Exploring the known unknowns of Neutrino Physics

Alumni Meet 2014

Institute of Physics, Bhubaneswar

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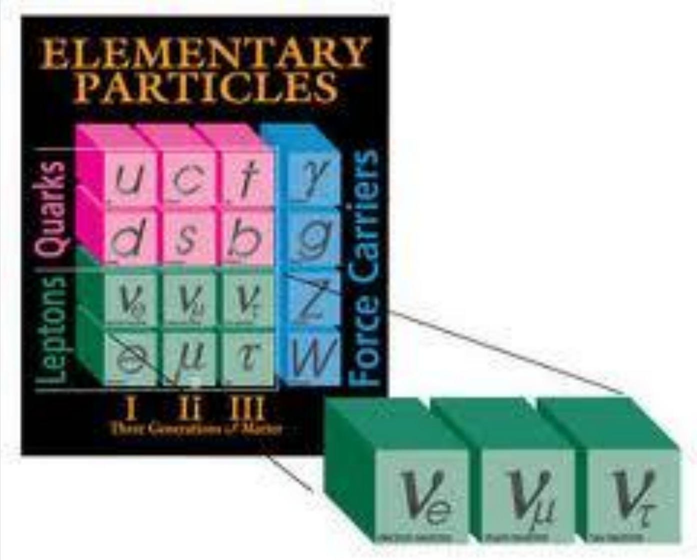
Amitava Raychaudhuri
University of Calcutta

Plan

- Quarks and Leptons: Neutrinos
- Solar neutrino problem
- Atmospheric neutrino anomaly
- Neutrino oscillations? Yes!
- Do neutrinos have a mass? Yes!
- Ordering of Neutrino masses?
- The India-based Neutrino Observatory (INO)
- Measuring neutrino mass
- Is the neutrino its own antiparticle? Majorana neutrino
- Why is neutrino mass so small? Origin?



Neutrino properties

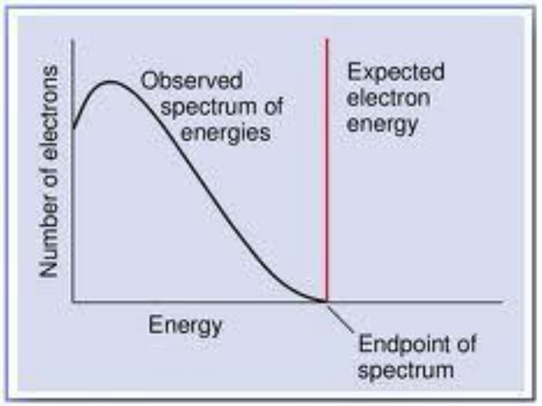
Neutrino properties

- Very light,
- Uncharged
- Hardly interact

- Produced e.g., in beta decay

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

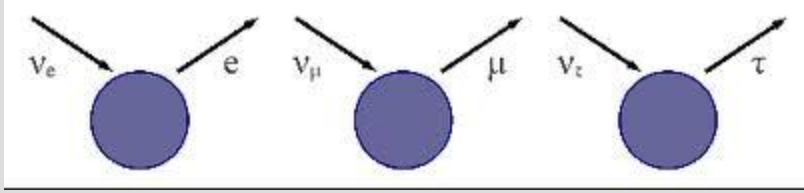
- Harmless, Very difficult to detect



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

Wolfgang Pauli

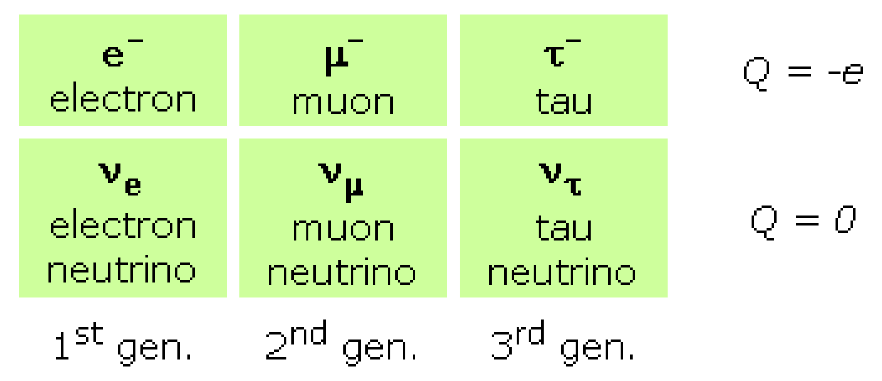
Neutrino properties (contd.)



Three types: ν_e , ν_μ, ν_τ are known.

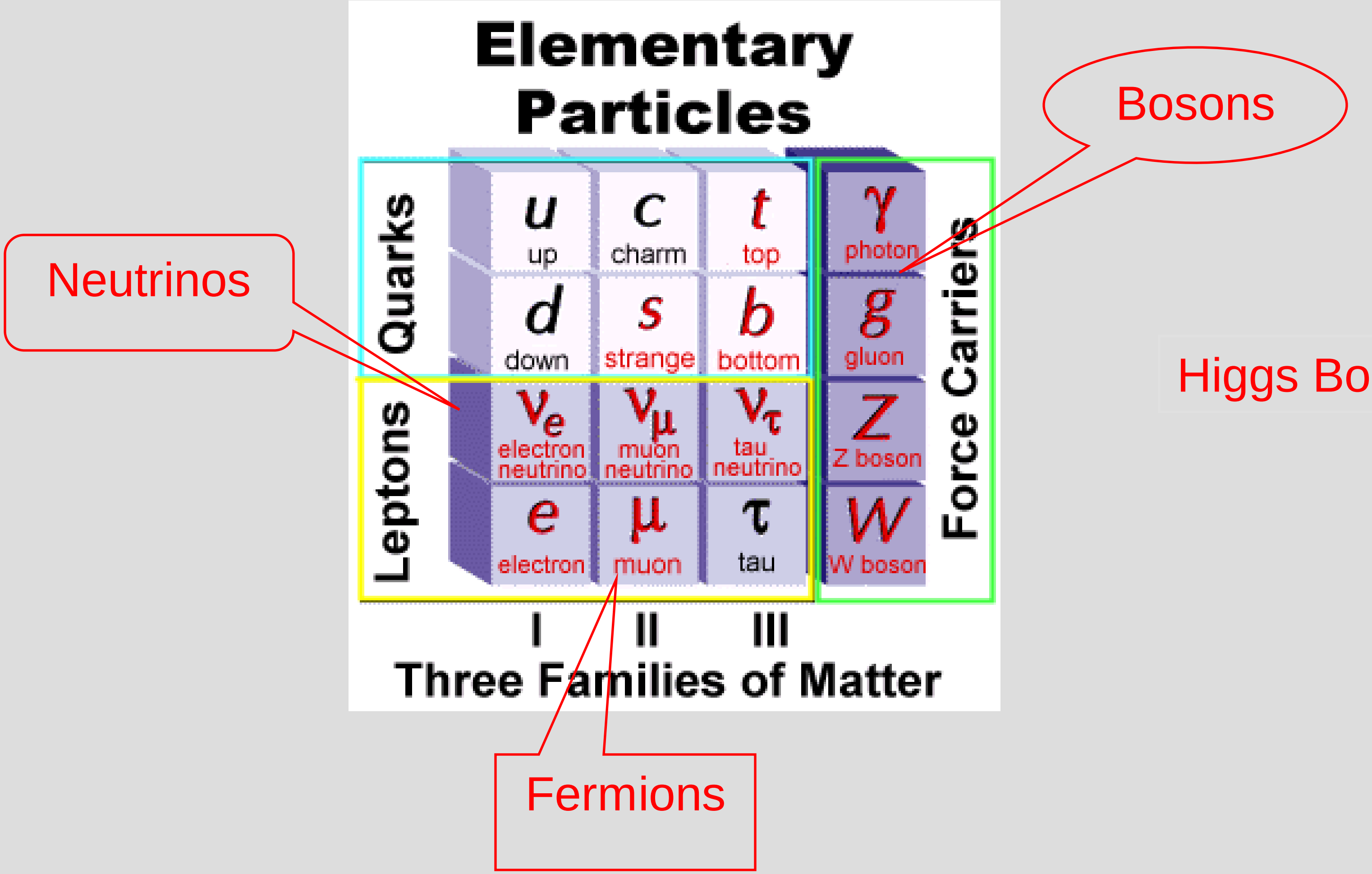
A ν_e is produced from an initial electron (e). Similarly, ν_μ, ν_τ are associated with μ, τ leptons.

Most properties discovered in the past decade



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



Neutrinos

Bosons

Fermions

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.

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

W± exchange

CC: Charge current

$\nu_e + n \rightarrow e + p$

Z exchange

NC: Neutral current

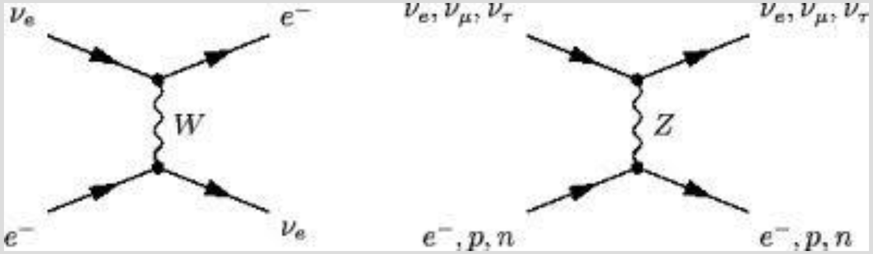
$\nu_x + p \rightarrow \nu_x + p$

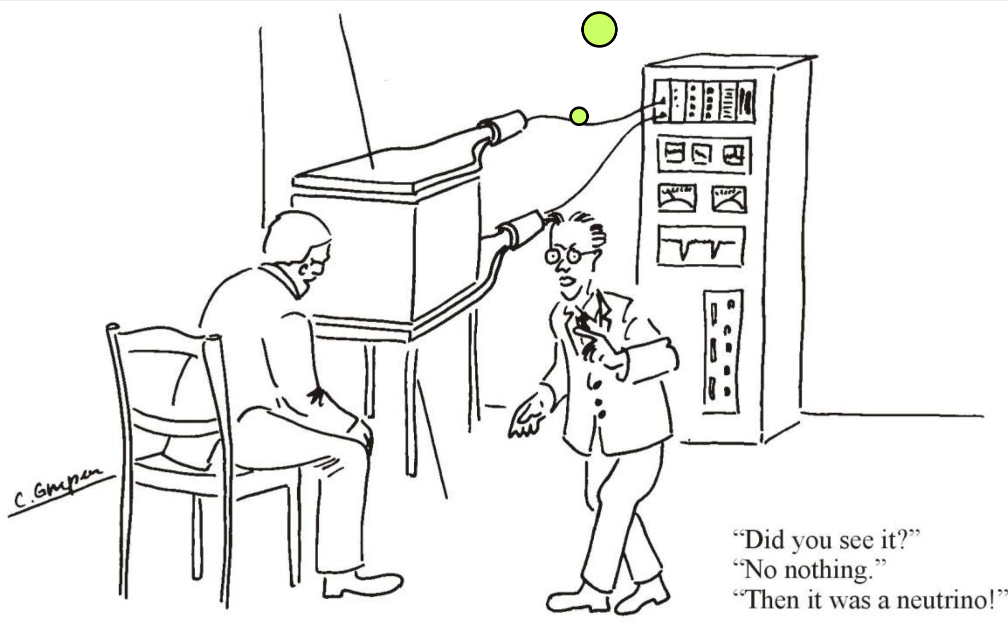
$\nu_x + n \rightarrow \nu_x + n \quad (x = e, \mu, \tau)$

Did you see it?

No, Nothing!

Then it was a neutrino





Neutrino Sources

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

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

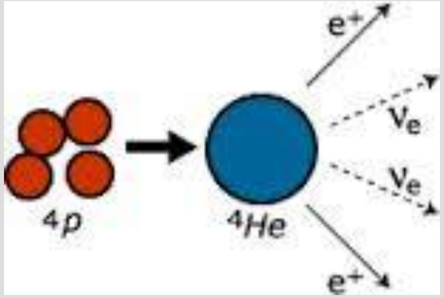
Experimentally observed:

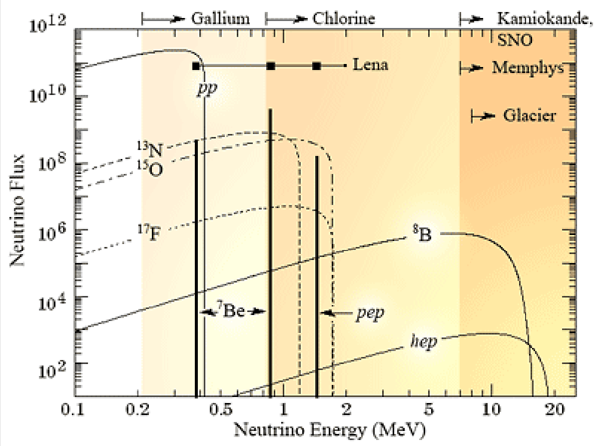
- Solar neutrinos (Fusion reactions)
- Atmospheric neutrinos (pion decay)
- Accelerator neutrinos (pion decay)
- Reactor antineutrinos (Fission reactions)

Future possibilities:

- Neutrino factories

Solar neutrinos





- Sun generates heat and light through fusion reactions

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

  $p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$ ← *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 …

Solar neutrino results

Expt	Obsvd/Predn	E_{th} (MeV)	Type
Homestake (from 1968)	0.335 ± 0.029	0.8	Radiochemical $\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$ (CC)
GNO, SAGE, Gallex	0.584 ± 0.039	0.233	Radiochemical $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$ (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)
SNO NC	1.008 ± 0.123		$\nu + d \rightarrow n + p + \nu$ (NC)

Ray Davis
Nobel: 2002

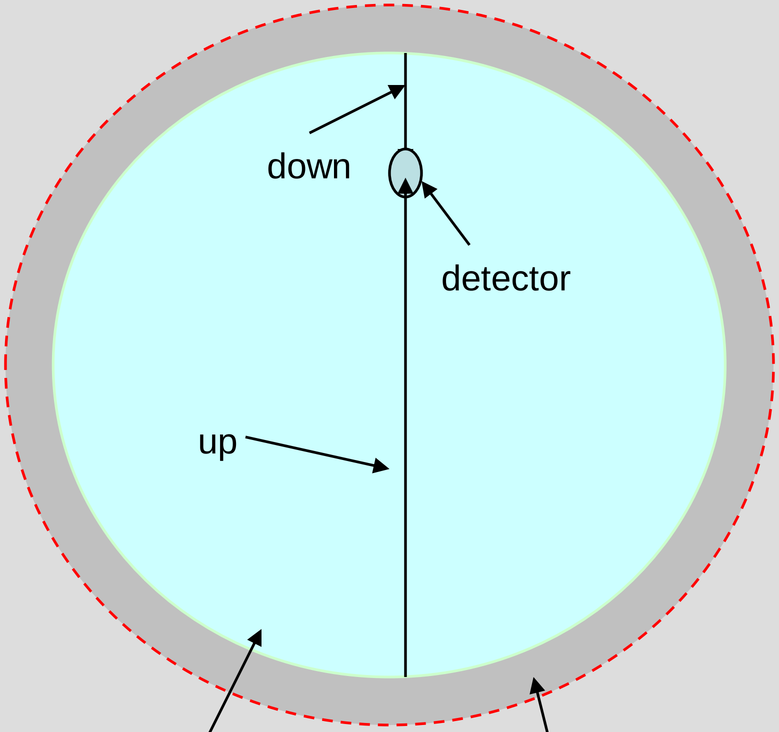
Atmospheric neutrinos

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

Typical energy ~ 1 GeV

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

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)



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

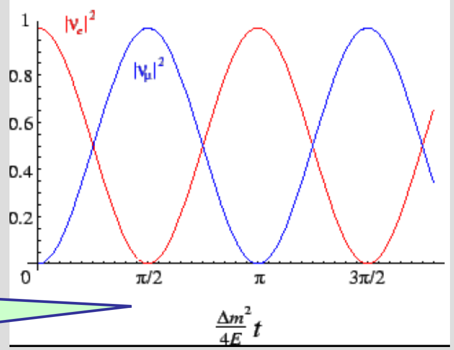
No such effect for ν_e (1997)

Masatoshi Koshiba
Nobel: 2002

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.



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

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 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:

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

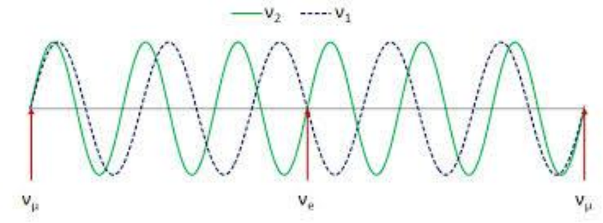
$$|\nu_\mu\rangle = -|\nu_1\rangle \sin\theta + |\nu_2\rangle \cos\theta$$

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 $\boxed{\lambda = 4\pi E/\Delta}$

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 $\approx$ 1)

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

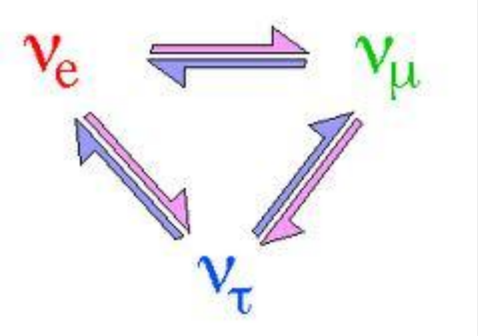
  ν_μ oscillates to ν_τ

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

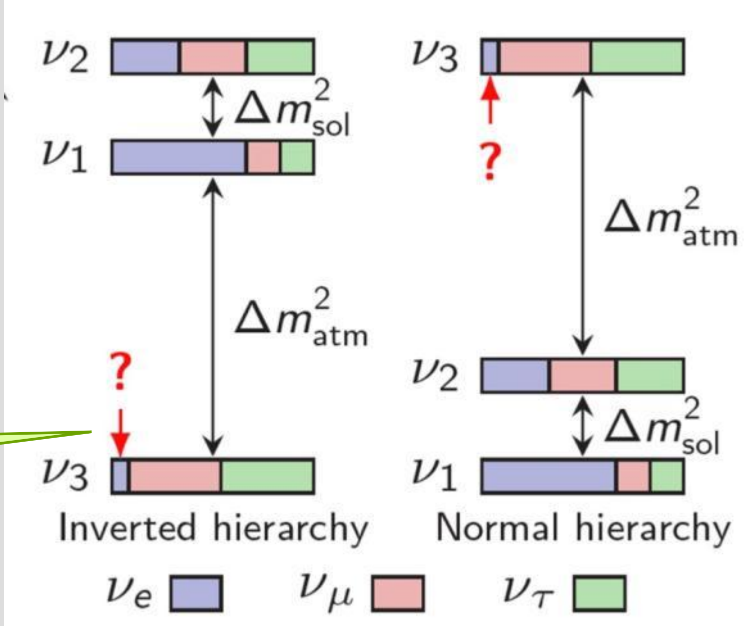
$\theta_{13} \sim 9^0$ (2012) Daya Bay and RENO experiments

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?

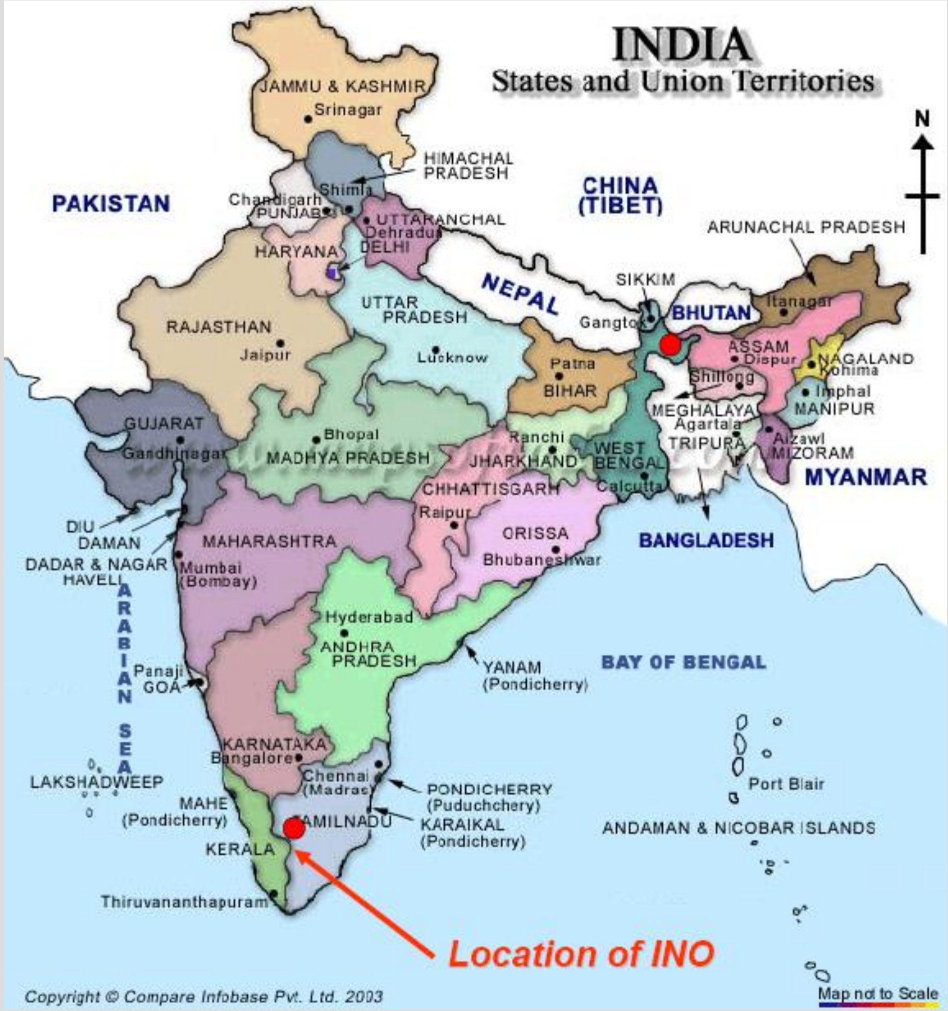
Not known!

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 ⇒ Majorana neutrino!**
- **New physics is needed if $m_\nu \neq 0$?. Many new ideas.**

India-based Neutrino Observatory

INO site



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

Near TamilNadu-Kerala border

1km rock coverage

India-based Neutrino Observatory (INO)

- **Advantages: Good mountain coverage (reduce cosmic rays)**
  Only low latitude neutrino detector site
- **Location: Bodi Hills Nilgiris**
  (good rocks, seismic stability, easy access)
- **Observatory will house several experiments**

- **ICAL Design: 50 kT magnetized (1 Tesla) Iron,**
  Resistive Plate Chamber (RPC) detectors

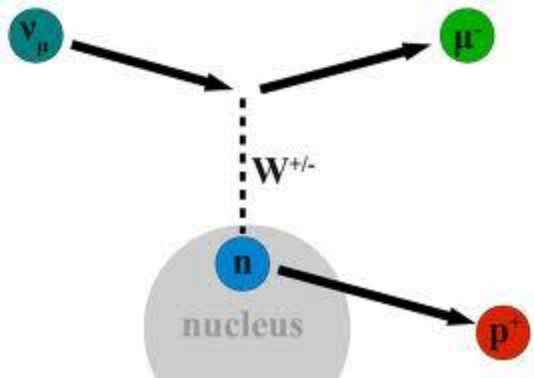
- **R & D Work being pursued:**
  - **a) Site survey, geological study, DPR preparation, cost estimate (done)**
  - **b) Prototype fabrication, magnet design (done)**
  - **c) Engineering (ongoing)**
  - **d) Detector simulation (ongoing)**

Underground!
Where the
acton will be!

INO: Physics prospects

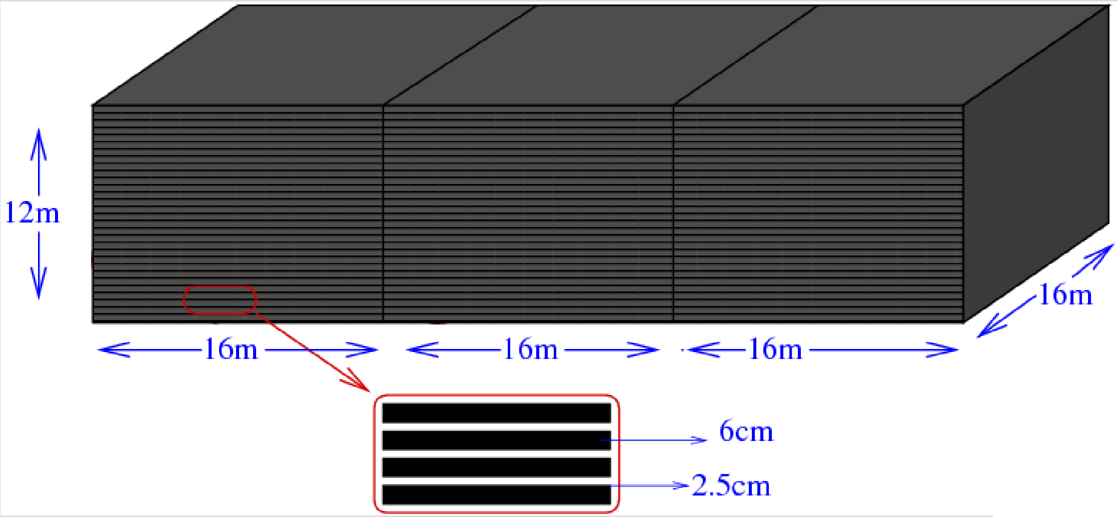
Measurements with *atmospheric neutrinos* and *cosmic muons*

- direct observation of oscillation (fall & rise)
- precision measurement of oscillation parameters
- neutrino mass hierarchy (for $\theta_{13} > 7°$)



- Addressing the θ_{23} octant ambiguity
- Probing CP and CPT violation
- 1-100 TeV cosmic muon flux measurement by e^+e^- pair counting

Schematic of 50 kton ICAL

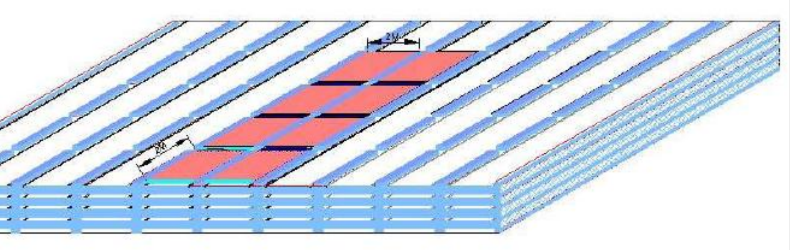


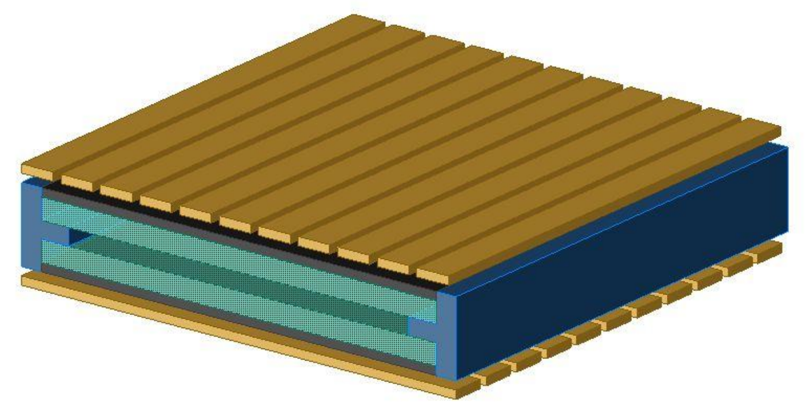
Large Mass

Good tracking and energy resolution

Good directionality

Charge ID





Ease of construction

6cm thick Fe plates

2.5cm gap for RPC trays

2mx2m RPCs interleaved

ICAL Properties

What ICAL can do

✓ Measure ν_μ ($\bar{\nu}_\mu$) induced μ^- (μ^+)

✓ Muon charge identification (~ 95% for E > 1 GeV if large part of track visible)

✓ Muon energy measurement – $\sigma_E \sim 15\%$ at 5 GeV

✓ Muon direction reconstruction – $\sigma_\theta \sim 10\%$

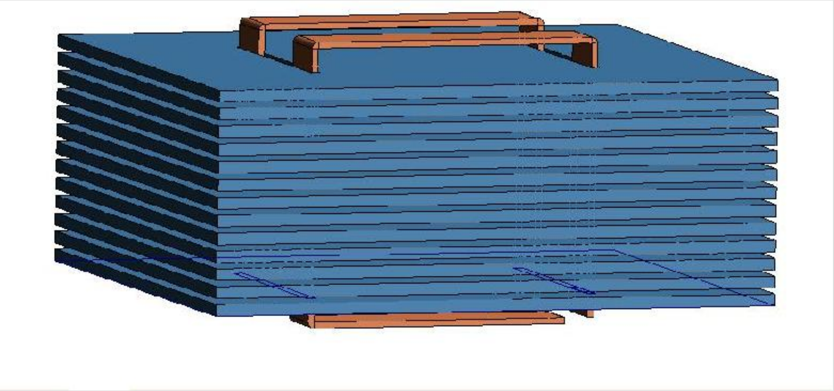
✓ Neutrino L, E reconstruction - $\sigma_E \sim 25\%$, $\sigma_L \sim 18\%$ for atmos. ν_μ

✗ ***Poor*** for ν_e ($\bar{\nu}_e$) since thickness of Fe (6 cm) ~ 3 × L_{rad}

Development of glass RPCs

ICAL Protoype

- Mass 40 tons
- Low carbon steel
- 13 layers iron
- Size 22.5m x 2.3m



RPC size: 1m x 1m

12 layers

About 1000 readout channels

B = 1.5 Tesla

Cosmic rays, Beam test

Present Status

Project Report evaluated, Final financial clearance imminent

Site and infrastructure related DPRs submitted

R&D on glass RPC in progress: size, lifespan,…

Bakelite RPCs also being examined

Design of Magnet module in progress

ICAL prototype being tested at VECC

Vendor development (RPC related) ongoing

Spokesperson & Project Director: N.K. Mondal, TIFR

Further info available at http://www.imsc.res.in/~ino

Other possibilities at INO

Search for 0ν2β in ^{124}Sn via cryogenic bolometer (*feasibility ongoing*)

Nuclear cross sections for astrophysics using 500 kV accelerator (proposal submitted for funding)

Dark matter (DINO)

Life sciences

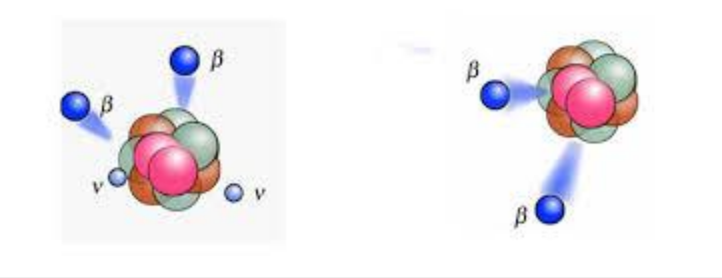
Majorana Neutrino?

- 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!

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

- 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 $2e^-$ invariant mass
- Current limit $\langle m_\nu \rangle < 0.2$ eV.



Fermion mass

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

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

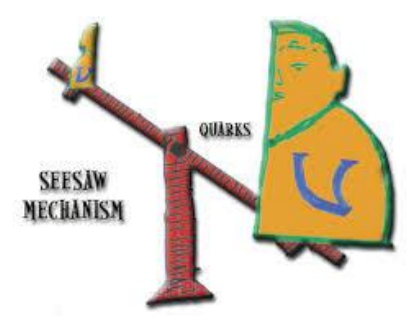
- Fermion mass couples left to right:

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

- 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: $m_\nu = (\mathrm{const})/M$



Simplest new physics

- Left-right symmetric model $\Rightarrow$ ν_R required by symmetry.
- Nature is parity violating. Left-right symmetry is broken at a high energy scale, M_R.
- Neutrino mass matrix: $\begin{bmatrix} 0 & m \\ m & M_R \end{bmatrix}$ M_R » 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?

Supersymmetry

Bosons ⇐⇒ Fermions

Supersymmetry puts bosons and fermions in a supermultiplet ⇒ Superfield: $L \equiv (l, \tilde{l}\,)$, $U = (u, \tilde{u})$

Many attractive features. Search is on for squarks and sleptons.

Interactions written as a superpotential in terms of superfields.

Supersymmetry (contd.)

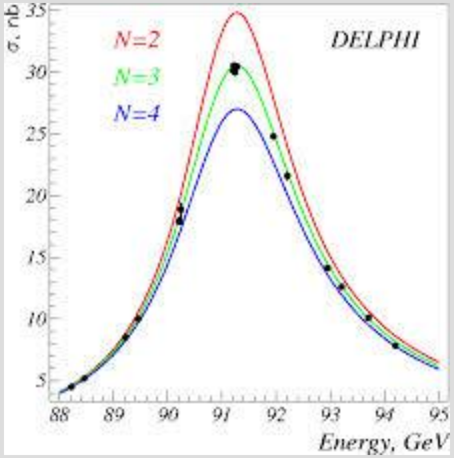
Supersymmetric interactions can violate lepton and baryon number.

Baryon number violation implies proton decay. This is not seen!

Often, an additional symmetry, R-parity, is imposed on the superpotential to exclude *all* baryon number and lepton number violating terms. R-parity conservation requires SUSY particles to be produced in pairs.

However, one can selectively retain L-violating terms to generate a neutrino mass and yet maintain proton stability.

Looking Ahead



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

"Quarks. Neutrinos. Mesons. All those damn particles
you can't see. That's what drove me to drink.
But now I can see them!"

Thank you!!