Neutrino Mass: An evolving mystery

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PUSHING THE FRONTIERS OF SCIENCE

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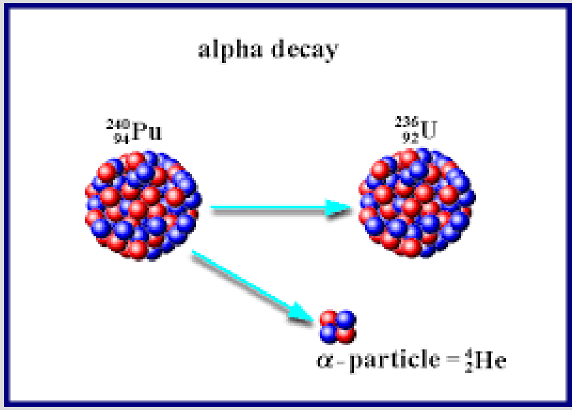
Radioactive decays



Compare: α and β decays

- α-decay: the parent nucleus, X, becomes a different nucleus, Y, by the emission of an α-particle.
  $X_N^A \rightarrow Y_{N-4}^{\mathbf{A-2}} + \alpha \qquad \alpha \equiv (2n)(2p) \qquad E_\alpha = M_X - M_Y$

- β-decay: Inside the nucleus $n \rightarrow p + e^- + \overline{\nu}_e$
  $X_N^A \rightarrow Y_N^{\mathbf{A+1}} + e^- + \overline{\nu}_e \qquad E_\beta \neq M_X - M_Y$

Our focus

(No neutrino would give equality!)

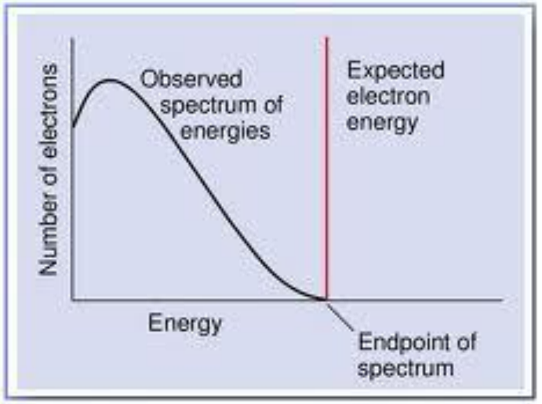
Neutrino properties

- Very light
- Uncharged
- Hardly interact

- Produced e.g., in beta decay
  Ensures conservation of energy
  Another important example $\pi^+ \rightarrow \mu^+ + \nu_\mu$

- Can pass from one end of the earth to another without interaction

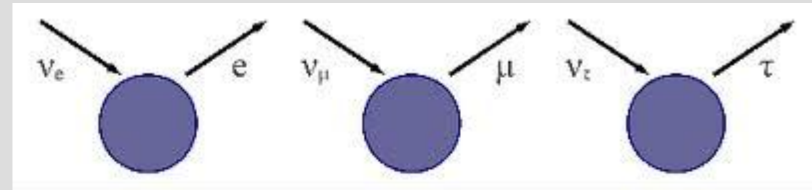
- Harmless, Very difficult to detect



Single beta decay energy spectrum. The observed spectrum is continuous and not at a constant energy as was initially expected. [D. Stewart]

Wolfgang Pauli

Neutrino properties (contd.)



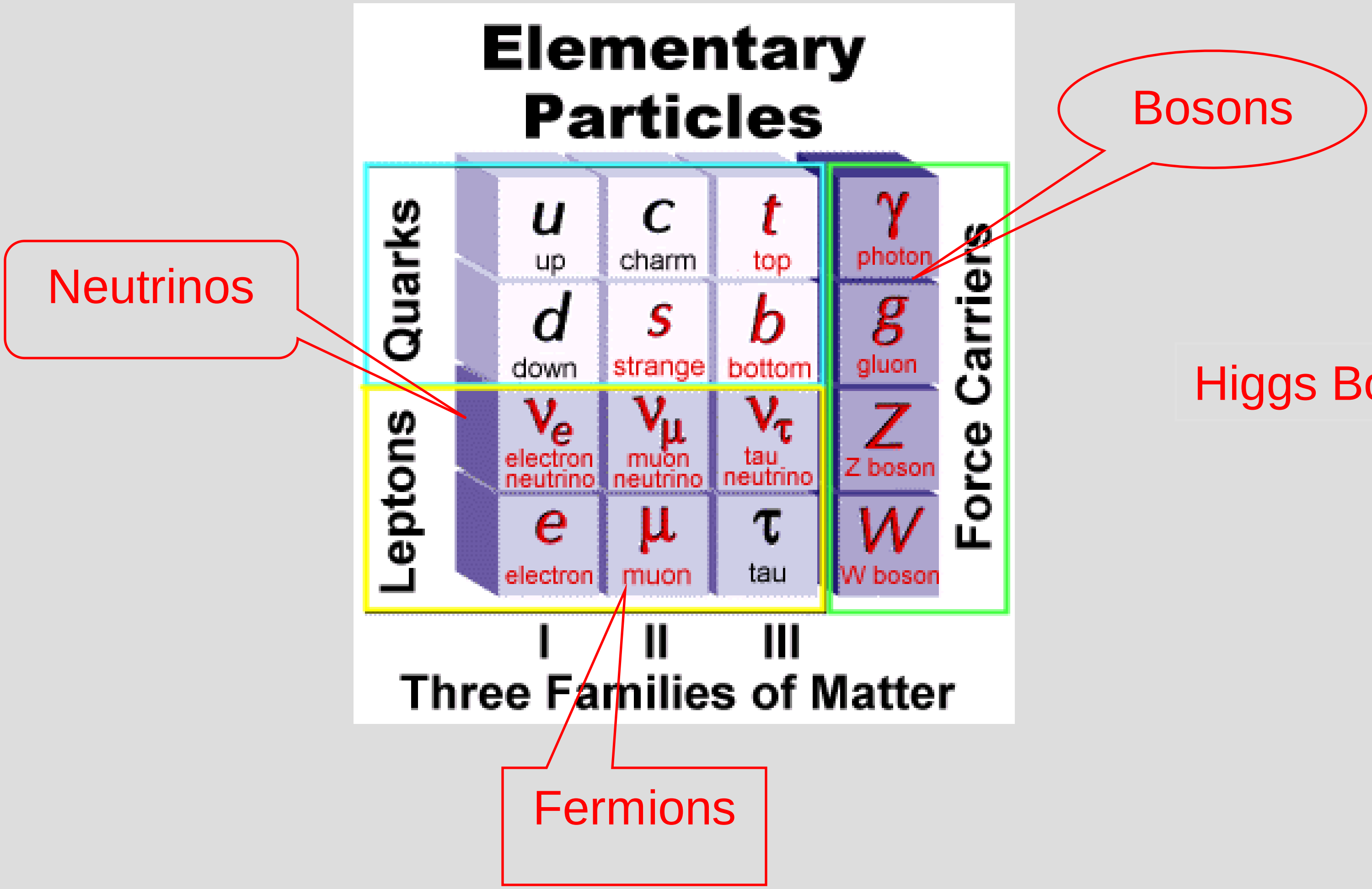
Three types: ν_e , ν_μ, ν_τ are known.

A ν_e is produced from an initial electron (e). Similarly, ν_μ, ν_τ are associated with μ, τ leptons.

Many properties discovered in the past two decades

e^- electron	μ^- muon	τ^- tau	$Q = -e$
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	$Q = 0$
1st gen.	2nd gen.	3rd gen.	

Elementary particles



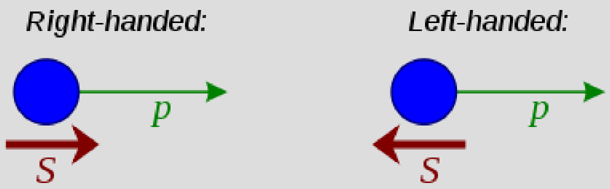
Higgs Boson!

Source: http://electron9.phys.utk.edu/phys250/modules/module6/images/simplemodel2.gif

Standard Model

- The Standard Model describes strong and electroweak interactions.
- Mediated by gluons, W-boson, Z-boson, and photon.
- Fermions: Left- and right-handed quarks, left- and right-handed charged leptons, left-handed neutrino. No ν_R!

Parity violation!



- Masses of W, Z , quarks and leptons via Higgs mechanism.
- No ν_R in SM $\Rightarrow$ Neutrino is massless. Chosen for consistency with information of that era.
- (B-L) is a symmetry of the Standard Model

Neutrino interactions

CC: Charged current

$\nu_e + n \rightarrow e + p$

W$^{\pm}$ exchange

NC: Neutral current

$\nu_x + p \rightarrow \nu_x + p$

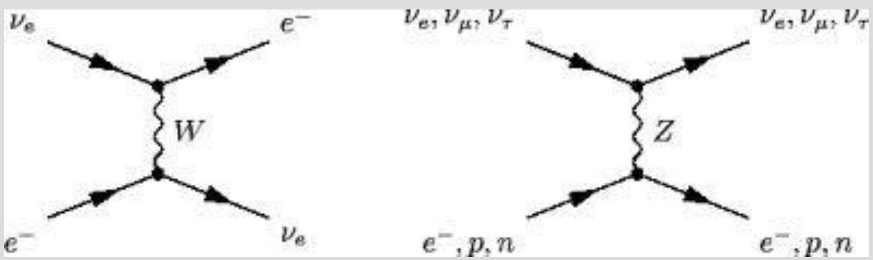
$\nu_x + n \rightarrow \nu_x + n$ $(x = e, \mu, \tau)$

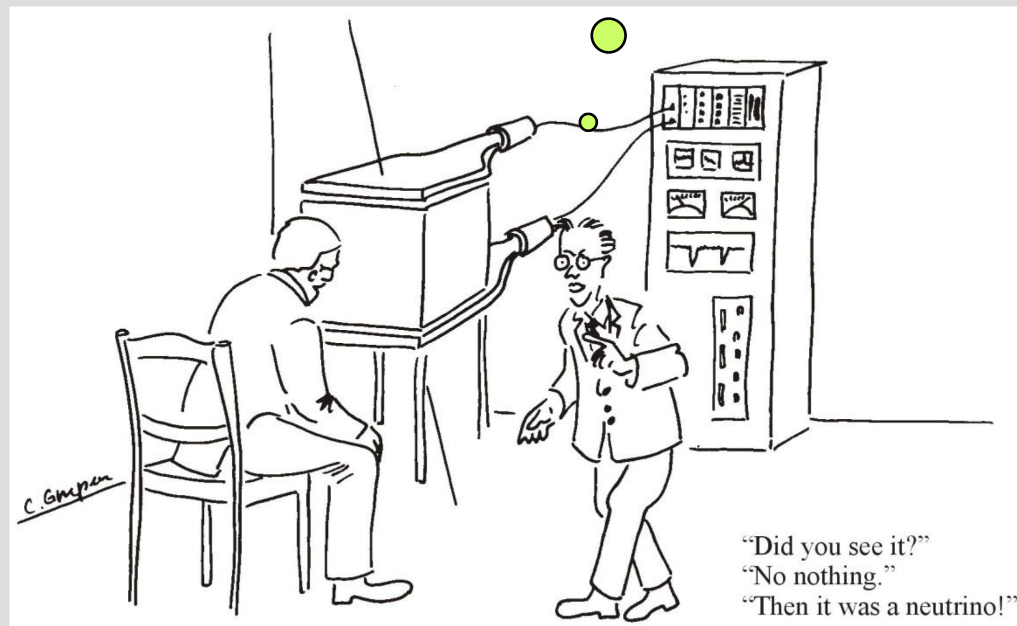
Z exchange

Did you see it?

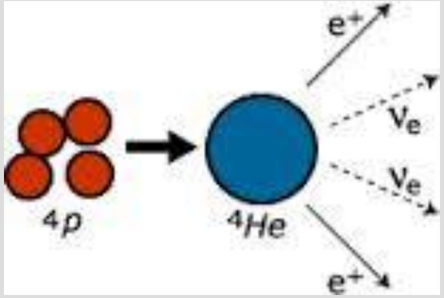
No, Nothing!

Then it was a neutrino





Solar neutrinos

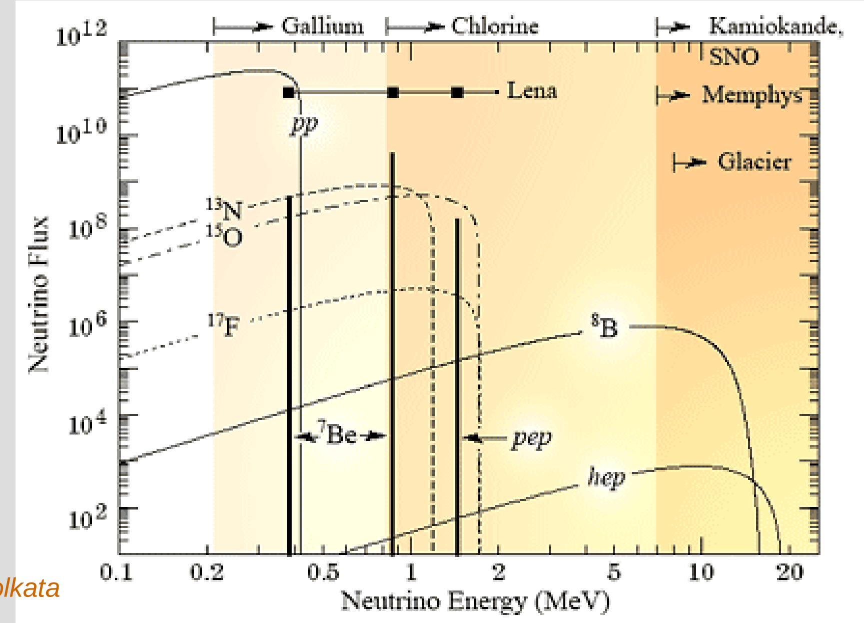


- Sun generates heat and light through fusion reactions

  $4p \rightarrow {}^4He + 2\,e^+ + 2\,\nu_e + 27\ MeV$ (i)

- Just like sunlight, solar neutrinos are reaching us (day & night!)

- Robust prediction of the number of solar neutrinos reaching the earth as a function of energy is possible. These have been detected by several experiments. But …



Solar neutrino results

Pioneering experiment using the reaction:

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^- \quad \mathrm{(CC)}$$

Observed No. of Solar ν_e/ Expected No. of Solar $\nu_e = 0.335 \pm 0.029$

Ray Davis Jr
Nobel: 2002

Other experiments later found similar shortfalls!

Possibilities:

Are ν_e decaying on the way to the earth?

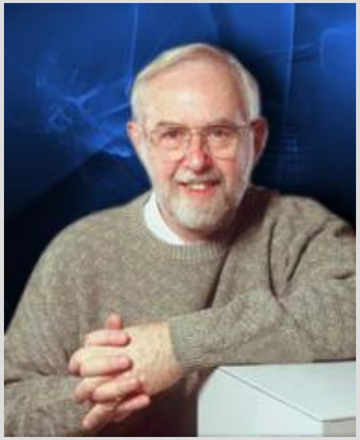
Are ν_e oscillating to some other type on the way to the earth?

What is happening?

An experiment that detects neutrinos of all types is the answer:

If neutrinos are decaying then the number will show a decrease

If oscillations take place then only the type of neutrino is changed. Not the total number of neutrinos.



A.B. McDonald
Nobel 2015

At SNOLab in Canada an experiment depending only on neutral current interactions (same for all neutrinos) was performed.

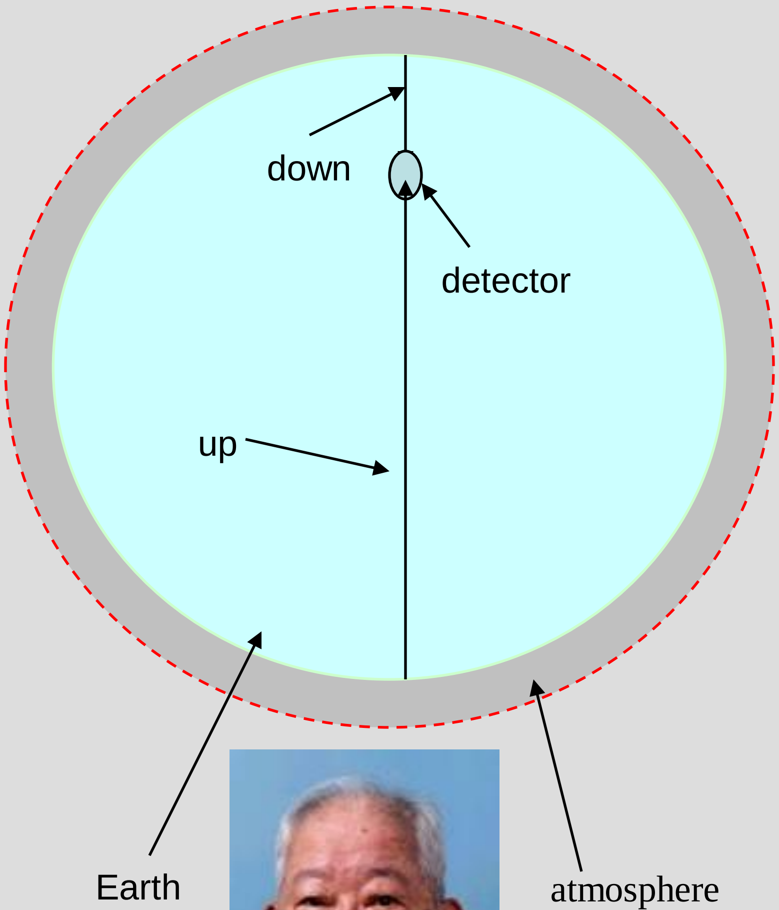
$$\nu + d \rightarrow n + p + \nu \text{ (NC)}$$

Observed No. of ν/ Expected No. of $\nu = 1.008 \pm 0.123$

Not decay! Neutrinos oscillate!

Atmospheric neutrinos

Neutrinos are produced in the atmosphere from pion and kaon decays
e.g. $(\pi^- \rightarrow \mu^- + \nu_\mu)$, $(\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu)$
and the charge conjugate processes
Typical energy ~ 1 GeV



Expect equal no. of neutrinos from all directions:

Seen: No. of ν_μ depends on zenith angle (up-down asymmetry). Fewer upgoing!
No such variation for ν_e

Effect of oscillations!
ν_μ oscillating to ν_τ

T. Kajita
Nobel 2015

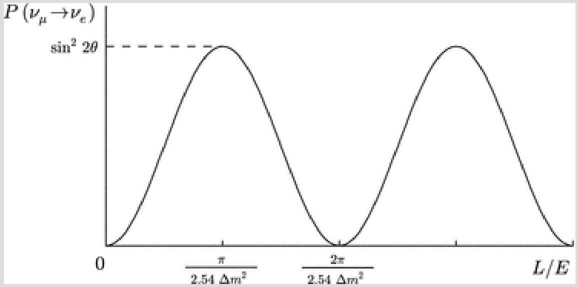
Masatoshi Koshiba
Nobel: 2002

Neutrino oscillations

- A quantum mechanical phenomenon relying on the superposition principle.
- In the oscillation of a pendulum, the bob alternately reaches the left and right end-points of the trajectory.
- During travel, a ν_e becomes a ν_μ and then back again to a ν_e. This oscillation process continues.

The oscillation wavelength (and hence probability!) depends on the neutrino energy. $\lambda = 4\pi E/\Delta$, $\Delta = (m_2^2 - m_1^2)$

Oscillation establishes neutrinos have non-zero mass



Neutrino oscillations

Mass ↔ Flavour states:

$$|\nu_e\rangle = |\nu_1\rangle \cos\theta + |\nu_2\rangle \sin\theta$$

$$|\nu_\mu\rangle = -|\nu_1\rangle \sin\theta + |\nu_2\rangle \cos\theta$$

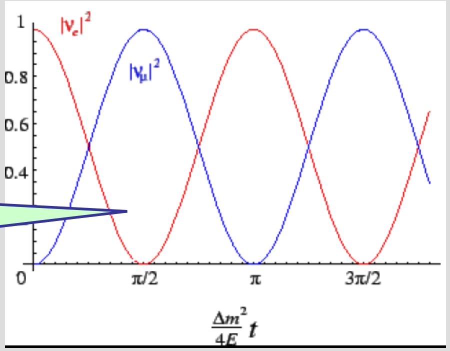
- Mass eigenstates are stationary states.
- Flavour eigenstates are produced and detected.

- Oscillations between neutrinos (e.g., ν_e and ν_μ) is a consequence.

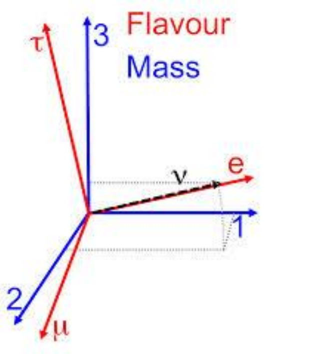
c = cosθ
s = sinθ

$\mathrm{Prob}(\nu_e \rightarrow \nu_\mu, L) = 4\, c^2 s^2 \sin^2(\pi L/\lambda)$

Maximal mixing
$\theta = \pi/4$



More on ν oscillations



- Essential ingredients: (i) $\Delta = m_1^2 - m_2^2 \neq 0$, (ii) $\sin\theta \neq 0$.

- Matter effect: Mass is a measure of inertia.
  In a medium inertia (and hence mass) changes.
  Neutrino mass and mixing affected by medium (MSW effect)

- Solar neutrino problem: $\Delta = 6.07 \times 10^{-5}$ eV^2 (ii) $\tan^2\theta = 0.41$
  (Best fit -- MSW LMA)

  ν_e oscillates to another `active' neutrino (SNO NC $\approx$ 1)

- Atmospheric neutrino anomaly: $\Delta = 3 \times 10^{-3}$ eV^2 (ii) $\sin^2 2\theta = 1$
  (Best fit)

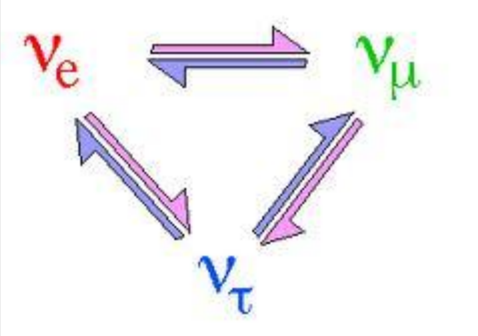
  ν_μ oscillates to ν_τ

m_e= 5,00,000 eV

Three neutrino mixing matrix

Two flavour mixing:

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$



In reality there are three flavours (3 angles, one phase):

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}.$$

The phase δ signals CP non-conservation

All three mixing angles must be non-zero for CP-violation

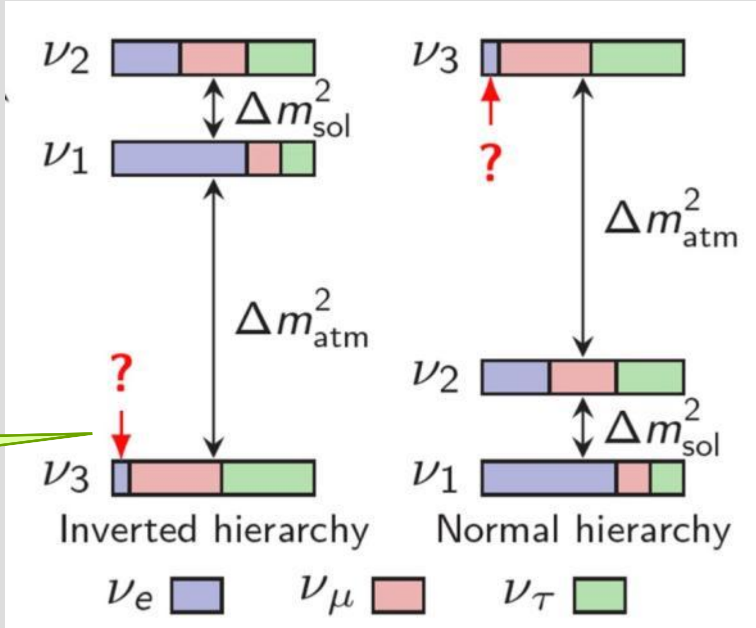
$\theta_{13} \sim 9^0$ (2012) Daya Bay and RENO experiments

Three neutrino mass ordering

Solar neutrinos: $m_2^2 - m_1^2 > 0$:

From atmospheric neutrinos,
only $|m_3^2 - m_1^2|$ is known

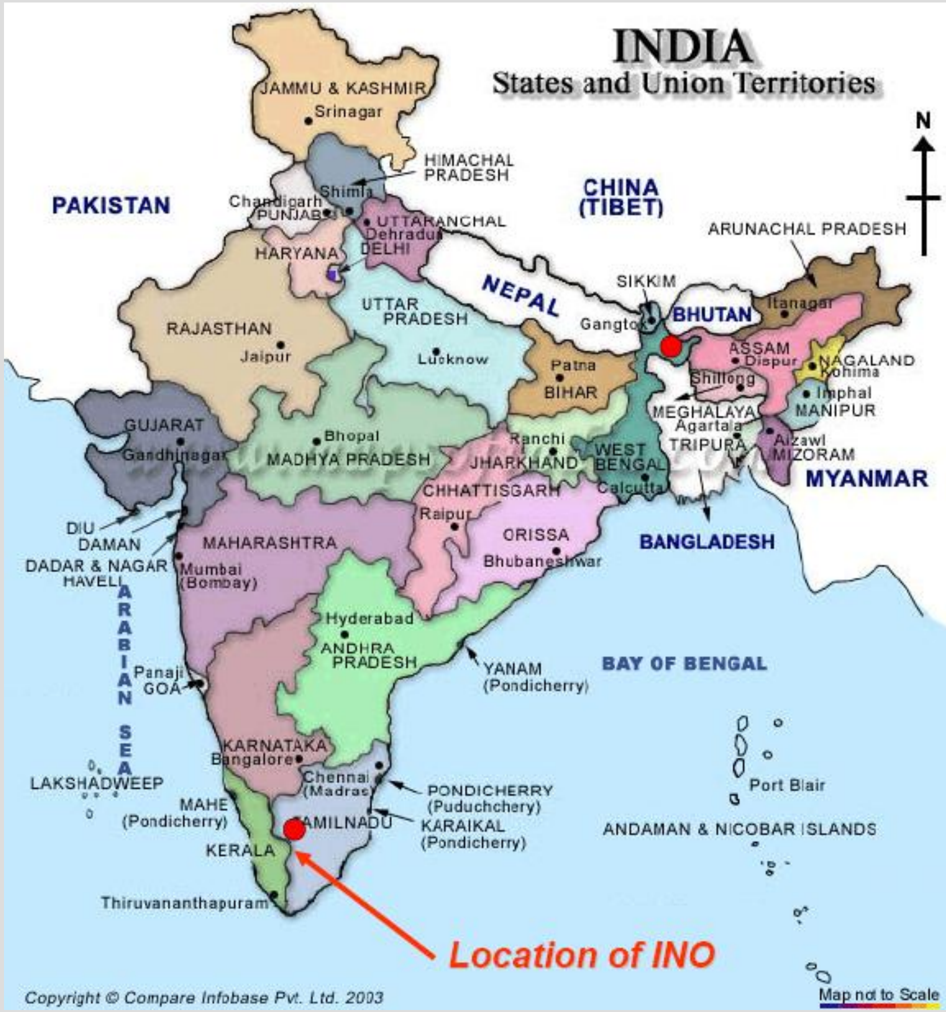
$\theta_{13} \neq 0$?



Normal mass ordering?
or
Inverted mass ordering?

Not known!

India-based Neutrino Observatory



Pottipuram: $9^0$57'N, $77^0$16'E

(Bodi Hills)

Near TamilNadu-Kerala border

1km rock coverage to block other particles.

Iron calorimeter detector

ICAL strategy

- **A 50,000 ton detector with a magnetic field.**
- **Look for oscillation signals in atmospheric neutrinos. They come with a range of energies.**
- **A ν_μ ($\bar{\nu}_\mu$) interaction produces μ^- (μ^+), which can be distinguished in ICAL due to the magnetic field.**
- **Helps determine normal or inverted ordering of neutrino mass.**
- **CPT violation, tomography of the earth, other expeiments at INO!**

Majorana Neutrino?

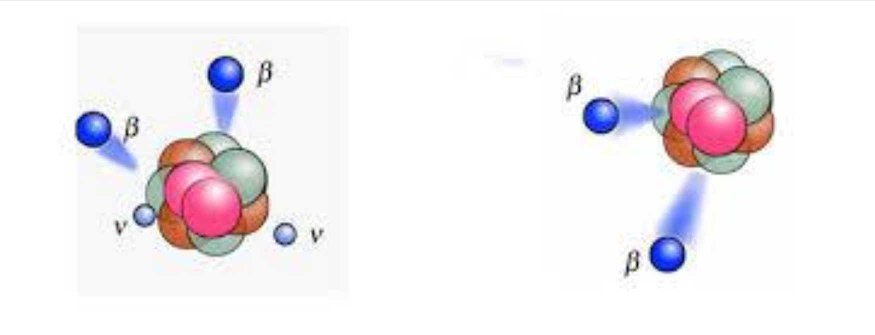
- Can the neutrino be its own anti-particle? ($\nu \equiv \nu^c$?)
  The photon is its own anti-particle. (Also π^0)
- In such an event, lepton number is not conserved!

- A consequence $\Rightarrow$ Neutrino-less double beta decay ($0\nu2\beta$ process)

P.B. Pal, V. Nanal, A. Shrivastava

- Normal double beta decay ($2\nu2\beta$) : $X \rightarrow Y + 2\,e^- + 2\nu_e$

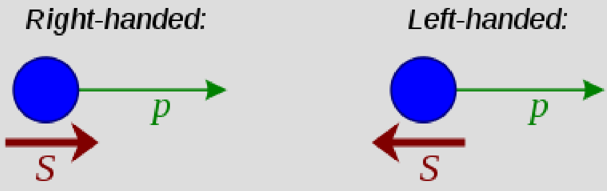
- Neutrino-less double beta decay ($0\nu2\beta$) : $X \rightarrow Y + 2\,e^-$ ($\propto \langle m_\nu \rangle^2$)
- Look for peak in $2e^-$ total energy
- Current limit $\langle m_\nu \rangle$ < 0.2 eV.



Fermion mass

- Fermions have spin! Left- and right-handed fermions:

$$\psi = \psi_L + \psi_R$$



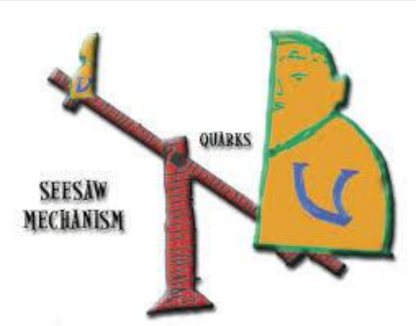
- Fermion mass couples left to right:

$$m\,\bar{\psi}\,\psi = m(\bar{\psi}_R\,\psi_L + \bar{\psi}_L\,\psi_R)$$

- Standard Model: There is no right-handed neutrino.
- If there is only left-handed (or right-handed) component then m=0.

How to get $m_\nu \neq 0$?

- The mundane way is to add a ν_R to the SM.
- This solves the problem but has no explanation of the smallness of m_ν.
- This is the major hurdle in neutrino model building. To explain the smallness, one always needs new physics associated with some heavy scale, M (See-saw!). For Majorana mass, lepton number violation is also needed.
- Generic form of see-saw: m_ν = (const)/M



N Khan

Looking Ahead

- What is the mass ordering of neutrinos? Normal or inverted?
- CP-violation in neutrino sector?
- Importance of matter effects.
- Majorana neutrinos

- INO
- Unique experiment with huge magnetic detector.

- Explaining neutrino mass:
- New physics: new interactions, symmetries, etc.
- Astroparticle physics: e.g. Supernova, Nucleosynthesis

A. Dighe


Thank You!