MODULE-3

- Solar Neutrino Puzzle
- Atmospheric Neutrino Puzzle
- Neutrino Oscillation Phenomena

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Neutrino Physics

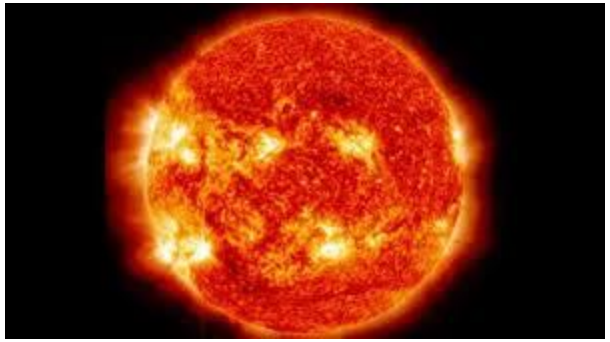
Why do we study Neutrino Physics?

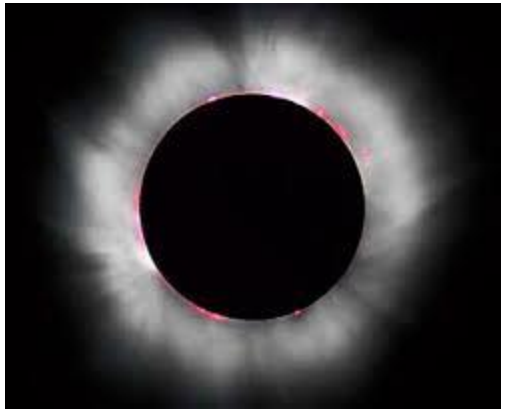
Our sun generates its power output through a chain of nuclear fusion reactions which begin with

$$p + p \rightarrow d + e^{+} + \nu_e$$

$$\text{Spin:} \quad \frac{1}{2} \quad \frac{1}{2} \quad 1 \quad \frac{1}{2} \quad \frac{1}{2}$$

Conservation of angular momentum ensures the existence of neutrinos in the above equation. Without the hypothesis of neutrino the above reaction would not have occurred and the nuclear fusion chain at the core of the sun would not have started. Hence, instead of shinning glow of the Sun we would have seen a dark Sun.





Properties:

- Spin -$\frac{1}{2}$ fermion obeying Pauli's exclusion principle
- Belong to Lepton families and exist in three flavours : $\nu_e,\ \nu_\mu\ ,\nu_\tau$
- Having tiny mass
- Neutrinos being very weakly interacting particles escape detection or very hard to detect through ordinary matter.
- According to the SM, neutrinos are assumed to be massless as only left-handed neutrinos exist, no right-handed ones.
- They travel almost at the speed of light in vacuum.
- Existence of tiny neutrino mass indicates that there must be Physics beyond the SM.
- Neutrinos take part in the Weak Interactions and Gravitational interactions. They being neutral do not participate in EM interactions.
- Nuclear $\beta\ -$ decay phenomena proves the existence of neutrinos which shows parity violation. It was experimentally verified around 1956 by Wu's experiment.

Sources:

- Nuclear Reactors
- Particle Accelerators
- Cosmic Rays Showers
- Supernovae and Neutron stars

→ Controlled Energy ν

→ High Energy ν

Detectors: Radiochemical & Chrenkov

Topics :

1. **Solar Neutrino :** Neutrinos produced at the core of the Sun due to thermonuclear fusion reactions.
2. **Atmospheric Neutrino :** Neutrinos produced by collision between cosmic showers and particles in atmosphere.
3. **Neutrino oscillation:** A neutrino created with a specific flavor can transform into other flavors.

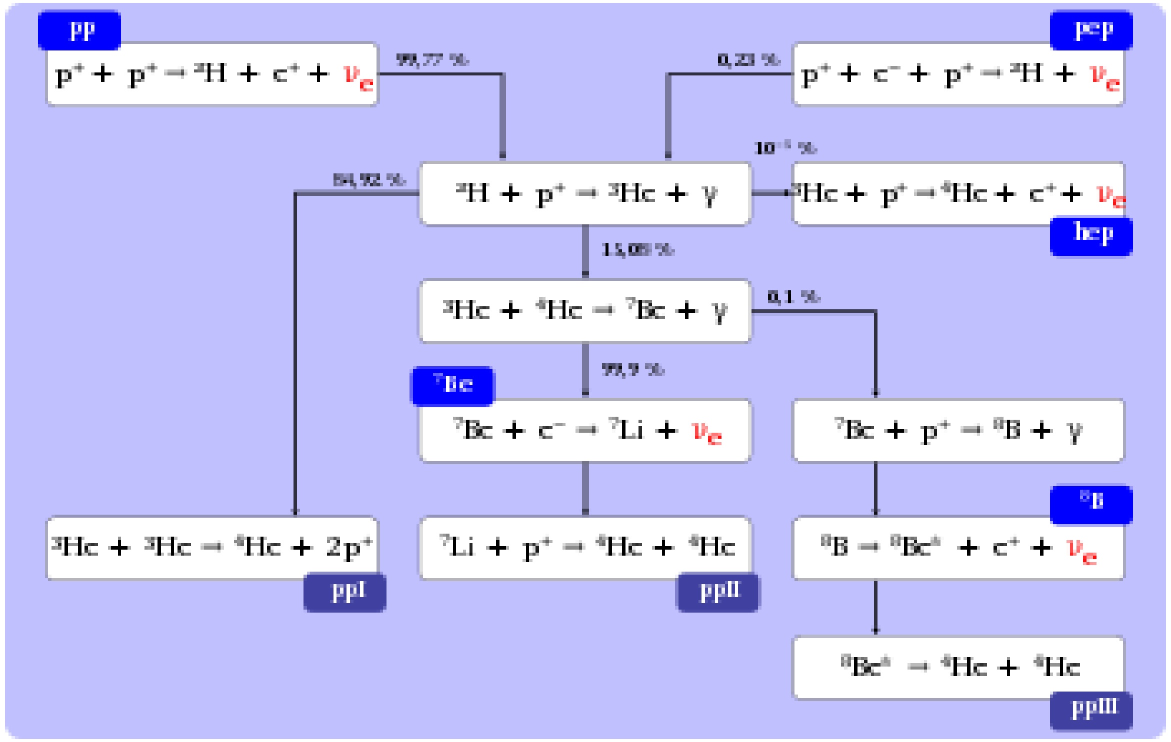
Solar Neutrinos
&
Solar Neutrino Problem

The Sun is a copious source of electron neutrinos (ν_e). These ν_e's are produced in the core of the Sun due to thermonuclear fusion reactions that generate solar energy. The underlying nuclear process is :

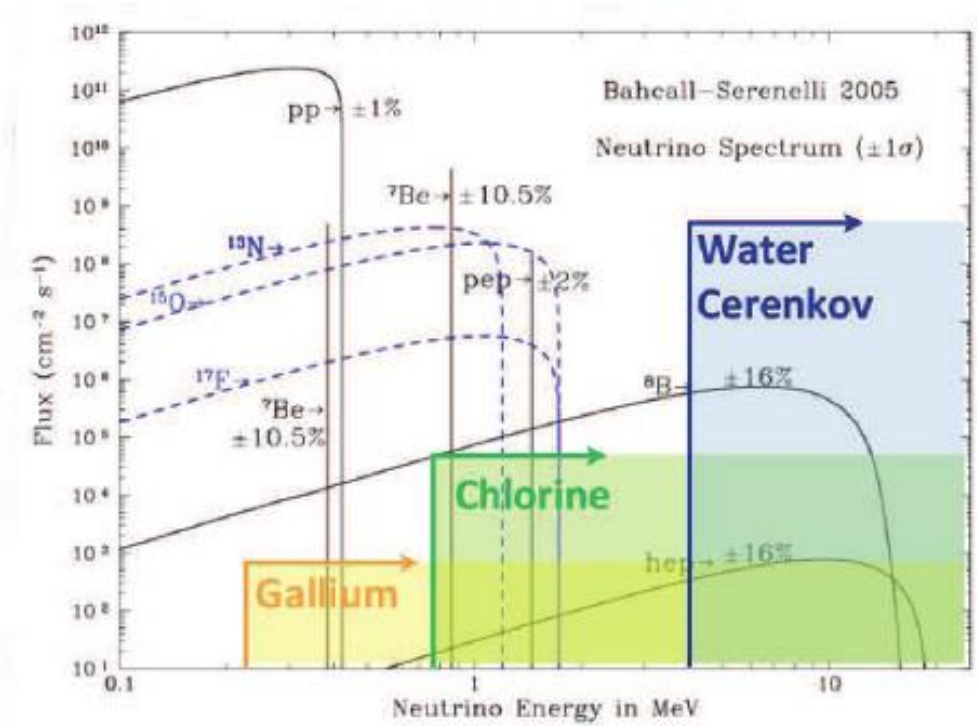
$$4p \rightarrow \alpha + 2e^{+} + 2\nu_e + 25\ MeV \quad \text{---------} \ (1)$$

About 98% of the total energy released is in the form of heat and light. Rest is carried by the neutrinos. Photons get scattered and re-scattered by interaction with solar matter and takes about 10^4 years to come out.

ν_e's being weakly interacting, it takes about 8 minutes to reach Earth's surface from the Sun. Thus neutrinos carry information about the Sun's interior.



- The main reaction for production of solar neutrinos is given by Eq. (1). The reaction is the effective process driven by a cycle of reactions, e.g., pp – chain (see the previous figure) or the CNO cycle .
- The SSM is the model used for neutrino flux calculations and this model was developed by Bahcall and his collaborators. They estimated solar neutrino fluxes.



- Solar neutrino spectrum represents neutrino flux vs neutrino energy.
- pp chain produces high ν_e-flux having small neutrino energy.
- B^8 produces low ν_e-flux having large neutrino energy.
- Low energy neutrinos are detected using Gallium, Chlorine or Water as detector material for ν_e detection.
- The target (i.e.,detector materials) is exposed to the Sun and the product is extracted using radiochemical techniques.

Detection of neutrinos is the most difficult task! Why? Weakly interacting particle
Typical requirements are : Large detector volume; High detection sensitivity; Low background events

Radiochemical Detectors

Neutrino energy and direction of ν_e's can not be determined.
Chemical separation of product nuclei is difficult .

$$Z^A + \nu_e = (Z+1)^A + e^-$$

The Cl^{37} Experiment (**Homestake Experiment**)
The Ga^{71} Experiments (**SAGE, GALLEX,GNO**)

Chrenkov Detectors

Direction of flight of ν_e can be determined.
The recoil e-energy gives information about the incident ν_e energy.

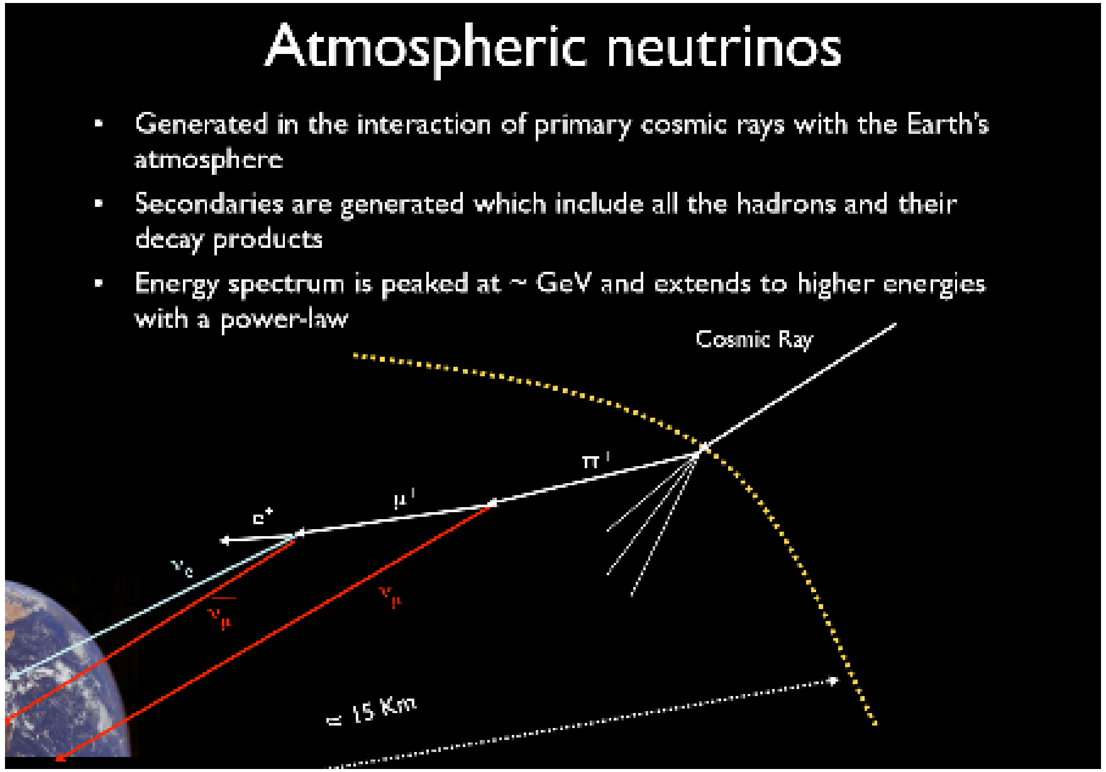
$$\nu_e + e^- \rightarrow \nu_e + e^-$$

Charged leptons produced from ν_e interactions produce Chrenkov light.
The Kamiokande Experiment
SuperKamiokande Experiment
The Sudbury Neutrino Observatory (SNO)

Solar neutrino flux measured is **one third to half** of that expected from the SSM. This phenomenon of deficit in number is known as **Solar Neutrino Problem**. The **Kamiokande Experiment** not only confirmed the deficit problem but also verified that the captured ν_e's are of solar origin.

Atmospheric Neutrinos
&
Atmospheric Neutrino Problem

Atmospheric Neutrino Problem



Atmospheric neutrinos are produced in the collision of primary cosmic rays (typically protons) with nuclei on the upper atmosphere. This produces a shower of hadrons, mostly pions. The decay of pions finally lead to ν_e and ν_μ according to the following reactions:

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu)$$
$$\mu^{\pm} \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$

Based on this simple decay chain shown above, one predicts a flux ratio of muon neutrinos to electron neutrinos as $2:1$. The anomaly in the atmospheric neutrino flux predicted from theoretical calculations and estimated from observed data is known as ***Atmospheric Neutrino Problem***.

Solution to Solar Neutrino Problem

The Sun produces only electron type neutrinos through nuclear fusions. When neutrino detectors became sensitive enough to measure the flow of electron neutrinos from the Sun, the number detected was much lower than predicted. In various experiments, the deficit was between one half and two third. According to **neutrino oscillation** phenomenon if one of the neutrino flavors transform into the other flavors during their journey from the Sun to the Earth, and neutrino detectors placed are capable of identifying all flavors of neutrinos, the discrepancy goes away and thus the problem is solved.

Solution to Atmospheric Problem

The Atmospheric Neutrino Problem can be resolved if we further invoke the idea of neutrino oscillation. This discrepancy was confirmed by many experimental groups like Kamiokande , SuperKamiokande and SNO. However, if the detector can detect all flavors of neutrinos, the discrepancy goes away and hence, the problem is solved

Neutrino Oscillation

Two Flavour Neutrino Oscillation

Flavour eigen states : $|\nu_e\rangle \quad |\nu_\mu\rangle$

Mass eigen states : $\quad |\nu_1\rangle \quad |\nu_2\rangle$

Let us assume, at $t = 0$, a beam consisting of only $|\nu_e\rangle$

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

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

At some latter time t, the flavor eigen state $|\nu_e(t)\rangle$ becomes (in natural unit system, $c = 1; \frac{h}{2\pi} = 1$)

$|\nu_e(t)\rangle = cos\theta|\nu_1\rangle e^{-iE_1 t} + sin\theta|\nu_2\rangle e^{-iE_2 t}$

Where mass eigen states at some latter time t are defined as :$|\nu_i(t)\rangle = e^{-iE_i t}|\nu_i\rangle$ with $i = 1 - 2$.

Probability of transforming a pure $|\nu_e\rangle$ beam at $t = 0$ to a $|\nu_\mu\rangle$ beam at latter time t (during which the distance travelled, L $\approx ct$) is defined by $P_{\nu_e \to \nu_\mu} = \left|\langle\nu_\mu|\nu_e(t)\rangle\right|^2$

$$\langle\nu_\mu|\nu_e(t)\rangle = \left(-sin\theta\langle\nu_1| + cos\theta\langle\nu_2|\right)\left(cos\theta|\nu_1\rangle e^{-iE_1 t} + sin\theta|\nu_2\rangle e^{-iE_2 t}\right)$$

$$= -e^{-iE_1 t}sin\theta cos\theta + e^{-iE_2 t}sin\theta cos\theta \;\; ; \text{ using } \langle\nu_i|\nu_j\rangle = \delta_{ij}$$

$$P_{\nu_e \to \nu_\mu} = \left|\langle \nu_\mu | \nu_e(t) \rangle\right|^2$$

$$= \left(-e^{iE_1 t} sin\theta cos\theta \; + e^{iE_2 t} sin\theta cos\theta\right)\left(-e^{-iE_1 t} sin\theta cos\theta \; + e^{-iE_2 t} sin\theta cos\theta\right)$$

$$= 2\sin^2\theta\cos^2\theta - \left(e^{i(E_1-E_2)t} + e^{-i(E_1-E_2)t}\right)\sin^2\theta\cos^2\theta$$

$$= \frac{1}{2}\sin^2 2\theta(1 - \cos(E_1 - E_2)\,t)$$

$$= \sin^2 2\theta \sin^2 \frac{(E_1 - E_2)}{2} t \quad \text{---------------------------- (1)}$$

ν's being moving with velocity approximately equal to c, i.e., in ultra-relativistic limit, E $\approx p$.

Therefore, $E = \sqrt{p^2 + m^2} = p\left(1 + \frac{m^2}{p^2}\right)^{\frac{1}{2}} \approx p + \frac{m^2}{2p} \approx p + \frac{m^2}{2E}$

Now $E_1 - E_2 \approx \frac{m_1^2 - m_2^2}{2E} = \frac{\Delta m_{12}^2}{2E}$; $E_1 \approx E_2 \approx E$

Here we are using Natural unit system which is clear from the above relativistic energy equation. In this system we choose, $c = \hbar = 1$, i.e., $L = T = M^{-1}$

From Eq. (1) we get,

$$P_{\nu_e\to\nu_\mu} = \sin^2 2\theta \, \sin^2\left[\frac{\Delta m_{12}^2}{4E} L\right] \text{ ----------- } (2)$$

$$= \sin^2 2\theta \, \sin^2\left[1.27 \times \frac{\Delta m_{12}^2 (eV^2)}{E(GeV)} L(Km)\right]$$

In SI system the argument of 2nd sinusoidal term in Eq. (2) is

$$\left.\frac{\Delta m_{12}^2}{4E} L\right|_{Nat} = \left.\frac{\Delta m_{12}^2}{4E} L\left(\frac{c^3}{\hbar}\right)\right|_{SI}$$

$$= \frac{\Delta m_{12}^2 (eV^2)}{4E(GeV)} L(Km) \times \left[\frac{1}{5.6\times 10^{35}}\right] \times \left[\frac{1}{1.6\times 10^{-10}}\right] \times [10^3] \times \left[\frac{(3\times 10^8)^3}{1.05\times 10^{-34}}\right]$$

$$= 1.27 \times \frac{\Delta m_{12}^2 (eV^2)}{E(GeV)} L(Km)$$

Problem : Show that the conversion factor of the argument is $\left(\frac{c^3}{\hbar}\right)$.

- The probability of transformation is non-zero when $\Delta\mathrm{m}^2 \neq 0$ which implies that neutrinos are not massless.
- L denotes the position of the detector w.r.t the source.
- The probability would be maximum when $\theta = \frac{\pi}{4}$
- The oscillation period is $1.27 \times \frac{\Delta\mathrm{m}_{12}^2}{E} L \approx 2\pi$
- $\frac{\Delta\mathrm{m}_{12}^2}{E} L \ll 1$ gives non-oscillation region.
- $\frac{\Delta\mathrm{m}_{12}^2}{E} L \approx 1$ gives the region of appreciable oscillation.
- $\frac{\Delta\mathrm{m}_{12}^2}{E} L \gg 1$gives the region of average effect.
- The absolute values of neutrino masses can not be predicted from the oscillation phenomena.

If neutrinos from a reactor have energy $E \approx 1\ GeV$, and $\Delta\mathrm{m}_{12}^2 \approx 0.1\ eV^2$, the detector should be placed at a distance of $\approx 12Km$. [$1.27 \times 0.1 \times L = \frac{\pi}{2}$; $L = 3.14 \times \frac{10}{2.54} \approx 12Km$]