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$\not{CP}$ in Neutrino Interactions

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$\cancel{CP}$ in Neutrino Interactions

CP violation ($\cancel{CP}$) is —

- The breaking of matter-antimatter symmetry
- Needed for the baryogenesis that makes our existence possible

$\cancel{CP}$ in Quark Interactions

So far, $\cancel{CP}$ has been seen in the laboratory only in processes involving quarks.

What has been seen includes —

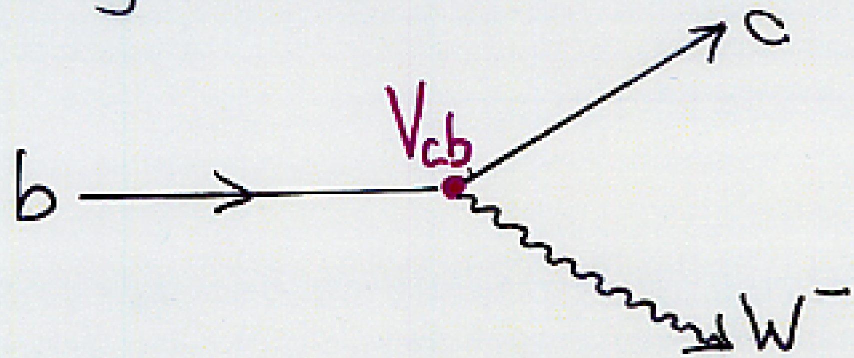
$$K_L(CP \simeq -1) \longrightarrow \pi^+\pi^- (CP = +1)$$

$$\Gamma(K_L \to \pi^- \ell^+ \nu) \neq \Gamma(K_L \to \pi^+ \ell^- \bar{\nu})$$

$$\mathrm{Amp}(K^0 \to \pi^+\pi^-) \neq \mathrm{Amp}(\overline{K^0} \to \pi^+\pi^-)$$

$$\Gamma(B_d(t) \to \psi K_s) \neq \Gamma(\overline{B_d}(t) \to \psi K_s)$$

In the S(tandard) M(odel), all these effects come from a complex phase factor $e^{-i\Delta}$ in the unitary quark mixing matrix V:



V would have no meaning if the quarks had no masses. $\cancel{CP}$ from V requires these masses.

$\not{CP}$ in Neutrino Interactions

Neutrinos almost certainly change (oscillate) from one flavor to another.

$$\text{Flavor Change} \Longrightarrow \left\{ \begin{array}{c} \text{Neutrino Mass} \\ \text{and Mixing} \end{array} \right\}$$

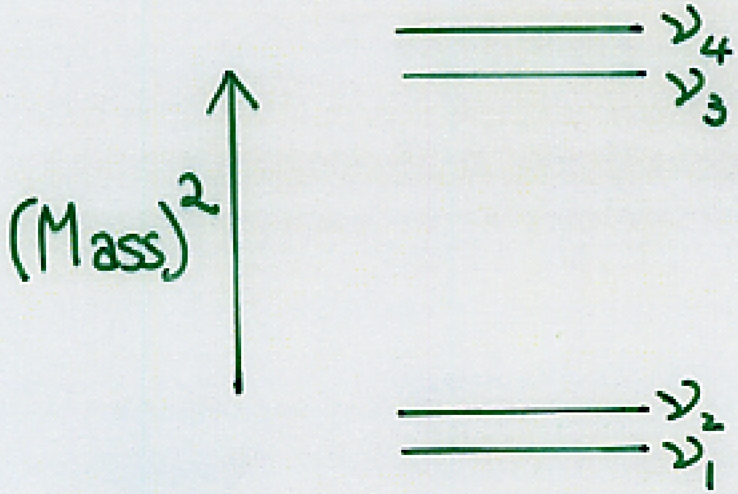
$\therefore$ Neutrinos almost certainly have masses and mix.

$\therefore$ The leptons, including the neutrinos, are like the quarks.

The stage is set for $\not{CP}$ from phases in a unitary leptonic mixing matrix U.

Neutrino Masses and Mixing

There is some spectrum of three or more neutrino mass eigenstates ν_m:



$$\mathrm{Mass}\,(\nu_m) \equiv M_{\nu_m}$$

When $W^+ \to \ell^+ + \nu_\ell$, where $\ell = e, \mu,$ or τ, the produced neutrino state $|\nu_\ell\rangle$ is

$$|\nu_\ell\rangle = \sum_m U^*_{\ell m}\, |\nu_m\rangle$$

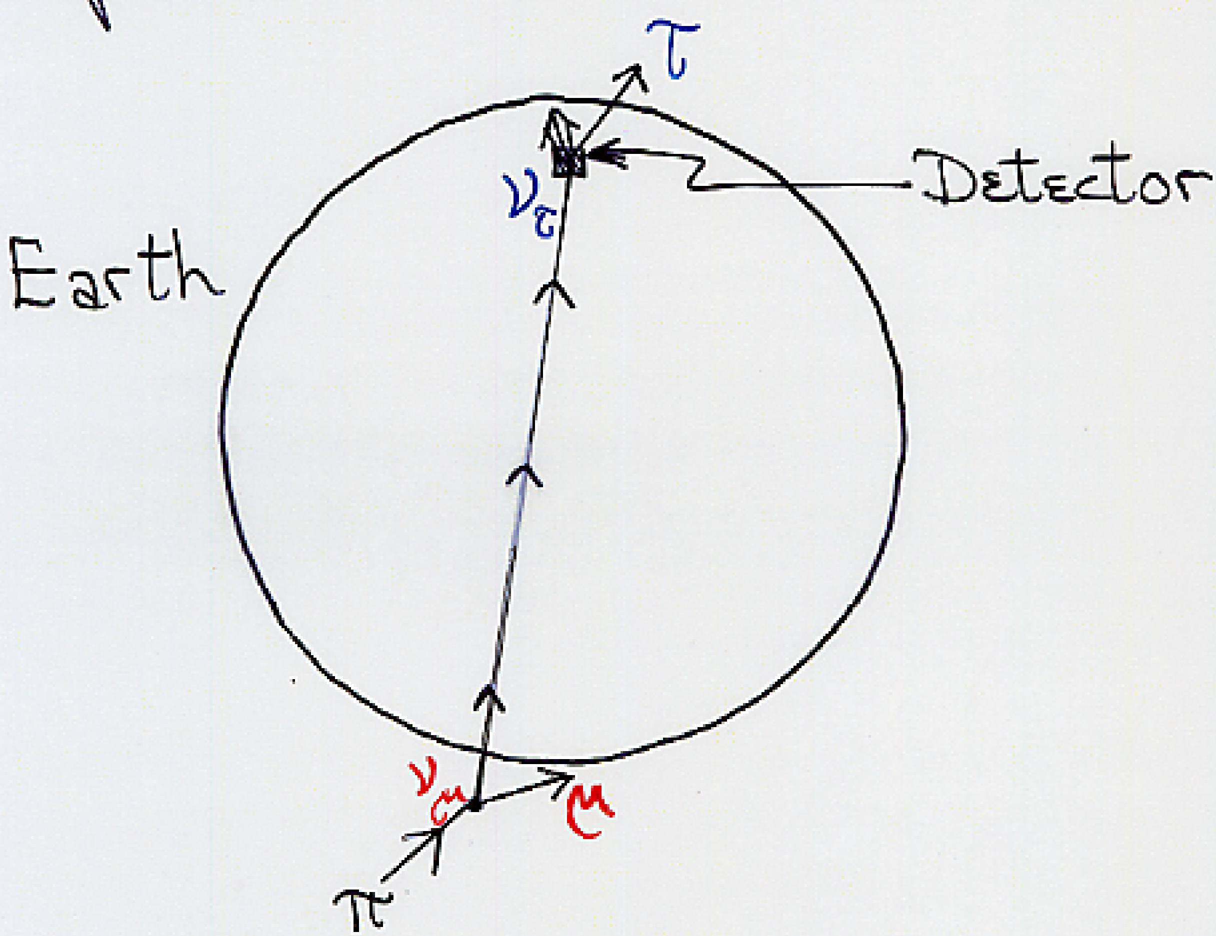
Neutrino of flavor ℓ

Unitary Leptonic Mixing Matrix

Flavor-ℓ fraction of $\nu_m = |\langle \nu_\ell | \nu_m \rangle|^2 = |U_{\ell m}|^2$.

2] Neutrino oscillation: A neutrino is born in association with a charged lepton ℓ (e.g. μ). It then interacts and produces a different charged lepton $\ell' \neq \ell$ (e.g. τ).

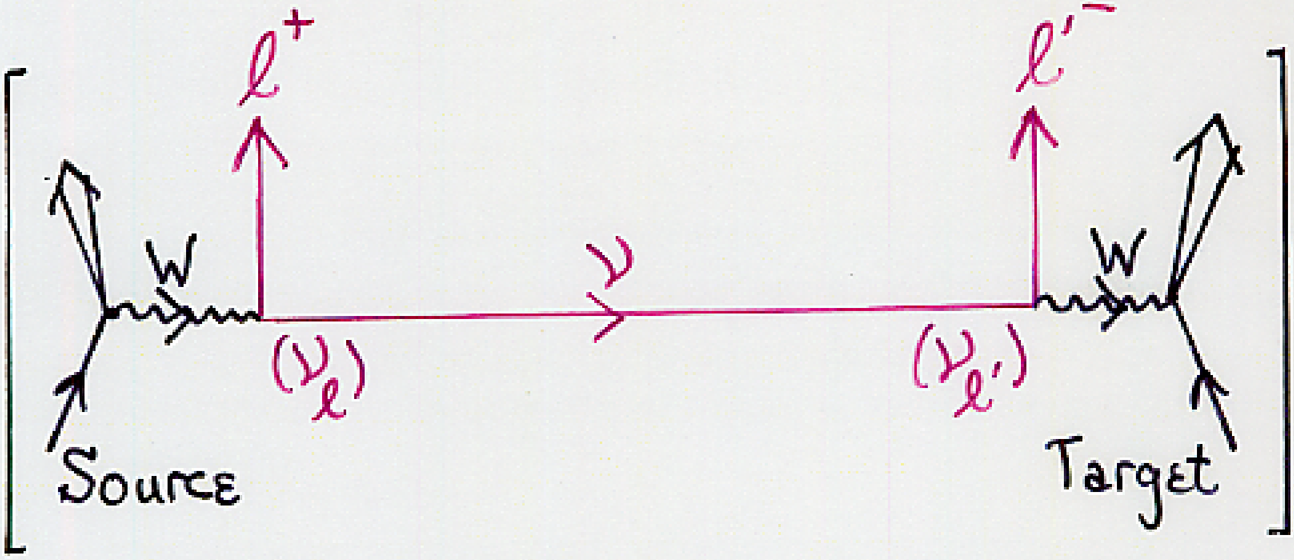
Example —

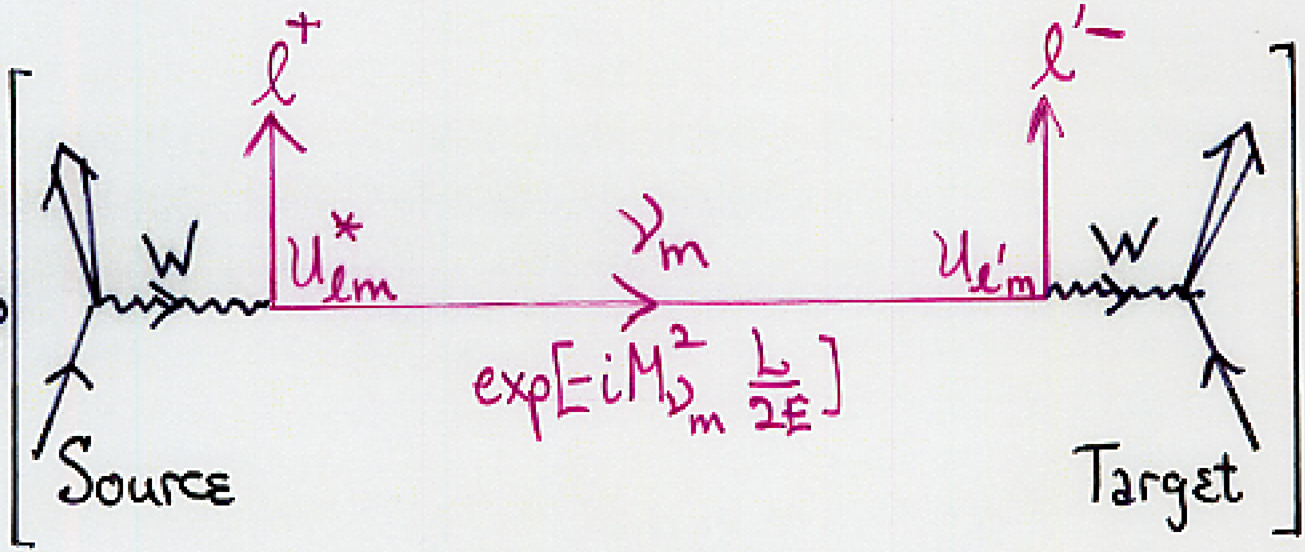


$\nu_\mu \longrightarrow \nu_\tau$ Oscillation

Oscillation Probabilities

(B.K., Stodolsky way)

Amp 

$= \sum_m$ Amp 

$$= \sum_m U^*_{\ell m}\, e^{-iM^2_{\nu_m}\frac{L}{2E}}\, U_{\ell' m} \equiv \mathrm{Amp}(\nu_\ell \to \nu_{\ell'})$$

L = distance the neutrino travels

E = neutrino energy

The oscillation probability is then —

$$P(\nu_\ell \to \nu_{\ell'}) = |\,\mathrm{Amp}(\nu_\ell \to \nu_{\ell'})|^2 =$$

$$= \delta_{\ell\ell'} - 4\sum_{m>m'} \mathrm{Re}(U^*_{\ell m} U_{\ell' m} U_{\ell m'} U^*_{\ell' m'}) \sin^2(\delta M^2_{mm'} \frac{L}{4E})$$

$$+ 2\sum_{m>m'} \mathrm{Im}(U^*_{\ell m} U_{\ell' m} U_{\ell m'} U^*_{\ell' m'}) \sin(\delta M^2_{mm'} \frac{L}{2E}).$$

$$P(\bar{\nu}_\ell \to \bar{\nu}_{\ell'} ; U) \underset{\text{CPT}}{=\!=} P(\nu_{\ell'} \to \nu_\ell ; U)$$

$$\underset{\text{Above}}{=\!=} P(\nu_\ell \to \nu_{\ell'} ; U^*)$$

[1.4] The oscillation probability is then —

$$P(\overset{(-)}{\nu}_\ell \to \overset{(-)}{\nu}_{\ell'}) = |\mathrm{Amp}(\overset{(-)}{\nu}_\ell \to \overset{(-)}{\nu}_{\ell'})|^2 =$$

$$= \delta_{\ell\ell'} - 4\sum_{m>m'} \mathrm{Re}(U^*_{\ell m} U_{\ell' m} U_{\ell m'} U^*_{\ell' m'}) \sin^2(\delta M^2_{mm'} \tfrac{L}{4E})$$

$$\overset{+}{\underset{(-)}{}} 2\sum_{m>m'} \mathrm{Im}(U^*_{\ell m} U_{\ell' m} U_{\ell m'} U^*_{\ell' m'}) \sin(\delta M^2_{mm'} \tfrac{L}{2E}).$$

$$P(\bar{\nu}_\ell \to \bar{\nu}_{\ell'} ; U) \underset{CPT}{=} P(\nu_{\ell'} \to \nu_\ell ; U)$$

$$\underset{\text{Above}}{=} P(\nu_\ell \to \nu_{\ell'} ; U^*)$$

Complex phases in U can lead to the ~~CP~~

$$P(\nu_\ell \to \nu_{\ell'}) \neq P(\bar{\nu}_\ell \to \bar{\nu}_{\ell'}) .$$

Evidence for Oscillation

There are 3 pieces of evidence that neutrinos oscillate:

Neutrinos	Evidence of Oscillation	Required δM^2 (eV^2)
$\overset{(-)}{\nu}_\mu$ Atmospheric	Compelling	3×10^{-3}
ν_e Solar	Compelling	4×10^{-10} to 2×10^{-4}
$\bar{\nu}_\mu$ LSND (KARMEN)	Unconfirmed	0.2 to 1, or 7

If all 3 of these oscillations are genuine, then nature must contain —

- At least 4 neutrino masses
- Correspondingly, ν_e, ν_μ, ν_τ, $\nu_{s(terile)}$??

If there are only 3 masses, then we must have

$$\sum \delta M^2 = (M_{\nu_3}^2 - M_{\nu_2}^2) + (M_{\nu_2}^2 - M_{\nu_1}^2) + (M_{\nu_1}^2 - M_{\nu_3}^2) = 0 .$$

Solar Neutrinos

The sun produces only ν_e.

But the solar neutrino flux arriving at earth includes ν_μ and/or ν_τ:

$$\phi_{\mu\tau} = (3.41^{+0.66}_{-0.64}) \times 10^6/\text{cm}^2\,\text{sec}$$

(SNO; April 20, 2002)

The ν_μ / ν_τ flux is 5.3σ from zero.

With Super-K $\nu_{sol}-e$ data included,

$$\phi_{\mu\tau} = (3.45^{+0.65}_{-0.62}) \times 10^6/\text{cm}^2\,\text{sec},$$

5.5σ from zero.

Change of ν flavor does occur.

Most-favored flavor-change mechanism:

Large Mixing Angle—
Mikheyev Smirnov Wolfenstein
—Effect

(LMA — MSW)

Flavor change within the sun.

An interplay between ν masses and mixing and flavor-preserving ν-e interactions.

ν masses and mixing are still implied.

7]

Atmospheric Neutrinos

Compelling evidence for atmospheric

$$\nu_\mu \longrightarrow \nu_?$$

$\nu_?$ mostly ν_τ

Mixing ~ Maximal

Matter effects negligible at $E_\nu \sim 1$ GeV.

This is flavor change via—

oscillation in "vacuum".

8)

Certainly—

We should seek $\not{CP}$ in ν oscillations.

Seeing it would establish that $\not{CP}$ is not a peculiarity of quarks.

What do we expect to see?

Ar.8) Suppose there are only 3 neutrinos, and the behavior of solar neutrinos is due to the Large Mixing Angle MSW effect. Then—

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

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

With Large-Mixing MSW,

$$0.20 < \sin^2\theta_\odot < 0.30 \quad (90\%\,\mathrm{CL}).$$

(SNO)

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

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

Note the contrast between $\mathcal{U}$ and the quark mixing matrix, V.

With B ≡ Big and s ≡ small,

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

but

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

Are big leptonic mixings due to a symmetry, perhaps broken so that the mixings are not quite maximal?

The phases $\alpha_{1,2}$ do not affect ν oscillation.

[P xpar]

We will have

$$P(\nu_\ell \to \nu_{\ell'}) \neq P(\bar{\nu}_\ell \to \bar{\nu}_{\ell'})$$

if δ and s_{13} are nonvanishing.

Searches —

Off-Axis Detectors [Beam ~ Monochromatic]

Superbeams [Many $\pi \to \mu \nu_\mu$]

Neutrino Factories [$\mu \to e \nu_\mu \nu_e$]

Let $P(\nu_\ell \to \nu_{\ell'}) - P(\bar{\nu}_\ell \to \bar{\nu}_{\ell'}) \equiv \Delta_{\cancel{CP}}(\ell\ell')$.

If there are only 3 neutrinos,

$$\Delta_{\cancel{CP}}(e\mu) = \Delta_{\cancel{CP}}(\mu\tau) = \Delta_{\cancel{CP}}(\tau e)$$

$$= 16 J\, k_{12} k_{23} k_{31} ,$$

where

$$J \equiv \mathrm{Im}(U_{e1}^* U_{e3} U_{\mu 1} U_{\mu 3}^*) \cong \frac{1}{4} \sin 2\theta_\odot \sin\theta_{13} \sin\delta ;$$

and

$$k_{mm'} \equiv \sin\left[1.27\, \delta M^2_{mm'} (\mathrm{eV}^2) \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right] .$$

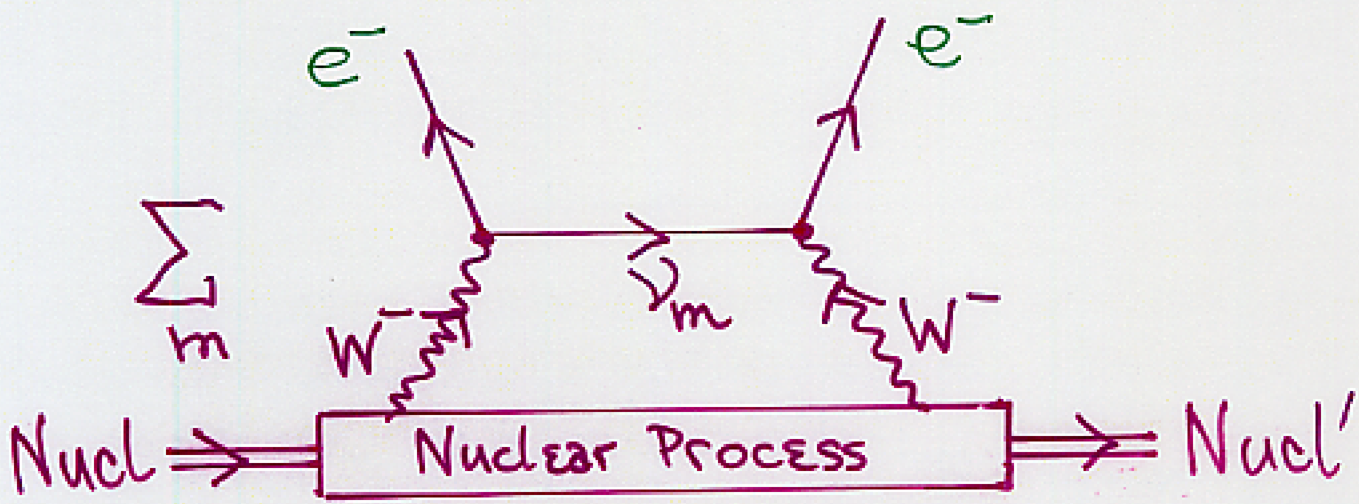
- Just one $\cancel{CP}$ difference
- No hadronic uncertainties
- But, small due to $\sin\theta_{13}$ and $\delta M^2_\odot$

Where can the phases $\alpha_{1,2}$ play a role?

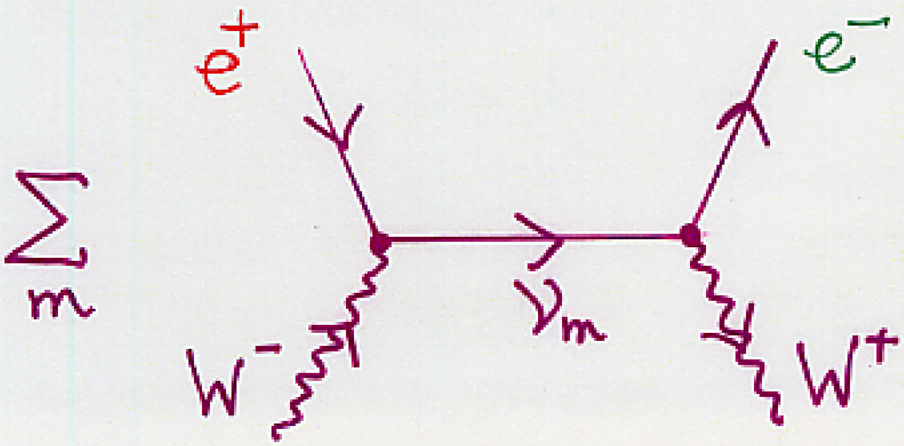
If $\bar{\nu}_m \neq \nu_m$, nowhere!

But if $\bar{\nu}_m = \nu_m$, $\alpha_{1,2}$ influence—

Neutrinoless Double Beta Decay ($\beta\beta_{0\nu}$)



The heart of this, in the cross channel, is



The amplitude for this, $Amp_{\beta\beta}$, is

$$Amp_{\beta\beta} = \sum_m \overbrace{\langle e^- W^+ | H | \nu_m \rangle}^{\propto U_{em}} \langle \nu_m | H | e^+ W^- \rangle$$

ν_m helicity

Standard Model weak interaction

Helicity

Must be the same for $|\nu_m\rangle$ and $\langle \nu_m|$.

$$\text{But} \quad \left\{ \begin{matrix} \langle e^- W^+ | H | \nu_m(RH) \rangle \\ \langle \nu_m(LH) | H | e^+ W^- \rangle \end{matrix} \right\} \sim \mathcal{O}\left(\frac{M_{\nu_m}}{E_\nu}\right)$$

$\therefore$ ν_m contribution $\propto M_{\nu_m}$

$$\mathrm{Amp}_{\beta\beta} = \sum_{\substack{m \\ \nu_m \text{ helicity}}} \overbrace{\langle e^- W^+ | H | \nu_m \rangle}^{\propto U_{em}} \langle \nu_m | H | e^+ W^- \rangle$$

$$\langle e^- W^+ | H | \nu_m \rangle \underset{CPT}{=\!=} \langle \bar{\nu}_m | H | e^+ W^- \rangle$$

$$\underset{\substack{\text{when} \\ \bar{\nu}_m = \nu_m}}{=\!=} \langle \nu_m | H | e^+ W^- \rangle$$

Then

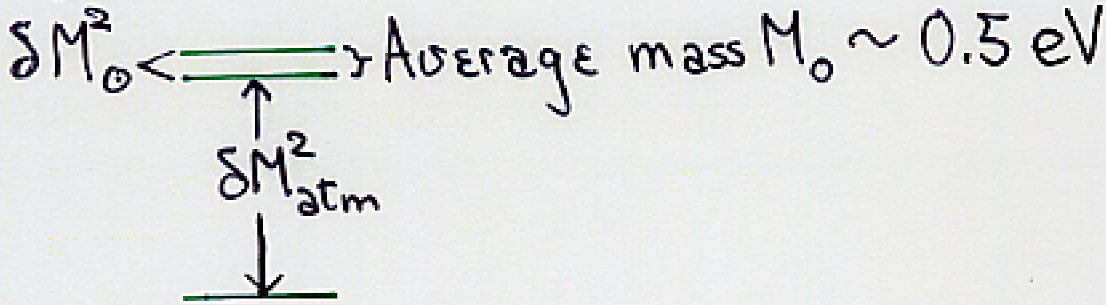
$$|\mathrm{Amp}_{\beta\beta}| \propto \left| \sum_m M_{\nu_m} U_{em}^2 \right| \equiv M_{\beta\beta} .$$

$\Gamma_{\beta\beta 0\nu} \propto M_{\beta\beta}^2$ depends on $\alpha_{1,2}$.

Can We Measure $\alpha_{1,2}$?

An optimistic scenario:

The ν spectrum is —



Then —

$$M_{\beta\beta} = M_0 \sqrt{1 - \sin^2 2\theta_\odot \sin^2\left(\frac{\alpha_2 - \alpha_1}{2}\right)}$$

M_0: Measured in KATRIN tritium β decay exp.

$\theta_\odot$: Measured in $\boxed{\text{KamLAND}}$ reactor exp.

$M_{\beta\beta}$: Measured in $\beta\beta_{0\nu}$ exp., after nuclear matrix element is conquered

If $M_0 \cos 2\theta_\odot \leq M_{\beta\beta} \leq M_0$, learn $\alpha_2 - \alpha_1$.

If $M_{\beta\beta}$ is not in this range, $\bar{\nu} \neq \nu$.

The α_i: Majorana $\cancel{CP}$ phases.

They occur only for Majorana particles.

Majorana $\cancel{CP}$ phases and our existence

Why does the universe contain much more matter (of which we are made) than antimatter?

Why is $\Delta B \equiv \#(\text{Baryons}) - \#(\text{Antibaryons}) \neq 0$?

Symmetry suggests that $\Delta B = 0$ at $t = 0$.

How did $\Delta B \neq 0$ subsequently arise?

Sakharov: $\cancel{CP}$ is required.

Example: $(X^+ \to p + \ldots) \overset{CP}{\Longrightarrow} (X^- \to \bar{p} + \ldots)$

If no $\cancel{CP}$, the rates are equal.

Is the observed $\Delta B \neq 0$ due to $\not{CP}$ in Leptonic interactions?

A two-step process:

1) Generate $\Delta L \equiv \#(\text{Leptons}) - \#(\text{Antileptons}) \neq 0$ before the electroweak phase transition, when the universe cooled through $\sim 100\,\text{GeV}$

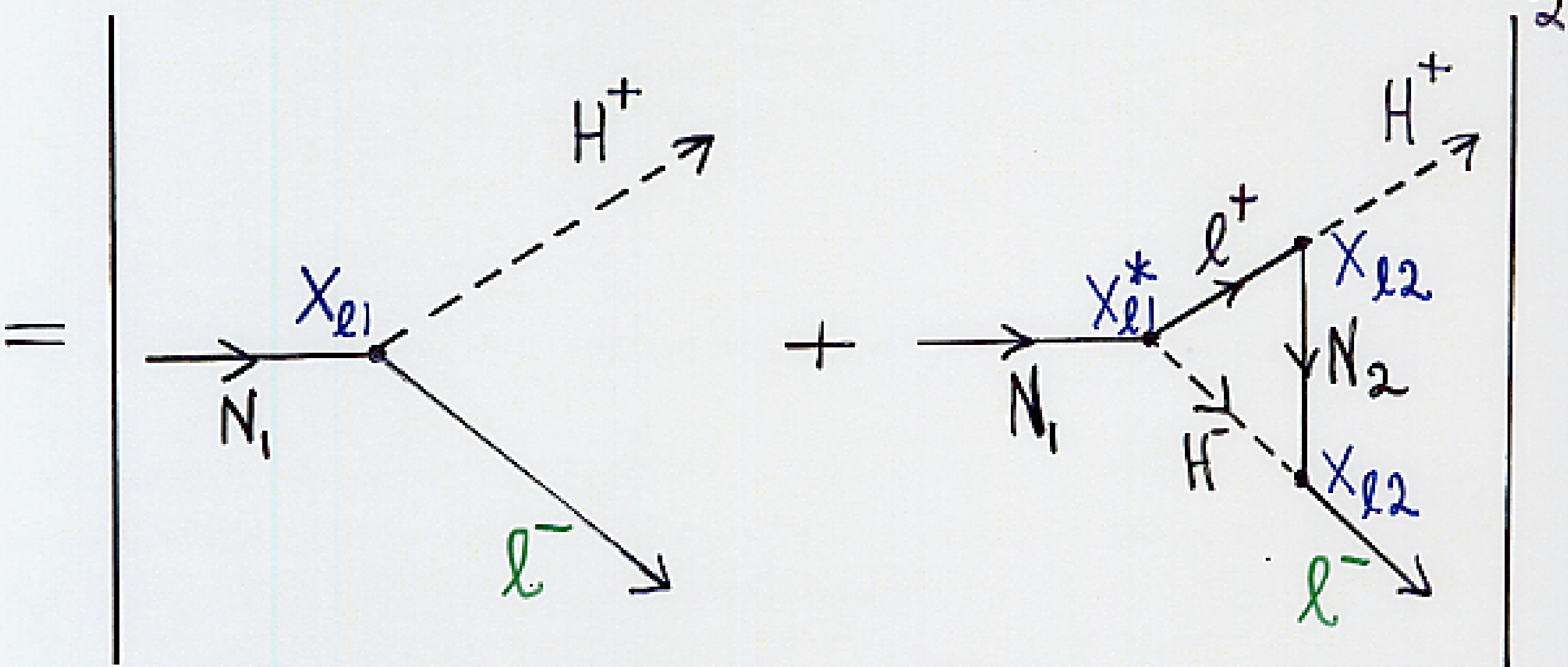
2) Convert the $\Delta L \neq 0$ to $\Delta B \neq 0$ by expected B−L conserving processes at the electroweak phase transition

$\Delta L \neq 0$ can be generated by $\not{CP}$ in the decays of very heavy Majorana neutral leptons N.

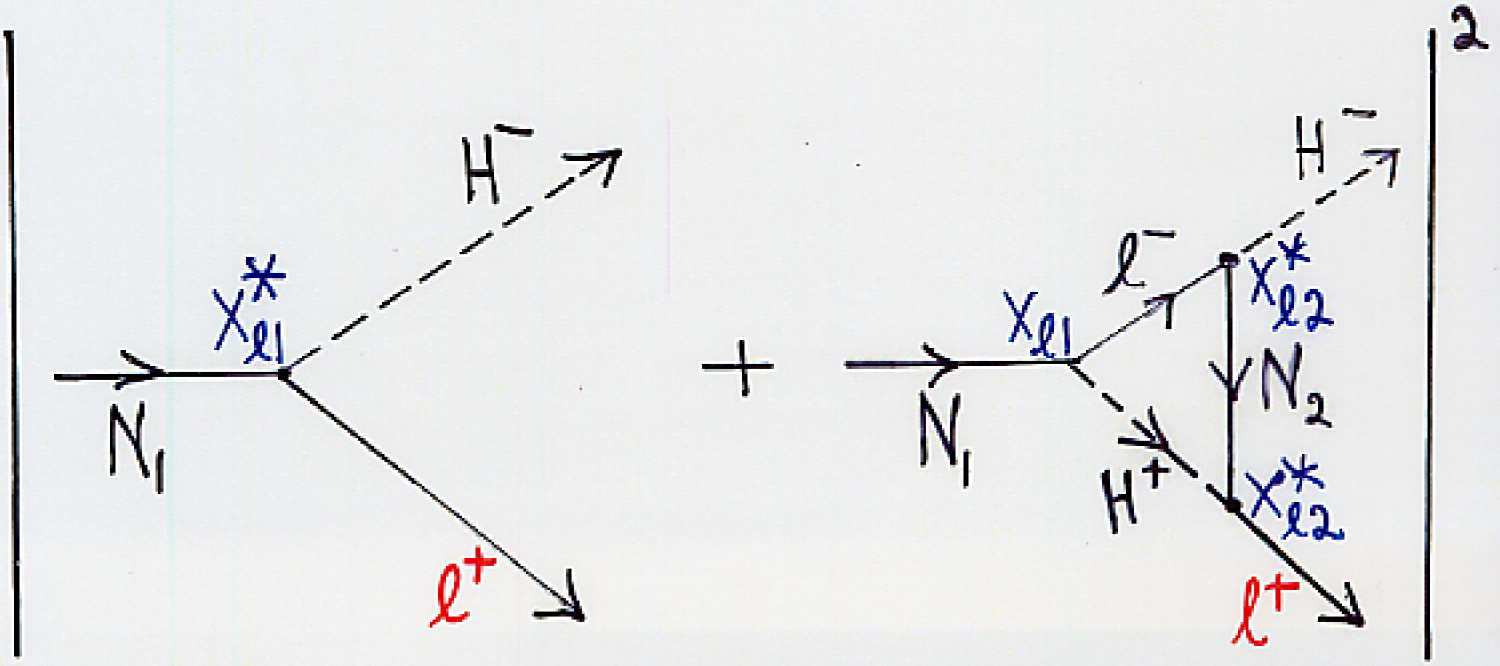
(Fukugita & Yanagida
Buchmüller & Plümacher)

With $N_{1,2}$ two such leptons, and $H^{\pm}$ a charged Higgs particle —

$$\Gamma(N_1 \to \ell^- H^+) =$$



Then CPT $\Rightarrow \Gamma(N_1 \to \ell^+ H^-) =$



[4] X is a $\mathcal{U}$ matrix for heavy neutral leptons.

$\Gamma(N_1 \to \ell^- H^+)$ and $\Gamma(N_1 \to \ell^+ H^-)$ can differ if X breaks CP by being complex.

$\Gamma(N_1 \to \ell^- H^+) - \Gamma(N_1 \to \ell^+ H^-)$ depends on —

$$\arg\left[X_{\ell 1}^2 / X_{\ell 2}^2\right].$$

In

$$\Gamma(\beta\beta_{0\nu}) \propto M_{\beta\beta}^2 = \left|\sum_m M_{\nu_m} \mathcal{U}_{em}^2\right|^2,$$

$\cancel{CP}$ depends on —

$$\arg\left[\mathcal{U}_{e1}^2 / \mathcal{U}_{e2}^2\right].$$

In both cases, $\cancel{CP}$ is coming from Majorana $\cancel{CP}$ phases.

$\Gamma(\beta\beta_{0\nu})$ violates CP

$\Rightarrow \left\{ \begin{array}{l} \text{Nature contains the kind of } \not{CP} \\ \text{phases that can generate } \Delta L \neq 0 \end{array} \right.$

(L.N. Chang, J. Ellis, Gavela, B.K., Langacker, Murayama)

The Lepton–Quark Connection

Similarities and differences—

- Both have masses
- Both mix
- The mixing matrices U_{lepton} and V_{quark} are quite different in character
- $\not{CP}$ can come from phases in both mixing matrices

But are leptonic mass, mixing, and $\not{CP}$ related to quark mass, mixing, and $\not{CP}$?

G(rand) U(nified) M(odels), which make the quarks brothers of leptons, suggest that they are related.

In a GUT-based see-saw model of ν mass, one naturally expects for the heaviest ν,

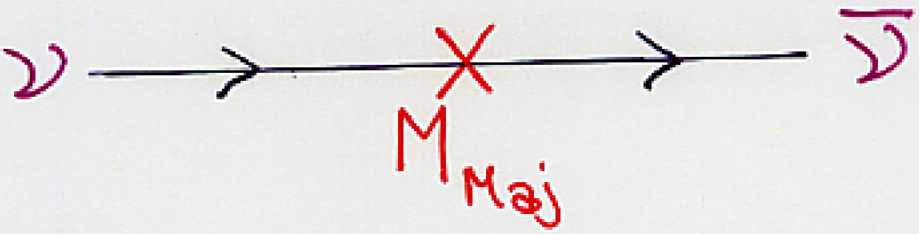
$$M_\nu \sim \frac{M_{top}^2}{M_{GUT}} \sim 0.003 \text{ eV} .$$

Atmospheric ν oscillation $\Rightarrow$

$$M_\nu \gtrsim \sqrt{\delta M_{atm}^2} \simeq 0.05 \text{ eV} .$$

Quark-Lepton connections are highly model dependent:

Neutrinos can have Majorana masses



These have no quark analogue.

In nature, are there quark effects closely related to neutrino effects?

Quite possibly!

(Chang, Masiero, Murayama)

In SU(5) GUTS, for each generation, one has a family like—

$$(\nu_\tau, \tau^-, b^c, b^c, b^c)_L .$$

This relates $\nu_{\tau L}$ to b^c_L, or to b_R.

Atmospheric ν oscillation $\Rightarrow$

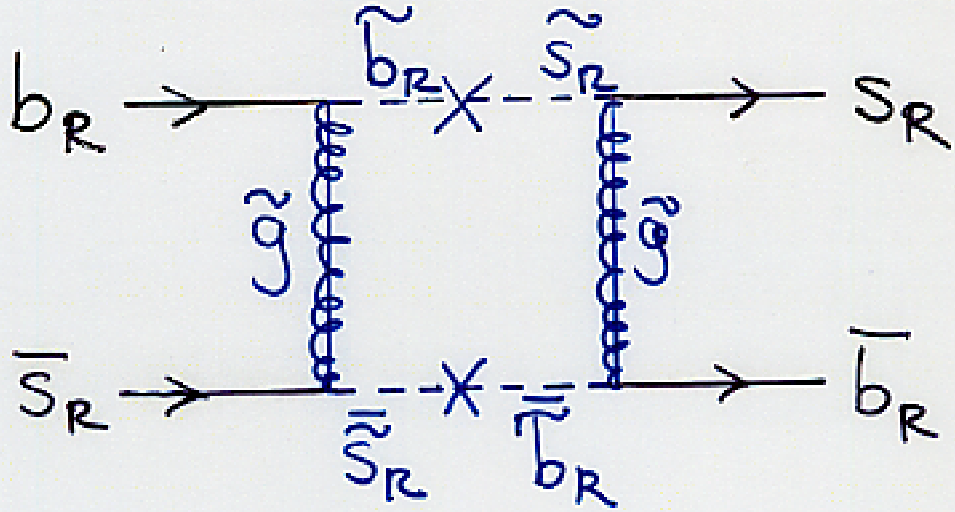
~Maximal $\nu_{\mu L} - \nu_{\tau L}$ mixing.

$\therefore$ ~Maximal $s_R - b_R$ mixing.

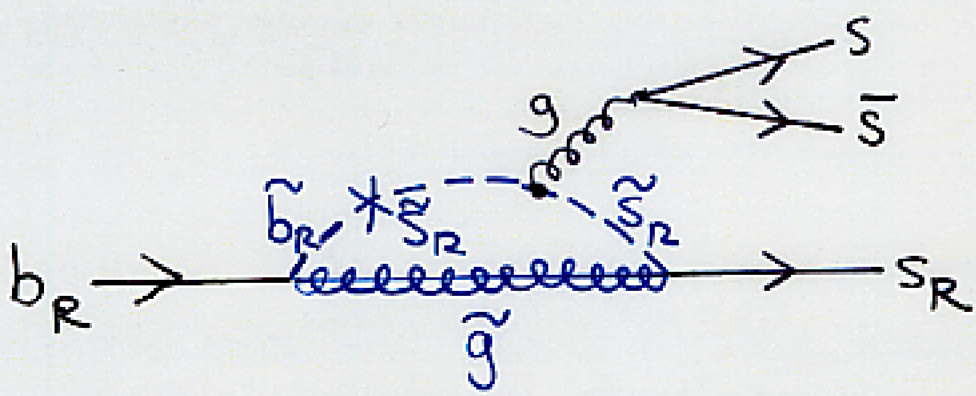
Right-handed quarks don't couple to the W boson.

But in a SUSY-GUT, $s_R - b_R$ mixing can be accompanied by $\underbrace{\tilde{s}_R - \tilde{b}_R}_{\text{squarks}}$ mixing.

Big squark mixing leads to–



$\Longrightarrow$ Potentially big change in the Size and Phase of $B_s - \overline{B}_s$ mixing



$\Longrightarrow$ Potentially significant contribution to Penguin Processes like $B_d \rightarrow \eta' K_s$

Consequences

- Penguin and non-penguin probes of "β" will give different answers

- B_s and non-B_s probes of "γ" will give different answers

** The study of B mixing and $\cancel{CP}$ will reveal that physics beyond the Standard Model is present

Conclusion

$\not{CP}$ has become a very exciting field.

Both the leptons and the quarks are important parts of the picture.

$\not{CP}$ in ν oscillation would show that $\not{CP}$ is not a peculiarity of quarks.

Baryogenesis may have come from leptonic $\not{CP}$.

Mixing and $\not{CP}$ among the quarks and among the leptons might be related in a deep way.