Seesaw/KEK
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THE OPEN NEUTRINO QUESTIONS

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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

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

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?

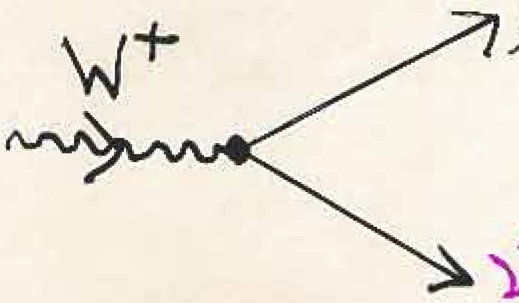
Do neutrino interactions violate CP?

Is leptonic $\cancel{CP}$ responsible for the baryon asymmetry in the universe?

Are there surprises?

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

Leptonic Mixing



l_α^+ $(l_e \equiv e,\ l_\mu \equiv \mu,\ l_\tau \equiv \tau)$

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

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

Mass eigenstate

Unitary Leptonic Mixing Matrix

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

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

What Have We Already Learned?

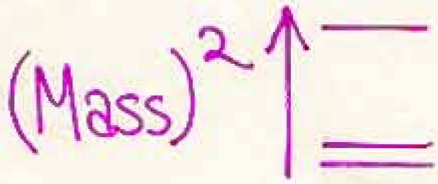
We do not know how many neutrino mass eigenstates ν_i there are.

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

The reason:

Neutrinos	Required Δm^2 (eV^2)
Solar	$10^{-(4-5)}$
Atmospheric	$\sim 10^{-3}$
LSND	~ 1

Only 3 neutrinos $\Longrightarrow$



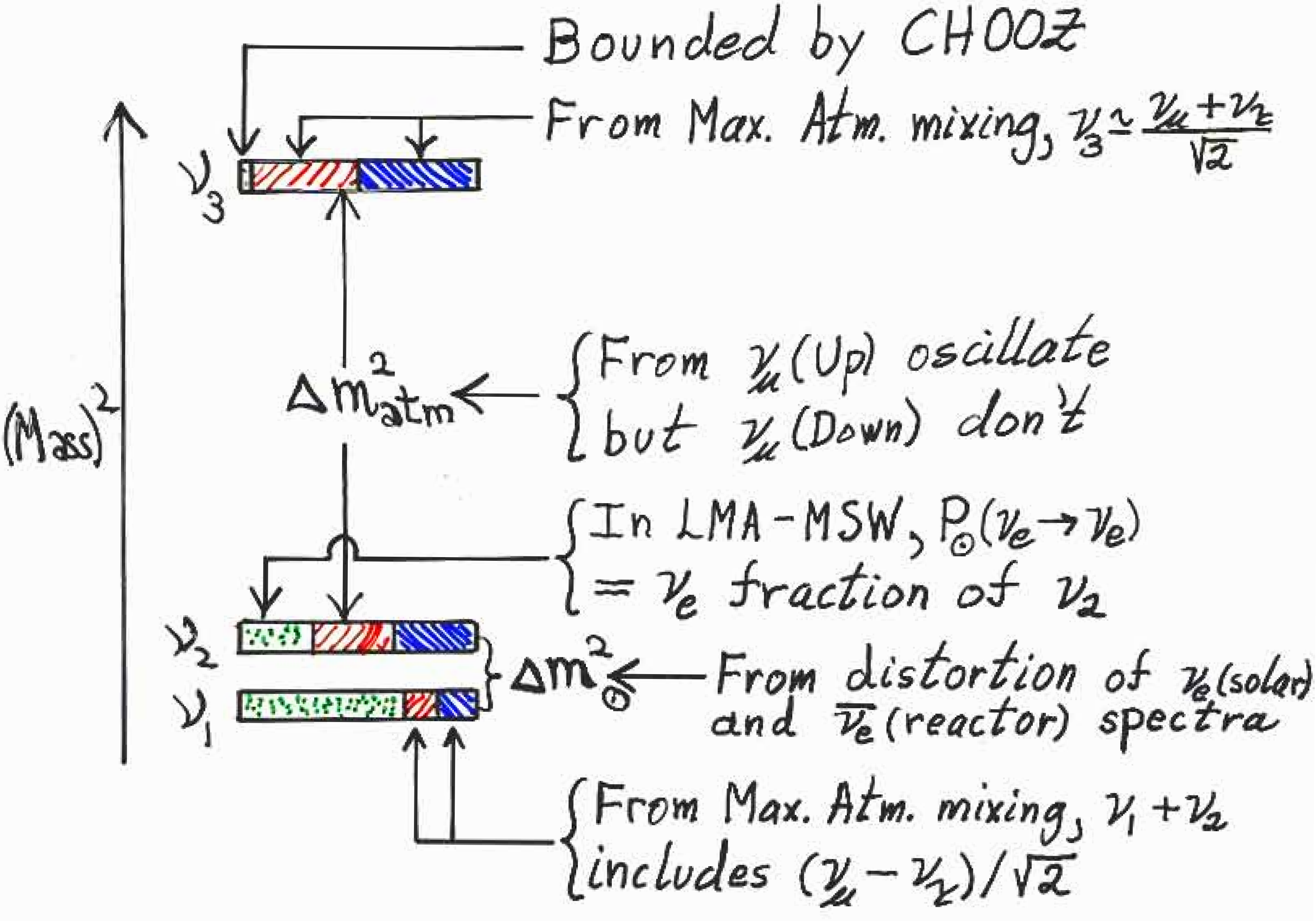
$$\Longrightarrow \quad \Delta m^2_{LSND} = \Delta m^2_{atm} + \Delta m^2_{\odot}.$$

BK

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

Then the spectrum looks like  or  .

If it is like  :



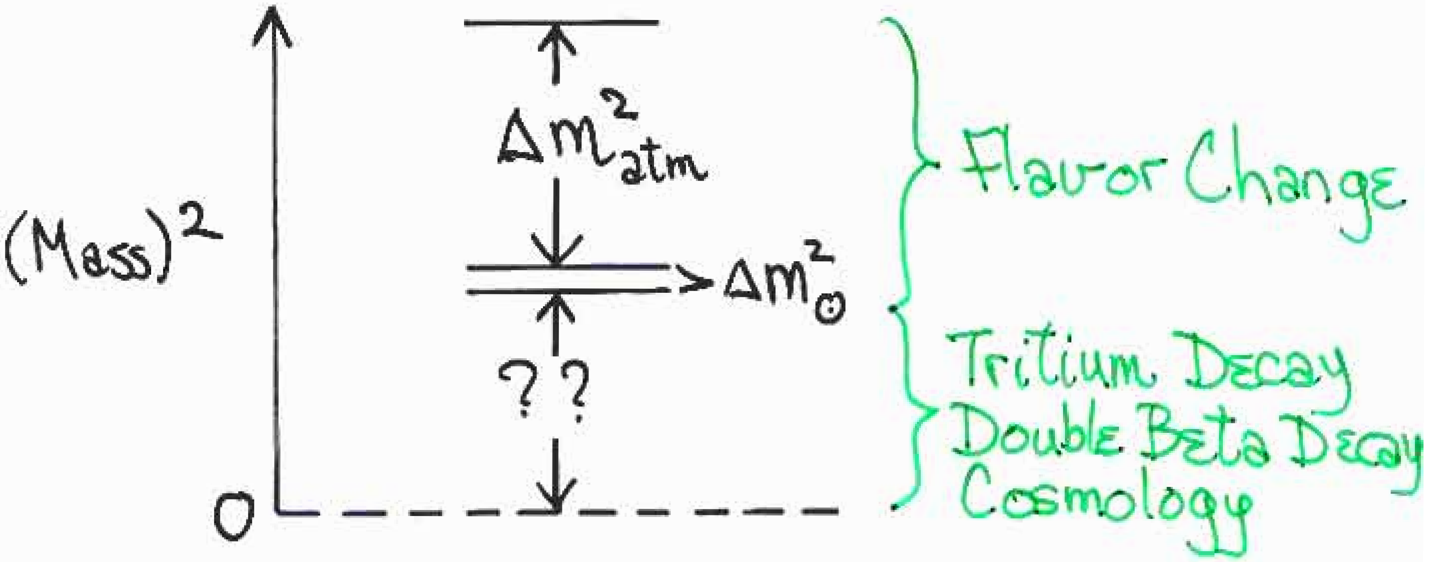
🟩 $\nu_e\,[|U_{ei}|^2]$ 🟥 $\nu_\mu\,[|U_{\mu i}|^2]$ 🟦 $\nu_\tau\,[|U_{\tau i}|^2]$

The Future — Open Questions

* 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  ?

GUTS:   : Symmetry

(Albright) (Babu & Mohapatra)

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 → Nucl′ + $2e^-$.

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

How $\overset{-}{=}$ vs. $\overset{=}{-}$ 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

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

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,

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

A Cosmic Connection

WMAP + Other Cosmological Data

+ Cosmological Assumptions

$$\Rightarrow \sum_i \underset{\underset{\text{Mass}(\nu_i)}{\uparrow}}{m_i} < 0.71 \text{ eV}.$$

(95% CL
Spergel et al.)

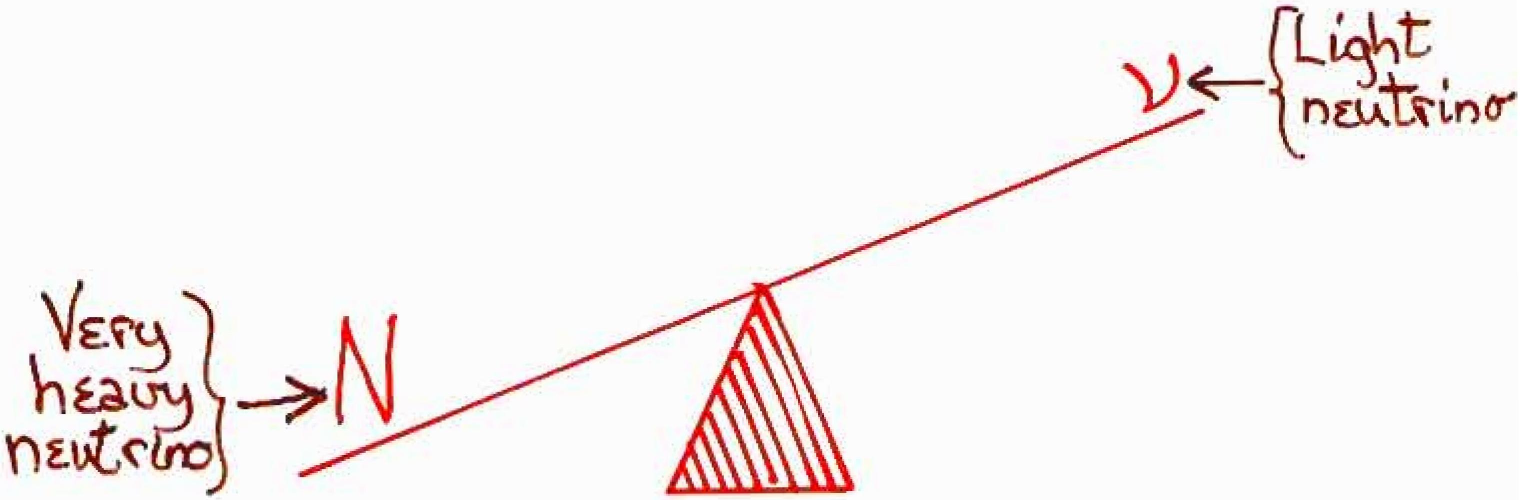
If there are only 3 neutrinos,

$$\underset{\underset{\sqrt{\Delta m^2_{atm}}}{\uparrow}}{0.04 \text{ eV}} \lesssim \text{Mass}[\text{Heaviest } \nu_i] < \underset{\underset{\text{Cosmology}}{\uparrow}}{0.23 \text{ eV}}$$

* Why are ν masses $<<$ quark and charged lepton masses?

An outstanding answer—

The See-Saw mechanism



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

(Gell-Mann, Ramond, Slansky; Yanagida)

Perhaps $\cancel{CP}$ in N decays led to the baryon asymmetry of the universe.

(Fukugita & Yanagida)

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The see-saw mechanism grows out of naturally expected

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

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

Then there is no conserved L to distinguish a mass eigenstate ν_i from $\bar{\nu}_i$, or N_i from $\bar{N}_i$. Hence —

$$\bar{\nu}_i = \nu_i$$

$$\bar{N}_i = N_i$$

Majorana Neutrinos

With this in mind —

* Is each light mass eigenstate —

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

or

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

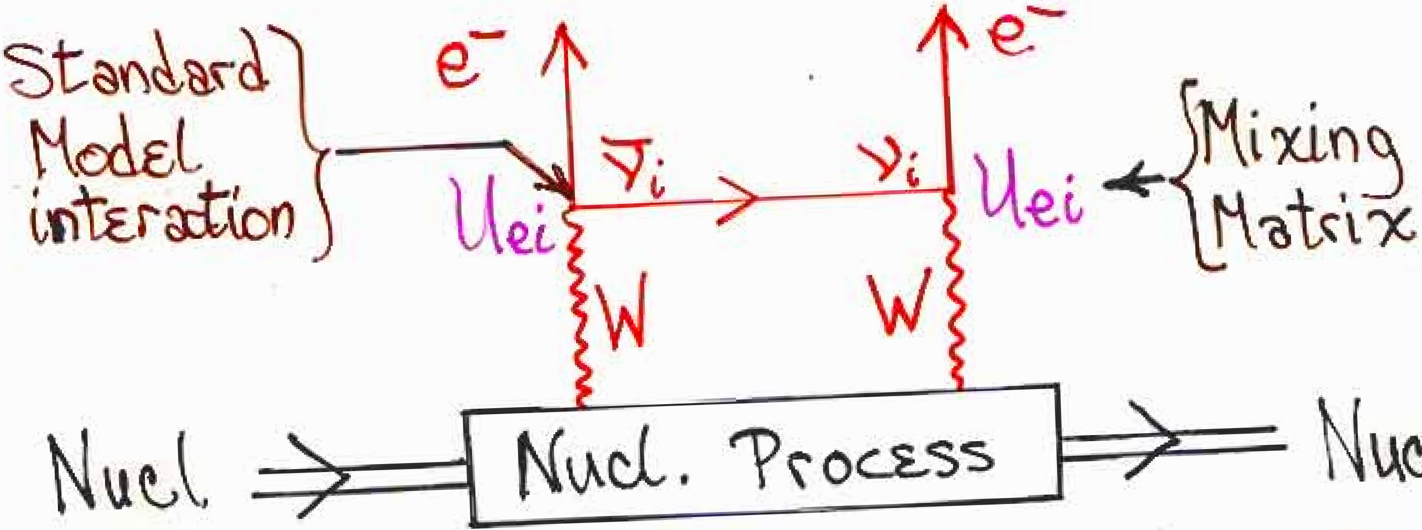
$0\nu\beta\beta$ [Nucl → Nucl′ + $2e^-$]

$\Rightarrow \cancel{L}$; $\overline{\nu}_i = \nu_i$; a Majorana mass term

Quarks and charged leptons cannot have Majorana mass terms, since $q \leftrightarrow \overline{q}$ would not conserve electric charge.

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

The dominant mechanism is expected to be—



Mass(ν_i)

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

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

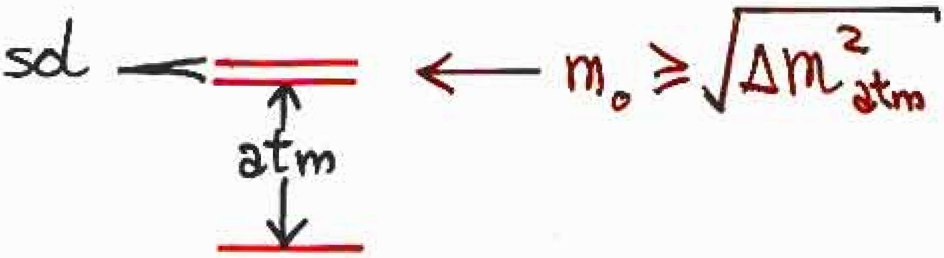
$$\text{Amp}[0\nu\beta\beta] \propto \left|\sum_i m_i U_{ei}^2\right| \equiv m_{\beta\beta}$$

$0\nu\beta\beta$ violates L. Standard Model interactions conserve L. The $\cancel{L}$ in $0\nu\beta\beta$ comes from underlying Majorana mass terms.

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

Desirable sensitivity: $m_{\beta\beta} \sim 10$ meV.

If the spectrum looks like —



then —

$$m_{\beta\beta} \geq m_0 \cos 2\,\theta_\odot \,.$$

At 90% CL,

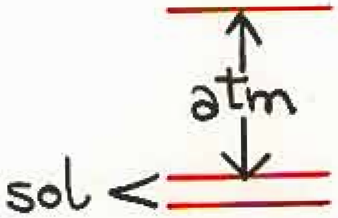
$m_0 > 43$ meV (SuperK L/E analysis)

$\cos 2\theta_\odot > 0.28$ (SNO),

so

$$m_{\beta\beta} > 12 \text{ meV} \,.$$

If the spectrum looks like —



then

$0 < m_{\beta\beta} <$ Present Bound [(0.3–1.0) 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, Murayama, Peña-Garay

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

* What is the leptonic mixing matrix $\mathcal{U}$?

For 3 neutrinos –

$$\mathcal{U} = \overset{\text{Atmospheric}}{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}} \times \overset{\text{Cross-Mixing}}{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}}$$

$$\times \underset{\text{Solar}}{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}} \times \underset{\text{Majorana } \cancel{CP} \text{ Phases}}{\begin{bmatrix} e^{i\frac{\alpha_1}{2}} & 0 & 0 \\ 0 & e^{i\frac{\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{bmatrix}}$$

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

$$\theta_{23} \simeq \theta_{atm} \quad , \quad \theta_{12} \simeq \theta_{\odot}$$

$\delta, \alpha_1, \alpha_2$ are $\cancel{CP}$ phases.

Only δ can affect neutrino oscillation.

All effects of δ depend on $\sin\theta_{13}$.

The 90% CL mixing-angle ranges—

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

(Super-K)

$$0.73 \lesssim \sin^2 2\theta_{\odot} \lesssim 0.92$$

(SNO)

$$\sin^2 2\theta_{13} \lesssim 0.2$$

(CHOOZ)

Clearly, θ_{atm} and $\theta_{\odot}$ are large, unlike any quark mixing angles.

But what is θ_{13}? How small is it??

Both $\not{C}\!\not{P}$ in oscillation and the possibility of telling  from  depend on θ_{13}.

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How Big Do We Expect θ_{13} To Be?

Sorry –

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

H.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 $\nu_\mu \to \nu_e$ or $\nu_e \to \nu_\mu$ while traveling $L >$ Several hundred km.

*Do neutrino interactions violate CP?

$$\text{Prob}(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) = \text{Prob}(\nu_\alpha \rightarrow \nu_\beta ; U \rightarrow U^*)$$

δ leads to –

$$\text{Prob}(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \underset{\uparrow\ \not{CP}}{\neq} \text{Prob}(\nu_\alpha \rightarrow \nu_\beta).$$

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.

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Nature May Surprise Us

MiniBooNE is exploring the number of neutrino species.

MiniBooNE is a Short Baseline (SBL) $\nu_\mu \to \nu_e$ oscillation search sensitive to $\Delta m^2 \gtrsim \mathcal{O}(1\,\mathrm{eV}^2)$. It seeks to confirm or refute LSND.

Most theorists today:

MiniBooNE will refute LSND.

Most theorists five years ago:

Leptonic mixing angles will prove to be small.

Suppose MiniBooNE Sees a $\nu_\mu \to \nu_e$ Signal

(B.K. & S.Parke)

There will be questions to answer, such as —

- * Is the $\nu_\mu \to \nu_e$ signal consistent with the LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal?

- * How many large oscillation frequencies Δm^2 are involved? Just one ($4\nu_i$), or more ($>4\nu_i$)?

There will be implications for the Long Baseline (LBL) and reactor experiments:

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LBL $\nu_\mu \to \nu_e$ experiments may see oscillation coming from both Δm^2_{atm} and Δm^2_{LSND}.

Reactor $\bar{\nu}_e$ disappearance experiments sensitive to Δm^2_{atm} effects may see disappearance due to Δm^2_{LSND} as well.

If there are N mass eigenstates ν_i —

- U is $N \times N$
- There are $N-1$ independent $\Delta m^2_{ij} \equiv m_i^2 - m_j^2$

Implications for $\cancel{CP}$

$\cancel{CP}$ in ν oscillation requires at least 3 nondegenerate ν_i.

When there are only 3 ν_i, $\cancel{CP} \propto \Delta m^2_\odot$.

When there are 4 ν_i, there are new $\cancel{CP}$ effects that remain even when $\Delta m^2_\odot \longrightarrow 0$.

Where are these new effects most significant?

Suppose there are 4 ν_i.

If we neglect $m_2^2 - m_1^2 \equiv \Delta m_\odot^2$ and small matter effects,

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) = 4\Big\{ |U_{\mu 4} U_{e4}|^2 \sin^2\Delta_{41} + |U_{\mu 3} U_{e3}|^2 \sin^2\Delta_{31}$$

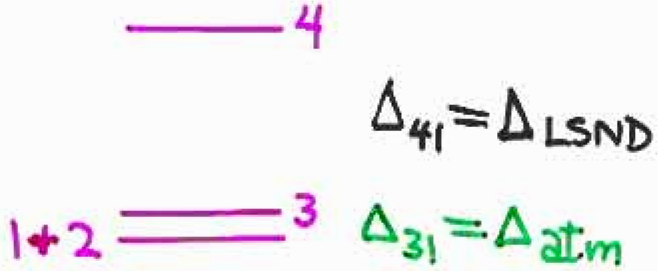
$$+ 2|U_{\mu 4} U_{e4} U_{\mu 3} U_{e3}| \sin\Delta_{41} \sin\Delta_{31} \cos\Delta_{43} \cos\delta_{CP}$$

$$\overset{(-)}{+} 2|U_{\mu 4} U_{e4} U_{\mu 3} U_{e3}| \sin\Delta_{41} \sin\Delta_{31} \sin\Delta_{43} \sin\delta_{CP} \Big\}.$$

Here,

$\Delta_{ij} \equiv \Delta m_{ij}^2 \frac{L}{4E}$ and $\delta_{CP} \equiv \arg(U_{\mu 4} U_{e4}^* U_{\mu 3}^* U_{e3})$.

Example: 3+1



The CP-odd term is maximal, and potentially quite significant, where

$$\Delta_{atm} = \Delta_{31} = \frac{\pi}{4}.$$

$$-2 \langle \sin\Delta_{41} \sin\Delta_{31} \sin\Delta_{43} \rangle_E \sin\delta_{CP}$$

$$= -\frac{1}{2} \langle \sin 2\Delta_{43} + \sin 2\Delta_{31} - \sin 2\Delta_{41} \rangle_E \sin\delta_{CP}$$

$$\cong -\frac{1}{2} \sin\delta_{CP} \quad \text{at } \Delta_{31} = \frac{\pi}{4}.$$

Practical considerations such as the $\sim \frac{1}{L^2}$ falling of beam fluxes may make another point a better place to work.

Inspired by the exciting discoveries in neutrino physics,

But keenly aware of the need for a coherent plan for the future,

The American Physical Society Divisions of —

- Particles and Fields
- Nuclear Physics
- Astrophysics
- Physics of Beams

are sponsoring a year-long

STUDY OF THE PHYSICS OF NEUTRINOS

Background information at: www.neutrinooscillation.org/studyaps/

The Structure of the Study

Chairmen

Stuart Freedman, Boris Kayser

Organizing Committee

Janet Conrad, Guido Drexlin,
Belen Gavela, Takaaki Kajita,
Paul Langacker, Keith Olive,
Bob Palmer, Georg Raffelt,
Hamish Robertson, Stan Wojcicki
Lincoln Wolfenstein

Working Groups — The Central Element

Each working group is defined by an experimental approach.

The groups and their leaders —

Solar and Atmospheric Neutrino Experiments

John Bahcall <jnb@ias.edu>, Josh Klein <jrk@physics.utexas.edu>

Reactor Neutrino Experiments

Gabriela Barenboim <gabriela@fnal.gov>, Ed Blucher <blucher@hep.uchicago.edu>

Superbeam Experiments and Development

Bill Marciano <marciano@bnl.gov>, Doug Michael <michael@hep.caltech.edu>

Neutrino Factory and Beta Beam Experiments and Development

Stephen Geer <sgeer@fnal.gov>, Michael Zisman <mszisman@lbl.gov>

Neutrinoless Double Beta Decay and Direct Searches for Neutrino Mass

Steve Elliott <elliotts@lanl.gov>, Petr Vogel <pxv@caltech.edu>

What Cosmology/Astrophysics and Neutrino Physics can Teach Each Other

Steve Barwick <barwick@HEP.ps.uci.edu>, John Beacom <beacom@fnal.gov>

Theorists participate in all working groups.

They will also discuss issues like how best to use future measurements to discriminate among theoretical models.

Coordinator of theoretical discussions:

Rabi Mohapatra <rmohapat@physics.umd.edu>

International participation in the study is warmly encouraged!

To join any working group, just contact its leaders.

Contact information at —

home.fnal.gov/~boris/NeutrinoStudy2.ppt

Summary

The discovery of ν mass and mixing has raised very interesting questions.

Let's go answer them!