HEPAP
July 24, 2003

Overview of Neutrino Physics

Boris Kayser

Evidence for Flavor Change

Neutrinos	Evidence of Flavor Change
Solar	Compelling
Reactor ($L \sim 180$ km)	Very Strong
Atmospheric	Compelling
Accelerator ($L = 250$ km)	Interesting
Stopped μ^+ Decay (LSND) ($L \approx 30$ m)	Unconfirmed

The observed flavor changes are not due to flavor-changing interactions with matter, but to —

neutrino masses and mixing.

Prob [Atmospheric ν flavor change] depends on —

$$\frac{L\,(\text{Distance } \nu \text{ travels})}{E\,(\nu \text{ energy})}.$$

Time elapsed in ν rest frame during journey

$$= m\,(\nu \text{ mass}) \times \frac{L}{E}.$$

A.1)

What Would We Like to Know?

What physics is responsible for neutrino masses and mixing?

How many neutrino species are there?
Are there sterile neutrinos?

What is the neutrino mass spectral pattern?

What is the scale of neutrino mass?

Are neutrinos Majorana particles ($\bar{\nu} = \nu$)?

What is the leptonic mixing matrix?

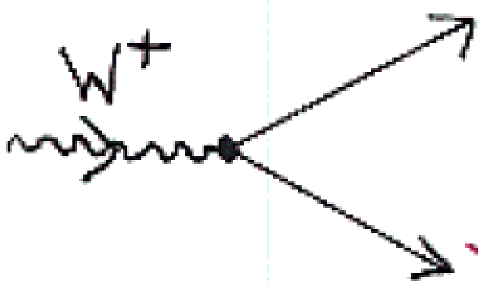
Do neutrino interactions violate CP?

Is leptonic $\not{CP}$ responsible for the baryon asymmetry in the universe?

Are there surprises?

- Rapid ν decay?
- Non-Standard-Model ν interactions?
- ???

Leptonic Mixing



$\to l_\alpha^+ \quad (l_e \equiv e,\ l_\mu \equiv \mu,\ l_\tau \equiv \tau)$

$\to \nu_\alpha = \sum_i U_{\alpha i}^* \nu_i$

Neutrino of flavor α (ν_e, ν_μ, or ν_τ) — ν_α

Unitary Leptonic Mixing Matrix — $U_{\alpha i}^*$

Masseigenstate — ν_i

$$\nu_i = \sum_\alpha U_{\alpha i} \nu_\alpha$$

Flavor-α fraction of $\nu_i = |U_{\alpha i}|^2$.

What Have We Already Learned?

We do not know how many neutrino mass eigenstates ν_i there are.

Assuming CPT, confirmation of LSND by MiniBooNE would imply there are more than 3.

$n\ \nu_i \Rightarrow \mathcal{U}$ is $n \times n$, and $n-3$ linear combinations of the ν_i are sterile neutrinos $\nu_{s_1}, \nu_{s_2}, \ldots$, which don't couple to W or Z.

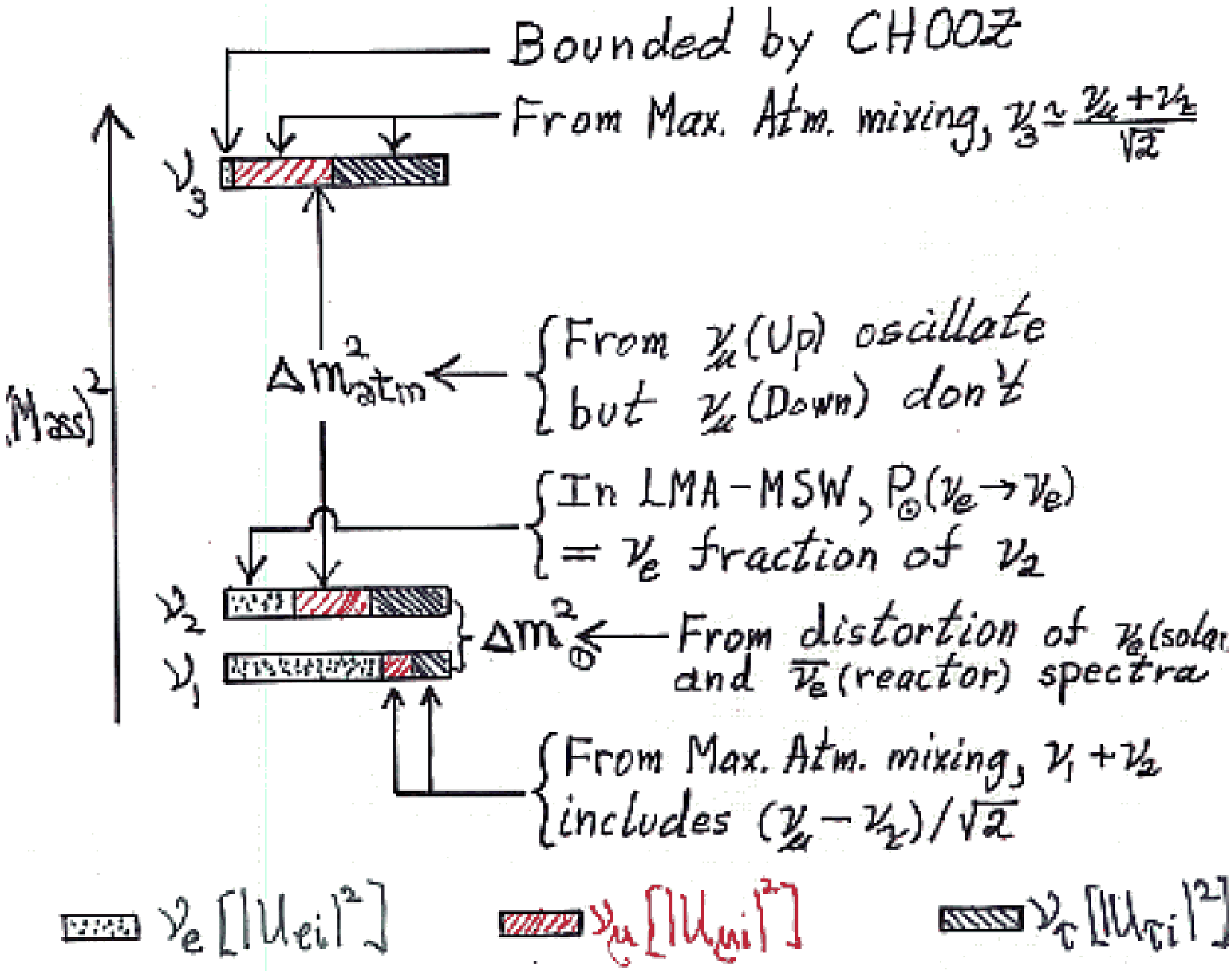
Neutrino physics would be greatly affected.

(Fermilab study group)

If LSND is not confirmed, nature may contain only 3 neutrinos.

Then the spectrum looks like  or  .

If it is like  :



[I.3]

Parameter Ranges

(Mass)^2 splittings —

$$1.3 \times 10^{-3} < \Delta m^2_{atm} < 3.0 \times 10^{-3}\ eV^2$$

(Super-K [Hayato], 90% CL)

$$5.4 \times 10^{-5} < \Delta m^2_{\odot} < 10 \times 10^{-5}\ eV^2$$

— or —

$$14 \times 10^{-5} < \Delta m^2_{\odot} < 19 \times 10^{-5}\ eV^2$$

(Gonzalez-Garcia & Peña-Garay; 3σ)

The absolute mass scale —

$$0.04\ eV \lesssim \text{Mass}[\text{Heaviest } \nu_i] < 0.23\ eV$$

↑ $\sqrt{\Delta m^2_{atm}}$

Cosmology ↑
(Spergel et al. + assumptions; 95% CL)

F.10

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 —

Atmospheric / Cross-Mixing

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

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

Solar / Majorana CP Phases

$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$ [27]

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

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

[H.4] The 90% CL mixing-angle ranges —

$$\sin^2 2\theta_{atm} > 0.9$$

(Super-K)

$$0.73 \lesssim \sin^2 2\theta_{\odot} \lesssim 0.94$$

(Lisi)

$$\sin^2 2\theta_{13} \lesssim 0.1$$

(CHOOZ, Palo Verde)

[9.6]

CP Violation ($\not{CP}$)

$$P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = P(\nu_\alpha \to \nu_\beta \, ; \, U \to U^*)$$

δ leads to $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq P(\nu_\alpha \to \nu_\beta)$.

All effects of δ are $\propto s_{13}$.

High priority:

Show $\theta_{13} \neq 0$.

Determine its rough size.

This rough size will help determine what facility is needed to study $\not{CP}$.

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

The Future — Open Questions

* Does neutrino flavor truly oscillate ?

When matter effects may be neglected,

$$P(\nu_\alpha \to \nu_\beta) \sim \sin^2\left[\Delta m^2 \frac{L}{4E}\right].$$

This signature feature of neutrino flavor change has yet to be seen.

Perhaps KamLAND can see this undulation for $\Delta m^2 = \Delta m^2_\odot$.

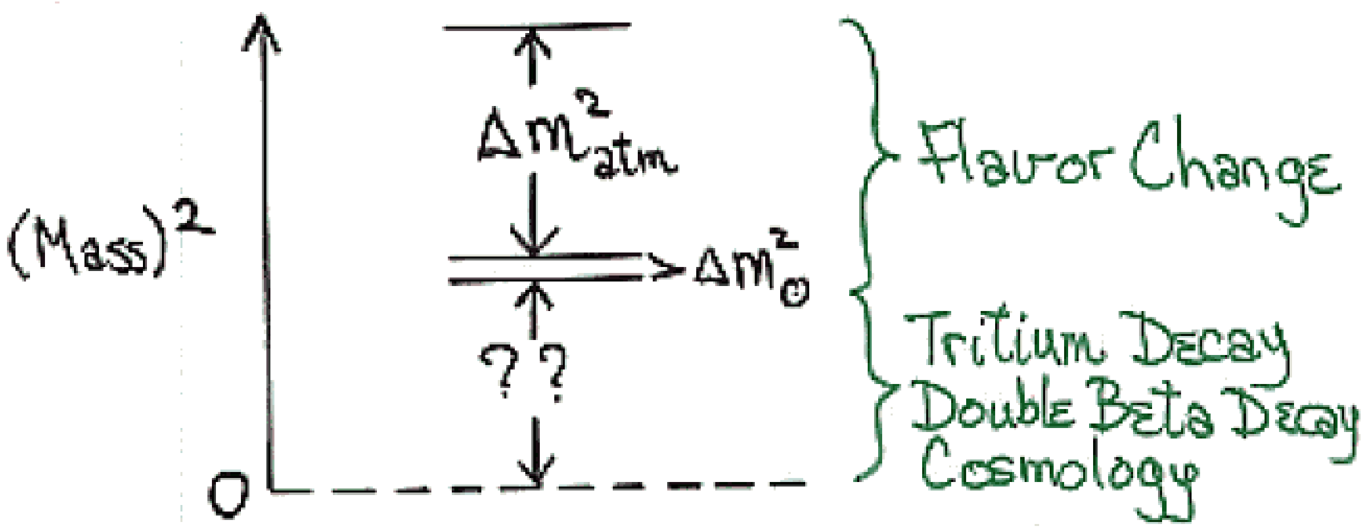
Hopefully, MINOS can see it (in $1/E$) for $\Delta m^2 = \Delta m^2_{atm}$.

R.7]

* How many neutrino species are there?
  Do sterile neutrinos exist?

MiniBooNE

* What are the masses of the mass eigenstates ν_i?



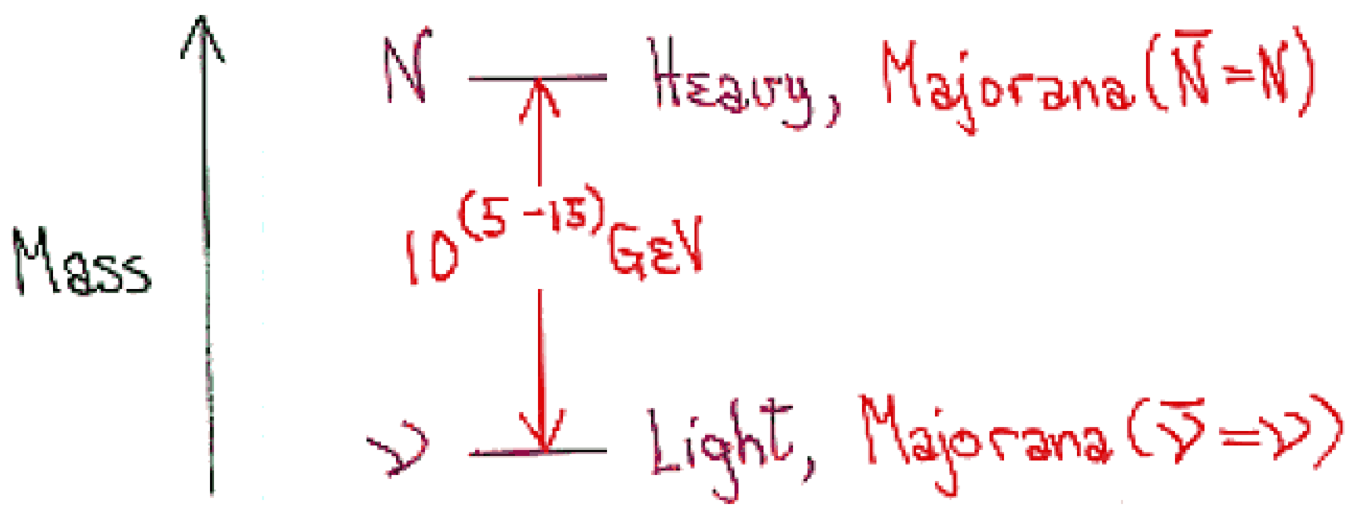
Is the spectral pattern  or  ?

* Why are ν masses $\ll$ quark and charged lepton masses?

Most popular answer –

The See-Saw mechanism

(Gell-Mann, Ramond, Slansky; Yanagida; Mohapatra & Senjanovic)



$$m_\nu\, m_N \sim m^2_{\text{quark or charged lepton}}$$

H.b)

The see-saw mechanism grows out of naturally expected

Majorana ($\nu \leftrightarrow \bar{\nu}$) mass terms.

These have no analogue for quarks or charged leptons, since $q \leftrightarrow \bar{q}$ would not conserve electric charge.

Majorana mass terms violate L, the lepton number that distinguishes antileptons from leptons.

Then there is no conserved L to distinguish $\bar{\nu}_i$ from ν_i. Hence —

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

With this in mind —

* Is each mass eigenstate —

- A Majorana particle
  ($\bar{\nu}_i = \nu_i$; No conserved L)

or

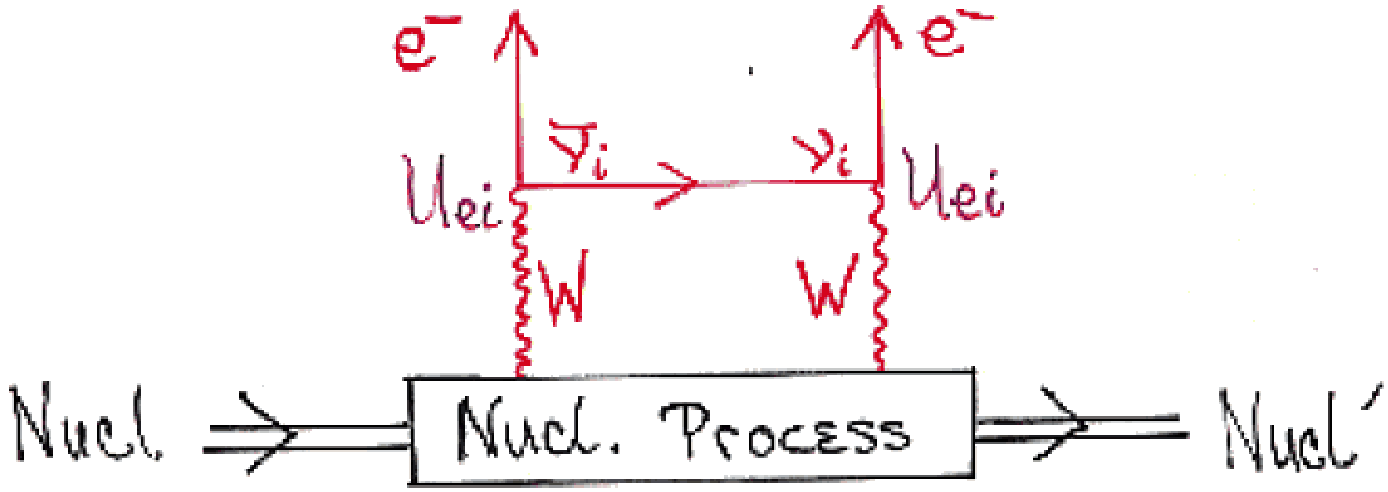
- A Dirac particle
  ($\bar{\nu}_i \neq \nu_i$; $L(\bar{\nu}_i) = -L(\nu_i)$) ?

$0\nu\beta\beta$ [Nucl → Nucl′ + $2e^-$]

$\Rightarrow \not{L}$; $\bar{\nu}_i = \nu_i$; a Majorana mass term

Rate[$0\nu\beta\beta$] $\neq 0$ $\Rightarrow$ The physics of ν masses is unlike the physics of the masses of all other fermions.

B.K. The dominant mechanism is expected to be—



$\bar{\nu}_i$ is emitted $\left[RH + O\left(\frac{m_i}{E}\right) LH\right]$ ← Mass(ν_i)

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

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

$0\nu\beta\beta$ violates L. Standard Model interactions conserve L. The $\not{L}$ in $0\nu\beta\beta$ comes from underlying Majorana mass terms.

$$\therefore \text{Amp}[0\nu\beta\beta] \propto \nu \text{ mass}$$

H.9] The virtue of this:

Amp[$0\nu\beta\beta$] $\propto m_{\beta\beta}$ is a measure of the ν mass scale.

* What is the leptonic mixing matrix U?

Is $\theta_{23} \simeq \theta_{atm}$ maximal?

What is $\theta_{12} \simeq \theta_{\odot}$?

What is the small mixing angle θ_{13}?

Does U contain phases that lead to $\not{CP}$ in ν oscillation or elsewhere?

F.13

Major Questions for Future Accelerator ν Experiments

* How big is θ_{13}?

* Does neutrino oscillation violate CP?

  If there are only 3 neutrinos,

  $$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \propto \sin\theta_{13}.$$

* If there are only 3 neutrinos, is the spectral pattern like

   or like  ?

  Answering this depends on θ_{13}.

* Is atmospheric ν mixing truly maximal?

  Is a symmetry, like CP in $K^0 \leftrightarrow \bar{K}^0$, involved?

How Big Do We Expect θ_{13} To Be?

Sorry —
The size of θ_{13} is an experimental question.

Why Is $\not{CP}$ in ν Oscillation So Interesting?

Demonstrating that $\not{CP}$ in oscillation is nonzero would establish that $\not{CP}$ is not a peculiarity of quarks.

Leptonic $\not{CP}$ might have been the $\not{CP}$ that made baryogenesis possible.

In the See-Saw mechanism, the light neutrinos have very heavy Majorana neutral lepton partners N.

Perhaps in the early universe there was

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

$\uparrow$

$\not{CP}$

(Leptogenesis)

Standard Model (B−L)-conserving, but B- and L-violating, processes would then have converted some of this antilepton excess into a baryon excess.

(Fukugita & Yanagida)

How Is ~~CP~~ in ν Oscillation Related To ~~CP~~ in Leptogenesis?

The relation is model-dependent

However —

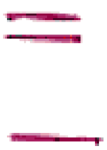
It is not likely that we have one without the other.

(Davidson, Pascoli, Petcov, Rodejohann, Yanagida)

A.12)

Why Is  vs.  Interesting?

For a given center of gravity,

 involves more degeneracy than .

Degeneracy could be caused by an underlying symmetry.

In the simplified limit of  with —

- $\Delta m^2_\odot = 0$ & $m_3 = 0$
- θ_{atm} & $\theta_\odot$ maximal; $\theta_{13} = 0$
- Only Majorana masses ,

$\tilde{L} \equiv L_e - L_\mu - L_\tau$ is conserved.

(Babu & Mohapatra)

$\tilde{L}$ conservation forbids Nucl $\rightarrow$ Nucl$'$ + $2e^-$.

But don't worry: $\theta_\odot$ is not maximal.

A.13

Why Is Any Deviation of θ_{atm} From Maximality Interesting?

The observed maximal or near-maximal mixing may be caused by a symmetry.

In a simplified picture,

$$1 - \sin^2 2\theta_{atm} \propto \left(\frac{\text{Symmetry Breaking Scale}}{\nu_\mu - \nu_\tau \text{ Mixing Scale}} \right)^2 .$$

Hopefully, major features of the ν masses and mixings, such as broken symmetries, will allow us to discriminate among competing theoretical models.

1.10|

How θ_{13} May Be Measured

$\sin^2\theta_{13} = |U_{e3}|^2$ is the small ν_e piece of ν_3. ν_3 is at one end of Δm^2_{atm}.

∴ We need an experiment with L/E sensitive to Δm^2_{atm}, and involving ν_e.

Possibilities

Reactor $\bar{\nu}_e$ disappearance while traveling $L \sim 1$ km.

Accelerator $\nu_\mu \rightarrow \nu_e$ or $\nu_e \rightarrow \nu_\mu$ while traveling $L >$ Several hundred km.

How $\frac{\text{—}}{=}$ vs. $\frac{=}{\text{—}}$ May Be Determined

We determined that $m(K_L) > m(K_S)$ by—

- Passing kaons through matter (Regenerator)
- Beating the unknown Sign$[m(K_L) - m(K_S)]$ against the known Sign[Regeneration Amp.]

We will determine

$$\text{Sign}[m^2(\text{—}) - m^2(=)] = S$$

by—

- Passing neutrinos through matter (Earth)
- Beating the unknown sign S against the known Sign[forward $\nu_e e \to \nu_e e$ Amp.]

At superbeam energies $E \lesssim 2$ GeV,

$$\sin^2 2\theta_{13}[\text{In Earth}] \cong \sin^2 2\theta_{13}\left[1 \underset{\bar{\nu}}{\overset{\nu}{\pm}} S \frac{E}{6\,\text{GeV}}\right].$$

4.12

How ~~CP~~ in Oscillation May Be Found

Superbeams: $\nu_\mu \to \nu_e$ vs. $\bar{\nu}_\mu \to \bar{\nu}_e$

ν Factory or β Beams : $\nu_e \to \nu_\mu$ vs. $\bar{\nu}_e \to \bar{\nu}_\mu$

Complementarity

In practice, individual oscillation probabilities depend on the ~~CP~~ phase δ, on CP-conserving variables like θ_{13}, and on matter effects.

Complementary measurements will be needed to disentangle the parameters.

Planning the Future

Non-accelerator experiments, especially $0\nu\beta\beta$, have a crucial role to play.

It is highly likely that there is gold ($\not{C}\!\!\not{P}$, the character of the ν mass spectrum) in the accelerator/reactor neutrino physics hills.

We don't know how deeply one must dig to find it. This depends on θ_{13}.

A staged approach seems sensible: Reactors and gradually more powerful superbeams and detectors, and finally a neutrino factory.

The optimal strategy for uncovering the physics is still being worked out. We need to construct a coherent plan.

Can we explain to our colleagues and the public that future neutrino physics will be one program?

Every group, laboratory, funding agency, or country that contributes to a well-performed experiment, at any stage, should share credit for the eventual success of the whole program.