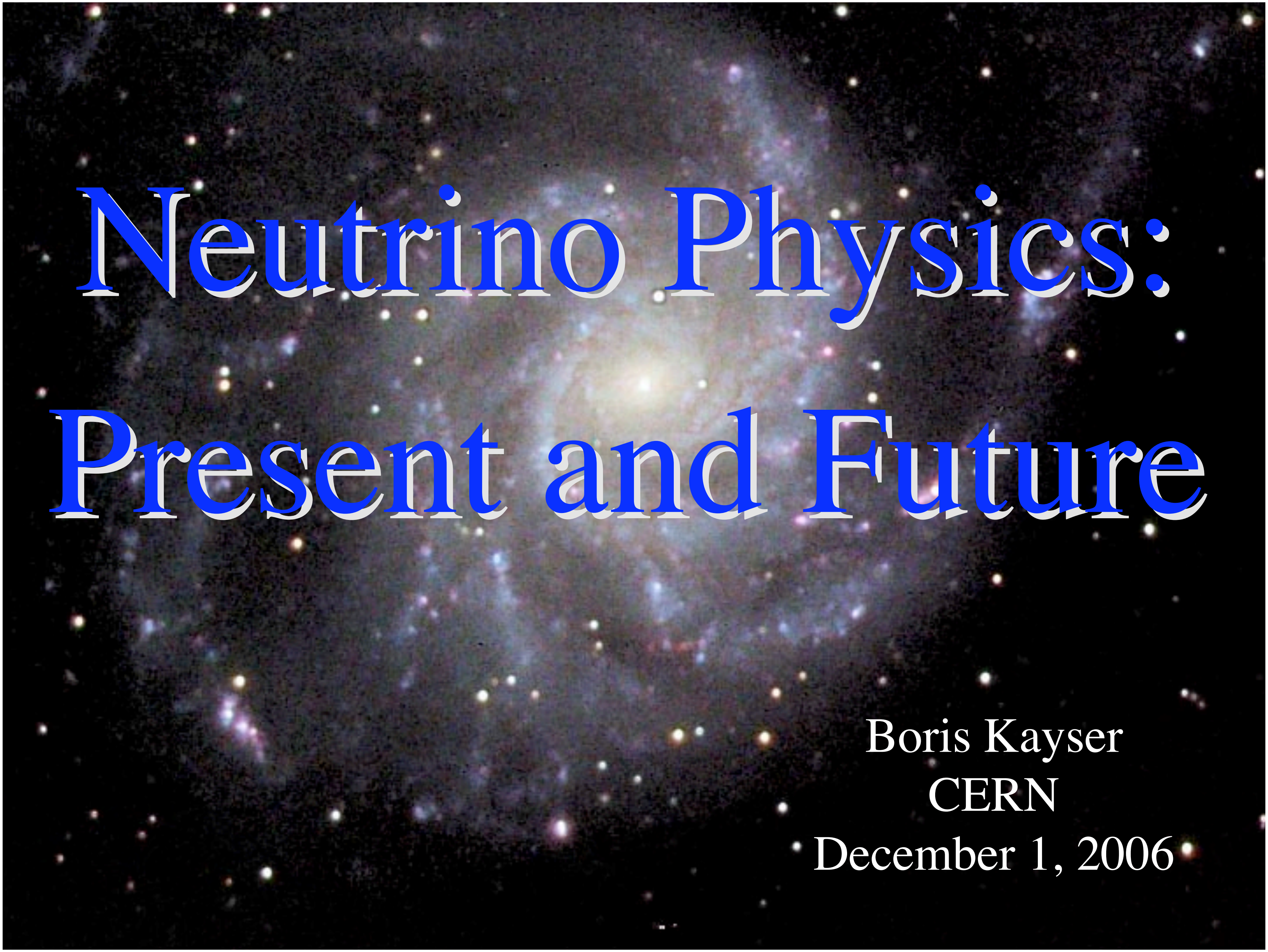

Neutrino Physics: Present and Future

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CERN
December 1, 2006

Leptogenesis

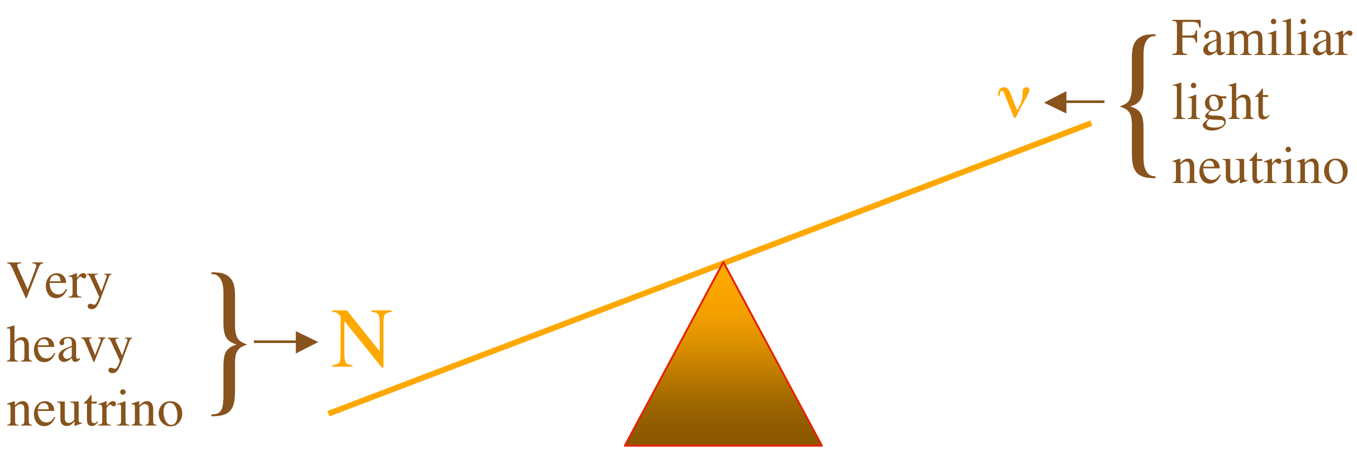
If the quarks can't generate the observed

MATTER-antimatter asymmetry,

maybe the **leptons** can!

The most popular theory of why neutrinos are so light is the —

See-Saw Mechanism



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

In the see-saw picture, the heavy neutrinos N, like the light ones ν, are Majorana particles. Thus, an N can decay into ℓ^- or ℓ^+.

In the early universe, before the neutral Higgs field develops its vacuum expectation value, the Higgs particles φ^+ and φ^0 in —

$$\begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

are ordinary massless particles. We can have —

$$N \to \ell^- + \varphi^+ \quad \text{and} \quad N \to \ell^+ + \varphi^-$$

If CP is violated in N decays, we will have —

$$\Gamma(N \rightarrow \ell^- + \varphi^+) \neq \Gamma(N \rightarrow \ell^+ + \varphi^-),$$

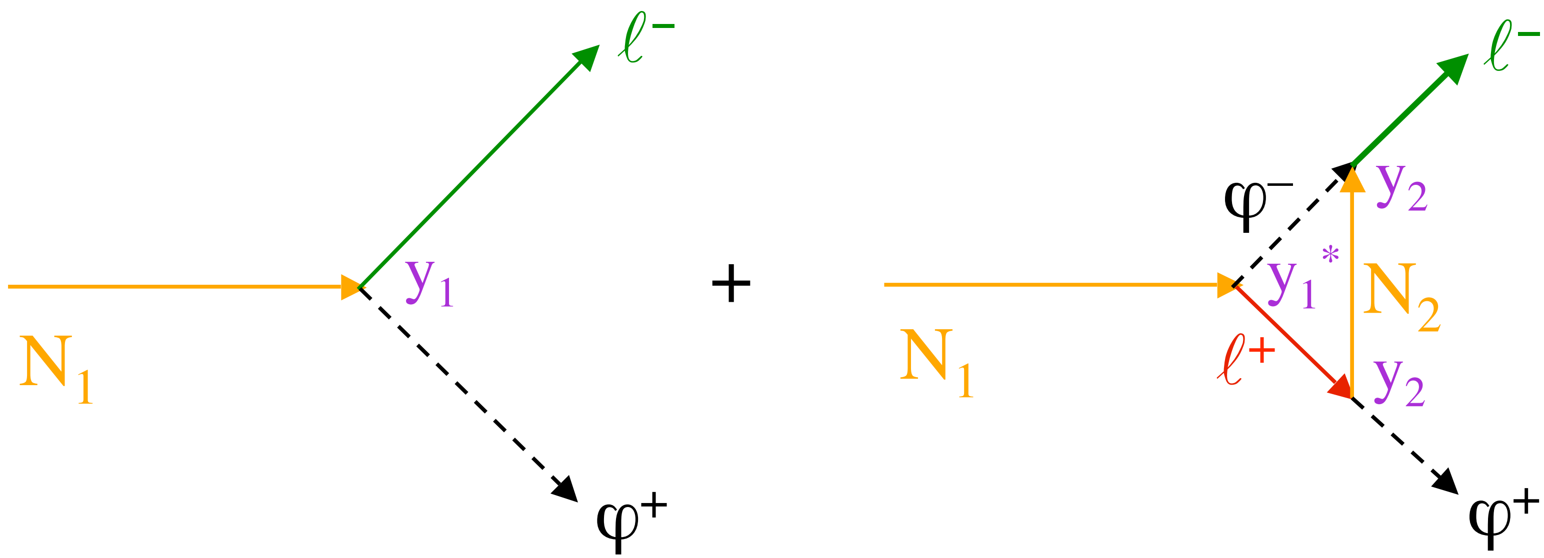
producing a universe with unequal amounts of leptonic matter and antimatter.

The detailed mechanism for $\not{C}\not{P}$ in these decays makes it very natural.

How $\cancel{CP}$ In N Decays Comes About

Corresponding to the 3 light neutrinos, ν_1, ν_2, and ν_3, there are 3 heavy see-saw partners, N_1, N_2, and N_3.

The decay $N_1 \rightarrow \ell^- + \varphi^+$ involves an interference between the diagrams —



Here, the y_i are the (α-suppressed) Yukawa coupling constants

$$\mathcal{L}_{\text{See-Saw}} = -\sum_{i=1}^{3} \frac{M_i}{2}\overline{N_{iR}{}^{c}}\, N_{iR} - \sum_{\alpha,\, i=1}^{3} y_{\alpha i}\left[\overline{\nu_{\alpha L}}\,\overline{\varphi^0} - \overline{\ell_{\alpha L}}\,\varphi^-\right] N_{iR} + h.c.$$

$$\text{Amp}(N_1 \rightarrow \ell^+ + \varphi^-) = \text{Amp}(N_1 \rightarrow \ell^- + \varphi^+;\ y \Rightarrow y^*)$$

Complex y_i will lead via interference to $\cancel{CP}$.

The decay rates were —

$$\Gamma(N_1 \rightarrow \ell^- + \varphi^+) = |a y_1 + b y_1{}^* y_2{}^2|^2$$

and

$$\Gamma(N_1 \rightarrow \ell^+ + \varphi^-) = |a y_1{}^* + b y_1 y_2{}^{*2}|^2$$

These rates produced a matter – antimatter asymmetry if —

$$\Delta \equiv \Gamma(N_1 \rightarrow \ell^- + \varphi^+) - \Gamma(N_1 \rightarrow \ell^+ + \varphi^-)$$

$$\propto \ \mathrm{Im}(ab^*)\mathrm{Im}(y_1{}^{*2} y_2{}^2) \neq 0.$$

(***Leptogenesis***)

$$\Gamma(N \to \ell^- + \varphi^+) \neq \Gamma(N \to \ell^+ + \varphi^-)$$

generates a LEPTON asymmetry.

What about the BARYON asymmetry that we see?

Non-perturbative Standard Model **sphaleron processes**, occuring after N decay, will change the total baryon number B, and the total lepton number L, while conserving B – L.

If N decay produced more ℓ^+ than ℓ^-, then some of this antilepton excess will be reprocessed by the (B – L) conserving sphaleron processes into the baryon excess that we see today.

Leptogenesis and Today's Neutrinos

The hypothesis that the matter-antimatter asymmetry of the universe is due to ***Leptogenesis*** suggests that —

$$\text{Mass[Each } \nu_i] < 0.13 \text{ eV.}$$

(Buchmüller, Di Bari, Plümacher)

{Assumes hierarchical (non-degenerate) N_i}

Recall that from oscillation and cosmological data —

$$0.04 \text{ eV} \lesssim \text{Mass[Heaviest } \nu_i] < (0.07 - 0.4) \text{ eV.}$$

Coincidence??

If ν oscillation violates CP, then quite likely so does N decay.

Thus, observing CP violation in neutrino oscillation would lend credence to the hypothesis that Leptogenesis was the original source of the

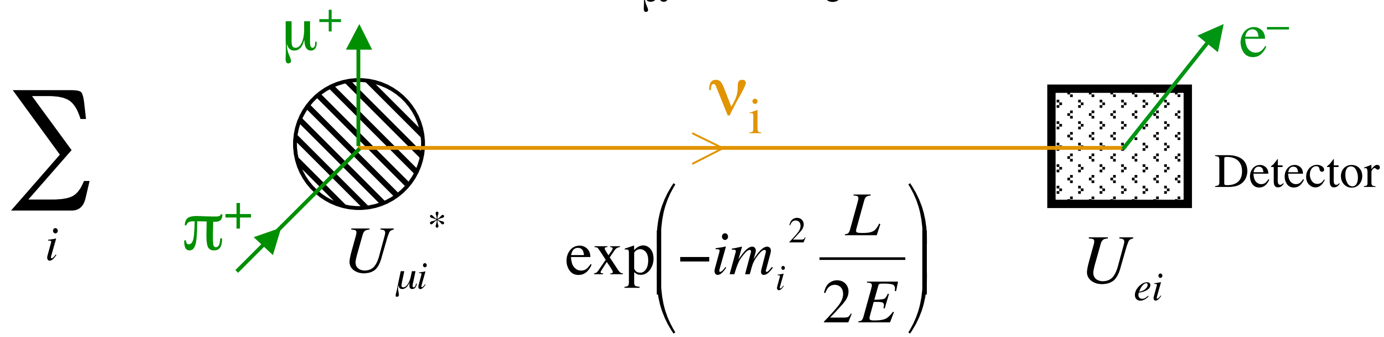
MATTER-antimatter asymmetry

How To Search for ~~CP~~

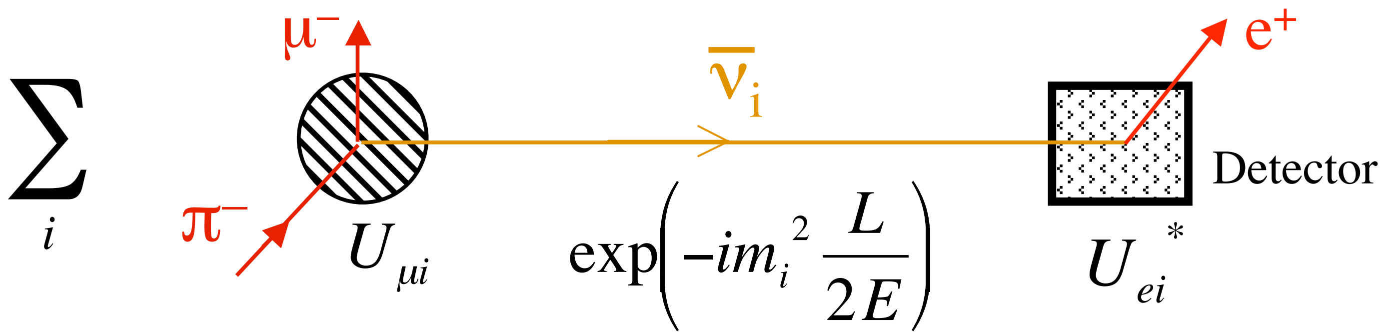
Look for $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$

"$\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta$" is a different process from $\nu_\alpha \rightarrow \nu_\beta$ even when $\bar{\nu}_i = \nu_i$

$\nu_\mu \to \nu_e$



“ $\bar{\nu}_\mu \to \bar{\nu}_e$ ”



CPT: $P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\beta \to \bar{\nu}_\alpha)$

$\therefore \quad P(\nu_\alpha \to \nu_\alpha) = P(\bar{\nu}_\alpha \to \bar{\nu}_\alpha)$

No CP violation in a *disappearance* experiment.

But if δ is present, $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$:

$$P\left(\bar{\nu}_\mu \to \bar{\nu}_e\right) - P\left(\nu_\mu \to \nu_e\right) = 2\cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\delta$$
$$\times \sin\left(\Delta m^2{}_{31}\frac{L}{4E}\right)\sin\left(\Delta m^2{}_{32}\frac{L}{4E}\right)\sin\left(\Delta m^2{}_{21}\frac{L}{4E}\right)$$

Separating $\not{CP}$ From the Matter Effect

Genuine $\not{CP}$ and the matter effect both lead to a difference between ν and $\bar{\nu}$ oscillation.

But genuine $\not{CP}$ and the matter effect depend quite differently from each other on L and E.

To disentangle them, one may make oscillation measurements at different L and/or E.

The Future

Accelerator neutrino experiments studying —

$$\nu_\mu \leftrightarrow \nu_e \quad \text{and} \quad \bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$$

can probe ***CP violation***, ***the mass hierarchy***, and (as can reactor experiments) $\boldsymbol{\theta_{13}}$.

The sensitivity needed will depend on at least the order of magnitude of $\boldsymbol{\theta_{13}}$.

Neutrino Factories and β Beams

The ultimate in sensitivity. Crucial if $\sin^2 2\theta_{13} \lesssim 0.01$.
Have intense, flavor-pure beams.

Neutrino Factory: A muon storage ring, producing neutrinos via —

Doesn't make μ^-

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

β Beam: A boosted-radioactive-ion storage ring, producing neutrinos via, e.g., —

$$^{18}\mathrm{Ne} \to {}^{18}\mathrm{F} + e^+ + \nu_e$$

Monoenergetic ν_e from e^- capture

Then look for $\nu_e \to \nu_\mu$

What Physics Is Behind Neutrino Mass?

The Most Popular Hypothesis — The See-Saw Mechanism

The See-Saw Mechanism — A Summary —

This assumes that a neutrino has *both* a Majorana mass term $m_R \overline{\nu_R{}^c} \nu_R$ and a Dirac mass term $m_D \overline{\nu}_L \nu_R$.

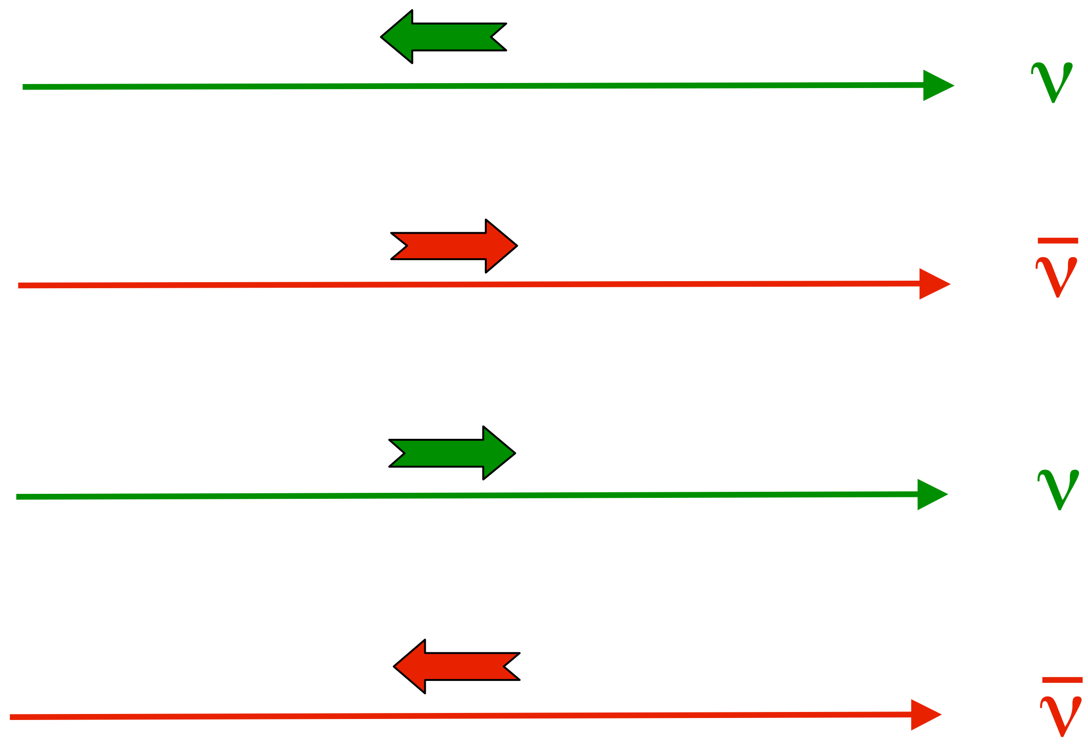
No SM principle prevents m_R from being extremely large.

But we expect m_D to be of the same order as the masses of the quarks and charged leptons.

Thus, we assume that $m_R >> m_D$.

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

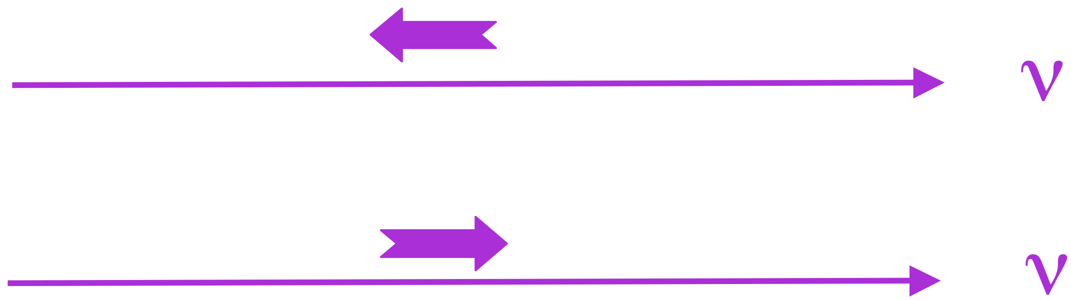
We have 4 mass-degenerate states:



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

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

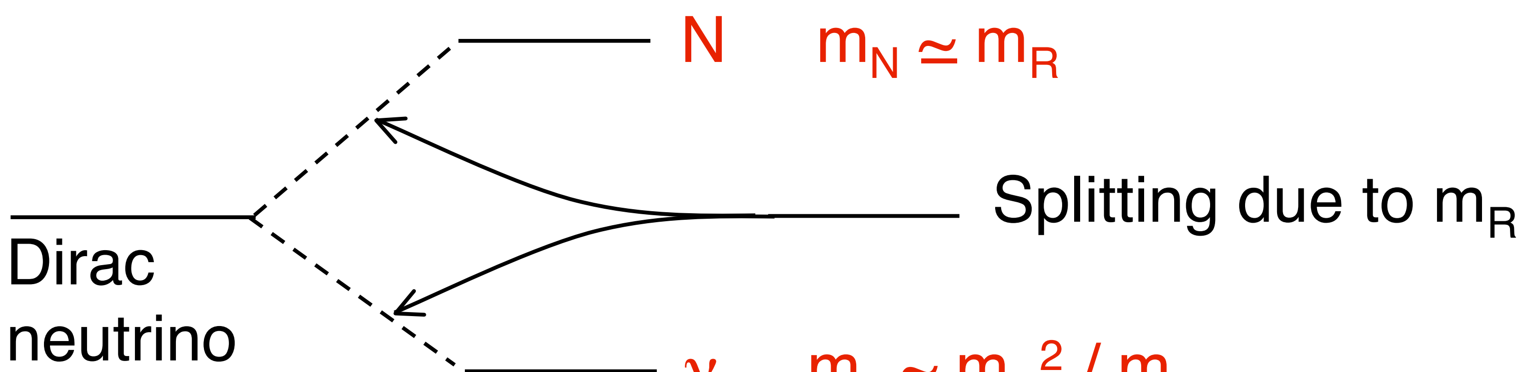
We have only 2 mass-degenerate states:



This collection of 2 states is a Majorana neutrino.

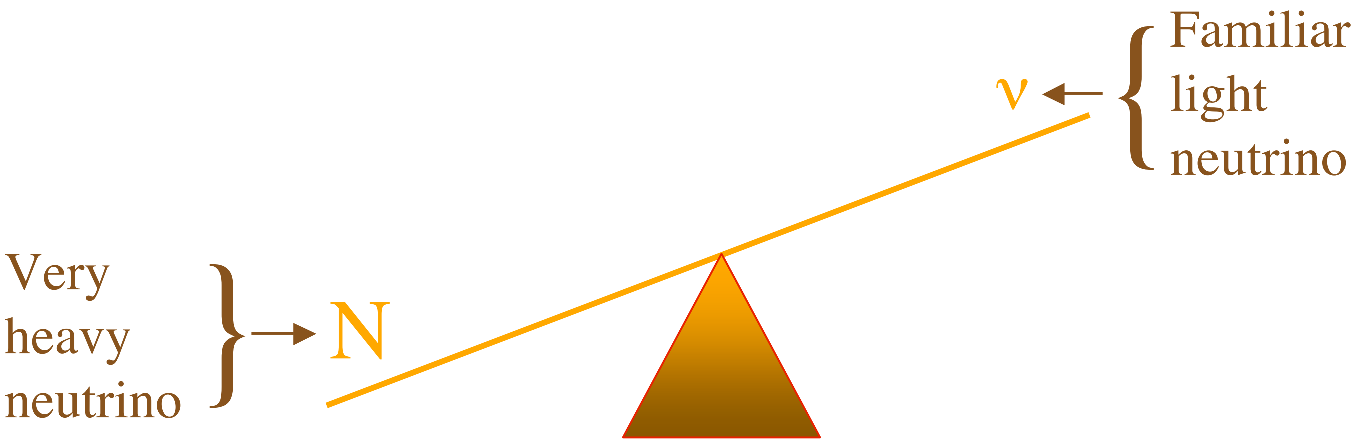
What Happens In the See-Saw?

The Majorana mass term splits a *Dirac* neutrino into two *Majorana* neutrinos.



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

The See-Saw Relation



Predictions of the See-Saw

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

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??

A Possible Consequence of the See-Saw — *Leptogenesis*

In *Leptogenesis*, it is ~~CP~~ in the decays of the heavy *See-Saw* partners N that is the origin of the matter-antimatter asymmetry of the universe.

Leptogenesis is an outgrowth of the *See-Saw* mechanism.

We have learned a lot about the neutrinos in the last decade.

What we have learned raises some very interesting questions.

Exciting times lie ahead.

The See-Saw Mechanism — For the Dedicated —

For a *Dirac* neutrino mass eigenstate ν of mass m, the mass term in the Lagrangian density is —

$$L_m = -m\bar{\nu}\nu$$

Then —

$$\langle \nu \text{ at rest} \,|H_m|\, \nu \text{ at rest}\rangle = \left\langle \nu \text{ at rest} \,\middle|\, m\int d^3x\ \bar{\nu}\nu \,\middle|\, \nu \text{ at rest} \right\rangle = m$$

Hamiltonian

For a *Majorana* neutrino mass eigenstate ν of mass m, the mass term in the Lagrangian density is —

$$L_m = -\frac{m}{2}\bar{\nu}\nu$$

with $\underbrace{\nu^c = \text{(phase factor) x } \nu}_{\text{Antineutrino = Neutrino}}$

Then —

$$\langle \nu \text{ at rest} \left| H_m \right| \nu \text{ at rest} \rangle = \langle \nu \text{ at rest} \left| \frac{m}{2} \int d^3x \, \bar{\nu}\nu \right| \nu \text{ at rest} \rangle = m$$

{The matrix element of $\bar{\nu}\nu$ is doubled in the Majorana case.}

Chiral fields:

Chirally left- and right-handed fermion fields satisfy the constraints —

$$P_L f_L \equiv \frac{(1-\gamma_5)}{2} f_L = f_L \qquad \text{and} \qquad P_R f_R \equiv \frac{(1+\gamma_5)}{2} f_R = f_R$$

For a *massless* fermion, chirality = helicity.

In the Standard Model (SM), only chirally left-handed fermion fields couple to the W boson.

Therefore, it is convenient to express the SM in terms of "underlying" chiral fields.

Expressed in terms of chiral fields, any mass term connects only fields of *opposite* chirality:

$$\underbrace{\bar{g}_R f_L}_{\text{Chiral fermion fields}}$$

$$\underbrace{\bar{j}_L k_L = \bar{j}_R k_R}_{\text{Chiral fermion fields}} = 0$$

For example —

$$\bar{j}_L k_L = \overline{\left(\frac{1-\gamma_5}{2}\right) j}\left(\frac{1-\gamma_5}{2}\right) k = \bar{j}\left(\frac{1+\gamma_5}{2}\right)\left(\frac{1-\gamma_5}{2}\right) k = 0$$

Note: Charge conjugating a chiral field reverses its chirality.

Dirac Mass Term

For quarks, charged leptons and *maybe* neutrinos.

Suppose ${\nu_L}^0$ and ${\nu_R}^0$ are underlying chiral fields in terms of which the SM, extended to include neutrino mass, is written.

The Dirac mass term is then —

$$L_D = -m_D \overline{{\nu_R}^0} {\nu_L}^0 + \text{ h.c. } = -m_D (\overline{{\nu_R}^0} {\nu_L}^0 + \overline{{\nu_L}^0} {\nu_R}^0)$$

In terms of $\nu \equiv {\nu_L}^0 + {\nu_R}^0$, $L_D = -m_D \bar{\nu}\nu$, since

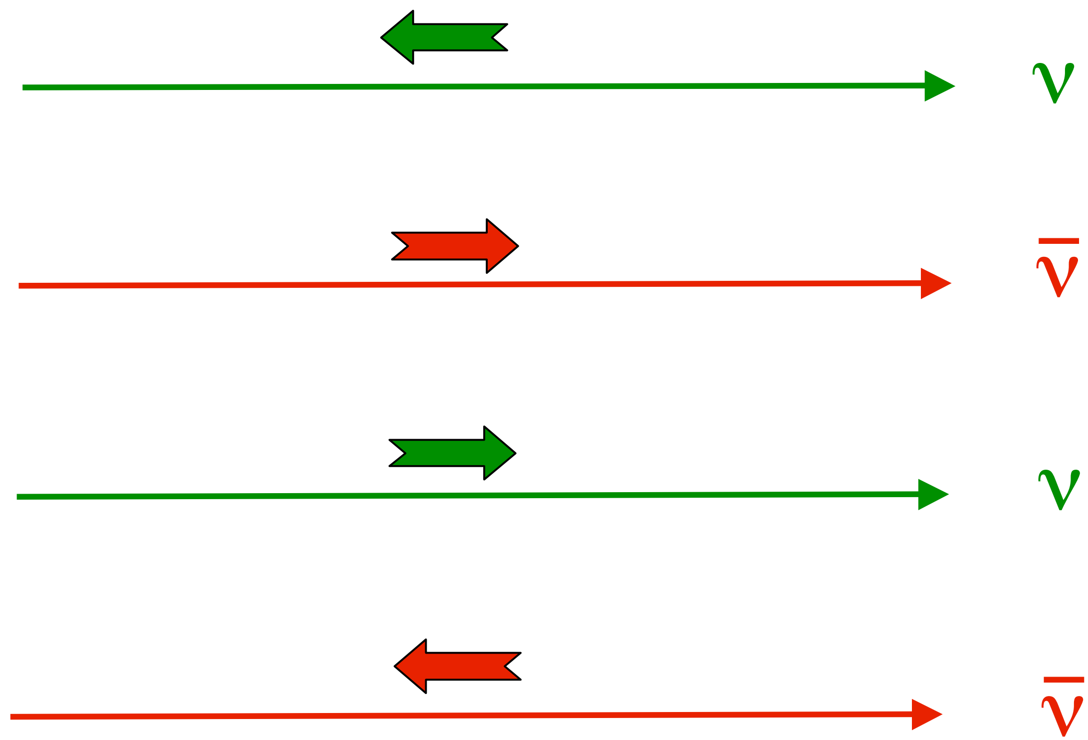
$$\bar{\nu}\nu = \overline{\left({\nu_L}^0 + {\nu_R}^0\right)}\left({\nu_L}^0 + {\nu_R}^0\right) = \overline{{\nu_R}^0} {\nu_L}^0 + \overline{{\nu_L}^0} {\nu_R}^0$$

ν is the mass eigenstate, and has mass m_D.

We have 4 mass-degenerate states:

L is conserved.

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



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

Majorana Mass Term

For neutrinos only.

Suppose $\nu_R{}^0$ is an electroweak singlet chiral field.

The right-handed Majorana mass term is then —

$$L_R = -\frac{m_R}{2}\overline{\left(\nu_R{}^0\right)^c}\nu_R{}^0 + \text{ h.c. } = -\frac{m_R}{2}\left[\overline{\left(\nu_R{}^0\right)^c}\nu_R{}^0 + \overline{\nu_R{}^0}\left(\nu_R{}^0\right)^c\right]$$

In terms of $\nu \equiv \nu_R{}^0 + \left(\nu_R{}^0\right)^c$, $L_R = -\frac{m_R}{2}\bar{\nu}\nu$, since

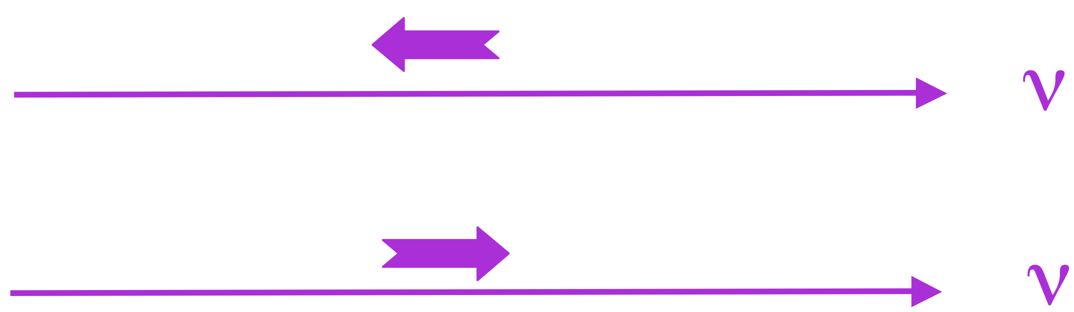
$$\bar{\nu}\nu = \left[\overline{\nu_R{}^0 + \left(\nu_R{}^0\right)^c}\right]\left[\nu_R{}^0 + \left(\nu_R{}^0\right)^c\right] = \overline{\left(\nu_R{}^0\right)^c}\nu_R{}^0 + \overline{\nu_R{}^0}\left(\nu_R{}^0\right)^c$$

ν is the mass eigenstate, and has mass m_R.

$$\nu^c = \left[\nu_R{}^0 + \left(\nu_R{}^0\right)^c\right]^c = \left(\nu_R{}^0\right)^c + \nu_R{}^0 = \nu$$

Thus, ν is its own antiparticle. It is a Majorana neutrino.

We have only 2 mass-degenerate states:



The See-Saw

We include *both* Majorana and Dirac mass terms:

$$L_m = -m_D \overline{\nu_R{}^0}\nu_L{}^0 - \frac{m_R}{2}\overline{\left(\nu_R{}^0\right)^c}\nu_R{}^0 + \text{ h.c.}$$

$$= -\frac{1}{2}\left[\overline{\left(\nu_L{}^0\right)^c}, \overline{\nu_R{}^0}\right]\begin{bmatrix} 0 & m_D \\ m_D & m_R \end{bmatrix}\begin{bmatrix} \nu_L{}^0 \\ \left(\nu_R{}^0\right)^c \end{bmatrix} + \text{ h.c.}$$

We have used $\overline{\left(\nu_L{}^0\right)^c} m_D \left(\nu_R{}^0\right)^c = \overline{\nu_R{}^0} m_D \nu_L{}^0$.

$M_\nu = \begin{bmatrix} 0 & m_D \\ m_D & m_R \end{bmatrix}$ is called the neutrino mass matrix.

No SM principle prevents m_R from being extremely large.

But we expect m_D to be of the same order as the masses of the quarks and charged leptons.

Thus, we assume that $m_R >> m_D$.

M_ν can be diagonalized by the transformation —

$$Z^T M_\nu Z = D_\nu$$

With $\rho \equiv m_D / m_R << 1,$

$$Z \cong \begin{bmatrix} 1 & \rho \\ -\rho & 1 \end{bmatrix} \overbrace{\begin{bmatrix} i & 0 \\ 0 & 1 \end{bmatrix}}^{\text{Makes eigenvalues positive}}$$

and

$$D_\nu \cong \begin{bmatrix} m_D{}^2 / m_R & 0 \\ 0 & m_R \end{bmatrix}$$

Define $\begin{bmatrix} \nu_L \\ N_L \end{bmatrix} \equiv Z^{-1} \begin{bmatrix} {\nu_L}^0 \\ \left({\nu_R}^0\right)^c \end{bmatrix}$ and $\begin{bmatrix} \nu \\ N \end{bmatrix} \equiv \begin{bmatrix} \nu_L + (\nu_L)^c \\ N_L + (N_L)^c \end{bmatrix}$.

Majorana neutrinos

Then —

$$L_m = -\frac{1}{2}\frac{{m_D}^2}{m_R}\bar{\nu}\nu - \frac{1}{2} m_R \bar{N} N$$

Mass of ν

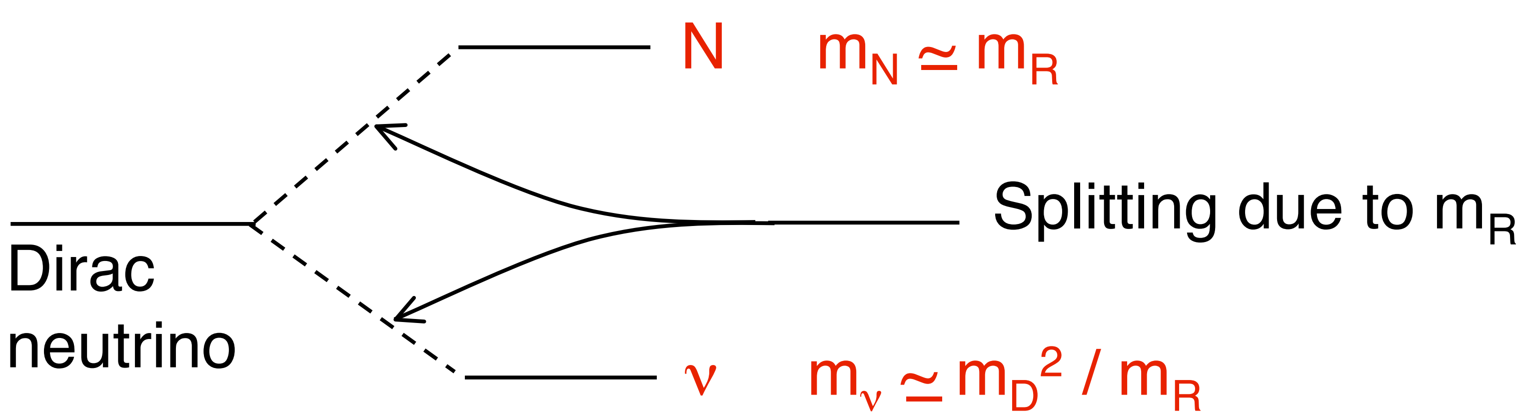
Mass of N

(Mass of ν) x (Mass of N) = $m_D{}^2 \sim m_{\text{quark or lepton}}{}^2$

The See-Saw Relation

What Happened?

The Majorana mass term split a Dirac neutrino into two Majorana neutrinos.



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