale.

For example, in the straightforward (type I) See-Saw model,

$$\mathcal{L}_{new} = -\frac{1}{2}\sum_i m_{N_i} \overline{N_i^c} N_i + \sum_{\substack{\alpha=e,\mu,\tau \\ i}} y_{\alpha i}\left[\bar{\nu}_\alpha \overline{H^0} - \bar{\ell}_\alpha H^-\right] N_i + h.c.$$

The $\boldsymbol{N_i}$ interact with the rest of the world only through the Yukawa coupling above.

They do not couple to the SM *W* or *Z* bosons.

$\therefore$ They are sterile neutrinos.

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The $\boldsymbol{N_i}$ interact with the rest of the world only through the Yukawa coupling above.

They do not couple to the SM W or Z bosons.

∴ They are sterile neutrinos.

At a lower mass scale –

Are There eV-Scale Largely-Sterile Neutrino Mass Eigenstates?

$$\text{Probability}\left(\text{Oscillation}\right) \propto \sin^2\left[1.27\Delta m^2\left(\text{eV}^2\right)\frac{L\left(\text{m}\right)}{E\left(\text{MeV}\right)}\right]$$

Anomalies in Short-Baseline neutrino experiments suggest possible ν or $\bar{\nu}$ oscillations that are too fast to be driven by the known squared-mass splittings Δm^2.

- Two accelerator-based experiments may see too fast $\nu_\mu \to \nu_e$ or $\bar{\nu}_\mu \to \bar{\nu}_e$

- Various reactor experiments may see too fast $\bar{\nu}_e \to$ Not $\bar{\nu}_e$

- Two e-capture experiments may see too fast $\nu_e \to$ Not ν_e

Are the anomalies caused by well-established, but misunderstood, physics, such as incorrectly estimated backgrounds?

(Talk by Lauren Yates)

Or, are the anomalies due to New Physics (NP)?

If so, is that NP really ***oscillation***, driven by a $\sim 1\ \mathrm{eV}^2\ \Delta m^2$, as most commonly assumed?

If so, there must exist ***1 or more additional neutrino mass eigenstates***, beyond the well-established ***3***.

Given the measurements of the Z boson, the additional neutrino mass eigenstates must be largely sterile.

Is this picture, based on one or more extra, largely-sterile, neutrino mass eigenstates a viable description of the data????

Joachim Kopp during a physics program in Mainz:

One can think of the Short-Baseline data as comprising three data sets: $\nu_\mu \to \nu_e$, $\nu_\mu \to \nu_\mu$, and $\nu_e \to \nu_e$.

The data in each set can be successfully fitted with a 3+1 model (one extra, largely-sterile, mass eigenstate).

But the three fits are not consistent with each other. There is tension between them.

Diaz, Argüelles, Collin, Conrad, and Shaevitz;
arXiv:1906.00045:

"Separate fits to the appearance and disappearance oscillation data sets within a 3+1 model do not show the expected overlapping allowed regions in parameter space."

Regarding the question of what is going on in the short-baseline experiments:

"The situation is unclear, but is very thought-provoking."

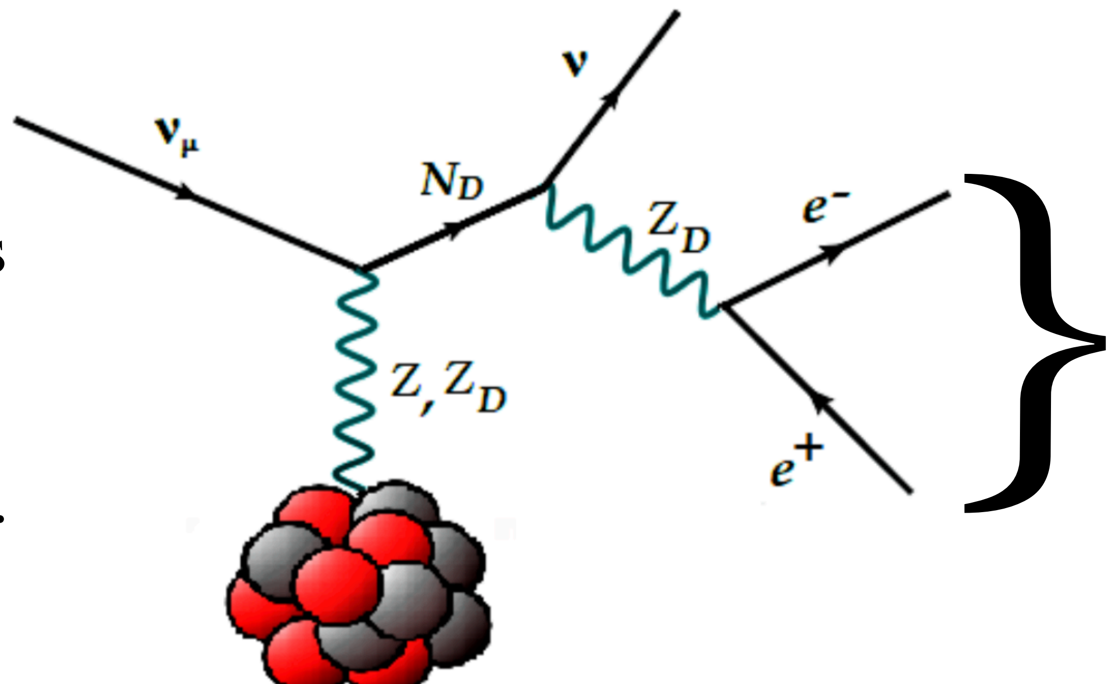
Thoughts on whether there is an eV-scale sterile neutrino: Talk by Alain Blondel

*Are the Short-Baseline Anomalies New Physics That Is **Not** Oscillation?*

Bertuzzo, Jana, Machado, and Zukanovich-Funchal; arXiv:1807.09877; PRL 121 (2018) 241801:

The anomalous low-energy electron-like excess reported by MiniBooNE is due to —

N_D and Z_D masses between a few tens and a few hundreds of MeV.



This is what MiniBooNE sees.

Ballett, Pascoli, and Ross-Lonergan
arXiv:1808.02915; PRD99 (2019) 071701:

A similar model.

Pedro Machado:

These models are constrained,
but not un-fixably ruled out.

*Are There **Heavy** (1 eV << Mass < 1 TeV) Largely-Sterile Neutrino Mass Eigenstates?*

Such heavy neutrinos are being sought
at CERN, Fermilab, J-PARC, and KEK.

(Several coming talks at this conference)

Should a heavy neutrino be discovered, study of its decays could tell us whether all the neutrinos, including the established 3 light ones, are Majorana particles, or Dirac particles.

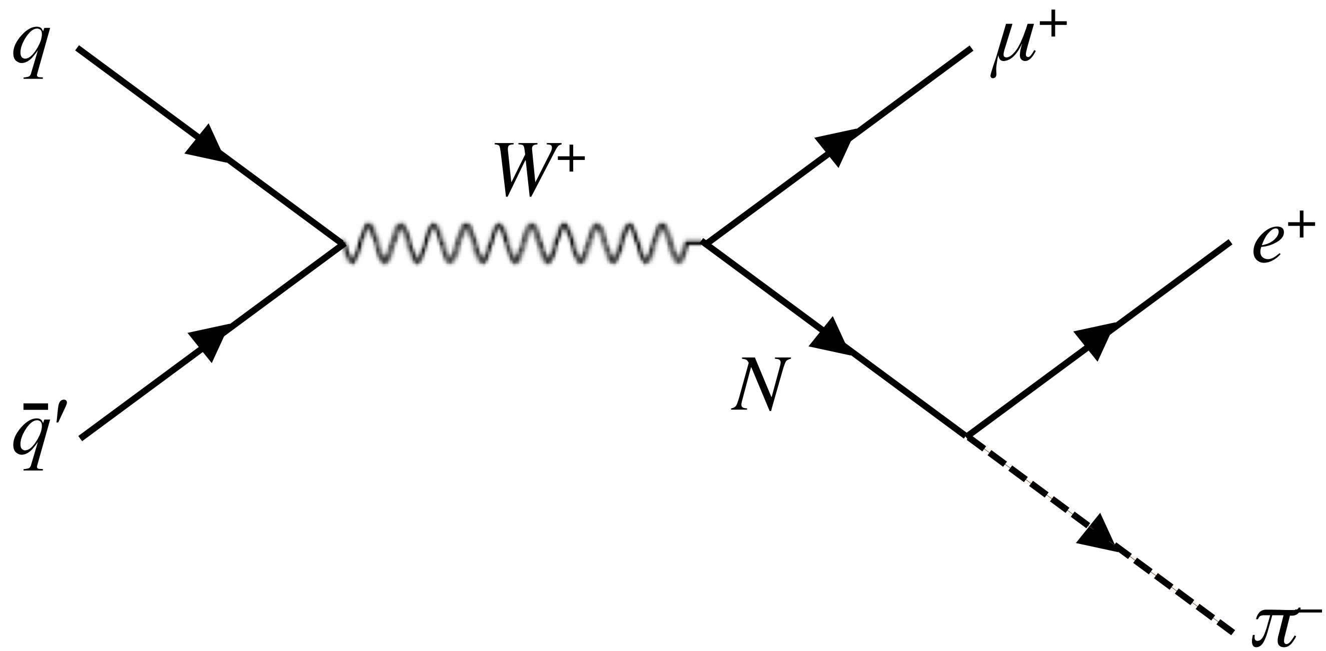
Balantekin, de Gouvêa, and BK;
arXiv:1808.10518; PL B789 (2019) 488

How To Tell the Majorana or Dirac Character of a Heavy Neutrino N

Decays of a Heavy Neutrino

Suppose there is a heavy neutral lepton ***N*****.**

A chain like —



would violate lepton number conservation, and signal that N is a Majorana neutrino.

To look for this, a detector must have charge discrimination.

Suppose the detector does not have charge discrimination, but can study decays like —

$$N \rightarrow \nu + X$$

$$\nu_1, \nu_2, \text{or } \nu_3 \qquad\qquad X = \bar{X}$$

where, depending on the mass of N, we could have —

$$X = \gamma, \pi^0, \rho^0, Z^0, \text{or } H^0$$

If N is produced via SM interactions at an accelerator neutrino facility by processes like $K^+ \rightarrow N + e^+$, it will be ~ fully polarized.

With θ the N-rest-frame emission angle of X relative to the N polarization direction,

Rotational invariance:

$$\frac{d\Gamma\left(N \to \nu + X\right)}{d\left(\cos\theta\right)} = \Gamma_+\left(1+\cos\theta\right) + \Gamma_-\left(1-\cos\theta\right)$$

$$= \Gamma_0\left(1+\alpha\cos\theta\right);\ -1 \le \alpha \le +1$$

If neutrinos are Majorana particles,

CPT and rotational invariance (and nothing more)

$$\Rightarrow \Gamma_+ = \Gamma_-$$

$$\Rightarrow \alpha = 0$$

The angular distribution is isotropic.

But if neutrinos are Dirac particles,

$$\frac{d\Gamma(N \to \nu + X)}{d(\cos\theta)} = \Gamma_0 (1 + \alpha\cos\theta), \text{ with –}$$

X	γ	π^0	ρ^0	Z^0	H^0
α	$\frac{2\Im m(\mu d^*)}{\lvert\mu\rvert^2+\lvert d\rvert^2}$	1	$\frac{m_N^2-2m_\rho^2}{m_N^2+2m_\rho^2}$	$\frac{m_N^2-2m_Z^2}{m_N^2+2m_Z^2}$	1

Except in very special circumstances,
these angular distributions are not isotropic.

Probably Advantageous *N* Decay Modes

Imagine a detector at a neutrino facility that can identify e, μ, and π, *but has no electric charge discrimination*.

The angular distribution in the decays

$$\overset{(-)}{N} \to \ell^{\mp} + X^{\pm}$$

e or μ $\qquad\qquad$ π or ϱ

with specific ℓ and X, but including indiscriminately both the $\ell^{-}X^{+}$ and $\ell^{+}X^{-}$ events, can also reveal whether N is a Dirac or Majorana particle.

Measuring the ℓ and X momenta would allow reconstruction of the N.

One would know where the N rest frame is in each event, so the angular distribution of the daughter X in the N rest frame could be determined directly.

A peak in the ℓX invariant mass distribution at the N mass would help get rid of backgrounds.

Angular Distributions

If N is a Majorana fermion,

from CPT and rotational invariance:

$$\frac{d\mathrm{Rate}\left(N \to \ell^- X^+\right)}{d\left(\cos\theta\right)} + \frac{d\mathrm{Rate}\left(N \to \ell^+ X^-\right)}{d\left(\cos\theta\right)}$$ is isotropic.

If N is a Dirac fermion,

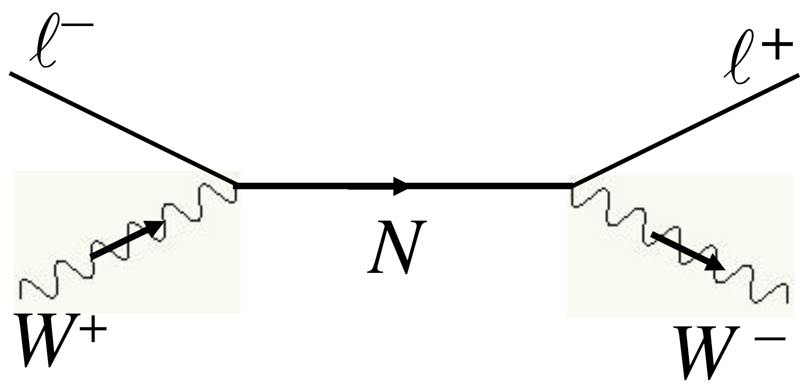
from CPT and rotational invariance,
plus the Standard-Model weak interaction,
and expected high N ($\bar{N}$) polarization:

$$\frac{d\mathrm{Rate}\left(N \to \ell^- X^+\right)}{d\left(\cos\theta\right)} + \frac{d\mathrm{Rate}\left(\bar{N} \to \ell^+ X^-\right)}{d\left(\cos\theta\right)}$$ is far from isotropic.

What Does the Majorana or Dirac Character of *N* Say About the Other Neutrinos?

1. If lepton number L is not conserved, the neutrino mass eigenstates will be Majorana particles.

2. If N has been shown to be a Majorana neutrino, consider —



As this illustrates, lepton number is no longer conserved.

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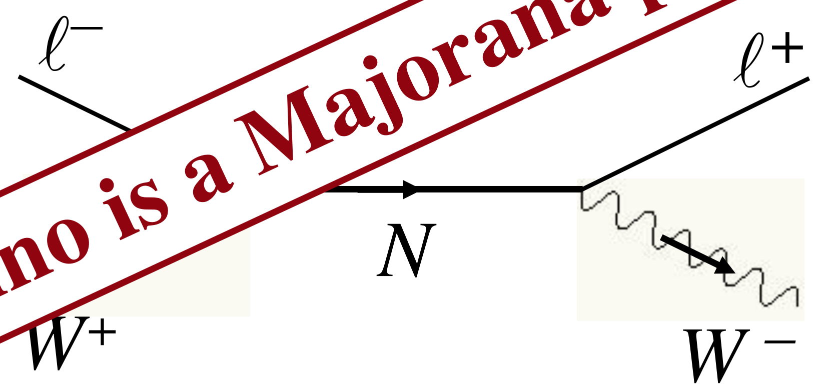

If one neutrino is a Majorana particle, they all are.

As this illustrates, lepton number is no longer conserved.

Summary

Whether it is important that there are **3** generations is unclear.

Also unclear is whether there are additional neutrinos beyond the **3** that we know.

If heavy neutrinos should be discovered, their decays could tell us whether all the neutrinos are Majorana or Dirac particles.