Thesis Title
Second Line if Necessary

by

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Abstract

This is my abstract.

Acknowledgments

Blah blah blah.

Statement of Originality

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Chapter 1

Introduction

The cosmic sky has entranced humans for as far as recorded history can trace. As technology evolved, so too did the observation of the universe around us; from the naked eye to primitive telescopes, and eventually to present day space telescopes, like the Hubble Space Telescope and the upcoming James Web Space Telescope **(NEED TO CITE THESE)**. These growing technological leaps have also resulted in the exploration of the incredibly small and eventually resulted in the discovery of the neutrino [36]. It was perhaps inevitable that these two seemingly separate areas of physics would eventually meet.

Will need to make this a general introduction to the topics, and less like the background.

Chapter 2

Background

2.1 Neutrinos

The neutrino is a fundemental particle first proposed by Wolfgang Pauli [14], and then later discovered in 1956 using the byproducts of β^- decay [36]. As research continued into the elusive neutrino, another flavour of neutrino was discovered in 1962 called the muon neutrino (ν_μ) [17] and eventually the final flavour of the tau neutrino (ν_τ) [28].

2.1.1 Oscillations

Alongside the discovery of the neutrino and their flavours, another problem arose in the field of neutrino physics: the solar neutrino problem [31]. During the 1960's, an experiment was proposed by Bahcall and Davis to measure the solar neutrino flux, referred to as the Homestake experiment [18, 7]. This was a tank of ^{37}Cl, built underground to avoid cosmic backgrounds, and used the simple reaction[18, 7]

$$\nu_e +^{37} \mathrm{Cl} \rightarrow e^- +^{37} \mathrm{Ar} \tag{2.1}$$

to measure the expected solar neutrino flux from the sun.

Solar neutrinos originate from nuclear processes that occur in the sun, such as the PP chain, or the CNO cycle, and can be detected in experiments on Earth [25]. Depending on the energy and process in producing the neutrino, we can expect to detect particlar flavours of neutrinos in experiments like the Homestake experiment. In particular, using the predicted distribution of the internal electron density of the Sun, and a spectrum of the produced electron flavours, one could predict the expected flux of solar neutrinos [25]. In particular, one could predict the influx of electron neutrinos, as was exactly done for the Homestake experiment. It was found that the measured flux was consistently around 30% the theoretical amount [18, 7, 25], and hence was coined the solar neutrino problem.

Neutrino detectors continued to be constructed to research and understand these fundemental particles, such as Super-Kamiokande [42], the collaboration of Kamiokande [26] and the IMB [15] experiments. Another class of solar neutrino detectors were those that used the Gallium chain

$$\nu_e + ^{71}\mathrm{Ga} \rightarrow e^- + ^{71}\mathrm{Ge}\,, \tag{2.2}$$

such as GALLEX [40]. Regardless, the same issue persisted as there continued to be a distinct dissonance between the theoretical expectations of solar neutrinos and the observed experimental results. That was, until the Sudbury Neutrino Observatory (SNO) made a distinct change in their approach to solar neutrino detection compared to predecessors by using heavy water [8]. This allowed for the following interactions

[8],

$$\nu_e + d \rightarrow p + p + e^- \tag{2.3}$$

$$\nu_l + d \rightarrow p + n + \nu_l \tag{2.4}$$

where we have the Charged Current (CC) interaction in equation 2.3 and the Neutral Current (NC) interaction in equation 2.4. This meant that all flavours of neutrinos could be detected, and using it to detect solar neutrinos showed the theoretical flux originally predicted [8].

This result had an astounding implication; the neutrinos were changing on their journey from the Sun [8]. In the Standard Model, all the neutrino flavours have masses that are identically zero, and this would mean that there is no possible way for the neutrinos to somehow change flavour on their journey to the detectors [25]. Clearly there was a change in flavour, and thus the Standard Model must be incorrect about the masses of the neutrinos.

The classic demonstrative method to see this is to consider the mixing of two neutrino flavours (like ν_μ and ν_e) [25]. In analogy to quark flavour mixing [19], we know the mixing of the flavours occurs in the transformation from the mass to the flavour basis. In particular, for two mass and flavour states one can find [25],

$$P(\nu_e \rightarrow \nu_\mu, ct) = \sin^2 2\theta \sin^2\left(\frac{\pi ct}{L}\right) \tag{2.5}$$

where θ is the mixing between the two flavour states, $L = \frac{4\pi E}{\Delta m^2}$ is the vacuum oscillation length, and $\Delta m^2 = m_2^2 - m_1^2$. Here it is easy enough to see that the oscillation probability vanishes if the masses are identical, and this naturally extends into the three flavour case. The vacuum oscillation length, L, is an important and useful quantity as it describes the distance a neutrino must travel before an oscillation is expected [25]. Experiments like the long-baseline neutrino oscillation experiment Tokai-to-Kamioka (T2K) attempt to use this length to probe the mixing angles of the three neutrino flavours.

Similar to the CKM matrix for quark mixing [19], the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [33] gives a relation between the mass and flavour states:

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \tag{2.6}$$

and we see that

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.7}$$

where $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$, δ_{CP} is the Charge-Parity violation phase [33], and η_i are the Majorana phases. If neutrinos are not their own anti-particles, or in other words are Dirac fermions, we can expect $\eta_i = 0$. If they are their own anti-particles, also knowns as Majorana, then the phases η_i play a more imporant role [24].

2.1.2 Interactions

Neutrinos are neutral and interact only through the Weak interaction. The Weak interaction is a force that is mediated by the $W^\pm$ and Z^0 massive bosons, and is the

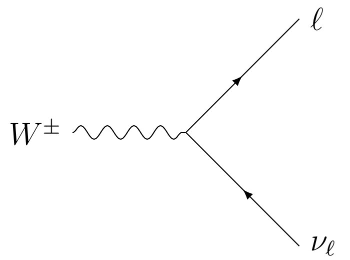

Figure 2.1: The Feynmann diagrams for the vertices that would be included in neutrino interactions using the charged $W^\pm$ boson on the left and the neutral Z^0 boson on the right.

force responsible for decays. The main vertices involved in neutrino interactions are shown in Figure 2.1, where the interacting lepton corresponds with the interacting neutrino flavour.

All interaction involving neutrino production or detection utilize these vertices in some shape or form. We refer to interactions that use the $W^\pm$ boson as the Charged Current (CC) interaction [23], and those that use the Z^0 boson as being Neutral Current (NC) interactions [23].

It is natural to notice that these interactions require something to interact with, or in other words, the neutrinos must propagate through non-vacuum media and hit targets. We have up to this point only considered oscillations of neutrinos in vacuum, and another imporant aspect is to consider the effect interactions could have on these oscillations. In particular, it is noted that certain flavours of neutrinos can be more strongly influenced by media than others [25, 34]. In particular, electron neutrinos (ν_e) being first generation and majority of regular everyday matter being first generation would result in this stronger coupling [25, 34]. This difference in coupling would result in changes in the oscillation that could be complex.

This phenomena comes to a head with the Mikheyev–Smirnov–Wolfenstein (MSW) effect. The mixing angle and oscillation length vary with the electron density in the medium which varies the rate at which these neutrinos mix [25, 34]. In particular there is a resonance mixing angle (and hence resonence electron density) at which the mixing is maximized [25, 34]. The electron density in the sun at the center starts far above the resonance and ends below the resonance at the edge, hence the produced electron neutrinos experience this resonance oscillation along their path out of the solar center [25, 34]. The MSW effect is currently understood to be the reason for the solar neutrino problem [25].

2.1.3 Production & Sources

As was discussed in subsection 2.1.2 and 2.1.1, neutrinos produced in the fusion process hold great historical significance, and in the attempt to resolve the solar neutrino problem we have come to better understand neutrinos and their processes. The leading reaction chain is the *pp* chain [24, 25], which is given by [24]

$$p + p \to d + e^+ + \nu_e \,. \tag{2.8}$$

All other chains that fall under the *pp* chain follow a similar idea; through the charged current interaction, there is the production of an electron neutrino during the fusion of two reactants [24].

Another site where we can observe neutrino production is in the atmosphere [21, 24, 41]. These neutrinos are primarily produced by the decay of pions and muons [24],

$$\pi^+ \to \mu^+ + \nu_\mu \,, \tag{2.9}$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \tag{2.10}$$

and the charge conjugate π^- [24]. The production of these decaying pions and muons is initiated by cosmic rays interacting with the nucleons in the atmosphere [21, 24, 41]. Looking at the inciting interactions, a natural and useful ratio is

$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \tag{2.11}$$

of the number densities [24]. It is also useful to note that atmospheric neutrinos can be both downward heading and upward heading, as they can travel through the earth. These two different directions will experience different travel lengths and can be used to probe neutrino oscillations [24]. There have been studies done on the atmospheric neutrino flux with experiments across the globe [24, 41].

Neutrinos can also be generated by the natural decay of rare elements in the Earths crust [9]. In particular, the main source is of β^- decays in elements like ^{238}U, ^{232}Th and ^{40}K [9]. Measuring the geo-neutrino flux holds interesting consequences in the Geology and Physics community, for example predictions of the radiogenic contributions by neutrino producing processes can be predicted [9].

Production of neutrinos by β^- decay also occurs in reactors [35]. The fission process involving ^{235}U uses a chain reaction of neutron production to fuel more fissions [35], and this neutron rich environment promotes the classic bound neutron decay,

$$n \to p + e^- + \bar{\nu}_e\,. \tag{2.12}$$

The benefit of using reactor neutrinos lies in the flavour purity; the production mechanism promotes the creation of electron anti-neutrinos [35].

Accelerator neutrinos are produced by firing a beam of protons at a target to produce secondary mesons that decay and produce neutrinos [29]. This process is similar to the atmospheric neutrino production process as the idea is similar: secondary mesons produced by high energy primaries that then decay and produce neutrinos. The benefit of this production method is they are generally produced in a collimated beam within some angular error due to the momentum based production [29]. This effectively produces a neutrino beam that can then be used in later processing.

Supernovas can produce high energy neutrinos that can travel thousands of years before reaching detectors on earth [32]. These provide both unique insights into the universe, as they will leave a higher energy signature [32] and the vast distance travelled allows for the neutrino to arrive at the earth in a mass eigenstate. The reason for arriving in the eigenstate occurs as a result of the large distance allowing for the competing mass states to decouple [32].

Another proposed galactic source of high energy neutrinos are Active Galactic Nuclei (AGN) which are potentially the most powerful producers of radiation in the universe [13]. AGNs are known for accelerating protons up to $10^{20} - 10^{21}$ eV, and provide a potential pathway for producing incredibly high energy neutrinos [13].

2.2 Detection Techniques

With a plethora of neutrino sources, some of which have been discussed, the method of detection becomes increasingly important. For the purposed of this text, we only consider a couple of techniques that are of interest. To begin, we can consider the GALLAX type experiments that use the chain identified in equation 2.2. These are blind to the other flavours of neutrinos, as was already discussed, but they did motivate using Germanium as a potential neutrino detection method. In particular there are propositions that these detectors may provide $\mathcal{O}$(1kg) modular mass, $\mathcal{O}$(100eV) threshold and $\mathcal{O}(1\text{kg}^{-1}\text{keV}^{-1}\text{day}^{-1})$ background experiments [37]. In particular, detectors like these could be sensitive to low energy solar neutrinos through neutrino-nucleus elastic scattering [11] where the lower energy neutrinos can have an amplified signal through internal charge amplification [11].

Another class of neutrino detectors use calorimeters as a method of detecting energy deposits from secondaries in neutrino producing processes [20, 30]. These signals can then be used to reconstruct the neutrino flavour and energies [20, 30]. Two examples of such detectors are MINOS [20] and ICAL [30]. The former uses a proton beam on a graphite target to produce showers of hadrons that are then focused by two magnetic horns in a calorimeter [20]. These hadron showers consist of pions and, at higher energies, kaons which produce our neutrinos in their decays [20]. ICAL is a calorimeter array located at the India-based Neutrino Observatory [30] that can use external sources of neutrinos (atmospheric) to probe the mixing angles [30]. In particular ICAL can be particularly sensitive between neutrinos and anti-neutrinos [30].

2.2.1 Vavilov-Cherenkov

Now that we have an appreciation for some novel techniques in detecting neutrinos, we discuss one that is of particular interest for the purposes of this thesis: Vavilov-Cherenkov (VC) Radiation. VC Radiation was discovered in 1934 by Vavilov [39] and Cherenkov [16] and then later in 1937 explained by Tamm and Frank [38]. In essence, VC Radiation is the emmission of electromagnetic radiation due to a charged particle traveling in a medium at a velocity, v, that exceeds the phase velocity, v_p, of light in that medium [22]. In particular, if we suppose the velocity of light in vacuum is c, then VC Radiation will occur if

$$v > v_p = \frac{c}{n(\omega)}\,, \tag{2.13}$$

where $n(\omega)$ is the frequency dependent index of refraction in that medium [22]. In particular, if the light is emmitted along a wave-vector $\vec{k}$ from a charged particle traveling with velocity $\vec{v}$, then the angle between the two vectors is θ_0 and can be described by

$$\cos\theta_0 = \frac{c}{n(\omega)\cdot v} \tag{2.14}$$

where $v = |\vec{v}|$ [22]. Due to the electromagnetic radiation wavefront being a result of spherical emmissions [22], the process is very similar to that of the acoustic sonic boom for macroscopic objects [22] which serves as an excellent analogy.

This particular form of radiation is incredibly useful for neutrino detection. We can use the secondary leptons produced in CC interactions, like those in Figure 2.1, to produce VC Radiation that can be detected by ultra sensitive photon detectors.

2.3 Neutrino Telescopes

Generally one considers only Telescopes as those that utilise the visible part of the electromagnetic spectrum, and in general this is true, but as technology has advanced we have found that using even other wavelengths of light has resulted in different information to be gained from the imaging of the universe. This idea can be extended to include other sources or even particles to image with, like the neutrino. Due to the weakly interacting nature of the neutrino it can travel great distances before interacting and can provide direct sources where cosmic rays may be ambigious about their source. Neutrino Telecopes use exactly this principle to reconstruct neutrinos from cosmic sources with the potential to image the sky one day in an entirely different lens.

The DUMAND experiment [6] was the first to propose the use of large photo-multiplier tubes in deep ocean to detect high energy neutrinos. Though it was never brought to fruition, it was the first of its kind and paved the way for future VC Radiation based neutrino telescopes such as Baikal [10], AMANDA [5], ANTARES [3], and IceCube [2]. We will discuss a few of these that are relevant.

2.3.1 IceCube

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector built in the Antarctic ice [2]. Its primary scientific goal was the detection and characterization of astrophysical neutrinos along with their sources [2], but also has many other scientific goals including indirect detection of dark matter, exotic particle searches, neutrino oscillations, and supernova neutrinos [2].

Neutrino detection occurs through VC Radiation of charged particles from neutrino interactions traveling through the ice [2]. IceCube has the advantage of having a very large volume coverage in order to compensate for the small neutrino cross-section and low astrophysical sources flux [2]. The detection is done through the Digital Optical Module (DOM) consisting of 10″ Photo-Multiplier Tubes (PMTs) which are sensitive to the VC photons [2]. The full array is has 5160 DOMs on 86 vertical strings where each string consists of 60 DOMs [2]. The array sits between

1450 meters and 2450 meters below the surface of the ice [2].

The detection medium of ice is novel in the neutrino telescope field and offers both advantages and disadvantages over water [27]. Ice that has been undisturbed, like that in the Antarctic, offers pure conditions and is stationary when compared with the flow of most large bodies of water [27]. However, equipment that is used in the ice is not recoverable [27] and hence difficult to repair. Moreover, ice offers a shorter scattering length than one would expect in water [27] and due to the ice being layered this effect is layer dependent and was studied in detail to build reference tables [27].

IceCube has been successful in its original physics goal [2] and in 2017 detected a high energy neutrino estimated to have an energy of 290 TeV [1]. This was coincident in direction and time with a gamma-ray flare from blazar TXS 0506+056 [1]. Studying previously collected data in search for more high energy events of the same caliber from the same direction supported the claim that blazars can be a source of high energy neutrinos [1]. IceCube is continuing to collect data and explore more of its physics goals.

2.3.2 ANTARES

The ANTARES Neutrino Telescope is the first operational Neutrino Telescope in the Mediterranean Sea [3] adopting heavily from DUMAND [6] and Baikal [10]. Similar to other Neutrino Telescopes, the main method of neutrino detection arises from VC Radiation from secondary leptons produced in neutrino interactions [3]. The array is composed of 12 mooring lines lined with 25 Optical Modules (OMs) that contain PMTs for a total of 885 OMs (the 12$^{\text{th}}$ line has a different number of OMs) [3].

Compared to the experiments that use ice, like Icecube [2, 1, 27] and AMANDA [5], ANTARES uses ocean water as the medium of VC Radiation from high energy neutrino induced leptons [3]. The benefit over ice is that the attenuation/scattering length is longer, and the lack of layering reduces the reconstruction difficulties [3, 27]. The difficulties are that the water shifts, and hence can both rotate the detectors slightly and move their relative positions [3, 27]. To account for this shifting, ANTARES uses a High Frequency Long Base Line (HFLBL) acoustic system providing 3D positions of hydrophones positioned along the mooring lines [3]. To account for the tilting, each OM is given a set of tiltmeter-compass sensors giving the local tilt angles of each OM structure [3]. Moreover, there are backgrounds from ^{40}K decay and bioluminesence to consider [27].

ANTARES was finished construction in 2008 and has been collecting data since [3]. They have achieved their design goals and are able to achieve a positional accuracy better than 20 cm for each OM with the expected time resolution of 1 ns [3]. This experiment shows the feasibility of water based Neutrino Telescopes and opens the doors for future Ocean Neutrino Telescopes.

2.3.3 KM3NET

Chapter 3

The Pacific Ocean Neutrino Explorer

The Pacific Ocean Neutrino Explorer (P-ONE) is a proposed Neutrino Telescope planned to run in the Pacific Ocean near the West Coast of Vancouver Island, Canada [4]. As with other Neutrino Telescopes, P-ONE hopes to detect and characterize astrophysical neutrinos from galactic and extra-galactic sources for extremely high energy neutrinos [4]. In particular, due to the planned multi-cubic kilometer coverage, it would be suitable for neutrinos from sources such as Blazars [1]. Moreover P-ONE hopes to provide an avenue for research in exotic particle searches, dark matter, neutrino oscillations, supernova neutrinos, tau neutrino studies (ν_τ) and oceanography studies [4].

3.1 Geometry

The geometry of the detector is incredibly important, as the layout and positions of the detectors can drastically change the results and the sensitivies [2]. The first proposed Explorer phase for P-ONE corresponds to the first 10 string-segment to be deployed [4]. Each string will be composed of 20 photo-sensors and atleast two calibration modules [4], with the strings organized in an array similar to that of

IceCube [4, 2]. In order to avoid using thousands of strings to get a larger coverage, it can achieve a similar amount of information using a segmented approach where 6 more arrays similar to those of the Explorer are added around it [4]. This design is drawn in Figure 3.1.

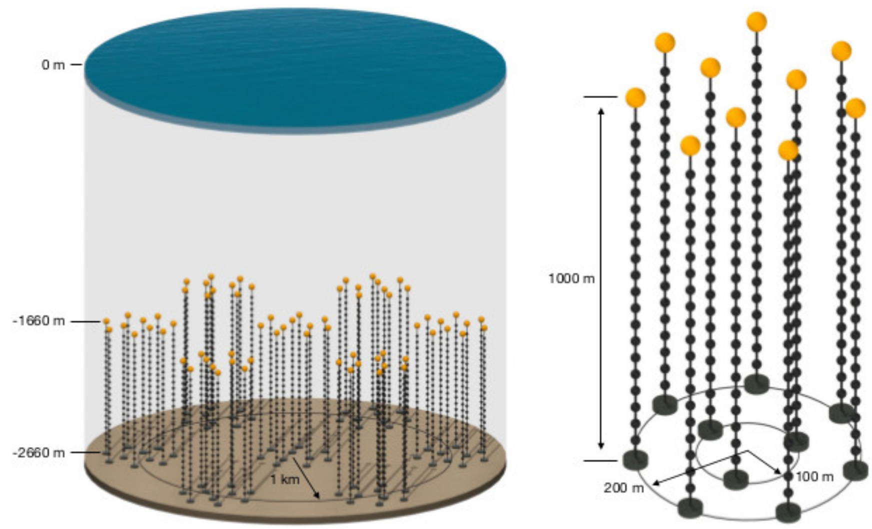

Figure 3.1: Left: Proposed full detector of the P-ONE detector. Right: Proposed array for the Explorer deployment of P-ONE.

With the current proposed geometry, the detector will be incredibly sensitive to horizontal incoming high energy muons from neutrino astrophysical neutrino sources [4].

3.2 Detectors

Similar to previously constructed Neutrino Telescopes, P-ONE will primarily use Vavilov-Cherenkov Radiation from leptons produced through neutrino interactions. This electromagnetic radiation is then detected through highly sensitive optical modules that consist of Photo-Multiplier Tubes (PMTs).

3.2.1 Photo-Multiplier Tubes

3.2.2 Digital Optical Modules

Adopted from the DOMs in IceCube that house the PMTs.

3.2.3 mDOMs

Proposed redesign of the IceCube DOM to increase the granularity of light detection. In place of one large PMT, multiple smaller PMTs can line the same space and coverage at the cost of gaps between detectors. The benefit being that individual hits on the smaller PMTs can provide extra information using the acceptance angle and directionality of that particular PMT. Moreover, in theory this can also reproduce the standard DOM data as the signal collected by a single PMT in the array can be collected and treated as a hit for the entire DOM. This gives the mDOMs a felxibility that isn't present for standard DOMs. In IceCube the standard DOMs use single 10″ diameter PMTs [2], where the mDOMs would use multiple 3″ diameter PMTs.

3.3 Strings for Absorption length in Water

The Pathfinder mission for P-ONE is the STRings for Absroption length in Water (STRAW) and its follow up STRAW-b, which were deployed in 2018 and 2020 respectively. The purpose of these missions was to test the technical details of running an experiment like P-ONE, such as the hardware limitation, to provide data to measure the Attenuation length of light in water for light in wavelengths between 350 nm and 600 nm, characterize the bioluminescence of deap-sea living organisms and the ^{40}K dissolved in the salty water [12].

The basic design of STRAW is the same as that of standard Neutrino Telescopes; using PMTs for detecting photons and calibrating light emmitting sources on mooring lines to collect data [12]. In this particular case STRAW uses two vertical mooring lines with 3″ PMTs and Precision Optical Calibrationn Modules (POCAMs) for the calibration sources [12], which provide isotropic and short pulsed flashes of light. The attenuation length L_T in water can be realized using the known photon intensity N_0, the wavelength from the POCAM flashes and the distance r to each particular PMT with effective collection area A_{det} measuring an intensity $N(r)$ [12]. This yields

$$N(r) = \frac{N_0}{4\pi r^2} \exp\left(-\frac{r}{L_T}\right) A_{\text{det}} \, . \tag{3.1}$$

3.4 Ocean Networks Canada

Ocean Networks Canada (ONC) is the institution that has supported and provided infrastructure for running an experiment of the scale that P-ONE is.

Chapter 4

Simulation

4.1 IceCube Framework

4.2 Simulating Neutrinos

4.3 Simulating Muons

4.4 Detector Response

Chapter 5

Reconstruction

A telescope is only as good as it's ability to identify distinct sources. In the case of a neutrino telescope this translates directly to how well observed events can be reconstructed for the direction of high energy events. IceCube ises several reconstruction methods [2] and has several data quality checks it must go through before a result is given any weight. Similarly, ANTARES has had years of work put into the reconstruction software in order to reach the accuracies is t can now [3]. There are several software techniques that need to be applied before a result can be taken seriously, and usually this pipline begins with a simple and quick initial guess fit.

5.1 Linefit

Any robust reconstruction method requires an initial guess (generally referred to as a seed) in order to be used, but getting this first guess can be non-trivial. Moreover, reconstruction piplines can be incredibly sensitive to the initial guess and ensuring the quality of this fit is difficult in its own right.

The standard method for a first guess in such situations is the linefit/linear fit. This is a simple track fit that minimizes the χ^2 on the observed hits given in an event.

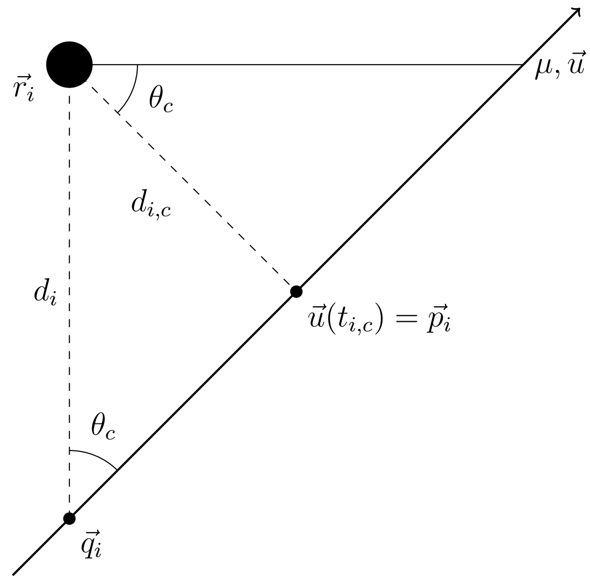

Figure 5.1: Drawing of muon track and Vavilov-Cherenkov Radiation hitting a single DOM.

5.2 Likelihood

Chapter 6

Results

6.1 Likelihood

Chapter 7

Summary and Conclusions

7.1 Summary

7.2 Future Work

7.3 Conclusion

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