The Knowns and Unknowns of Neutrinos

RINP2

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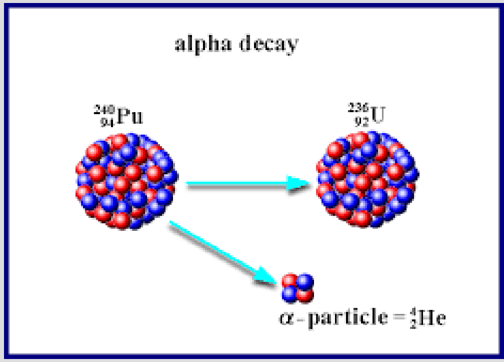
Neutrino properties

The dog that did not bark

Radioactive decays



Types: α, β, and γ decays

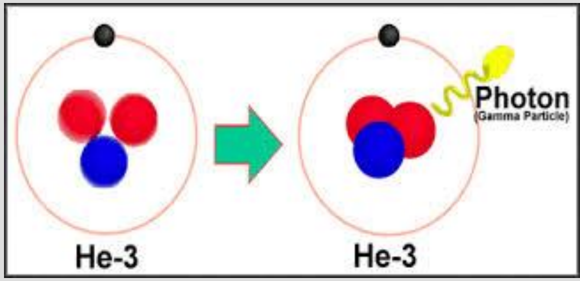
- α-decay: the parent nucleus, X, becomes a different nucleus, Y, by the emission of an α-particle.
  $X_N^A \rightarrow Y_{N-4}^{\mathbf{A-2}} + \alpha$ $\quad \alpha \equiv (2n)(2p)$ $\quad E_\alpha = M_X - M_Y$

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

Our focus

(No neutrino would give equality!)

- γ -decay: Nucleus de-excites by emitting high-energy γ-ray
  $(X_N^A)^* \rightarrow X_N^{\mathbf{A}} + \gamma$ $\quad E_\gamma = M_{X^*} - M_X$



Units

- Velocity of light. Choose units such that $c = 1$
- $E = m c^2 \Rightarrow$ Mass and energy in same units

- High energy ~ GeV (Giga-electron-volts) = 10^9 eV
- Nuclear binding energy ~ MeV
- Mass of proton ~ 1GeV

- Quantum mechanics: Angular momentum ~ $\hbar$ units
- Spin of electron $\hbar/2$
- We often choose units such that $\hbar = 1$

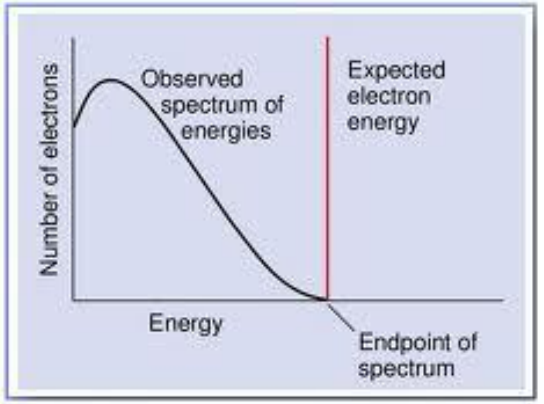
Neutrino properties

- 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

- **Neutrino interactions:**

  No strong interaction, no electromagnetic interaction.

  Only weak interactions (2 types: CC and NC)

  Cross section ⇒ σ (ν_e +e → ν_e +e) ~ 10^{-43} cm^2

  c.f. σ ~ 10^{-27} cm^2 (em), ~10^{-23} cm^2 (strong)

- **Sterile ν : No weak interactions**

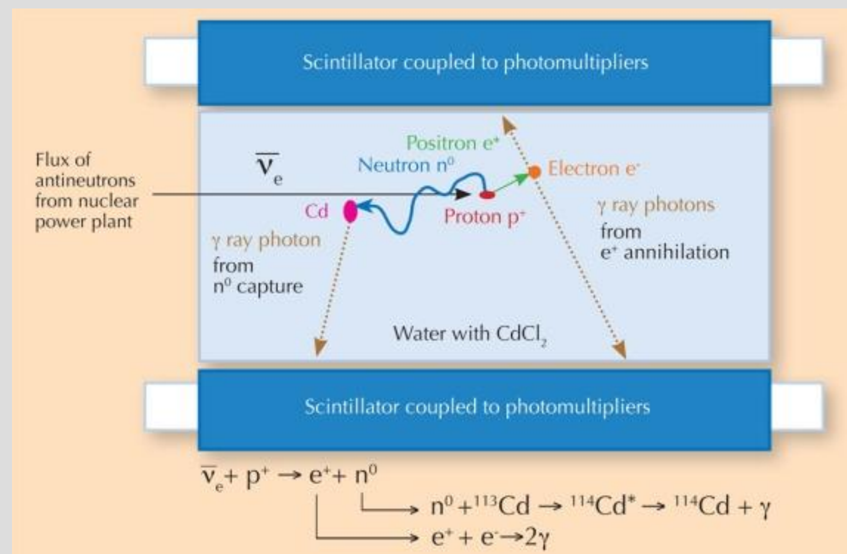
First neutrino detection (1953)

Need an intense neutrino source
One option: Test of nuclear device (X)
Chosen: Nuclear power plant (√)
Copious source of antineutrinos

- Detector: 200 litres of water
- Inverse beta decay $\overline{\nu} + p \rightarrow e^{+} + n$
- 40kg of dissolved $Cd\,Cl_4$

Fred Reines (Nobel 1995)

- e^{+} promptly annihilates: 2γ
- n is slowed down by Cd
- Then absorbed by Cd
- Delayed photon from Cd γ -decay
- Coincidences observed.



Neutrinos detected!

Types of Neutrinos

Leon Lederman,
Melvin Schwartz,
Jack Steinberger
$\nu_\mu \neq \nu_e$
Nobel 1988

Brookhaven Accelerator: 15 GeV energy proton beam

p + target material $\rightarrow$ many pi mesons + other stuff

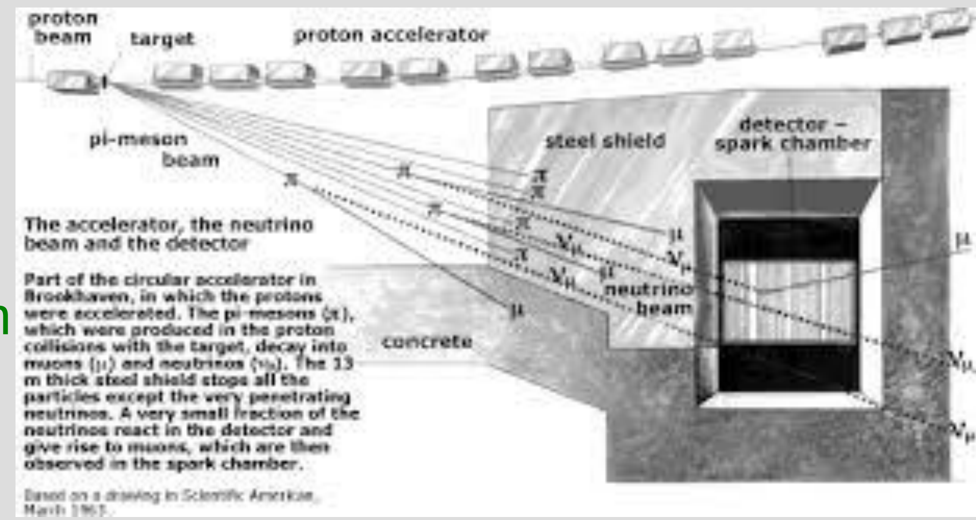
$\pi^\pm$ are unstable particles. They decay!

Pion decay: $\pi^+ \rightarrow \mu^+ + \nu$ (?)

- All the particles are made to hit a 13.5m steel wall
- $\pi^\pm$ $\mu^\pm$ are absorbed in the wall.
- Only neutrinos remain.

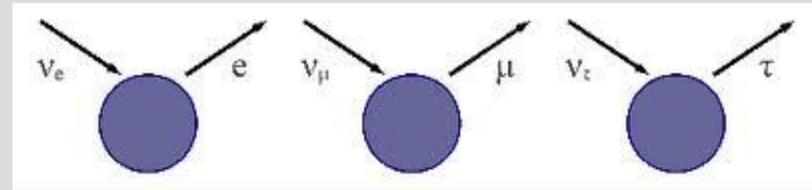
- 5ton spark chamber detector
- 1” Aluminium ⅜” gap (Ne gas)
  $\nu_\mu \rightarrow \mu^-$ $\nu_e \rightarrow e^-$: No $e^\pm$ seen

- $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  $\nrightarrow \mu^+ + \nu_e$ (Not allowed)



Concept of man-made neutrino beams (1962)

Neutrino properties (contd.)



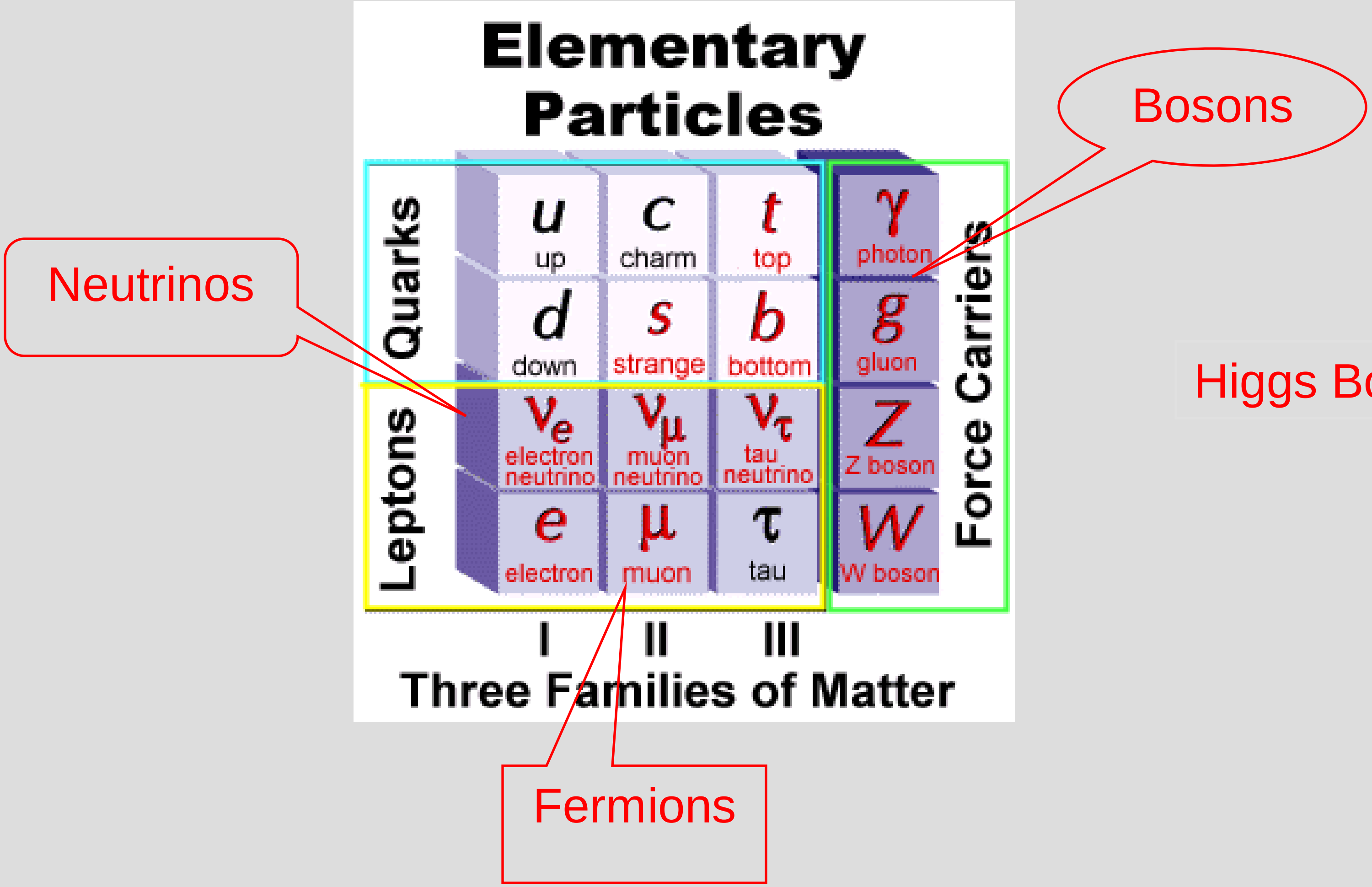
Three types: ν_e , ν_μ, ν_τ are known.

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



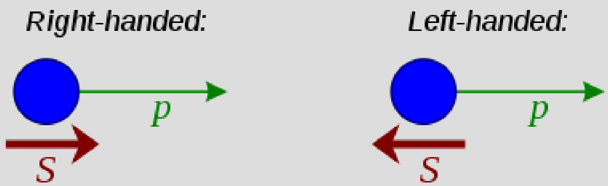
Higgs Boson!

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

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

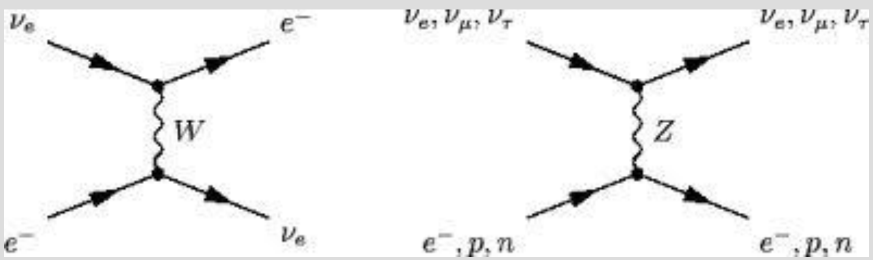
$\nu_x + n \rightarrow \nu_x + n$ $(x = e, \mu, \tau)$

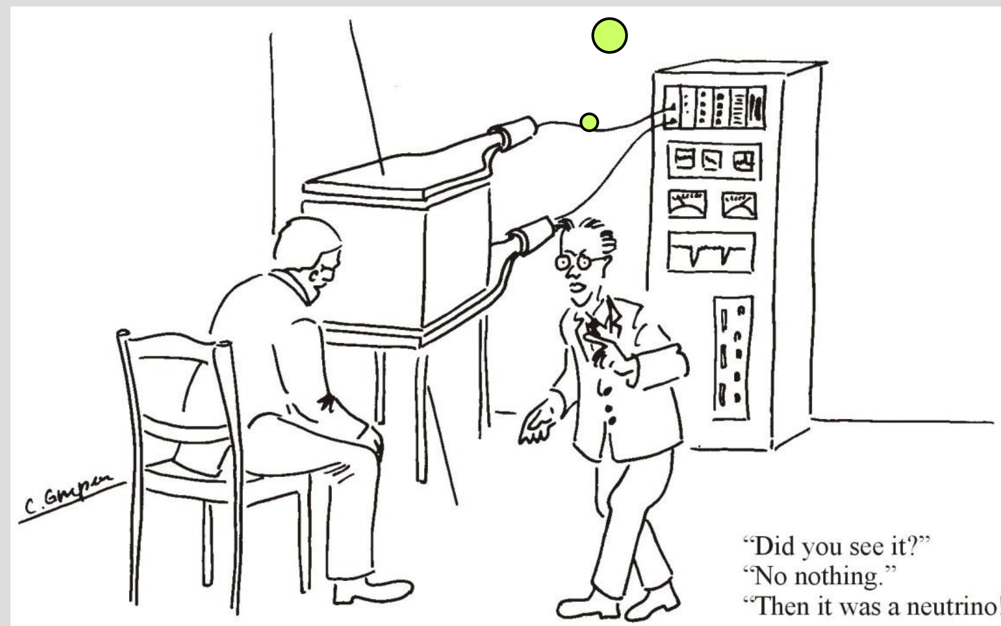
Z exchange

Did you see it?

No, Nothing!

Then it was a neutrino





Neutrino Sources

50 billion neutrinos/sec from the natural radioactivity of the earth

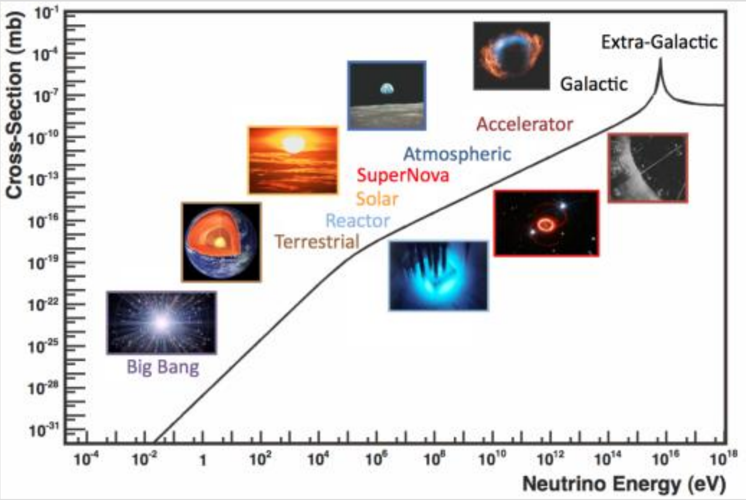
E ~ 0.1 ~ 20 MeV; Flux ~10^{12} /cm^2/s

Experimentally observed:

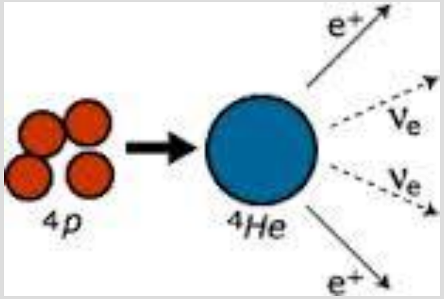
- Solar neutrinos (Fusion reactions)
- Atmospheric neutrinos (pion decay)
- Accelerator neutrinos (pion decay)
- Nuclear Reactor antineutrinos (Fission reactions)

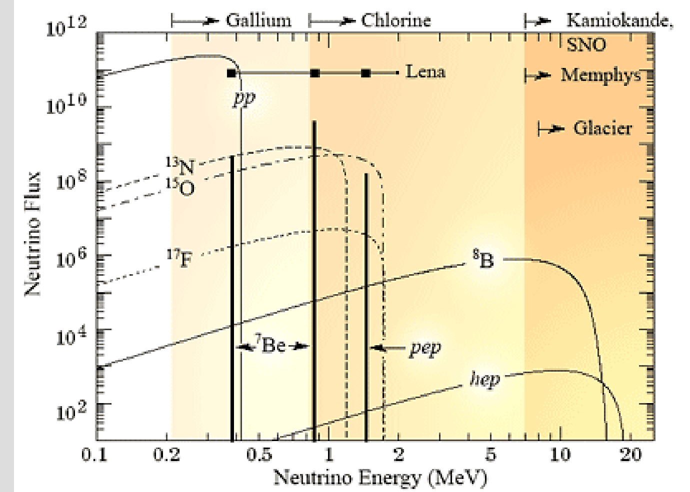
Future:

- Long baseline expts such as DUNE, H2K



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!)

- Reaction (i) does not take place in one go. Rather, it is the consequence of a cycle of reactions, e.g.

  $p + p \rightarrow {}^2H + e^+ + \nu_e$ ← *pp neutrinos*

  The ν_e energy spectra from these reactions are well-known.

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

Reactor neutrinos

- Nuclear power stations run on fission reactions.
- A heavy nucleus, such as Uranium or Plutonium, breaks into lighter nuclei and neutrons and other particles.
- A large flux of electron antineutrinos are produced.
- Energy in the few MeV range.

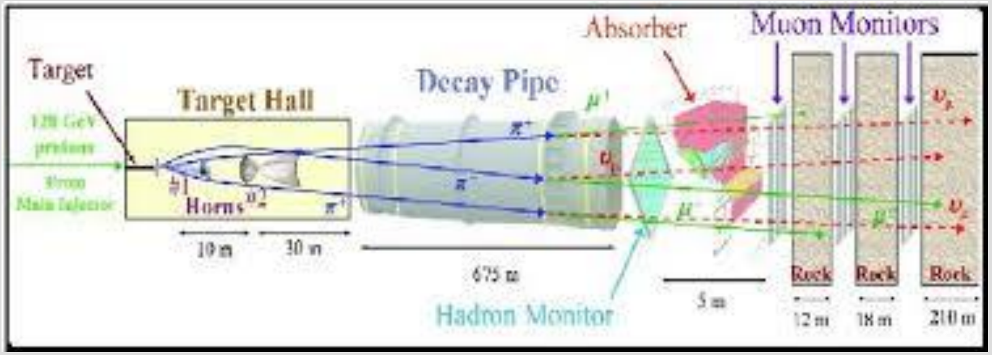
Daya Bay, China ⇒

- Excellent source for neutrino experiments.

  France, China, Korea and other countries

Neutrino beams

- High energy (few 1000 MeV) neutrinos are produced at accelerators. A high energy proton beam hits a target and produces many particles (among them $\pi^{\pm}$)
- Pions decay to produce neutrinos ($\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$)
- Neutrinos from CERN or Fermilab (USA)

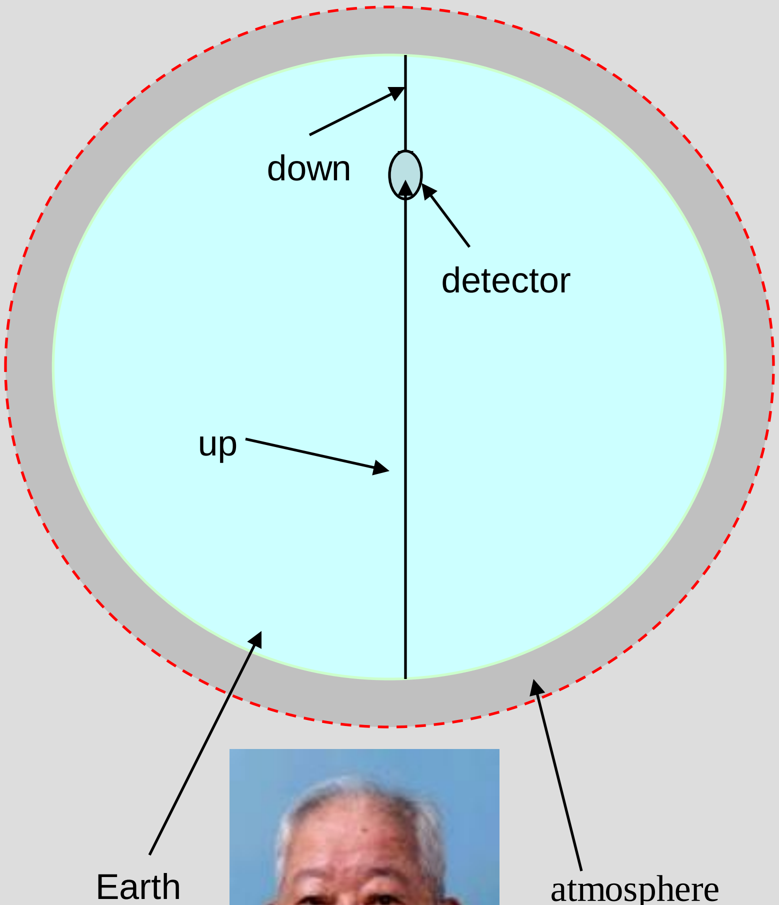


Atmospheric neutrinos

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

Expectation: $R = (\# \nu_\mu + \bar{\nu}_\mu)/(\# \nu_e + \bar{\nu}_e) \approx 2$

SuperK: $R_{obs}/R_{mc} = 0.635 \pm 0.035 \pm 0.083$ (sub-GeV)
$= 0.604 \pm 0.065 \pm 0.065$ (multi-GeV)



T. Kajita

No. of ν_μ depends on zenith angle (up-down asymmetry)

No such effect for ν_e (1997)

Masatoshi Koshiba
Nobel: 2002

Solar neutrino results

Expt	Obsvd/Predn	E_{th} (MeV)	Type
Homestake (from 1968)	0.335 ± 0.029	0.8	Radiochemical $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ (CC)
GNO, SAGE, Gallex	0.584 ± 0.039	0.233	Radiochemical $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$ (CC)
K, SuperK (1989)	0.459 ± 0.017	5.0	Water Cerenkov $\nu_e + e \rightarrow \nu_e + e$ (CC + NC)
SNO CC	0.347 ± 0.027	6.75	Cerenkov $\nu_e + d \rightarrow p + p + e^-$ (CC)

Ray Davis
Nobel: 2002

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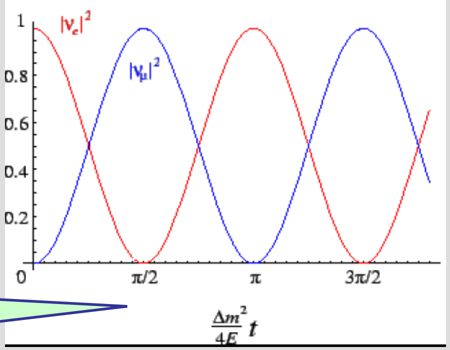
SNO CC	0.347 ± 0.027	6.75	Cerenkov $\nu_e + d \rightarrow p + p + e^-$ (CC)
SNO NC	1.008 ± 0.123	2.2	$\nu + d \rightarrow n + p + \nu$ (NC)

A.B. McDonald

Neutrino oscillations

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.



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

$c = \cos\theta$

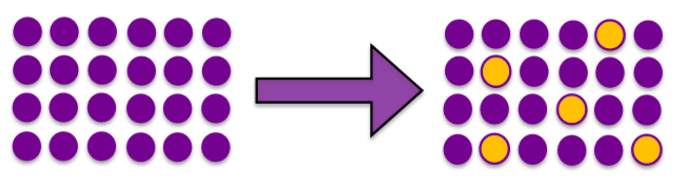
$s = \sin\theta$

Maximal mixing

$\theta = \pi/4$

The oscillation wavelength (and hence probability!) depends on the neutrino energy.

Neutrino oscillations (contd.)



How does this help?

- Solar neutrino detectors look for ν_e. Some (Cl, Ga and SNO CC) are totally insensitive to ν_μ, ν_τ. SK has a smaller sensitivity (about 1/6) to other types. Only SNO NC is equally sensitive to all.

  If some ν_e have oscillated to a ν_μ when they reach the detector then they will not be seen (except in SNO NC). Count will be less.

- Atmospheric ν_e, ν_μ are detected through the e^-, μ^- they produce. At their higher energies, the ν_e hardly oscillates, while the ν_μ oscillates to ν_τ, which do not produce μ^-. This reduces the measured ratio R. Also, the zenith angle dependence seen for ν_μ is explained.

- Other experiments (at nuclear reactors and using neutrino beams) have seen clear signals for neutrino oscillation.

Some Quantum Mechanics

Stationary states: $H\,|\Psi_n\rangle = E_n\,|\Psi_n\rangle$

Time evolution: $|\Psi_n(t)\rangle = \exp(-iE_n t)\,|\Psi_n(0)\rangle$ (only a phase)

General state (t=0): $|\Psi(0)\rangle = \sum a_n\,|\Psi_n(0)\rangle$

General state (any t): $|\Psi(t)\rangle = \sum a_n \exp(-iE_n t)\,|\Psi_n(0)\rangle$

Phase differences $\sim (E_i - E_j)t$ → physics consequences

Neutrino stationary states: $|\nu_1\rangle$, $|\nu_2\rangle$

(mass eigenstates)

Neutrino flavour eigenstates: $|\nu_e\rangle$, $|\nu_\mu\rangle$

Mass ↔ Flavour states:

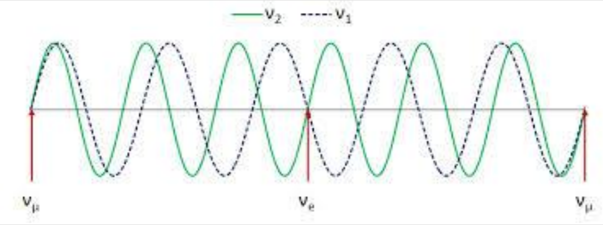
$$|\nu_e\rangle = |\nu_1\rangle \cos\theta + |\nu_2\rangle \sin\theta$$

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

Quantum Mechanics of neutrino oscillations (contd.)

$|\nu_e\rangle$ produced at $t = 0 \rightarrow |\Psi(0)\rangle = |\nu_e\rangle = |\nu_1\rangle \cos\theta + |\nu_2\rangle \sin\theta$

At a later time: $|\Psi(t)\rangle = |\nu_1\rangle \cos\theta\, e^{-iE_1 t} + |\nu_2\rangle \sin\theta\, e^{-iE_2 t}$



$\text{Prob}(\nu_e \rightarrow \nu_\mu, L) = |\langle \nu_\mu | \Psi(t)\rangle|^2 = 4\, c^2 s^2\, |e^{-iE_1 t} - e^{-iE_2 t}|^2$

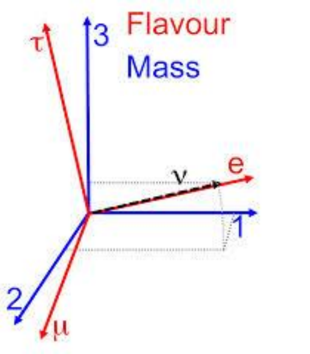
Neutrinos are ultra-relativistic: $p \gg m \Rightarrow E_i = (p^2 + m_i^2)^{1/2} \approx p + m_i^2/2p$

$$(E_1 - E_2)t = (m_1^2 - m_2^2)t/2p \equiv (\Delta/2p)t = \Delta L/2E$$

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

Survival Prob. = $\text{Prob}(\nu_e \rightarrow \nu_e, L) = 1 - \text{Prob}(\nu_e \rightarrow \nu_\mu, L)$

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 ≈ 1)

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

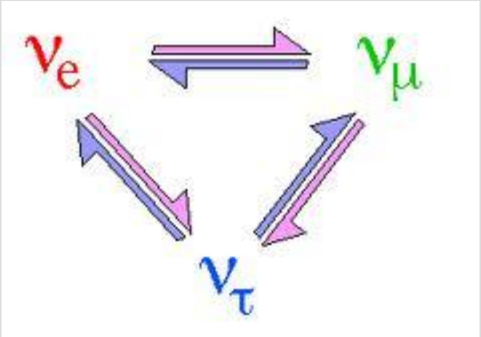
  ν_μ oscillates to ν_τ

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

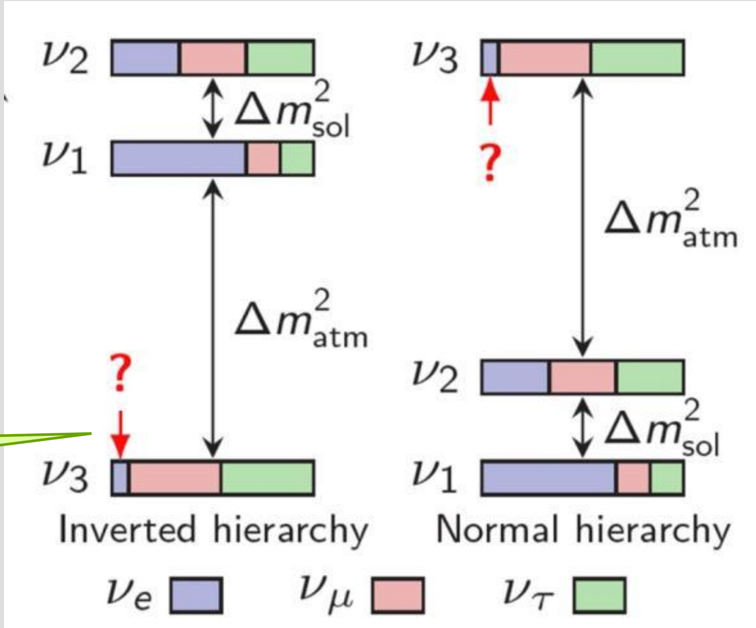
$\theta_{13} \sim 9^0$ (2012) Daya Bay and RENO experiments

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

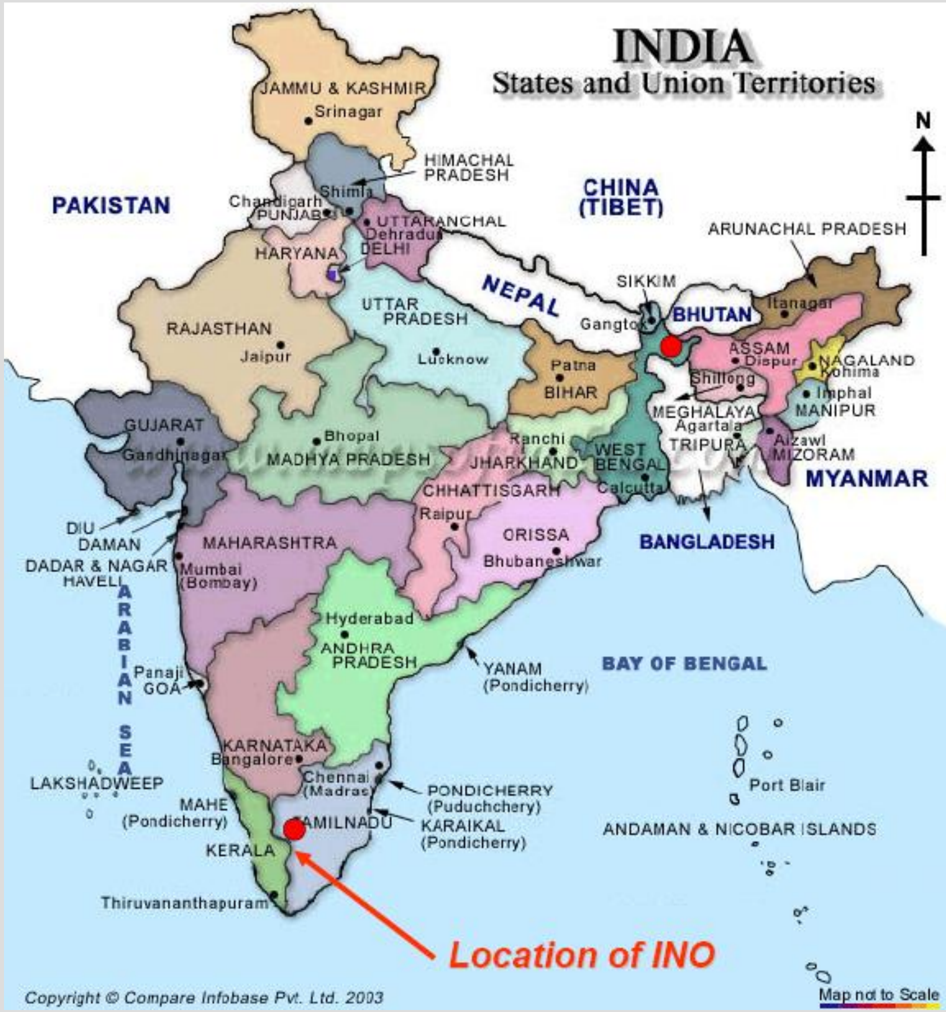
Inverted mass ordering?

Not known!

Open issues

- **Standard model (SM) of particle physics has massless neutrinos.**
- **Oscillations signal mass difference. What is the neutrino mass?**
- **What is the mass ordering? Is there CP-violation?**
- **Is the neutrino its own anti-particle $\Rightarrow$ Majorana neutrino!**
- **New physics is needed if $m_\nu \neq 0$?. Many new ideas.**

India-based Neutrino Observatory



Pottipuram: $9^0 57'$N, $77^0 16'$E (Bodi Hills)

Near TamilNadu-Kerala border

1km rock coverage

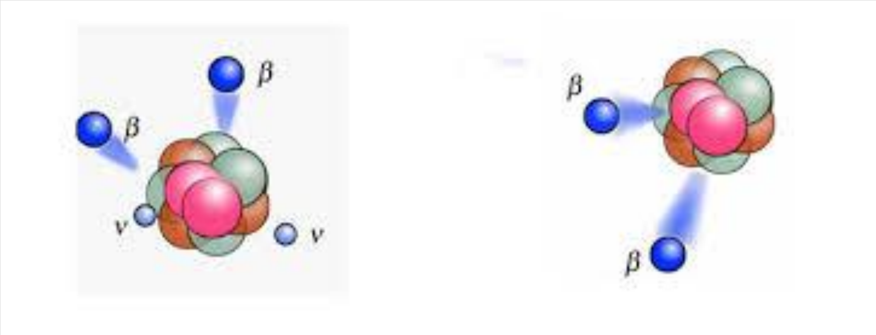
V.M. Datar

Majorana Neutrino?

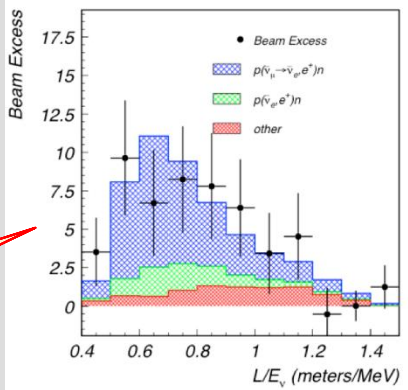
- Can the neutrino be its own anti-particle? ($\nu \equiv \nu^c$?)
  The photon is its own anti-particle. (Also π^0)
- In such an event, lepton number is not conserved!
- A consequence $\Rightarrow$ Neutrino-less double beta decay ($0\nu2\beta$ process)

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.



Sterile neutrino?



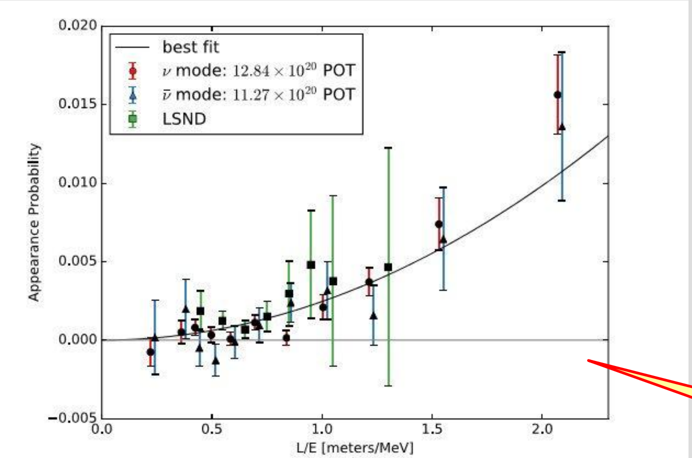
LSND

Prob($\nu_\mu \rightarrow \nu_e$, L) = $4 c^2 s^2 \sin^2(\Delta L/4E)$
(Δ L/ 4E) should not be too small nor too large

$\Delta = m_2^2 - m_1^2$ is fixed by the neutrino masses $\Rightarrow$ This fixes the region of (L/E) to which experiment should be sensitive.

Conversely observation of oscillations at a certain (L/E) $\Rightarrow$ Indicative of a certain ($msy_2^2 - m_1^2$)

LSND Experiment (1995) used a $\bar{\nu}_\mu$ beam from π^+ decay and observed oscillations.
L = 30 m, 36 MeV ≤ E ≤ 52.8 MeV For this (L/E) $\Rightarrow \Delta \cong$ 1 -10 eV^2



MiniBooNE
+ LSND

Is this result correct?

MiniBooNE (2018) with L~ 0.5 km and
200 MeV ≤ E ≤ 1250 MeV get similar results

Note (L/E) is similar. 4th sterile neutrino?

M.R. Janani

Does not match with solar and atmospheric neutrino!
4th neutrino? Sterile?

Neutrino-Nucleus scattering (COHERENT Expt)

- This is **not** an oscillation phenomenon.

- Normally we consider neutrinos scattering off electrons or perhaps quarks.

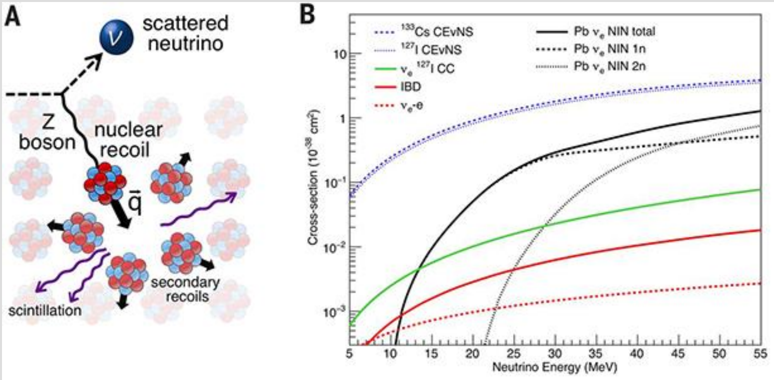
- Neutrino-Nucleus elastic scattering (much like Dark Matter detection)

B. Mukhopadhyaya

- Here, neutrinos scattering *coherently* off nuclei. Scattering mediated by Z-boson exchange. Energy must be low (< 50 MeV) so that the wavelength is comparable to the nuclear size.

The cross section $\propto N^2$, where N is the no. of neutrons in the nucleus

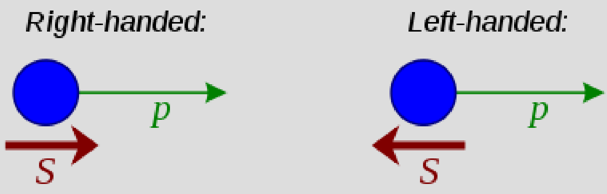
Pulsed beam (helps background estimation)
Small-sized detector (14.6 kg)
CsI scintillator,
6.7σ signal E ~ 16 – 53 MeV



Fermion mass

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

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



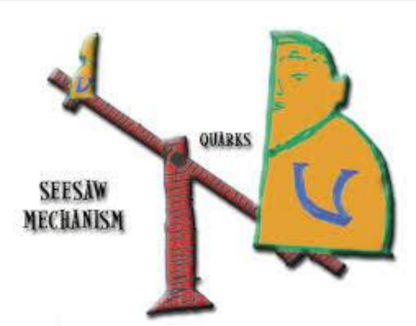
- Fermion mass couples left to right:

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

- 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

Simplest new physics

- Left-right symmetric model $\Rightarrow \nu_R$ required by symmetry.
- Nature is parity violating. Left-right symmetry is broken at a high energy scale, M_R.
- Neutrino mass matrix: $\begin{bmatrix} 0 & m \\ m & M_R \end{bmatrix}$ $\quad M_R \gg m$
- Two Majorana neutrinos: ν_L (mass m_ν), ν_R (mass M_R)
- See-saw mass formula: $m_\nu = (m^2)/M_R$.
- Pati-Salam model and other grand unified theories contain left-right symmetry.
- How to test for M_R?

Physics Nobel Prize 2015

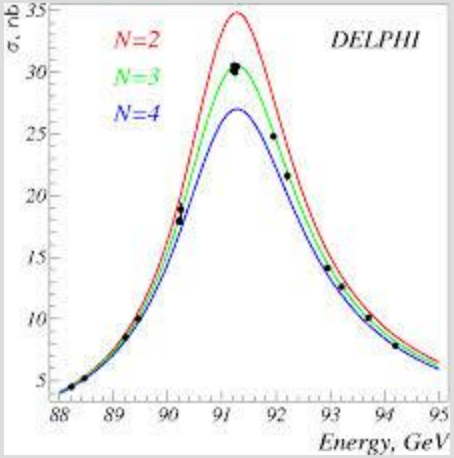
Takaaki Kajita (Japan)

&

Arthur B. McDonald (Canada)

For the discovery of neutrino oscillations which shows that neutrinos have mass

Looking Ahead



- Mixing between three neutrinos
- CP-violation in lepton sector
- Majorana neutrinos
- Sterile neutrinos
- Long baseline experiments
- INO
- Neutrino mass matrix
- New physics: new interactions, symmetries, etc.
- Astroparticle physics: e.g. Supernova, Nucleosynthesis

A. Dighe

Thank You!