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Neutrino Properties

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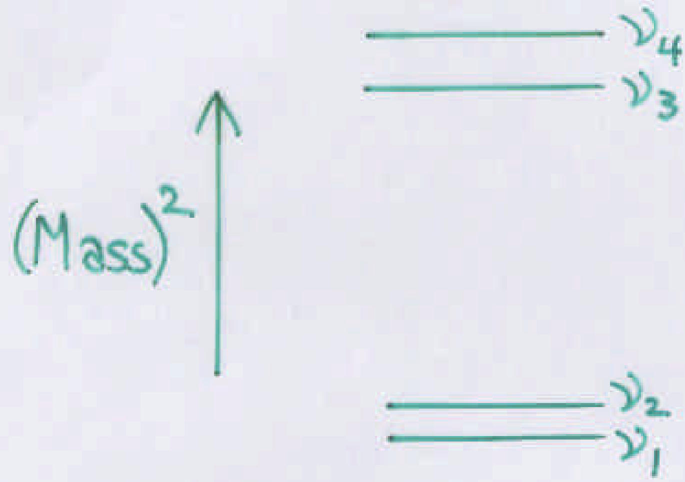
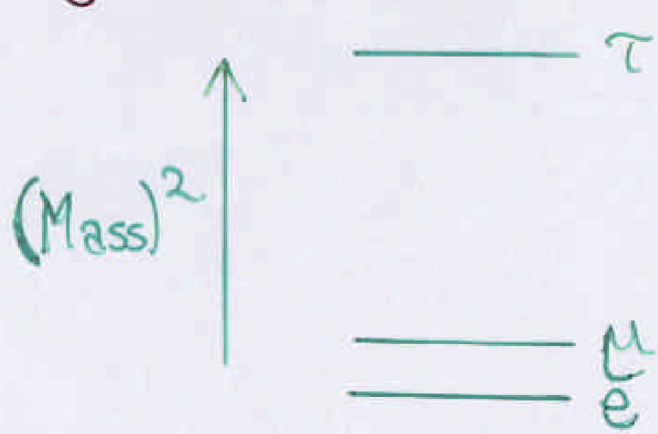
NEUTRINO PROPERTIES

Neutrinos almost certainly have masses and mix.

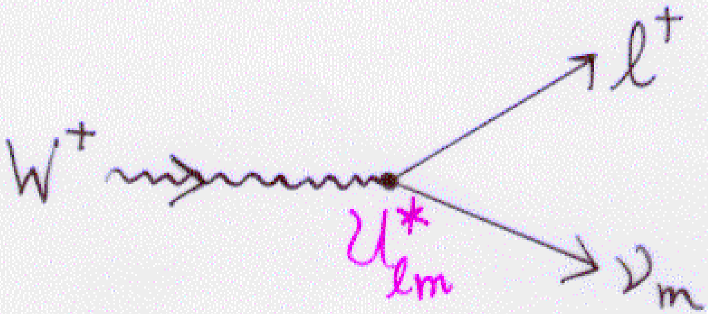
There is some spectrum of three or more neutrino mass eigenstates ν_m:



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

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

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

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 $\delta M^2_{mm'} \equiv M^2_m - M^2_{m'}$.)

- 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?

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} or 10^{-5}
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.

How Much Do the Mass Eigenstates Weigh?

Oscillation experiments yield only (mass)^2 splittings:

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

Suggested relative (mass)^2 spectra: Smirnov

Studies of the β energy spectrum in

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

may not be able to gain sensitivity to

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

(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

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

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

may be large or small.*

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

$$\sqrt{\delta M^2_{Atmos}} \sim \sqrt{4\times 10^{-3}\, eV^2} \sim 0.06\ eV.$$

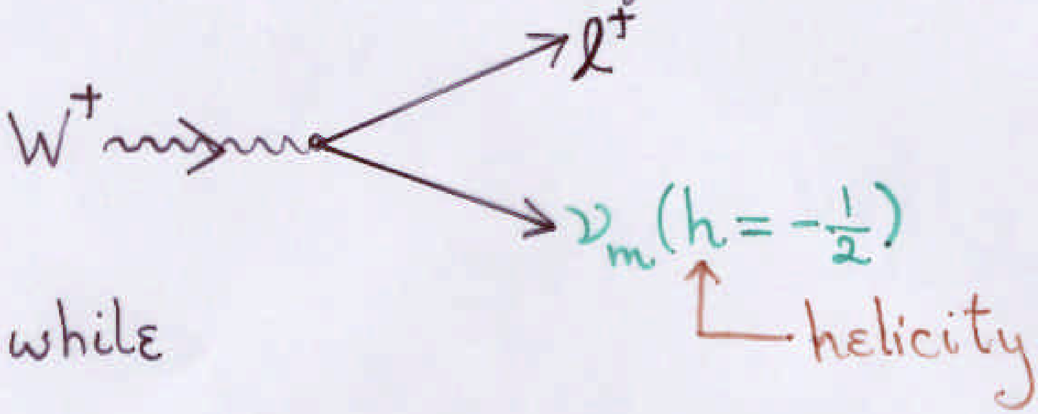
It is important to study tritium decay, but is there a more sensitive probe of absolute masses??

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

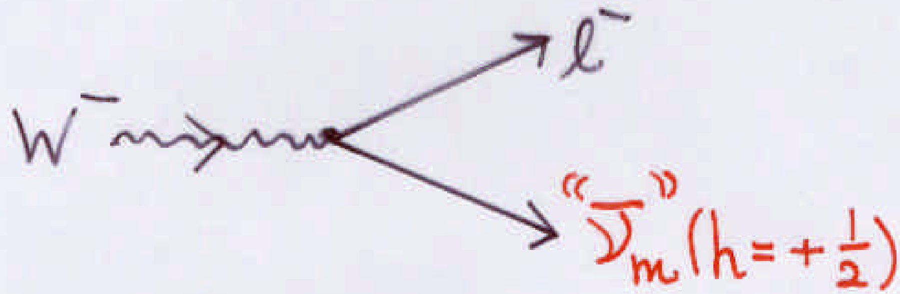
* Studies of supernova neutrinos may be able to probe ~ few eV masses of neutrinos strongly coupled to μ or τ. (Beacom, Boyd, Mezzacappa)

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?

10| 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

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

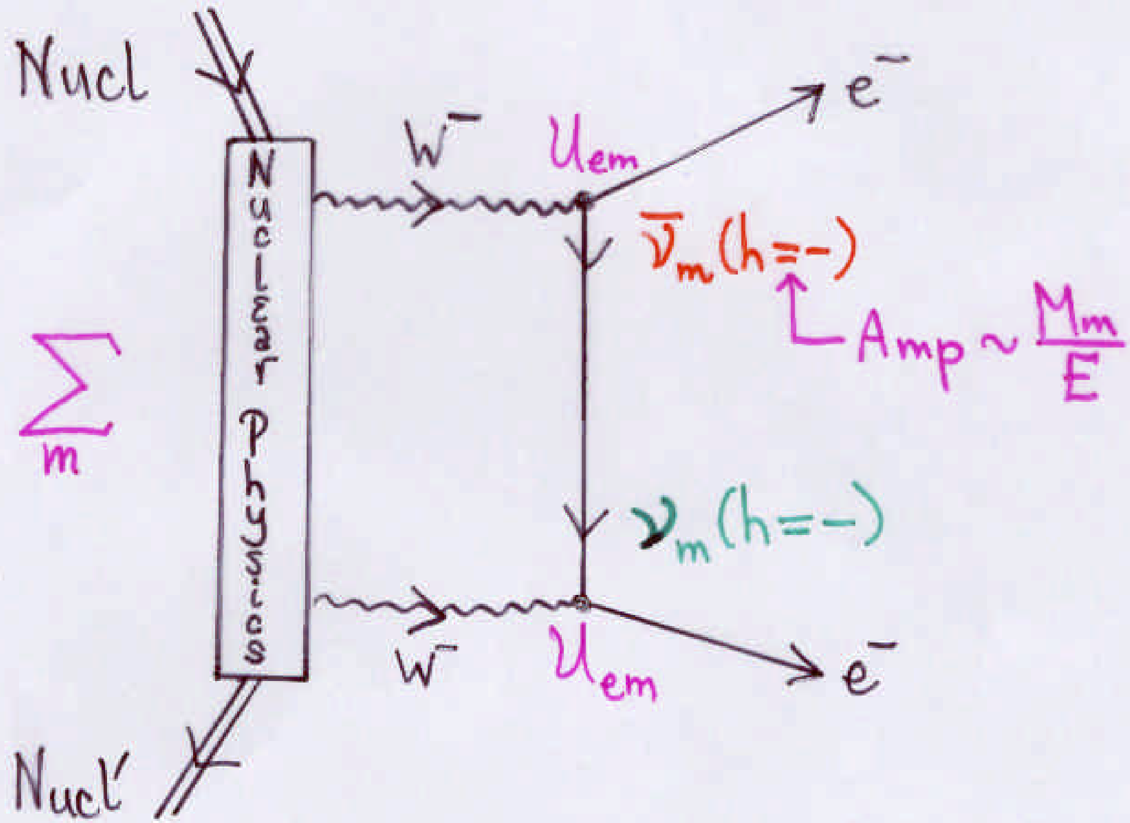
Dirac neutrino

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

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

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

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



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

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

12 Can we distinguish between Majorana and Dirac neutrinos via—

Probability

$$P[\nu_\ell(RH) \to \nu_\ell(RH)] = P[\nu_\ell(LH) \to \nu_\ell(LH)] \quad \text{Majorana}$$

but

$$P[\bar{\nu}_\ell(RH) \to \bar{\nu}_\ell(RH)] \neq P[\nu_\ell(LH) \to \nu_\ell(LH)] \quad \text{Dirac}$$

in a constant magnetic field?

(Balaji & Grimus)

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

With L = distance a neutrino travels,
and E = neutrino energy,
the oscillation probability is

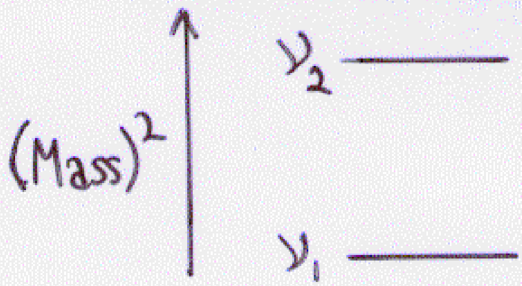
$$P(\overset{(-)}{\nu}_{\ell} \rightarrow \overset{(-)}{\nu}_{\ell'}) =$$

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

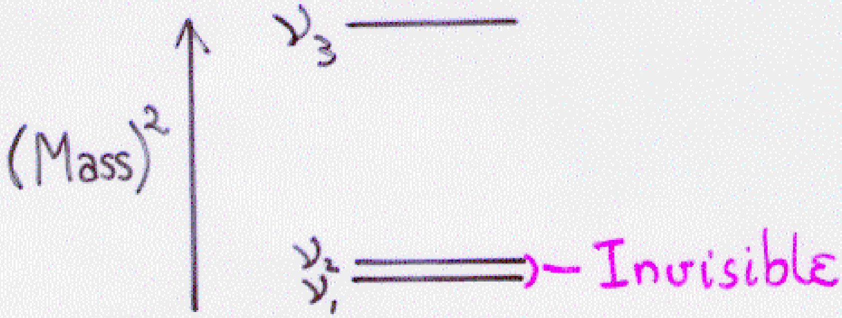
$$\underset{(-)}{+} 2 \sum_{m>m'} \Im(U^*_{\ell m} U_{\ell' m} U_{\ell m'} U^*_{\ell' m'}) \sin\left(\delta M^2_{mm'} \frac{L}{2E}\right)$$

Complex phases in U can lead to $\cancel{CP}$.

Oscillation involving only 2 neutrinos



or effectively 2 neutrinos



depends only on the sizes of the $U_{\ell m}$.

Sizes $|U_{\ell m}|$ can be determined this way.

Phases of combinations of 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 ~~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.

CP Phases	Affect ν Oscillation	Affect $\beta\beta_{0\nu}$
Universal	Yes	No
Majorana	No	Yes

If there are only 3 neutrinos, then, with $P(\nu_\ell \to \nu_{\ell'}) - P(\bar{\nu}_\ell \to \bar{\nu}_{\ell'}) \equiv \Delta_{CP}(\ell\ell')$,

$$\Delta_{CP}(e\mu) = \Delta_{CP}(\mu\tau) = \Delta_{CP}(\tau e)$$
$$= 16\, J\, s_{12} s_{23} s_{31} ,$$

where

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

and

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

Life is simple, but hard.

Authors who have discussed $\cancel{CP}$:

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 light ν_e

In the 4-neutrino spectrum with heavy ν_e,

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

where

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

and

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

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

What Are the Magnetic and Electric Dipole Moments of Neutrinos?

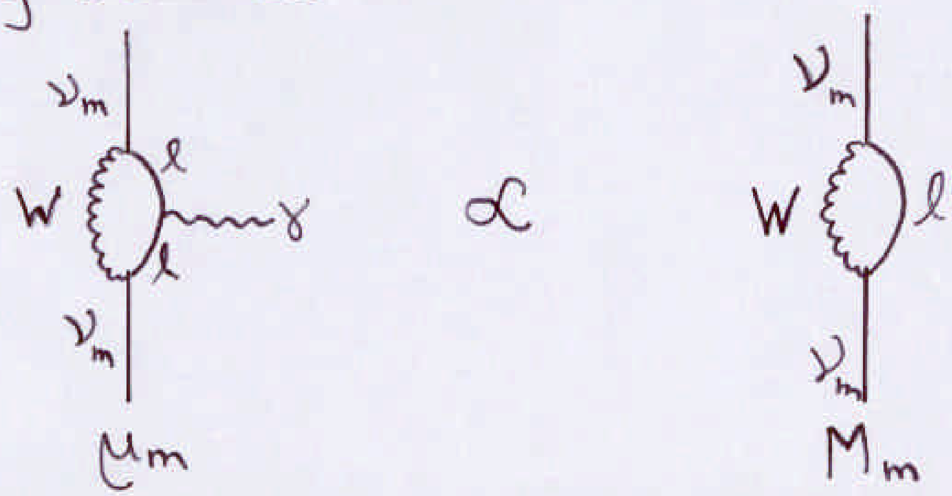
$$\text{Moment}[\bar{\nu}_m] \underset{CPT}{=\!=} -\text{Moment}[\nu_m]$$

$$\therefore \text{ If } \bar{\nu}_m = \nu_m, \text{ Moment} = 0.$$

Only Dirac neutrinos can have non-transition dipole moments.

Both Majorana and Dirac neutrinos can have transition moments.

In simple extensions of the Standard Model, neutrino magnetic dipole moments μ_m are tiny because



$$\mu_m = 3.2 \times 10^{-19} M_m(\text{eV}) \mu_{\text{Bohr}}$$

(Lee & Shrock; Fujikawa & Shrock)

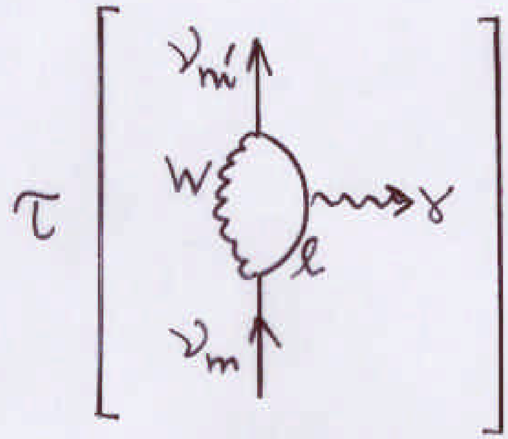
Electric dipole moments must violate $\cancel{CP}$ too.

There are models with much bigger moments.

One can look for neutrino magnetic moment contributions to ν-e scattering, using reactor neutrinos or solar neutrinos.

Beacom & Vogel

What Are the Neutrino Lifetimes?



$\gg 1$ sec

Exotic decay modes may yield shorter lifetimes.

(Pakvasa; B.K. & Mohapatra)

If some neutrino ν_m decays rapidly ($\tau < 1$ sec)

then the atmospheric neutrino data, usually explained in terms of $\nu_\mu \to \nu_\tau$ oscillation, can be equally well explained in terms of neutrino decay.

(Barger, Learned, Lipari, Lusignoli; Pakvasa, Weiler

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Conclusion

We are just beginning to learn –

- How many neutrinos there are
- How much they weigh
- Their nature
- Their interactions

In neutrino physics, interesting years lie ahead.