ICHEP 2000
Osaka
July 28, 2000

Neutrino Mass: The Present and the Future

Boris Kayser

NEUTRINO MASS

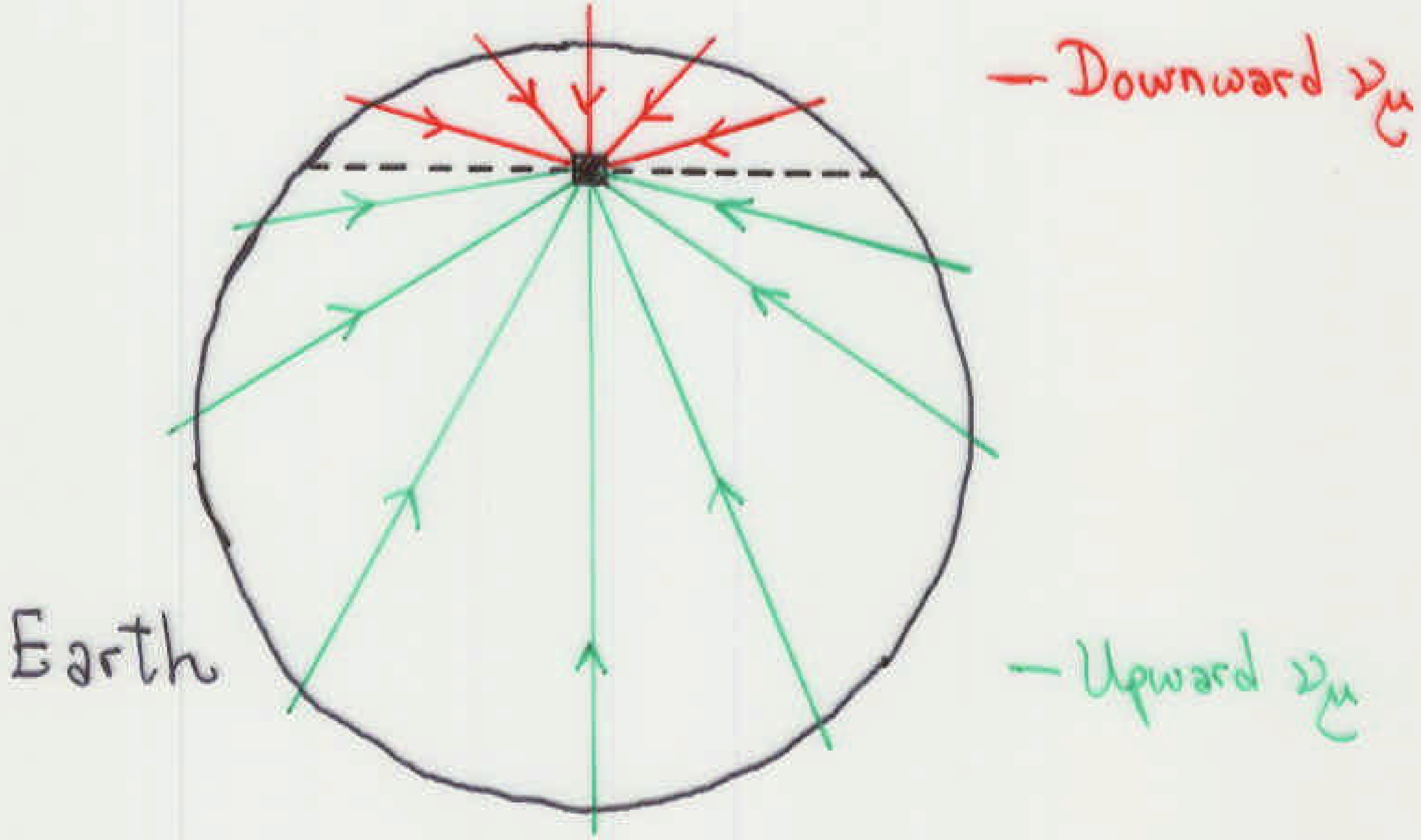
Where Do We Stand?

What Would We Like To Learn?

Do neutrinos have masses?

Almost certainly!

The most compelling single piece of evidence is the Up/Down asymmetry of the atmospheric ν_μ flux.

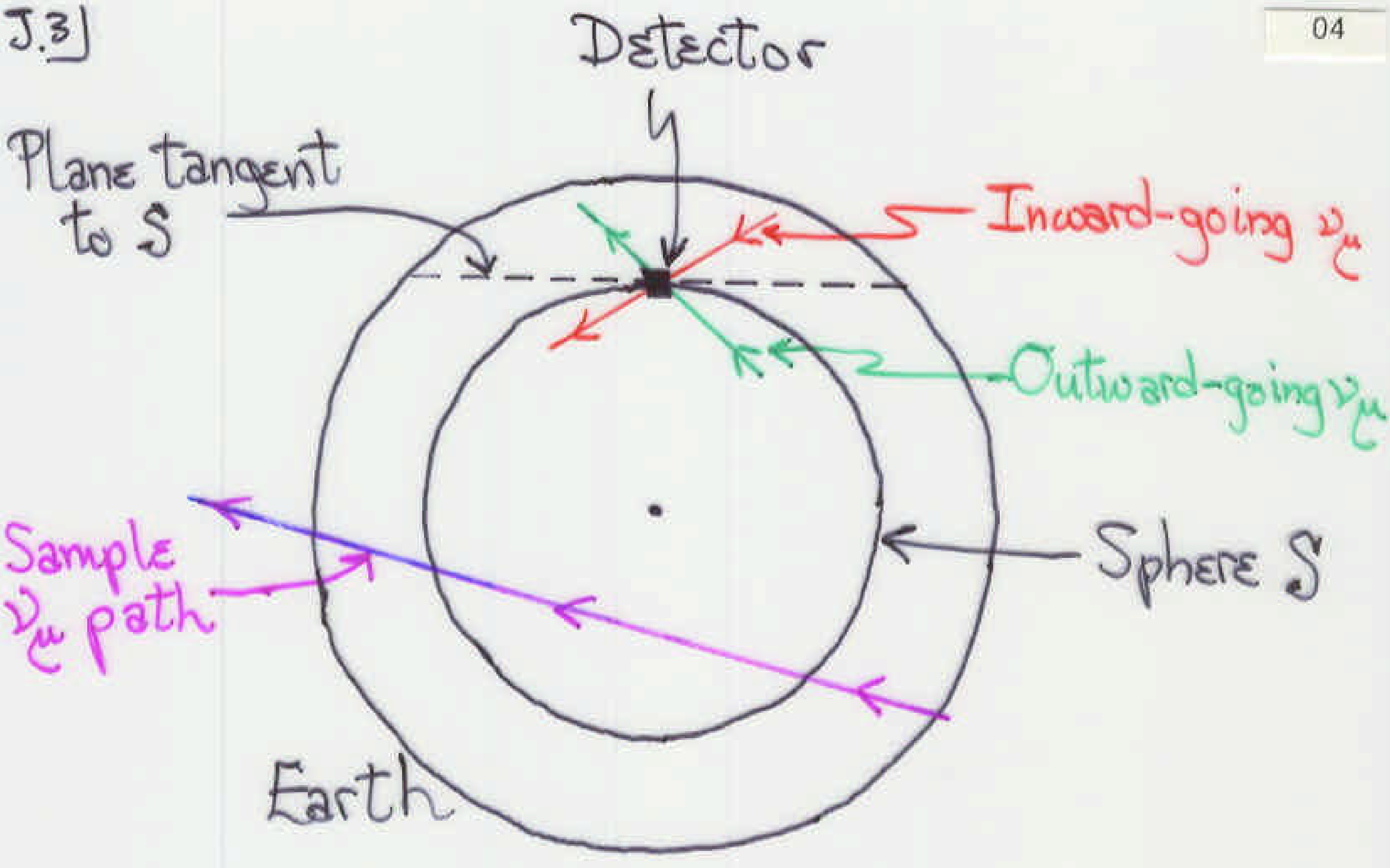


For $E_\nu >$ A few GeV, the flux of cosmic rays that produce ν_{Atmos} is isotropic.

Suppose nothing increases or decreases the atmospheric ν_μ flux during earth traversal.

Then, for $E_\nu >$ A few GeV, we must have

ν_μ Flux Down $\cong$ ν_μ Flux Up.



Any ν_μ that enters S later exits S.

∴ In a steady state—

Total ν_μ flux into S = Total ν_μ flux out of S.

Cosmic-ray isotropy ⇒ Spherical symmetry.

⇒ At each point of S—

ν_μ flux into S = ν_μ flux out of S

∴ ν_μ Flux Down = ν_μ Flux Up

With just a bit more work—

$$\nu_\mu \text{ Flux}(\theta_z) = \nu_\mu \text{ Flux}(\pi - \theta_z).$$

SuperK Down vs. Up

Down : $+0.2 < \cos\theta_z < +1.0$

Up : $-1.0 < \cos\theta_z < -0.2$

In the Multi-GeV data,

$$\frac{\nu_\mu(\text{Up})}{\nu_\mu(\text{Down})} = 0.56 \pm 0.05.$$

(Kearns)

Something is adding or removing muon neutrinos within the earth.

$\nu_\mu \rightarrow \nu_?$ oscillation

is the most attractive hypothesis.

Neutrino oscillation, which implies neutrino mass (or extra dimensions?) fits the ν_{Atmos} data in detail.

Neutrino decay, which also implies neutrino mass, also fits the ν_{Atmos} data.
(Barger, Learned, Lipari, Lusignoli, Pakvasa, Weiler)

Decay is theoretically less likely than oscillation.

Both the oscillation and decay explanations of the data imply neutrino mass and neutrino mixing.

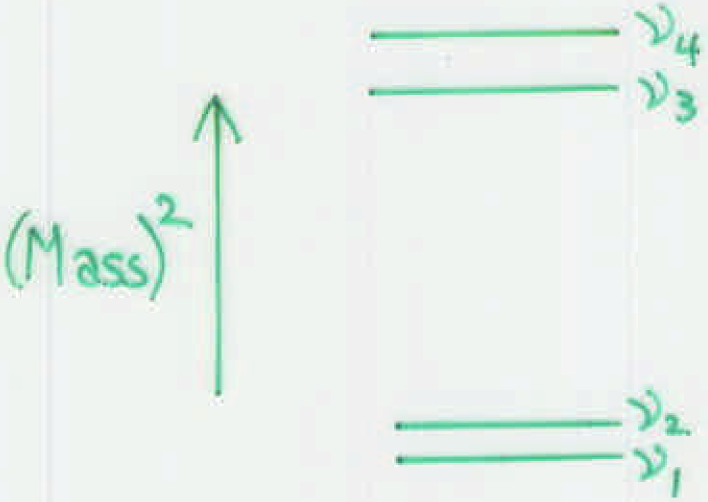
Further Evidence for Neutrino Oscillation

Neutrinos	Evidence of Oscillation
Solar	Strong
LSND	Unconfirmed

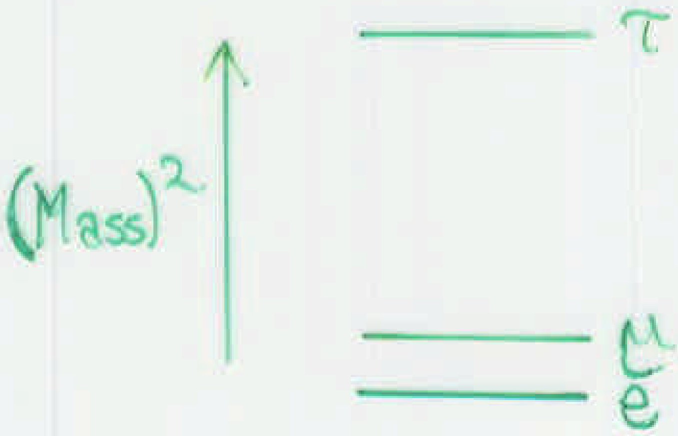
In view of the evidence for oscillation—

Neutrinos almost certainly have masses and mix.

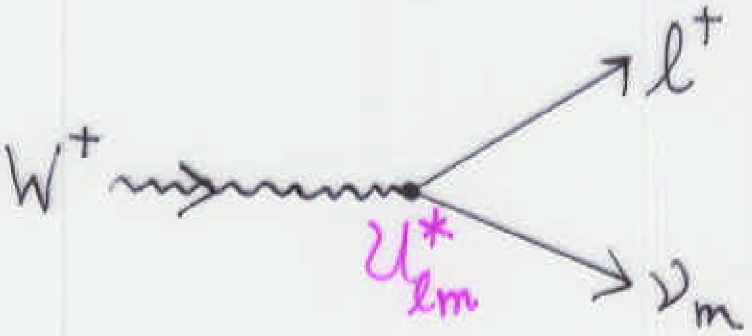
There is some spectrum of three or more neutrino mass eigenstates ν_m:



This is the neutrino analogue of the spectrum of charged-lepton mass eigenstates $\ell = e, \mu$, and τ:



2) Mixing means that the weak interaction couples a given charged lepton of definite mass, ℓ, to more than one neutrino of definite mass, ν_m.



U is the Maki-Nakagawa-Sakata leptonic mixing matrix.

The neutrino state produced in association with a specific charged lepton ℓ is

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

Neutrino of flavor ℓ

Neutrino of mass M_m

3) If there are, say, four neutrino mass eigenstates, then one linear combination of them,

$$|\nu_{\text{sterile}}\rangle = \sum_m U^*_{sm} |\nu_m\rangle,$$

has no normal weak couplings.

Having discovered that neutrinos have masses and mix —

What Would We Like To Learn?

- How many neutrino flavors, active and sterile, are there? Equivalently, how many neutrino mass eigenstates are there?
- What are the masses, M_m, of the mass eigenstates, ν_m?

(Oscillation experiments can measure only mass splittings $\delta M^2_{mm'} \equiv M^2_m - M^2_{m'}$.)

4)

- Are the neutrinos of definite mass—

  * Majorana particles ($\bar{\nu}_m = \nu_m$),

  or

  * Dirac particles ($\bar{\nu}_m \neq \nu_m$)?

- What are the elements $U_{\ell m}$ of the leptonic mixing matrix?

- Does the behavior of neutrinos, in oscillation and other contexts, violate CP invariance?

- What are the electromagnetic properties of neutrinos? What are their dipole moments?

- What are the lifetimes of the neutrinos?

5

What is Known Now About These Questions, and How Will We Learn More?

How Many Neutrinos Are There?

Most people believe that if $\nu_\odot$, ν_{Atmos}, and ν_{LSND} all oscillate, then there are more than 3 neutrinos:

3 neutrinos can fit $\nu_\odot$, ν_{Atmos}, and ν_{LSND}:

Teshima, Sakai, Inagaki
Thun & McKee
Barenboim & Scheck
Ohlsson & Snellman
Haug, Faessler, Vergados

No they can't:
Giunti

6) With only 3 neutrino mass eigenstates,

$$\sum \delta M^2 = (M_3^2 - M_2^2) + (M_2^2 - M_1^2) + (M_1^2 - M_3^2) = 0.$$

But–

Oscillating Neutrinos	Required $\lvert \delta M^2 \rvert$ (eV^2)
Solar	10^{-10} to 10^{-4}
Atmospheric	10^{-3}
LSND	1
	$\sum \delta M^2 \neq 0$

∴ Must add a 4th mass eigenstate.

Since $Z \to \nu_\ell \bar{\nu}_\ell$ yields only 3 distinct neutrinos of definite flavor, the 4 flavor eigenstates corresponding to the 4 mass eigenstates must be —

$$\nu_e\,,\ \nu_\mu\,,\ \nu_\tau\,,\ \nu_{\text{sterile}}\,.$$

Solar + Atmospheric + LSND Oscillations

$\Rightarrow$ A new breed of neutrino.

7]

How Much Do the Mass Eigenstates Weigh?

Oscillation experiments yield only $(\text{mass})^2$ splittings:

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

Some viable relative $(\text{mass})^2$ spectra ⟶

Studies of the β energy spectrum in

$$^3H \to {}^3He + e^- + \bar{\nu}$$

may not be able to gain sensitivity to

$$M_m \lesssim 1\ \mathrm{eV}\ .$$

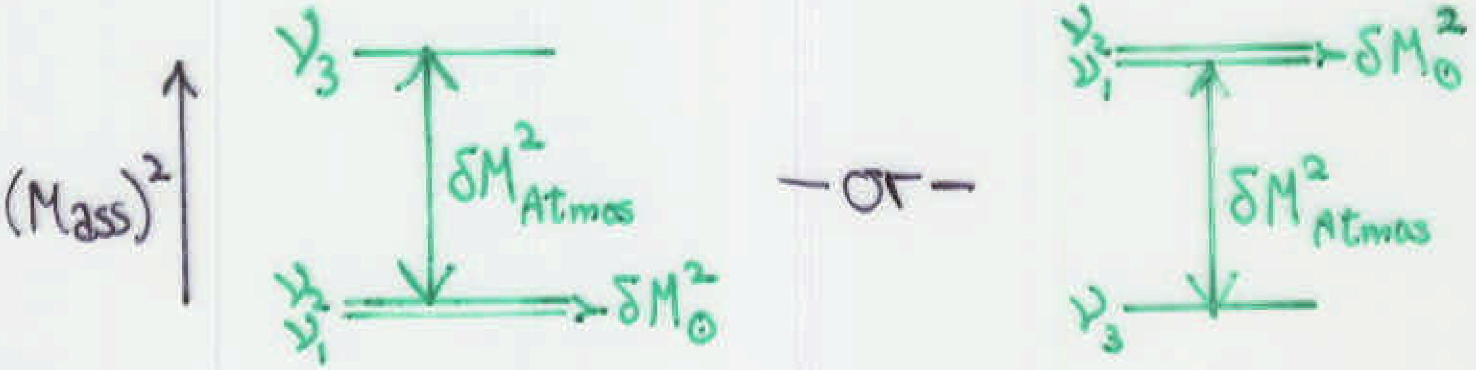
(Otten)

There may be a mass eigenstate that weighs this much.

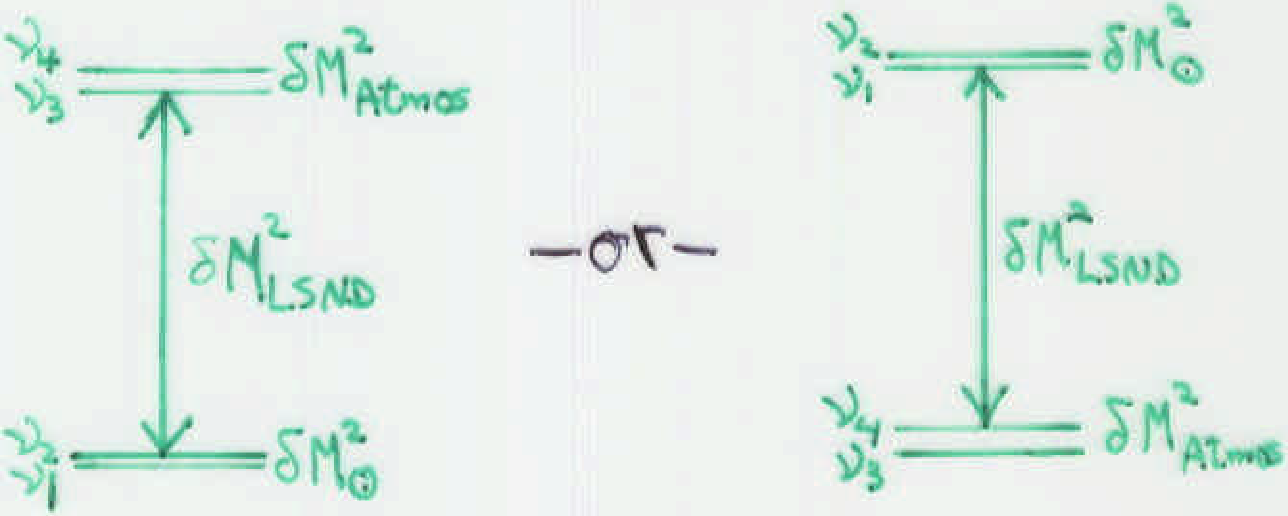
If the LSND oscillation is genuine, there is at least one neutrino ν_H with mass

$$M_H \geq \sqrt{\delta M^2_{LSND}} \gtrsim \sqrt{0.2\ \mathrm{eV}^2} \approx 0.4\ \mathrm{eV}.$$

If LSND is set aside



If LSND is included



Each mass eigenstate is a superposition of ν_e, ν_μ, ν_τ, and, in the 4-neutrino case, $\nu_{sterile}$.

0.6] Some analyses suggest these are the only 4-neutrino spectra allowed by all the data.

(Barger, Pakvasa, Weiler, Whisnant)
(Bilenky, Giunti, Grimus, Schwetz)

In these 4-neutrino spectra, ν_{Sterile} must play a significant role in either the $\nu_\odot$ or ν_{Atmos} oscillation.

SuperK analyses disfavor a dominant ν_{Sterile} role in either $\nu_\odot$ or ν_{Atmos} oscillation.

Implications ??

8) $BR({}^3H \to {}^3He + e^- + \bar{\nu}_H) \sim |U_{eH}|^2$

may be Large or small.*

If the LSND oscillation is not genuine, the heaviest mass eigenstate may have a mass no larger than

$$\sqrt{\delta M^2_{Atmos}} \sim \sqrt{3\times 10^{-3}\,eV^2} \sim 0.06\,eV.$$

It is important to study tritium decay, but is there a more sensitive probe of absolute masses??

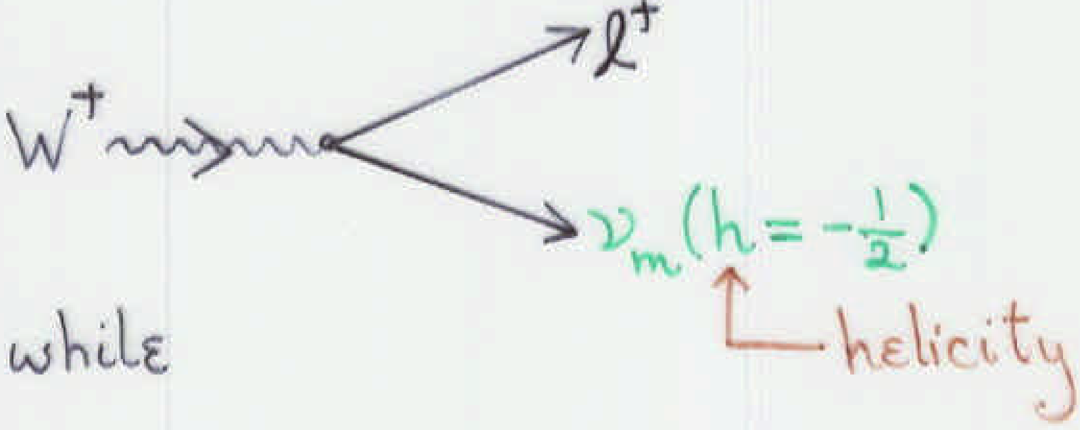
Neutrinoless double beta decay can perhaps shed light on neutrino masses, as we shall see.

---

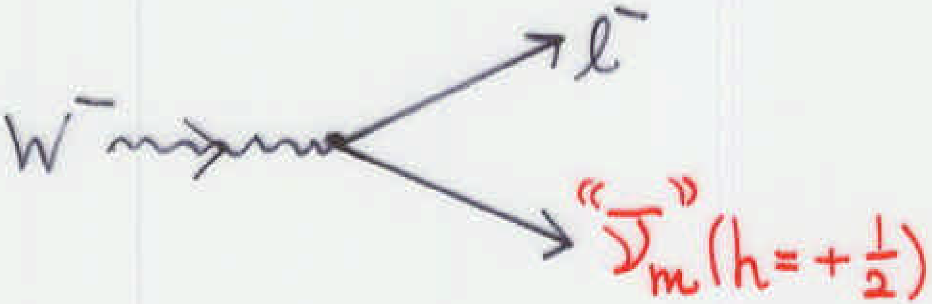
* Studies of supernova neutrinos may be able to probe ~ few eV masses of neutrinos strongly coupled to μ or τ. (Beacom, Boyd, Mezzacappa)

Does $\bar{\nu}_m = \nu_m$?

What does this question mean?



while



Is helicity the only difference between $\nu_m(h=-)$ and $\bar{\nu}_m(h=+)$?

Would a $\bar{\nu}_m(h=+)$ become a $\nu_m(h=-)$ if we could somehow reverse its helicity?

If so, then

$$\bar{\nu}_m(h) = \nu_m(h).$$

Majorana
neutrino

However, $\bar{\nu}_m(h=+)$ and $\nu_m(h=-)$ may differ by a conserved quantum number (usually the lepton number L), in addition to having opposite helicity.

If they do have this added difference, then

$$\bar{\nu}_m(h) \neq \nu_m(h).$$

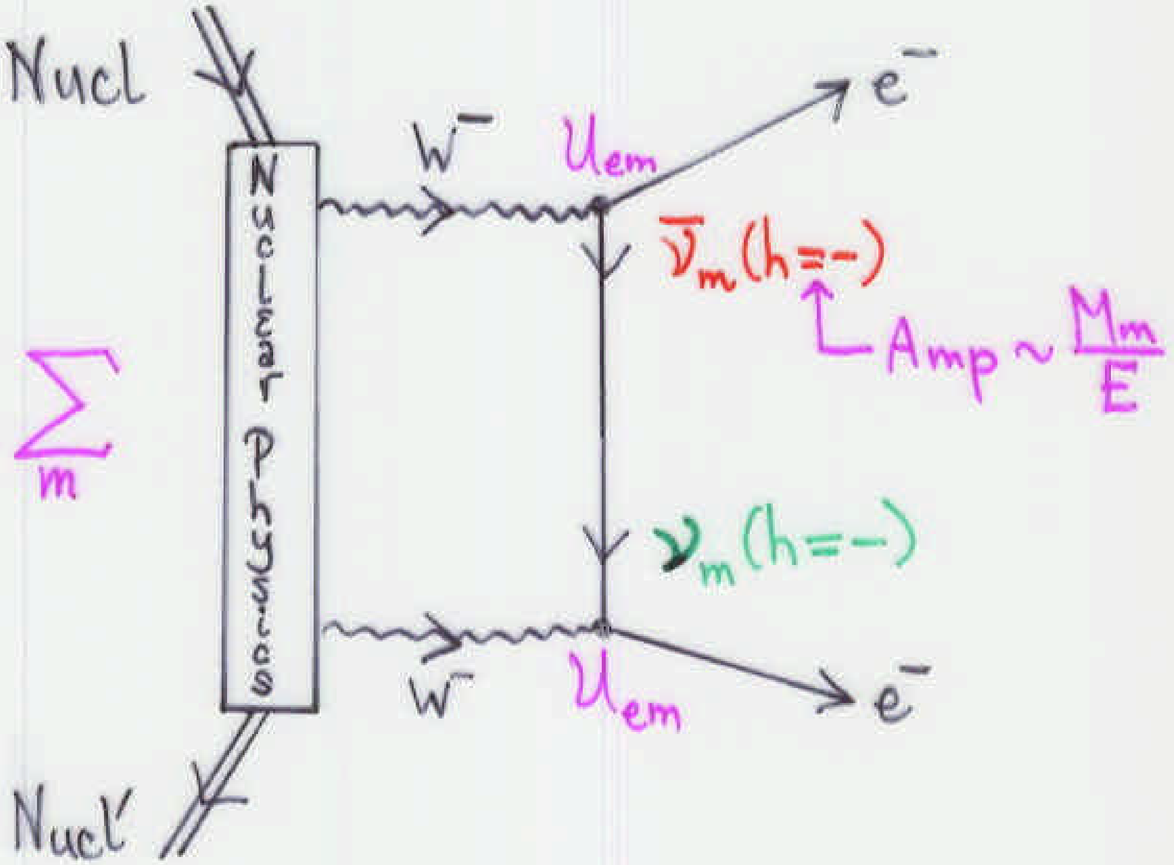
Dirac
neutrino

The "see-saw" explanation of why neutrinos are so light predicts that they are Majorana particles.

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

III To try to show that neutrinos are Majorana particles, look for neutrinoless double beta decay ($\beta\beta_{0\nu}$):

$$\text{Nucl} \rightarrow \text{Nucl}' + 2e^-.$$



Iff $\bar{\nu}_m(h) = \nu_m(h)$,

$$\text{Amp}[\beta\beta_{0\nu}] = \underbrace{\left(\sum_m M_m U_{em}^2\right)}_{M_{\beta\beta}} \times (\text{Nuclear Factor}).$$

13

What Are the Mixing Matrix Elements $U_{\ell m}$?

With L = distance a neutrino travels,
and E = neutrino energy,

the oscillation probability is

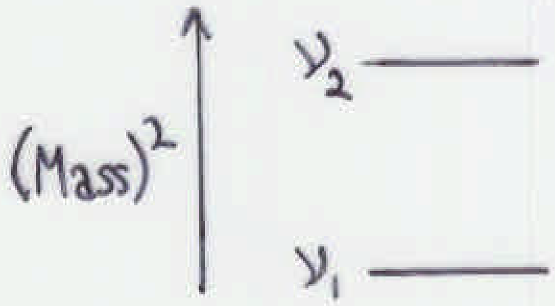
$$P(\overset{(-)}{\nu}_{\ell} \rightarrow \overset{(-)}{\nu}_{\ell'}) =$$

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

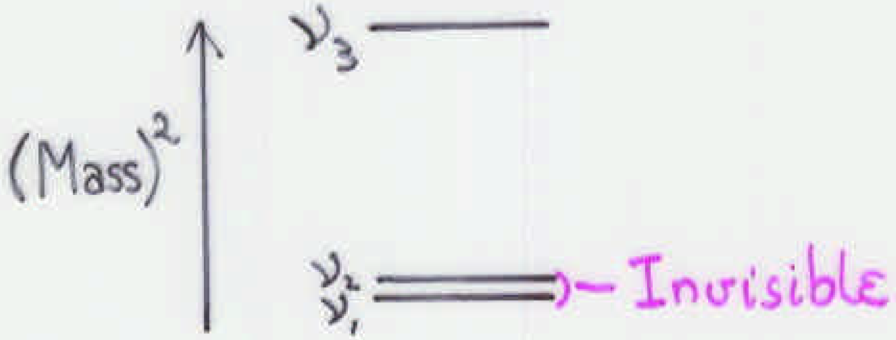
$$\pm 2 \sum_{m>m'} \mathrm{Im}(U^*_{\ell m} U_{\ell' m} U_{\ell m'} U^*_{\ell' m'}) \sin\left(\delta M^2_{mm'} \frac{L}{2E}\right).$$

Complex phases in U can lead to $\not{CP}$.

Oscillation involving only 2 neutrinos



or effectively 2 neutrinos



depends only on the sizes of the $\mathcal{U}_{\ell m}$.

Sizes $|\mathcal{U}_{\ell m}|$ can be determined this way.

Phases of combinations of $\mathcal{U}$ elements could be determined from the $\cancel{CP}$ asymmetries

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

Possible $\not{CP}$ Phases in $\mathcal{U}$

Number of Neutrinos	Universal	Majorana (Only if $\bar{\nu}_m = \nu_m$)
2	0	1
3	1	2
4	3	3

Why extra phases when $\bar{\nu}_m = \nu_m$?

Because then

$$\text{Charge conjugate}(\nu_m) \equiv \gamma_2 \nu_m^* = \nu_m,$$

so phases cannot be removed from $\mathcal{U}$ by phase-redefining ν_m.

$\not{C}\not{P}$ Phases	Affect ν Oscillation	Affect $\beta\beta_{0\nu}$
Universal	Yes	No
Majorana	No	Yes

If there are only 3 neutrinos, then, with $P(\nu_\ell \to \nu_{\ell'}) - P(\bar{\nu}_\ell \to \bar{\nu}_{\ell'}) \equiv \Delta_{\not{C}\not{P}}(\ell\ell')$,

$$\Delta_{\not{C}\not{P}}(e\mu) = \Delta_{\not{C}\not{P}}(\mu\tau) = \Delta_{\not{C}\not{P}}(\tau e)$$
$$= 16\, J s_{12} s_{23} s_{31} ,$$

where

$$J \equiv \mathrm{Im}(U_{e1} U_{e2}^* U_{\mu 1}^* U_{\mu 2}) ,$$

and

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

Life is simple, but hard.

Authors who have discussed $\not{CP}$:
Arafune & Sato; Bernabeu; Dick, Freund, Lindner, Romanino; Fisher, B.K., McFarland; Gago, Pleitez, Funchal; Schubert; Many Others.

What Can $\beta\beta_{0\nu}$ Teach Us?

From a measured $\tau_{\beta\beta_{0\nu}}$ and a calculated nuclear matrix element, we would know

$$M_{\beta\beta} \equiv \sum_m M_m \mathcal{U}_{em}^2 .$$

$M_{\beta\beta}$ is a different combination of neutrino masses than those measured in neutrino oscillation.

$M_{\beta\beta}$ could test mass spectra suggested by oscillation.

$|M_{\beta\beta}| \gtrsim 0.03$ eV would exclude:

- The 3-neutrino mass hierarchy:

- The 4-neutrino spectrum with $\delta M^2_\odot$ on the bottom

In the 4-neutrino spectrum with $\delta M^2_\odot$ on the top,

$$|M_{\beta\beta}| = \sqrt{\delta M^2_{LSND}}\,\sqrt{1 - \sin^2 2\theta_\odot \sin^2 \alpha_{CP}}\ ,$$

where

$\theta_\odot$ = the mixing angle for $\nu_\odot$ oscillation,

and

α_{CP} = a Majorana $\cancel{CP}$ phase in $\mathcal{U}$.

(Barger, Whisnant; Bilenky, Giunti, Grimus, B.K., Petcov; Klapdor-Kleingrothaus, Päs, Smirnov)

C)

Conclusion

We are just beginning to learn-

- How many neutrinos there are
- How much they weigh
- Their nature
- Their couplings $\mathcal{U}^*_{\ell m}$ to the W boson

In neutrino physics, interesting years lie ahead.