The Knowns and Unknowns of Neutrinos

RINP2
Visva-Bharati
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Neutrino properties

The dog that did not bark
Radioactive decays

Types: $\alpha$, $\beta$, and $\gamma$ decays

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

- **$\beta^-$-decay:** Inside the nucleus
  \[ n \rightarrow p + e^- + \bar{\nu}_e \]
  \[ X_N^A \rightarrow Y_{N+1}^{A+1} + e^- + \bar{\nu}_e \quad E_\beta \neq M_X - M_Y \]
  (No neutrino would give equality!)

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

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

- High energy $\sim \text{GeV}$ (Giga-electron-volts) $= 10^9 \text{eV}$
- Nuclear binding energy $\sim \text{MeV}$
- Mass of proton $\sim 1\text{GeV}$

- Quantum mechanics: Angular momentum $\sim \hbar$ 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
Neutrino properties

• Neutrino interactions:

No strong interaction, no electromagnetic interaction.

Only weak interactions (2 types: CC and NC)

Cross section $\Rightarrow \sigma \left( \nu_e + e \rightarrow \nu_e + e \right) \sim 10^{-43} \, \text{cm}^2$

c.f. $\sigma \sim 10^{-27} \, \text{cm}^2 \, (\text{em}), \sim 10^{-23} \, \text{cm}^2 \, (\text{strong})$

• Sterile $\nu$: No weak interactions
First neutrino detection (1953)

- Detector: 200 litres of water
- Inverse beta decay $\bar{\nu} + p \rightarrow e^+ + n$
- 40kg of dissolved Cd Cl$_4$

- $e^+$ promptly annihilates: 2$\gamma$
- $n$ is slowed down by Cd
- Then absorbed by Cd
- Delayed photon from Cd $\gamma$-decay
- Coincidences observed.

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

Fred Reines (Nobel 1995)
**Types of Neutrinos**

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 \( \frac{3}{8}” \) gap (Ne gas)
\( \nu_\mu \rightarrow \mu^- \) \( \nu_e \rightarrow e^- : \) No \( e^\pm \) seen

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

**Concept of man-made neutrino beams (1962)**
Neutrino properties (contd.)

Three types: $\nu_e$, $\nu_\mu$, $\nu_\tau$ are known.
A $\nu_e$ is produced from an initial electron (e). Similarly, $\nu_\mu$, $\nu_\tau$ are associated with $\mu$, $\tau$ leptons.

Many properties discovered in the past two decades.
Elementary particles

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 $\nu_R$! Parity violation!

- Masses of $W$, $Z$, quarks and leptons via Higgs mechanism.
- No $\nu_R$ 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
\[ \nu_e + n \rightarrow e + p \]

NC: Neutral current
\[ \nu_x + p \rightarrow \nu_x + p \]
\[ \nu_x + n \rightarrow \nu_x + n \quad (x = e, \mu, \tau) \]

W± exchange
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

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

E ~ 0.1 ~ 20 MeV; Flux ~$10^{12}$/cm²/s
Solar neutrinos

- Sun generates heat and light through fusion reactions
  \[ 4p \rightarrow ^4\text{He} + 2\ e^+ + 2\ \nu_e + 27\ \text{MeV} \]  

- 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.
  \[ p + p \rightarrow ^2\text{H} + e^+ + \nu_e \leftarrow \text{pp neutrinos} \]
  The \( \nu_e \) 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 …

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Reactors 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.
- Excellent source for neutrino experiments.

France, China, Korea and other countries

Daya Bay, China
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)
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 \(\sim 1\) GeV

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

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

No. of \(\nu_\mu\) depends on zenith angle (up-down asymmetry)

No such effect for \(\nu_e\) (1997)
# Solar neutrino results

<table>
<thead>
<tr>
<th>Expt</th>
<th>Obsvd/Predn</th>
<th>$E_{th}$ (MeV)</th>
<th>Type</th>
<th>Equation</th>
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<td>Homestake</td>
<td>0.335 ± 0.029</td>
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-Ray Davis
Nobel: 2002
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<td>SNO NC</td>
<td>1.008 ± 0.123</td>
<td>2.2</td>
<td>$\nu + d \rightarrow n + p + \nu$ (NC)</td>
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A.B. McDonald

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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 $\nu_e$ becomes a $\nu_\mu$ and then back again to a $\nu_e$. This oscillation process continues.

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

**Maximal mixing**

$\theta = \pi/4$

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

$c = \cos \theta$

$s = \sin \theta$
Neutrino oscillations (contd.)

How does this help?

- Solar neutrino detectors look for $\nu_e$. Some (Cl, Ga and SNO CC) are totally insensitive to $\nu_\mu$, $\nu_\tau$. SK has a smaller sensitivity (about 1/6) to other types. Only SNO NC is equally sensitive to all. If some $\nu_e$ have oscillated to a $\nu_\mu$ when they reach the detector then they will not be seen (except in SNO NC). Count will be less.

- Atmospheric $\nu_e$, $\nu_\mu$ are detected through the $e^-$, $\mu^-$ they produce. At their higher energies, the $\nu_e$ hardly oscillates, while the $\nu_\mu$ oscillates to $\nu_\tau$, which do not produce $\mu^-$. This reduces the measured ratio $R$. Also, the zenith angle dependence seen for $\nu_\mu$ is explained.

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

Stationary states: \( H |\Psi_n> = E_n |\Psi_n> \)

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

General state (t=0): \( |\Psi(0)> = \sum a_n |\Psi_n(0)> \)
General state (any t): \( |\Psi(t)> = \sum a_n \exp(-iE_n t) |\Psi_n(0)> \)
Phase differences \( \sim (E_i - E_j) t \) \( \rightarrow \) physics consequences

Neutrino stationary states: \( |\nu_1>, |\nu_2> \)
(mass eigenstates)

Neutrino flavour eigenstates: \( |\nu_e>, |\nu_\mu> \)

Mass \( \leftrightarrow \) Flavour states:
\[
|\nu_e> = |\nu_1> \cos\theta + |\nu_2> \sin\theta \\
|\nu_\mu> = -|\nu_1> \sin\theta + |\nu_2> \cos\theta
\]
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: $|\Psi(t)\rangle = |\nu_1\rangle \cos \theta e^{-iE_1t} + |\nu_2\rangle \sin \theta e^{-iE_2t}$

$$\text{Prob}(\nu_e \rightarrow \nu_\mu, L) = |<\nu_\mu|\Psi(t)>|^2 = 4 \ c^2 \ s^2 \ |e^{-iE_1t} - e^{-iE_2t}|^2$$

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

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

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

Survival Prob. $= \text{Prob}(\nu_e \rightarrow \nu_e, L) = 1 - \text{Prob}(\nu_e \rightarrow \nu_\mu, L)$
More on $\nu$ 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)
  $\nu_e$ 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)
  $\nu_\mu$ oscillates to $\nu_\tau$

  $m_e = 5,000,000$ 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):

![Triangular diagram with neutrino symbols](image)

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

The phase $\delta$ 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!

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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°57’N, 77°16’E (Bodi Hills)

Near TamilNadu-Kerala border

1km rock coverage

V.M. Datar

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Can the neutrino be its own anti-particle? ($\nu \equiv \nu^c$?)
The photon is its own anti-particle. (Also $\pi^0$)

In such an event, lepton number is not conserved!

A 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 ($0\nu2\beta$) : $X \rightarrow Y + 2 \; e^- \quad (\propto \langle m_\nu \rangle^2)$

Look for peak in $2e^-$ total energy

Current limit $\langle m_\nu \rangle < 0.2 \; \text{eV}$.
Sterile neutrino?

\[ \text{Prob}(\nu_\mu \rightarrow \nu_e, L) = 4 \, c^2 \, s^2 \, \sin^2 \left( \frac{\Delta \, L}{4\,E} \right) \]

\( \Delta = m_2^2 - m_1^2 \) 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 \( (m s_{\nu_2}^2 - m_{\nu_1}^2) \)

LSND Experiment (1995) used a \( \nu_\mu \) beam from \( \pi^+ \) decay and observed oscillations. \( L = 30 \, \text{m}, \, 36 \, \text{MeV} \leq E \leq 52.8 \, \text{MeV} \) \( \Rightarrow \Delta \approx 1 - 10 \, \text{eV}^2 \)

Is this result correct?

MiniBooNE (2018) with \( L \approx 0.5 \, \text{km} \) and \( 200 \, \text{MeV} \leq E \leq 1250 \, \text{MeV} \) get similar results

Note \( (L/E) \) is similar. \( 4^{\text{th}} \) sterile neutrino?

M.R. Janani

Does not match with solar and atmospheric neutrino!
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)
- 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,
6.7$\sigma$ signal $E \sim 16 - 53$ 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 $\nu_R$ to the SM.

- This solves the problem but has no explanation of the smallness of $m_{\nu}$.

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

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:
  $$
  \begin{pmatrix}
  0 & m \\
  m & M_R
  \end{pmatrix}
  \quad M_R \gg m
  $$

- Two Majorana neutrinos: $\nu_L$ (mass $m_\nu$), $\nu_R$ (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

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

Takaaki Kajita (Japan) &
Arthur B. McDonald (Canada)
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

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Thank You!