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Neutrino Astronomy

Ashmita Panda[1]★
[1]*National Institute of Science Education and Research (NISER), Bhubaneswar, India*

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ABSTRACT

Neutrinos are subatomic particles with no charge and almost zero rest mass that interact only via gravity and weak interaction. Neutrino Astronomy aims to study astrophysical objects by observing the neutrinos emitted from them. Due to their negligible interaction with matter, neutrinos are unlikely to scatter from their trajectories like photons. So they can be used to study phenomenon invisible to optical telescopes. Also, as neutrinos hardly scatter, they provide very strong directional information. In this report, first the theory of neutrinos is summarised, followed by a discussion on various astrophysical neutrino sources and neutrino detectors. To conclude, simulations and results from neutrino experiments, especially IceCube Neutrino Detector have been added.

Key words: Neutrinos – IceCube Neutrino Detector – Ultra-high energy neutrinos

1 INTRODUCTION

Neutrino astronomy is the branch of astronomy which aims to study astrophysical objects by observing the properties of the neutrinos emitted from them. Neutrinos are subatomic particles with no charge and almost negligible mass (Zuber 2020). They interact to other standard model particles weakly only via the weak interaction and gravity. They make excellent astronomical telescopes because due to their negligible interactions, they are unlikely to scatter from their trajectory like photons do. The give very strong directionality information, and can be used to probe phenomenon invisible to optical telescopes.

Neutrinos on Earth can be obtained from various sources. Cosmic rays hitting the atmosphere of the Earth produces a cascade of particles, primarily mesons like pions which decay into muons and muon anti-neutrinos. The muons in turn decay into electrons, electron anti-neutrinos and muon neutrinos (Zuber 2020). The nuclear chain reactions, namely the pp and the CNO cycle for energy production inside stars like the Sun also produce neutrinos as their by-products (Zuber 2020). Thus, we observe a flux of solar neutrinos on Earth. Ultra-high energy neutrinos can be obtained from various astrophysical sources, like supernovae, gamma-ray bursters, active galactic nuclei (AGN) and so on (Zuber 2020; Mé száros 2017).

Such ultra-high energy neutrino fluxes have been detected on Earth by the IceCube Neutrino Observatory (Gaisser & Halzen 2014), which is a one cubic kilometer Cherenkov neutrino detector built on Antarctic ice near the Amundsen-Scott South Pole Station.

In this report, I will briefly discuss the theory of neutrinos as standard model particles. I will then describe the various astrophysical sources of ultra-high energy neutrinos, following it up with a discussion of the IceCube detector working principles and results. To conclude, I will summarise the results and discuss the future prospects of Neutrino Astronomy.

★ E-mail: ashmita.panda@niser.ac.in

2 NEUTRINO PHYSICS

2.1 Neutrinos as Standard Model Particles

Neutrinos are leptons, i.e., spin-1/2 particles of the standard model which satisfy the Dirac equation (Zuber 2020).

$$i\gamma^{\mu}\partial_{\mu}\psi - m\psi = 0 \tag{1}$$

μ runs from 0 to 3. γ^{μ} represents the 4×4 Dirac matrices, one for each value of μ and ψ is the four component spinor representing the neutrino.

$$\gamma_0 = \begin{pmatrix} \mathbb{1} & 0 \\ 0 & -\mathbb{1} \end{pmatrix} \qquad \gamma_i = \begin{pmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{pmatrix} \tag{2}$$

Here, σ_i represent the Pauli matrices and $\mathbb{1}$ is the identity matrix.

It is electrically neutral with a rest mass almost equal to zero. It takes no part in strong interactions. Due to the short range of the weak force and negligible gravitational interaction on account of almost zero rest mass of the neutrino, it barely interacts with any other standard model particle.

2.2 Handedness of Neutrinos

Experimentally, it is observed that neutrinos only exist as left-handed particles and right-handed antiparticles, i.e., all neutrinos are left-handed and all anti-neutrinos are right-handed. Left-handed implies that the spin of the particle or (anti-particle) is oriented in a direction opposite to its momentum. Correspondingly, right-handed implies the spin and momentum of the particle (or anti-particle) point in the same direction (Zuber 2020).

Left- and right-handed projection operators, or also known as chirality operators, can be defined using $\gamma_5 = i\gamma_0\gamma_1\gamma_2\gamma_3$.

$$P_L = \frac{1}{2}(1 - \gamma_5) \qquad P_R = \frac{1}{2}(1 + \gamma_5) \tag{3}$$

The neutrino spinor can be written as :

$$\psi_{\nu} = \psi_L = P_L\psi = \frac{1}{2}(1 - \gamma_5)\psi \tag{4}$$

2.3 Charge Conjugation

The charge conjugation operator flips all the quantum numbers that a particle (or anti-particle) has associated with it, effectively converting it to its corresponding anti-particle (or particle) (Zuber 2020).

The charge conjugation operator can be defined using γ matrices.

$$C = i\gamma_0\gamma_2 \tag{5}$$

The charge conjugated spinor ψ^c corresponding to ψ can be written as :

$$\psi^c = C\overline{\psi}^T \tag{6}$$

$\overline{\psi}$ represents the spinor corresponding to the anti-neutrino and T is the transpose operation.

Using the definitions of chirality and charge conjugation operators, we can write (Zuber 2020) :

$$P_{L,R}\psi = \psi_{L,R} \xrightarrow{\text{under } C} P_{L,R}\psi^c = (\psi^c)_{L,R} = (\psi_{R,L})^c \tag{7}$$

Thus, under the action of the charge conjugation operator, a right(or left-)-handed particle gets converted to a right(or left-)-handed anti-particle. From equations (6) and (7), we can also conclude that a right(or left-)-handed particle is equivalent to its corresponding left(or right-)-handed antiparticle.

2.4 Dirac or Majorana?

A fermion is known as a Majorana particle if it is identical to its own anti-particle. For a Dirac fermion, the particle and anti-particle are distinct entities. Till now, it is not clearly known if neutrinos are Dirac fermions or Majorana fermions.

If they are Majorana fermions, the only distuinguishing feature of the neutrino and the corresponding anti-neutrino would be the change in chirality. In this case, the lepton number would also be violated in weak interactions. But this will not be possible if neutrinos are Dirac fermions.

One possible way to probe the nature of neutrinos would be to look for lepton number violating processes, like the neutrinoless double beta decay. Double beta decay processes follow the equation :

$$(A, Z) \longrightarrow (A, Z+1) + 2e^- + 2\overline{\nu}_e \tag{8}$$

The decay would be neutrinoless if the neutrino emitted in the process gets reabsorbed to lead to the completion of the reaction. This can be possible only if the neutrino is a Majorana fermion.

Thus far the neutrinoless beta decay process has not been observed experimentally.

2.5 Neutrino Oscillations

Neutrinos exist as three flavors due to their weak interaction with the other leptons, electron neutrino (ν_e), muon neutrino (ν_μ) and tau neutrino (ν_τ). As it has got a non-zero rest mass, the flavor eigenstates $|\nu_\alpha\rangle$ of the neutrinos are not the same as the mass eigenstates $|m_i\rangle$ (Zuber 2020). They can be linked by a unitary matrix, given as :

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|m_i\rangle \tag{9}$$

The stationary states of the system are actually the mass eigenstates, instead of the flavor eigenstates. They have a time dependence of the form :

$$|m_i(x,t)\rangle = e^{-iE_i t}|m_i(x,0)\rangle \tag{10}$$

Also noting that the flavor eigenstates of the neutrinos are the state in which they are produced and detected, we can see that a neutrino with flavor $|\nu_\alpha\rangle$ at time $t = 0$ oscillates to a flavor $|\nu_\beta\rangle$ in time t.

$$|\nu_\alpha\rangle = \sum_{i\beta} U_{\alpha i}U^*_{\beta i}e^{ipx}e^{-iE_i t}|\nu_\beta\rangle \tag{11}$$

3 NEUTRINO SOURCES

3.1 Atmospheric Neutrinos

When cosmic rays, primarily made up of protons, hit the atmosphere of the Earth, they produce a cascade of particles mostly pions (mesons), which are extremely short lived. They in turn decay to form muons and their corresponding muon neutrinos and anti-neutrinos. The muons, also being short lived, decay to form electrons and corresponding electron neutrinos and anti-neutrinos (Zuber 2020).

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \qquad \mu^+ \longrightarrow e^+ + \nu_e + \overline{\nu}_\mu \tag{12}$$

$$\pi^- \longrightarrow \mu^- + \overline{\nu}_\mu \qquad \mu^- \longrightarrow e^- + \overline{\nu}_e + \nu_\mu \tag{13}$$

3.2 Solar Neutrinos

Neutrinos are produced inside the Sun via the nuclear chain reactions, i.e., as byproducts of the pp chain and the CNO chain reactions.

Most of the energy of the Sun is generated by the pp-chain reaction. The main steps of the pp-chain are given as (Zuber 2020):

$$\begin{aligned}
&p + p \longrightarrow d + e^- + \nu_e \\
&d + p \longrightarrow^3 He + \gamma \\
&^3He +^3 He \longrightarrow^4 He + 2p \\
&^3He +^4 He \longrightarrow^7 Be + \gamma
\end{aligned}$$

The beryllium-7 formed in this process can have two possible paths going forward, it can either interact with an electron to produce lithium, or interact with a proton to produce boron, leading to beryllium-8 and then helium nuclei.

$$\begin{aligned}
\text{Case 1 :} \quad & ^7Be + e^- \longrightarrow^7 Li + \nu_e \\
& ^7Li + p \longrightarrow 2^4He \\
\text{Case 2 :} \quad & ^7Be + p \longrightarrow^8 B + \gamma \\
& ^8B \longrightarrow^8 Be * + e^+ + \nu_e \\
& ^8Be* \longrightarrow 2^4He
\end{aligned}$$

The lithium-channel dominates the production of solar neutrinos compared to the boron channel.

3.3 Supernovae Neutrinos

Supernovae are extremely high energy events in astrophysics which involve the explosion of massive stars. There are two primary ways a supernova explosion is caused, either by core collapse of stars, which usually occurs in stars with mass greater than eight solar masses, or by explosion of a white dwarf when it exceeds the Chandrashekhar mass limit.

The core collapse of a star in a process in which the pressure created from the nuclear fusion is no longer able to balance out the effect of gravity on the core, the system becomes unstable and the outer layers of the star explode out.

A massive star develops an onion-like structure towards the end of its lifetime, with a dense iron core and an extended envelope (fig 1).

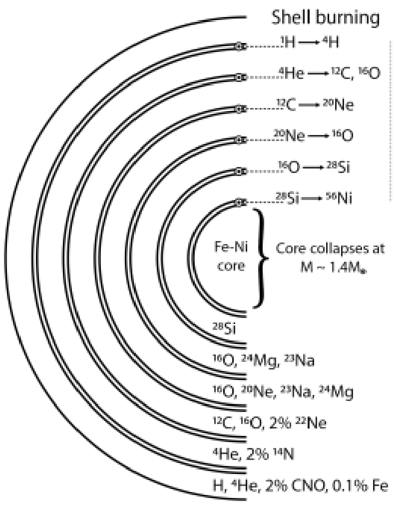

Figure 1. Onion-like structure of a massive star with an Iron core (Zuber 2020)

The iron core is maintained under its weight by the pressure created by the degenerate electrons. Towards the end of the star's lifetime, two main processes start to occur. First, the iron core starts to disintegrate via reaction to photons to alpha particles and neutrons. Secondly, the electrons start getting captured by protons and heavy nuclei in the core to produce electron neutrinos and neutrons.(Zuber 2020)

$$\gamma +^{56} Fe \longrightarrow 13\alpha + 4n - \text{energy} \tag{14}$$

$$e^- + p \longrightarrow n + \nu_e \tag{15}$$

So, the electrons in the system start to degrade, and as electron pressue formed the main force balancing the core, it becomes unstable against the force of gravity and collapses upon itself.

In the process of collapsing, when the core hits a density of around 10^{12}g cm^{-3}, the neutrinos formed are unable to escape from the core, i.e., the core starts collapsing so rapidly that the neutrinos cannot escape fast enough. They get trapped inside. Eventually when the core density becomes around 10^{14}g cm^{-3}, i.e., it becomes comparable to nuclear densities, the strong interaction comoes into play and makes further collapse impossible. The nucleons trapped inside start acting repulsively, which causes the collapse to slow down and produce a shock wave moving outwards. The shock wave dissociates the heavy nuclei which free the neutrinos, which produces a neutrino burst. Travelling outwards, the shockwave rips apart the outer layers, blowing them away and causing an explosion.

3.4 Active Galactic Nuclei (AGN)

An active galactic nuclei (AGN) is an extremely lumonious but compact region present at the centre of some galaxies which constitute some of the brightest lumonious objects in the Universe. The emission are assumed to be caused by the presence of a supermassive black hole at the centre of such galaxies which accretes mass onto itself.

An AGN has two bright jets emitting from it in opposite directions, perpendicular to the plane of the disk. If we observe an AGN such that we lie in the line of sight one of these jets, i.e., if one of the jets was directed towards us, the AGN is known as a Blazar. The luminosity of the blazar is much brighter than other AGN because of the effect of relativistic beaming.

Neutrinos are produced via the process of acceleration due to the relativistic jets of AGNs and Blazars. The jets produced could accelerate protons which could then lead to neutrino production in a way similar to artifical particle accelerators. The proton beam collides with some fixed target which produces secondary particles like pions. The pions then decay to form neutrinos by the reactions illustrated in equations (12) and (13) in the atmospheric neutrino section.

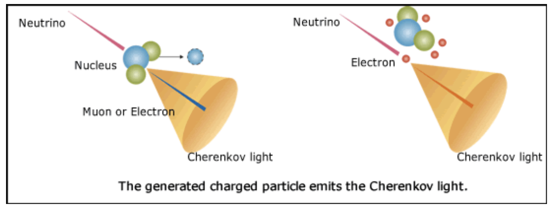

Figure 2. Mechanism of Cherenkov Detection

4 CHERENKOV DETECTORS

While there can be several kinds of detectors used to detect neutrinos like scintillators, tracking calorimeters and others, in this report, I am only going to focus on Cherenkov detectors.

4.1 Mechanism

The Cherenkov detectors utilise Cherenkov radiation to detect neutrinos from various astrophysical sources. Cherenkov radiation is the radiation emitted when charged particles like electrons or muons travel through a medium faster than the speed of light in that particular medium. An important point to note is that this speed does not exceed the speed of light in vacuum, so principle of relativity is not violated.

Water or ice are most commonly used as the material for the Cherenkov detectors. The Cherenkov radiation is produced as a ring around the moving particle and detected via photo-multiplier tubes which surround the medium.

These dectectors primarily work on the principle that neutrinos produce charged particles on interaction with atomic nuclei. These charged particles produced when passed through the medium would produce Cherenkov radiation which can be detected (refer to fig 2). The radiation which is detected can be studied to estimate the properties of the neutrino detected, like the energy or the flavor, along with directionality information.

4.2 IceCube Neutrino Observatory

The IceCube Neutrino Observatory is an ice Cherenkov detector built at the Amundsen-Scott South Pole Station at Antarctica (fig 3). It detects neutrinos by the method described in the previous section using upward moving muons (or leptons). Downward moving muons mainly arise from cosmic ray showers. Upward moving muons,which hit the detector after travelling through the Earth could be generated mostly by the interaction of neutrinos with atomic nuclei as it is extremely unlikely for muons to travel through the Earth without being absorbed. But neutrinos can do so. Neutrinos crossing through the Earth hit the IceCube detector,interact with the nuclei, produce muons which in turn produce Cherenkov radiation which is detected (fig 4).

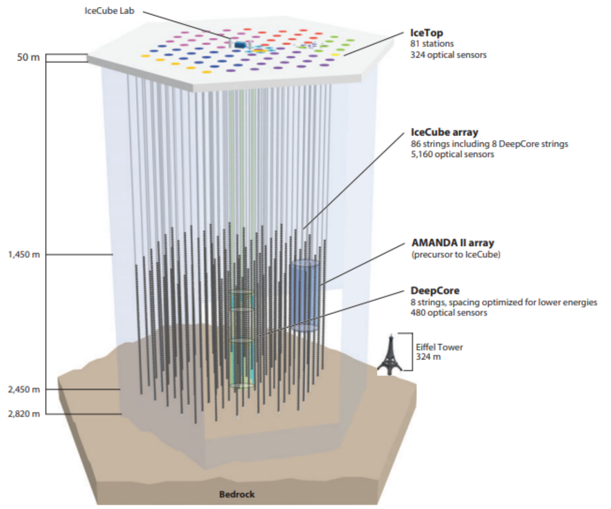

Figure 3. Structure of IceCube detector (Gaisser & Halzen 2014)

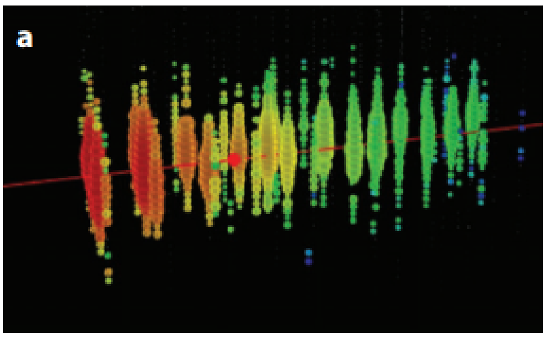

Figure 4. The trace of a neutrino-induced muon signal generated in the IceCube detector (event reconstruction). Different colours indicate different time of arrival of the Cherenkov photons. Red represents early time and purple represents late time. The number of photons detected is indicated by the relative size of the dots. (Gaisser & Halzen 2014)

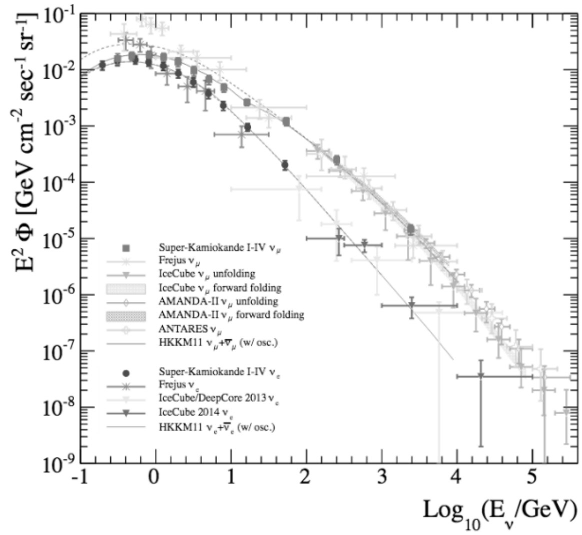

Figure 5. Atmospheric Neutrino observation data from various experiments (Zuber 2020)

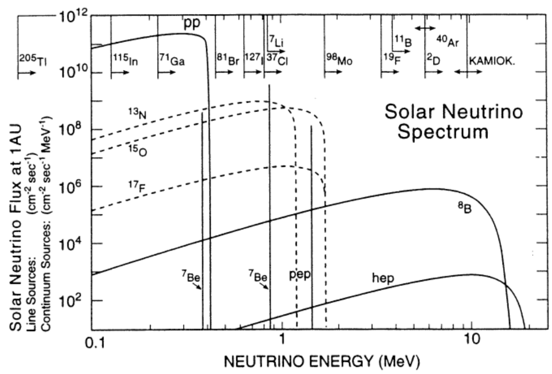

Figure 6. The expected solar neutrino flux from different nuclear reactions in the Sun along with the range in which they can be detected in different experiments. (Zuber 2020)

5 OBSERVATIONS

Over the past several years, many neutrino events have been detected at various detectors like Kamiokande, Super-Kamiokande,IceCube and so on. They have lead to not only verification of the existence of neutrinos, but also of neutrino properties like neutrino oscillations.

Atmospheric neutrinos have been detected by almost neutrino experiments (fig 5). Zuber (2020) The solar neutrinos have also been detected by experiments like Super-Kamiokande (fig 6). They also gave rise to the famous solar neutrino problem in the Homestake Experiment in the 1960s when only roughly one-third of the expected solar neutrino flux was observed on the Earth. The problem was solved when the theory of neutrino oscillations was formalised and people realised that neutrinos can oscillate between three flavors during their flight. On account of only neutrino flavor being detected, the mismatch between expected and observed neutrino numbers was showing up. The IceCube neutrino observatory is capable of detecting extremely high energy neutrinos, even on the scale of PeV energies while providing very precise directional information (fig 7).

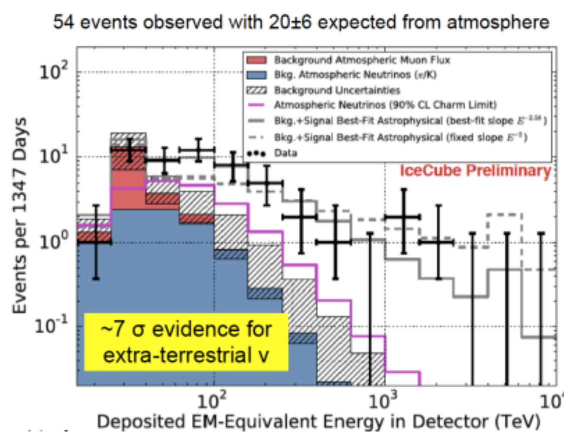

Figure 7. The spectrum of very high energy neutrinos detected by the IceCube detector. It contains neutrinos of all flavors. (Mé száros 2017)

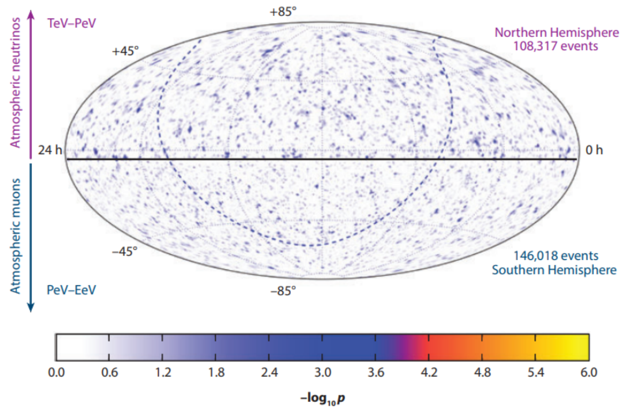

Figure 8. The sky map of the observable Universe marking the probability distribution of the location of neutrino point sources. (Gaisser & Halzen 2014)

6 CONCLUSION

Neutrinos are coming up as excellent candidates for astronomy in the near future. The detection of extemely high energy neutrinos from outside our solar system and galaxy in the IceCube detector open up many possibilities of probing extra-galactic structures via the neutrino channel. The strong directionality information coded in neutrino detection also helps us identify the point sources from which the neutrinos may have emerged and mark them in the sky map (fig 8). The identification of the actual sources of such high energy neutrinos remains to be an open problem. We cannot concretely say if the neutrinos are coming from AGNs or gamma-ray bursts or supernovae and so on. Future research direction would attempt to use the spectrum of gamma-rays along with the neutrino spectrum to address this issue.

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