Elementary Particle Detection and Neutrino Oscillation

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Elementary Techniques of Particle Detection Using Coincidence

1. Introduction:

Everything in the universe is made up of some basic fundamental particles, the building blocks of matter. To understand the world we should first understand these particles and it is only possible through their detection by 'Particle Detectors'. When certain radiation falls on a matter full or a part of its energy gets transferred to it. The basic working principle of the detector is to convert this transferred or deposited energy to some detectable form that allow us to sense it. One of the well-known and widely used such detector called 'Scintillator' is discussed in the following sections. The various properties of it when exposed to a high energy radiation, how it works have been analysed through some series of experiments.

1.1 Elementary Particles:

One of the basic ways to categorise these particles is through their charge. It is easier to detect the charged particles rather than the neutral ones as the charged particles interact with the detecting materials through direct interaction.

Standard model of particle physics consists of twelve elementary particles (six quarks and six leptons) and their anti-particles. Three leptons (Light mass) are charged (electron, muon and tau) and three are neutral (electron neutrino, muon neutrino, tau neutrino). Quarks possess fractional charge. Six flavours of quarks are up, down, strange, charm, top and bottom. All the baryons (heavy mass: proton, neutron, lambda etc) and mesons (middle mass: pions, kaons, eta etc) are made up of quarks. Baryons are formed by three quarks while mesons consist of one quark and one anti- quark. Each type of particles interacts by different force interactions discussed below.

1.2 Fundamental Forces of Nature:

Four fundamental forces dominating our nature are Strong force, Electromagnetic force, Weak force and Gravitational force. Each type of these interactions between particles is mediated by some mediator bosons (spin zero or integral spin). Leptons mainly interact through weak interaction mediated by W or Z boson while the quarks are subjected to strong interaction carried by gluons. Electromagnetic force is mediated by photons and gravitational force by hypothetical particle graviton.

Each particle carrying some electrical charge is influenced by electromagnetic field which makes it easily detectable. For any massive particle gravitational influence exists though its effect is negligible compare to other forces.

1.3 Scintillators:

Scintillator detectors rely on the emission of photon when exposed to incoming radiation. The scintillating material used for detection has the fluorescence property that enables it to emit the deposited energy as a small flash of light (scintillation).

Fundamental working principle of scintillator is following

I. High energy particle beam ionizes the medium.
II. Ionized electrons slow down causing excitation.
III. Excited electron comes down to normal state through emission of photon.
IV. The collected light is converted into electrical signal and amplified by PMT connected with the scintillator.
V. Electrical signal is processed further and analysed.

Scintillator detectors possess a fast response and recovery time which makes it highly acceptable in modern particle physics experiments. The scintillating media which are in use can be of six types: organic crystals, organic liquids, inorganic crystals, gases, glasses and plastics. Plastic scintillating medium consists of solid solutions of luminescent plastic solvent in a transparent plastic medium.

1.4 Photomultiplier Tube (PMT):

Scintillating material coupled with the photomultiplier completes the detector. PMT converts the weak light output produced in the scintillator into a comparatively amplified electrical signal.

It consists of a photosensitive cathode, a string of dynodes and an anode. Electrons are liberated from cathode by photo-electric effect. Dynodes are kept at increasing high voltage ladder which helps the avalanche of electrons. An incoming photon incident on the photocathode produces photo electrons. Electrons are then directed and accelerated towards the first dynode because of the voltage applied where they transfer some of their energy to produce secondary electrons. All electrons are then directed towards the second dynode for further amplification in the same process. Total electrical signal is then collected through the anode for further processing and analysing.

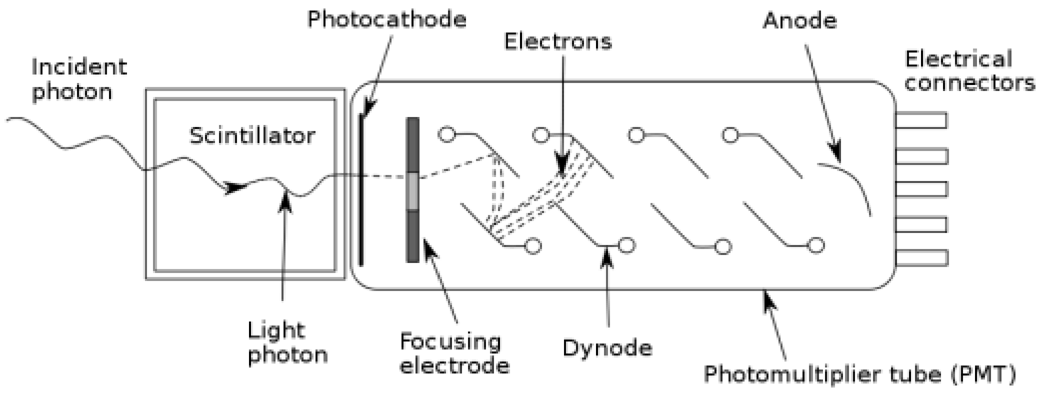


Figure 1: Block diagram of a PMT coupled scintillating detector (source: wikipedia)

1.5 Scintillating Paddle:

Using plastic as a scintillating material is advantageous because of its high availability, cheap cost and flexibility. One of the greater requirements of scintillator is to collect the light signal with minimum loss of transmission and absorption. That is why in plastic scintillating paddle internal reflection is enhanced by smoothing the surfaces of it.

An aluminium foil is used to cover the paddle for better reflection. It reflects the light transmitted through the paddle surfaces back into the paddle. A black tape is wrapped around it to provide isolation from ambient light.

Apart from the reflection another concerned issue is to guide the light from paddle to PMT with minimum loss. Light guide of suitable shape is connected with the paddle which guides the light by internal reflection between its walls to the PMT.

A Cookie is used to couple the light pipes to the PMT which is made up of the same material as that of the light guide.

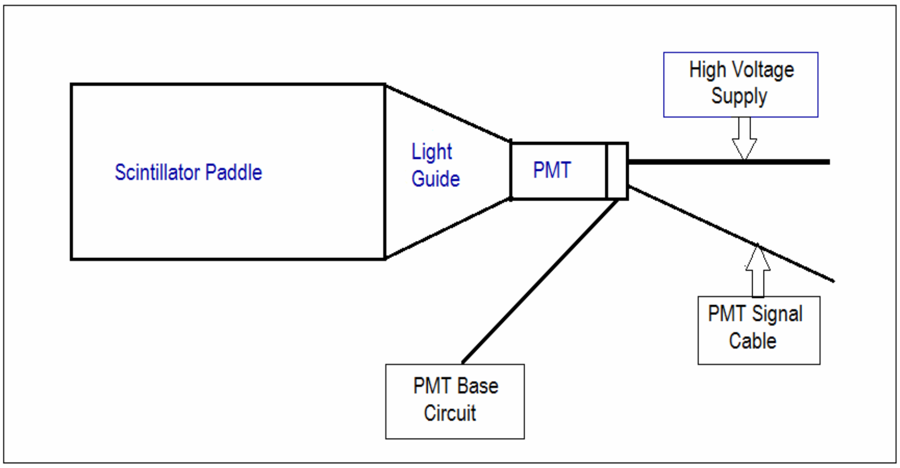


Figure 2: Basic components of Plastic Scintillators Paddle

2. Coincidence Experiment:

A coincident signal is basically an overlapping of two incoming signals. The experimental set up consists of two crossed scintillating paddles. One of the aspects of this experiment is to differentiate between the true and accidental coincidences which might be coming from photomultiplier noises. It also differentiates the desired radiation from its background.

Specifications of the two crossed paddles:

Width of both paddles = 2 cm

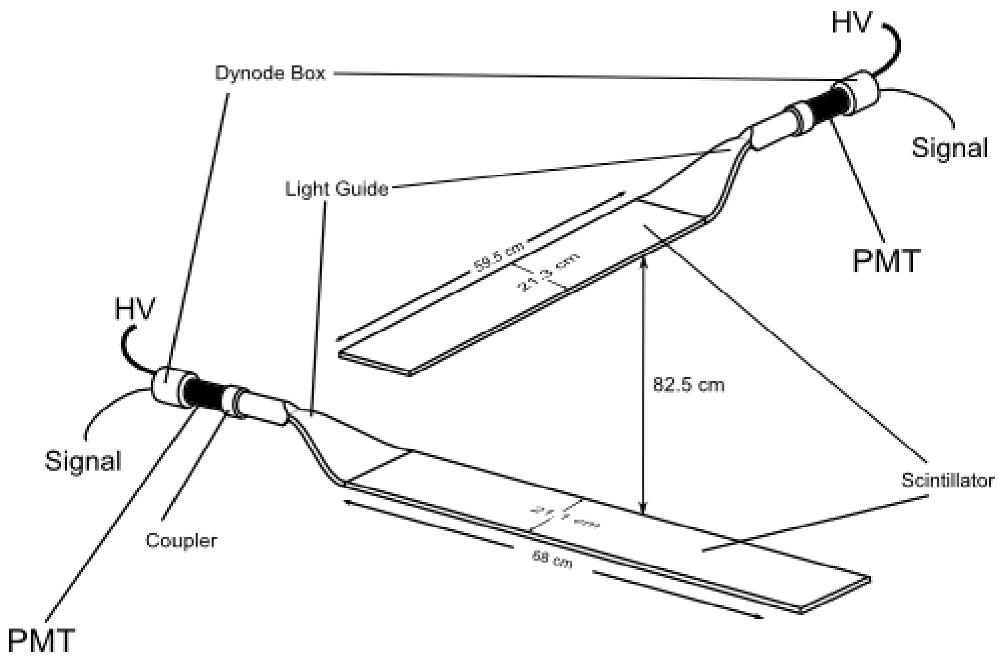


Figure 3: Dimensions of the two paddles used in coincidence setup

Set up:

A series of electrical components are used to character the PMT signals which are electrically amplified image of the light output coming from the paddles.

The block diagram of the coincidence set-up is:

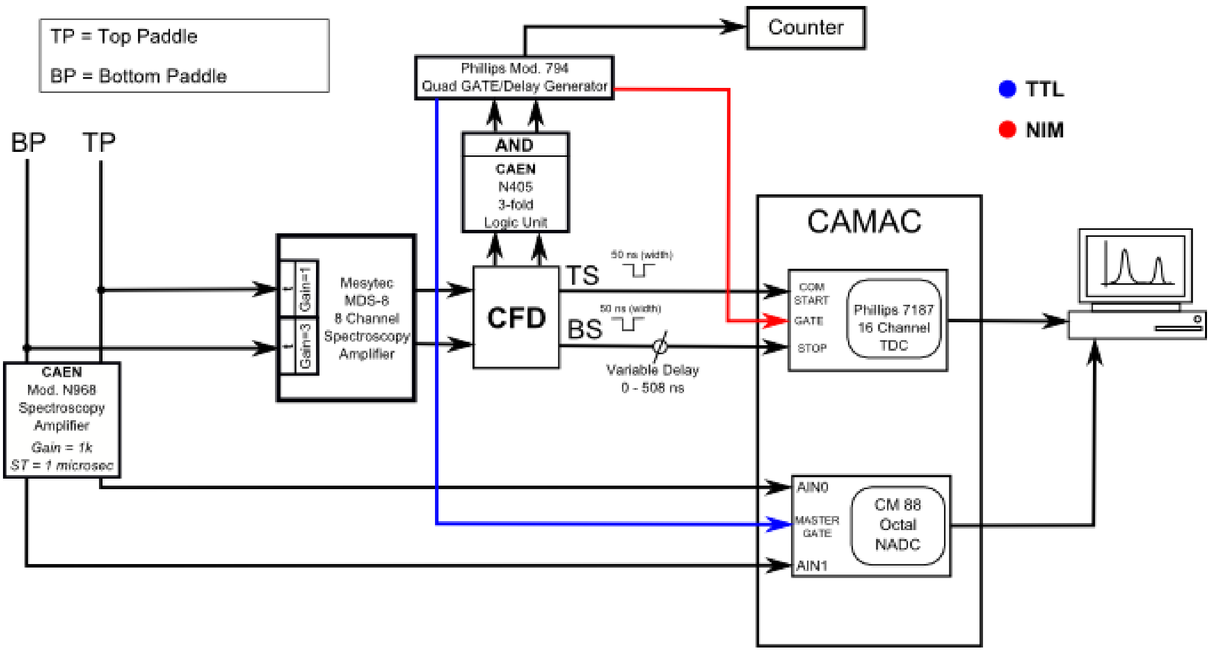


Figure 4: Block Diagram of Coincidence Set-up

2.1 NIM (Nuclear Instrument Module):

NIM is a modular system that is a collection of basic electronic components like amplifier, discriminator etc. It is highly flexible and provides the facility to interchange of each component without affecting the whole set-up. A standard NIM can accept 12 single-width modules (width 1.35 inch and height 8.75 inch) or less multiple-width modules. The basic components of NIM module used for time of flight coincidence set-up are discussed briefly.

Spectroscopy Amplifier:

Spectroscopy amplifier amplifies the PMT signals further and gives a pulse for ADC (Analog to Digital Converter) to operate without causing much loss of the raw signal. It also provides minimum sensitivity of the output to the variations of detector rise time and decorates the output with maximum signal to noise ratio.

Discriminator:

The constant fraction discriminator splits the input timing signal into two branches. One gets attenuated and the other being inverted and delayed. Finally the two branches are being summed up to produce the output logic signal which will be independent of the input pulse height. A threshold is also set to cut the background noise.

Delay Generator:

Delay is introduced between the START (Coming from upper scintillator) and the STOP (generates from lower one) pulses.

Logic Unit:

The Logic Unit AND-ed the signals that is, when the both signals coming from the two PMT overlap, it generates a coincident signal.

2.2 CAMAC System:

CAMAC (Computer Automated Measurement and Control) is sketched for computer disciplined data acquisition.This software based system is reliable and capable of controlling large event rates.

ADC:

A copy of the signals from spectroscopy amplifier are directly fed to the ADC (Analog-to-Digital Converter) which in turn converts the amplitude of the signal voltages to a proportional channel no.An ADC is defined by its resolution power (band with) and the signal to noise ratio which decides how accurately it measures the signal.

TDC:

Time-to-digital converter is basically used for time-interval measurement. The time interval between two consecutive events is converted into a digitized channel no. by a fixed factor (calibration constant).

So any unknown radiation when processed through it, it can give an idea about the time distribution of the incident radiation by means of its calibration constant.

Display Scaler:

It displays the graphical representation of the time distribution curve from TDC in terms of counts versus channel no. of TDC. Similarly deposited energy distribution in both the scintillating paddles also visualized through it in a similar fashion.

3. Coincidence of cosmic muons:

Though cosmic ray consists of variety of particles (muons, electrons, neutrinos, and their antiparticles etc) almost 80% of the cosmic ray particles reaching earth surface is muons. Muons itself is unstable and decays into an electron and two neutrinos with half-life 2.2 μs. Due to the high energy of the cosmic ray muons (GeV order) they will usually not be stopped by single detector paddle. So there is greater probability of getting simultaneous pulses from the two crossed scintillating paddles. Coincidence is being used to count the muon events in a way to distinguish them from the background radiation as well as photomultiplier noise.

Energy Spectra of cosmic ray muons:

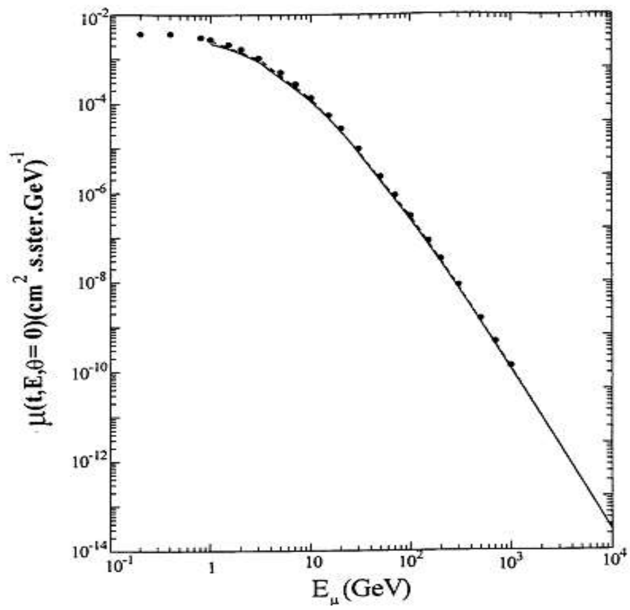


Figure 5: Atmospheric Muon Flux at sea level

The muon flux at sea level for zenith angle zero (θ=0) is shown in figure. The received energy of muons at sea level is in the range of 1 to 10^4 GeV. The most probable energy for the incoming muon flux is around 1 GeV.

ADC spectrum:

ADC spectrum of a particular measurement is shown. It follows a landau distribution.

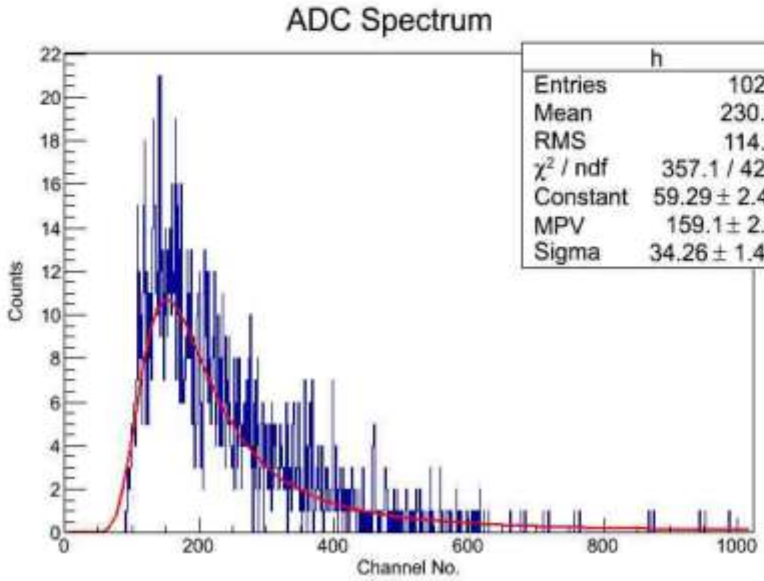


Figure 6: ADC Spectrum of incident cosmic cay muons

Two Dimensional Plot of Energy, Time Correlation:
Energy versus time distribution for the upper scintillating paddle is shown in figure 7.

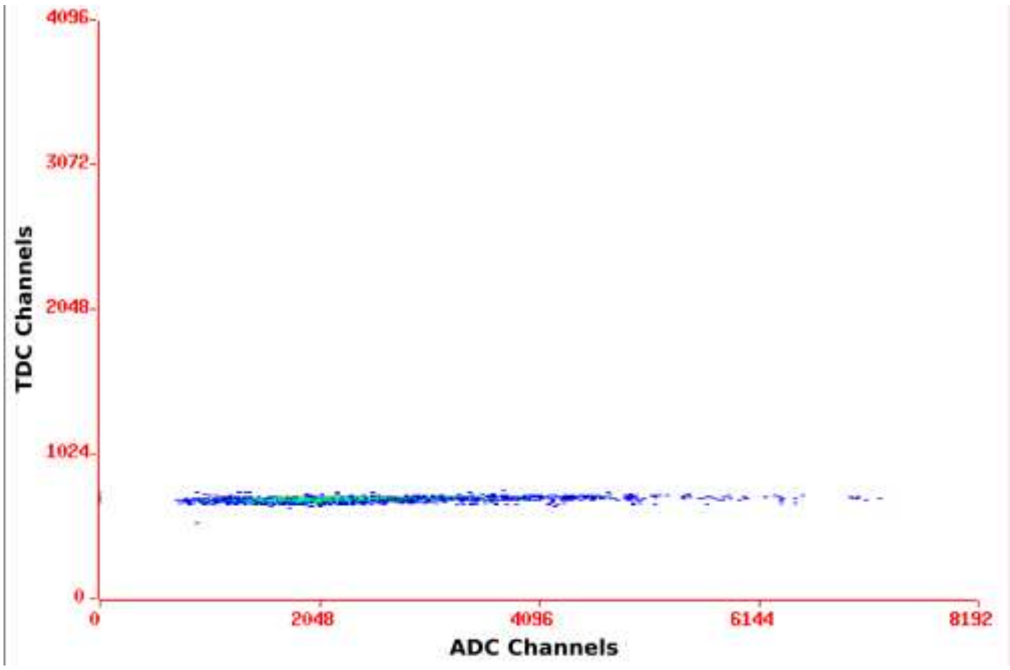


Figure 7: ADC versus TDC channel no. for the upper paddle

The x and y projection of this plot give us the corresponding ADC spectrum and TDC spectrum. For the lower paddle the nature of the plot is same as the upper one.

3.1 Scintillator plateau:

Keeping one PMT at a fixed voltage and by varying the voltage of the other one we can see how the count rates have been changed. During this experiment the upper scintillator was kept at 1870 volts and the voltage of the lower one is varied upto 1880 volts. The time duration for the counts to be registered for each set of voltage was 100s.

Graphical result of count rates versus PMT voltage is shown below in Figure 8.

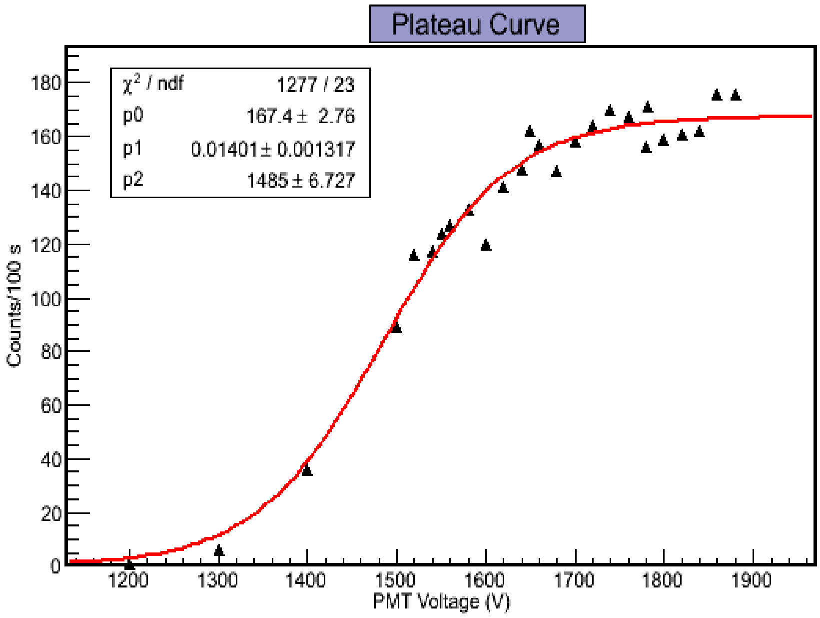


Figure 8: Plateau curve for one photomultiplier tube

Conclusion:

Up to 1200 volts no counts were registered. But with the increase of voltage further lower channel had started counting and count rates were increased rapidly until it reaches a saturated state or plateau region (above 1700 volts). Both PMT should be operated in the middle of this plateau range so that any drift of the PMT characteristics does not influence the counting ability of the whole detector.

3.2 Calibration of TDC:

The time delay between the start and the stop signal was varied in the delay generator by a known interval of 30 ns. The peak channel no. of the TAC Curve was shifted inward in accordance with the decrement of delay time.The proper timing of the signals can be verified by observing the counting rate versus changes in the relative delays of pulses.

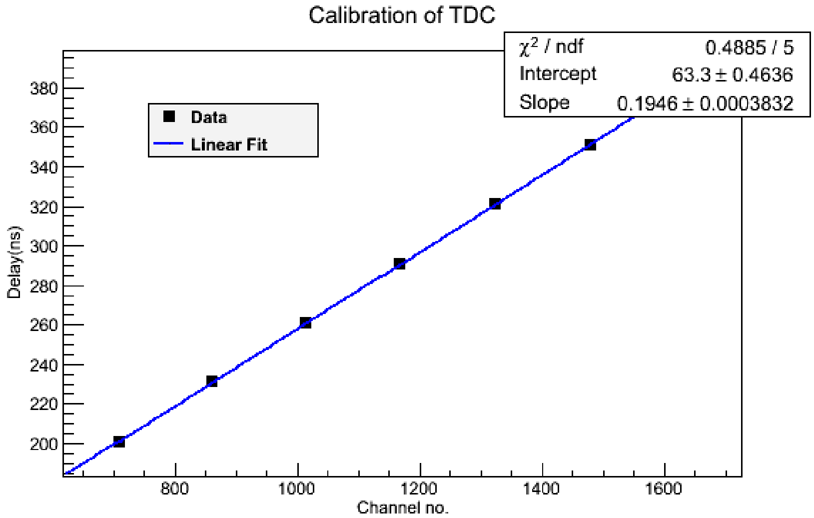


Figure 9:

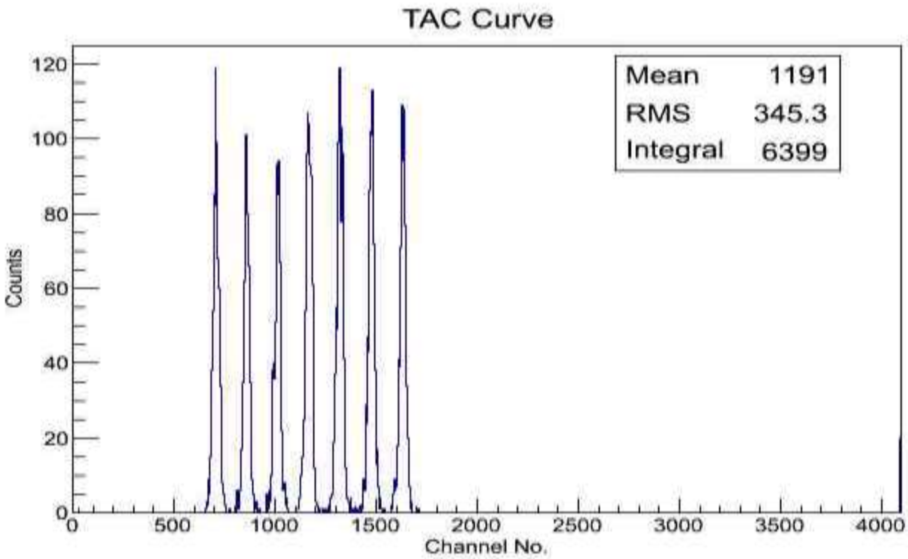


Figure 10:

The Figure 10 corresponds to seven individual distributions for seven different time delays. Each distribution follows some Gaussian form. Total counts for all seven distributions are indicated by the integral value shown in the graph.

Time resolution of TDC:

Calibration constant = 0.1946 ns/channel.

FWHM of the TAC curve= (33 * 0.1946) ns

= 6.4 ns

3.3 Linearity of PMT:

Peak channel no. of the landau distribution of ADC spectra corresponds to the most probable deposited energy. Varying the voltage of a single PMT we can see the variation of this peak channel no. It is depicted from the following figure that the variation is almost linear which is desired.

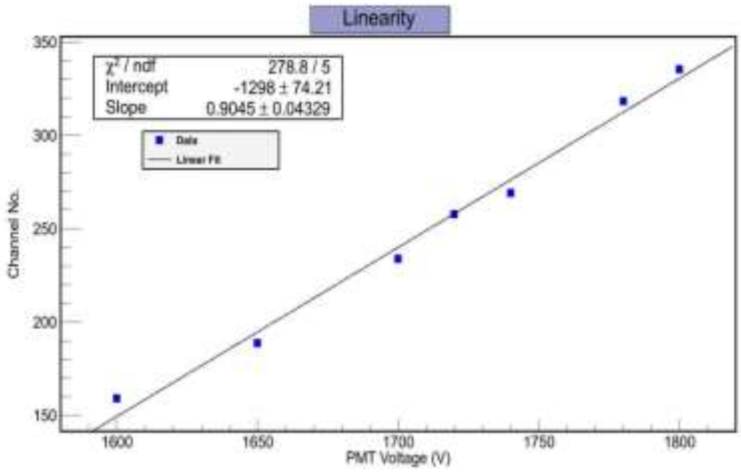


Figure 11: Linearity of Photo-multiplier tube

4. Coincidence of Gamma ray:

4.1 ^{22}Na: a positron emitter:

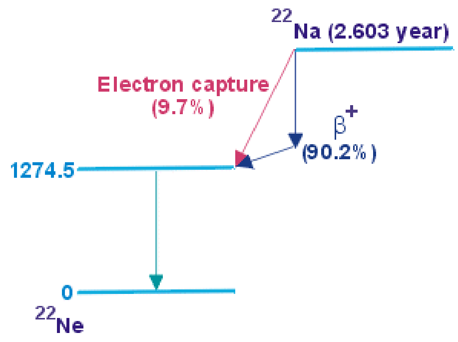
^{22}Na is a radioactive isotope of sodium which decays through various processes. The decay of ^{22}Na is dominated by emission of positron (positive electron) by 90.2%. While passing through the matter emitted positron (β^+) continuously loses its energy before coming to rest and is being capturedby the surrounding electrons of the matter. Two oppositely directed gamma rays of energy 0.511 MeV each are being produced by the annihilation of electron-positron.

$$e^- + e^+ = \gamma + \gamma$$

^{22}Na can also decays through electron capture (9.7%) and produces excited ^{22}Ne which in turn de-excites through the emission of a 1.27 MeV photon.

$$^{22}Na + e^- = {}^{22}Ne + \gamma \ (1.27 \text{ MeV})$$

The decay processes are shown in the figure beside.



4.2 Procedure:

The two photons produced by the electron positron annihilation can be detected by the coincidence set up discussed above. To examine the change of coincident count we have put the source in different positions and recorded the data for analysing. In this case one photon was detected by the upper scintillator and the other through the lower one.

The same coincidence setup mentioned above has been used to see the coincidence of gamma-rays. The coincident events were not only because of the photon coincidence but also include the cosmic ray muons.

PMT voltage:

Upper channel = 1870 volts

Lower channel = 1900 volts

Discriminator threshold voltage = 5 mV.

Due to the low Z of the detecting material (plastic scintillators) threshold was reduced to 5mV (primarily set to 30 mV) to see the coincidence.

4.3 Experimental Data:

Count rates per 100 s at different position of the source are listed below.

I. On the upper scintillator: 4735
II. Near the upper paddle: 1725
III. At middle of the paddles: 1382
IV. Near the lower paddle: 1692
V. On the lower scintillator: 4167
VI. Muon coincidence rate: 301

The variation of the coincidence counts rate is proportional to the product of the two solid angles (Ω_1 , Ω_2) subtended by the source to both the detectors when placed in between the two detectors and the strength of the source (S) that is $r_{12} \alpha \Omega_1\Omega_2 S$.

Now if d be the distance between the detectors and x and (d-x) are the distances of the detectors from the source then the functional variation of r_{12} is given by

$$r_{12} \alpha 1/(x^2(d-x)^2)$$

Graphical variation is shown in the Figure 12.

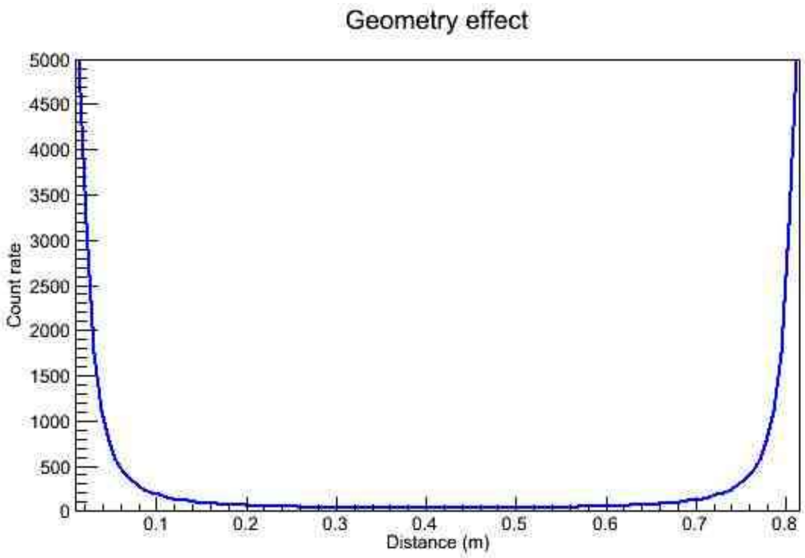


Figure 12:

Here the distance is the separation of the source to a particular detector. Considering d = 0.825 m. Therefore

$$r_{12} \alpha 1/(x^2(0.825-x)^2)$$

It is shown that the count rate of coincidence is lowest when we place the source in the middle of both the detectors. But as we move the source toward the detectors the counts rate becomes very large. This is in accordance with the experimental data

4.4 Geometry Effect:

Typical dimensions of the two scintillator paddles are: Lower Paddle (68cm, 21.1cm**,** 2cm) and the upper one (56.5cm, 21.3cm, 2cm) and they are vertically separated by 82.5cm .As both the scintillators are perpendicular to each other so when we put the source in the middle of them the solid angles covered by outgoing photons are not same for both which produces a low coincident count rate. As we go nearer to the paddles due to the geometrical effect exposed area of the paddles increases which in turn increase the counts. But when we place the source on any one of the paddles we have got the maximum events. It is because a huge flux passes through that specific paddle and at the same time almost the whole area of the other scintillating paddle is being exposed to the gamma rays and giving rise to a very high counts. For the same reason the counts is larger for the source kept on upper paddle as the area of the lower paddle is comparatively larger.

5. Angular Distribution of Muons:

5.1 Introduction:

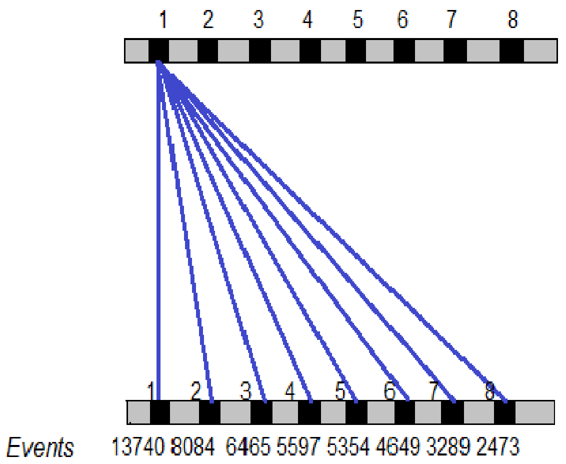
It is found that the vertical intensity of cosmic ray muons is larger than in the inclined direction and more or less it is found to obey $\cos^2\theta$ law where θ is the inclination angle with the vertical direction.

The angular distribution of secondary cosmic ray muons is demonstrated by the following experiment. Measurement of the coincident muon flux with inclination angles gives us an idea about whether muon intensity strictly follows the $\cos^2\theta$ law or not.

5.2 Set up:

Same coincidence technique is used to examine the angular distribution of muons. Sixteen scintillating paddles, eight in the upper plane and eight in the lower plane is mounted on the hodoscope. Each paddle is coupled with two PMTs on both end of it for better efficient result. Rest of the electronics are same as time of flight set up using two paddles discussed above. 50,000 registered coincidence counts were analysed for the muon angular dependence.

5.3 Experimental Data:



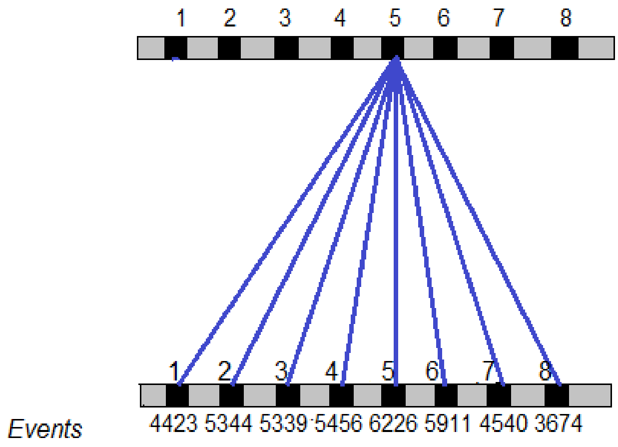


Figure 13(a): Figure 13(b):

The coincidence of first scintillation paddle of the upper plane with all the lower paddles is depicted in Figure 13(a). Similarly coincidence counts of the 5th upper scintillator with all lower ones are shown in Figure 13(b).

From the above figures it is explained that the events are maximum for the vertically aligned paddles i.e. 1st $\rightarrow$1st, 5th $\rightarrow$5th with zero inclination angle (θ=0).

5.4 Graphical Results:

The counts versus inclination angle curves for both data-set are shown below.

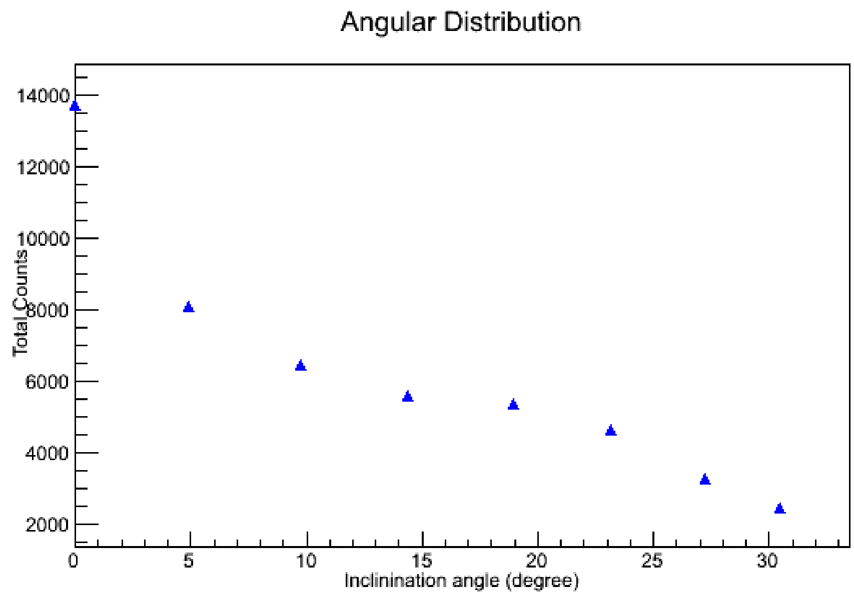


Figure 14: Counts versus Inclination angle for 1st upper with all lower paddles

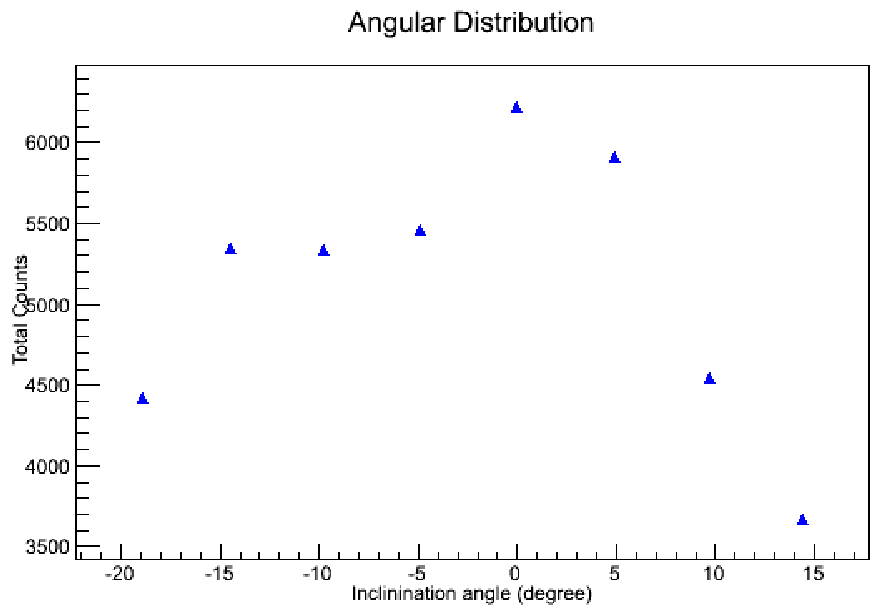


Figure 15: Counts versus Inclination angle for 5th upper with all lower paddles.

Neutrino Flavour Oscillation

Introduction:

In the way of exploring the origin of universe, neutrinos are the most abundant particle ever discovered. Our entire knowledge of the base of matter relies on the Standard Model of particle physics. But the discovered property of changing identity (oscillation) of neutrinos cannot be justified by the standard model theory which enforces the requirement of major changes in it. The basic properties of neutrinos, their oscillation (2-flavour) are being discussed in the following sections.

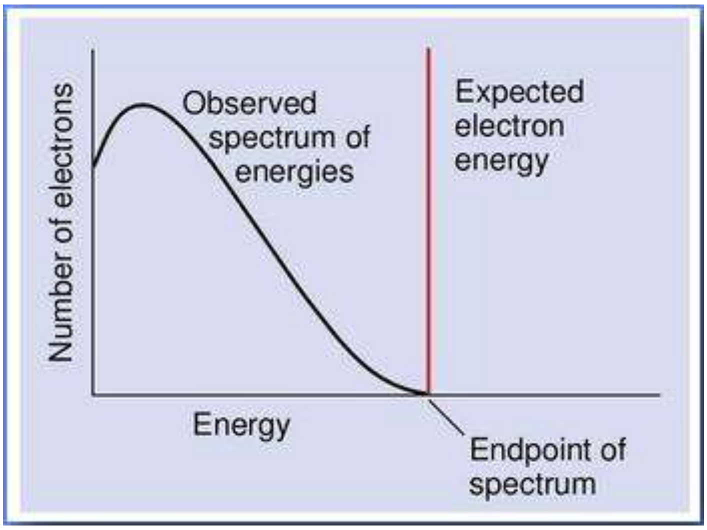
What is Neutrino?

"Neutrino is the most tiny quantity of reality ever imagined by human being"….F. Reines.

In modern particle physics Standard Model allows us to describe the particles of matter and the way they interact. Among all the fundamental particles included in Standard Model, Neutrino so called 'ghost particle' is the least understood mysterious particle. According to Standard Model twelve particles are the base of matter. Six quarks: up, down, charm, strange, top and bottom quark and six leptons: electron, muon, tao and three neutrinos (electron neutrino, muon neutrino and tao neutrino). Each charged lepton is being associated with its corresponding neutral neutrino.

Discovery of Neutrino:

The existence of neutrino was first predicted by Wolfgang Pauli in 1930 to rescue the endangered conservation laws in nuclear beta decay. When a parent nucleus decays into a daughter nucleus with emission of an electron, the electron energy should be fixed. But experiments showed a continuous energy spectrum which violates the universal conservation laws of energy and momentum.



(Source: www.cobra-experiment.org)

Pauli suggested that the total energy (energy difference between parent and daughter nucleus) is being carried by the electron and an associated neutral particle (Neutrino). We know now that the particle coming out in the nuclear beta decay process with electron is an anti-neutrino. After 25 years of its prediction, existence of neutrino (electron neutrino) was experimentally verified by F. Reines and C. Cowan in 1956.

Basic Properties of Neutrino:

Neutrinos are charge less (neutral) and lightest lepton (spin ½ particle). They exist in three flavours. Though in standard model neutrinos are considered to be massless particle, the small but non-zero mass (less than one millionth of the mass of the electron) of the neutrino is now experimentally verified which allow their flavour oscillation that is neutrinos of a particular flavour can oscillate into other flavours without any external influence.

Undetectable Neutrinos:

Neutrinos are concerned with the weak interaction which allows them to pass through the whole world without any deviation. Because of their neutrality they are not influenced by the electromagnetic interaction and smallness of their mass makes them unaffected by the gravity. That is why neutrinos are undetectable by direct measurement. They can only be observed through indirect measurement of their corresponding charged leptons.

Neutrinos can interact by the charged and neutral current interaction.

I. Neutral Current Interaction: It is mediated by the exchange of Z boson. In this process neutrino can transfer some of its energy and momentum to the target particle of the medium. If the target particle is charged and light weight can obtain a high speed emitting 'Cherenkov radiation' which can be directly measured but the flavour information of the neutrino will be lost in this way.

II. Charged Current Interaction: It is caused by the exchange of charged W boson. Neutrino in this case creates its partner charged lepton but it should have sufficient energy to create the partner's mass. The partner lepton can be detected which will give us information of the neutrino's flavour.

Sources:

We live in the Neutrino Sea. The biggest source of neutrino is our sun which produces a neutrino flux of almost 60 billion per cm^2 per sec. Different neutrino sources and their energy order are following.

I. Solar neutrinos (1 MeV): Neutrinos coming from the sun.

II. Atmospheric neutrinos (1GeV): Neutrinos produced in cosmic background.

III. Supernovae neutrinos (10 MeV): Coming from supernovae (SN 1987A).

IV. Geo neutrinos (0.1 MeV): Coming from earth.

V. Artificial neutrinos (MeV- GeV): Neutrinos coming from reactors (MeV) and different high energy experiments.

Apart from these we have relic neutrinos from cosmic neutrino background of energy in meV range. Recent research is going on the search for sterile neutrinos, the 4^{th} neutrino.

Neutrino mass:

Standard model assumes that neutrinos are massless. But the experimental investigations of neutrino flavour oscillation prove the existence of massive neutrinos. If neutrinos are massless or equal mass particles no oscillation is possible. But oscillation is now experimentally proved phenomenon. So, different flavours of neutrinos have different masses.

Masses of neutrinos of the 3-flavour is listed below

I. Electron Neutrino < 2.2 eV

II. Muon Neutrino < 170 keV

III. Tao Neutrino < 15.5 MeV

Neutrino Oscillation:

A neutrino produced with a fixed flavour can change its identity while travelling that is, it can be transformed into another flavours without any external influences. The idea of oscillation was put forward by Pontecorvo in 1957 (neutrino-antineutrino oscillation). Flavour transition was first considered by Maki, Nakagawa and Sakata in 1962.

Flavour of neutrino is not fixed as it is determined by a linear combination of three mass eigen state. As neutrino propagates the amplitude of different mass eigen states in that particular flavour state oscillates which in turn causes the flavour change. The mixing between neutrinos mass and flavour eigen states are determined by the mixing angle.

Mathematically it is described below:

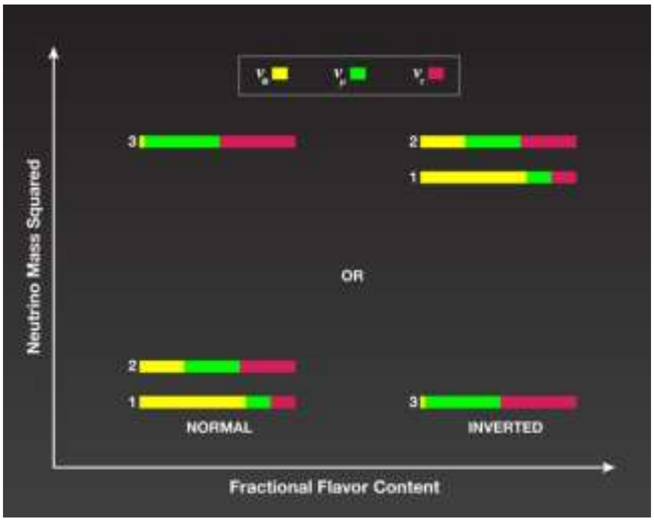
$$|\nu'_a\rangle = U^*_{ai}\,|\nu_i\rangle$$

The flavour eigen states on the L.H.S is related to the mass eigen states on the R.H.S by a unitary transformation. For 3-flavour mixing summation of *i* is over 1,2,3.

Neutrino Mass Hierarchy:

Neutrino flavour mass is determined by the contribution of three mass eigen values (m_1 , m_2 , m_3) corresponding to three mass eigen states (ν_1 , ν_2 , ν_3). From experimental aspects we can only measure the flavour states not the mass states of neutrinos and from oscillation probablity the mass squared difference (Δm^2). According to our current knowledge $m_2 > m_1$ and the difference between them is small as $(\Delta m^2)_{21}$ is positive and small. But experimental measurements show that mass squared difference m_2 , m_3 is quite large and as the exact value of the masses are not known we don’t know wheather m_3 is smaller or larger than m_1 ,m_2. This leads to the hierachy of neutrino mass having two possibilities: $m_3 > m_2 > m_1$ which is called normal hierarchy and $m_2 > m_1 > m_3$ called inverted hierarchy.

Both normal and inverted hierachy and the proportions of the mass eigen states in a particular flavour state are depicted in the following figure.



(Source : Ref.8)

2-Flavour Oscillation:

The simplest case of neutrino oscillation is to consider the oscillation between two neutrino species for example electron and muon neutrino. For two-flavour oscillation only two mass eigen states have been considered.

Linear superposition of flavour and mass eigen states is:

$$\begin{pmatrix} |\nu_e > \\ |\nu_\mu > \end{pmatrix} = U \begin{pmatrix} |\nu_1 > \\ |\nu_2 > \end{pmatrix} = \begin{pmatrix} U_{\alpha 1} & U_{\alpha 2} \\ U_{\beta 1} & U_{\beta 2} \end{pmatrix} \begin{pmatrix} |\nu_1 > \\ |\nu_2 > \end{pmatrix}$$

Where U is a unitary transformation matrix given by

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

Where θ is the mixing angle.

Oscillation probability for 2-flavour case:

Let us consider that a source is producing a particular flavour of neutrino flux say $\nu\mathbf{e}$ .The probability that another flavour say ν_μ can be detected at the detector placed at some distance(L) is given by

$$\mathbf{P(\nu_e \rightarrow \nu_\mu \, ; \, L) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 \, L/E);}$$

Where Δm^2 in eV^2 , L is in km and E in GeV or L is in m and E in MeV

Mixing angle θ:

The mixing angle θ determines the difference of mass to flavour eigen states. For θ=0, the oscillation probablity will be zero i.e flavour and mass eigen states will be the same. In this case a particular neutrino type will propagate from source to the detector without any flavour transition. Same situation will occur for θ=90. The maximal oscillation will occur for θ=45 when one flavour neutrino will oscillate into other flavour at some point along the path between source and the detector.

The probablity amplitude of oscillation is determined by the value of $\sin^2 2\theta$.

Mass squared difference (Δm^2):

For two flavour oscillation only two mass eigen states have been considered with eigen value say m_1 and m_2. Mass squared difference is then defined by $\Delta m^2 = m_1^2 - m_2^2$. The probablity will remain same for both positive or negetive value of Δm^2. For $\Delta m^2 = 0$,no oscillation will occur. This leads to the fact that neutrino must be massive and mass states must have different masses.

The phase of the probablity is given by the factor Δm^2 (L/E).

The factor L/E:

This factor plays an important role in controlling the oscillation experiment. Here L is the distance between the source and the detector, E is the energy of produced neutrino. If we consider a particular value of Δm^2 then the phase of probablity will completely depend on this ratio (L/E) which can be adjusted to build our experimental setup to be maximally sensitive to the oscillation probablity. Rather we can configure our setup such that

$$1.27 \times \Delta m^2 \times (L/E) = \pi/2$$

$$\text{Or,}\quad L/E = \pi/(2.54\ \Delta m^2)$$

Survival Probablity:

If we start with a particular neutrino flavour then the probablity of detecting the same at the detector is called survival probablity.

$$\begin{aligned} P(\nu_e \rightarrow \nu_e; L) &= 1 - P(\nu_e \rightarrow \nu_\mu ; L) \\ &= 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2\ L/E) \end{aligned}$$

In case of 'disapearance experiment' where we start with a particular type and see how many neutrinos have been lost before reaching the detecor, survival probablity is being measured. On the oth2er hand apearance experiment where we see how many other type neutrinos are being detected, oscillation probablity is considered.

Oscillation and Survival Probablity of Neutrinos:

I. Let us consider a particular set of parameters: $\sin^2 2\theta$=0.8 corresponding θ=31.73 degree , energy of the electron neutrino E_ν = 4 MeV and the mass squared diffrence $\Delta m^2 = 2.43 \times 10^{-3}$ eV^2.

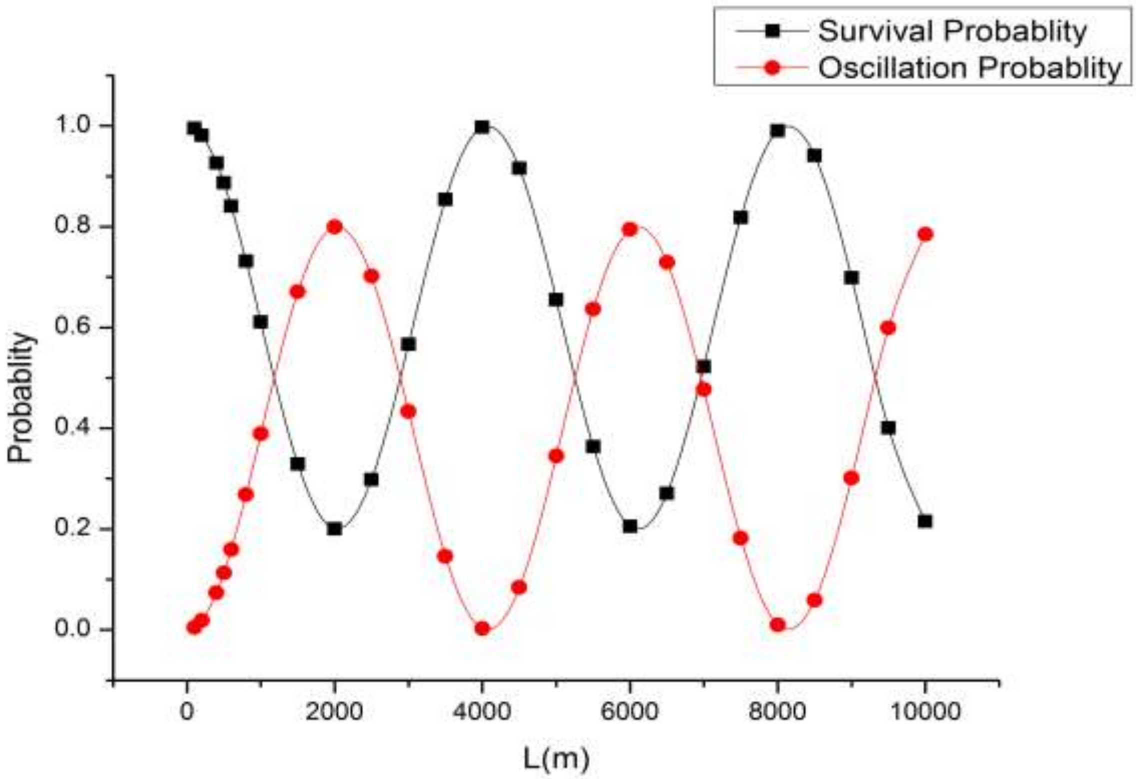
At L=0, the oscillation probablity is zero but corresponding survival probablity is one. As the value of L increases the oscillation begins to increase until it reaches the first maximum value at

$$(1.27 \times 2.43 \times 10^{-3}/4) \times L = \pi/2$$

Or, $$L= (\pi \times 1000 \times 4)/(1.27 \times 2.43 \times 2)$$

Or, $$L = 2035.96 \text{ m}$$

At this point oscillation is maximum. As the amplitude of oscillation $\sin^2 2\theta = 0.8$, so 80% of the intial neutrinos have oscillates away at this maximal mixing. As L increases further the oscillation dies at L= (2035.96 x 2)m = 4071.92 m where the flux is entirely composed of its intial flavour.

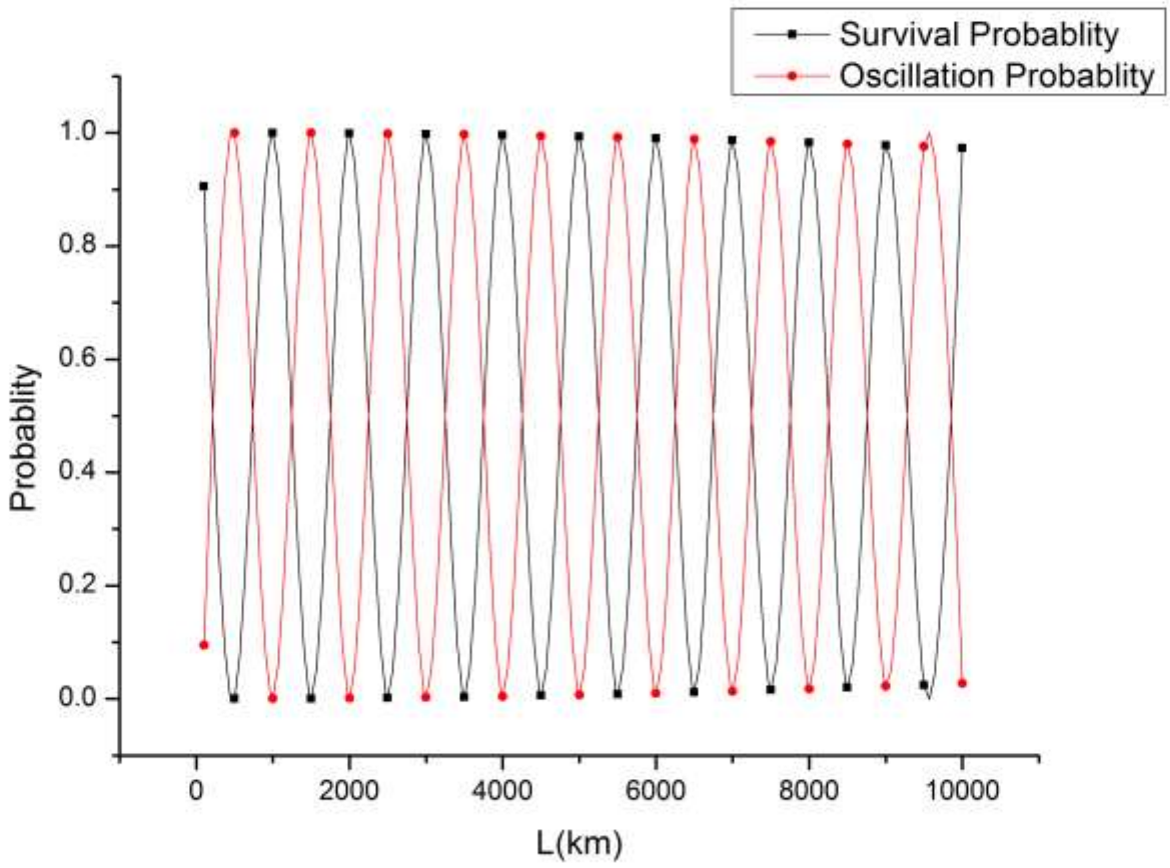


II. The oscillation and survival probability of neutrinos specified by the following parameters are shown below.

Maximal mixing angle, $\theta_m = \pi/4$, amplitude of the oscillation is $\sin^2 2\theta_m = 1$.

Energy of the neutrino, $E_\nu = 1$ GeV

Mass squared difference, $\Delta m^2 = 0.0025\ eV^2$



At L=0 km, the oscillation probability (P_{osc}) is zero and the survival probability (P_{sur}) is maximum i.e we have started with a fixed flavour of neutrinos coming from the source. As they travel the probability of oscillation increases with decrement of P_{sur}. First maximum of P_{osc} occurs at

$$(1.27 \times 0.0025/1) \times L\ (km) = \pi/2$$

Or, $$L = 494.49 \text{ km}$$

At this point oscillation has its maximum value. As the amplitude of the oscillation is one ($\sin^2 2\theta_m=1$), 100% of the neutrino flux oscillates away at this point leaving no information about the initial neutrino flavour.

At L = (494.49 x 2) km = 988.98 km, $P_{sur} = 1$ and initial flavour fluxes can be obtained here without any oscillation phenomenon. In this way oscillatory nature of both probabilities propagates with the propagation of the neutrinos.

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