Argonne $\nu$ Workshop
May 16, 2003

# Majorana Neutrinos
# or
# Dirac Neutrinos?

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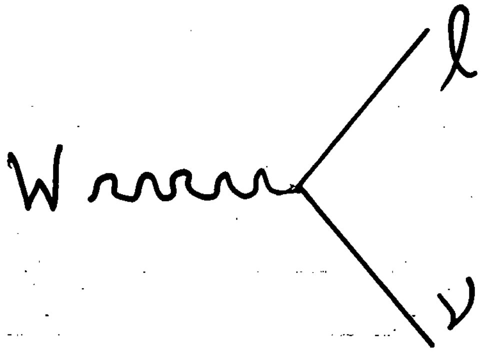
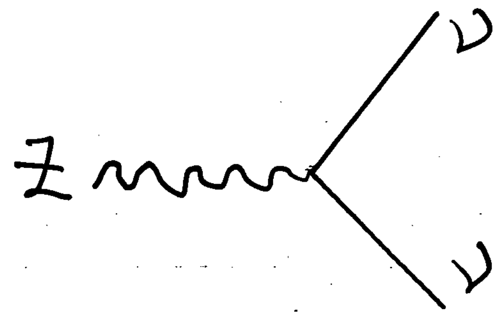
# MAJORANA NEUTRINOS
## — or —
# DIRAC NEUTRINOS?

The S(tandard) M(odel)




and

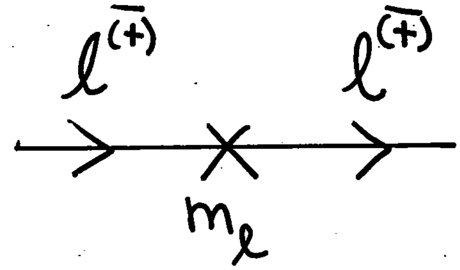



couplings conserve the Lepton Number L defined by—

$$L(\nu) = L(\ell^-) = -L(\bar{\nu}) = -L(\ell^+) = 1.$$

So do the Dirac charged-lepton mass terms

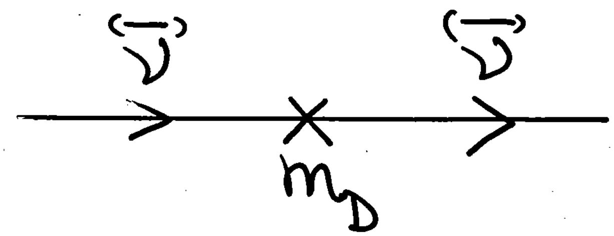
$$m_\ell \, \overline{\ell_L} \, \ell_R$$



Original SM: $m_\nu = 0$.

Why not add a Dirac mass term,

$$m_D \bar{\nu}_L \nu_R$$




Then everything conserves $L$, so for each mass eigenstate $\nu_i$,

$$\bar{\nu}_i \neq \nu_i \quad \text{(Dirac neutrinos)}$$

$$[L(\bar{\nu}_i) = -L(\nu_i)]$$

3. The Dirac mass term would arise from—

$$f \times \text{Higgs} \times \overline{\nu}_L \nu_R \longrightarrow \underbrace{f \overbrace{\langle \text{Higgs} \rangle_0}^{174\text{ GeV}}}_{m_\nu} \overline{\nu}_L \nu_R$$

Atmospheric $\nu$ oscillation suggests that—

$$m[\text{Heaviest } \nu_i] \sim 0.05 \text{ eV}.$$

Then

$$f = \frac{0.05 \text{ eV}}{174 \text{ GeV}} \sim 10^{-13}.$$

Surely such infinitesimal couplings are not the ultimate explanation of light $m_\nu$.

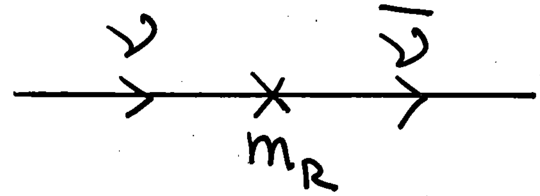
Perhaps SUSY* or extra dimensions can explain it without our having to go to Majorana mass terms.

*Murayama's talk

The Dirac mass term required $\nu_R$.

With $\nu_R$ introduced, no SM principle prevents the occurrence of the Majorana mass term

$$m_R \overline{\nu_R^c} \nu_R$$




This does not conserve L, and now

$$\bar{\nu}_i = \nu_i \qquad \text{(Majorana neutrinos)}$$

[No conserved L to distinguish $\bar{\nu}_i$ from $\nu_i$]

We note that $\bar{\nu}_i = \nu_i$ means —

$$\bar{\nu}_i(h) = \nu_i(h).$$

helicity

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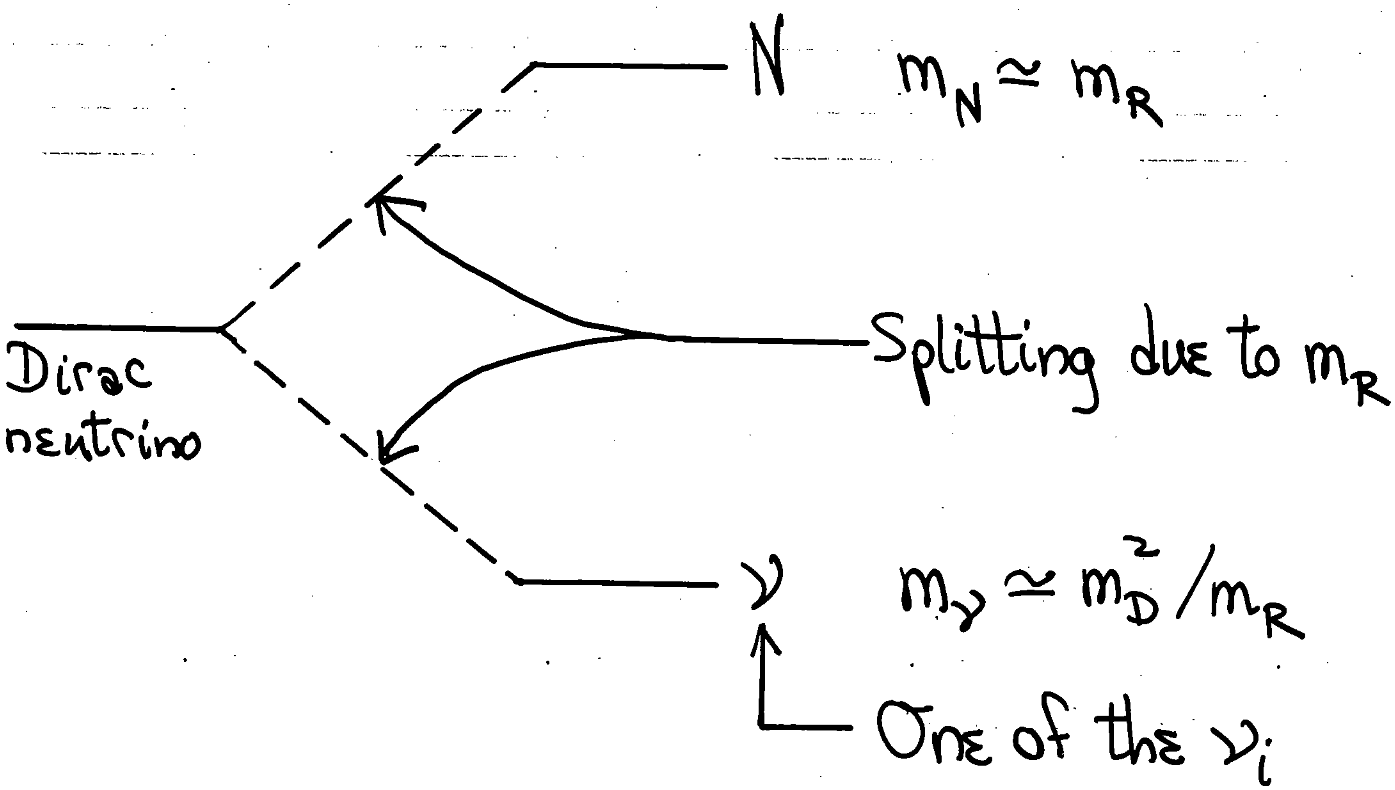
In the See-Saw Mechanism,

$$\mathcal{L}_{mass} \sim \left[\overline{\nu_L}, \overline{\nu_R^c}\right] \begin{bmatrix} 0 & m_D \\ m_D & m_R \end{bmatrix} \begin{bmatrix} \nu_L^c \\ \nu_R \end{bmatrix}$$

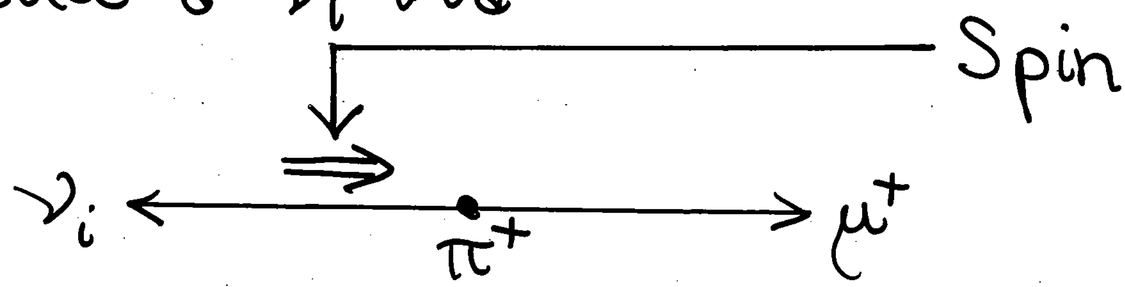
with $m_R \gg m_D \sim m_{q\,or\,l}$.



# Ideas That Do Not Work

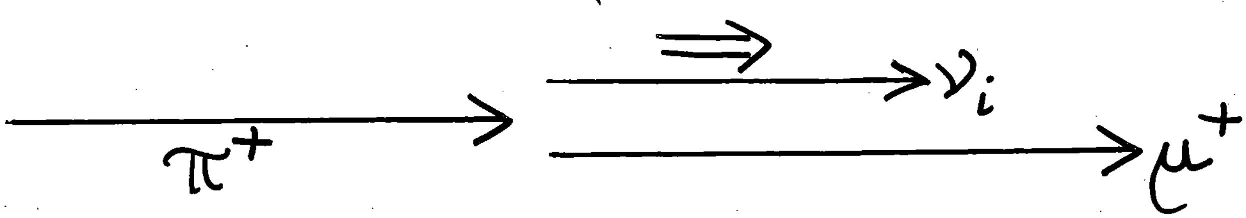
1) Give the neutrino a Boost

Produce a $\nu_i$ via—



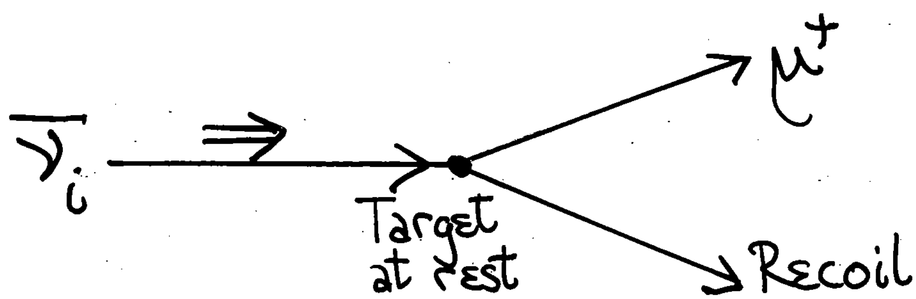

Pion Rest Frame

$$\beta_\pi(\text{Lab.}) > \beta_\nu(\pi \text{ Rest Frame})$$




Lab. frame

The SM weak interaction causes—




If $\nu_i \xrightarrow{\Rightarrow} = \bar{\nu}_i \xrightarrow{\Rightarrow}$,

our $\nu_i \xrightarrow{\Rightarrow}$ will make $\mu^+$ too.

# Minor technical difficulties

$$\beta_\pi(\text{Lab}) > \beta_\nu(\pi \text{ Rest Frame})$$

$$\Rightarrow \frac{E_\pi(\text{Lab})}{m_\pi} > \frac{E_\nu(\pi \text{ Rest Frame})}{m_{\nu_i}}$$

$$\Rightarrow E_\pi(\text{Lab}) \gtrsim 10^5 \text{ TeV if } m_{\nu_i} \sim 0.05 \text{ eV}$$

Fraction of all $\pi$-decay $\nu_i$ that get helicity flipped

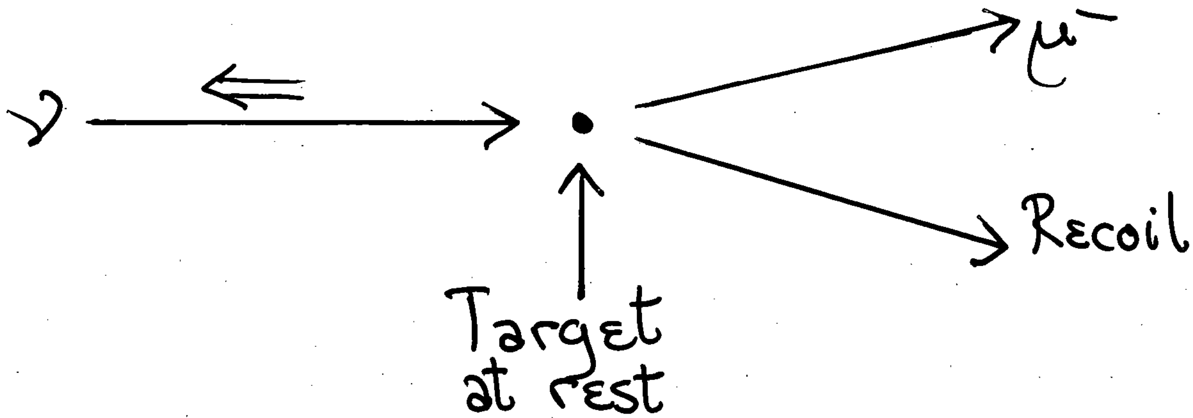
$$\simeq \left(\frac{m_{\nu_i}}{E_\nu(\pi \text{ Rest Frame})}\right)^2 \sim 10^{-18} \text{ if } m_{\nu_i} \sim 0.05 \text{eV}$$

Since L-violation comes only from Majorana neutrino <u>masses</u>, any attempt to observe it will be at the mercy of the neutrino masses.

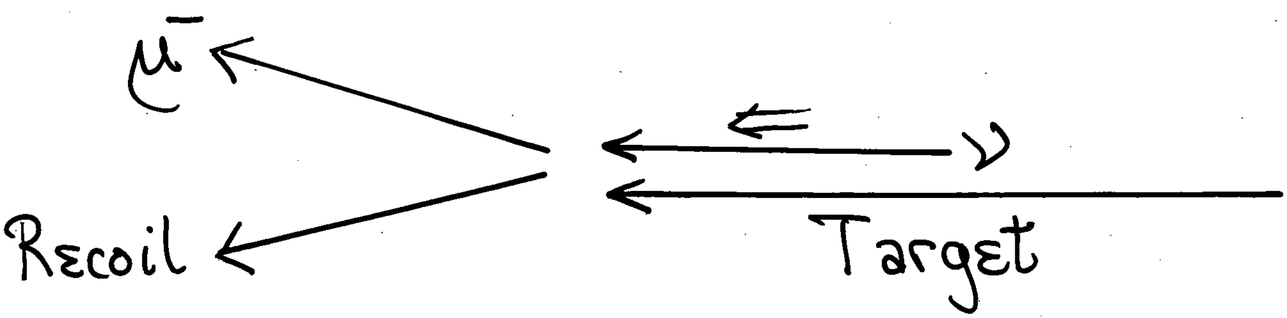
(BK & L Stodolsky)

2) Give yourself a Boost

Run faster than a neutrino, to make—




look like—




Even though $\nu$ is Right-Handed in your frame, the produced muon is still a $\mu^-$, not a $\mu^+$. This follows from Lorentz invariance. There is no test of Majorana vs. Dirac character here.

(LBL news)

# The Idea That Can Work — Neutrinoless Double Beta Decay

Inputs from the present data:

If LSND is confirmed by MiniBooNE, then there must be at least 4 $\nu$ mass eigenstates, or else CPT is violated.

We will assume LSND is not confirmed, and that nature contains only 3 $\nu$ mass eigenstates.

We also assume the now very strongly favored Large Mixing Angle-MSW explanation of $\nu_\odot$ behavior.

# Predictions

- Each $\overline{\nu_i} = \nu_i$ (Majorana neutrinos)

- The light neutrinos have heavy partners $N$

How heavy ??

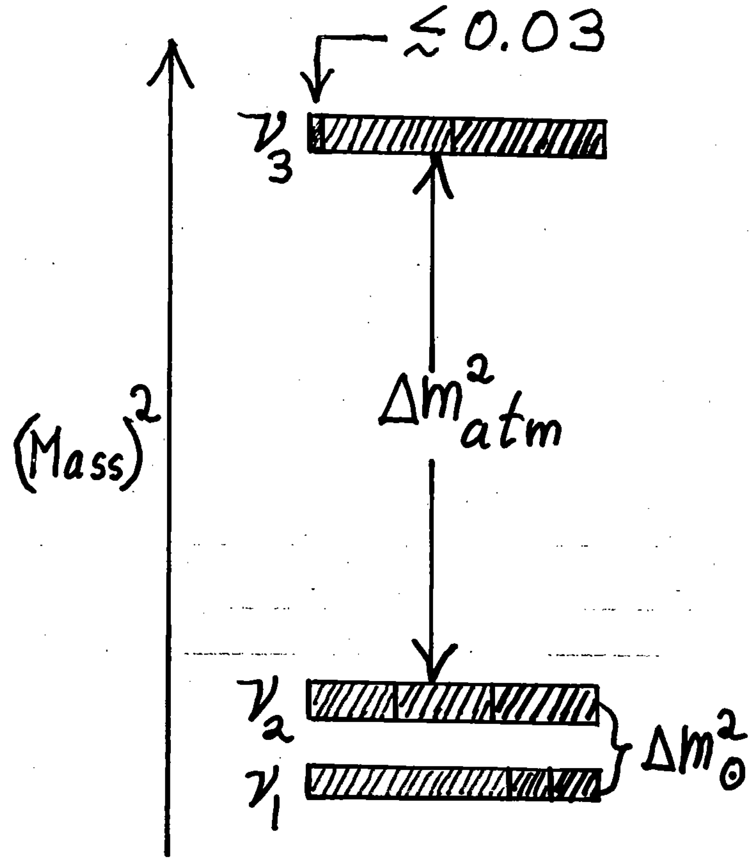
$$m_N \sim \frac{m_{top}^2}{m_\nu} \sim \frac{m_{top}^2}{0.05\,\text{eV}} \sim 10^{15}\,\text{GeV}$$

Near the GUT scale.

Review of see-saw: hep-ph/0211134

How can we confirm that $\overline{\nu_i} = \nu_i$ ?

b) The 3-$\nu$ spectrum is or :




$$1.6 \times 10^{-3} < \Delta m^2_{atm} < 3.9 \times 10^{-3}\, eV^2$$

(Super-K; 90% CL)

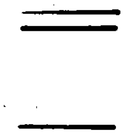
$$5.6 \times 10^{-5} < \Delta m^2_\odot < 9.0 \times 10^{-5}\, eV^2$$

— or —

$$13 \times 10^{-5} < \Delta m^2_\odot < 18 \times 10^{-5}\, eV^2$$

(Fogli et al.; 95% C

$\nu_e$ $[|U_{ei}|^2]$ $\nu_\mu$ $[|U_{\mu i}|^2]$ $\nu_\tau$ $[|U_{\tau i}$

The spectrum could be  instead of 

[F.10]

Corresponding to the flavor content shown,

Close pair $\to \nu_1, \nu_2$ Isolated $\to \nu_3$

$$U \approx \begin{array}{c c} & \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} & \begin{bmatrix} c\, e^{i\frac{\alpha_1}{2}} & s\, e^{i\frac{\alpha_2}{2}} & s_{13}\, e^{-i\delta} \\ -\frac{s}{\sqrt{2}}\, e^{i\frac{\alpha_1}{2}} & \frac{c}{\sqrt{2}}\, e^{i\frac{\alpha_2}{2}} & \frac{1}{\sqrt{2}} \\ \frac{s}{\sqrt{2}}\, e^{i\frac{\alpha_1}{2}} & -\frac{c}{\sqrt{2}}\, e^{i\frac{\alpha_2}{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \end{array}$$

$c \equiv \cos\theta_\odot$ , $s \equiv \sin\theta_\odot$ , $s_{13} \equiv \sin\theta_{13}$

With LMA1-MSW,

$0.25 \lesssim \sin^2\theta_\odot \lesssim 0.40$ (90% CL) (Fogli et al.)

From bounds on reactor $\bar{\nu}_e$ oscillation,

$\sin^2\theta_{13} \lesssim 0.03$ (90% CL) (CHOOZ, Palo Verde)

# The Mixing Matrix

The flavor content picture shows the $|U_{\alpha i}|^2$, but not the signs or phases of the $U_{\alpha i}$.

For 3 neutrinos —

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}$$

$$\times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\frac{\alpha_1}{2}} & 0 & 0 \\ 0 & e^{i\frac{\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij}\ , \quad s_{ij} \equiv \sin\theta_{ij}$$

[2ν]

$$\theta_{12} \simeq \theta_\odot \simeq 34^\circ\ , \quad \theta_{23} \simeq \theta_{atm} \simeq 45^\circ$$

$$\theta_{13} \lesssim 10^\circ$$

## Surprise!

With B ≡ Big and s ≡ small,

$$V_{(\text{quarks})} = \begin{bmatrix} 1 & s & s \\ s & 1 & s \\ s & s & 1 \end{bmatrix},$$

but

$$\mathcal{U}_{(\text{leptons})} = \begin{bmatrix} B & B & s \\ B & B & B \\ B & B & B \end{bmatrix}.$$

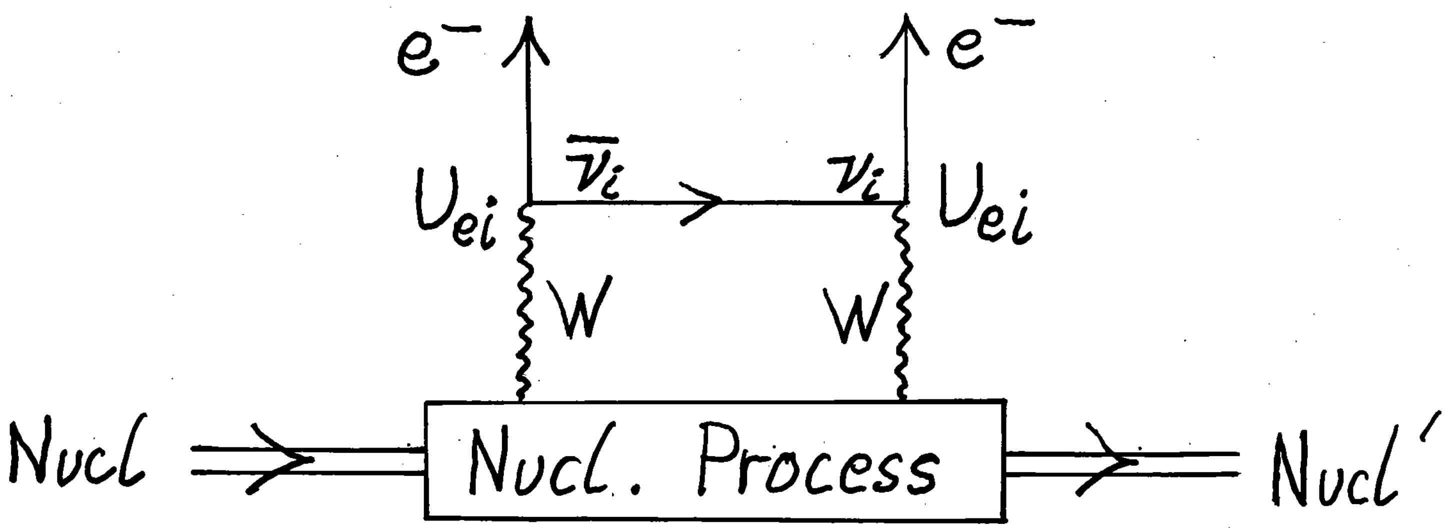
Does this mean that leptonic mixing has a different origin than quark mixing does??

Assuming CPT invariance —

$0\nu\beta\beta$ $[\text{Nucl} \to \text{Nucl}' + 2e^-] \Rightarrow \overline{\nu}_i = \nu_i$.

(Schechter + Valle)

The dominant mechanism is expected to be —




Mass(

$\overline{\nu}_i$ is emitted $[RH + \mathcal{O}(\frac{m_i}{E})\, LH]$

$\therefore$ Amp$[\nu_i$ contribution$] \propto m_i$

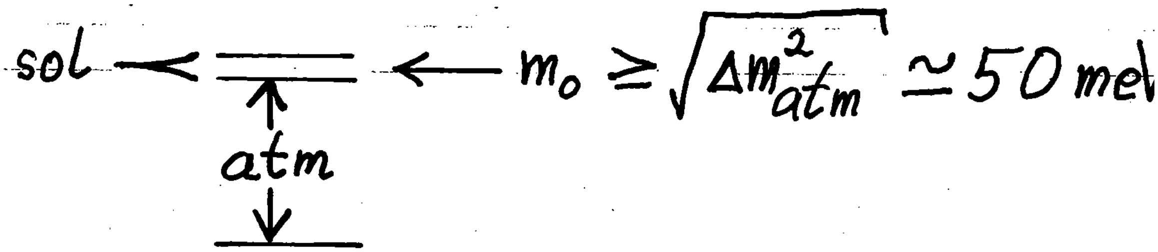
$$\text{Amp}\,[0\nu\beta\beta] \propto \left| \sum_i m_i U_{ei}^2 \right| \equiv m_{\beta\beta}$$

5.4

$m_{\beta\beta}$ is a measure of the $\nu$ mass scale.

Desirable sensitivity: $m_{\beta\beta} \lesssim 50$ meV.

If the spectrum looks like —



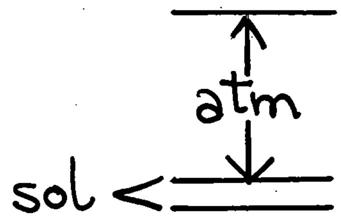

then —

$$m_{\beta\beta} \cong m_0 \sqrt{1 - \sin^2 2\theta_\odot \sin^2\left(\frac{\alpha_2 - \alpha_1}{2}\right)}$$

$$\geq m_0 \cos 2\theta_\odot .$$

$\cos 2\theta_\odot \gtrsim 0.2$ @ 90% CL.

If the spectrum looks like —




then

$$0 < m_{\beta\beta} < \text{Present Bound } [(0.3-1.0)\text{ eV}].$$

(Petcov et al.)

## Analyses of $m_{\beta\beta}$ vs. Neutrino Parameters

Barger, Bilenky, Farzan, Giunti, Glashow, Grimus, BK, Kim, Klapdor-Kleingrothaus, Langacker, Marfatia, Monteno, Pascoli, Päs, Peres, Petcov, Rodejohann, Smirnov, Vissani, Whisnant, Wolfenstein

Review of $\beta\beta$ Decay: Elliott & Vogel

# Majorana CP-Violating Phases

The 3x3 quark mixing matrix: 1 $\cancel{CP}$ phase

When $\bar{\nu}_i = \nu_i$ —

The 3x3 lepton mixing matrix: 3 $\cancel{CP}$ phases

The 2 extra phases, $\alpha_1$ and $\alpha_2$, are called Majorana phases.

Each Majorana phase is associated with a particular $\nu$ mass eigenstate $\nu_i$:

$$\mathcal{U}_{\alpha i} = \mathcal{U}^{0}_{\alpha i}\, e^{i\frac{\alpha_i}{2}} \; ; \; \text{all } \alpha \,. \qquad [\mathcal{U}]$$

Majorana phases have physical consequences only in physical processes that involve violation of L.

They do not affect $\nu$ flavor oscillation, but they do affect $0\nu\beta\beta$.

# Why do Majorana phases influence processes with $\cancel{L}$?

## Example

$l_e \equiv e,\ l_\mu \equiv \mu,\ l_\tau \equiv \tau$

$$l_\beta^- W^+ \longleftarrow \nu \longleftarrow l_\alpha^+ W^-$$

$$\mathrm{Amp} = \sum_i \underbrace{\langle l_\beta^- W^+ | H | \nu_i \rangle}_{\sim U_{\beta i}} \langle \nu_i | H | l_\alpha^+ W^- \rangle$$

$$\langle l_\beta^- W^+ | H | \nu_i \rangle \underset{\mathrm{CPT}}{=} \langle \overline{\nu}_i | H | l_\beta^+ W^- \rangle$$

$$= \langle \nu_i | H | l_\beta^+ W^- \rangle$$

When $\overline{\nu}_i = \nu_i$

13 Then

$$\text{Amp} \sim \sum_i U_{\beta i} U_{\alpha i}.$$

Suppose the CP phase $\delta = 0$, so $U$ is real apart from the Majorana phases:

$$U_{\alpha i} = |U_{\alpha i}| e^{i\frac{\alpha_i}{2}}.$$

Then

$$\text{Amp} \sim \sum_i |U_{\beta i}||U_{\alpha i}| e^{i\alpha_i}.$$

The relative values of the $\alpha_i$ will clearly affect the interference terms in $|\text{Amp}|^2$.

M.6

$$\Gamma[e^+W^- \rightarrow \nu \rightarrow \mu^- W^+]$$

$$= K \frac{\sin^2 2\theta}{E^2}\left[m_1^2 + m_2^2 - 2m_1 m_2 \cos\left(\Delta m^2 \frac{L}{2E} - \alpha\right)\right]$$

(Schechter & Valle)

$$\Gamma[e^-W^+ \rightarrow \nu \rightarrow \mu^+ W^-]$$

$$= K \frac{\sin^2 2\theta}{E^2}\left[m_1^2 + m_2^2 - 2m_1 m_2 \cos\left(\Delta m^2 \frac{L}{2E} + \alpha\right)\right]$$

Here,

$K$ = irrelevant constant $= |S|^2$

$m_{1,2}$ = masses of $\nu_{1,2}$

$\Delta m^2 = m_2^2 - m_1^2$

Note the two rates are not the same.

M:7

In the quark sector, the mixing matrix loses its meaning when all quarks of a given charge are degenerate.

What happens here when $m_1 = m_2 \equiv m$?

$$\Gamma[e^+ W^- \rightarrow \nu \rightarrow \mu^- W^+]$$

$$= \overline{\Gamma[e^- W^+ \rightarrow \nu \rightarrow \mu^+ W^-]}$$

$$= K \sin^2 2\theta \, \frac{4m^2}{E^2} \sin^2 \frac{\alpha}{2}$$

When Majorana phases are present, the mixing matrix is still meaningful even when the neutrino masses are of equal size.

# Why?

The Majorana phase $\alpha$ associated with neutrino $\nu_1$ may be viewed as the phase of its mass:

$$\text{mass}(\nu_1) = \underset{\text{Real}}{m_1} e^{i\alpha}$$

Even when $m_1 = m_2$, $\alpha$ distinguishes $\nu_1$ from $\nu_2$.

# Can Majorana Phases Lead to Manifest $\cancel{CP}$?

(de Gouvêa, BK, Mohapatra)

Manifest $\cancel{CP}$:

$$\text{Rate}[\text{Process}] \neq \text{Rate}[\overline{\text{Process}}]$$

Does this happen in $0\nu\beta\beta$?

$0\nu\beta\beta$: $\quad \text{Nucl} \rightarrow \text{Nucl}' + 2e^-$

$$\text{Amp} = (\text{Nucl Factor}) \times \left(\sum_i m_i U_{ei}^2\right)$$

$\overline{0\nu\beta\beta}$: $\quad \overline{\text{Nucl}} \rightarrow \overline{\text{Nucl}'} + 2e^+$

$$\text{Amp} = (\text{Nucl Factor}) \times \left(\sum_i m_i U_{ei}^{*2}\right)$$

$$\Gamma[0\nu\beta\beta] = \Gamma[\overline{0\nu\beta\beta}]$$

What does it take to have manifest $\cancel{CP}$ ?

$$\mathrm{Amp}[\mathrm{Process}] = \sum_i a_i \underbrace{e^{i\varphi_i}}_{\text{CP-even phase}} \underbrace{e^{i\alpha_i}}_{\text{CP-odd phase}}$$

$$\mathrm{Amp}[\overline{\mathrm{Process}}] = \sum_i a_i e^{i\varphi_i} e^{-i\alpha_i}$$

$$\neq \{\mathrm{Amp}[\mathrm{Process}] \ \underline{\text{or}} \ \mathrm{Amp}^*[\mathrm{Process}]\}$$

$0\nu\beta\beta$ lacks CP-even phases.

But

$$\ell_\alpha^+ W^- \longrightarrow \nu \longrightarrow \ell_\beta^- W^+$$

has them.

$$\text{Amp}[\ell_\alpha^+ W^- \to \nu \to \ell_\beta^- W^+] =$$

$$= \underset{\text{Kinematics}}{S} \sum_i \underbrace{U_{\alpha i} U_{\beta i}}_{\text{Has Maj. phases}} \frac{m_i}{\underset{\text{helicity suppression}}{E}} \underbrace{e^{-i m_i^2 \frac{L}{2E}}}_{\nu \text{ propagator; CP-even}}$$

Distance ($L$)

$$\text{Amp}[\ell_\alpha^- W^+ \to \nu \to \ell_\beta^+ W^-] =$$

$$= S \sum_i U_{\alpha i}^* U_{\beta i}^* \frac{m_i}{E} e^{-i m_i^2 \frac{L}{2E}}$$

Suppose only 2 neutrinos matter:

$$U = \begin{array}{c c} & \begin{array}{cc} \nu_1 & \nu_2 \end{array} \\ \begin{array}{c} \nu_e \\ \nu_\mu \end{array} & \begin{bmatrix} c e^{i\frac{\alpha}{2}} & s \\ -s e^{i\frac{\alpha}{2}} & c \end{bmatrix} \end{array}$$

$c \equiv \cos\theta$

$s \equiv \sin\theta$

$\alpha \equiv$ a Majorana phase

# Why Are There 3 Generations?

If baryogenesis arose from $\cancel{CP}$ in quark mixing, we could argue that—

It takes $\geq 3$ generations to have $\cancel{CP}$ in quark mixing.

It takes $\cancel{CP}$ in quark mixing to have baryogenesis.

It takes baryogenesis to have us.

But $\cancel{CP}$ in quark mixing is completely inadequate for baryogenesis.

Majorana phases can produce the manifest $\cancel{CP}$

$$\Gamma[N \to \ell^+ + \text{Higgs}^-] > \Gamma[N \to \ell^- + \text{Higgs}^+]$$

in the early universe. <u>This</u> may be the origin of baryogenesis.

It takes only 2 generations to have manifest $\cancel{CP}$ from Majorana phases.

So why are there 3 ??

# Conclusion

It is likely that the physics of neutrino masses is quite different from its quark counterpart.

It is likely that the difference involves Majorana neutrino masses. Then $\bar{\nu} = \nu$.

Majorana neutrinos are quite distinctive fermions, with interesting ~~CP~~ possibilities.

Searching for $0\nu\beta\beta$ is the way to confirm that $\bar{\nu} = \nu$.