Candidacy paper

Neutrino Flavors

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Nuetrino Flavors and the use in Detectors

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Understanding the sources of neutrinos and other cosmic particles has always been a main focus of astrophysics. Understanding neutrino flavors and their ratios can give us a deeper understanding of the neutrino sources. In this paper, neutrino flavors, the oscillation between flavors, how the flux ratios give insight into sources, and how these neutrino fluxes can be measured will be discussed.

I. INTRODUCTION

Neutrino's were first postulated by Wolfgang Pauli in 1930 to try and preserve conservation of energy, momentum, and angular momentum in the newly discovered beta decay. He hypothesized a tiny, uncharged particle that was produced in the beta decay that was taking away these quantities, leaving them still conserved. It took until 1956 [1] to confirm the existence of these particles, due to the small cross-section and neutral charge of the neutrino.

Due to these properties, the neutrino is a useful particle when trying to probe the universe. The fact that the neutrino has no charge means it will not be bent in the magnetic fields that permeate the universe; while the low cross-section means that the particle can travel vast distances without interacting. This means that neutrinos point back to their source, allowing us to find and probe objects very far away.

In 1962, at Brookhaven, an experiment gave evidence [2] that there had to be more than one type of neutrino. This observation arose from the fact that the reaction

$$\mu^+ \rightarrow e^- + \gamma \tag{1}$$

never occurs. This led to a conservation of lepton number for each type of lepton, where the particle and neutrino are given a lepton number of +1, and their antiparticles are given a lepton number of -1. The tau neutrino was given life after the tau meson was detected at SLAC [3], but was only found in 2000 [4].

Since neutrinos have a very small cross section($\sim 10^{-32}$ cm^2 at 10^9 GeV, [5]), you need a very large detector to collect data. There are a couple different ways to detect neutrinos. One such was is through visible or radio Cerenkov radiation. Cerenkov radiation occurs when a charged particle travels faster than light inside a medium. To be able to detect this radiation the medium should be a dielectric that is transparent to visible and/or radio waves.

The most common dielectric is water, as used in IMB, Kamiokande, and Super Kamiokande. However, there are new experiments that use ice as the medium in the Antarctic: IceCube, ANITA, and ARA. There are various reasons to set up neutrino experiments in the Antarctic, the best being that the Antarctic ice is very deep and very clear. This ice is transparent to both visible and radio Cerenkov radiation, making it ideally suited to a large range of energies.

This paper is organized as follows. In section II, detailed analysis will cover neutrino flavors and their oscillations. A look at how the neutrinos interact in matter will occur in Section III. Section IV will cover experiments IceCube and ANITA and how these experiments can detect the different flavors. In section V, a look at how the measurement of the different neutrino flux measurements can help us understand the source. In section VI, we will discuss the conclusions.

II. OSCILLATIONS

An interesting problem concerning solar neutrinos was discovered in the 1960's. The current theory for how the Sun is powered involved a reaction like

$$p + p + p + p \rightarrow {}^4He + 2e^+ + 2\nu_e + 24.8\ MeV \tag{2}$$

which is actually the sum of other sub-reactions. There are other reactions that involve heavier atoms such as Be. Using these equations, along with how much power from the Sun, we can see how many neutrinos are expected from the Sun($> 10^{11}$ neutrinos/cm^2/s [6]). But when experiments were done, there was a deficit in solar neutrinos. Either the theory of how the Sun works was wrong or something was happening to the neutrinos.

A theory [7] was presented that the neutrinos could oscillate between the flavors. This theory states that neutrinos propagate with mass eigenstates and that the flavor states we see are actually different compositions of these mass eigenstates. A simple example of just two states is as follows: We have two flavor states, ν_e and ν_μ . We also have two mass eigenstates, ν_1 and ν_2. The flavor states will be a linear combination of the two mass eigenstates, with an arbitrary mixing angle θ.

$$\begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix} = \begin{pmatrix} cos(\theta) & sin(\theta) \\ -sin(\theta) & cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \tag{3}$$

We can see that these flavor states are orthonormal. Propagation in space is given by

$$\nu_1(t) = \nu_1(0)e^{-iE_1 t} \tag{4}$$
$$\nu_2(t) = \nu_2(0)e^{-iE_2 t}$$

where $\hbar$ = c = 1. If at t=0 the neutrino was a muon-type neutrino, $\nu_\mu(0)$=1 and $\nu_e(0)$=0, we can see that

$$\nu_1(0) = \nu_\mu(0)cos(\theta) \tag{5}$$
$$\nu_2(0) = \nu_\mu(0)sin(\theta)$$

and

$$\nu_\mu(t) = cos(\theta)\nu_1(t) + sin(\theta)\nu_2(t) \tag{6}$$

By using these equations, we can get the amplitude and probability of flavor oscillations

$$A_\mu = \frac{\nu_\mu(t)}{\nu_\mu(0)} = cos^2(\theta)e^{-iE_1 t} + sin^2(\theta)e^{-iE_2 t} \tag{7}$$
$$P(\nu_\mu \to \nu_\mu) = A_\mu A_\mu^* = 1 - sin^2(2\theta)sin^2(\frac{(E_2 - E_1)t}{2})$$

The states ν_1 and ν_2 will have a fixed momentum p in vacuum, so if the masses are such that $m_i << E_i$ (where i = 1,2)

$$E_i = p + \frac{m_i^2}{2p} \tag{8}$$

Combining these and putting $\hbar$ and c back in, as well as t = L/c, we get

$$P(\nu_\mu \to \nu_\mu) = 1 - sin^2(2\theta)sin^2(\frac{1.27\Delta m^2(eV^2)L(km)}{E(GeV)}) \tag{9}$$
$$P(\nu_\mu \to \nu_e) = 1 - P(\nu_\mu \to \nu_\mu)$$

From this result, we can see that the flavors will oscillate with time or distance traveled. An image of these oscillations can be seen in Figure 1. This could be expanded into three flavors by making the mixing matrix a 3x3 Unitary matrix [8], normally called the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix that is of the general form

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \tag{10}$$

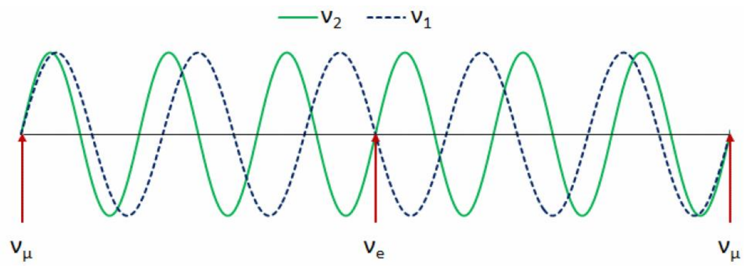


FIG. 1: A simple look at how a traveling neutrino can stay in one mass eigenstate, but shifts between flavors.

Image from [9]

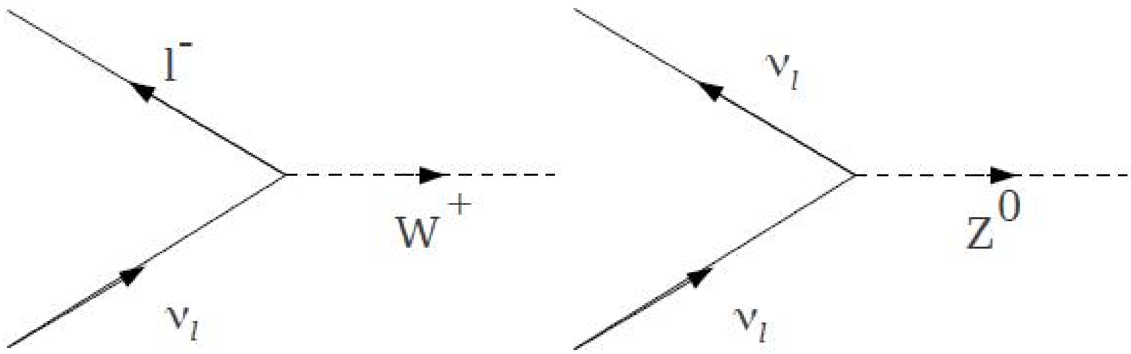
where the flavors states are represented as (e, μ, τ) and the mass states as (1,2,3).

This result is viable for neutrinos passing through vacuum. When passing through matter, one must worry about the MSW (Mikhaev-Smirnov-Wolfenstein [10]) effect. This effect takes into account the extra potential of the surrounding matter and gives a different effective mass for the particles. These new masses will give different probabilities for the oscillations.

While this theory could solve the solar neutrino problem, was it possible to see these oscillations from other experiments? An easy way to tell if neutrinos are oscillating is to conduct an experiment in which there is only one type of neutrino. If these neutrinos oscillate, there should be evidence of different flavors.

Evidence of oscillations can be proven in a few different ways. One such example is using neutrinos from reactor([11], [12]). These neutrinos are mostly of the electron flavor (with a small impurity of muon flavor). The simple experiment has the neutrinos travel and then interact a certain distance away. The interaction will produce electrons(due to conservation of lepton number) during charged current interactions. However, these reactor neutrinos are low energy ($\lesssim 10MeV$) so if the neutrino did change flavors, we would not be able to see any charged current interactions because there is not enough energy present to crest the muon/tau. This results in "missing neutrinos" and is evidence of oscillations. Other experiments could be performed at higher energies, so we can see the muon (or tau). Thus when the pure sample source gives different leptons, we know that oscillations must have taken place.

One prime example of proof of oscillations is due to atmospheric neutrinos([13], [14]). In the atmosphere, charged pions will decay to produce other particles via



(a) A Charged Current Interaction (b) A Neutral Current Interaction

FIG. 2: A look at the weak interactions of a neutrino. l = (e, μ,τ)

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \tag{11}$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \qquad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Looking at these decay chains we can see that for every electron flavored neutrino (ν_e, $\bar{\nu}_e$) we get two muon flavored neutrinos (ν_μ,$\bar{\nu}_\mu$). When these atmospheric neutrinos are measured and a ratio calculated

$$R = \frac{(\frac{N_\mu}{N_e})_{obs}}{(\frac{N_\mu}{N_e})_{calc}} \simeq .6 \tag{12}$$

If there were no oscillations, this ratio should be 1. Since it is lower than 1, that shows that some of the ν_μ have oscillated flavors.

With these oscillations, neutrinos must have a mass. This goes against the Standard Model which calls for massless neutrinos. New physics beyond the Standard Model is now necessary to understand these oscillations better.

III. INTERACTIONS

Neutrinos only interact through the weak force. This gives two distinct types of reactions that we can observe, charged current and neutral current interactions. Charged current interactions (CC)(Figure 2a) use the $W^\pm$ boson with a mass of 82 GeV, while neutral current interactions (NC) (Figure 2b) use the Z^0 boson, mass of 92 GeV.

CC interactions are easier to track due to the production of charged particles which interact through the electromagnetic force. NC interactions can occur, but are harder to find since they can only create hadronic cascades and are similar for all three flavors. NC interactions have a lower cross-section than CC interactions, making the CC interactions ~ 6 times more frequent.

An interesting note about ν interactions is the handedness of neutrinos. Theory currently states that all neutrinos have a left-handed (LH) helicity, meaning that the spin of the neutrino is opposite the direction of motion. This gives the antineutrino a right-handed (RH) helicity. For most particles, the handedness of the particle is frame dependent. If we have a LH electron, we can boost to a frame where the electron's momentum has flipped, giving it a RH helicity. Since neutrino's were thought to be massless, they could have a state of definite helicity, same as the photon. However, since new theory states that neutrinos must have a mass, they cannot be traveling at the speed of light and thus cannot have a state of definite helicity.

While there seems to be no problem with this solution, one arises when trying to find a RH neutrino. In no experiments conducted have we found any neutrinos that were not LH. This may be due to neutrinos only being created in LH states and with such a low mass, the probability of finding a RH neutrino is very small(at 1 MeV, RH neutrinos cannot exceed 1 in 10^{10} [15]). This conflict has not been settled yet, but there is speculation that the neutrino is it's own antiparticle. These types of particles are called Majorana particles, and could solve the conflict. If the neutrino is its own antiparticle, then the antineutrino is really just a neutrino, but with RH helicity instead of LH. However, there has been no proof of this case.

IV. DETECTING NEUTRINOS

Both IceCube and ANITA are using the Antartic ice to help find neutrinos. IceCube uses the visible Cerenkov technique to identify neutrinos, while ANITA uses the radio technique. In this section, we will introduce the detectors, how the detector can be used to identify the flavors, and finally examination of the data taken.

A. Visible Cerenkov Technique

The most common type of neutrino detector depends on visible Cerenkov radiation. This radiation is emitted when a particle travels faster than the phase velocity of light inside a medium ($v \geq \frac{c}{n}$) where n is the index of refraction of the medium. The particle will emit radiation at an angle governed by

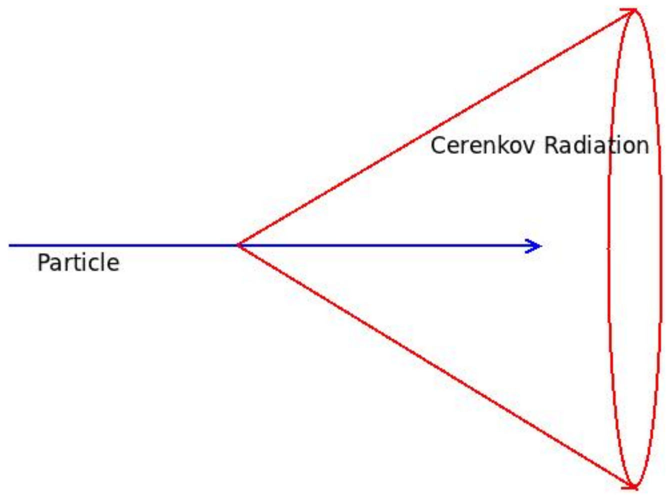


FIG. 3: A look at how Cerenkov radiation is emitted from a particle. Using optical sensors, such as photomultiplier tubes, we can detect this radiation.

$$cos(\theta) = \frac{1}{n\ \beta} \tag{13}$$

This radiation will form a cone around the particle, as shown in Figure 3.

Since a neutrino has a very small mass (< 1 eV), it will travel at almost the speed of light in all media. Most of the energy ($\sim$ 75 %) is given to the lepton created in CC interactions, making $\beta \approx 1$. This gives

$$cos(\theta) \approx \frac{1}{n} \tag{14}$$

so theta is a constant for the medium. The cone will form a ring on the wall, helping with direction of the particle as well as identification. The photomultiplier tubes can also help track the particle as it moves through the medium, useful for muon and tau particles.

Visible Cerenkov detectors are very useful for detecting neutrinos. These type of detectors typically have a sensitivity to neutrino energies in the range of TeV-PeV. This lower energy limit is due to the Cerenkov radiation not propagating far enough to trip more than one detector, while the upper energy is limited by the flux of the neutrinos.

B. IceCube

One detector that uses the visible Cerenkov technique is IceCube. Icecube is a kilometer scale visible Cerenkov detector set in the Antartic Ice. It was built starting back in 2004, and the

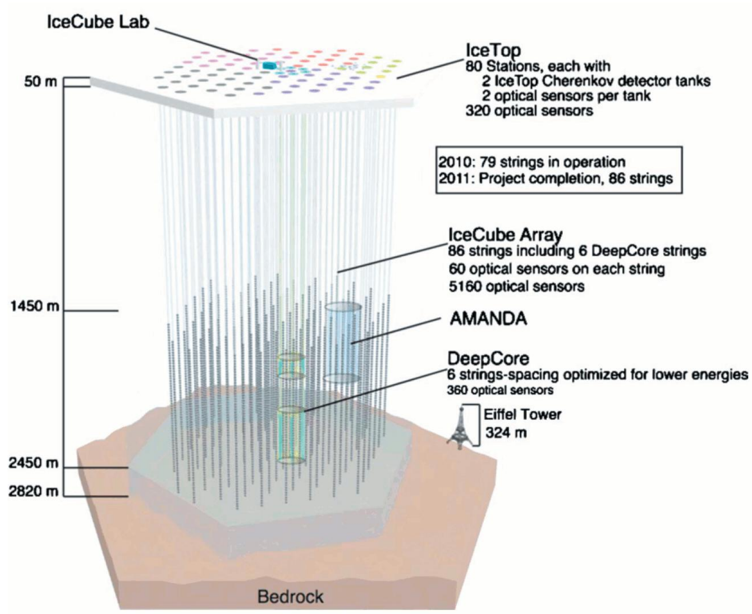


FIG. 4: A schematic of IceCube. Image from [16]

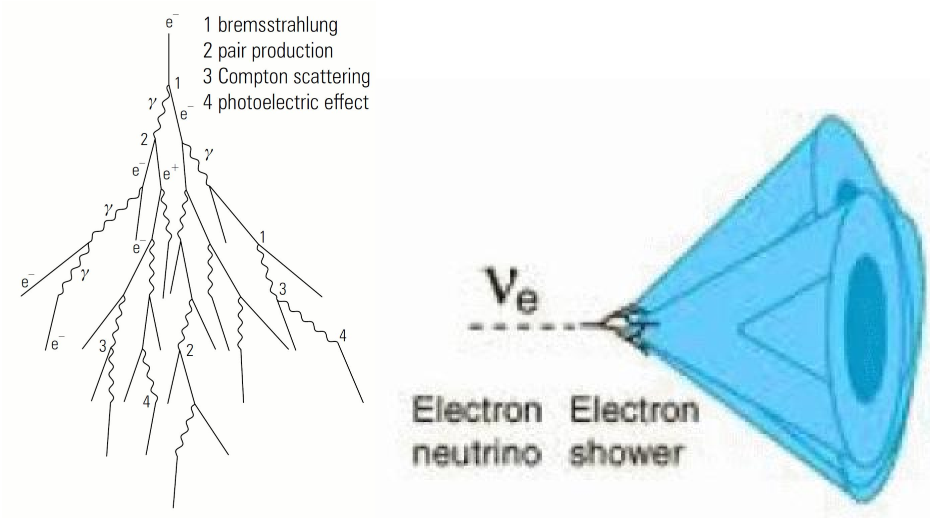
final strings were put in place this past year. IceCube is composed of 86 strings in the ice, each of which have 60 optical sensors(such as photomultiplier tubes), giving IceCube a total of 5160 optical sensors. These sensors at spread out over depths of 1,450 to 2450 meters, covering a volume of 1 km^3 [17]. Part of these sensors are in what is called the "Deep Core". The Deep Core has sensors closer together, optimized for lower energies. Deep Core can measure energies as low as 10 GeV, while the rest of the array will measure energies as low as 100 GeV.

On the surface, IceCube has 80 stations each with 2 Cerenkov detector tanks and 2 sensors per tank, called IceTop. These stations are used to collect data on cosmic ray showers. A look at cosmic ray fluxes can be seen in Figure 8. IceTop also acts in concert with IceCube to help determine composition of these showers, and can even be used to veto showers that occur in IceCube.

C. Flavor Identification in IceCube

1. Electron Flavored Neutrinos

When a ν_e interacts with matter, it creates an electromagnetic or hadronic shower. These showers are due to the original products of the interaction having a lot of energy. This energy can be radiated away through bremsstrahlung and pair production at higher energies($\gtrsim$ 10's of MeV [18]), and ionization, Møller scattering, and Compton scattering at lower energies($\lesssim$ 10's of MeV



(a) An electromagnetic shower. Image from [19]

(b) A Cerenkov cone from an electromagnetic shower. Image from [20]

FIG. 5: How an electron creates a shower and subsequent radiation.

[18]). From bremsstrahlung, the photon that is given off can have enough energy to undergo pair production which creates more particles that then undergo the same radiative processes, creating more particles. This gives rise to the shower, which can be seen in Figure 5a. This will continue on until the particles fall below the the radiation threshold and lose energy by ionization processes.

Since neutrinos travel at almost the speed of light, the products tend to have high energy and will travel faster than light inside the medium; each of these particles will produce Cerenkov radiation. With all of these particles radiating, the Cerenkov cone is not very well defined and looks “fuzzy”. A picture of this is shown in Figure 5b.

There are various characteristics of these produced showers. One of the more useful characteristics is the Moliere radius. This radius is the width of the shower in which about 90% of the energy lies within. This also helps develop a scale for the radation. Electromagnetic radiation of wavelengths longer than this scale tends to be coherent, while the radiation less than this scale is not. This is very important for the radio Cerenkov experiments, which will be discussed later.

The original produced particle (normally an electron or positron) will not travel very far before getting stopped by the medium. This is advantageous for most experiments due to the fact that all of the incident energy has been radiated away, allowing reconstruction of the energy of the initial lepton or hadron created from neutrino interaction. This reconstruction gives insight to the initial energy of the neutrino.

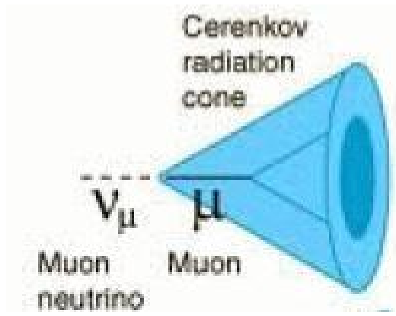


FIG. 6: A picture of the Cerenkov cone produced by muons. The cone is sharper than the electron (Figure 5*b*). Although not shown here, the muon would continue on. Image from [20]

2. Muon Flavored Neutrinos

$\nu_\mu's$ are very similar to the electron flavored, instead of electrons(positrons), $\nu_\mu's$ will produce muons. But these muons will also radiate like the electrons; at high energies($>$ 10's of GeV [18]) the muon will go through bremsstrahlung and pair production, while at lower energies ($<$ 10's of GeV [18])it will lose energy through ionization. The biggest differences between the muon and the electron is that the muon has a decay length, is much more massive than the electron ($\sim$ 200 times), and it also has a smaller cross section. What this means is that the muon will create a track through the detector that is easy to follow, but the muon's decay length is large enough(6300 m at 10^9 eV) that the muon will escape the detector before decaying, which makes reconstruction of the initial energy almost impossible. Experiments using visible Cerenkov detectors can tell the difference between electron and muon type neutrinos due to the "sharpness" of the Cerenkov cone, (see Figure 6) as well as the track length of the charged particle. An electron will be stopped inside the detector, leaving a very short track. It will create an electromagnetic shower, which affects the Cerenkov cone produced. The muon will travel further, leaving a longer track length. The Cerenkov cone produced is sharper because it does not have a large number of particles all radiating. These distinctions lead to experiments being able to distinguish between muon and electron flavors.

3. Tau Flavored Neutrinos

$\nu_\tau's$ are a bit different than the other types of neutrinos. While similar to muons, taus decay much faster, a decay length of 4.9x10^{-5} m at 10^9 eV. This can give the tau flavor a "double-bang" signature which derives from the tau decay length being small (compared to the muon). The

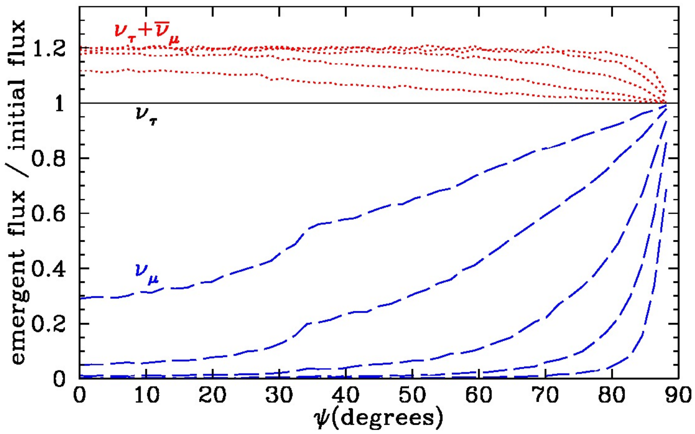


FIG. 7: A look at how the flux changes will nadir angle. Notice that the ν_τ is always 1, but by measuring both tau and muon flavors we have a higher percentage to see the tau neutrino. The data is based on a monte-carlo simulation done in [21].

neutrino interacts with the medium, creating a tau particle, along with a small shower. The tau particle will travel some distance before decaying itself, causing another shower. This distance must be far enough that the two showers can be distinguished. If both of these events occur in the detector, one would see two signature showers. This should only occur for the tau because the muon decay length is bigger than the volume of the detector.

Another theory presented by Beacom and Kolbe [21] details another way to distinguish tau neutrinos that travel through the Earth. They state that ν_τ will decay, producing a τ particle. The τ will decay in flight, producing another ν_τ. This chain will continue on until the neutrino has lost enough energy so that the Earth is transparent. As a side product of these chains, $\bar{\nu}_\mu$ and $\bar{\nu}_e$ will be produced. This chain could produce upward going muons through the detector, but the muon track itself would not distinguish that it was a product of a tau chain. Only through knowledge of the angle and how much Earth the particle went through would lead to knowing if the muon was indeed part of the tau chain. They show that by measuring the muon tracks, it increases the chances to measure the tau.(See figure 7)

Tau neutrinos are a very useful tool because ν_τ are rare occurences from atmospheric neutrinos. The only way these occur in the atmosphere is by neutrino oscillation from muon neutrinos. So the background for such events is much lower.

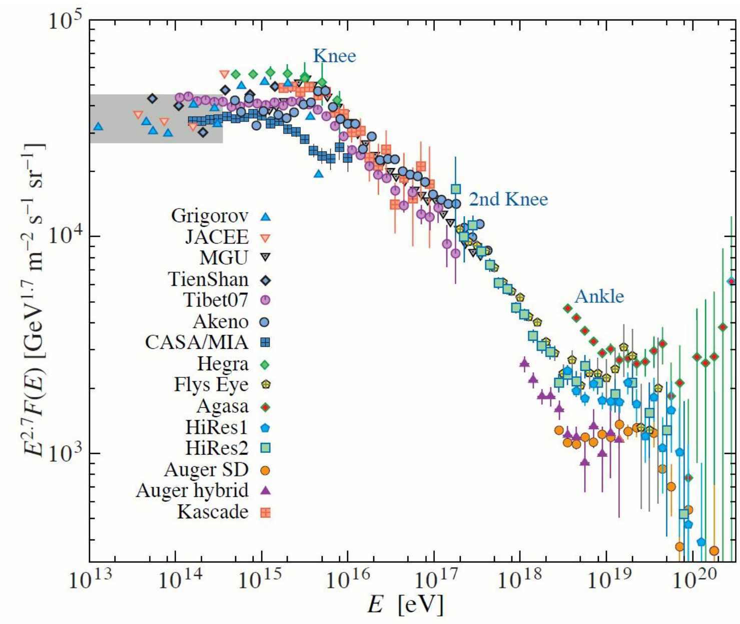


FIG. 8: A look at cosmic rays fluxes. The fluxes change shape at what are called the "knee", "second knee", and "ankle". These changes are indicators that the source of these rays has changed. At the ankle is where the GZK effect needs to be taken into account. Image from [18]

D. Radio Cerenkov Technique

Cerenkov radiation can also be present in the radio spectrum. These electromagnetic or hadronic showers that the neutrinos cause will develop a charge asymmetry. This asymmetry arises due to Compton scattering introducing new electrons, positrons being annihilated, and the photoelectric effect. This is called the Askaryan Effect [23], and was experimentally observed in 2000 [24]. Experiments have arisen that will use this Askayran effect to find neutrinos, such as ANITA, which uses the Antarctic Ice a a medium for this type of experiment.

The radio technique relies on the radiation being coherent, to strengthen the signal seen. This happens when the wavelength of the Cerenkov radiation is greater than the length between particles emitting those cones. A useful measure is the Moliere radius, due to the fact that most of the particles will be inside this length. Thus the spacing between radiating particles is even smaller, leading to coherent radiation. In a dense enough medium, the Moliere radius for a shower is $\lesssim$ 10 cm. This corresponds to a frequency $\gtrsim$ 1 GHz, or the radio region.

An electron, as stated before, will interact quickly after being produced and will create secondary particles. These particles will last a longer time due to the Landau-Pomeranchuk-Migdal (LPM [25]) effect, which suppress bremsstrahlung and pair production cross sections. This suppression

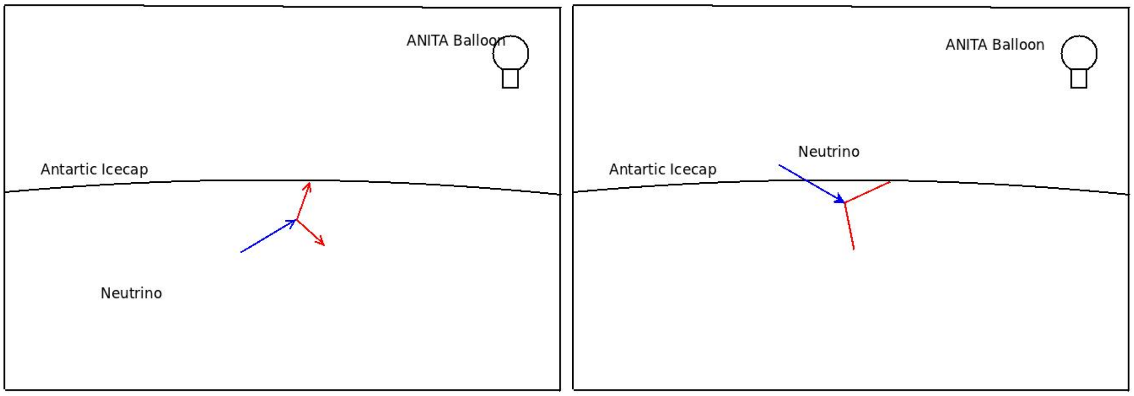
FIG. 9: A look at the final product of ANITA-II. The inset is a picture captured during the flight, with the balloon between 33-35 km above the surface of the Antarctic. Image from [22].

occurs at energies where the interaction length of the particle becomes less than or comparable to the intermolecular spacing. Since bremsstrahlung depends on a nucleus, the cross-section will be reduced, lengthening the shower. As opposed to muons/taus, which will travel a further distance before interacting or decaying, leaving a trail of small showers through bremsstrahlung or pair production.

Radio techniques are a very good way to probe these higher energies. Radio detectors are sensitive from the PeV-ZeV range, due to the signal being weak at lower energies. Due to the Askayran effect, the power rises as the square of the incident neutrino, instead of proportional to the energy. This means that radio techniques have a much higher chance of detecting these higher energy neutrinos than the visible detectors.

E. ANITA

The ANtarctic Impulsive Transient Antenna (ANITA) has been deployed 2 times over the last half decade, ANITA-I in 2006-2007 and ANITA-II from 2008-2009. This experiment relies on the radio Cerenkov technique. ANITA is interested in ultra-high energy neutrinos, on the order of $10^{18} eV$ and higher. However, it can also detect cosmic rays, allowing it to determine fluxes(Figure 8). What is interesting about these energies is that, according to the GZK (Greisen,Zatsepin and Kuzmin) effect [26], cosmic rays will interact with the cosmic microwave background and produce neutrinos. As such, the only way to probe the sources that can accelerate particles to such high energies is through detection of these neutrinos.



(a) A upward going neutrino. The neutrino cannot come straight up because the interaction-length is less than the diameter of the Earth.

(b) A down going neutrino. Due to the angle of the Cerenkov cone ($\sim 57°$), we are able to see some of these events

FIG. 10: Pictures of possible Anita events.

$$\begin{aligned} p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow \ \pi^+ \ &+ n \\ \pi^+ \ &\rightarrow \mu^+ + \nu_\mu \\ \mu^+ &\rightarrow e^+ + \nu_e + \bar{\nu}_\mu \end{aligned} \tag{15}$$

$$\begin{aligned} p + \gamma_{\text{CMB}} \rightarrow \ \pi^0 \ &+ p \\ \pi^0 \ &\rightarrow \gamma + \gamma \end{aligned} \tag{16}$$

This limits the amount of neutrinos ANITA could possible see. At these energies, the interaction length of a neutrino is smaller than the diameter of the Earth. This limits ANITA to seeing neutrinos with a general upward trend (see Figure 10a). ANITA cannot see directly down going neutrinos because the Cerenkov cone would be down going as well and not make it to the balloon. Since the Cerenkov angle in the ice is $\sim 57°$, shallow down going neutrinos that will "skim" the Earth can also be seen (Figure 10b).

The ANITA experiment has been reiterated a couple of times, with a third experiment currently being worked on. ANITA-I used 32 antennas arranged in a ring, lofted into the air with a giant balloon. The array was in the air for approximately 28 days. Some of the antennas in the array are horizontal polarization(H-pol) and others vertical polarization (V-pol). The V-pol antennas were actually set off from vertical by $\sim 10°$. The angle is set so the antennas point into the volume the detector can see, rather than out past the horizon. The reason both polarizations are needed is

energy of model	ν_μ	RMS	ν_τ	RMS	$\theta_{23} = 45°$	RMS
10^{21}eV	2.23	0.58	2.55	0.52	2.40	0.58
10^{20}eV	2.05	0.61	2.56	0.57	2.34	0.64
$10^{19.5}$eV	1.95	0.56	2.50	0.58	2.25	0.63
10^{19}eV	1.79	0.58	2.45	0.57	2.31	0.60

TABLE I: A table produced from [27].It lists the $\log_{10}$(mean(time/ns)) separating the radio pulses in multiple bang events at different energies.

due to the background noise from cosmic rays. As cosmic rays bounce of the ice, they will create a signal that is mostly horizontal. But the neutrinos, which create a Cerenkov cone, will have a signal that is vertical due to the polarization of the cone. So we need both polarizations to help identify the source.

ANITA-II added 16 more antennas to the array to help with the neutrino sensitivity.

F. Flavor Identification in ANITA

Determining the difference between the flavors for the radio Cerenkov technique is much harder to do than for the visible technique. Theory states that a key way to identify the different types of flavors is through multiple interactions from the same event. When any neutrino interacts, it will create a hadronic shower. The lepton that was created (to conserve lepton number) will travel some distance before interacting again. When it does interact(or decay), there will be another shower that will produce more radio Cerenkov radiation. Depending on what lepton is created dictates how much time passes between the showers.

There has been work done to give credence to this theory [27] that used a Monte-carlo simulation to help find average times between the "bangs" that each flavor would give off as it passes through Antarctic Ice(Table I).

G. Results

IceCube started taking data in 2008 back when there were only 40 strings taking data (2400 detectors). The detector had a volume of .5 km^3 centered at 1948 m below the Antarctic surface. IceCube first began publishing results in 2009, with just over 333 days of live time. IceCube had seen neutrinos during this live time, but the true question was whether those neutrinos were

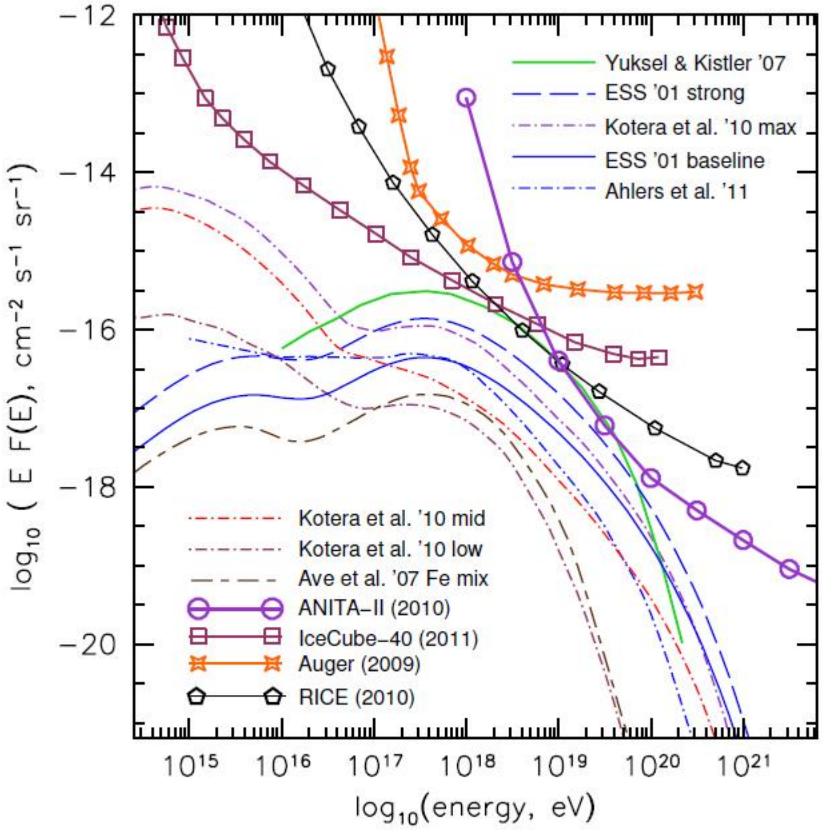


FIG. 11: A look Constraints on the neutrino flux. This includes both experimental and theoretical models. Image from [28]

cosmic in nature. Several criteria were applied to the data set in hopes of finding a cosmic neutrino. However, after the criteria had been specified, IceCube did not have a single event that met all the criteria.

ANITA-II flew over Antarctic during the 2008-2009 season for 31 days, with a live time of 28.5 days. It flew at a height of 33-35 km above the surface, and was able to see a volume of ~ 1.6 km^3 of ice([22]). After criteria had been applied to this data, ANITA-II saw no cosmic neutrinos.

From these results, with the exception of solar neutrinos and neutrinos from SuperNova 1987A, there have been no detection of cosmic neutrinos. Not seeing these events can still help us understand the neutrino flux. Specifically, we can make constraints on the neutrino flux from these data sets and the lack of events; see Figure 11.

Looking at Figure 11, we can see that IceCube is pushing the lower theoretical models with their 40-string data. IceCube has just started taking data with all 80 strings and we hope to see

ratios at source	decays	ratios at Earth	ν_e fraction
1 : 2 : 0	none	1 : 1 : 1	0.33
	Normal	6 : 1 : 1	0.75
	Inverted	0 : 1 : 1	0
0 : 1 : 0	none	1 : 2 : 2	0.2

TABLE II: This table shows how the ratio at the source can be changed by the time the neutrinos reach Earth. The results are from a Monte-Carlo simulation discussed in [29]. A full table with more possibilities are given in that paper.

better constraints. ANITA-II also has gotten close the theoretical models, and with ANITA-III proposed to take data in 2013-2014, it will be interesting to see how those constraints change.

V. NEUTRINO RATIOS

The usefulness of understanding the ratios of the fluxes for different flavors is not to be underestimated. A true understanding of the ratios gives insight into the production of the particles. While the mechanism behind atmospheric neutrinos seems to be very well understood, extra-solar to extra-galactic neutrinos are not as well known. Many theories state that these astrophysical neutrinos arise from pion and kaon decays, as well as the decay of their daughter particles.

There has been evidence from atmospheric and reactor neutrino data that ν_μ and ν_τ are maximally mixed [29]. This leads to the conclusions that the mass eigenstates contain equal parts of ν_μ and ν_τ, as well as the fact that in the mass eigenstates, the neutrino ratios are 1:1:1. This would lead us to believe that on Earth the flavor ration would be 1:1:1. Checking this ratio would give us a handle of the astrophysical sources. If the ratio differs quite far from the expected, we know something interesting is happening. One possibility would be that the daughter particles of the pion and kaon particles (mostly muons) do not have time to decay themselves, the ratio would shift into $\sim$ 0:1:0 at the source. This would shift the flavor ratio's accordingly, $\sim$ 1:2:2.

Different measured flavors would lead to different ratios at the source, giving us a hint at what is truly happening at these sources. If the physics are different than what is expected(only 3 stable mass eigenstates), it would lead to very different ratios at Earth (Table II). Such things can include more mass states that decay. It has been pointed out in [30] that anomalous ratios could point toward CPT violation.

VI. CONCLUSION

As we have seen, neutrinos come in three different flavors. Understanding the flux of a neutrino flavor can give key insights into the sources of these neutrinos (Table II), and into different objects around the universe. But due to the low cross-section and flux of the cosmic neutrinos, it is very hard to detect these neutrinos. Great steps have been made in that direction, with both IceCube and ANITA ready to take the next step in detecting these cosmic neutrinos. (Figure 11)

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