Atmospheric Neutrino Detection Using a Large Water Cerenkov Detector.

Russell Clark
Louisiana State University and Agricultural & Mechanical College

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ATMOSPHERIC NEUTRINO DETECTION USING A LARGE WATER CERENKOV DETECTOR

A Dissertation
Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Doctor of Philosophy in The Department of Physics and Astronomy

by
Russell Clark
B.S., Northern Kentucky University, 1991
M.S., Louisiana State University, 1995
August, 1997
Dedicated to Anna and Lori,
for what better reason do I have to live?
And to Toni,
who has endured for better and for worse.
ACKNOWLEDGMENTS

The 90's have been a very interesting decade for me. During this time my Father passed away, I got married, my children were born and I have received three college degrees in physics. I have lived in Cincinnati, Chicago, Baton Rouge and Honolulu. It may not make a movie-of-the-week but for me it has been a great adventure. I have spent a total of six years in graduate school at Louisiana State University and I find there is no one phrase that could sum up this experience. There have been moments of frustration, anxiety, despair and depression but these were largely balanced by other moments of enlightenment, joy, exaltation and celebration. Through it all, there have been many that have provided me with assistance, encouragement and support. Now I would like to take the time and express my gratitude to them.

First and foremost I would like to thank my family. Specifically I would like to express my thanks to my wife Toni for all the years she has indulged this odd little quest of mine. And to Anna and Lori for finding it in their hearts to love their absentee father. I would also like to thank my Mother, Anna Clark, for her love and support while raising this difficult child and my Father, Russell Clark, for all the Saturdays at the Natural History Museum. The debt I owe my parents is immense though I never realized just how so till I had children of my own. I would also like to thank my wife's parents Sandy and Christopher Gates. Their support in hard times has been invaluable.
I would like to thank my mentor, Bob Svoboda. There are many things Bob has taught me about becoming a physicist which are not written in any text. In all the work I have done, he has had the uncanny ability to know when to step in and help and when to leave me alone so that I could learn by my own mistakes. The latter had to be difficult as it meant I was sometimes much slower in completing a given task, but I can think of no better learning experience. This shows that Bob has always placed my education ahead of his own best interest. Could there be any better definition of a good mentor? Bob has also been a good friend. I have always enjoyed his unique perspective of life.

The IMB collaboration consists of a large number of people. I owe them all my gratitude for allowing me to tinker with their data. In particular, I would like to thank John Breault, Dave Casper, Wojciech Gajewski, Todd Haines, Danka Kielczewska and Hank Sobel for their assistance and useful criticism.

I would also like to thank the members of my thesis committee who are Michael Cherry, John Ditusa, Rajiv Kalia and Marty Tittlebaum. They have all been critical, supportive and understanding during the time I have put this work together.

There are many people who have helped me muddle through all the "mundane" but necessary tasks over the years. I couldn't hope to name them all but I will list a few here. I would like to thank the office staff of the Department of Physics and Astronomy at LSU, namely Ophelia Dudley, Jim Fernandez, Frank Favoloro, Beverly Rodriguez, Karen Casio, Karla
Lockwood, Gail Spears and Cathy Mixon. I would also like to thank the office staff of the Department of Physics and Astronomy at the University of Hawaii for their assistance during the time I spent there.

I spent almost a full year living in Hawaii while assisting in the construction of the DUMAND array. There were a number of people there who made the adventure enjoyable. The work was hard, the hours were long but we all managed to have fun. My deepest regret about the cancellation of DUMAND is that I will lose touch with most of them. With this in mind, I would like to thank Jeff Bolesta, Peter Gorham, Shinji Kondo, Shige Matsuno, Marc Mignard, Bob Mitiguy and Marc Rosen. A special thanks goes to John Learned for his unparalleled hospitality and for showing me the definition of akamai. In addition I would like to thank the crew of the Thomas G. Thompson for hosting that crazy gang of physicists when they would rather have been heading home for the holidays.

I would like to thank Mark Meta, Jennifer Stacey and especially Randy Michaels and Dave Schrefrie for helping me scan the IMB data. This was dull, repetitive work that required steady concentration. Day in and day out they muddled through this task. I could not have done it without them.

Finally, I would like to thank my friends for the support that only friends can give. A special thanks goes to my life-long friend Ray Daley. No one has ever made me laugh harder than he has. And I would like to thank my comrades in arms during graduate school, Donavan Hall, Andrew Morse, Erik Young, Rob Nichols, Rich Miller, Ed Clayton, Parker Altice, Rob Sanford and Erik Blaufuss. Friday and pizza will forever be one word in my mind.
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ABSTRACT

A 2.1 kton-yr exposure of data from the Irvine-Michigan-Brookhaven detector has yielded 72 atmospheric neutrino events with a vertex contained inside the fiducial volume and at least 0.95 GeV of visible Čerenkov energy. The ratio of muon-like events with respect to the total number of events was calculated for the data and the Monte Carlo simulation. The ratio of these two ratios \( \frac{\text{muon-like}_{\text{data}}}{\text{muon-like}_{\text{MC}}} \) was found to be \( 1.1^{+0.07}_{-0.12} \text{(stat.)} \pm 0.11 \text{(syst.)} \). The zenith angle dependence of this ratio of ratios is consistent with being flat. The region of \( \sin^2(2\theta) > 0.5 \) and \( \delta m^2 > 9.8 \times 10^{-3} eV^2 \) has been excluded to the 90% confidence level for \( \nu_\mu \rightarrow \nu_e \) oscillations while the region of \( \sin^2(2\theta) > 0.7 \) and \( \delta m^2 > 1.5 \times 10^{-2} eV^2 \) has been excluded to the 90% confidence level for \( \nu_\mu \rightarrow \nu_\tau \) oscillations. This dissertation describes in detail the analysis that produced these results. In addition, the Deep Under Water Muon And Neutrino Detector (DUMAND) is described in detail. Included is a description of the attempted construction of the DUMAND array in December of 1993.
CHAPTER 1

OVERVIEW OF NEUTRINO PHYSICS AND THE ATMOSPHERIC NEUTRINO ANOMALY

1.1 INTRODUCTION

For over a decade now, atmospheric neutrinos have posed a puzzle which is referred to as the atmospheric neutrino anomaly. Basically, neutrinos come in three different flavors. The puzzle is that the predicted ratio of two flavors does not match the ratio that have been measured. This dissertation will examine this puzzle by looking at the high energy (greater than 1 GeV) neutrino flux from the Irvine-Michigan-Brookhaven (IMB) detector.

This work is divided into seven chapters. This first chapter will summarize the relevant physics, give a historical review and introduce the puzzle of the atmospheric neutrino anomaly. The second chapter will describe the Irvine-Michigan-Brookhaven experiment, which was used to collect the data analyzed for this work. The third chapter will describe the data reduction process which was used to sort out neutrino interactions from the background. The fourth chapter will describe the computer simulation used to model the neutrino flux, interactions and detector response. The fifth chapter will describe the methods used to identify the neutrino. The sixth chapter will summarize the results of this analysis and examine the implications of this result.
The seventh chapter stands alone. It is a description of the DUMAND experiment which was intended to look for extra-terrestrial neutrinos. The chapter will describe the experiment, its goals and the first attempts at its construction. Unfortunately the DUMAND experiment was cancelled before it could collect any useful data. Still it represents two years of work by the author and is included here for completeness.

1.2 HISTORICAL OVERVIEW

This section presents some of the early work on neutrinos that is directly related to experimental results given in subsequent chapters.

1.2.1 THE DISCOVERY OF THE NEUTRINO

The history of the neutrino starts in 1930 when Wolfgang Pauli postulated the particle as a solution to a puzzle involving nuclear decays (Pauli 1933). At that time, it was known that radioactivity produced three types of radiation corresponding to three types of nuclear decay called \( \alpha \), \( \beta \) and \( \gamma \). The \( \alpha \) particles are actually \( ^4He \) nuclei. The model for \( \alpha \)-decay was that of the tightly bound \( ^4He \) tunneling out of the nuclear potential of a much larger nucleus. The \( \gamma \) particles, which are actually photons, were understood to be emitted in the de-excitation of the nucleus in much the same way that photons are emitted in the de-excitation of orbital electrons. The \( \beta \) particles, which are either electrons or positrons, failed to fit either of these models.

The real mystery for \( \beta \)-decay was that the electrons or positrons emitted have a continuous energy spectrum. Only the proton, electron and neutron (discovered in 1932) were known to exist at this time, so \( \beta \) emission was assumed to be a simple two body decay. Given that the recoil energy of the
nucleus is very small, the electron energy spectrum should have been strongly peaked at the binding energy. The continuous spectrum therefore implied violation of energy conservation. Also, the spin and angular momentum of the emitted electron did not match the spin and angular momentum of the parent nucleus.

Many assumed the electrons existed in the nucleus prior to the decay. Rutherford, however, reasoned this could not be the case. The addition of proton and electron spins did not always yield the correct nuclear spin. In addition, the Heisenberg Uncertainty Principle predicted a large kinetic energy for electrons in such a confined space. Rutherford predicted that only a massive neutral particle could exist with the proton in the nucleus which was confirmed when Chadwick discovered the neutron in 1932. The presence of the neutrons meant that electrons and positrons did not exist in the nucleus, so that the tunneling model used for $\alpha$-decay could not be applied to $\beta$-decay.

Pauli introduced a new particle because it was clear that a three-body decay could explain the mystery. He claimed this new particle would have a small mass, no charge and very low cross section. These properties would make the particle near impossible to detect and that would explain why $\beta$-decay was always thought to be a two-body rather than three-body. Since $\beta$-decay products could be either electrons or positrons, it was clear this new particle had to have a corresponding anti-particle as well. Furthermore, conservation of momentum arguments meant the new particle had to have spin $\frac{1}{2}\hbar$. 

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Eurico Fermi named this new particle the neutrino and took the concept a little further. He realized that both the electron and anti-neutrino (or positron and neutrino) had to be created in the $\beta$-decay process. He developed a model for $\beta$-decay based on the model for photon creation in atomic and nuclear decays. The crucial difference is that he introduced a new force for this type of interaction. The low cross section of the neutrino and anti-neutrino implied a short range force weaker than either the electromagnetic or strong nuclear forces. Accordingly, this new force was called the weak nuclear force (Fermi 1934).

There are two basic types of $\beta$-decay. The first is $\beta^-$-decay in which an electron and anti-neutrino are emitted. This decay changes a neutron to a proton as shown in equation (1.1).

$$\frac{4}{Z}X_N \rightarrow \frac{4}{Z+1} Y_{N-1} + e^- + \bar{\nu}_e$$  \hspace{1cm} (1.1)

The second is $\beta^+$-decay in which a positron and neutrino are emitted. This decay changes a proton to a neutron as shown in equation (1.2).

$$\frac{4}{Z}X_N \rightarrow \frac{4}{Z-1} Y_{N+1} + e^+ + \nu_e$$  \hspace{1cm} (1.2)

Once the role of the neutrino in $\beta$-decay was understood, it was reasoned that inverse $\beta$-decay should also be possible. These reactions, given by equations (1.3), are often referred to as charged current interactions since the exchange particle for the weak interaction in this case is either a $W^+$ or a $W^-$. 

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\begin{align}
\frac{1}{2}X_N + \nu_e & \rightarrow \frac{1}{2}X_{N+1} Y_{N-1} + e^- \\
\frac{1}{2}X_N + \bar{\nu}_e & \rightarrow \frac{1}{2}X_{N-1} Y_{N-1} + e^+ ~ (1.3)
\end{align}

These reactions could be used to experimentally detect the neutrino. The problem was the extremely low cross section, which was estimated to be on the order of $6 \times 10^{-48} \text{ m}^2$ (Reines 1953). At the time Pauli proposed the neutrino, there were no sources on Earth capable of producing a high enough flux for the contemporary detectors. This changed during World War II when nuclear reactors were developed.

Cowan and Reines experimentally verified the existence of the neutrino in 1953 using a nuclear reactor as a source (Reines 1953). They built a detector consisting of layers of liquid scintillator and $\text{CdCl}_2$ dissolved in water. The liquid scintillator was viewed with banks of 5 inch photomultiplier tubes. The reactor produced both $\nu_e$ and $\bar{\nu}_e$ but the positron and neutron from the $\bar{\nu}_e$ yielded a unique signature when they interacted in the detector. The positron annihilated almost immediately, producing a pair of 511 keV gamma rays which were picked up as showers in the liquid scintillator. The neutron bounced around in the detector till it was captured in a cadmium nucleus, producing gamma rays with a few $\text{MeV}$ total energy. The modulation time for the neutron capture was a few microseconds. A neutrino interaction in the detector would therefore produce a 1.022 $\text{MeV}$ shower followed a few microseconds later by a second shower with a few $\text{MeV}$ total energy. They measured the number of such back-to-back shower events both with the reactor operating and with the reactor shut down and found a difference.
Figure 1.1: Schematic diagram of the detector used by Cowan and Reines to detect the neutrino by inverse $\beta$-decay.
in the rate of $0.41 \pm 0.20$ counts/minute (Reines 1953), which they attributed to $\bar{\nu}_e$ interactions.

1.2.2 THE DISCOVERY NEUTRINO FLAVORS

Pauli had originally proposed only one type of neutrino. This being the type produced along with the electrons in $\beta$-decay. At the time of the experiment of Cowan and Reines, this was the only type that had been postulated. Later it was discovered that neutrinos could also be produced by the pion decay reactions:

$$\pi^+ \rightarrow \mu^+ + \nu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}.$$  \hspace{1cm} (1.4)

where the charged lepton produced was a muon and not an electron. Could it be that the neutrinos produced by $\beta$-decay are different than those produced by pion decay. This question was addressed in 1959 at the Brookhaven National Laboratory. A beam of accelerated protons was aimed at a Beryllium target. Pions were selected out of the products and allowed to decay. The muons produced from these decays were stopped with massive iron shielding before they could decay. This produced a purified beam of neutrinos from the pion decay. On the other side of the shielding was a spark chamber set up to look for charged tracks produced by the neutrino interactions. A total of 29 muon-like events and 6 electron-like events were observed in the spark chambers (Danby 1962). Nearly equal numbers of muon and electron-like events should have been observed had the neutrinos from $\beta$-decay been the
same as those from pion decay, so this was a clear indication that they were different.

The fact that $\beta$-decay produced one type of neutrinos and pion decay produced another implied a conserved quantum number, which is now referred to as lepton flavor. Since electrons (or positrons) are produced in $\beta$-decay, the neutrinos are referred to as electron neutrinos ($\nu_e$). Likewise, since muons are produced in pion decay, the neutrinos are referred to as muon neutrinos ($\nu_\mu$). This explains the Brookhaven experiment. Most of the observed leptons in the detector were muons since most of the incident neutrinos were $\nu_\mu$ and lepton flavor was conserved in the interactions. In 1975, Perl et al. (Perl 1975) discovered the tauon which is a third type of charged lepton. This then implied a new flavor of neutrino which is referred to as the tau neutrino ($\nu_\tau$). It also implied that the two-flavor model should actually be a three-flavor model which can be written as:

$$
\begin{pmatrix}
  e^- \\
  \nu_e \\
  e^+
\end{pmatrix}
\begin{pmatrix}
  \mu^- \\
  \nu_\mu \\
  \mu^+
\end{pmatrix}
\begin{pmatrix}
  \tau^- \\
  \nu_\tau \\
  \tau^+
\end{pmatrix}
$$

(1.5)

1.2.3 WEAK INTERACTIONS

Fermi based his original weak interaction theory on the formalism of quantum electrodynamics as developed by Heisenberg and Pauli (Pauli 1984). For simplicity, he choose to represent weak interactions as occurring at a point. This is a good approximation since the weak force has a very small range. By this time, Dirac had already developed his relativistic equation for
fermions. With this in mind, the $\beta^-$-decay matrix element may be written as:

$$M = G(\bar{\psi}_p O \psi_n)(\bar{\psi}_e O \psi_{\nu_e}),$$  \hspace{1cm} (1.6)

where $\psi$ is a Dirac four component spinor ($\bar{\psi} = \psi^* \gamma_4$), $O$ is a $4 \times 4$ matrix operator and $G$ is the weak coupling constant (Perkins 1987). For $O$, Fermi had a choice of five different forms which were scalar (S), vector (V), tensor (T), axial vector (A) and pseudo-scalar (P). Electromagnetic interactions were known to have vector couplings, so Fermi assumed that weak interactions would be similar.

There are essentially two types of nuclear transitions in $\beta$-decay. The first are called Fermi transitions and the second are called Gamow-Teller transitions. The distinction is that the spin of the nucleus changes by one unit of angular momentum in Gamow-Teller transitions but does not change at all in Fermi transitions. Fermi's original theory of weak interactions with vector couplings only worked for the Fermi transitions. Had he chosen scalar couplings, this would still have been true. For Gamow-Teller transitions, either tensor or axial vector couplings were needed.

In 1956 Lee and Yang investigated the "$\tau$-$\theta$ paradox." The $\tau^+$ and $\theta^+$ particles had identical masses and lifetimes and could only be distinguished by the fact that one decayed into three pions while the other decayed into two pions. The two and three pion final states have different parities. Since this is a weak decay, Lee and Yang proposed that the $\tau^+$ and $\theta^+$ could actually be the same particle ($K^+$) if the weak force does not conserve parity. This
was a little surprising, as it was known that the electromagnetic and strong forces both conserve parity (Lee 1956). The non-conservation of parity was quickly confirmed by Wu et. al. using polarized $^{60}$Co nuclei (Wu 1957).

Goldhaber et. al. (Goldhaber 1958) showed in 1958 that neutrinos and anti-neutrinos have definite and opposite helicities. This was not entirely unexpected, since the Dirac equation predicts definite helicity for massless particles. Accordingly, Goldhaber found neutrinos to be left handed (spin is aligned opposite of the momentum) and anti-neutrinos to be right handed (spin is aligned with the momentum). The conservation of helicity meant that the lepton and anti-leptons in $\beta$-decay had to have opposite helicities. This reduced the number of possible forms for the operators since the scalar and tensor forms would produce lepton and anti-leptons with the same helicity. The matrix element could now be written as:

$$M = G[C_V (\bar{\psi}_p O_V \psi_n) (\bar{\psi}_e O_V \psi_{\nu_e}) + C_A (\bar{\psi}_p O_A \psi_n) (\bar{\psi}_e O_A \psi_{\nu_e})],$$  \hspace{1cm} (1.7)$$

where $C_V$ and $C_A$ refer to the relative strengths of the vector and axial vector components respectively (Perkins 1987).

The fact that neutrinos and anti-neutrinos have opposite helicities and that weak interactions do not conserve parity means that charge conjugation (C) or spatial inversion (P) operations may not be applied individually to neutrinos. Doing so would produce states that are not observed in nature. For instance, applying P to a neutrino would result in a right handed neutrino. Rather both the C and P operators have to be applied in order to convert neutrino states to anti-neutrino states or vice versa. Lee and Yang
(Lee 1957) pointed out that this was acceptable provided that the application of C, P and time reversal (T) remained invariant according to the Lüders-Pauli theorem (Lüders 1954).

The non-conservation of parity meant that the weak theory of interactions had to be altered once more. The definite parity of the previous matrix element (1.7) could be removed by rewriting it as:

$$M = \frac{G}{\sqrt{2}}[(\bar{\psi}_p O_V \psi_n)(\bar{\psi}_e O_V (C_V + C'_{V} \gamma_5) \psi_{\nu_e}) + \nonumber$$

$$\nonumber (\bar{\psi}_p O_A \psi_n)(\bar{\psi}_e O_A (C_A + C'_{A} \gamma_5) \psi_{\nu_e})] \quad (1.8)$$

where $\gamma_5 = \gamma_1 \gamma_2 \gamma_3 \gamma_4$. The invariance of the reaction under T means that $C_V, C'_V, C_A$ and $C'_A$ are all real coefficients. Also, since the Goldhaber experiment had shown that neutrinos have definite left handed helicity and anti-neutrinos have definite right handed helicity, $C_V = C'_V$ and $C_A = C'_A$.

Now equation (1.8) could be written as:

$$M = \frac{G}{\sqrt{2}}[C_V(\bar{\psi}_p O_V \psi_n)(\bar{\psi}_e O_V (1 + \gamma_5) \psi_{\nu_e}) + \nonumber$$

$$\nonumber C_A(\bar{\psi}_p O_A \psi_n)(\bar{\psi}_e O_A (1 + \gamma_5) \psi_{\nu_e})]. \quad (1.9)$$

Lee and Yang proposed using $O_V = \gamma_\mu$ and $O_A = i\gamma_\mu \gamma_5$ (Lee 1957). With the definition $C_A/C_V = \lambda$ and $C_V = 1$, equation (1.9) may be written as:

$$M = \frac{G}{\sqrt{2}} (\bar{\psi}_p \gamma_\mu (1 - \lambda \gamma_5) \psi_n)(\bar{\psi}_e \gamma_\mu (1 + \gamma_5) \psi_{\nu_e}). \quad (1.10)$$

In the case of reactions that involve only leptons (such as muon decay) $\lambda = \pm 1$. This is called the two-component neutrino theory. The two operators
(1 ± γ5) project out the proper helicities for neutrinos (left-handed) and anti-neutrinos (right-handed). In strong interactions only the axial coupling is effected so that λ deviates from unity. When applied in general to weak interactions this is called the V-A theory.

1.2.4 THE PARTON MODEL

In 1962, Gell-Mann proposed that all hadrons were in fact composite particles built from more fundamental particles called partons (Gell-Mann 1962). Partons, which were later called quarks, have fractional charges and only carry a fraction of the total hadron mass. Each quark or anti-quark also carries a quantum number known as color. The possible colors are red, anti-red, green, anti-green, blue and anti-blue. Only colorless combinations may be observed (such as red + anti-red). His original theory consisted of three quarks called up (u), down (d) and strange (s). This theory was strengthened with the discovery in 1964 of the Ω− by Barnes et al. (Barnes 1964). The Gell-Mann theory had predicted the Ω− which is comprised of three strange quarks.

Hadrons containing the strange quark, such as kaons, had been discovered in cosmic ray interactions during the 1950’s. They had been arbitrarily assigned a quantum number called strangeness. Strangeness was found to be conserved by the strong and electromagnetic forces, but not by the weak force. The parton model gave justification to the strangeness number by virtue of the strange quark, but did not explain why it was not conserved in weak interactions. Cabibbo suggested that the weak force couples to a mixed state of d and s quarks (Cabibbo 1963). Now, instead of the quark doublet:
there would instead be:

$$
\begin{pmatrix}
    u \\
    d
\end{pmatrix}
\nonumber
$$

(1.11)

where $\theta_C$ is mixing angle between the d and s states. This is called the Cabibbo angle.

1.2.5 THE ELECTROWEAK THEORY

As previously mentioned, Fermi had built his original theory of weak interactions theory from a modified version of the electromagnetic interaction theory. The major differences between the two are the presence of axial vector couplings, parity non-conservation and massive vector bosons in the weak interaction theory. Weinberg (Weinberg 1967) and Salam (Salam 1968) independently developed a theory that merged the electromagnetic and weak interaction theories into a single framework. This is called the electroweak theory. In this theory, a globally symmetric potential with multiple minima is chosen for the Lagrangian. Normally the Lagrangian is expanded perturbatively, but this is only possible about one of the minima. Thus, a choice has to be made and the symmetry of the potential is broken. This is referred to as spontaneous symmetry breaking.

The use of a globally symmetric potential produces massless scalar bosons, but does not produce any vector bosons as the photon, $W^\pm$ and $Z^0$ are known to be. This problem can be explained by the Higgs mechanism. Here a switch is made from global symmetry to local symmetry. By making an appropriate gauge transformation (Higgs 1966), the so-called Higgs mechanism produces
both a massive vector boson and a massive scalar particle which is called the Higgs particle. Ultimately, t'Hooft showed in 1971 that this type of theory was renormalizable (t'Hooft 1971), but it still contained divergencies at high energy (Gell-Mann 1968). Weinberg then included a new neutral, vector boson called the $Z^0$ which cancelled the unwanted divergencies (Weinberg 1971).

The presence of the $Z^0$ meant that a new type of neutrino interaction was possible. In $\beta$-deacy the nucleons undergo a change in their charge (neutron to proton, proton to neutron) and so they are called charged current interactions. These new type of neutrino interactions do not involve a change of charge and so were called neutral current interactions. As with charged current interactions, neutral currents conserve lepton number.

1.2.6 NEUTRAL CURRENTS AND THE GIM MECHANISM

Neutral current reactions were first observed by the Gargamelle bubble chamber at CERN (Hasert 1973). They were seen as neutrino interactions that produced hadrons but no charged lepton. All neutral current reactions that have been observed conserve the strangeness quantum number ($\Delta s = 0$) (Perkins 1987). At the time, there was no reason to believe that $\Delta s = 1$ (such as $K^+ \rightarrow \pi^+ \nu \bar{\nu}$) should not be possible but no such reactions were observed. In 1970, Glashow, Iliopoulos and Maiani (GIM) (Glashow 1970) proposed a theory which introduced a new quark called charm. In this theory, mixing of the known quarks with the charm quark cancelled the $\Delta s = 1$ contributions. This is often called the GIM mechanism. With the addition of a fourth quark there existed two doublets:
\[
\begin{pmatrix}
  u \\
  d_c
\end{pmatrix}
= \begin{pmatrix}
  u \\
  d \cos \theta_c + s \sin \theta_c
\end{pmatrix}
\]
(1.13)
and
\[
\begin{pmatrix}
  c \\
  s_c
\end{pmatrix}
= \begin{pmatrix}
  c \\
  s \cos \theta_c - d \sin \theta_c
\end{pmatrix}
\]
(1.14)

The GIM mechanism was confirmed when the \(J/\Psi\) particle was discovered in 1974 (Aubert 1974, Augustin 1974). The \(J/\Psi\) particle is a meson consisting of a charm quark and anti-quark pair. Based on the threshold for charm production, the mass of the charm quark was estimated to be around 1 GeV.

1.2.7 THE STANDARD MODEL

The discovery of the \(\Upsilon\) particle in 1977 (Herb 1977, Innes 1977) introduced the possibility of yet another quark doublet. The \(\Upsilon\) is a meson consisting of a quark and anti-quark pair. This new quark was called bottom and the mass was estimated to be around 4 GeV. From that point on, it seemed likely that a sixth quark would eventually be found to complete the doublet. This would be called the top quark. It took 17 years before the top quark was finally discovered (Abachi 1995, Abe 1994). The main reason for the delay was the mass of the top quark, which is now estimated at roughly 175 GeV.

The top quark had to be produced in pairs so that the threshold energy for their production was around 350 GeV.

During the years between the discoveries of the bottom and top quarks, the \(W^\pm\) (Arnison 1983, Banner 1983) and \(Z^0\) (Arnison 1983, Bagnaia 1983) vector bosons were observed experimentally at CERN. Recall that these are the bosons that mediate weak interactions. The \(W^\pm\) has a mass of 80 GeV while the \(Z^0\) has a mass of 91 GeV. The \(Z^0\) was later produced in abundance.
at the LEP $e^+e^-$ collider. The width of the $Z^0$ resonance depends on the decay channels available to it. Since the $Z^0$ may decay into a neutrino and anti-neutrino pair, the width depends in part on the number of neutrinos in the universe. An analysis of the $Z^0$ width revealed there are $2.991 \pm 0.016$ possible neutrino flavors (LEP 1995).

The sum of all known fundamental particles fall into three general categories which are quarks, leptons and the exchange bosons. There are a total of 6 quarks and 6 anti-quarks which fall into three doublets. Likewise, there are 3 charged leptons and 3 charged anti-leptons. These are closely associated with 3 neutrinos and 3 anti-neutrinos. The fundamental particles (minus the exchange bosons) are generally arranged in the following fashion:

$$
\begin{pmatrix}
  u \\
  d
\end{pmatrix}
\begin{pmatrix}
  s \\
  c
\end{pmatrix}
\begin{pmatrix}
  b \\
  t
\end{pmatrix}
\begin{pmatrix}
  e^- \\
  \nu_e
\end{pmatrix}
\begin{pmatrix}
  \mu^- \\
  \nu_\mu
\end{pmatrix}
\begin{pmatrix}
  \tau^- \\
  \nu_\tau
\end{pmatrix}.
\quad (1.15)
$$

A similar arrangement may be made for the anti-particles. This collection is part of the Standard Model which is the name given to the collection of interaction theories for these particles. There are two basic interaction theories in the Standard Model. These are the electroweak theory which covers both electromagnetic and weak interactions and quantum chromodynamics which covers strong interactions.

1.3 NEUTRINO DETECTION

Neutrinos have always presented particular challenges to both experimentalists and theorists. This has been true since the early days of $\beta$-decay studies till today. The main reason for the difficulty lies with the weak force.
Both of the exchange bosons (the $W^\pm$ and the $Z^0$) are very massive (80 $GeV$ and 91 $GeV$ respectively) which gives the weak force a very short range. In turn this means the cross section for weak interactions is very small.

In the case of neutrinos, there are two basic methods which are commonly used to avert this difficulty. The first is to produce a large flux of neutrinos to overcome the small cross section. Traditionally this is done with either a nuclear reactor or with an accelerator. Most reactors produce $\bar{\nu}_e$ through $\beta$-decay and most accelerators produce $(\nu_\mu + \bar{\nu}_\mu)$ through pion decay.

A second method for neutrino detection is to build a massive detector that covers a large area. The basic idea is to put a great deal of matter in the path of neutrinos to increase the chances of an interaction. If a detector is large and massive enough it becomes possible to see neutrino interactions from naturally occurring sources. The interaction rates are typically low but may be integrated over long periods of time.

1.4 NEUTRINO PRODUCTION BY COSMIC RAYS

The most abundant source of naturally occurring neutrinos on the Earth come from cosmic ray interactions. Cosmic rays are completely ionized nuclei that enter the Earth's atmosphere isotropically from space. They undergo hadronic interactions in the upper atmosphere and produce abundant numbers of pions. These pions may then decay by the reactions (1.4) producing a $\nu_\mu$ or a $\bar{\nu}_\mu$. The muons which are produced in reactions (1.4) may also decay producing more another $\nu_\mu$ or $\bar{\nu}_\mu$ plus a $\nu_e$ or $\bar{\nu}_e$. The neutrinos produced by cosmic ray interactions may then be observed with a large detector (Markov 1960, Greisen 1960, Kuzmin 1962).
1.4.1 ATMOSPHERIC NEUTRINO MEASUREMENTS

Atmospheric neutrinos have been measured experimentally for over 30 years. In some cases, the experiments were designed specifically to look for atmospheric neutrinos. In other cases they were just studied as a source of background. What follows is a brief description of some of the experiments that have made measurements of atmospheric neutrinos.

1.4.1.1 CASE-WITWATERSRAND-IRVINE (CWI)

The Case-Witwatersrand-Irvine experiment (Reines 1971, Crouch 1978) operated from December, 1967 to October, 1971. The detector was located 3.3 km underground in a gold mine in South Africa and was composed of 20 separate modules, which were called bays. Each bay had three tanks aligned vertically and filled with a liquid scintillator. The scintillator in each tank was viewed by four (two on each end) photomultiplier tubes. Each tank was 5.47 m long and 0.127 m wide. The total height of all three tanks was 2.0 m. These tanks were surrounded on two sides by arrays of flash tubes which provided some directional information. Eight of the bays were set side by side while the remaining 12 were set single file.

The total mass of the detector was 17.8 tons and it covered an area of 175 m². Most of the events recorded were upward-going events which could be attributed to neutrino interactions in the rock outside the detector. Since electrons stop very quickly in rock, the detector could only measure muons from charged current νμ and ¯νμ interactions. Therefore it could only measure the absolute muon neutrino flux from the atmosphere. A total of 450 muon events were collected.
1.4.1.2 KOLAR GOLD FIELDS (KGF)

The Kolar Gold Fields experiment (Krishnaswamy 1971) which ran from early 1965 to June, 1969, was very similar to the CWI experiment. It was composed of seven modules. Each module had several tanks of liquid scintillator viewed by photomultiplier tubes and was surrounded by arrays of flash tubes. Not all the modules had the same dimensions. Two of them employed magnets to aid in determining the momentum of the muons. The detector was located in a gold mine in Southern India at a depth of 2.3 km. Like the CWI experiment, the KGF detector measured muons which originated outside the detector and so could only place a limit on the absolute muon neutrino flux. A total of 165 events were collected.

1.4.1.3 BAKSAN SCINTILLATION TELESCOPE

The Baksan Scintillation Telescope (Chudakov 1978) was located in the Caucasus region of the former Soviet Union. It began collecting data in 1980 and is still running. The detector is composed of 3156 modules, each 70 cm by 70 cm by 30 cm and containing liquid scintillator. Each module is viewed by a photomultiplier tube. These modules are arranged to cover a 300 m$^2$ area. The total mass of the liquid scintillator is 330 tons. As with the CWI and the KGF detectors it measures only muon neutrino events which originate outside the detector.

1.4.1.4 LARGE AREA SCINTILLATOR DETECTOR (LASD)

The Large Area Scintillator Detector (Cherry 1986) was built in the Homestake Mine surrounding the Davis solar neutrino experiment. This experiment ran from January 1st, 1985 to May 6th, 1987 (Cebula 1990).
It was composed of 200 modules each 800 cm by 30 cm by 30 cm and filled with liquid scintillator. The modules covered a total 160 m² and the total mass of the liquid scintillator was 140 tons.

1.4.1.5 MONOPOLE, ASTROPHYSICS AND COSMIC RAY OBSERVATORY (MACRO)

The name of the Monopole, Astrophysics and Cosmic Ray Observatory (MACRO) (Ahlen 1994, 1993) describes its purpose very well. Eventually the detector will be comprised of 6 "super" modules but for now only one has been completed. A single super module is 12.6 m by 12 m by 4.8 m and composed of ten horizontal planes of limited streamer tubes with passive material between the planes. The super modules are surrounded on five sides by planes of liquid scintillator counters. These are arranged so there are 32 counters in two horizontal planes and 21 counters in three vertical planes. The counters are 11 m long tanks viewed by 20 cm photomultiplier tubes. There are two tubes (one at each end) of the horizontal counters and only one tube at the end of each vertical counter. Outside of these liquid scintillator counters there are 3 cm by 3 cm by 12 m planes of horizontal and vertical streamer tubes. The detector is located 3.2 km underground in the Gran Sasso Laboratory in Italy. The main goal of the detector is to search for possible magnetic monopoles, but it also has reasonable muon tracking abilities. Like all of the detectors described so far it only observes muon neutrinos from the surrounding rock.
1.4.2 NUCLEON DECAY DETECTORS

During the later part of the 1970's several experiments were proposed to search for nucleon decay as a way of testing the SU(5) theory. By the early 1980's many of these were built and collecting data. The basic idea was to build a massive detector and therefore provide a very large number of protons.

One possible channel for proton decay is:

\[ p \rightarrow \pi^0 + e^+. \] (1.16)

There are a number of possible channels but this one will serve as a good example. Compare reaction (1.16) to the neutrino interaction:

\[ \bar{\nu}_e + p \rightarrow e^+ + n + \pi^0. \] (1.17)

Here the neutrino enters the detector unobserved and interacts with a proton producing a positron, a \( \pi^0 \) and a recoil neutron. It is difficult to distinguish this from a proton decay reaction since the main difference between the two is the kinematics. The products of reaction (1.16) would come from a proton nearly at rest and so would be "back-to-back" while the products of the neutrino interaction would scatter forward due to the initial neutrino momentum.

Normally neutrino interactions are rare owing to their small cross section, but the proton decay experiments had to be built large and massive. This meant that atmospheric neutrinos created a significant background in the proton decay search. As such, many of the experiments were forced to study the atmospheric neutrino interactions in detail. After many years of running,
no proton decay in the mode (1.16) was ever observed and the SU(5) theory was disproved. By that time though, a large number of atmospheric neutrino interactions had been collected. This section will introduce the nucleon decay experiments that have played pivotal roles in measuring the atmospheric neutrino spectrum.

Nucleon decay experiments had two advantages over earlier atmospheric neutrino experiments. First, they were built to look for contained events. A contained event has a vertex that originates inside the volume of the detector. A valid proton decay event could not have particle tracks coming from outside the detector. If this were the case, there could be no way to be certain the entering particle did not initiate a reaction that merely appeared to be a proton decay. Second, the products of a proton decay had to be identified with reasonable certainty. This was both to be certain the event was a proton decay and to allow the study all of the channels if proton decay were observed.

These two capabilities allowed the number of electron neutrinos to be measure simultaneously with the number of muon neutrinos. The earlier experiments had relied on neutrino interactions in the rock surrounding the detector which precluded the observation of electrons. Furthermore, the identity of muons or electrons in the products allowed the flavor of the parent neutrino to be identified as well. For the first time the number of muon neutrinos produced in the atmosphere could be compared to the number of electron neutrinos. This will be discussed in more detail in section 1.5.

There were two basic types of proton decay experiments built during this time. The first type were called water Čerenkov detectors. A total of
two such detectors were built as will be discussed below. These detectors contained a large mass of pure water viewed by many photomultiplier tubes. The disadvantages were that only charged particles could be observed and the vertex resolution was poor (about 1 m). The advantages were that the detector mass was cheap and the entire volume could be viewed all at once.

The second type of detectors were iron calorimeters. Generally these were layered detectors that consisted of particle detectors sandwiched between slabs of iron. The iron provided the protons and acted as an initiator for hadronic cascades. The disadvantages of these detectors were the cost and density of the material. The main advantages were their fine grain resolution (typically about 1 cm) and their ability to see strongly interacting neutral particles.

1.4.2.1 IRVINE-MICHIGAN-BROOKHAVEN (IMB)

The Irvine-Michigan-Brookhaven experiment was a water Čerenkov detector. It had a total fiducial mass of 3.3 kilotons which was viewed by 2048 photomultiplier tubes each 20 cm in diameter. The exact details of the detector will be provided in chapter 2. IMB was located 600 m underground in a salt mine near Cleveland. It ran nearly ten years and collected almost 1000 total neutrino interactions.

1.4.2.2 KAMIOKANDE

The Kamioka Nucleon Decay Experiment (or Kamiokande) (Arisaka 1985, Kajita 1986) was the second water Čerenkov detector. The fiducial mass of the detector was 1.04 kilotons so it was smaller than IMB. Kamiokande was designed to look for solar neutrinos as well as proton decay. For this reason,
the energy threshold had to be lower than that of IMB, since solar neutrinos are much lower in energy than atmospheric neutrinos. The volume of water was viewed with 948 photomultiplier tubes, each 50 cm in diameter. The large size and number of these tubes meant they were packed very close together so that most of the surface of the volume was covered by the tubes. The Kamiokande detector was smaller than IMB, but it had a much better energy and vertex resolution. The detector also included a veto region. This was a small volume of water surrounding and optically separated from the inner volume. It was viewed by a low density of photomultiplier tubes. The purpose of the veto region was to look for entering tracks from cosmic ray muons. Kamiokande ran from the early 1980's to 1996 and collected over 300 atmospheric neutrino interactions.

1.4.2.3 FRÉJUS

The Fréjus experiment (Berger 1990) was a fine grain iron calorimeter located in the Franco-Italian Alps. The iron was segmented with Geiger and flash tubes to provide energy and direction information for the particle tracks. It had a fiducial mass of 0.55 kilotons, ran for nearly three years and collected a total of 109 events.

1.4.2.4 SOUDAN 2

The Soudan 2 experiment (Goodman 1995) is another fine grain iron calorimeter. The iron is segmented with drift tubes and the total mass of the detector is 0.96 kilotons. The detector is located in Soudan, Minnesota and started collecting data in 1987 when installation began. The installation
finished in 1993 and full detector operation began. To date, the experimental collaboration has only reported 100 contained neutrino events.

1.4.2.5 KOLAR II

The Kolar II experiment (Krishnaswamy 1986) was an iron calorimeter much like the Soudan 2 experiment using iron segmented by proportional tubes. The detector was located at the site of the original Kolar experiment in Southern India. The total mass of the detector was 0.10 kilotons and it measured 35 contained neutrino events.

1.4.2.6 NUCLEON STABILITY EXPERIMENT (NUSEX)

The NUcleon Stability EXperiment (NUSEX) (Battistoni 1986) ran from 1979 to 1988 and used limited streamer tubes for the tracking of particles. The detector was located beneath Mont Blanc and had a fiducial mass of 0.13 kilotons. NUSEX collected a total of 50 contained neutrino events.

1.5 THE ATMOSPHERIC NEUTRINO ANOMALY

The expected number muon and electron neutrinos from the atmosphere may be roughly predicted by the reactions:

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
\[ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \]

(1.18)

and

\[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]
\[ \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu. \]

(1.19)
Since pions are produced in abundance by cosmic ray interactions there should be about twice as many muon neutrinos as electron neutrinos. The advantage of such a flavor ratio is that large uncertainties in the absolute flux of atmospheric neutrinos will largely cancel. The flavor ratio may vary somewhat from experiment to experiment due to a number of factors (see section 4.2.1). Some of these factors are due to variations in the neutrino flux at different locations and some are due to detector systematics. The variations generally make a direct comparison of the results from different detectors very difficult.

To overcome this, the measured result from a given detector is generally divided by the predicted result which comes from a computer simulation called a Monte Carlo (see section 4.1). The simulation includes the atmospheric neutrino fluxes, the neutrino-nucleon interactions and the response of the detector. The predicted value derived in this way should then include all the systematics of a particular detector. This ratio of ratios (measured/predicted) is then detector independent.

Neutrinos have no charge or mass, so it is impossible for a given detector to measure the neutrino flavor directly. Rather, the neutrino flavor must be inferred from a measurement of the charged lepton flavor from charged current interactions. In general, if an event is found to contain a muon, it is called muon-like and if an event is found to contain an electron, it is called electron-like. The method for determining events to be muon-like or electron-like will be described in section 5.2. The ratio of ratios is then defined as:
Table 1.1: A summary of the ratio of ratios as measured by several different detectors. The error bars are statistical only.

<table>
<thead>
<tr>
<th>Name</th>
<th>Detector Type</th>
<th>Ratio of Ratios ($f$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMB</td>
<td>Water Čerenkov</td>
<td>$0.71 \pm 0.04$ (Becker-Szendy 1992)</td>
</tr>
<tr>
<td>Kamiokande</td>
<td>Water Čerenkov</td>
<td>$0.80 \pm 0.04$ (Fukuda 1994)</td>
</tr>
<tr>
<td>Soudan 2</td>
<td>Iron Calorimeter</td>
<td>$0.81^{+0.07}_{-0.13}$ (Goodman 1995)</td>
</tr>
<tr>
<td>Fréjus</td>
<td>Iron Calorimeter</td>
<td>$1.0 \pm 0.06$ (Berger 1990)</td>
</tr>
<tr>
<td>NUSEX</td>
<td>Iron Calorimeter</td>
<td>$1.0^{+0.09}_{-0.12}$ (Aglietta 1989)</td>
</tr>
</tbody>
</table>

This ratio will be equal to 1 if the measured ratio of neutrino flavors is the same as the predicted ratio.

IMB found a value of $f = 0.76 \pm 0.09$ (stat.) in 1986 (Haines 1986). In 1988 the Kamiokande experiment reported $f = 0.78 \pm 0.08$ (stat.) (Hirata 1988). Thus the atmospheric neutrino anomaly was born. Since 1988, many of the experiments that were originally intended to look for proton decay have produced a ratio of ratios. Some have reported this ratio as less than 1 while others have not. Table 1.1 shows a summary of the results that have been reported. The IMB and Kamiokande detectors have collected, by far, the largest number of atmospheric neutrino events out of all the detectors listed.

Figure 1.2 shows the number of electron-like and muon-like events from the IMB data and Monte Carlo as a function of momentum (Becker-Szendy...
Figure 1.2: The number of electron-like (top plot) and muon-like (bottom plot) events from IMB. The solid line is from the Monte Carlo while the points are from the data (Becker-Szendy 1992). Likewise, figure 1.3 shows the same for Kamiokande (Hirata 1992). In both figures, there is an excess of electron-like events in the data compared to the Monte Carlo and a deficit of muon-like events. This fact indicates the cause of the atmospheric neutrino anomaly may be neutrino oscillations.

If the neutrinos have mass then it is very likely the different flavors have different masses. This is reasonable since the different changed leptons have different masses. This being the case, the mass eigenstates may not be the
Figure 1.3: The number of electron-like (top plot) and muon-like (bottom plot) events from Kamiokande. The solid line is from the Monte Carlo while the points are from the data (Hirata 1992).
same as the flavor eigenstates and mixing may occur which is referred to as neutrino oscillations (see section 6.3.2).

1.5.1 THE ANOMALY AT HIGH ENERGY

Most of the contained neutrino events collected by the nucleon decay experiments were below 1 GeV in neutrino energy. The is just because the detectors were designed to look for the products of proton decay. The mass of the proton is 1 GeV which means the total energy of all the decay products would have to sum to 1 GeV (ignoring the small initial momentum a proton may have inside a nucleus). Also, the flux of cosmic rays, and therefore of atmospheric neutrinos, falls off as a power law in energy which means the total number of events above 1 GeV was very small. The IMB detector only observed such events once every 3 or 4 days.

A study of high energy events which have at least 1 GeV total energy could reveal some important information about the atmospheric neutrino anomaly. One aspect of neutrino oscillations is that the probability for a single neutrino to oscillate to a new flavor is a function of the flight distance divided by the neutrino energy (see section 6.3.2). The flight distance for atmospheric neutrinos varies from the height of the atmosphere (downward-going events) which is 10 km to the diameter of the earth (upward-going events) which is nearly 13,000 km. At low energy a number of oscillations may occur over either of these lengths and so the ratio of ratios will be the same no matter from what direction the neutrinos originated. At high energy, however, the number of oscillations will be different for upward and downward-going events. Essentially, there should be an up-down asymmetry
to the ratio of ratios at high energy if neutrino oscillations are the cause of
the atmospheric neutrino anomaly (see section 6.3.3).

Figure 1.4 shows the muon-like fraction of events for the data and Monte
Carlo as a function of zenith angle for IMB (Becker-Szendy 1992). Figure 1.5
shows the same for Kamiokande (Hirata 1992). It is clear from both figures
that no up-down asymmetry exists in the low energy (below 1 GeV) data.
This leaves the possibility of seeing the effect in the high energy (above 1
GeV) data.

One of the first attempts to look for the atmospheric neutrino anomaly
at high energy came from the IMB experiment (Becker-Szendy 1992). In this
case, upward-going muons were examined. Like the early experiments which
measured atmospheric neutrinos, these upward-going muons came from neu­
trino interactions in the rock surrounding the detector. No electron neutrino
events could be observed in this manner so the total number of upward-going
muons could only be compared to the calculated absolute muon neutrino flux.
This made the results difficult to interpret as there is roughly a 20% uncer­
tainty (Gaisser 1996) in the absolute flux. This limitation was overcome by
observing the ratio of muons which stopped in the detector to those that
passed on through. This was referred to the stopping fraction. Just as was
the case for the ratio of ratios, a number of the systematic errors in the
absolute rates cancel out in this fraction.

The reason for using the stopping fraction was the large energy difference
between the two types of events. The mean energy of the stopping events
was estimated as 6 GeV while the mean energy of the through-going events
Figure 1.4: The fraction of muon-like events versus zenith angle from IMB (Becker-Szendy 1992). The solid line is from the Monte Carlo while the points are from the data. Upward-going events are on the left (-1) while downward-going events are on the right (+1).
Figure 1.5: The fraction of muon-like events versus zenith angle from Kamiokande (Hirata 1992). The solid line is from the Monte Carlo while the points are from the data. Upward-going events are on the left (-1) while downward-going events are on the right (+1).
was estimated as 100 GeV. Since neutrino oscillations depend on energy this ratio should have been sensitive to their effect. The measured stopping fraction was 0.160 ± 0.019 while the average of several different flux models was 0.159 ± 0.009. The error comes from the maximum difference between models (Becker-Szendy 1992). Thus there was no indication of neutrino oscillations from this test.

One disadvantage to the stopping fraction employed by IMB was that it was not sensitive to the up-down asymmetry that should be present for the ratio of ratios simply because it was limited to just upward-going events. The Kamiokande collaboration approached the question of the atmospheric neutrino anomaly at high energy (above 1.33 GeV) by examining their contained neutrino events in this range. They referred to this sample of events as their multi-GeV set and found that the ratio of ratios did indeed show an up-down asymmetry as expected for neutrino oscillations (Fukuda 1994).

Figure 1.6 shows the numbers of electron-like and muon-like events as a function of zenith angle in their multi-GeV sample for both the data and the Monte Carlo. Figure 1.7 shows the ratio of ratios they found for this sample as a function of zenith angle. Notice that downward-going events have a ratio of ratios consistent with 1 while upward-going events have a ratio of ratios less than 1. This is up-down asymmetry strongly implies the existence of neutrino oscillations.

1.5.2 THE MOTIVATION FOR STUDYING IMB DATA

Currently the Kamiokande result stands alone. Just after their result was published in 1994, there were no other experiments with data that could
Figure 1.6: The number of electron-like (top plot) and muon-like (bottom plot) events versus zenith angle for the Kamiokande multi-GeV sample of data (Fukuda 1994). The solid lines are for the Monte Carlo while the points are for the data. Upward-going events are on the left (-1) while downward-going events are on the right (+1).
Figure 1.7: The Kamiokande ratio of ratios versus zenith angle (Fukuda 1994). Upward-going events are on the left (-1) and downward-going events are on the right (+1).
potentially confirm the result except for IMB. The question is, do the IMB contained neutrino interactions show the same up-down asymmetry that Kamiokande saw in their data? This question will be addressed by this dissertation. An analysis of the IMB contained events with at least 1 GeV of visible energy in the detector have been studied. The details of this analysis and the results will be presented in the following chapters.
2.1 INTRODUCTION

The Irvine-Michigan-Brookhaven (IMB) detector started operation in August of 1982 and shut down March 30th, 1991. The main goal of the detector was to look for nucleon decay as described in section 1.4.2. Nucleon decay was never observed in the IMB detector, which set an upper limit on the proton lifetime close to $10^{33}$ years (McGrew 1994). This is well over the $10^{31}$ years predicted by the minimal SU(5). Since atmospheric neutrinos were known to be a significant background for many nucleon decay channels, these particles were collected and studied in detail. The IMB atmospheric neutrino sample has been used in this analysis to see if the measured ratio of neutrino flavors is the same as the theoretically predicted ratio.

Figure 2.1: A side view of the IMB detector cavity showing the long sloping tunnel which was filled to form the floor of the laboratory area.

2.2 LOCATION AND DIMENSIONS

The IMB detector was constructed in the Morton Salt Mine near Cleveland, Ohio with coordinates 41.72° north latitude and 81.27° west longitude (Mudan 1989). It was situated under 600 m of rock which is equivalent to being 1570 m under water. This overburden reduced the rate of cosmic rays in the detector to roughly 2.7 Hz. The experiment site consisted of a large water tight tank plus additional rooms for electronics, water purification and storage. The tank was constructed by excavating a long sloping cavity which was flat on one end. The sloping section was then filled in so that a rectangular cavity was formed as shown in figure 2.1. The top of this filled section became the floor of the laboratory space.
The detector area was lined with 2 layers of non-reflective black polyethylene with a drainage grid between them. Outside of these plastic layers was a layer of concrete. A pump in this region removed any water which may have leaked out of the polyethylene liner. This prevented the water from dissolving the salt walls and structurally undermining the detector. The “roof” of the detector was a floating platform that could rise and fall with the water level. Above this was an air filled space for maintenance. The detector area was sealed from the rest of the laboratory with an opaque wall. Cables going from the detector to the lab were passed through light baffles to prevent photons from leaking in along the guides.

The tank itself was aligned with the geographic coordinates of north, south, east and west. The east and west walls measured 17.8 m in length, the north and south walls measured 24.2 m and the top and bottom walls measured 18.5 m. This gave a total volume of 7969 m$^3$ which translated to roughly 8 kilotons of water. This water was purified through one of two filtration systems as shown in figure 2.2. Recirculation of the entire detector took about 30 days. The filters removed small particles down to about 0.001 $\mu$m (Becker-Szendy 1993) plus ions and biological growth, which helped to maximize the attenuation and scattering lengths.

There were a total 2048 photomultiplier tubes in the detector. They were suspended a distance of 0.5 m from the walls and spaced roughly 1 m apart. All the tubes pointed toward the inside of the detector. The east and west walls had an array of 16 by 16 tubes while the other four walls had an array of 24 by 16. The tubes were grouped together in small grids called patches.
Figure 2.2: The water filtration system used in IMB (Becker-Szendy 1993).
Figure 2.3: A schematic drawing of the IMB detector showing the geographic orientation, the dimensions and the photomultiplier grids.

Each patch contained an 8 by 8 grid of tubes. There were a total of 32 patches in the detector. As will be mentioned in section 2.4, the tubes in each patch shared common sets of electronics, such as power supplies.

The detector coordinate system was defined with the origin at the geometric center of the tank. The x axis pointed in the east direction, the y axis pointed in the north direction and the z axis pointed in the up direction. Figure 2.3 shows a schematic drawing of the IMB detector.

2.3 PHOTOMULTIPLIER TUBES

The job of a photomultiplier tube is to convert a single photon into an electronic pulse in a short span of time. It does this through the photoelectric effect wherein a photon striking certain materials is absorbed and an electron is emitted. In a photomultiplier tube the material is deposited as a thin layer
inside a transparent, evacuated glass tube. The photomultiplier tubes for IMB used $Na_2K'Sb$. An electric field was generated in the tube such that emitted electrons were driven towards the base where they collided with the first in a series of plates called dynodes. An electric potential was maintained between these plates such that accelerated electrons from the photo-cathode which struck the first dynode generally knocked out $\approx 5$ electrons (Casper 1990). These were then driven to the next dynode where, again, each knocked out more electrons. So each dynode essentially multiplied the total number of electrons which struck it.

The photomultiplier tubes in IMB had 14 dynodes so the final gain of the signal was on the order of $10^6$ which could easily be registered by a pulse height discriminator. The average time resolution for the photomultiplier tube and wave shifter plate combination used in IMB was about 13 $ns$ (FWHM) for a single photoelectron and about 5 $ns$ at 10 photoelectrons (Becker-Szendy 1993). A photoelectron is an electron produced by a photon striking the photo-cathode surface. Figure 2.4 shows a cross section of the type of photomultiplier tubes used in IMB.

There were three versions of the IMB detector due to two major photomultiplier tube upgrades. These are called IMB-1, IMB-2 and IMB-3 respectively. Both major upgrades involved changes in either the photomultiplier tubes and/or the associated electronics. The total number of photomultiplier tubes (2048) remained constant throughout the life of IMB.

IMB-1 used 12 $cm$ hemispherical photomultiplier tubes made by EMI Ltd. They were set inside a PVC housing which covered the base of the
Figure 2.4: A cross sectional diagram for the photomultiplier tubes used in IMB.
tube, but left the glass hemisphere exposed. The edge of the housing was beveled and glued with epoxy to the glass. The opposite end of the PVC housing was covered with a plexiglass lid mounted with an O-ring seal. An opaque cover inside the plexiglass prevented light contamination caused by any arcing inside the tube. The high voltage power/signal cable entered through a water tight fixture in the side of the PVC housing. The whole assembly was made neutrally buoyant by attaching smaller PVC cylinders with lead shot.

By May of 1984, the predictions of proton decay from the minimal SU(5) had been ruled out and it became necessary to increase the sensitivity of the detector to study possible super-symmetric decays. The decision was made to use wave shifter plates connected to the hemispheres of the photomultiplier tubes. These plates, which were constructed from a clear acrylic containing a wave shifting compound, absorbed some of the light that missed the photo-cathodes of the photomultiplier tubes. The absorbed light was then re-emitted in an isotropic direction inside the plate and at a longer wavelength. Some of the re-emitted light was trapped by total internal reflection. A fraction of this made its way to the photo-cathode surface to be recorded. The wave shifting plates used in IMB-2 were 60 cm square and 1.3 cm thick. They contained bis-MSB as the wave shifting compound. One plate was connected to each of the 12 cm tubes (Becker-Szendy 1993).

Not long after the upgrade to IMB-2, the aging photomultiplier tubes began to fail at a substantial rate by developing cracks near the base of the glass envelope. This allowed moist air to enter which eventually caused
random sparking within the tube. So not only did these tubes stop detecting light, but actually became light sources. Plans were already underway to replace these tubes with 20 cm Hamamatsu R1408 photomultiplier tubes and so the increasing failure rate simply accelerated the schedule. By May of 1986 all the 12 cm tubes had been replaced and the wave shifter plates had been fitted to the new 20 cm tubes. This was the IMB-3 configuration which had nearly 400% overall better light collection efficiency than IMB-1. Figure 2.5 shows the photomultiplier and wave shifter plate assembly that was used in IMB-3.

2.4 ELECTRONICS

High voltage was supplied to each photomultiplier tube through a 75 Ω cable. There were two lengths of cable, 170 and 230 feet, which were accommodated with appropriate delays in the electronics. The longer cables were necessary for tubes on the side of the detector opposite the tank entrance. It would have been simpler to use 230 foot cables for all the tubes in the detector, but using the shorter cables were possible helped reduce costs. When a photon struck the tube it generated a current at the last dynode as described in section 2.3. This pulse was detected through the power supply line using an RC circuit so that only a single cable was needed per tube. Each cable ran from the tube to a “cable paddle card”. Each cable paddle had eight channels of the 75 Ω cables. High voltage was provided through a single input and distributed to each of the eight channels. The voltage was varied for each channel through the use of socketed resistors. The photomultiplier tube signals were extracted from each channel on the paddle by using eight
Figure 2.5: The photomultiplier tube and wave shifter plate assembly used in IMB-3 (Becker-Szendy 1993).
different RC circuits. Figure 2.6 shows a schematic of a cable paddle card. Generally, the eight photomultiplier tubes on each cable paddle were placed spatially close together and chosen so that the gains were closely matched.

The cable paddle cards plugged directly into a circuit board called the "8-channel" card. These cards contained custom discriminators and analog-to-digital converters. The purpose of the discriminators was to select photomultiplier pulses above a given threshold, usually 20 mV, which was set to eliminate a substantial fraction of the tube noise. Sixteen such 8-channel cards were set inside a single electronics crate. The 128 total tubes in each crate then formed the two patches. Figure 2.7 shows a schematic of an 8-channel card.

A photomultiplier tube provides two basic pieces of information about the light it receives. There is the total charge (which is proportional to the total amount of light received) and the time. When a discriminator fired for a particular channel on one of the 8-channel cards, it started charging a capacitor at a constant rate. This was called the "T1 ramp", as the amount of charge was proportional to the time since the discriminator fired. It also collected the initial and subsequent charges on a second capacitor called the "Q ramp." The Q ramp was proportional to the integrated charge from the photomultiplier tube and therefore it was proportional to the total amount of light collected. These two ramps continued to collect charge until a Digitize Gate signal was received telling them to stop (see the next section). If no such signal arrived within roughly 600 ns, then the discriminator and the ramps reset automatically.
Figure 2.6: A schematic of a cable paddle card (Casper 1990).

C1 - 0.01 μF 3kV
R1 - 1.2 MΩ 1W
R2 - 1.2 MΩ 1W (Socketed)
R3 - 300Ω .25W
Figure 2.7: A schematic of an 8-channel card (Casper 1990).
2.5 TRIGGERS

Once a discriminator fired, a 55 ns logic pulse was produced by the 8-channel card for that channel. Similar outputs from all 8 channels were summed together and sent to the crate backplane. Each crate had 16 such 8-channel cards so this was equivalent to two patches. The crate backplane thus made two separate analog sums of the 8-channel logic outputs, one for each patch. Thus 32 separate sums were produced by the crates. Each was proportional to the number of tubes that had fired in each patch in the last 55 ns. These 32 sums were called the "Patch OR-outs." Simply taking the analog sum of the Patch OR-outs gave the total number of tubes that had fired in the detector in the last 55 ns. When this number exceeded $20 \pm 1$, the detector was triggered. This was called the $N_{\text{tubes}}$ trigger.

Each patch had its own logic discriminator. When the number of firing tubes in a given patch exceeded 9, this discriminator produced a 150 ns logic pulse. The analog sum of these 150 ns pulses from all the patches indicated the number that had 9 or more firing tubes in the last 150 ns. If more than 2 patches in the last 150 ns had more than 9 tubes firing within a 50 ns window, then the detector was triggered. This was called the $N_{\text{patches}}$ trigger.

Triggering of the detector marked the start of an "event" and a global signal was sent to several different places. A universal clock was read out fixing the trigger time to better than one millisecond. The supervisor electronics locked out further triggers and prepared to read out the detector information. A "Digitize Gate" signal was sent to each of the crates holding the 16
8-channel cards. Once this signal was received by the crates, the T1 and Q ramps were stopped and frozen in place and the discriminator reset.

At this time a third capacitor began charging at a constant rate. This was the "T2 ramp." If the discriminator fired then the T2 ramp was stopped. If the discriminator had not fired prior to the Digitize Gate signal, then the Q ramp was allowed to charge. So it was possible to have both T1 and T2 values for a single channel. The Q ramp value was associated with the T1 value if the discriminator fired before the Digitize Gate signal and with the T2 value if it fired after the signal. About 15 µs (Becker-Szendy 1993) after the Digitize Gate signal was sent the T1, Q and T2 ramp values were read out. The purpose of the T2 ramp was to catch the decay products from particles generated in the primary interaction. In particular, the T2 time scale was long enough to catch the decay of muons produced in the primary interaction. The plan was to use these decays as a method of identifying muons in the primary interaction.

2.6 DATA STORAGE

The T1, Q and T2 analog values were all converted to digital values using a custom Analog to Digital Converter (ADC). The digital values could range between 0 and 511 counts. The charging rate on the T1 capacitor was chosen so that 1 count corresponded to 1 ns. The charging rate on the T2 capacitor was chosen so 1 count corresponded to 15 ns. For the Q ramp, a count of 1 corresponded to 0.1 photoelectrons. The digitization took about 2.5 ms in IMB-3.

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After digitization, the data from the whole detector was moved to a temporary buffer which took about 1 ms. At this point all the capacitors for the T1, Q and T2 ramps were grounded and the discriminators were reset so that the detector was available for the next event. The temporary buffer could hold up to 256 separate events (Becker-Szendy 1993). Finally the data was transferred from the temporary buffer to the memory of the monitor computer and then written to an 8 mm tape drive.

2.7 CALIBRATION

Each of the 2048 photomultiplier tubes in the IMB detector had slightly different responses to incident light. That is to say they varied in gain, noise level, the size of one photoelectron, etc. Likewise, there were variances between the T1, Q and T2 ramps and the associated electronics. In addition to the channel-to-channel differences, there were also systematic variations. In general, the response of the photomultiplier tubes and the associated electronics varied with the amount of light received. The calibration process measured the individual and systematic variations between channels so that off-line corrections could be applied, making the response of the detector much more uniform.

The data stored on the 8 mm tapes were the raw ADC counts of T1, Q and T2 ramps for each photomultiplier that received light during the event. The calibration routines applied the necessary corrections for each channel while converting these ADC counts to the useful units of ns and the number of photoelectrons (p.e.s). To simplify the analysis of the data, the T1 time was multiplied by the velocity of light in water so that it had units of distance.
This velocity was 22.5 cm/ns assuming the index of refraction for the water to be 1.33.

The method for this was, in principle, straightforward. A well defined source of light was placed in the detector so that it generated hits on all the photomultiplier tubes. There were two possible sources. The first was a 337 nm Nitrogen laser which provided light in short pulses less than 1 ns in width. The second was a dye laser set to emit 385 nm light in pulses that were roughly 3 ns in width (Becker-Szendy 1993). In IMB-3 pulses from the dye laser were fed into the detector by a fiber optic cable which terminated in a 500 ml flask filled with a mixture of 97.5% distilled water and 2.5% diffusing liquid called Ludox which was manufactured by Du Pont (Becker-Szendy 1993). This liquid distributed the light isotropically. The flask was referred to as the diffusing ball and is shown in figure 2.8. Part of the light from the laser was also sent to a photo-diode so the time of the pulse could be accurately marked. The light pulses sent to the diffusing ball were passed through two sets of filter wheels. Each wheel had eight different attenuation filters. Combinations of filters from both wheels yielded a total of 64 different attenuation levels. The laser and the filter wheels could both be controlled by the monitor computer during the calibration process.

2.7.1 TIMING CALIBRATION

Three different calibration measurements were performed at a time. The first two were the timing calibrations for the T1 and T2 time scales. Not only did the timing response vary from channel to channel, but higher light levels tended to produce earlier times. This was due to two different factors.
Figure 2.8: The diffusing ball used in to distribute the laser pulses isotropically in the IMB detector (Becker-Szendy 1993).
called "discriminator walk" and "first photoelectron effect." The discriminator thresholds were set to fire at the single photoelectron level. If several photons struck the photo-cathode and produced several photoelectrons then the resulting pulse would cross the discriminator threshold earlier than the pulse for a single photoelectron. This is called discriminator walk. The travel time of photons in the detector and of electrons from the photo-cathode to the first dynode vary slightly depending on position. The discriminator is usually fired by the first pulse from the first photon. Statistically this will happen earlier for larger light levels and is called the first photoelectron effect. Both discriminator walk and first photoelectron effect taken in combination are referred to as time "slewing."

It is also possible at very high light levels for at least one photon to pass through the photo-cathode and strike the first dynode directly. This produces a pulse much earlier than expected and is therefore called "pre-pulsing." Pre-pulsing was not a big problem in IMB since even at the highest light levels the probability of it occurring was much less than 1%. No attempt was made to account for pre-pulsing in the calibration procedure.

The goal of the timing calibration was to fit the function:

\[ T_1\text{calibrated} = -A_1 \times T_1\text{raw} + B_1 + F(Q_{\text{raw}}) \]  

(2.1)

where the variables \(T_1\) and \(Q\) represent the time and pulse height respectively. The distance from the diffusion ball to each photomultiplier tube was slightly different just due to the geometry of the detector. The variable \(B_1\) was a correction for those differences in distance. Basically, it was the
expected time for a photomultiplier tube hit from the diffusion ball at low light levels. The function $F$ had the arbitrary form:

$$F(Q_{\text{raw}}) = C \times \ln(Q_{\text{raw}} - Q_{\text{pedestal}})$$  \hspace{1cm} (2.2)

where $Q_{\text{pedestal}}$ was the pulse height on the tube with no incident light. Since the T2 times were digitized in steps of 15 ns, it was not necessary to include the discriminator walk or first photoelectron effect. Accordingly, the function used for the T2 calibration was just:

$$T_{2\text{calibrated}} = -A_2 \times T_{2\text{raw}} + B_2.$$  \hspace{1cm} (2.3)

Note that the slopes $A_1$ and $A_2$ for the T1 and T2 scale were negative. This is due to the fact that their values increased with time so that earlier times had larger values than later times.

Two types of triggers were used in the calibration procedure. The first type had a fixed time between the laser trigger (from the photo-diode) and the global trigger. This was called the "fixed" trigger. The second type had a varying time $\Delta t$ between the laser trigger and the global trigger. This was called the "ramped" trigger. During the time of calibration, the normal $N_{\text{tubes}}$ and $N_{\text{patches}}$ triggers were turned off to screen out cosmic rays. A calibration "run" involved collecting laser triggered events in two separate groups of files. The light level was varied between the files by changing the filter wheel combination. The first set of files constituted the ramped trigger run. The second set of files constituted the fixed trigger run. Calibration runs were performed once every two weeks on average. Table 2.1 shows the
dates of calibration runs performed during the time that the data for this analysis was collected.

The slope of the timing calibrations \( A_1 \) and \( A_2 \) were determined using the ramped trigger data with a least squares fit to \( \Delta t \) versus \( T_{1,\text{raw}} \) or \( T_{2,\text{raw}} \). The pulse height value \( Q_{\text{pedestal}} \) was determined from the ramped and fixed trigger data and was based on the minimum \( Q_{\text{raw}} \) value for the photomultiplier tube in the entire calibration run. The intercepts \( B_1 \) and \( B_2 \) plus the time slewing parameter \( C \) were determined with the fixed trigger data. A linear least squares analysis was applied to \( T_1 \) versus \( \ln(Q_{\text{raw}} - Q_{\text{pedestal}}) \) to determine \( C \). This then fixed the value for \( B_1 \). In practice, \( B_1 \) represents the time for a photon to travel from the diffusion ball to the photomultiplier tube at low light levels.

Generally the calibration parameters varied little between runs. The next several figures will show the average of each calibration parameter for the runs made while the data used in this analysis was collected. The number of the calibration run may be found in table 2.1. Figure 2.9 shows the average \( Q_{\text{pedestal}} \) for all the calibration runs. Figures 2.11 and 2.10 show the average \( A_1 \) and average \( B_1 \) respectively from equation (2.1). Figures 2.12 and 2.13 show the average \( A_2 \) and \( B_2 \) respectively from equation (2.3).

### 2.7.2 PULSE HEIGHT CALIBRATION

The \( Q \) (pulse height) calibration was a little trickier for a number of reasons. The intensity of the laser pulses varied over long periods of time so that the number of photons produced could not be known precisely. The exact light output of the diffusing ball was also not known. These two facts
Table 2.1: The dates for calibration runs performed during the time the data used in this analysis was collected.

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<th>Date</th>
<th>Type of Trigger</th>
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<td>10-24-89 ramped</td>
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<td>03-22-90 fixed</td>
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Figure 2.9: The average $Q_{\text{pedestal}}$ for the calibration runs made while the data used in this analysis was collected.
Figure 2.10: The average T1 slope $A_1$ for the calibration runs made while the data used in this analysis was collected.
Figure 2.11: The average $T_1$ intercept $B_1$ for the calibration runs made while the data used in this analysis was collected.
Figure 2.12: The average T2 slope $A_2$ for the calibration runs made while the data used in this analysis was collected.
Figure 2.13: The average T2 intercept $B_2$ for the calibration runs made while the data used in this analysis was collected.
conspired so that the total number of photons striking each photomultiplier tube was uncertain. Instead only the number of photoelectrons produced could be measured directly. Therefore a statistical method was employed to find the Q calibration parameters.

The discriminator threshold on each channel was set at the 0.2 photoelectron limit so that it was almost guaranteed to fire when struck by a single photon. The probability that it would fire was called the “occupancy” and is given by Poisson statistics as:

$$O = \sum_{N=1}^{\infty} P(N) = 1 - e^{-<N_{pe}>}$$  \hspace{1cm} (2.4)$$

where $P(N > 0)$ is the probability that at least one photoelectron will be measured given a mean number of $<N_{pe}>$ photoelectrons. This equation can be inverted so that:

$$<N_{pe}> = -\ln(1-O).$$  \hspace{1cm} (2.5)$$

The fact that the discriminator fires for a given tube implies it received at least one photoelectron. This being the case, the mean number of measured photoelectrons $<N>$ is:

$$<N> = \frac{\sum_{N=1}^{\infty} NP(N)}{\sum_{N=1}^{\infty} P(N)}.$$  \hspace{1cm} (2.6)$$

Given that:

$$P(0) + \sum_{N=1}^{\infty} P(N) = 1$$  \hspace{1cm} (2.7)$$

this can be reduced to:

$$<N> = \frac{\sum_{N=1}^{\infty} NP(N)}{1 - P(0)} = \frac{<N_{pe}>}{1 - P(0)}.$$  \hspace{1cm} (2.8)$$
From equation (2.4) and (2.7), $P(0) = 1 - O$. This may be combined with equation (2.5) to give:

$$\langle N \rangle = \frac{-\ln(1 - O)}{O}. \quad (2.9)$$

The statistical uncertainty in $\langle N_{pe} \rangle$ from equation (2.5) goes as $\frac{1}{1-O}$. Therefore as $O$ approaches 1 the uncertainty in $\langle N_{pe} \rangle$ grows very large. Equation (2.9) is really only valid for low light levels and was only used for $\langle N_{pe} \rangle \leq 2.5$ photoelectrons. It does have the distinct advantage that it does not depend on the absolute light intensity or the distribution of light from the diffusing ball.

To calibrate the low light levels, the filter wheels were set for low transmittance and a large number of laser pulses sent to the detector. This generated a large number of events. The total charge $Q_{\text{raw}}$ measured was proportional to $\langle N \rangle$. The equation for the $Q$ calibration was then:

$$\langle N \rangle = c_0 + c_1 Q_{\text{raw}}. \quad (2.10)$$

The parameters $c_0$ and $c_1$ were determined by making a linear least squares fit to $\langle N \rangle$ versus $Q_{\text{raw}}$ for each channel.

At high light levels the occupancy $O$ is nearly 1 so the calculation had to be modified. Here the number of photoelectrons produced $\langle N_{pe} \rangle$ was proportional to the transmittance of a particular filter combination $T$ giving:

$$\langle N_{pe} \rangle = -\ln(1 - O) = c'_0 + c'_1 T. \quad (2.11)$$

The procedure was to first find $c'_0$ and $c'_1$ at low light levels by making a linear least squares fit to $-\ln(1 - O)$ versus $T$. The mean value of the total
charge \(Q_{\text{raw}}\) was calculated for each channel and for each transmittance. For the high light levels, Poisson statistics predicts that \(\langle N \rangle \approx \langle N_{\text{pe}} \rangle\). At the lower transmittance settings \(Q_{\text{raw}}\) was still linearly proportional to \(\langle N \rangle\) so that equation (2.10) could still be used with \(Q_{\text{raw}}\) replacing \(Q_{\text{raw}}\). At the higher settings a second order polynomial was used due to photomultiplier tube analog electronics saturation so that:

\[
\langle N \rangle = c_0 + c_1 Q_{\text{raw}} + c_2 (Q_{\text{raw}})^2.
\]  

(2.12)

In both cases, the parameters \(c_0\) through \(c_2\) were determined by making a fit to \(\langle N \rangle\) versus \(Q_{\text{raw}}\) for each channel. The overall average saturation level for the tubes was 258 photoelectrons. The overall average cutoff for the linear fit (equation (2.10) was 31 photoelectrons.

2.8 ABSOLUTE ENERGY CALIBRATION

The analysis and results which will be described in later chapters depends in part on knowledge of the energy for neutrinos interacting inside the detector. The actual neutrino energy could only be estimated for events in the IMB detector for three reasons. First, only charged particles generate Čerenkov light so the energy in the event due to neutral particles was simply not visible. In a charged current interaction the most frequent types of neutral particles were: (1) recoil neutrons, which typically carried very little of the total energy, (2) neutral pions, which decayed to two gamma rays nearly 100% of the time, and (3) gamma rays which produced electromagnetic showers. These same particles were present in neutral current interactions as well, but the scattered neutrino usually carried a significant fraction of the initial
neutrino energy so that a large part of the energy was not visible. Secondly, it was possible that one or more charged particles in each event would exit before dropping below the Čerenkov threshold. For these exiting tracks, only a fraction of their total energy was observed. Thirdly, some charged particles had low enough energy that they were below the Čerenkov threshold and did not produce light. Just as in the case of the neutral particles, the contribution in energy from these particles was not visible. Fourthly, the IMB detector only measured the total number of photoelectrons, which is proportional to the number of Čerenkov photons striking the photomultiplier tubes and wave shifter plates. Thus the energy of each track was not observed directly.

The total Čerenkov energy deposited in the detector was small compared to the energy deposited by ionizational energy loss. Fortunately, both of these quantities are roughly proportional to the distance of travel for relativistic particles. Thus they are also proportional to each other. Equation (4.12) gives the number of Čerenkov photons emitted per unit length of track. Less than 1% of the total Čerenkov photons emitted were actually measured by the photomultiplier tubes. The total number of photons that struck each tube depended on the position of the tube relative to the particle track. The photoelectrons (which were proportional to the photons) in the detector constituted a flux \( \phi_{pe}(\Omega) \) where \( \Omega \) was the solid angle from the point of emission. The total number of photoelectrons then was just:

\[
N_{pe}^{total} = \int dx^3 \int d\Omega \, \phi_{pe}(\Omega) e^{-\frac{r}{\lambda}}
\] (2.13)

where \( r \) is the distance the photon travelled from the point of emission to the photomultiplier tube and \( \lambda \) represents the absorption, attenuation and
scattering lengths of Čerenkov light in the detector. The integration over \( dx^3 \) is for all emission points on each particle track. The mean total flux was the number of recorded photoelectrons divided by the sum of the solid angles subtended by all the tubes. This is written as:

\[
\langle \phi_{\text{pe}}(\Omega) \rangle = \frac{\sum N_{\text{pe}}^i}{\sum \eta_i}
\]

where \( i \) refers to each individual tube and \( \eta \) is the amount of solid angle subtended by tube \( i \). The summations were taken over all hit photomultiplier tubes in the event. To find the total number of Čerenkov photons in a given event, the mean photoelectron flux from equation (2.14) was calculated and used in the numerical integration of equation (2.13).

The next step in determining the energy of particles in the detector involved relating the total number of Čerenkov photons to the amount of ionizational energy deposition. This was not a straightforward task as different types of particles have different rates of energy loss. Likewise, some types of particles, such as electrons, produce many secondary particles while others, such as muons, do not. Here nature provided an easy mechanism for relating the total number of photoelectrons to the total visible energy of the event. Approximately 250,000 cosmic ray muons per day penetrated the overburden of rock and entered the detector. Such cosmic ray muon events were extensively simulated and then compared to the real events so that the actual energy of the events could be compared with the total number of photoelectrons measured. The energy spectrum of the cosmic ray muons extended up to around 500 GeV and peaked around 100 GeV (Mcgrew 1994). Other types of particles were also simulated so the energy could be determined in
Figure 2.14: The number of photoelectrons versus the particle energy for simulated electron events (McGrew 1994). Note that the plot is very linear.

A software algorithm was developed by Clark McGrew to calculate the total visible energy for each event (McGrew 1994). This algorithm numerically integrates equation (2.13) using the track geometries in each event and the simulated response of the detector to all the different types of particles.
When applied to the events in the final data sample of this analysis it found that 1 photoelectron is equivalent to 0.95 MeV. Figure 2.15 shows the visible energy versus the number of photoelectrons for this sample which is very linear. In a similar fashion, this algorithm was applied to the sample of Monte Carlo events used for this analysis. In this case, the algorithm found that 1 photoelectron is equivalent to 1.00 MeV. Figure 2.16 shows the visible energy versus the number of photoelectrons and again demonstrates the relationship is very linear.
Figure 2.15: The visible energy versus the number of photoelectrons for the final sample of data events from this analysis.
Figure 2.16: The visible energy versus the number of photoelectrons for the final sample of Monte Carlo events from this analysis.
CHAPTER 3

THE DATA REDUCTION PROCESS

3.1 INTRODUCTION

The previous chapter introduced and described the IMB detector in general. This chapter will introduce a specific analysis of the IMB data. During its lifetime, the detector provided a wealth of valuable physics, some of which has been outlined in Chapter 1. As such, data from IMB has been extensively analyzed in many different ways. Details of this previous work exists elsewhere and will not be discussed here unless it is directly pertinent to the current analysis.

The goal of this analysis was to find all the neutrino interactions in the detector where the uncorrected visible energy was greater than or equal to 1000 photoelectrons. This corresponded to a neutrino energy of about 1 \( GeV \). The physics motivation for this was outlined in section 1.5.2. Because the IMB detector was originally designed to look for nucleon decay, events with more than 1.5 \( GeV \) were considered uninteresting. Limitations of data storage devices made it necessary to cut out the highest energy events on-line. On average, events with 900 or more photomultiplier hits had more than 1 \( GeV \) of total energy so this became essentially a cut on high energy events. This restriction was lifted in the last year of running with the introduction of 8 \( mm \) tape drives for data storage.
3.1.1 THE DATA SAMPLE

The effect of cutting events with at least 900 hits was to cut off the high energy tail of the neutrino spectrum. Therefore only the data collected after this restriction was lifted has been used in this analysis. The data sample is composed of 236 live days from February 28th, 1990 to March 30th, 1991. Roughly 55 million events were saved to tape in this time. The total exposure of the sample was 2.1 kiloton-years.

In order for a neutrino interaction event to be used in the analysis, it had to satisfy two simple criteria. First, the sum of the raw visible energy had to be at least 1000 photoelectrons and second, the vertex of the interaction had to fit inside the fiducial volume of the detector. The fiducial volume was defined to be 2.5 m in from each wall. These criteria defined and shaped the analysis effort.

3.1.2 THE DATA REDUCTION PROCESS

Nearly all of the data collected by the IMB detector were cosmic ray muon events. These muons entered the detector at a rate of about 3 Hz. The neutrino interactions of interest here happened about once every 3 days. So there were, on average, about 750,000 cosmic ray interactions for a single contained neutrino interaction. The first step of the analysis was to develop data reduction techniques to remove these background events, which meant cutting out 99.9998% of the data sample. The challenge, of course, was not to throw the baby out with the bath water.
3.1.3 THE ORIGINAL DATA REDUCTION SOFTWARE

Since the IMB detector collected data for nearly eight years, techniques had already been developed to differentiate entering events (mostly cosmic ray muons) from contained events, which could be either nucleon decay events or neutrino interactions. However, these techniques were developed with the assumption that most of the events would have less than 1.5 GeV of visible energy. This is certainly true for nucleon decay since the daughters cannot have more energy than the initial proton or neutron. It is also true for most atmospheric neutrino interactions since the flux falls off as a power law with increasing energy (see section 4.2.1). Most of the neutrino interactions originally studied were quasi-elastic, single track events. Furthermore, these events were mostly fully contained. That is, they had a vertex inside the detector and the lepton stopped before it exited.

In the original analysis of IMB data, software cuts were applied to the archived data set to eliminate as many of the entering cosmic ray muon events as possible. Basically, the software would use the timing information from each channel that received light to find the most likely vertex. If this vertex was outside the fiducial volume, the event was rejected. Events fitted with a vertex inside the fiducial volume were saved and later examined by physicists with a computer graphics display package to make the final decision as to whether each was entering or contained.

Two independent software algorithms were employed by the IMB collaboration in the analysis. The first was developed by the collaborating institutions in the eastern part of the country (such as Boston University) and
was called the east coast analysis. The second was developed by the institutions in the western part of the country (such as the University of California Irvine) and was called the west coast analysis. Events in the final sample were those agreed upon by a summary data committee. Only the west coast analysis will be discussed here, though the east coast analysis is similar.

The west coast data reduction software consisted of three parts. The first was called PASS0. This program was optimized to run very fast as it had to examine all the raw events from the data tapes. Basically, it tested a number of preset grid points in the detector to see which was closest to the actual vertex. It did this by assuming the source of the Čerenkov light to be a point rather than a track and then calculating the time each channel should have received light. For short tracks, the point source assumption was not unreasonable. The difference between the calculated time and the actual measured time was called the timing residual. This will be described in more detail later. The grid point with the smallest timing residual was taken as being closest to the real vertex. If this grid point was well outside the fiducial volume then the event was rejected. PASS0 rejected about 90% of the entering tracks in the sample (McGrew 1994).

The next part was called PASS1 and used the grid point vertex from PASS0 as a starting point for a more sophisticated vertex fitter. That fitter was not confined to specific grid points, but the philosophy was the same. If the fitted vertex fell outside the fiducial volume, the event was rejected. Finally, the last part of the data reduction software was called PASS2. This was a very sophisticated fitter that used both the timing information and the
geometry of the Čerenkov cone to find a good vertex and track direction for
the event. Again, if the vertex fell outside the fiducial volume the event was
rejected by PASS2.

All three software routines were tested with several samples of Monte
Carlo events and found to work quite effectively for the quasi-elastic, single
track, fully contained events that dominated the original analysis. However,
there were two problems that became apparent. First, the recovery efficiency
was found to decrease with increasing energy (McGrew 1994) so that it was
actually quite poor for events above 1 GeV. This may be seen in figure 3.1
which shows the recovery efficiency for Monte Carlo events up to 1.5 GeV.

The second problem concerned the path length of the events, which is
defined to be the distance from the vertex to the closest wall along the track
direction. Essentially, this is just the distance the particle could travel in the
detector. It was found that the recovery efficiency was poor for the short
path length events, indicating the loss of events near the edge of the fiducial
volume (Kielczewska 1994). This may be seen in figure 3.2 where the recovery
efficiency versus path length has been plotted.

Before this analysis could begin, both of these problems had to be ad-
dressed. A careful study of the software was performed and from this it was
determined that both problems actually stem from a single cause. Basically
the vertex fitter was fitting many partially-contained events outside the fidu-
cial volume. These are events that have a contained vertex and one or more
exiting tracks. Because the particles producing Čerenkov light were traveling
faster than the speed of light in water, they tended to arrive at the exit point
Figure 3.1: The recovery efficiency versus visible energy up to 1.5 GeV for Monte Carlo events (McGrew 1994).
Figure 3.2: The recovery efficiency versus path length for Monte Carlo events. The filled circles are $\nu_e$ events while the open circles are $\nu_\mu$ events.
before the Čerenkov light emitted near the vertex reached the detector walls. Thus the photomultiplier hits near the exit point generally had the earliest times. This caused the vertex fitter, which only used the timing information, to mistake the exit point as being an entry point. That is, the fitted vertex was placed very close to the exit point. Since this is outside the fiducial volume, these events were rejected.

This now explains both problems described earlier. The more energy an event has, the more likely it is to be partially contained. This is just due to the fact that the particles will travel farther in the detector before dropping below the Čerenkov threshold. In the case of showering particles like electrons, the shower will propagate farther. Likewise, many short path length events may be partially contained since the distance the particles travel before exiting is not very large.

In the study, PASS0 was not used since this routine was written almost a decade ago and computing power has increased significantly since then. Rather, PASS1 was used as the first step in the reduction chain. Since PASS1 used the grid point vertex from PASS0 as a seed for its own vertex fitter one modification was necessary in order to use it on the raw data. Without the PASS0 seed, the initial vertex was chosen at the origin of the detector and a little more time was allotted to allow the procedure to find the best vertex.

The vertex fitter based on the timing information is used extensively throughout both the PASS1 and PASS2 routines. Furthermore, both of these routines were optimized for lower energy events where the atmospheric neutrino flux dominates. For these reasons, it was decided to write new data
reduction routines for this analysis. These new routines used techniques from the original software whenever possible but largely represent new and original work. The next section will describe, in detail, these new routines.

3.1.4 THE NEW DATA REDUCTION SOFTWARE

The new data reduction software had several different stages. The initial software stage was called PASS1A to distinguish it from the original PASS1 routine. It made a very simple, low resolution vertex fit of each event that had more than 1000 photoelectrons. At the next stage the events were separated into two categories based on the number of hit photomultiplier tubes the event contained. Events with more than 600 hits were examined by PASS1B and PASS1C. Events with less than 600 hits were examined by PASS1D and PASS1E. The justification for this separation will be discussed in the sections below. Each of the software stages utilized a number of tools in examining and fitting the events. These tools will be introduced and described as necessary.

The philosophy of the new data reduction software was straightforward. Each routine applied a series of tests to each event. If the event passed the first test, it went on to the second and so forth. If at any point an event failed a test, it was rejected and the next event was selected for examination. If an event passed all the tests in a routine it was saved for the next software stage. In some instances, a single test determined the event was very likely to be a contained neutrino interaction in which case it was saved immediately without any further tests being applied in that stage.
3.1.4.1 PASS1A

The PASS1A software checked every event with four different tests. First, it checked to see if the raw visible energy was above 1000 photoelectrons. After this, the events were "cleaned" of photomultiplier hits that were not directly related to the event. These were usually caused by random noise or by scattered light. To eliminate these hits, a simple algorithm was employed which compared the time of every tube with its eight nearest neighbors. If the tube was found to be significantly out of time with its neighbors, then it was assumed to be a noise hit. These noise hits were ignored in the final three checks made by PASS1A. All the stages of the data reduction software used this same cleaning procedure. Table 3.1 shows a summary of the cuts applied to the data by PASS1A. These cuts will be described below.

As in all the data reduction software, the times were converted to a distance by multiplying by \( \frac{c}{n} \) where \( c \) is the velocity of light and \( n \) is the index of refraction in water which is taken to be 1.33. This allowed the timing information to be expressed in units of distance (cm) rather than units of time (ns). These times will be noted as \( r \) rather than \( T_1 \).

Having met the 1000 photoelectron criteria, PASS1A next checked to see if the event was a "corner clipper." Corner clippers were cosmic ray muons that cut across the right angle edges of the detector. They were characterized by two clusters of hit photomultiplier tubes, both containing a significant amount of light very close in time. PASS1A checked the earliest 80 tubes in an event to see if there were any that had at least 2 photoelectrons and a \( \Delta r \) less than 1800 cm. If there were one or more such tubes, the PASS1A...
choose the one which was closest to the edge of a wall. Using this tube, it
then calculated the average time difference with all the other tubes in the
event.

The average time difference was:

$$\Delta r = \frac{1}{N_{\text{hits}}} \sum_{i=1}^{N_{\text{hits}}} |\tau_{\text{clip}} + d_i - \tau_i|$$  \hspace{1cm} (3.1)

where $\tau_{\text{clip}}$ was the time of the initial tube chosen by PASS1A, $\tau_i$ was the
time of tube $i$ and $d_i$ was the distance between the two tubes. If this average
was less then 400 cm, it indicated that the tube chosen for $\tau_{\text{clip}}$ was close to
an entry point, in which case PASS1A rejected the event. This is referred
to as Cut 1 in table 3.1. The maximum time difference in calculating the
average was set at 600 cm. Figure 3.3 shows the distribution of this average
for cosmic ray muon events. Simulated neutrino events are not shown in the
figure because only 2.2% of them contained early tubes that met the criteria
for $\tau_{\text{clip}}$.

The vertex reconstruction was based mostly on the timing information
from each photomultiplier tube. The start time of the event was called $\tau_0$.
The measured time of a particular tube labeled $i$ was $\tau_i^m$, while the calculated
time was $\tau_i^c$. For this vertex fitter the photons were assumed to come from
a point source rather than having been emitted along a track in order to
reduce the calculation time. The calculated time for a tube then was just:

$$\tau_i^c = \tau_0 + d_i$$  \hspace{1cm} (3.2)

where $d_i$ is the distance from the vertex to tube $i$. The first step in the
reconstruction was to assume a vertex which was initially taken as the center
Figure 3.3: The average time difference between an early tube near the edge of a wall and all other hit tubes in the event. This was used to check for corner clipping events. Only cosmic ray muon events are shown. All events to the left of the bold line were rejected.
of the detector. If the assumed, or trial, vertex was close to the actual vertex then the quantity:

\[ R_i = \tau_i^m - \tau_i^e = \tau_i^m - (\tau_0 + d_i) \]  \hspace{1cm} (3.3)

was close to zero. \( R_i \) was called the timing residual. Likewise, the average of all the timing residuals should be close to zero. This can be written as:

\[ \langle R \rangle = \frac{1}{N_{\text{hits}}} \sum_{i=1}^{N_{\text{hits}}} |R_i|. \]  \hspace{1cm} (3.4)

The basic goal of the vertex fitter was to minimize \( \langle R \rangle \). To do this it calculated the vector \( \vec{R} \):

\[ \vec{R} = \frac{1}{N_{\text{hits}}} \sum_{i=1}^{N_{\text{hits}}} R_i \hat{\mu}_i \]  \hspace{1cm} (3.5)

where \( \hat{\mu}_i \) was a unit vector pointing from the trial vertex to the tube. The total vector \( \vec{R} \) then pointed in the direction where the vertex should be moved to reduce \( \langle R \rangle \). The vector \( \vec{R} \) was then added to the vertex to find a new vertex:

\[ \vec{V}_{\text{new}} = \vec{V}_{\text{old}} + \vec{R}. \]  \hspace{1cm} (3.6)

This process was then repeated till until the vertex exited the detector, the size of \( \vec{R} \) became smaller than 5 cm or it made more than 80 iterations.

This describes the original vertex fitter used by the PASS1 routine and the basis of the vertex fitter for PASS1A. As mentioned in section 3.1.3, this vertex fitter could potentially confuse an exit point in partially contained events as being an entry point and thus reject them. Thus this original vertex fitter had to be modified to avoid this problem.
The solution was to note a characteristic of the exit point in partially contained events. The Čerenkov cone of the track was aimed directly at the exit point, so the tubes there received a great deal of light. In addition to \( R \), the new vertex fitter also calculated:

\[
\hat{A} = \frac{\sum_{i=1}^{N_{hit}} Q_i \hat{\mu}_i}{\sum_{i=1}^{N_{hit}} Q_i}
\]  

(3.7)

where \( Q_i \) was the number of photoelectrons received by tube \( i \). \( \hat{A} \) was called the anisotropy vector and pointed from the vertex to the "center of mass" of the \( Q \) distribution. If the event contained an exiting track, this generally pointed at the exit point since this was the area of the greatest concentration of light. At each iteration of the vertex reconstruction, the trial vertex was moved in the direction of \( s(\hat{R} - |\hat{R} \cdot \hat{A}| \hat{A}) \) where \( s \) was the step size for moving the trial vertex and the dot product was required to be greater than zero. This had the effect of moving the trial vertex towards the optimal position for the timing residuals but away from any exit points. The reason for excluding negative values of the dot product was to make sure the exit point could only repel the vertex and not attract it. Also, as a trial vertex approached an exit point \( \hat{R} \) would begin to point in exactly the same direction as \( \hat{A} \), thus the contribution from the dot product would be greater.

Once the vertex reconstruction was finished PASS1A checked to see if it fell within 135 cm of any wall. If so, the event was rejected. This is referred to as Cut 2 in table 3.1. The distance of a vertex from the closest wall is called the fiducial distance. The distributions of the fiducial distances from PASS1A for cosmic ray muon and simulated neutrino events are shown in figure 3.4.
Figure 3.4: The distributions of fiducial distances from PASS1A for cosmic ray muons (solid line) and simulated neutrinos (dashed line). All events to the left of the bold line were rejected.
Table 3.1: Summary of PASS1A cuts.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Neutrino Saved (%)</th>
<th>Neutrino Rejected (%)</th>
<th>Cosmic Ray Saved (%)</th>
<th>Cosmic Ray Rejected (%)</th>
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<td>---</td>
<td>75.7</td>
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<td>---</td>
<td>22.0</td>
<td>---</td>
<td>9.4</td>
</tr>
<tr>
<td>III</td>
<td>---</td>
<td>1.9</td>
<td>---</td>
<td>8.5</td>
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<tr>
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<td>74.7</td>
<td>25.3</td>
<td>6.3</td>
<td>93.7</td>
</tr>
</tbody>
</table>

The final test applied by PASS1A was to check the number of early tube hits. The start time of each event ($\tau_0$) was determined in the process of fitting the vertex. Normally most of the photomultiplier hits came after this time, but sometimes a few fell before it. If several of the hits came before $\tau_0$ then that was a good indication of an entry point. Events with 5 or more such early tubes were rejected. This is referred to as Cut 3 in table 3.1. Figure 3.5 shows the fraction of early tubes for cosmic ray muon and simulated neutrino interactions.

PASS1A rejected about 95% of the 55 million events in the sample. Events saved by PASS1A were passed along to PASS1B if they had 600 tube hits or more and to PASS1D if they had less than 600 hits.

3.1.4.2 PASS1B

The PASS1B routine was considerably more complicated than PASS1A. Since PASS1A eliminated about 95% of the total data sample, PASS1B could afford to take more time with each event. Only events with more than 600 photomultiplier hits were examined by PASS1B, which meant that a significant number of the events it examined were partially contained. As mentioned in the previous section, the standard vertex fitter based solely on
Figure 3.5: The fraction of early photomultiplier tubes for cosmic ray muons (solid line) and simulated neutrinos (dashed line). All events to the right of the bold line were rejected.
the timing residuals tended to place the vertex of the partially contained events outside the fiducial volume. For this reason, cuts based on the vertex position had to be applied very carefully. Table 3.2 shows a summary of the cuts applied to the data by PASS1B, which are described below.

PASS1B first applied a shape test to the timing distribution of each event. This was called the RING algorithm, though it had nothing to do with Čerenkov rings. The RING algorithm first adjusted the photomultiplier times such that they all fell between 0 and 1 using the equation:

\[
time = \frac{\tau}{T_{\text{max}} - T_{\text{min}}}.
\]  

(3.8)

The times were then histogrammed and the area under the histogram normalized to one. The timing distribution of the event could then be compared directly with the timing distributions from other events.

Imagine a cosmic ray muon entering the detector. As it passes through the photomultiplier plane from the outside it initially generates a small number of hits. The number of hits increases as the muon crosses the detector and nears the opposite side just due to the geometry of the Čerenkov cone.

Most of the muons that make it through the rock to the detector have enough energy that they pass completely through it, generating an exit point on the other side. This produces a tall peak in the distribution late in the event.

Now consider a neutrino interaction. The neutrino enters unobserved and interacts with a nucleon in the water causing charged particles to emerge from the vertex. Kinematics dictate the directions for a single event, but in averaging a large number of events together the directions are essentially
random and will hit the wall at about the same time. The timing distribution will then tend to increase smoothly, peak at the center and taper off smoothly.

Figure 3.6 shows a comparison of the two different timing distributions for entering cosmic ray muon events randomly selected from the data tapes and Monte Carlo contained neutrino events. Both distributions were formed by fitting a large number of histograms for each type of event. The form for cosmic ray muons displayed in figure 3.6 was used as a comparison for events examined by RING. The procedure was simple and went as follows. First a histogram of the normalized timing distribution was generated. Then, bin by bin, the difference was taken between this generated histogram and the fitted histogram. The absolute value of this difference in each bin was summed up and then divided by the number of bins which was 100. This was called the RING value. In general, the RING value would be close to zero if the event being examined was an entering cosmic ray muon but it would be large if it were a contained neutrino interaction. Figure 3.7 shows the distributions of RING values for cosmic ray muons and simulated neutrinos. PASS1B rejected events which had a RING value below 0.425. This is referred to as Cut 1 in table 3.2.

At this stage, PASS1B performed two different vertex fits to the event. The first fit looked for early clusters of hit photomultiplier tubes. If such a cluster was found, it was assumed to be an entry point. This was called the "entering" vertex. The second fit was much like the vertex fit based on timing residuals used in PASS1A. In this case though, the anisotropy vector was not applied in moving the trial vertex. Rather, negative residuals were
Figure 3.6: Fitted timing distributions for entering cosmic ray muons (solid line) and contained neutrino events (dashed line).
Figure 3.7: The distributions of RING values for cosmic ray muons (solid line) and simulated neutrino (dashed line) events. All events to the left of the bold line were rejected.
weighted more heavily in calculating $\bar{R}$. This is because the tubes around the exit point will generally come earlier than expected so the residual will be positive. So again, this was a measure designed to avoid mistaking the exit point as an entry point. The second vertex fit was called the “contained” vertex.

PASS1B applied a number of tests that used a comparison of the entering and contained vertices. The first was a test for multiple tracks. There were essentially two ways for a single event to have multiple tracks. The first was to be a neutrino interaction that produced several particles (the types of particles produced will be discussed in the next chapter). The second was to be a multiple entering cosmic ray muon. These muons are generated from high energy cosmic ray showers in the atmosphere. By the time they reach the depth of the detector the individual muon tracks from these showers are nearly parallel, in the same way that light rays from a distant point source are nearly parallel.

In either case, multiple track events were easy to pick out since the entering vertex fit would be very poor. The easiest way to evaluate a particular vertex fit was to examine the average of the timing residuals as calculated by equation (3.4). If $\langle R_{\text{entering}} \rangle$ is small, the vertex fit is good. A comparison of $\langle R \rangle$ for the entering and contained vertices is shown in figure 3.8.

The entering vertex fitter found the most likely entry point on a wall of the detector. For contained neutrino events with multiple tracks there was no real entry point so $\langle R_{\text{entering}} \rangle$ was large. For multiple cosmic ray muon events the entering vertex fitter could only choose one entry point and so the
Figure 3.8: The contained vertex residuals versus the entering vertex residuals for cosmic ray muon (dots) and simulated neutrino (crosses) events. All events within the bold solid lines were saved while those within the bold dashed lines were rejected.
timing residuals of the other track or tracks were very bad by default and \( \langle R_{\text{entering}} \rangle \) would be large.

If an event had a large \( \langle R_{\text{entering}} \rangle \) it was almost certainly a multiple track event. The trick was to determine which type of multiple track event it was. The two types could be sorted out by examining \( \langle R \rangle \) for the contained vertex. In the case of multiple track neutrino events, \( \langle R_{\text{contained}} \rangle \) would be small. For the case of multiple cosmic ray muons events, \( \langle R_{\text{contained}} \rangle \) would be large. PASSIB checked the \( \langle R_{\text{contained}} \rangle \) for all events with \( \langle R_{\text{entering}} \rangle \) greater than or equal to 300 cm and saved the event immediately if \( \langle R_{\text{contained}} \rangle \) was less than 120 cm or rejected it if \( \langle R_{\text{contained}} \rangle \) was greater than 250 cm. These are referred to as Cut 2 and Cut 3 in table 3.2 respectively.

After checking for multiple muon candidates, PASSIB next looked at the causality of the event based on the entering vertex. The causality \( V_i^c \) for a particular photomultiplier tube \( i \) was defined to be:

\[
V_i^c = \frac{d_i}{\tau_i^m}
\]

(3.9)

where \( d_i \) is the distance from the tube to the vertex. Notice that the causality is unitless. Since \( \tau_i^m = c t_i / n \) this can be rewritten as:

\[
V_i^c = \frac{n d_i}{c t_i} = \frac{n v_i}{c} = \beta_i n.
\]

(3.10)

PASSIB generated a 100 bin histogram of the causality for all the tubes in the event based on the entering vertex. The width of each bin was 0.02. The causality histogram for the event was then compared to a fitted causality distribution based on a large sample of cosmic ray muons. Figure 3.9 shows this fitted distribution. Just like the RING value, the differences between the
fitted distribution and the histogram were summed and this sum was divided by the total number of bins. This was the CAUSAL value. Like the RING value, the CAUSAL value was small if the event had a causality distribution similar to that of entering cosmic ray muons. The entering vertex is generally a poor fit for a contained neutrino event, so the CAUSAL value tended to be large.
Partially contained neutrino events presented a problem for the CAUSAL value. If an exit point was chosen as the entering vertex then the CAUSAL value could be small. Essentially the CAUSAL value could be fooled in the same way the vertex fitter could be fooled. To avoid this problem, the distance from the vertex to the most likely exit point was calculated. This distance was taken to be the average distance to the photomultiplier tubes that received the most light. If this distance was less than 250 cm, the CAUSAL value was ignored. Otherwise, if the CAUSAL value was less than 0.50 the event was rejected. This is referred to as Cut 4 in table 3.2. The relationship between the CAUSAL value and the distance to the exit point is shown in figure 3.10.

The causality distribution for the entering vertex in a contained neutrino event generally peaked below 1. The reason is that light which reached the tubes actually came from a contained vertex which was (on average) closer to each tube. So if the light had come from the entering vertex, it would have travelled faster than \( c \). If the peak of the causality distribution was at 0.90 or lower, the event was saved immediately as being a candidate neutrino interaction. This is referred to as Cut 5 in table 3.2.

The simplest way to compare the quality of the entering and contained vertices was to take the ratio:

\[
\text{r}_{\text{compare}} = \frac{R_{\text{contained}}}{R_{\text{entering}}}.
\]  

(3.11)

For cosmic ray muon events, the contained vertex tended to be slightly worse than the entering vertex so the ratio was larger than 1. The opposite was true for contained neutrino events. In fact, the entering vertex tended to be much
Figure 3.10: The distance to the exit point from the entering vertex versus the CAUSAL value bins for cosmic ray muon (dots) and simulated neutrino (filled circles). All events within the bold lines were rejected.
Figure 3.11: The ratio $r_{\text{compared}}$ versus the number of hit tubes in the events for cosmic ray muon (filled circles) and simulated neutrino (crosses) events. All events below the bold line were saved.

worse than the contained in this case so the ratio was significantly smaller than 1. This effect was slightly dependent on the number of hit tubes in the event and hence on the total energy or multiplicity of the event. Figure 3.11 shows the ratio $r_{\text{compared}}$ versus the number of tubes in the event. PASS1B saved the event immediately if the ratio proved to be sufficiently smaller than one. This is referred to as Cut 6 in table 3.2.
Figure 3.12: The RING value distribution at a second point in the PASS1B program for cosmic ray muon (solid line) and simulated neutrino (dashed line) events. All events to the left of the bold line were rejected.

At this point, many of the cosmic ray muon events had been eliminated and many of the contained neutrino events had been saved so PASS1B checked the RING value again. If the RING value was less than 0.70 and the contained vertex was outside the fiducial volume the event was rejected. This is referred to as Cut 7 in table 3.2. Figure 3.12 shows the RING value distributions for cosmic ray muon and simulated neutrino events at this point in the program.
The next series of tests applied by PASS1B involved not just the vertex information but also the direction of a track coming from the vertex. To do this it was necessary to fit this track direction. Most cosmic ray muon events only have a single track. For this reason, even with multiple track neutrino interactions, only one track was fit in each event.

There were two methods employed to fit the track direction. The first was to calculate the normalized anisotropy vector \( \hat{A} \), where \( \hat{A} \) is defined in equation (3.7). \( \hat{A} \) points from the vertex to the center of mass for the light distribution in the detector. Therefore it generally points very close to the direction of the most energetic track. This initial fit of the track direction was improved by varying it randomly within a small cone about \( \hat{A} \) to find the direction that encompassed the most light within the cone. If this produced a track with a very short path length (less than 50 cm), then a second method was used which was called the RESOLVER fitter. This fitter is the same one used in the PASS2 routine from the original software.

The track vertex and direction were now used to correct the number of photoelectrons received by each tube \( Q_{\text{corrected}} \). This was different from the calibrated value because the angular acceptance of the photomultiplier tube and wave shifter plate combination was not uniform. Photons striking the tube at normal incidence had a higher probability of being recorded than those striking at large angles. Therefore a correction was necessary to account for this varying angular acceptance. This could be calculated if the track of the charged particle was known. The mean of the corrected \( Q \) values \( \langle Q_{\text{corrected}} \rangle \) was calculated using:
\[ Q_{i}^{\text{corrected}} = Q_i (0.3 + 0.3 \cos \phi_i + 0.4 |\cos \phi_i|)^{-1} \]  

(3.12)

where \( \phi_i \) was the angle a photon made with the normal vector to the plane of the wave shifter plate. This equation was chosen such that when \( \phi_i = 0 \), \( Q_{i}^{\text{corrected}} = Q_i \) and when \( \phi_i = \frac{\pi}{2} \), \( Q_{i}^{\text{corrected}} = 3Q_i \). Notice that when \( \phi_i = \pi \), \( Q_{i}^{\text{corrected}} = 2.5Q_i \). This accounts for the fact the wave shifter plates may still receive light even when the photon comes from behind the tube. The \( Q_{i}^{\text{corrected}} \) values were averaged for all the hit tubes in the events producing a \( \langle Q_{\text{corrected}} \rangle \).

Cosmic ray muons that entered the detector were generally very energetic. Normally they would cross the detector and then exit. Because these were muons, they distributed their energy very evenly (see section 5.2) so that \( \langle Q_{\text{corrected}} \rangle \) tended to be large. Contained neutrino events, however, tended to produce multiple tracks. In any given event, there might have been one or more tracks that exited but then there were usually several that did not. Thus the total energy in the event was spread out unevenly and \( \langle Q_{\text{corrected}} \rangle \) was small. This by itself was not enough to sort out the events so it was used in conjunction with the CAUSAL value. Recall that low CAUSAL values were an indication of entering cosmic ray muons. If \( \langle Q_{\text{corrected}} \rangle \) was less than or equal to 5 and the CASUAL value was greater than or equal to 0.8, the event was immediately saved. This is referred to as Cut 8 in table 3.2. Figure 3.13 shows \( \langle Q_{\text{corrected}} \rangle \) versus the CASUAL value for cosmic ray muons and simulated neutrinos.

Since nearly 80% of the cosmic ray muon events had been eliminated and nearly 60% of the contained neutrino events had been saved, PASS1B now
Figure 3.13: The average number of photoelectrons ($Q_{\text{corrected}}$) versus the CAUSAL value for cosmic ray muon (crosses) and simulated neutrino (filled circles) events. All events within the bold lines were saved.
rechecked cuts that had already been made. The RING value was tested once again for all events (inside and outside the fiducial volume). The lower cutoff of 0.425 used at the start of the program was moved up to 0.60 so that events with low RING values were rejected. This is referred to as Cut 9 in table 3.2. Figure 3.14 shows the RING value distribution at this point in the program. Also, each event was checked to see if it could be a corner clipper. A corner clipper test was performed in PASS1A by looking for an entry point near the edge of a wall which was in time with the rest of the hit tubes. As was the case for PASS1A, contained neutrino interactions typically did not meet the criteria for $\tau_{clp}$. For cosmic ray muon events, if the average $\Delta \tau$ was greater than 10 cm the event was rejected. This is referred to as Cut 10 in table 3.2.

The fact that most of the events had been either saved or rejected by this point also made it feasible to run the slow, but more accurate RESOLVER fitter on each event. RESOLVER always fit the vertex inside the detector volume. If, however, there was a cluster of early tubes before the RESOLVER $\tau_0$ and near the RESOLVER vertex, then that was a good indication of an entry point. PASS1B calculated the distance from the RESOLVER vertex to each tube that received light before $\tau_0$. If the distance on any of these tubes was less than 600 cm the event was rejected. This is referred to as Cut 11 in table 3.2.

Finally, there were some entering cosmic ray events that could not be eliminated by applying any of these tests individually. For each test they may have come close to failing but just managed to slip by. Three of the tests
Figure 3.14: The last RING value distribution for cosmic ray muon (solid line) and simulated neutrino (dashed line) events. All events to the left of the bold line were rejected.
Figure 3.15: The distributions of the weighted score for cosmic ray muon (solid line) and simulated neutrino (dashed line) events. All events to the left of the bold line were rejected.

were used in conjunction to catch these culprits. A weighted sum was formed using the RING value, the width of the causality distribution and \( Q_{\text{corrected}} \). The sum was calculated so that contained neutrino events scored high and cosmic ray muon events scored low. Figure 3.15 shows the distributions of the weighted score for cosmic ray muons and simulated neutrino events. PASS1B rejected all events with a weighted sum below 1.5. This is referred to as Cut 12 in table 3.2.
Table 3.2: Summary of PASS1B cuts.

<table>
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<th>Cut</th>
<th>Neutrino Saved (%)</th>
<th>Neutrino Rejected (%)</th>
<th>Cosmic Ray Saved (%)</th>
<th>Cosmic Ray Rejected (%)</th>
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<td>--</td>
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</tr>
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</tr>
<tr>
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<td>--</td>
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</tr>
<tr>
<td>Cut 5</td>
<td>4.5</td>
<td>--</td>
<td>0.2</td>
<td>--</td>
</tr>
<tr>
<td>Cut 6</td>
<td>24.9</td>
<td>--</td>
<td>0.1</td>
<td>--</td>
</tr>
<tr>
<td>Cut 7</td>
<td>--</td>
<td>6.0</td>
<td>--</td>
<td>4.8</td>
</tr>
<tr>
<td>Cut 8</td>
<td>7.7</td>
<td>--</td>
<td>0.1</td>
<td>--</td>
</tr>
<tr>
<td>Cut 9</td>
<td>--</td>
<td>6.2</td>
<td>--</td>
<td>16.0</td>
</tr>
<tr>
<td>Cut 10</td>
<td>--</td>
<td>0.2</td>
<td>--</td>
<td>0.9</td>
</tr>
<tr>
<td>Cut 11</td>
<td>--</td>
<td>1.6</td>
<td>--</td>
<td>1.6</td>
</tr>
<tr>
<td>Cut 12</td>
<td>--</td>
<td>2.6</td>
<td>--</td>
<td>0.6</td>
</tr>
<tr>
<td>Final</td>
<td>69.2</td>
<td>30.8</td>
<td>0.9</td>
<td>99.1</td>
</tr>
</tbody>
</table>

Events that passed all the tests in PASS1B were saved and later examined by the PASS1C software. Of the events saved by PASS1A, about 55% were sent to PASS1B. Only 1% of the events examined by PASS1B were saved.

3.1.4.3 PASS1C

Visual examination (see section 3.1.5) of events saved by PASS1B made it clear that many could be eliminated in a simple fashion. Thus was born PASS1C. In the visual scanning process each event was usually fitted with an automatic fitter. The track and vertex could be adjusted by hand and then the event was evaluated to see if it could be entering or not. Many of the techniques developed in the visual scanning of the events were repetitious and were eventually automated in PASS1C. Table 3.3 shows a summary of the cuts applied to the data by PASS1C.
A substantial fraction of the cosmic ray muon events saved by PASS1B lacked a clear entry point due either to geometry or the fact the muon may have entered the detector at the site of a non-functioning tube. These events could be identified visually by first using the PASS1B contained vertex fitter, finding the anisotropy vector $\hat{A}$ then projecting the vertex back along the track direction to the point where it intersected the photomultiplier plane. If the event were truly an entering event, then the average timing residuals $\langle R \rangle$ would be small for this vertex. In fact, an even better criteria was the peak of the timing residual distribution.

PASS1C applied two tests to the events. It first found a possible entering vertex (as described above) and then looked at the fraction of timing residuals that fell in a window (150 cm) around zero. If that fraction was greater than 0.45 then the event was rejected. This is referred to as Cut 1 in table 3.3.

Next PASS1C checked to see how well the Čerenkov cone fit the ring pattern in the detector. It did this by checking the number of tube hits inside the cone of the fitted track divided by the number of tube hits outside the cone ($f_{in/out}$). It also checked to see what fraction of tubes falling inside the cone actually received light ($f_{occ}$). If there was very little light outside the cone and if most of the tubes inside the cone received light, then the cone fit was considered good. The fraction of tubes inside the ring pattern which received light versus the fraction of hit tubes outside the cone is shown in figure 3.16. If $f_{in/out}$ was greater than 1.053$f_{occ} - 0.674$ and $\langle R \rangle$ was less than 750 cm then the event was rejected. This is referred to as Cut 2 in table 3.3.
Figure 3.16: The fraction of hit tubes inside the cone which received light ($f_{occ}$) versus the fraction of tubes outside the cone ($f_{in/out}$) for cosmic ray muons (filled circles) and simulated neutrinos (dots). All events below the bold line were rejected.
Table 3.3: Summary of PASS1C cuts.

<table>
<thead>
<tr>
<th></th>
<th>Neutrino Saved (%)</th>
<th>Neutrino Rejeted (%)</th>
<th>Cosmic Ray Saved (%)</th>
<th>Cosmic Ray Rejeted (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut 1</td>
<td>--</td>
<td>11.8</td>
<td>--</td>
<td>34.1</td>
</tr>
<tr>
<td>Cut 1</td>
<td>--</td>
<td>0.1</td>
<td>--</td>
<td>20.4</td>
</tr>
<tr>
<td>Final</td>
<td>88.1</td>
<td>11.9</td>
<td>45.5</td>
<td>54.5</td>
</tr>
</tbody>
</table>

Any events that passed these two tests were saved by PASS1C. Overall about 50% of the events saved by PASS1B were rejected by PASS1C.

3.1.4.4 PASS1D

PASS1D examined all events with less than 600 hit photomultiplier tubes that survived PASS1A. These were typically different than the events sent to PASS1B. There were fewer partially contained neutrino events and a great deal more corner clipping cosmic ray muon events. Table 3.4 shows a summary of the cuts applied to the data by PASS1D.

Some partially contained neutrino events could look very much like corner clippers. These events had a vertex inside the fiducial volume but the track directions of the charged particles took them immediately outside. If it happened in the middle of a wall there was no problem. If it happened near the edge of a wall or a corner of the detector, then the event could be confused as a corner clipping cosmic ray muon. The design of PASS1D was largely motivated by the need to distinguish these near-wall partially-contained events from the corner-clipping muon events.

As was the case for PASS1B, the event vertex was fitted twice. Once assuming it was contained inside the detector and once assuming it had to have an entry point on a wall. First the contained vertex was fitted.
A different vertex fitter was used than the one in PASS1B. Here, the vertex and the track were fitted together as a means of improving the vertex fit. The fitter started by finding a vertex with the vertex fitter from PASS1A, then used that vertex to calculate the anisotropy vector $\hat{A}$. The cone shape was evaluated based on the fraction of tube hits inside cone ($f_{\text{in}}$) and the fraction of tubes inside that received light ($f_{\text{occ}}$). The vertex was moved forward and backward along the track direction ($\hat{A}$) to maximize both $f_{\text{in}}$ and $f_{\text{occ}}$ simultaneously. This same vertex fitter was used extensively in the visual scanning as well (see section 3.1.5).

PASS1D then checked to see if the contained vertex was outside the fiducial volume. To ensure that partially contained events were not lost at this earliest stage, $f_{\text{occ}}$ was also checked, since it was usually near 1 for exiting cosmic ray muons. If the fiducial distance was less than $687.5 f_{\text{occ}} - 412.5 \text{ cm}$ the event was rejected. This is referred to as Cut 1 in table 3.4. Figure 3.17 shows $f_{\text{occ}}$ versus the fiducial distance for cosmic ray muons and simulated neutrinos.

Next, PASS1D calculated the timing residual asymmetry of the event. For corner clippers, the tubes were all close in time due to the geometry of the event, so $\langle R \rangle$ was usually not very large. Thus it was not a good measure of the vertex fit for these events. However, if a corner clipper was fit inside the fiducial volume then the timing residuals were often asymmetric. One side of the circular pattern had late residuals while the opposite side had early residuals. PASS1D gauged this effect by calculating the residual asymmetry with the contained vertex as follows:
Figure 3.17: The fraction of hit tubes inside the cone versus the fiducial distance for cosmic ray (dots) and simulated neutrino (crosses) events. All events below the bold line were rejected.
\[ \text{residual asymmetry} = \frac{\langle R_{\text{side}1} \rangle - \langle R_{\text{side}2} \rangle}{\langle R_{\text{total}} \rangle}. \] (3.13)

The choice of sides was arbitrary so PASS1D calculated the residual asymmetry for eight different orientations. The orientation which produced the largest value was then chosen as the residual asymmetry for the event. By itself the residual asymmetry was not a good indicator of entering or contained events so it was used in conjunction with a value called the fast ratio.

The causality for each tube was calculated as in equation (3.10). If this was greater than \( n = 1.33 \) the tube was considered to be "fast" which just means the photons traveling from the vertex to the tube would have travelled faster than \( c/n \). PASS1D calculated the fraction of these fast tubes, referred to as the fast ratio. For a contained vertex the fast ratio is a measure of how many tubes are out of time with the vertex. If the event is an entering cosmic ray muon, the contained vertex (on average) will be closer to the tubes than the actual vertex. Thus the light will appear to arrive at the tubes early. For corner clipping events the contained vertex will be "off center" with the tubes which will produce a large residual asymmetry. Therefore if the fast ratio was greater than 0.10 and the residual asymmetry was greater than 0.40 the event was rejected. This is referred to as Cut 2 in table 3.4. Figure 3.18 shows the fast fraction versus the residual asymmetry for cosmic ray muons and simulated neutrinos.

At this point, PASS1D fitted an entering vertex. It did this by using each of the 2.5% earliest tube hits in the event as a trial vertex. The track direction for each trial vertex was found by looking for an exit point in the remaining number of photomultiplier hits which were not on the same wall.
Figure 3.18: The fraction of fast tubes versus the residual asymmetry for cosmic ray muon (dots) and simulated neutrinos (crosses). All events within the bold lines were rejected.
The cone shape was evaluated in the same manner as it was for the contained vertex track. The combination of entry and exit points that produced the best cone shape was then used as the entering vertex. This was called the CLIPPER-FIT and was also used extensively in the visual scanning.

As before, the causality for each tube was calculated using the entering vertex. The number of fast tubes using the entering vertex was then divided by the number of fast tubes using the contained vertex. Corner clipping events tended to have a higher fraction of fast tubes based on the entering vertex since the muon crossed between the walls faster than \( c/n \). The number of fast tubes tended to be much smaller when using the contained vertex since it was much farther away from the tubes than it should have been. Thus the ratio of the number of fast tubes would be large for corner clipping events while the opposite was true for contained neutrino events. If the ratio was smaller than 1.5 the event was rejected. This is referred to as Cut 3 in table 3.4. Figure 3.19 shows the distributions of the (entering/contained) fast tube ratio for cosmic ray muons and simulated neutrinos.

If the fraction of fast tubes using the entering vertex was more than 0.60 then the event was likely to be a contained neutrino event and was immediately saved. This is referred to as Cut 4 in table 3.4. Figure 3.20 shows the distributions of the fast tube fraction using the entering vertex for cosmic ray muons and simulated neutrinos.

If the earliest photomultiplier hits in the event just happened to fall near the center of the Čerenkov cone for the entering vertex, then this was a good indication the event was actually a partially contained neutrino interaction.
Figure 3.19: The distributions of the (entering/contained) fast tube ratio for cosmic ray muon (solid line) and simulated neutrino (dashed line) events. All events to the left of the bold line were rejected.
Figure 3.20: The distributions of the fast tube fraction using the entering vertex for cosmic ray muon (solid line) and simulated neutrino (dashed line) events. All events to the right of the bold line were saved.
In the case of entering cosmic ray muons, the exit point also produced early hits but the hits around the entry point were even earlier. If the charged particle came from a vertex inside the fiducial volume then there was no entry point and the tubes around the exit point had the earliest times. PASS1D immediately saved any event where at least one hit tube near the center of the Čerenkov cone was the earliest tube in the event. This is referred to as Cut 5 in table 3.4. Figure 3.21 shows the distributions of the number of early tubes near the center of the cone for cosmic ray muons and simulated neutrinos.

At this point in the program, a number of entering tracks had been excluded based on the entering vertex. Now the contained vertex with its associated track were considered once again. If the fraction of hit tubes inside the cone was greater than 0.90, the event was immediately saved. If the fiducial distance was less than 225 cm, the event was rejected. And if the residual asymmetry was less than 0.20, the event was immediately saved. These cuts are referred to in table 3.4 as Cut 6, 7 and 8 respectively. Figures 3.22, 3.23 and 3.24 show the distributions for the fraction of hit tubes inside the cone, the fiducial distance and the residual asymmetry respectively for cosmic ray muon and simulated neutrino events.

The average residual $\langle R \rangle$ was calculated for the entering vertex. If this was less than 50 cm, the event was rejected. This is referred to as Cut 9 in table 3.4. The distributions of $\langle R_{entering} \rangle$ for cosmic ray muons and simulated neutrinos are shown in figure 3.25.
Figure 3.21: The distributions of the number of early tubes near the center of the Čerenkov cone for cosmic ray muon (solid line) and simulated neutrino (dashed line) events. All events to the right of the bold line were saved.
Figure 3.22: The distributions of the fraction of hit tubes inside the cone for cosmic ray muon (solid line) and simulated neutrino (dashed line) events. All events to the right of the bold line were saved.
Figure 3.23: The distributions of the fiducial distance for cosmic ray muon (solid line) and simulated neutrino (dashed line) events. All events to the left of the bold line were rejected.
Figure 3.24: The distributions of the residual asymmetry for cosmic ray muon (solid line) and simulated neutrino (dashed line) events. All events to the left of the bold line were saved.
Figure 3.25: The distributions of the average residual $\langle R \rangle$ for the entering vertex. Cosmic ray muon events are shown as solid lines while simulated neutrino events are shown as dashed lines. All events to the left of the bold line were rejected.
The cone shape based on the entering vertex was checked at this point by calculating both the fraction of light outside the Čerenkov cone \((f_{\text{out}})\) and the fraction of hit tubes inside \((f_{\text{occ}})\). If \(f_{\text{occ}}\) was greater than \(2.5f_{\text{out}}\) this indicated the cone fit from the entering vertex was good and the event was rejected. This is referred to as Cut 10 in Table 3.4. Figure 3.26 shows \(f_{\text{out}}\) versus \(f_{\text{occ}}\) for cosmic ray muons and simulated neutrinos.

Next the cone shape from the entering vertex was compared to the cone shape from the contained vertex by taking the ratio:

\[
\frac{r_{\text{occ}}}{r_{\text{entering}}} = \frac{f_{\text{occ}}}{f_{\text{occ, contained}}} \quad (3.14)
\]

If an event was a contained neutrino event, the track direction may have been fitted correctly but the entering vertex will be too far back so that the Čerenkov cone will be larger than the ring pattern on the wall. In this case, \(r_{\text{occ}}\) will be small. On the other hand, if the event was an entering cosmic ray muon, the contained vertex will be too far forward and the Čerenkov cone will be smaller than the ring pattern. This being the case, \(r_{\text{occ}}\) will be large. If \(r_{\text{occ}}\) was greater than 1.0 the event was rejected. This is referred to as Cut 11 in Table 3.4. Figure 3.27 shows the distribution of \(r_{\text{occ}}\) for cosmic ray muons and simulated neutrinos.

Finally, PASS1D used the causality of each tube based on the entering vertex to find the fraction that were very fast (greater than 1.6) or very slow (less than 0.4). That is, it found the fraction of tubes where the causality was outside a window centered on \(n = 1.33\). If this fraction was greater than 1.0 the event was rejected. This is referred to as Cut 12 in Table 3.4. Figure 3.28
Figure 3.26: The fraction of light outside the Čerenkov cone \( f_{\text{out}} \) versus the fraction of tubes inside the cone which received light \( f_{\text{occ}} \) for cosmic ray muon (filled circles) and simulated neutrino (crosses) events. All events above the bold line were rejected.
Figure 3.27: The distribution of $r_{occ}$ for cosmic ray muon (solid line) and simulated neutrino (dashed line) events. All events to the right of the bold line were rejected.
**Table 3.4: Summary of PASS1D cuts.**

<table>
<thead>
<tr>
<th>Cut</th>
<th>Neutrino Saved (%)</th>
<th>Neutrino Rejected (%)</th>
<th>Cosmic Ray Saved (%)</th>
<th>Cosmic Ray Rejected (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut 1</td>
<td>--</td>
<td>3.0</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Cut 2</td>
<td>--</td>
<td>6.5</td>
<td>--</td>
<td>56.7</td>
</tr>
<tr>
<td>Cut 3</td>
<td>--</td>
<td>12.4</td>
<td>--</td>
<td>19.1</td>
</tr>
<tr>
<td>Cut 4</td>
<td>18.2</td>
<td>--</td>
<td>0.1</td>
<td>--</td>
</tr>
<tr>
<td>Cut 5</td>
<td>26.2</td>
<td>--</td>
<td>0.3</td>
<td>--</td>
</tr>
<tr>
<td>Cut 6</td>
<td>3.9</td>
<td>--</td>
<td>0.4</td>
<td>--</td>
</tr>
<tr>
<td>Cut 7</td>
<td>--</td>
<td>6.1</td>
<td>--</td>
<td>9.8</td>
</tr>
<tr>
<td>Cut 8</td>
<td>3.3</td>
<td>--</td>
<td>0.3</td>
<td>--</td>
</tr>
<tr>
<td>Cut 9</td>
<td>--</td>
<td>5.1</td>
<td>--</td>
<td>4.0</td>
</tr>
<tr>
<td>Cut 10</td>
<td>--</td>
<td>1.6</td>
<td>--</td>
<td>0.4</td>
</tr>
<tr>
<td>Cut 11</td>
<td>--</td>
<td>1.7</td>
<td>--</td>
<td>1.1</td>
</tr>
<tr>
<td>Cut 12</td>
<td>--</td>
<td>1.0</td>
<td>--</td>
<td>1.0</td>
</tr>
<tr>
<td>Final</td>
<td>62.6</td>
<td>37.4</td>
<td>1.4</td>
<td>98.6</td>
</tr>
</tbody>
</table>

shows the distributions of the fraction for cosmic ray muons and simulated neutrinos.

The events which survive all the tests in PASS1D were saved. About 45% of the events from PASS1A were examined by PASS1D. Of these about 2% were saved and later examined by PASS1E.

### 3.1.4.5 PASS1E

PASS1E, similar to PASS1C, was based on techniques developed largely by visually scanning the events from PASS1D. Table 3.5 shows a summary of the cuts applied to the data by PASS1E. The first task of PASS1E was to see how much light fell outside the CLIPPER-FIT Čerenkov cone. If there was a large amount of light outside \( f_{out} \), this indicated the presence of multiple tracks. Since CLIPPER-FIT did very poorly with multiple entering...
Figure 3.28: The distributions of the fraction of tubes outside a velocity window centered on 1.33 for cosmic ray muon (solid line) and simulated neutrino (dashed line) events. All events to the right of the bold line were rejected.
cosmic ray muons, the presence of other tracks strongly implied the event was a contained neutrino interaction. If \( f_{\text{out}} \) was greater than 0.40 the event was immediately saved. This is referred to as Cut 1 in table 3.5. Figure 3.29 shows the distributions of \( f_{\text{out}} \) for cosmic ray muons and simulated neutrinos.

PASS1E next applied three different tests to the contained vertex which was fitted the same way as in PASS1D. First, if the vertex fell within 150 cm of any wall, the event was rejected. This is referred to as Cut 2 in
Figure 3.30: The distributions of $\langle R \rangle$ using the contained vertex for cosmic ray muon (solid line) and simulated neutrino (dashed line) events. All events to the left of the bold line were saved.

table 3.5. Second, if $\langle R \rangle$ for the 5% earliest photomultiplier hits was less than 200 cm the event was immediately saved. This was a good indication the earliest tubes were not due to an entry point. This is referred to as Cut 3 in table 3.5. Figure 3.30 shows the distributions of $\langle R \rangle$ for cosmic ray muons and simulated neutrinos.

Finally, a slightly different version of the causality (equation (3.10)) was calculated for each tube:
Figure 3.31: The number of fast tubes ($V_c'$) for cosmic ray muon (solid line) and simulated neutrino (dashed line) events. All events to the right of the bold line were rejected.

$$V_c' = 1 - \frac{d}{c t} = 1 - \frac{v}{c} = 1 - \beta. \tag{3.15}$$

If more than one tube had $V_c'$ greater than 2.0 the event was rejected. This is referred to as Cut 4 in table 3.5. Overall, PASS1E rejected about 57% of the events saved by PASS1D.
Table 3.5: Summary of PASS1E cuts.

<table>
<thead>
<tr>
<th></th>
<th>Neutrino Saved (%)</th>
<th>Neutrino Rejected (%)</th>
<th>Cosmic Ray Saved (%)</th>
<th>Cosmic Ray Rejected (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut 1</td>
<td>45.2</td>
<td>--</td>
<td>3.4</td>
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</tr>
<tr>
<td>Cut 2</td>
<td>--</td>
<td>1.2</td>
<td>--</td>
<td>1.7</td>
</tr>
<tr>
<td>Cut 3</td>
<td>16.1</td>
<td>--</td>
<td>3.4</td>
<td>--</td>
</tr>
<tr>
<td>Cut 4</td>
<td>--</td>
<td>7.6</td>
<td>--</td>
<td>41.4</td>
</tr>
<tr>
<td>Final</td>
<td>91.2</td>
<td>8.8</td>
<td>56.9</td>
<td>43.1</td>
</tr>
</tbody>
</table>

3.1.5 THE VISUAL SCANNING

The data reduction software could not reliably cut all the entering cosmic ray muon events without also cutting a substantial number of contained neutrino events. The final decision for any event had to be made by human beings. This meant that each event saved by the PASS routines had to be visually scanned using a custom graphics display package. This was quite a large and tedious task since the PASS routines saved approximately 20,000 such events.

The custom visual scanning software package displayed all the event information in three dimensions. Basically, it showed a wire frame display of the detector which could be rotated and viewed from any angle. The number of photoelectrons and the time were graphically represented for each photomultiplier tube which received light in the event. The package allowed multiple vertices and tracks to be fit to each event. These could be adjusted at will by the user.

To prepare for the task of scanning events from the PASS routines, a large number of random cosmic ray events were gathered from the data tapes.
Monte Carlo simulated neutrino events (see Chapter 3) were placed at random into this sample, which was then broken up into practice sets. Each set contained 50 events which was a reasonable amount to scan in one sitting. Each person involved in the scanning process scanned these practice sets until he or she could consistently find near 100 percent of the Monte Carlo events while saving only a small fraction of the random cosmic ray data events. Events saved by the data reduction software were also broken into groups of 50 so they would be similar to the practice sets.

The basic method of scanning was to assume the event was an entering muon and try to fit it as such. There were a number of automatic vertex and track fitters available to the scanners (such as RESOLVER, CLIPPER FIT and the contained vertex fitter from PASS1D). Most of these have been described in the sections on the PASS routines. Of course the automatic fitters were not perfect (or else the visual scanning would not be necessary) so the scanners typically had to adjust the tracks by hand. There were also a number of ways to evaluate the fits to each event which have also been described in the sections on the PASS routines (such as the timing residuals and the causality).

Once the event was fit by the scanner, she or he decided if it could be an entering event or not. Because only high energy neutrino interactions were of interest to this analysis, this was not a terribly difficult decision. Most of the contained neutrino interactions were very easy to recognize since there was enough light in each event to make the ring pattern appear clearly. This was especially true since about 60% of the neutrino events had multiple tracks
coming from a single vertex. Boredom was the biggest danger in the scanning process. As mentioned earlier, the number of events scanned in one sitting was limited to 50 in order to break the monotony. Also, every event (or file of 50 events) was scanned by two different people. This doubled the time needed to visually scan the sample, but it reduced the probability of someone accidently missing a neutrino event.

Simulated neutrino events were included in the data sample from the PASS routines to test the efficiency of the scanning process. None of the people scanning knew which events were fake and which were real. The efficiency was estimated by dividing the number of simulated events found by the scanners by the number placed in the files. The result was $0.98 \pm 0.02$. The visual scanning of the data eliminated all but 83 of the roughly 20,000 events saved by the data reduction software.

These 83 events were fit by hand using the same scanning software package used in the visual scanning. Each event was first fitted with a single track using the fitters used in the data reduction routines. This track was then adjusted by hand to best fit the event. The goodness of the fit was determined using the timing residuals ($R$) and by noting how well the Čerenkov cone of the track fit the ring pattern on the detector walls. About 60% of the events had multiple rings, in which case each ring was fitted with a track from the event vertex. From this hand fitting procedure, 74 events were found to fit inside the fiducial volume.
3.1.5.1 PASS1F

PASS1F was written to examine events that had been saved by the visual scanning process and then hand fitted. The purpose of the routine was to eliminate any possible "contamination" of cosmic ray muons in the final sample of contained neutrino interactions. It was very simple in nature only applying one test to each event.

Since each event had been visually scanned and hand fitted prior to running PASS1F, most of the possible contamination had already been removed and only events that fit near the edge of the fiducial volume were of concern. For this reason, PASS1F saved all events where the distance of the vertex from the nearest wall was at least 350 cm. The most likely source of cosmic ray contamination was from corner clipping cosmic ray muon events. The CLIPPER-FIT was used to find an entering track for each event. This track was then tested to see how well it fit the corner clipping scenario. If $f_{acc}$ was greater than 0.75, the fraction of photoelectrons inside was greater than 0.85, the $\langle R \rangle$ for the vertex was less than 100 cm and the average $\langle R \rangle$ was less than 500 cm, then the event was rejected. Only two events in the final sample of events were eliminated by PASS1F.

3.1.6 THE EFFICIENCY OF THE DATA REDUCTION PROCESS

The data reduction process (PASS routines plus the visual scanning) was obviously very critical to the analysis. The process was time consuming, taking well over a month to run the software on all the data tapes and about 6 months to visually scan the remaining events. Therefore it was critical to design software that would not introduce systematic errors as it would not
be practical to restart the process from scratch. This is why there are 6 (not counting PASS1F) different PASS routines. Each routine was written and tested on the data individually so that any source of systematic errors could be spotted as early as possible in the process.

One of the most likely sources of systematic errors had to do with partially contained events. As mentioned in section 3.1.3, a vertex fitter based on timing residuals alone can be fooled by the exit point in partially contained events. An event is partially contained if one or more charged tracks from the neutrino interaction exit the detector rather than stopping. How often this happens depends on the geometry and the neutrino energy.

The types of particles produced by a neutrino interaction are leptons (electrons or muons, depending on the neutrino flavor), recoil nucleons and pions. The pions and nucleons are strongly interacting particles so they do not travel far as a rule. Electrons also do not travel far but they do generate showers which may propagate for long lengths. Even so, muons generally travel much farther than electrons and are the most likely to exit the detector. This means that a systematic bias towards partially contained events is more likely to effect muons than electrons.

The fraction of events with partially contained tracks increases as the neutrino energy increases. This is just due to the fact that daughters of the interaction have more energy. A 5 GeV muon can cross the entire IMB detector diagonally so that all events in this energy range are partially contained. Based on this, if there is a problem with partially contained events, the
efficiency for saving neutrino events should decrease with increasing neutrino energy.

The efficiency can be defined as the number of events which fit inside the fiducial volume over the number which actually exist inside. To test the efficiency of the data reduction process, a large number of Monte Carlo simulated neutrino interactions (see chapter 4) were generated at random points inside the detector volume (both inside and outside the fiducial volume). The simulated events were treated the same as the data events using the PASS routines and performing the visual scanning. Figure 3.32 shows the efficiency as a function of neutrino energy. Figure 3.33 shows the efficiency as a function of path length. Here, path length is defined to be the distance from the vertex to the closest wall along the track direction. In other words, it is the distance the particle may travel before exiting the detector. There is no indication in either figure of a large systematic due to partially contained events.

3.2 TRACK FITTING

A total of 83 neutrino events were found in the data sample using the data reduction process. Not all of these events, though, were expected to fit inside the fiducial volume. To find which ones would, they had to be fit as accurately as possible. The events had been fit initially by both the PASS routines and the human scanners. These fits, however, were not very accurate since the main goal was simply to exclude entering tracks. So the final stage of the data reduction process was to fit these events as precisely as possible.
Figure 3.32: The recovery efficiency for the new data reduction software versus the neutrino energy. The filled circles are $\nu_e$ events while the open circles are $\nu_\mu$ events.
Figure 3.33: The recovery efficiency for the new data reduction software versus the path length. The filled circles are $\nu_e$ events while the open circles are $\nu_\mu$ events.
Fitting the final set of events was really a two step process. First, two automatic fitters were applied to each event. These fitters were the contained vertex fitter used in PASS1D and the RESOLVER fitter which was used in PASS1B. These fits were stored along with the event data. The graphics scanning package was then used to examine each event. First, one of the two fits from the automatic fitters was selected as the best candidate. Then this fit was optimized by hand. In addition, the automatic fitters only fit one track. If the event contained multiple tracks, all the rest had to be fitted by hand.

Based on these hand fits, 74 out of the 83 events fit inside the fiducial volume. These 74 events were examined by PASS1F and 2 were determined to be entering cosmic ray muons. So a total of 72 events fit inside the fiducial volume of the detector. The resolution of a vertex is the distance from the fitted vertex to the actual vertex. A large number of Monte Carlo neutrino events which survived the data reduction process were fitted exactly as the data events were. Based on this the resolution of the hand fitting procedure could be determined. The mean resolution was 103.4 cm. Figure 3.34 show the distribution of vertex resolutions for $\nu_e + \bar{\nu}_e$ and $\nu_\mu + \bar{\nu}_\mu$. The mean resolutions are 93.0 cm and 107.6 cm respectively.
Figure 3.34: The vertex resolution for hand fitted tracks based on Monte Carlo neutrino interactions. The solid line is for $\nu_e + \bar{\nu}_e$ with a mean resolution of 93.0 cm while the dashed line is for $\nu_\mu + \bar{\nu}_\mu$ with a mean resolution of 107.6 cm.

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CHAPTER 4

THE ATMOSPHERIC NEUTRINO SIMULATION

4.1 INTRODUCTION

Computer simulations are an integral part of nearly all high energy physics experiments. They are used to design, build and optimize the detector and they are very often used as a comparison for the data that is collected. The simulations cover everything from the microscopic interactions of individual particles to the macroscopic response of the detector elements. For a single particle interaction there are usually several different “channels” through which it may progress. Each channel has a weighted probability which is based on the physics governing the interaction. At the heart of the matter, the choice of which channel the interaction takes is random. For this reason, computer simulations in high energy physics are often called Monte Carlo simulations (or just Monte Carlo’s) based on that city’s reputation as a gambling mecca.

The analysis of IMB data presented here relied very heavily on a Monte Carlo simulation. This chapter will describe the Monte Carlo that was used. It was not a single routine but actually a collection of many different programs written by many different people. The neutrinos observed in the detector actually came from primary cosmic ray interactions in the upper atmosphere so this was where the simulation started. From there, it simulated the interactions of the neutrinos with the oxygen and hydrogen nuclei in the water of the
detector. Finally, it simulated the response of the detector to the by products of the neutrino interaction. This last step was the personal contribution of the author.

4.2 THE ATMOSPHERIC NEUTRINO SIMULATION

Cosmic rays are totally ionized nuclei which stream in from outer space. The chemical and isotopic composition of these particles covers all the stable members of the periodic table, though the flux is dominated by light species, especially hydrogen. The flux is isotropic and follows a steep power law in energy. This spectrum is modified at low energies as the cosmic rays propagate through the magnetic field of the heliosphere. This is referred to as solar modulation. The effect of solar modulation is to bend the spectrum over around 200 MeV per nucleon. The Sun's magnetic field varies with the solar cycle. At times of high solar activity, the flux of cosmic rays will be at its lowest, while at times of low solar activity, the flux will be at its highest. The Earth's magnetic field also influences the low energy cosmic rays by altering their trajectories such that they cannot reach certain portions of the Earth's surface. So an observer on one point of the surface would see a different energy and angular spectrum than an observer at another position. This is called the geomagnetic effect.

The primary cosmic rays collide with nuclei in the upper atmosphere. These are hadronic interactions so a large number of charged pions are produced. Some of the pions will decay weakly by the reactions:

$$\pi^\pm \rightarrow \mu^\pm + (\nu_\mu)/(\bar{\nu}_\mu)$$  \hspace{1cm} (4.1)
producing a muon neutrino ($\nu_\mu$ or $\bar{\nu}_\mu$). The muons have a much longer life time than the pions, but some of these will decay before they reach the ground. The muon decay reactions are:

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu. \quad (4.3)$$

Here an electron neutrino ($\nu_e$ or $\bar{\nu}_e$) is produced along with a muon neutrino. Through the whole chain of decays there are roughly two muon neutrinos produced for every electron neutrino. This ratio, however, is not constant for all energies. At high energy, the primary cosmic ray interactions will generate kaons. These decay and produce muon neutrinos 63.5\% of the time through the reactions:

$$K^+ \rightarrow \mu^+ + \nu_\mu$$
$$K^- \rightarrow \mu^- + \bar{\nu}_\mu. \quad (4.4)$$

Many other kaon decay channels produce charged pions, which may then produce both electron and muon neutrinos through reactions (4.2). At still higher energies, charmed mesons such as $D^0$ or $D^\pm$ may be produced further changing the ratio of neutrino flavors.
4.2.1 THE ATMOSPHERIC NEUTRINO FLUXES

The first step in the simulation of atmospheric neutrinos was to calculate the flux, which varied with energy, zenith angle and position on the Earth. Generally, two basic methods have been used to perform the calculation in the past. The first method was to use the measured spectrum of muons at various depths in the atmosphere and work back to find the spectrum of pions and kaons produced by the primary cosmic ray interactions. Results from this type of calculation are given in (Markov 1961, Zatsepin 1962, Osborne 1965, Tam 1970, Volkova 1972, Volkova 1980, Perkins 1994). This initial method was mostly abandoned during the 1980s as faster computers became more widely available. This allowed the second method to be used which was to perform a Monte Carlo simulation of the cosmic ray interactions and track the secondaries in the atmosphere. Results from this type of calculation may be found in (Gaisser 1983, Mitsui 1986, Gaisser 1988, Lee 1988, Bugaev 1989, Honda 1990, Lee 1990, Kawasaki 1991, Agrawal 1996).

The atmospheric neutrino fluxes used in this analysis were provided in tabular form by T. Stanev of the Bartol Research Institute. Fluxes were also provided by M. Honda (Honda 1995) of ICRR as a comparison. The details of the flux calculation for the tables provided by T. Stanev are given in Agrawal et al. (Agrawal 1996) and so only a brief summary will be presented here. The calculation involved a Monte Carlo simulation starting with the primary cosmic ray interactions. The calculation was restricted to neutrino energies from 1 GeV and up so that solar modulation and geomagnetic effects were unimportant. The calculation was also one dimensional, which means the
secondaries always scattered forward along the direction of the primary. At low energies this might be a problem as roughly 50% of the secondaries would scatter in a direction away from the Earth. In the energy range of interest here, however, the secondaries strongly favor the forward direction so the one dimensional approximation is good.

The spectrum of cosmic rays came from a compilation of world data (Ormes 1978, Simpson 1983) and on recent high energy measurements (Swordy 1993, Asakimori 1993). Hadronic interactions in the simulation were handled by a model called TARGET, which is described in Gaisser, Protheroe and Stanev (1983). Nuclei were treated as collections of nucleons (Gaisser 1988). Thus any particular nucleus would just be treated as group of Z protons and (A-Z) neutrons all acting independently.

The basic simulation procedure was to generate a large number of primary cosmic ray interactions at discrete energies (Gaisser 1988). The secondaries produced were then tracked through the atmosphere and allowed to either interact or decay. Energy loss of the secondaries and all decay branches with more than 1% probability were included (Gaisser 1988). The output was a table of neutrino energies and directions for $\nu_e$, $\bar{\nu}_e$, $\nu_\mu$ and $\bar{\nu}_\mu$. The energy spectrum was generated by repeating the simulation for different primary cosmic ray energies and adding the resulting tables together.

This analysis involved all neutrino interactions which had at least 1 $GeV$ of visible energy deposited in the detector. Typically the entire energy of the event was not visible since some of the particles could exit before stopping and only charged tracks produced Čerenkov light. Thus the neutrino energy
of most events was greater than 1 GeV, though it was still possible that a few neutrinos with lower energy may have enough visible energy to make the cut. This is just due to the overall uncertainty in equating the number of photoelectrons to the amount of energy deposited. This “leakage” had to be included in the atmospheric neutrino simulation. The table of fluxes provided by T. Stanev had 10 energy bins per decade and 12 zenith angular bins (cos $\phi$). The lower edge of the first energy bin was 1 GeV. The fluxes in the tables provided by T. Stanev were extrapolated back to 0.8 GeV to cover any possible leakage from the low energy events. Figure 4.1 shows the atmospheric neutrino fluxes from the table integrated over all angles (Agrawal 1996). The extrapolated region of the fluxes are shown as dashed lines while the fluxes provided directly by the table are shown as solid lines. Only 0.3% of all the events generated in the extrapolated region had enough visible energy to pass the 1000 photoelectron cut applied to all events.

4.3 THE NEUTRINO-NUCLEON INTERACTION

The atmospheric neutrino flux calculation gave the rate of neutrinos passing through the detector volume. Only the neutrinos that interacted with nucleons in the water molecules could be detected. It was possible for neutrinos, especially electron neutrinos, to interact with the atomic electrons. The cross section for this is very small (on the order of $10^{-6} pb$), compared to the cross section on nucleons (on the order of $10^{-2} pb$), so these interactions were not modelled. The next step in the total atmospheric neutrino simulation then was to model the neutrino-nucleon interactions. The model used for this was developed by Wojciech Gajewski and Todd Haines (Haines 1986).
Figure 4.1: Neutrino fluxes integrated over all angles from the table provided by Agrawal et al. (Agrawal 1996). The upper curve is for $(\nu_\mu + \bar{\nu}_\mu)$ and the lower curve is for $(\nu_e + \bar{\nu}_e)$. Filled circles connected with solid lines denote points taken directly from the table while open circles connected by dashed lines denote the extrapolated points.
It simulated both charged current and neutral current neutrino interactions with nucleons inside either the oxygen or hydrogen nuclei of the water. It included quasi-elastic, inelastic and some deep inelastic scattering plus single and multiple pion production. It then propagated the daughters of the interaction through the nuclear environment.

There are many different channels for a single neutrino interacting with a nucleon. The channels may be broken up into two separate categories which are charged currents and neutral currents. Charged current interactions involve the exchange of a either a $W^+$ or $W^-$ vector boson and produce a charged lepton in the final state, hence the name. Neutral current interactions involve the exchange of a $Z^0$ vector boson producing a neutral lepton (neutrino) in the final state. Both types of interactions conserve lepton number. If, for example, a $\nu_e$ interacts then either a $e^-$ or a $\nu_e$ will be produced in the final state depending on whether the interaction was charged current or neutral current. Charged current interactions were easy to spot in a water Čerenkov detector due to the charged lepton that is produced. Neutral currents do not produce a charged lepton, but some of the neutrino energy is visible in the form of a recoil nucleon or by the production of pions.

Quasi-elastic neutrino interactions are the simplest in form. For charged current interactions these are just:

\[
\begin{align*}
\nu_l + n &\rightarrow l^- + p \\
\bar{\nu}_l + p &\rightarrow l^+ + n
\end{align*}
\]
Table 4.1: Neutrino-nucleon interaction channels for single pion production.

<table>
<thead>
<tr>
<th>Neutrino Interaction</th>
<th>Antineutrino Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_l \ p \rightarrow l^- \ p \ \pi^+$</td>
<td>$\bar{\nu_l} \ n \rightarrow l^+ \ n \ \pi^-$</td>
</tr>
<tr>
<td>$\nu_l \ n \rightarrow l^- \ n \ \pi^+$</td>
<td>$\bar{\nu_l} \ p \rightarrow l^+ \ p \ \pi^-$</td>
</tr>
<tr>
<td>$\nu_l \ n \rightarrow l^- \ p \ \pi^0$</td>
<td>$\bar{\nu_l} \ p \rightarrow l^+ \ n \ \pi^0$</td>
</tr>
<tr>
<td>$\nu_l \ p \rightarrow \nu_l \ n \ \pi^0$</td>
<td>$\bar{\nu_l} \ p \rightarrow \nu_l \ p \ \pi^0$</td>
</tr>
<tr>
<td>$\nu_l \ p \rightarrow \nu_l \ n \ \pi^+$</td>
<td>$\bar{\nu_l} \ n \rightarrow \nu_l \ n \ \pi^+$</td>
</tr>
<tr>
<td>$\nu_l \ n \rightarrow \nu_l \ n \ \pi^0$</td>
<td>$\bar{\nu_l} \ n \rightarrow \nu_l \ n \ \pi^0$</td>
</tr>
<tr>
<td>$\nu_l \ n \rightarrow \nu_l \ p \ \pi^-$</td>
<td>$\bar{\nu_l} \ n \rightarrow \nu_l \ p \ \pi^-$</td>
</tr>
</tbody>
</table>

where $l$ stands for the lepton flavor which could be either an electron ($e$), a muon ($\mu$) or a tauon ($\tau$). Neutral current interactions were also possible in the form:

$$\nu_l + N \rightarrow \nu_l + N \quad (4.6)$$

where $N$ represents either a proton or neutron. The quasi-elastic reactions used in the model for this analysis come from Llewellyn and Smith (Llewellyn 1972).

Neutrinos with sufficient energy could also produce one or more pions through interactions with nucleons. Single pion production in the neutrino-nucleon model used for this analysis was based on the model of Fogli and Nardulli (Fogli 1979) and included pion production by the isospin ($I$) $\frac{1}{2}$ and $\frac{3}{2}$ peaks as well as by non-resonant Born terms (Haines 1986). The model handled both charged current and neutral current interactions for all four neutrino types ($\nu_e$, $\nu_\mu$, $\nu_\tau$ and $\bar{\nu}_\mu$). All of the possible single pion production channels are listed in table 4.1.

Very high energy neutrinos actually interact with the individual quarks inside the nucleons. This is referred to as deep inelastic scattering.
simplest way to model this is to assume the "struck" quark receives the momentum transferred in the reaction and that the other two quarks are merely spectators. The color force lines between the quarks are stretched out as the struck quark propagates out. Eventually these color lines "break" as the struck quark picks up a partner from a quark anti-quark pair in the vacuum creating a meson. The remaining quark from the vacuum pair then picks up its own partner and so forth. This is the basis of the Field-Feynman fragmentation model (Field 1977) which was used in the neutrino-nucleon model for this analysis. Table 4.2 shows all the possible double pion production channels. Figure 4.2 shows the relative cross sections for single and double pion production. Comparisons to data may be found in Haines (1986).

The neutrino-nucleon interaction model generated an event by first choosing a flavor of neutrino (ν_e, ν_μ, ν_τ or ν_μ̄) and the type of nucleon (proton or neutron). The atmospheric neutrino flux table was used as a probability distribution function for randomly choosing the neutrino energy, flavor and
Figure 4.2: The single and multiple (two or three) pion production relative cross sections from the neutrino-nucleon interaction model. The solid lines are $\nu_e$, the dashed lines are $\bar{\nu}_e$, the dotted lines are $\nu_\mu$ and the dot-dashed lines are $\bar{\nu}_\mu$. 

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direction. The model decided if the interaction took place inside an oxygen nucleus or inside of a hydrogen (free proton) nucleus. If it occurred inside an oxygen nucleus, then the initial momentum of the nucleon was chosen assuming a Fermi sphere of 225 $MeV/c$ (Haines 1986). All the possible final states for this combination of neutrino and nucleon were generated and then given a weight which was basically the cross section for that channel. The weights from all the generated combinations were added to give a total weight which was multiplied by a random number between 0 and 1. This number was then compared to the maximum weight for the particular neutrino-nucleon combination. If the random number was less than the maximum weight the event was rejected and a new neutrino-nucleon combination was chosen. If it was greater than the maximum weight the model choose one of the final states at random based on the relative weights.

If the initial nucleon was a free proton, the model saved the generated event and moved on. If the initial nucleon was part of an oxygen nucleus, it then had to propagate the final state particles out. The event was rejected due to Pauli blocking if the momentum of the final nucleon was below the Fermi level of 225 $MeV/c$. For simplicity, the nucleus was assumed to be a very close collection of individual nucleons. The final state particles were stepped 0.2 $fm$ at a time through the nucleus. The meson-nucleon interactions included elastic scattering, charge exchange and absorption. The exact details of the nuclear propagation may be found in Haines (Haines 1986).
4.4 THE DETECTOR SIMULATION

The next step in the atmospheric neutrino Monte Carlo after the neutrino-nucleon interaction model was to propagate the final state particles through the detector. This was the job of the detector simulation, which had to accurately reproduce the physics of the particle interactions and the detector response. There were four basic types of particles that had to be tracked: Čerenkov photons, leptons, gamma rays and hadrons. The detector simulation was originally written by Bob Svoboda for use with the IMB detector. It was later modified to simulate events for the Super Kamiokande detector. At this point it picked up the name Yamihino Monte Carlo Algorithm (YMCA). The simulation included custom routines for the physics and tracking of photons, leptons and gamma rays and for the generation and tracking of Čerenkov light. These routines will be described below. The detector simulation also included hadronic interactions through a package called FLUKA.

4.4.1 PARTICLE TRACKING

The detector simulation had four running buffers to hold all the particles generated during a single event. There were buffers for gamma rays, electrons, muons and hadrons. The information stored for each type of particle included its position, direction, energy and time (that it was placed on the buffer). At the start of an event all the particles from a single neutrino-nucleon interaction were placed in their respective buffers and the event clock was set to zero. The simulation then took a single particle from a given buffer and tracked it through the detector. Any secondary particles generated by this particle were placed in the appropriate buffer. Čerenkov photons were
tracked through the detector as they were generated. Once all the buffers were empty, the event was over. The simulation then wrote out the relevant information and started the next event.

Once a particle was removed from the buffer, it was stepped in small increments from its current position along its track direction. In a single step, a number of physics processes could take place. For instance, a photon could either scatter or be absorbed. Each possible process was represented as a probability distribution which could be used to generate a random length for that step. The lengths from all the possible processes were compared. The smallest length was then chosen as the step size and the particle was moved this distance along its track to the point where the process occurred. There the process was carried out. Again, as an example, if the random length for a photon to scatter was less than the maximum step size, the photon was moved that distance along the track. There it was scattered by assigning it a new direction at which point it was ready for the next step in the tracking. All the particles were tracked until they either stopped, interacted, decayed or left the detector.

4.4.1.1 ĆERENKOV PHOTONS

Many materials (solids, liquids and gasses) have a phase velocity of light which is lower than the velocity of light in a vacuum. Relativistic charged particles passing through such a material may actually exceed the phase velocity of light in which case they will radiate. The energy radiated is normally trivial compared to ionizational energy loss but the radiation does provide a very useful way of detecting charged particles. This is particularly
true since the energy is radiated in a cone about the track of the particle. To see this, imagine a photon emitted by a relativistic charged particle as shown in figure 4.3. After time $t$, the particle has travelled a distance $\beta ct$ where $c$ is the speed of light in a vacuum, $\beta = v/c$ and $v$ is the velocity of the particle. In the same time $t$, the photon has travelled a distance $\frac{ct}{n}$ where $n$ is the index of refraction for the material. Successive photons emitted along the track length create a wave front at right angles to the photon directions. This may be used to find the cosine of the angle $\theta_c$ which is:

$$\cos \theta_c = \frac{ct}{\beta ct} = \frac{1}{\beta n}.$$  \hspace{1cm} (4.7)

Since $\beta$ is usually very close to 1 for most relativistic particles, the Čerenkov angle $\theta_c$ is just:

$$\theta_c = \cos^{-1} \left( \frac{1}{n} \right).$$  \hspace{1cm} (4.8)

The Čerenkov medium in the IMB detector was water which had an index of refraction of $n = 1.33$ so the Čerenkov angle $\theta_c$ was about $41^\circ$.

The geometry of the Čerenkov radiation creates a circular pattern on the walls of the detector. The photomultiplier tubes arranged in a grid on the sides of the detector measure the position and timing of these circular patterns allowing the tracks of charged particles to be reconstructed.

The number of Čerenkov photons produced by a particle with charge $z$ depends on the distance it travels $x$, its energy $E$, its velocity $\beta$, the wavelength of the emitted light $\lambda$ and the index of refraction of the material $n$. This is expressed in the equation:
Figure 4.3: The geometry of Čerenkov photon emission.
\[
\frac{d^2 N}{dx} = \frac{\alpha z^2}{\hbar c} \sin^2 \theta_c dE,
\]

where:

\[
\sin^2 \theta_c = 1 - \frac{1}{(\beta n)^2}
\]

from figure 4.3. Using \( E = \hbar c/\lambda \) this can be rewritten as:

\[
\frac{d^2 N}{dx} = -\frac{\alpha z^2}{\hbar c \lambda^2} \left(1 - \frac{1}{(\beta n)^2}\right) d\lambda.
\]

For simplicity assume that \( n \) is independent of \( \lambda \), then integration over \( \lambda \) yields:

\[
\frac{dN}{dx} = \frac{\alpha z^2}{\hbar c \lambda} \left(1 - \frac{1}{(\beta n)^2}\right)
\]

Notice that this equation becomes negative if \( \beta \) becomes less than or equal to \( 1/n \). Since a negative number of photons does not make sense, this defines the Čerenkov limit. Also note that the number of photons produced per unit length is inversely proportional to the wave length of the emitted light. This means that more photons will be produced at the blue end of the visible spectrum. All charged particles traveling through the water in the IMB detector emitted Čerenkov photons provided their velocity was above the Čerenkov threshold. The minimum velocity can be found using equation (4.7). Solving for \( \beta \) gives:

\[
\beta = \frac{1}{n \cos \theta_c}.
\]

The opening angle of the Čerenkov cone gets smaller as \( \beta \) gets smaller so in effect it collapses as the particle slows down. Inserting \( \theta_c = 0 \) into the
equation above yields $\beta = \frac{1}{n}$. Given that $n = 1.33$ the charged particles will emit Čerenkov light only if they have $\beta \geq 0.75$.

The number of photons emitted per unit length is given by equation (4.12). In small steps, the energy loss of a particle will not be very great so that $\beta$ will essentially be constant. Then equation (4.12) may be written as:

$$N_c = \frac{\alpha z^2}{hc\lambda} \left( 1 - \frac{1}{(\beta n)^2} \right) \Delta x$$

(4.14)

where $N_c$ is the number of Čerenkov photons produced in the distance $\Delta x$ at wavelength $\lambda$.

The sensitivity of the photomultiplier tubes in the IMB detector was good for the blue-green region of the visible spectrum. It peaked around 370 nm which is just slightly in the ultra-violet. To calculate the number of Čerenkov photons to generate at each step, the detector simulation first found the maximum number of photons that could be generated. This comes from integrating equation (4.14) over the range of $\lambda$ for which the photomultiplier tubes were sensitive. This maximum number is referred to as $N_{\text{max}}$.

Each photon generated had to be tracked individually through the detector. This required a great deal of computer calculation time slowing down the simulation. Both the photomultiplier tubes and the wave shifter plates were not 100% efficient in converting incident photons into photoelectrons. So not all photons that managed to strike one of these devices produced a hit. The detector simulation took advantage of this by using the known efficiencies of the photomultiplier tubes and the wave shifter plates to reduce the number of photons generated at each step. The equation used by the simulation to generate photons was:
\[ N_g = \epsilon N_{max} \left(1 - \frac{1}{(\beta n)^2}\right) \Delta x \] (4.15)

where \( \epsilon \) was the efficiency of either the photomultiplier tubes or the wave shifter plates.

Each photon generated in a step was given a random wavelength based on weighted probability from equation (4.14). The initial position of the photon was chosen at random along the track of the parent particle within \( \Delta x \). The photon was restricted to having an angle \( \theta_c \) with the track of the parent particle. Since only one angle (\( \theta_c \)) was fixed, the azimuthal angle had to be chosen at random. The polarization vector for the photon was calculated from the direction vector.

There were basically two things that could happen to a Čerenkov photon as it moved through the detector. It could scatter or it could be absorbed. The detector simulation handled both isotropic scattering and Rayleigh scattering. Mie scattering, which is diffractive scattering from small particles comparable in size to the photon wavelength, was ignored since forward scattering is strongly favored. This being the case, Mie scattering would not appreciably affect the Čerenkov cone pattern.

The isotropic scattering was generally caused by large particulates in the water and was independent of wavelength. The probability for isotropic scattering increased exponentially with the distance travelled by the photon so that:

\[ P = e^{-\alpha_{ISO} z_{ISO}}. \] (4.16)
This equation may be solved for \( x_{ISO} \) as a function of the probability \( P \) so that:

\[
x_{ISO} = \frac{1}{\alpha_{ISO}} \ln(P).
\]  \hspace{1cm} (4.17)

In a given step of the photon, \( x_{ISO} \) was calculated by generating \( P \) as a random number between 0 (or very near 0) and 1. The constant \( \alpha_{ISO} \) was fixed by comparing the detector response to actual events as will be discussed in section 4.4.4.

Rayleigh scattering is due to the electric dipole nature of the water molecules and is strongly wavelength dependent. In general:

\[
P = e^{-\alpha_{RAY}(\lambda)d_{RAY}},
\]  \hspace{1cm} (4.18)

where \( \alpha_{RAY}(\lambda) = \frac{d_{RAY}}{\lambda} \). Again, the constant \( d_{RAY} \) was fixed by comparing the detector response to the actual events as will be discussed below. Solving equation (4.18) yields:

\[
x_{RAY} = \frac{1}{\alpha_{RAY}(\lambda)} \ln(P)
\]  \hspace{1cm} (4.19)

where the detector simulation chooses \( P \) randomly between 0 and 1.

Absorption is also wavelength dependent though not nearly so much as Rayleigh scattering. The detector simulation used absorption in pure water as the model. Just as in the case of scattering, the absorption probability goes up exponentially with distance so that:

\[
x_{ARS} = \frac{1}{\alpha_{ARS}(\lambda)} \ln(P).
\]  \hspace{1cm} (4.20)
The absorption length $\alpha_{ARS}$ is wavelength dependent in this equation and is given by:

$$\alpha_{ARS}(\lambda) = \frac{\varepsilon_a(\lambda)}{d_{ARS}\varepsilon_a(\lambda_{max})}.$$  \hspace{1cm} (4.21)

The parameter $\varepsilon_a(\lambda)$ was a fourth order polynomial that had been empirically fit to pure water (Boivin 1986) and $d_{ARS}$ was fixed by comparing the detector response to actual events.

At each step, the three lengths $x_{ISO}$, $x_{RAY}$ and $x_{ARS}$ were calculated and compared to the maximum step size $x_{max}$. The step distance $\Delta x$ was set to the smallest of these four lengths and the photon was moved that distance along the track. If $x_{ISO}$ was the smallest distance, then a new direction was chosen at random. If $x_{RAY}$ was the smallest then a new direction was chosen for the photon which was weighted more heavily in the forward direction than in the isotropic case. If $x_{ARS}$ was the smallest, then tracking of the photon was stopped. Finally, if $x_{max}$ was the smallest length, then the photon was merely advanced that distance.

It was also possible for a photon to encounter a physical barrier such as a wall or a photomultiplier tube within the step distance $\Delta x$. This possibility was checked at each step as will be described in section 4.4.2.

4.4.1.2 LEPTONS

The detector simulation was designed to handle four different types of leptons. These were electrons, positrons, muons and anti-muons. There were a number of physics processes that affected each of these that were simulated with custom written routines. Each routine produced a length $x$
which characterized how far the lepton would travel before interacting. At each step, all the possible lengths were calculated and compared. Just as in the Čerenkov photon case, whichever length was smallest was chosen as the step distance $\Delta x$. The lepton was moved to this point and the relevant physics carried out. At each step, the leptons lost energy though ionization. For electrons and positrons, in the region below the Čerenkov threshold, the energy loss was calculated by integrating the energy dependent cross sections of Bhabha and Möller scattering. For muon and anti-muons the restricted ionizational energy loss formula was used (Barnett 1996).

There were two physics processes relevant for electrons in the detector simulation. Collisions of electrons with the nuclei inside the water molecules caused the electrons to accelerate which then produced radiation. This is called bremsstrahlung (which is German for braking radiation). A bremsstrahlung interaction results in the creation of a gamma ray and a slight change in the energy and direction of the electron. The routine used in the simulation was based on the model of Seltzer and Berger (Seltzer 1985). The second process was that of electron-electron scattering, or Möller scattering.

Due to the fact there were a large number of atomic electrons in the water, positrons were treated differently than electrons. As with electrons there was the possibility of bremsstrahlung. There was also the possibility of scattering from the atomic electrons. Positron-electron scattering is called Bhabha scattering and differs from Möller scattering due to the added contribution from the Feynman diagram where the electron and positron exchange places and where non-identical particles are present in the final state. Positrons had
the added possibility of annihilation with one of the atomic electrons. In this case, the initial positron disappeared to be replaced by a gamma ray. Only the $e^+ + e^- \rightarrow \gamma + \gamma$ case was treated in the simulation. The cross section for this process came from Heitler (Heitler 1954).

The most significant difference between muons and electrons is that of mass. The muon mass is about 207 times that of the electron. This means that muons lose a smaller fraction of their momentum in reactions with atomic electrons than do electrons or positrons. Muons and anti-muons are treated identically (with the exception of the sign of the charge) in the simulation and there are a total of five different physics processes treated in the simulation for them.

Muons, like electrons and positrons, lost energy through ionization as they moved through the water. They also generated $\delta$-rays, which are just ionized atomic electrons. Muons could also produce $e^-e^+$ pairs and bremsstrahlung gamma rays. In addition, they had the option of decaying. The decay was forced to happen by the simulation if the muon came to rest, but it could also occur in flight. An interaction length was calculated for each of these five processes and, as before, the shortest was used as the step distance $\Delta z$. The particle was then moved this distance and the interaction allowed to take place. One slight change for muons is that they were allowed to undergo multiple small angle scatters during each step. This scattering was caused by Coulomb interactions with the oxygen nuclei. The net effect of this multiple Coulomb scattering was to jitter the path of the muon slightly.
4.4.1.3 GAMMA RAYS

Gamma rays are high energy photons which could be produced in the detector in a number of different ways. These have been listed above and include such mechanisms as bremsstrahlung and positron annihilation. Gamma rays do not produce Čerenkov photons directly, but they can produce charged particles that will.

Gamma rays traveling through the water of the detector could either Compton scatter or produce an $e^+e^-$ pair. Compton scattering occurs when a gamma ray interacts with an atomic electron by kicking it out of its orbit. In return, the gamma ray loses some of its energy. The effect of Compton scattering is to produce an electron and change the energy and direction of the gamma ray. Gamma rays could also produce $e^+e^-$ pairs. Essentially the photon was absorbed in the Coulomb field of a nucleus and then the $e^+e^-$ pair was re-emitted. The differential cross section for this process in the detector simulation came from an empirical fit below $50\ MeV$ by Storm and Israel (Storm 1970) and from EGS4 (Nelson 1985) above $50\ MeV$.

4.4.1.4 HADRONS

The tracking of hadrons in the detector simulation was accomplished in part by custom physics routines and by a widely used simulation package called GEANT. This is a general detector Monte Carlo simulation developed and distributed by CERN. The Monte Carlo features of GEANT were not used for the IMB detector simulation. It simply provided an interface to another simulation package called FLUKA which had the specific task of modeling hadronic interactions. The physics process that did not involve
hadronic interactions and those that produced Čerenkov photons were all handled outside of GEANT by the detector simulation itself.

GEANT required the geometry of the detector and the composition of the detector materials. The composition determined the average Z and A of the material. This was accomplished by telling GEANT the detector was a large cube (with the dimensions of the detector) of water (H\textsubscript{2}O) surrounded by an infinite amount of rock (Si\textsubscript{2}O). The photomultiplier tubes and other structures were ignored.

All the physics routines, including FLUKA, used by GEANT work on the same basic principle as the detector simulation. Particles are stepped along their track direction. There is a maximum step and a number of physics processes that may occur within that step. The distance to each is calculated and the shortest distance is chosen. FLUKA calculated the distance to the next hadronic interaction which was then used by the detector simulation. Likewise, FLUKA actually carried out the interaction by generating secondaries and so forth.

Besides hadronic interactions, the other relevant hadron physics processes handled by the detector simulation were the production of \(\delta\)-rays, bremsstrahlung and particle decay. These were all handled by the same routines used for muons with the appropriate modifications for mass, charge, spin and decay lifetime.

4.4.2 GEOMETRY

The geometry of the IMB detector, at first glance, was very simple. It was just a big rectangular volume. This simple picture was complicated, however,
by the fact that it had 2048 photomultiplier tubes and wave shifter plates. At each step, the detector simulation had to determine if a Čerenkov photon struck one of these objects. This kind of geometrical check often involved using square roots which (in great numbers) slowed down the simulation.

The simulation was simplified by breaking the detector into a total of 4 volumes which were concentric. The first volume ran from the center of the detector to the face of the photomultiplier tubes. The second volume started at the face of the photomultiplier tubes and ran to the bottom of the wave shifter plates. The wave shifter plates were assumed to be infinitely thin in the simulation. The third volume started at the wave shifter plates and ran to the rock walls of the detector and the fourth volume extended from there to 1 m inside the rock.

Note that only photons in the second volume had the potential of striking either a photomultiplier tube or a wave shifter. Since the second volume is only 4% of the total volume, this saved a great deal of unnecessary position checking. At each step, the distance to the next volume was calculated. If this was less than the minimum step size, the particle was simply moved to the boundary.

4.4.3 ELECTRONICS

Simulating the electronic response of the detector was just as important as simulating the physics. The electronics, which were described in section 2.4, include the photomultiplier tubes, the data acquisition system (DAQ), the ADC converters and the detector trigger. Each of these had an effect on the data collected. The goal of the detector simulation was to make fake events
that looked as realistic as possible. Therefore the effect of the electronics had to be simulated as accurately as possible.

When a photon struck a photomultiplier tube two things could happen. The first was that it could have been reflected off the surface (this is true for the wave shifter plates as well). This was handled in the detector simulation by giving the photomultiplier tubes a reflection probability, then choosing a random number between 0 and 1 to see if the photon reflected or not. If it reflected, then the tracking of the photon would continue in a new random direction. The second is that the photon was absorbed by the photocathode where it may or may not have produced an electron. The probability that a photon produces an electron in the photocathode is called the quantum efficiency. This was estimated for the IMB tubes by comparing Monte Carlo events to data events and was factored into equation (4.15).

Every particle tracked in the simulation had a running clock that was updated at each step. The first photon that struck a particular tube fixed the time of that tube for the event. In the simulation, this time was known to the accuracy of the computer. In reality, the photomultiplier tubes were only accurate to about 13 ns. To account for this uncertainty in the tube time, the Monte Carlo time was "smeared" by choosing a random number from a fixed width Gaussian distribution centered on zero. This number was then added to the time of the tube. The width of the Gaussian was matched to the uncertainty for the tube.

At the end of an event, a number of electronic effects were added to the data. The photomultiplier tubes, even in the absence of light, constantly

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produced random pulses. Most of these were well below the one photoelectron level but some were large enough to fire the tube discriminator. This was called dark noise and was added into the simulation based on Poisson statistics. A number of noise hits were generated for the event and randomly distributed amongst all the tubes. If a tube already had a hit, the time of the noise hit was compared to the time for that tube. The noise hit time was used only if it came earlier. Dark noise hits were added to both the T1 (0 - 511 ns) and T2 (0.5 - 8.2 μs) time scales (see section 2.4).

Each cable paddle card received eight different photomultiplier channels (see section 2.4) which meant that cross talk between the channels was possible. The cross talk was proportional to the height of the pulse coming from the photomultiplier tube. A simple way to model this is to assume a triangular pulse from a singular hit on the tube. The current in the pulse ($I_i = \text{charge per time}$) for tube $i$ will then be:

$$I_i = \frac{2e}{\Delta t} G_i n_i$$  \hspace{1cm} (4.22)

where $e$ is the charge of a single electron, $\Delta t$ is the width of the pulse, $G_i$ is the gain of the tube and $n_i$ is the number of photoelectrons. Ohm's Law is just $V_i = I_i R$, which may be substituted into the equation above giving:

$$V_i = k_c G_i n_i$$  \hspace{1cm} (4.23)

where $k_c = \frac{2eR}{\Delta t}$. An adjacent channel $j$ would receive a fraction of this pulse height $\epsilon$, so that $V_j = \epsilon V_i$. Substituting this into equation (4.23) gives:

$$k_c G_j n_j = \epsilon k_c G_i n_i.$$  \hspace{1cm} (4.24)
This equation may be solved for the number of photoelectrons on the adjacent channel \( n_j \) which yields:

\[
\frac{n_j}{n_i} = \epsilon \frac{G_i}{G_j} n_i.
\]  

(4.25)

This equation shows that the number of cross talk photoelectrons on channel \( j \) from channel \( i \) is proportional to the number of photoelectrons on channel \( i \). The constant of proportionality is just the fraction of cross talk times the ratio of the photomultiplier tube gains. The gains of each tube were measured during the calibration process (see section 2.7). Cross talk was modeled in the detector simulation using equation (4.25). The number of photoelectrons \( n_j \) was calculated for the 7 adjacent channels to channel \( i \) where \( n_i \neq 0 \). The fraction of cross talk \( (\epsilon) \) was set at 1% in the simulation.

As mentioned in section 2.5 there are two different types of detector triggers. These are the \( N_{\text{tubes}} \) and the \( N_{\text{patches}} \) triggers. The triggers were designed to reduce the number of events caused by random noise in the detector yet retain a large fraction of very low energy events. This analysis was centered on high energy events so nearly all the simulated events met the trigger criteria. The two types of triggers were included in the electronics simulation but only about 3% of the generated events failed to trigger the detector. These were always events where the vertex was near a wall and all tracks exited immediately.

The purpose of the T2 scale was to catch secondary particles from decays in the primary interaction. In particular, it was designed to observe electrons from muon decay. It had an overall length of 8.2 \( \mu s \) which was several times the muon decay lifetime of 2.2 \( \mu s \). The resolution of the T2 scale...
was about 15 times lower than that of the T1 scale (roughly 1 ns), so event reconstruction was not really an option. Rather, decay products showed up as peaks in the T2 distribution. This will be discussed in more detail in section 5.2. Therefore, any electronic effects that might mask these peaks were very important if the T2 scale was to be of any use.

There were two electronic effects that were relevant to the T2 scale only. These were cable reflections and afterpulsing. At every point that a cable is connected to something else (another cable, a board, etc.), there exists the possibility that some of the signal will be transmitted and some of it will be reflected. There were two cable lengths used for the photomultiplier tubes in IMB, 170 and 230 feet. An electronic pulse travels about one foot per nanosecond so the time to travel the cable lengths was 170 and 230 ns. When a reflection occurred it had to travel down and then back up the cable so that these times are doubled giving 340 and 460 ns. The T2 scale started about 350 ns after the global trigger so the reflections from the 170 foot cables arrived at the end of the T1 scale. Since the channel that produced the reflection already had a hit, this did nothing more than add slightly to the total number of photoelectrons. The reflections from the 230 foot cables arrived just after the start of the T2 scale, setting the time for the channel. This made the observation of decay peaks in the earliest part of the T2 scale nearly impossible since they could not be distinguished from the cable reflection peaks.

Cable reflections were included in the simulation for all the tubes. Since the lengths of the cables were fixed, the time of the reflection was nearly
constant with only a small correction from the varying times the tubes received hits. The probability for a reflection to occur was measured by comparing the fraction of tubes that showed reflections to the total number of hit tubes for a large number of events. For each tube in an event, a random number between 0 and 1 was chosen. If this was larger than the calculated probability, the tube was given a reflection. The number of photoelectrons in the reflected pulse was taken to be few percent of the original pulse.

Afterpulsing is a trait that is common to some photomultiplier tubes. If a tube receives a large amount of light then it is possible to ionize one or more gas molecules which will then drift toward the photo-cathode. There, the ions will produce electrons which will in turn produce a pulse. Since the ions are much heavier than electrons, it takes them much longer to drift across the tube. In fact, it can take several $\mu$s for an ion to produce a secondary pulse. Afterpulsing was studied by Morton et al. (Morton 1967) who concluded that only photo-cathodes with $Cs$ or $K$ produced after pulses. The photo-cathode in the IMB tubes was $Na_2KSe$. They also showed that $H_2^+$, $N_2^+$, $A^+$ and $Xe^+$ contribute to afterpulsing but not $O_2^+$. Since afterpulsing can occur several $\mu$s after the original pulse, it is very relevant to the T2 scale. The exact drift times of each ion depends on a number of different factors unique to each tube. For this reason, no attempt was made to calculate the times explicitly. Instead a T2 distribution was generated from a large number of events. Aside from decay products (which were only in a small fraction of the events and came at random times), there are three components to the T2 distribution as shown in figure 4.4. These
are cable reflections, dark noise and afterpulsing. The cable reflection peaks could simply be subtracted from the distribution. Dark noise was exponential in the distribution since tubes with early hits cannot receive later hits. An exponential was fitted to figure 4.4 and then subtracted off. This left four peaks corresponding, presumably, to the four ions $H_2^+$, $N_2^+$, $A^+$ and $Xe^+$. These peaks were fitted as four different Gaussian functions and used to make the probability distribution shown in figure 4.5. At the end of each event, random tubes with T1 hits were given T2 hits to simulate afterpulses. The time of the T2 hits was chosen at random from the probability distribution in figure 4.5.

Another effect of the electronics was to limit the total amount of light recorded in an event. The analog to digital converters (ADCs) for the Q ramps only had 511 possible values. The calibration parameters determined, channel by channel, what the maximum ADC count of 511 corresponded to in photoelectrons. If the Q ramp exceeded this, the channel was saturated and only 511 would be recorded. The detector simulation had to include this saturation if the total energy of the Monte Carlo events was to be compared to the total energy of real events. This was accomplished with a decalibration routine which took the number of Monte Carlo photoelectrons in each channel and converted that value to ADC counts using the calibration parameters. Basically, the decalibration routine inverted the equations used in the calibration procedure. If the resulting number of ADC counts was more than 511 it was simply truncated to this value. Thus the ADC limits were automatically factored into the simulation.
Figure 4.4: The T2 time distribution showing the relevant features.
Figure 4.5: The probability distribution for observing an afterpulse in the T2 time scale.
Normally, Monte Carlo events have to be treated differently than actual data by most analysis routines since they do not require calibration. The added advantage of the decalibration was that the Monte Carlo events could be treated exactly as real data. The decalibration routine also allowed specific data tapes to be simulated. This was important as up to 10% of the photomultiplier tubes in the detector were dead in the last year of running.

4.4.4 WATER TUNING

There were a number of free parameters in the detector simulation which had to be determined by comparison with actual data. This is called tuning the Monte Carlo. The most important factors were the attenuation length, the isotropic scattering length and the rayleigh scattering length. These were introduced in section 4.4.1.1. The simulation was tuned using 364 cosmic ray muons which entered the detector near the center of the top wall and which went nearly straight down. These events were all fitted very carefully by hand and then simulated. Each muon event was given an energy of 200 GeV which roughly corresponds to the mean energy of cosmic ray muons at the depth of the IMB detector. The Monte Carlo events could then be compared directly with the actual events. The three relevant lengths were then adjusted to make the Monte Carlo events look like the real events.

The attenuation and scattering lengths may be adjusted simultaneously with a single plot which is shown in figure 4.6. The vertical axis is the ratio:

\[
\frac{\text{Number of hit tubes Monte Carlo}}{\text{Number of hit tubes data}}
\]

which should be equal to 1. This ratio was sensitive to the amount of
scattering in the Monte Carlo relative to the data. It was greater than or less than one if there was too much or too little scattering. The horizontal axis is the ratio:

\[
\frac{\text{Visible energy Monte Carlo}}{\text{Visible energy data}} \quad (4.27)
\]

which should also be equal to 1. This second ratio was sensitive to the amount of attenuation in the Monte Carlo relative to the data. It was greater than or less than one if there is too little or too much attenuation. The goal of the tuning process then was to have most of the simulated events with both ratios close to one. Figure 4.6 shows the result. Note there are a number of events in the upper right quadrant of the plot. The cosmic ray muons were very energetic and sometimes they would bremsstrahlung in the Monte Carlo. This produced a great deal of light and increased both ratios. Such bremsstrahlung events also occurred in reality but they were not used for the tuning of the simulation.

The results of this water tuning for contained neutrino events are shown in figures 4.7, 4.8 and 4.9. These figures show three different distributions where the solid line is for actual data, the dashed line is for events generated by the IMB detector simulation used in this analysis and the dashed line is for events generated by a different IMB simulation used in a previous analysis (Haines 1986). This older IMB simulation was also tuned and tested against real data. It is included here as a reference in making a comparison between the data and the Monte Carlo used for this analysis.

Figure 4.7 shows the number of measured photoelectrons (corrected for the angular acceptance of the photomultiplier tubes) versus the photon flight
Figure 4.6: A plot of scattering ratio versus the attenuation ratio used in the tuning of the simulation.
Figure 4.7: The number of photoelectrons versus the photon flight distance for the data (solid line), the Monte Carlo from this analysis (dashed line) and from the previous IMB analysis (dotted line).

distance. This is very sensitive to the water attenuation, especially at large distances. Figure 4.8 shows the visible energy distribution which is also sensitive to the water attenuation. Figure 4.9 shows the distribution of T1 time differences between each tube and its eight nearest neighbors. This distribution should be peaked close to zero since most tubes will be very close in time. Thus this plot is sensitive to the time smearing.
Figure 4.8: The visible energy distribution for the data (solid line), the Monte Carlo from this analysis (dashed line) and from the previous IMB analysis (dotted line).
Figure 4.9: The distribution of T1 differences for nearest neighbors for the data (solid line), the Monte Carlo from this analysis (dashed line) and from the previous IMB analysis (dotted line). The stripes in the dotted histogram are an effect of binning.
Table 4.3: A summary of the events in the atmospheric neutrino Monte Carlo sample.

<table>
<thead>
<tr>
<th>Neutrino Flavor</th>
<th>Total Generated</th>
<th>$E_{\text{visible}} \geq 1000$ p.e.</th>
<th>Passed Cuts</th>
<th>Fit Inside</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_{NC}$ inside FV</td>
<td>1099</td>
<td>115</td>
<td>87</td>
<td>84</td>
<td>0.80 ± 0.08</td>
</tr>
<tr>
<td>$\nu_{NC}$ outside FV</td>
<td>1524</td>
<td>141</td>
<td>23</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>$\nu_{e} + \bar{\nu}_{e}$ inside FV</td>
<td>1926</td>
<td>345</td>
<td>249</td>
<td>232</td>
<td>0.79 ± 0.05</td>
</tr>
<tr>
<td>$\nu_{e} + \bar{\nu}_{e}$ outside FV</td>
<td>2874</td>
<td>594</td>
<td>118</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>$\nu_{\mu} + \bar{\nu}_{\mu}$ inside FV</td>
<td>3774</td>
<td>811</td>
<td>598</td>
<td>574</td>
<td>0.79 ± 0.03</td>
</tr>
<tr>
<td>$\nu_{\mu} + \bar{\nu}_{\mu}$ outside FV</td>
<td>5469</td>
<td>949</td>
<td>149</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>16666</td>
<td>2955</td>
<td>1224</td>
<td>1009</td>
<td>0.79 ± 0.02</td>
</tr>
</tbody>
</table>

4.5 THE ATMOSPHERIC NEUTRINO MONTE CARLO SAMPLE

A total of 16666 random neutrino events with neutrino energy above 0.8 GeV were generated using this simulation. Table 4.3 shows a summary of all the Monte Carlo events generated. A total of 1009 events passed all the cuts and fit inside the fiducial volume. The efficiency was taken to be the number of events that fit inside divided by the number of events generated inside (with $E_{\text{visible}} \geq 1000$ p.e.s) so that the total efficiency for the whole data reduction process was $\frac{1009}{1224} = 0.79 \pm 0.02$. The separate efficiencies for ($\nu_{e} + \bar{\nu}_{e}$) and ($\nu_{\mu} + \bar{\nu}_{\mu}$) are listed in Table 4.3. Figure 4.10 shows the neutrino energy distribution for all the generated Monte Carlo events (top) and all the Monte Carlo events which passed the data reduction process (bottom).

The flux tables provided by T. Stanev were integrated with cross sections summed over all channels (Casper 1990) for neutrinos and antineutrinos on water. This gave the absolute rate of interactions in the detector as $2.42 \times 10^{-5}$ Hz. Given 16666 events, this corresponds to a total live time of 29.1 years.
Figure 4.10: The neutrino energy distribution for events generated in the Monte Carlo simulation. The top shows the distribution for all events while the bottom shows events passing all cuts.
Table 4.4: A summary of the data and Monte Carlo events showing the number of electron and muon-like events. The column BGS refers to Monte Carlo events generated with the fluxes from Agrawal et al. (Agrawal 1996) while the HKKM column refers to events generated with the fluxes from Honda et al. (Honda 1995). The number of Monte Carlo events has been normalized to the 2.1 kton-yr exposure of the data.

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>BGS</th>
<th>HKKM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron-like</td>
<td>25</td>
<td>31.2</td>
<td>29.2</td>
</tr>
<tr>
<td>Muon-like</td>
<td>47</td>
<td>41.9</td>
<td>40.4</td>
</tr>
<tr>
<td>Total</td>
<td>72</td>
<td>73.1</td>
<td>69.6</td>
</tr>
</tbody>
</table>

Table 4.4 compares the number of Monte Carlo events to the number of data events. The simulated events, like the data, passed all cuts and were assigned flavors by the flavor identification algorithm (see section 5.2).
CHAPTER 5

NEUTRINO FLAVOR IDENTIFICATION

5.1 INTRODUCTION

Cosmic ray interactions in the upper atmosphere produce roughly twice as many muon neutrinos as electron neutrinos (see section 4.2). The goal of this analysis was to measure the number of each flavor that interacted in the fiducial volume of the IMB detector and see if this was an accurate prediction. Chapter 2 described how the data was collected and how the background was eliminated to produce 72 contained neutrino events (see section 3.2). Chapter 3 described the atmospheric neutrino Monte Carlo simulation and it was used to generate events for comparison with the data. This chapter will describe how the neutrino flavor was determined for both data and Monte Carlo events which passed all cuts and had fitted vertex inside the fiducial volume of the detector.

5.2 SHOWERING AND NON-SHOWERING IDENTIFICATION

Electrons and muons tend, as a general rule, to behave very differently in most materials, including water. The reason has to due with the relative mass of the electron and muon (the muon being some 207 times heavier) and the presence of atomic electrons. When an electron propagates through a material it constantly interacts with the atomic electrons. Since the masses are equal, the momentum transfer is large. Also, electrons bend easily in the electromagnetic field of a nucleus and they can lose energy in a process called
bremsstrahlung. For these reasons, the electrons deposit their energy very quickly in the material. Muons are much heavier than the atomic electrons so the momentum transfer is small and the muons lose energy slowly. Therefore the change in energy over the change in distance \( \frac{dE}{dx} \) is much larger for electrons than muons. Consequently, muons can travel much farther in materials than electrons.

Since electrons deposit their energy very quickly, they generally create electromagnetic cascades or showers. The original (parent) electron generally produces a photon through bremsstrahlung. This photon may either produce an \( e^+e^- \) pair or Compton scatter which produces more photons and so forth. At each step in this process, the energy of the parent electron is divided among more and more secondaries. Eventually the remaining energy will not be enough to generate more secondaries and the shower will stop. Until that point, the production of secondaries by the parent electron is exponential.

The parent electron will produce Čerenkov photons in water, but so will all the charged secondaries (electrons and positrons). The shower generally spreads out as it propagates so the Čerenkov cones of all the secondaries will not necessarily fall inside that of the parent electron. This means that the Čerenkov ring will not be well-defined and there will be quite a bit of light outside the nominal Čerenkov cone of the parent electron. The same is true for positrons as well. Muons (and anti-muons) may produce gamma ray photons through bremsstrahlung, but this is not their major energy loss
mechanism. Therefore, they do not produce showers of secondaries like electrons and their Čerenkov ring is well defined.

Charged current neutrino interactions produce charged leptons as discussed in section 4.3. These interactions also conserve lepton number so that electron neutrinos only produce electrons and muon neutrinos only produce muons (the same being true for the anti-matter particles). Since electrons produce showers and muons do not, it is possible to distinguish the flavor of the neutrinos which interact. An event is determined to be a neutrino interaction if it has a vertex contained inside the fiducial volume and no visible entering tracks. If the event has a strongly showering track, it is taken to be either a \( \nu_e \) or a \( \bar{\nu}_e \). Accordingly, these types of events are referred to as being "electron-like." If the event has a strongly non-showering track it is taken to be either a \( \nu_\mu \) or a \( \bar{\nu}_\mu \). These types of events are referred to as being "muon-like."

Neutral current interactions are flavor-independent so it is not possible to determine the neutrino flavor. Fortunately, they also tend to be much lower in energy than charged current interactions since the final state neutrino retains most of the energy of the initial neutrino. Still, it is possible for them to produce a recoil nucleon and even some charged pions which produce enough Čerenkov light to pass the 1000 photoelectron cut. There was no way of separating the neutral current interactions from the charged current so the flavor identification routine tried to identify them as well. These neutral current interactions generally had many tracks, so some were bound to overlap. For this reason they were identified as electron-like about 60% of
the time. Therefore, they introduced only a slight bias in flavor. Fortunately, in the Monte Carlo sample the total fraction of neutral current events was around 9%, so the bias was not very significant.

In the discussion below, the actual flavor of Monte Carlo events will be indicated as either $\nu_e$, $\bar{\nu}_e$, $\nu_\mu$ or $\bar{\nu}_\mu$. The identified flavor of both Monte Carlo and data events will be indicated as electron-like or muon-like.

5.3 THE FLAVOR IDENTIFICATION SOFTWARE

There were a number of things that made the flavor identification of the contained neutrino events difficult. The first was the presence of multiple tracks in a single event. Only one track per event could be used in the flavor identification routine. From the Monte Carlo sample, it was determined that the charged lepton had the most visible energy about 85% of the time in charged current interactions. Therefore, the flavor identification routine used the track with the most visible energy in multiple track events. Both charged current and neutral current interactions could produce many tracks. These were mostly pions and possibly a recoil proton. Charged current interactions also produced a single charged lepton. The presence of multiple tracks made it difficult to use the amount of light outside the Čerenkov cone as an indication of flavor. It was also possible for two or more tracks to overlap, which made it difficult to use the $\frac{dE}{dx}$ profile of a track. The second thing that made the flavor identification difficult was the presence of partially contained tracks. The closer a particle gets to a wall the more intense the light. Exiting particles generally produced clusters of tubes which received many photoelectrons. This changed the $\frac{dE}{dx}$ profile which, again, made it difficult
to distinguish flavor. The presence of multiple tracks and partially contained
events meant that no single criteria could be used to determine the flavor of
the event. Rather a number of different criteria had to be considered.

The flavors of the contained neutrino events in this analysis were deter­
minded with a custom routine which was developed using both Monte Carlo
neutrino and real cosmic ray muon events. It was based on a likelihood func­
tion ($L$) that was calculated by taking the product of $n$ different factors $P_i$
so that:

$$L = \prod_{i=1}^{n} P_i(x_i). \quad (5.1)$$

Each factor $P_i$ was a ratio of distributions for the measured values $x_i$. These
measured values were generally anything that could distinguish muon-like
and electron-like events. There were a total of 12 such measured values and
they will be discussed in detail in section 5.3.2.

The basic technique in using a particular measured value $x_i$ was to first
generate the distribution of the value for ($\nu_\mu + \bar{\nu}_\mu$) events from the Monte
Carlo sample. Call this distribution $\mu(x_i)$. The next step was to generate
a second distribution of $x_i$ using ($\nu_e + \bar{\nu}_e$) Monte Carlo events. Call this
distribution $e(x_i)$. The likelihood factor $P_i(x_i)$ was then:

$$P_i(x_i) = \frac{\mu(x_i)}{e(x_i)}. \quad (5.2)$$

The distributions $\mu(x_i)$ and $e(x_i)$ were normalized so that they had the same
number of events. The factor $P_i$ was simply a measure of how much more (or
less) likely a particular event was to be non-showering than showering at a
particular value of $x_i$. In the flavor identification routine, the factors $P_i$ were
actually histograms. First, the $e(x_i)$ and $\mu(x_i)$ distributions were generated as histograms. Then bin-by-bin the ratio $\frac{e(x_i)}{\mu(x_i)}$ was calculated, giving the histogram of $P_i$.

For each event, all the various $x_i$ values were measured, then used to calculate the $P_i(x_i)$'s which were then used to calculate $L$. This amounted to finding the bin into which $x_i$ fell and then picking the value of $P_i$ from the proper histogram. None of the $P_i$ values were negative, so the natural logarithm of $L$ could be used rather than $L$ itself. If $L$ was greater than 1, $\ln(L)$ was positive. If $L$ was less than 1, $\ln(L)$ was negative.

5.3.1 TRACK PARAMETERS

The likelihood factors cannot be fully discussed until some of the track parameters used to determine them are first introduced. These parameters range from the very simple (such as the total amount of visible energy) to the complex (such as the muon decay probability). Since they will be used frequently in the discussion of the likelihood factors, they have each been given a name that will appear in italics.

The total amount of visible energy in the event was called $Q_{total}$. It was simply the sum of all the photoelectrons from all the tubes with hits in an event. The total amount of visible energy inside the Čerenkov cone of a particular event was called $Q_{inside}$ while the total amount outside the Čerenkov cone was $Q_{outside}$. The total amount of light in the event was $Q_{total} = Q_{inside} + Q_{outside}$. The distance from the vertex to the closest wall along the track direction was called Wall Distance. The Shower Length was
the distance from the track vertex to the point at which 63% of the total visible energy of the track \(Q_{\text{inside}}\) had been radiated.

The \(\frac{dQ}{dx}\) of a track was the amount of visible energy (in photoelectrons) deposited per unit of distance along the track. It was calculated by first correcting the number of photoelectrons for the attenuation in the water and the angular acceptance of each photomultiplier. The light received by a particular tube was assumed to have come from a particular point on the track based on the geometry of that track in the detector. This was called the photon emission point. Such a point was found for each photomultiplier tube inside the Čerenkov cone of the track. This in turn gave the amount of light radiated as a function of distance from the vertex. The \(\frac{dQ}{dx}\) parameter was determined by first finding the initial \(\frac{dQ}{dx}\) value over a 150 cm segment of track near the vertex which was called \(\frac{dQ}{dx}\) initial. This was repeated over successive sections of the track until the \(\frac{dQ}{dx}\) at a particular section dropped 40% below the initial value (\(\frac{dQ}{dx}\) initial). This defined the end of the track. The distance from the vertex to this point was called the Track Length. The total amount of visible energy radiated from the track in Track Length was called \(Q_{\text{sum}}\). \(\frac{dQ}{dx}\) was calculated as \((Q_{\text{sum}})/(\text{Track Length})\).

For each photomultiplier tube within the Čerenkov cone of a track, the distance from the vertex to the photon emission point was calculated. This distance \(d_x\) was then multiplied by the number of photoelectrons \(Q_i\) for that tube. These values were then summed for all channels and the result divided by the total number of photoelectrons for the track to give the Weighted Distance.
Similarly, a vector \((\vec{D}_i)\) between the vertex and each photomultiplier tube was calculated. The dot product of this vector and the track direction was calculated and multiplied by the number of photoelectrons for that tube. These values were summed and divided by the total number of photoelectrons for the track producing the Weighted Angle:

\[
Weighted\ Angle = \frac{1}{\sum Q_i} \sum_{i=1}^{N_{\text{hit}}} Q_i (\vec{D}_i \cdot \hat{\mu}),
\]

where \(\hat{\mu}\) was the unit vector pointing in the track direction.

5.3.1.1 MUON DECAY SIGNAL

Finally the T2 scale was searched for the possibility of a muon decay signal. The result was called the Muon Decay Signal. If a muon decayed in the detector during the T2 scale it would produce a spike in the distribution. Since photomultiplier tubes that received light during the T1 scale were susceptible to cable reflections and after pulsing (see section 2.4), only T2 hits without a corresponding T1 hit were considered.

To calculate the Muon Decay Signal, the T2 scale was first divided into 125 separate bins about 60 ns wide, which was ample time for most particles to cross the detector. In an event, the number of T2 without T1 hits in any given bin was small since most of the hits just came from dark noise. To find a possible muon decay signal, the number of hits in each bin was compared to the expected number of hits for each bin. This expected number was determined by first collecting a large number of energetic cosmic ray muon events from the data tapes. These were events in which the muon both

\[
Weighted\ Distance = \frac{1}{\sum Q_i} \sum_{i=1}^{N_{\text{hit}}} Q_i d_i.\quad (5.3)
\]
entered and exited the detector so that muon decay was very unlikely. The number of hits in each bin were summed together for all the events and this sum divided by the total number of events. This gave the average number of hits in each bin, which was taken as the expected number of hits.

The probability $M_i$ of observing a number of hits $N_{\text{obs}}^i$ or greater in a particular bin $i$ (based on the number expected $N_{\text{exp}}^i$) was given by:

$$M_i(\geq N_{\text{obs}}^i) = 1 - e^{-N_{\text{exp}}^i} \sum_{i=1}^{N_{\text{obs}}^i - 1} \frac{N_{\text{exp}}^i}{i!}.$$ (5.5)

This equation comes from Poisson statistics which were used in this case because the expected number of hits for each bin was generally less than 10. If $M_i$ was very small, then it was very likely a muon decay occurred in that bin. The minimum of all the $M_i$ values was taken to be the Muon Decay Signal. In essence, it is just the probability that the largest peak in the T2 scale occurred at random.

The muon lifetime is $2.2 \, \mu s$ while the length of the T2 scale is $8.2 \, \mu s$ long. Therefore, about 80% of all muons will decay by the end of the T2 scale. It is possible, however, for a $\mu^-$ to be captured by a nucleus with a capture time of $11.6 \, \mu s$. This process limits the number of $\mu^-$ decays in the T2 scale to about 65%. For cosmic ray muons, the ratio of $\mu^+$ to $\mu^-$ is about 5 to 4 so the total number of muon decays expected in the T2 scale for these events is roughly 73% (Casper 1990). A total of 645 stopping muon events were taken from the data tapes. Out of these 436 events had a Muon Decay Signal below 10%. This is the same as saying they had a muon decay signal to the 90% confidence level. The ratio $\frac{436}{645}$ is equal to $0.676 \pm 0.032$ which means the efficiency of the routine was $0.926 \pm 0.044$. 

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Table 5.1: A list of the values $x_i$ used in the likelihood function $L$.

<table>
<thead>
<tr>
<th>Value $x_i$</th>
<th>Value $x_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ( \frac{Q_{\text{out}}}{Q_{\text{total}}} )</td>
<td>7 ( \frac{Q_{\text{sum}}}{Q_{\text{total}}} ) ( \text{up to } Q_{\text{total}} )</td>
</tr>
<tr>
<td>2 Track Length</td>
<td>8 ( \frac{Q_{\text{sum}}}{Q_{\text{total}}} ) ( \text{up to } Q_{\text{total}} )</td>
</tr>
<tr>
<td>3 Weighted Angle</td>
<td>9 Muon Decay Signal</td>
</tr>
<tr>
<td>4 Track Length Wall Distance</td>
<td>10 Weighted Distance Shower Length</td>
</tr>
<tr>
<td>5 Weighted Distance Wall Distance</td>
<td>11 ( \frac{dQ}{dx} )</td>
</tr>
<tr>
<td>6 Shower Length</td>
<td>12 ( \frac{dQ}{dx} )</td>
</tr>
</tbody>
</table>

5.3.2 THE LIKELIHOOD FACTORS

The goal of the flavor identification routine was to separate muon-like events from electron-like events. Another way to think of this is to say that the goal of the routine was to correctly identify muon-like events, while everything else was assumed to be electron-like. This being the case, each likelihood factor was constructed to reward an event for being muon-like \( P_i(x_i) > 1 \), or punish it for being electron-like \( P_i(x_i) < 1 \).

Table 5.1 shows all the values $x_i$ used in the likelihood function $L$. A brief description of each will be given below, using the numbers in the table as a reference. All of the factors were used for multiple track events, but only factors 1, 2, 6, 9, 11 and 12 were used for single track events.

Some muon-like tracks had very little light outside the Čerenkov cone. This was especially true for single track events, but was even true for some multiple track events where other tracks were very weak. Factor 1 strongly
Fig. 5.1: The distribution for factor 1 ($Q_{\text{outside}}/Q_{\text{total}}$). The top plot shows the distributions for ($\nu_e + \bar{\nu}_e$) (dashed line) and ($\nu_\mu + \bar{\nu}_\mu$) (solid line) events. The bottom plot shows the ratio of the two distributions.

rewarded tracks with very little light outside the cone but only lightly punished anything else. This allowed it to be used for both single and multiple track events. The distribution of factor 1 is shown in figure 5.1.

As mentioned in section 5.2, muons generally traveled much farther in the detector than electrons. Factor 2 rewarded events with very long Track Lengths and punished events with short Track Lengths. The distribution of factor 2 is shown in figure 5.2. Gaps in this distribution (and all the others
Figure 5.2: The distribution for factor 2 (Track Length). The top plot shows the distributions for \((\nu_e + \bar{\nu}_e)\) (dashed line) and \((\nu_\mu + \bar{\nu}_\mu)\) (solid line) events. The bottom plot shows the ratio of the two distributions.

Electrons deposited their energy very quickly along their tracks while muons had a \(\frac{dQ}{dx}\) profile that was nearly constant. For this reason the Weighted Angle was usually about half the Čerenkov angle for muon tracks. If this was the case, then factor 3 rewarded the event. The distribution of factor 3 is shown in figure 5.3.
Figure 5.3: The distribution for factor 3 (Weighted Angle). The top plot shows the distributions for $(\nu_e + \bar{\nu}_e)$ (dashed line) and $(\nu_\mu + \bar{\nu}_\mu)$ (solid line) events. The bottom plot shows the ratio of the two distributions.
Figure 5.4: The distribution for factor 4 (\(Track \text{ Length} \div Wall \text{ Distance}\)). The top plot shows the distributions for \((\nu_e + \bar{\nu}_e)\) (dashed line) and \((\nu_\mu + \bar{\nu}_\mu)\) (solid line) events. The bottom plot shows the ratio of the two distributions.

Because muons generally traveled farther in the detector than electrons they also tended to exit more often. If the track exited the detector then the \(Track \text{ Length}\) was roughly equal to the \(Wall \text{ Distance}\) and the ratio of the two was nearly 1. Factor 4 rewarded these exiting tracks. The distribution of factor 4 is shown in figure 5.4.

The \(Weighted \text{ Distance}\) tended to be roughly one half of the \(Wall \text{ Distance}\) for exiting muons. Just as was the case for the \(Weighted \text{ Distance}\), this was
Figure 5.5: The distribution for factor 5 ($\frac{W_{\text{Weighted Distance}}}{W_{\text{Wall Distance}}}$). The top plot shows the distributions for $(\nu_e + \bar{\nu}_e)$ (dashed line) and $(\nu_\mu + \bar{\nu}_\mu)$ (solid line) events. The bottom plot shows the ratio of the two distributions.

due to the fact that the energy deposition of muons was nearly constant.

Factor 5 rewarded exiting tracks where the $\frac{W_{\text{Weighted Distance}}}{W_{\text{Wall Distance}}}$ was about half the Wall Distance. The distribution of factor 5 is shown in figure 5.5.

As already mentioned, electrons tended to radiate their energy very quickly along the track length. Therefore factor 6 punished events with small Shower Lengths. The distribution of factor 6 is shown in figure 5.6.
Figure 5.6: The distribution for factor 6 (Shower Length). The top plot shows the distributions for $(\nu_e + \bar{\nu}_e)$ (dashed line) and $(\nu_\mu + \bar{\nu}_\mu)$ (solid line) events. The bottom plot shows the ratio of the two distributions.
Some of the muons stopped in the detector rather than exiting. In general, it was difficult to distinguish these stopping muons from electrons. One difference was that once a muon stopped there was no more light produced along the track. This produced a hollow Čerenkov ring. Any light inside the cone was mainly due to scattering or the collapse of the cone as the muon dropped below the Čerenkov threshold. The shower generated by an electron, on the other hand, tended to produce a great deal of light inside the nominal Čerenkov cone. This produced a substantial fraction of hits inside the ring. Factor 7 rewarded tracks with hollow rings as a way of identifying stopping muons. The distribution of factor 7 is shown in figure 5.7.

The showering nature of electrons meant that a discernible amount of their energy could be radiated after a distance Track Length. In this case, the event was punished by factor 8. The distribution of factor 8 is shown in figure 5.8.

A very low value for the Muon Decay Signal was a very good indication that an event contained a muon. This, however, is not to say that it was a good indication the event was muon-like. A number of events had charged pion tracks which may or may not have been above the Čerenkov threshold. Some of these charged pions decayed through the reactions (4.2). The muons produced could then decay generating a muon decay signal. Factor 9 only lightly rewarded the event if it showed signs of having a muon decay. The distribution of factor 9 is shown in figure 5.9.

For muon tracks, the Weighted Distance tended towards the middle of the track and the Shower Length tended to be beyond that. In this case,
Figure 5.7: The distribution for factor 7 ($\frac{\text{Hits inside Shower Length}}{\text{Total hits}}$). The top plot shows the distributions for $(\nu_e + \bar{\nu}_e)$ (dashed line) and $(\nu_\mu + \bar{\nu}_\mu)$ (solid line) events. The bottom plot shows the ratio of the two distributions.
Figure 5.8: The distribution for factor 8 ($\frac{\ell_{\text{sum}}}{\ell_{\text{total}}}$ up to Track Length). The top plot shows the distributions for ($\nu_e + \bar{\nu}_e$) (dashed line) and ($\nu_\mu + \bar{\nu}_\mu$) (solid line) events. The bottom plot shows the ratio of the two distributions.
Figure 5.9: The distribution for factor 9 (Muon Decay Signal). The top plot shows the distributions for $(\nu_e + \bar{\nu}_e)$ (dashed line) and $(\nu_\mu + \bar{\nu}_\mu)$ (solid line) events. The bottom plot shows the ratio of the two distributions.
Figure 5.10: The distribution for factor 10 ($\frac{Weighted\ Distance}{Shower\ Length}$). The top plot shows the distributions for ($\nu_e + \bar{\nu}_e$) (dashed line) and ($\nu_\mu + \bar{\nu}_\mu$) (solid line) events. The bottom plot shows the ratio of the two distributions.

the ratio of the two was small and the event was rewarded by factor 10. For electron tracks, both the Weighted Distance and the Shower Length tended to come before the center of the track. In which case, the ratio was closer to one and factor 10 punished the event. The distribution of factor 10 is shown in figure 5.10.

Most muon tracks had about the same $\frac{d\Omega}{d\xi}$ value due to their non-showering nature. Factor 11 rewarded events with a $\frac{d\Omega}{d\xi}$ near this value and punished
The distribution for factor 11 ($\frac{dQ}{dz}$). The top plot shows the distributions for $(\nu_e + \bar{\nu}_e)$ (dashed line) and $(\nu_\mu + \bar{\nu}_\mu)$ (solid line) events. The bottom plot shows the ratio of the two distributions.

Events where the $\frac{dQ}{dz}$ was either very small or very large. The distribution of factor 11 is shown in figure 5.11.

The widths of the distributions of Shower Length and $\frac{dQ}{dz}$ was small for muon tracks since both of these quantities tended to stay constant over the length of the track. Electrons, however, tended to have large widths for these distributions. Therefore, factor 12 punished events where the ratio of these
two quantities was very small or very large. The distribution of factor 12 is shown in figure 5.12.

5.4 RESULTS OF THE FLAVOR IDENTIFICATION ROUTINE

The distribution of $\ln(L)$ for events in the Monte Carlo sample is shown in figures 5.13 (single track events) and 5.14 (multiple track events). In each case, the plots are broken down into $(\nu_e + \bar{\nu}_e)$ (top) and $(\nu_\mu + \bar{\nu}_\mu)$ (bottom).
Figure 5.13: The ln(L) distribution for all Monte Carlo single track events. The top plot shows $(\nu_e + \bar{\nu}_e)$ while the bottom shows $(\nu_\mu + \bar{\nu}_\mu)$.

Based on these distributions, events with $\ln L < 0$ were taken to be electron-like, while events with $\ln L \geq 0$ were taken to be muon-like. Figure 5.15 shows the ln(L) distribution for the data events along with the distribution for the Monte Carlo events. The number of Monte Carlo events in this plot has been normalized to that of the data.

From table 4.3, there were a total of 645 $(\nu_\mu + \bar{\nu}_\mu)$ Monte Carlo events that passed all cuts and fit inside the fiducial volume. Of these, 520 were identified.
Figure 5.14: The ln(L) distribution for all Monte Carlo multiple track events. The top plot shows $\left( \nu_e + \bar{\nu}_e \right)$ while the bottom shows $\left( \nu_\mu + \bar{\nu}_\mu \right)$. 

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Table 5.2: The assigned flavors (rows) versus the actual flavors (columns) for single track events. The total efficiency for correctly identifying $(\nu_\mu + \bar{\nu}_\mu)$ charged current events was $0.88 \pm 0.05$.

<table>
<thead>
<tr>
<th>Actual Flavor</th>
<th>Assigned Flavor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>e-like</td>
</tr>
<tr>
<td></td>
<td>121</td>
</tr>
<tr>
<td></td>
<td>0.89 ± 0.08</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>$\mu$-like</td>
</tr>
<tr>
<td></td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>0.11 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>0.13 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>0.87 ± 0.06</td>
</tr>
</tbody>
</table>

Table 5.3: The assigned flavors (rows) versus the actual flavors (columns) for multiple track events. The total efficiency for correctly identifying $(\nu_\mu + \bar{\nu}_\mu)$ charged current events is $0.79 \pm 0.04$.

<table>
<thead>
<tr>
<th>Actual Flavor</th>
<th>Assigned Flavor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>e-like</td>
</tr>
<tr>
<td></td>
<td>116</td>
</tr>
<tr>
<td></td>
<td>0.85 ± 0.08</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>$\mu$-like</td>
</tr>
<tr>
<td></td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>0.15 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>92</td>
</tr>
<tr>
<td></td>
<td>0.24 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>0.76 ± 0.04</td>
</tr>
</tbody>
</table>

correctly by the flavor identification routine, which gives an accuracy of $0.81 \pm 0.04$. The software misidentified 183 events (all flavors, including neutral currents) out of 1009, which gives $0.18 \pm 0.01$. Table 5.2 shows how the actual and assigned flavors compared for single track events, while table 5.3 shows how they compared for multiple track events. In general, the software was less accurate for multiple track events, as would be expected.

5.5 SYSTEMATIC CHECKS

Monte Carlo events were used extensively, though not exclusively, in the development of the flavor identification routine. If the Monte Carlo does not accurately reproduce the data, then there will be a large systematic error in
the final result. This section will address the systematic checks applied to the flavor identification routine to make sure it was working properly.

5.5.1 SHOWERING AND NON-SHOWERING IDENTIFICATION

If the flavor identification routine worked correctly then, at the very least, the distribution of $\ln(L)$ for the data should look like the distribution of $\ln(L)$ for the Monte Carlo. Figure 5.15 shows the distributions of $\ln(L)$ for the data (solid line) and the Monte Carlo (dashed line) events. The number of Monte Carlo events has been normalized to that of the data. It is clear from the figure that no large systematic difference exists between the data and the Monte Carlo events.

5.5.2 COSMIC RAY MUONS

Nature provides the means for testing the flavor identification routine on muons. A sample of 364 through-going cosmic ray muons was collected from the data tapes. This is the same muon sample used to tune the water parameters as described in section 4.4.4. A second sample of 645 stopping muons was collected from the tapes as well. All of the through-going events were identified correctly, which is not surprising since they are all exiting and have long tracks. This made them very easy for the flavor identification routine to identify. Stopping muons, on the other hand, were more difficult since they had to be separated from electron-like events based on their showering profile alone. If the showering profile was modelled improperly in the Monte Carlo, it was possible for these events to be misidentified. As it turned out, the flavor identification routine correctly identified 595 of these events, giving an accuracy of $0.92 \pm 0.04$. Figure 5.16 shows the $\ln(L)$ distribution for the
Figure 5.15: The distribution of $\ln(L)$ for the data (solid line) and the Monte Carlo (dashed line). The number of Monte Carlo events has been normalized to that of the data.
Figure 5.16: The distribution of $\ln(L)$ for a random sample of stopping and exiting cosmic ray muon events.

364 through-going and the 645 stopping cosmic ray muons. The peak of the distribution falls at 8 which is close to the peak at 7 for both data and Monte Carlo events in figure 5.15. This shows that the flavor identification routine is consistent for both data and Monte Carlo events.

### 5.5.3 MUON DECAY

One possible way to sort out flavors was to look for a muon decay in the $T_2$ scale. This was not a perfect indication of flavor since many of these
Table 5.4: A comparison of the fraction of events with a muon decay signal to the 90% confidence limit between the data and the Monte Carlo.

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>Monte Carlo</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron-like</td>
<td>0.40 ± 0.13</td>
<td>0.45 ± 0.03</td>
</tr>
<tr>
<td>muon-like</td>
<td>0.66 ± 0.12</td>
<td>0.60 ± 0.03</td>
</tr>
</tbody>
</table>

events contained charged pions that could decay and produce muons. This includes neutral current events (where the charged pion comes from a charge exchange reaction inside the nucleus) and single track events (where the pion could have been below the Čerenkov threshold). Still, it should have indicated if the events were systematically misidentified.

The *Muon Decay Signal* was used to check the consistency of the flavor identification routine between the data and Monte Carlo. If the data and Monte Carlo showed similar fractions of muon decays then this would be an indication the flavor identification routine was working. Table 5.4 shows the fraction of events with *Muon Decay Signals* at the 90% confidence limit. Within the statistical uncertainties, the fraction of decays is consistent for the data and the Monte Carlo.
CHAPTER 6
RESULTS AND DISCUSSION

6.1 INTRODUCTION

The ultimate goal of this analysis was to produce a ratio of the atmospheric neutrino flavors. From the reactions (4.2) and (4.3) there should be roughly twice as many $(\nu_\mu + \bar{\nu}_\mu)$ as $(\nu_e + \bar{\nu}_e)$. The exact ratio will vary slightly depending on factors like the pion and muon kinematics, the production of neutrinos from strange and charmed mesons at high energy and the effect of solar modulation and geomagnetic effects at low energy. The kinematics of pion and muon decay are very well understood and the other factors are reasonably well understood, so the flavor ratio has been calculated with about 5% uncertainty (Gaisser 1996).

The flavor ratio has been measured by several different experiments around the world and some have reported values that are not consistent with the prediction (see section 1.4.1). This chapter will present the results from an analysis of contained neutrino events from the IMB detector. It will conclude with a discussion on the implications of the result reported here and the possibilities for the future.

6.2 THE RATIO OF RATIOS

The uncertainties in the calculation of the atmospheric neutrino fluxes are generally around 20% (Gaisser 1996). This is mainly due to uncertainty in the flux of the primary cosmic rays. This uncertainty makes a comparison of
measured atmospheric neutrino fluxes to the calculated fluxes difficult since the detector systematic uncertainties must be folded in as well. Instead, the ratio of the muon neutrino flux to the total flux may be inferred by measuring the fraction of muon-like events. Such a ratio has the advantage that the uncertainties in the absolute fluxes largely cancel. The easiest way to form this ratio was to count the number of each type of neutrino interaction (electron-like and muon-like) collected in a given time. The number collected was proportional to the flux and the flavor ratio could be written as:

\[ R' = \frac{\text{muon-like}}{\text{electron-like}}. \] (6.1)

The uncertainty in \( R' \) is about 5% (Gaisser 1996).

Even if all detectors were exactly the same they would not measure the same atmospheric neutrino flavor ratio. This is due to geomagnetic effects which depend on the position of the detector on the Earth. Thus different experiments will measure slightly different flavor ratios. In addition, no two detectors are exactly alike. As discussed in section 1.4.1 there are many different types of experiments that have made measurements of atmospheric neutrinos. Each detector has its own set of systematic uncertainties, which include such things as the sensitivity to the two types of neutrino flavors and the energy threshold. The combination of the geomagnetic effects and the detector systematics makes it difficult to compare the results of each experiment directly.

The geomagnetic effects are generally included in any calculation of the atmospheric neutrino flux (see section 4.2.1) and the detector systematics are generally well understood for a given experiment. In principle, therefore,
it should be possible to account for the differences between detectors when comparing their results. The easiest way to do this is to first find the expected flavor ratio using a Monte Carlo simulation. Such a simulation would start with the predicted atmospheric neutrino fluxes and end with a sample of contained neutrino interaction events. The geomagnetic effects for the particular location of the detector as well as all the detector systematics would then be folded into this Monte Carlo sample. The standard way of using this information to produce a "detector independent" result is to form a ratio of ratios where the measured flavor ratio is divided by the Monte Carlo flavor ratio.

In this analysis, the flavor ratio \( R \) was actually the fraction of muon-like events over the total number of events so that:

\[
R = \frac{\text{muon-like}}{\text{total}}.
\]  

(6.2)

This is not much different than \( R' \) but has the advantage that the denominator is fixed and so \( R \) is statistically better behaved using standard error propagation techniques. Using \( R \), the ratio of ratios \( f \) is:

\[
f = \frac{R_{\text{data}}}{R_{\text{Monte Carlo}}} = \frac{(\frac{\text{muon-like}}{\text{total}})_\text{data}}{(\frac{\text{muon-like}}{\text{total}})_\text{MC}}.
\]  

(6.3)

6.3 RESULTS FROM THIS ANALYSIS

Chapter 2 concluded with a summary of the data events collected for this analysis. There were a total of 72 contained neutrino interactions which had a fitted vertex inside the fiducial volume of the IMB detector and at least 1000 photoelectrons. Chapter 3 concluded with a summary of the Monte Carlo
events generated for this analysis. A total of 1009 Monte Carlo events passed all the data reduction cuts and had a fitted vertex inside the fiducial volume. Chapter 4 described the flavor identification routine used to determine the flavor of each event. The data sample contained 47 muon-like and 25 electron-like events while the Monte Carlo contained 578 muon-like and 431 electron-like events. Using these numbers in equation (6.3) gives:

\[
\frac{f}{1009} = \frac{47}{578} = 1.1^{+0.07}_{-0.12}
\]  

(6.4)

where the error bars are statistical only.

The number of data events is small so it is not reasonable to use Gaussian errors bars in this case. The statistical uncertainties were derived by generating a large number of random trials. Each trial used the number of muon-like and total events from the data and Monte Carlo samples to produce an \( f_{\text{trial}} \). All of the \( f_{\text{trial}} \) values were sorted from small to large. This sorted distribution was then integrated from \( f \) to an upper limit such that the integral covered 34% of the total number of trials. This set the upper limit of the statistical uncertainty. Likewise, the sorted distribution was integrated from \( f \) to a lower limit such that the integral covered an additional 34% of the total number of trials, setting the lower limit of the statistical uncertainty. Figure 6.1 shows the distribution of \( f_{\text{trial}} \) events generated from the ratio of ratios \( f \) found by this analysis.
Figure 6.1: The distribution of trial ratio of ratios $f_{trial}$ generated from the actual ratio of ratios $f$ and used to set the upper and lower limits of the statistical uncertainties.
6.3.1 SYSTEMATIC ERRORS

There were a number of systematic errors for the ratio of ratios $f$ in this analysis which have been estimated. First, the uncertainty due to the atmospheric fluxes in the energy range of this analysis was taken as 5% as quoted by Gaisser et al. (Gaisser 1996). The uncertainty due to the data reduction process based on the Monte Carlo sample was estimated as less than one percent. This came from comparing the flavor ratio for the Monte Carlo sample before $(0.702 \pm 0.032)$ and after $(0.702 \pm 0.036)$ the data reduction process (for events with at least 1000 photoelectrons).

The total efficiency for correctly identifying events was calculated as:

$$\epsilon = F_s \epsilon_s + F_m \epsilon_m$$  \hspace{1cm} (6.5)

where $F$ and $\epsilon$ are the fraction and efficiency of single ($s$) or multiple ($m$) track events. The flavor identification routine was run on three different samples of events. The first was a sample of 645 stopping muons, the second was a sample 403 single track Monte Carlo events generated for a previous IMB analysis (Haines 1986) and the last was a sample of 390 single track events from the Monte Carlo sample used in this analysis (see table 5.2). The results are listed in table 6.1. Summing all three samples together gave an efficiency of $0.90 \pm 0.03$ for correctly identifying single track events. There is a systematic uncertainty of 10% between the largest (Stopping CR muons) and smallest (Current MC sample) values in table 6.1. Adding this uncertainty in quadrature with the statistical uncertainty gave an efficiency of $0.90 \pm 0.05$.

Table 6.2 shows the estimates for the variables in equation (6.5). The fractions of single and multiple track events came from averaging the fractions.
Table 6.1: The results of running the flavor identification routine on three different samples of single track events.

<table>
<thead>
<tr>
<th>Source</th>
<th>Correct ID</th>
<th>Total</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stopping CR muons</td>
<td>595</td>
<td>645</td>
<td>0.92 ± 0.04</td>
</tr>
<tr>
<td>Other IMB MC sample</td>
<td>364</td>
<td>403</td>
<td>0.90 ± 0.05</td>
</tr>
<tr>
<td>Current MC sample</td>
<td>349</td>
<td>398</td>
<td>0.88 ± 0.05</td>
</tr>
<tr>
<td>Total</td>
<td>1308</td>
<td>1446</td>
<td>0.90 ± 0.03</td>
</tr>
</tbody>
</table>

from the data and Monte Carlo samples. The single track efficiency $\epsilon_s$ was estimated as above and the multiple track efficiency $\epsilon_m$ came from the Monte Carlo sample. The efficiency for correctly identifying multiple track events is worse than the efficiency for single track events due to the complications that multiple tracks pose to the flavor identification routine. This being the case, the systematic uncertainty was estimated by varying $\epsilon_m$. The upper limit was chosen to be the same as $\epsilon_s$ since it is unlikely for the multiple track efficiency to be better than the single track efficiency. This gives an upper limit of 0.90 ± 0.06 to the total efficiency. The lower limit was found by shifting the cutoff between electron-like and muon-like events by one bin in the flavor likelihood function $\ln(L)$ distribution in figure 5.15 and by running the flavor identification routine on a sample of multiple track Monte Carlo events generated for a previous IMB analysis (Haines 1986). This gave a lower limit of 0.69 ± 0.04 for $\epsilon_m$, which gave a total efficiency of 0.77 ± 0.06. There is a 16% percent change between the upper and lower limits of the total efficiency, which is equivalent to an 8% uncertainty in the central value.

The multiple pion production cross section used in the neutrino-nucleon interaction model (see section 4.3) is not very well established experimentally.
Table 6.2: Estimates of the fractions and efficiencies for single and multiple track events.

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_s )</td>
<td>0.40 ± 0.04</td>
<td>(data and MC combined)</td>
</tr>
<tr>
<td>( F_m )</td>
<td>0.60 ± 0.04</td>
<td>(data and MC combined)</td>
</tr>
<tr>
<td>( \epsilon_s )</td>
<td>0.90 ± 0.05</td>
<td>(combined as in table 6.1)</td>
</tr>
<tr>
<td>( \epsilon_m )</td>
<td>0.78 ± 0.04</td>
<td>(from MC sample)</td>
</tr>
</tbody>
</table>

Since multiple track events have a lower efficiency for being correctly identified, a larger than expected fraction of multiple pion events could introduce a large systematic uncertainty. The total efficiency for correctly identifying events will be:

\[
\epsilon = F_0 \epsilon_0 + F_\pi \epsilon_\pi
\]  

(6.6)

where \( F_0 \) and \( \epsilon_0 \) are the fraction and efficiency for events with no pions while \( F_\pi \) and \( \epsilon_\pi \) are the fraction and efficiency for correctly identifying events with one or more pions. Note that \( F_0 = 1 - F_\pi \) so that:

\[
\epsilon = \epsilon_0 - F_\pi (\epsilon_0 - \epsilon_\pi).
\]  

(6.7)

The flavor identification routine was run on events with no pions and events with one or more pions giving \( \epsilon_0 = 0.88 \pm 0.05 \) and \( \epsilon_\pi = 0.67 \pm 0.06 \). The fraction \( F_\pi \) was the quantity in question so it was varied by a factor of two (approximately the uncertainty in measurements (Casper 1990)), giving upper and lower limits of the total efficiency as 0.85 and 0.78 respectively. There is a 9% difference between these two limits which is equivalent to having 4.5% systematic uncertainty in the central value.

Adding all the systematic uncertainties in quadrature gives a total systematic error of 10%. The value of \( f \) then is given as:
This result, within uncertainties, indicates that the measured and predicted flavor ratios are the same.

6.3.2 NEUTRINO OSCILLATION LIMITS

Prior results reported by IMB and other experiments (Haines 1986, Becker-Szendy 1992, Casper 1991, Bionta 1988, Fukuda 1994, Hirata 1988, Hirata 1992, Goodman 1995, Kafka 1994) have indicated a lower than expected ratio of ratios. This has been called the atmospheric neutrino anomaly (see section 1.5). One explanation for this anomaly is that the flavor ratio at the point of production is calculated correctly but is modified before the neutrinos reach any given detector. In other words, the production mechanisms are well understood and the neutrinos simply change flavor in flight.

This is possible if the neutrinos have mass and the mass eigenstates are different than the flavor eigenstates. In this case, mixing between the two basis would be possible if the masses of the different neutrinos are not equal. The simplest case of this is to assume that oscillations are possible only between two of the flavors and so there is only one mixing angle. Assume for the moment that the two flavors are \( \nu_\mu \) and \( \nu_\tau \) (\( \bar{\nu}_\mu \) and \( \bar{\nu}_\tau \) are included in this discussion implicitly). Then the unitary transformation between the two basis of flavor and mass will be given by:

\[
\begin{pmatrix}
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= \begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\]  

(6.9)

where \( \theta \) is the mixing angle and \( \nu_1 \) and \( \nu_2 \) are the mass eigenstates. This may be written out to give:

\[ f = 1.1^{+0.07}_{-0.12} \text{(statistical)} \pm 0.11 \text{(systematic)}. \]  

(6.8)
\[ \nu_\mu = \nu_1 \cos \theta + \nu_2 \sin \theta \]
\[ \nu_\tau = -\nu_1 \sin \theta + \nu_2 \cos \theta. \quad (6.10) \]

The amplitudes of the mass eigenstates are given by:

\[ \nu_1(t) = \nu_1(0)e^{-\frac{iE_1}{\hbar}t} \]
\[ \nu_2(t) = \nu_2(0)e^{-\frac{iE_2}{\hbar}t}. \quad (6.11) \]

Assume that only \( \nu_\mu \) exist at \( t = 0 \) so that:

\[ \nu_\mu(t) = \nu_\mu(0) \cos^2 \theta e^{-\frac{iE_1}{\hbar}t} + \nu_\mu(0) \sin^2 \theta e^{-\frac{iE_2}{\hbar}t}, \quad (6.12) \]

The probability of measuring a \( \nu_\mu \) at any time is just:

\[ P_{\nu_\mu \rightarrow \nu_\mu} = \left| \frac{\nu_\mu(t)}{\nu_\mu(0)} \right|^2 = 1 - \sin^2 2\theta \sin^2 \left( \frac{(E_2 - E_1)t}{2\hbar} \right) \quad (6.13) \]

with the appropriate trigonometric substitutions. The two energies can be found by noting:

\[ E_i = \sqrt{p^2c^2 + m_i^2} \approx pc + \frac{m_i^2}{2pc} \quad (6.14) \]

where \( m_i \) denotes the masses of the eigenstates and \( p \) is the momentum which will be the same for both. This can be substituted into equation (6.13) giving:

\[ P_{\nu_\mu \rightarrow \nu_\mu} = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 t}{4pc} \right) \quad (6.15) \]

where \( \Delta m^2 = m_2^2 - m_1^2 \). Since the masses are assumed to be very small the distance travelled (\( D \)) by a single neutrino in time \( t \) will just be \( D = ct \). Likewise, the momentum is just \( pc = E_\nu \). These can be substituted into equation (6.15) to give:
\[ P_{\nu_\mu \rightarrow \nu_\mu} = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 D}{4\hbar c E_\nu} \right). \] (6.16)

The factor \( \frac{1}{4\hbar c} \) will equal 1.27 if \( \Delta m^2 \) is measured in \((eV/c^2)^2\), \( D \) is measured in \( km \) and \( E_\nu \) is measured in GeV.

Equation (6.16) gives the probability that a muon neutrino with energy \( E_\nu \) will remain a muon neutrino as it moves through a distance \( D \). The probability for it change flavor to a \( \nu_\tau \) is just \( 1 - P_{\nu_\mu \rightarrow \nu_\mu} \) which is just:

\[ P_{\nu_\mu \rightarrow \nu_\tau} = \sin^2 2\theta \sin^2 \left( \frac{1.27\Delta m^2 D}{E_\nu} \right). \] (6.17)

In this simple scheme, there are two independent parameters which determine the level of oscillations; the mixing angle \( \theta \) and the squared mass difference \( \Delta m^2 \). These are two values which have to be determined experimentally. The customary way to do this is to form a plot of \( \Delta m^2 \) on the vertical axis and \( \sin^2 2\theta \) on the horizontal axis.

In this analysis, a grid was superimposed on this plot. At each grid point, a ratio of ratios \( f' \) was calculated which represented the expected result for that set of oscillation parameters. The denominator of \( f' \) was simply the flavor ratio from the Monte Carlo sample \( R_{Monte \ Carlo} \). Monte Carlo events were also used in the numerator. Here, all the charged current \( \nu_\mu \) or \( \bar{\nu}_\mu \) were weighted by the probability in equation (6.17) using the Monte Carlo neutrino energy, flavor and zenith angle. The flight distance of the neutrino \( D \) was directly related to the zenith angle \( \phi \) by the relationship:

\[ D = (r_e - d) \cos \phi + \sqrt{(r_e - d)^2 \cos^2 \phi + h^2 - d^2 + 2r_e(h + d)} \] (6.18)
where $r_e = 6371.315\ km$ is the radius of the earth, $d = 0.6\ km$ is the depth of the IMB detector and $h = 10.0\ km$ is the height of the atmosphere.

Charged current tauon neutrino interactions are exceedingly rare in the IMB detector. If a $\nu_{\mu}$ or $\bar{\nu}_{\mu}$ was determined to have oscillated to a $\nu_\tau$ or $\bar{\nu}_\tau$ then it was assumed that it would not be observed. This is due to the large tauon mass ($1.8\ GeV$) which places the center of mass energy very high for charged current $\nu_\tau$ interactions. Only neutral current $\nu_\tau$ interactions would be measurable in IMB and these are flavor-independent. The effect of the oscillations at each grid point then was to reduce the total number of $(\nu_{\mu} + \bar{\nu}_{\mu})$ events. The flavor assignments for each event (muon-like, electron-like) were used in the calculation of $f'$ at each point.

The statistical uncertainties of $f'$ were calculated in the same manner as the actual result. The only difference was in setting the upper and lower limits. The sorted distribution of $f'$ trials was integrated out from $f'$ in both the upper and lower directions until the integral encompassed 90% of the total number of trials. If the actual result from this analysis ($f$) was not in this range of $f'$, then the grid point on the parameter space plot was excluded to the 90% confidence level. Systematic errors were included in this calculation by varying $f'$ randomly within 10% while the random trials for the statistical uncertainties were being generated.

Based on the result from this analysis and the method described above, a region of the parameter space given by $\sin^2 2\theta < 0.5$ and $\Delta m^2 < 9.8 \times 10^{-3} eV^2/c^2$ was excluded to the 90% confidence level for $\nu_{\mu} \rightarrow \nu_\tau$ oscillations. This may be seen in figure 6.2.
Figure 6.2: The parameter space region excluded to the 90% confidence level for $\nu_\mu \rightarrow \nu_\tau$ oscillations (solid line) by this analysis. The allowed region for the Kamiokande multi-GeV set is indicated by the dashed line while the sub-GeV set is indicated by the dotted lines (Fukuda 1994).
A similar calculation may be performed for $\nu_\mu \rightarrow \nu_e$ oscillations. Here, the oscillation probability is derived in a similar fashion as equation (6.17) and is given as:

$$P_{\nu_\mu \rightarrow \nu_e} = \sin^2 \theta \sin^2 \left( \frac{1.27 \Delta m^2 D}{E_\nu} \right).$$  

(6.19)

As before, a region of the parameter space can be excluded using this equation. The major difference in the calculation is that both $\nu_\mu$ and $\nu_e$ were allowed to oscillate. There are small variations in the recovery efficiency as a function of neutrino energy for $\nu_e$ and $\nu_\mu$ events. These variations were included in the calculation by using the ratio of the efficiencies as a function of neutrino energy. Likewise, there were small differences in the flavor identification accuracy for $\nu_e$ and $\nu_\mu$ events. These differences were also included as ratios in the calculation.

If a particular event was initially a $\nu_e$ or $\bar{\nu}_e$, then the probability that it would be measured as electron-like is given by:

$$P_{e\text{-}\text{like}} = (P_{\nu_\mu \rightarrow \nu_e})(\epsilon_{ee}) + (P_{\nu_e \rightarrow \nu_\mu})(\epsilon_{e\mu})(\frac{\epsilon_{e\mu}(E_\nu)}{\epsilon_{e}(E_\nu)}).$$  

(6.20)

where $\epsilon_{ee}$ is the probability that an electron neutrino will be identified as electron-like and $\epsilon_{e\mu}$ is the probability that a muon neutrino will be identified as electron-like. $\epsilon_e(E_\nu)$ and $\epsilon_{e\mu}(E_\nu)$ are the probabilities as a function of energy that an electron or muon neutrino will pass all the software and scanning cuts and be fit inside the fiducial volume. The probability that an initial $\nu_e$ or $\bar{\nu}_e$ event will be measured as muon-like is given by:

$$P_{\mu\text{-}\text{like}} = (P_{\nu_\mu \rightarrow \nu_e})(\epsilon_{e\mu})(\frac{\epsilon_{e\mu}(E_\nu)}{\epsilon_{e}(E_\nu)}) + (P_{\nu_e \rightarrow \nu_\mu})(\epsilon_{e\mu}).$$  

(6.21)
where, again, $\epsilon_{\mu}$ is the probability that a muon neutrino will be identified as muon-like and $\epsilon_{e\mu}$ is the probability that an electron neutrino will be identified as muon-like. If the event is initially $\nu_\mu$ or $\bar{\nu}_\mu$, then the probabilities $P_{e-like}$ and $P_{\mu-like}$ will be given by:

$$
\begin{align*}
P_{e-like} &= (P_{\nu_\mu \rightarrow \nu_e})(\epsilon_{ee})\left(\frac{\epsilon_e(E_{\nu})}{\epsilon_\mu(E_{\nu})}\right) + (P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e})(\epsilon_{e\mu}) \\
\text{and} \\
P_{\mu-like} &= (P_{\nu_\mu \rightarrow \nu_e})(\epsilon_{\mu\mu}) + (P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e})(\epsilon_{e\mu})\left(\frac{\epsilon_e(E_{\nu})}{\epsilon_\mu(E_{\nu})}\right)
\end{align*}
$$

respectively.

A region of parameter space given by $\sin^2 2\theta < 0.7$ and $\Delta m^2 < 1.5 \times 10^{-2} eV^2/c^2$ was excluded to the 90% confidence level for $\nu_\mu \rightarrow \nu_e$ oscillations using equations 6.20, 6.21, 6.22 and 6.23. This may be seen in figure 6.3.

In reality, it is possible that mixing could take place between all three neutrino families and so there could be three different mixing angles and three different mass differences ($\Delta m^2$). Only two of the mass differences would be independent, so there could be as many as 5 unknown parameters which determine the oscillation. This three-flavor mixing would produce a very rich structure of oscillations (Ahluwalia 1997) which the available data from this analysis could not hope to sort out. For this reason, only two component oscillation models were explored.

6.3.3 THE ZENITH ANGLE DISTRIBUTION

The variables $\frac{1.27\Delta m^2 D}{E_{\nu}}$ in equation (6.17) form an effective "wavelength" for neutrino oscillations which varies inversely with the neutrino energy. If the mass squared difference $\Delta m^2$ and flight distance $D$ are fixed then the

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Figure 6.3: The parameter space region excluded to the 90% confidence level for $\nu_\mu \rightarrow \nu_e$ oscillations (solid line) by this analysis. The allowed region for the Kamiokande multi-GeV set is indicated by the dashed line while the sub-GeV set is indicated by the dotted lines (Fukuda 1994).
wavelength will depend entirely on the neutrino energy. Low energy neutrinos will have longer wavelengths than high energy neutrinos.

Figure 6.4 shows how this relationship effects the \( \sin^2 \left( \frac{1.27 \Delta m^2 R(\theta)}{4.5} \right) \) factor in equation (6.17). The neutrino energy in the top plot is 100 \( \text{MeV} \) while the neutrino energy in the bottom plot is 1 \( \text{GeV} \) and \( \Delta m^2 = 0.01 \) in both. The horizontal axis is the zenith angle with upward-going events on the left and downward-going on the right. The average value of the probability for all upward-going events is 0.5 in both plots. The neutrino flight distance is very long for upward-going events and so it covers many wavelengths of the oscillation. This is not necessarily true for downward-going events. In the case of the 100 \( \text{MeV} \) neutrinos, the shorter distance for downward-going events does cover enough wavelengths, so that the average is still large. However, in the case of the 1 \( \text{GeV} \) neutrinos, the distance for downward-going events covers only a fraction of a single wavelength and the average is very small.

The overall implication of figure 6.4 is that a low energy sample of atmospheric neutrinos should not have \( f \) dependent on zenith angle while a high energy sample could. Accordingly, the ratio of ratios \( f \) from this analysis was calculated in four separate zenith angle bins. The results are listed in table 6.3. The error bars in the table are statistical only. There is no significant evidence for neutrino oscillations in this distribution.

### 6.3.4 COMPARISON TO KAMIOKANDE

The Kamiokande collaboration reported a total of 135 muon-like events from their data out of a total of 233 and 162.2 muon-like events from their Monte Carlo out of a total of 229 (Fukuda 1994). Table 6.5 shows the
Figure 6.4: The $\sin^2 \left( \frac{1.27 \Delta m^2 P}{E_{\nu}} \right)$ factor for $\nu_\mu \to \nu_\tau$ oscillations versus the zenith angle. The neutrino energy in the top plot is 100 $MeV$ and 1 $GeV$ in the bottom and $\Delta m^2 = 0.01$ in both.
Table 6.3: The ratio of ratios for each of four total zenith angle bins. The first bin corresponds to upward-going events while the last bin corresponds to downward-going events. The zenith angles listed refer to the center of the bins.

<table>
<thead>
<tr>
<th>Bin</th>
<th>$(\cos \theta)$</th>
<th>Ratio of ratios $(f)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.75</td>
<td>1.3$^{+0.10}_{-0.30}$</td>
</tr>
<tr>
<td>2</td>
<td>-0.25</td>
<td>1.0$^{+0.12}_{-0.37}$</td>
</tr>
<tr>
<td>3</td>
<td>0.25</td>
<td>0.9$^{+0.17}_{-0.25}$</td>
</tr>
<tr>
<td>4</td>
<td>0.75</td>
<td>1.3$^{+0.09}_{-0.44}$</td>
</tr>
</tbody>
</table>

Kamiokande events as listed in their paper. MC A and MC B refer to Monte Carlo events generated with two different fluxes. In case A, the fluxes of Honda et al. (Honda 1990) were used while in case B the fluxes of Barr et al. (Barr 1989) and Volkova (Volkova 1980) were used. FC and PC stand for fully and partially contained events, respectively. The visible energy cutoff for their fully contained events was 1.33 GeV and 1500 (30% below 1200) photoelectrons for their partially contained events. Using equation (6.3) gives:

$$f_{\text{Kamiokande}} = \frac{135}{123.2} = 0.82^{+0.04}_{-0.05}. \quad (6.24)$$

Table 6.4 shows the values of $f_{\text{Kamiokande}}$ for each zenith angle bin using the numbers from their paper (Fukuda 1994). The Kamiokande results are compared with the results from this analysis in figure 6.5. There are two things to note from this plot. First, the values of $f$ from this analysis are consistently higher than the results from Kamiokande at each point. Second,
Table 6.4: The ratio of ratios for each of five total zenith angle bins using the results reported by Kamiokande.

<table>
<thead>
<tr>
<th>Bin</th>
<th>$(\cos \theta_z)$</th>
<th>Ratio of ratios $f_{\text{Kamiokande}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.8</td>
<td>$0.62^{+0.10}_{-0.14}$</td>
</tr>
<tr>
<td>2</td>
<td>-0.4</td>
<td>$0.71^{+0.07}_{-0.15}$</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
<td>$0.77^{+0.07}_{-0.13}$</td>
</tr>
<tr>
<td>4</td>
<td>0.4</td>
<td>$0.85^{+0.09}_{-0.11}$</td>
</tr>
<tr>
<td>5</td>
<td>0.8</td>
<td>$1.04^{+0.06}_{-0.14}$</td>
</tr>
</tbody>
</table>

the shape of the distribution from this analysis is basically flat while the Kamiokande result shows a zenith angle dependence.

Exactly how much do the two results differ? Another way to pose this question is to ask what are the chances that the results reported here are nothing more than a random fluctuation of the Kamiokande data. To answer this, a $\chi^2$ test was applied to the results of both experiments where:

$$\chi^2 = \sum_{i=1}^{N_{\text{bins}}} \left( \frac{f_{\text{IMB}}^i - f_{\text{Kamiokande}}^i}{\sigma_i} \right)^2$$

(6.25)

In this equation, $f_{\text{IMB}}^i$ are the ratio of ratios from this analysis in each bin $i$, $f_{\text{Kamiokande}}^i$ are the ratios reported by Kamiokande, $\sigma_i$ are the uncertainties from both experiments (added in quadrature) and $N_{\text{bins}}$ is the number of bins. There are two ways to consider this test. First, assume that only the shape is important. In this case, the results from this analysis were first normalized to the average of the Kamiokande results. This gave $\chi^2 = 5.45$. 

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Figure 6.5: The ratio of ratios for this analysis (filled circles) and Kamiokande (open squares).

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Table 6.5: A summary of Kamiokande events. FC stands for fully contained and PC stands for partially contained. See the text for an explanation of MC A and MC B.

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>MC A</th>
<th>MC B</th>
</tr>
</thead>
<tbody>
<tr>
<td>e-like</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FC</td>
<td>98</td>
<td>66.5</td>
<td>70.8</td>
</tr>
<tr>
<td>PC</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Total</td>
<td>98</td>
<td>66.5</td>
<td>70.8</td>
</tr>
<tr>
<td>μ-like</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FC</td>
<td>31</td>
<td>37.8</td>
<td>40.4</td>
</tr>
<tr>
<td>PC</td>
<td>104</td>
<td>124.4</td>
<td>125.4</td>
</tr>
<tr>
<td>Total</td>
<td>135</td>
<td>102.2</td>
<td>165.8</td>
</tr>
</tbody>
</table>

which corresponds to a probability of 0.23. In other words, just based on shape alone, there is only a 23% chance this distribution could have resulted from the Kamiokande distribution. In the second case, assume that both the shape and the height of the distribution are important. This gave $\chi^2 = 9.55$ which corresponds to a probability of 0.05. Therefore, based on both the shape and the height, there is only a 5% chance this result could be a random fluctuation of the Kamiokande result.

It is worth noting that the cuts used in this analysis were very simple. Basically, each event was required to have at least 1000 total photoelectrons and a fitted vertex inside the fiducial volume. This means that the data reduction techniques were the same for all events. No special consideration was given to fully contained, partially contained, single or multiple track events. The advantage of this is to limit the systematic uncertainties due to different analysis techniques for different classes of events when merged in the final sample. Such systematic uncertainties are very difficult to estimate. The Kamiokande collaboration used different analysis chains for fully and
partially contained events and they employed a cut on multiple track events which required at least one track to carry 80% of the total visible energy.

6.4 SYSTEMATIC CHECKS ON THE RESULT

This section will describe the checks made on both the data and the Monte Carlo to look for possible systematic errors in the results of this analysis.

6.4.1 COSMIC RAY CONTAMINATION

One very obvious systematic error would be cosmic ray muons that had mistakenly been fit as contained neutrinos. If this were the case it would increase the total number of muon-like events in the data flavor ratio, but not the Monte Carlo flavor ratio. Thus the ratio of ratios would be higher than expected. It would also influence the zenith angle distribution of $f$ since nearly all the events would be downward-going.

Should such contamination exist it would most likely show up as an excess of single track events in the top half of the detector since this is where the majority of the cosmic ray muons entered. Multiple track cosmic ray muons were very easy to spot by the data reduction software due to the exceptionally bad timing residuals of the second entry point. Any that were missed by the software were easily spotted by the human scanners. Figure 6.6 shows the $z$ (up-down) distribution of vertices for the data events (solid line) and the Monte Carlo (dashed line) events. No contamination is evident from this figure.

Of course, cosmic ray muons could have entered from the side. If they entered in the middle of a wall it was possible to make a good vertex fit to the entry point and thus exclude them. The only real problem came if
Figure 6.6: The $z$ distribution of vertices for single track data (solid line) and Monte Carlo (dashed) events. There is no clear excess of events in the top half of the detector.
the cosmic ray muon clipped an edge or corner of the detector. The close proximity of the entry and exit points made it difficult to use the timing residuals in fitting the vertex. In some cases, these events were fit with a contained vertex and an exiting track by the data reduction software. Only the human scanners could effectively tell the difference. If any of these events made it into the final sample of neutrino interactions then there would be an excess of downward-going tracks. Figure 6.7 shows the distribution of zenith angles for the data events (solid line) and the Monte Carlo events (dashed line). Again, no clear excess is apparent.

6.4.2 THE ROBUST RATIO OF RATIOS

Contamination by cosmic rays was the most direct way the result could be systematically biased, but perhaps there were other more subtle ways. Most likely any such effects would be linked to geometry. To see this, note that the major differences between muon-like and electron-like events are the length they travel in the detector and how quickly they deposit their energy along the track. Also note that partially contained events presented a special case to the vertex fitting routines due to the early and intense light they produced at the exit point. If there were some other systematic error besides cosmic ray muons at work in the detector or the analysis, then it would likely show up if \( f \) was examined as a function of geometry.

If the detector is divided into equal volumes, then \( f \) should be roughly the same in each volume regardless of how the divisions are made. No particular volume should be favored. If \( f \) depends on the way the equal volumes are distributed, then it would indicate some sort of systematic bias in the analysis.
Figure 6.7: The zenith angle distribution for the data (solid line) and the Monte Carlo (dashed line). The zenith angle is taken from the track with the maximum visible energy. There is no clear excess of downward-going events.
Table 6.6: The ratio of ratios $f$ in four equal volumes for the x, y and z axis respectively and four concentric volumes. The first bin is at the negative limit of the fiducial volume in the first three columns and is at the edge of the fiducial volume in the last column.

<table>
<thead>
<tr>
<th>Bin</th>
<th>$f$ for x</th>
<th>$f$ for y</th>
<th>$f$ for z</th>
<th>$f$ concentric</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.9$^{+0.17}_{-0.34}$</td>
<td>1.5$^{+0.14}_{-0.89}$</td>
<td>1.0$^{+0.14}_{-0.43}$</td>
<td>1.4$^{+0.24}_{-0.71}$</td>
</tr>
<tr>
<td>2</td>
<td>1.2$^{+0.08}_{-0.23}$</td>
<td>1.2$^{+0.13}_{-0.51}$</td>
<td>1.2$^{+0.09}_{-0.27}$</td>
<td>1.4$^{+0.13}_{-0.50}$</td>
</tr>
<tr>
<td>3</td>
<td>1.2$^{+0.09}_{-0.37}$</td>
<td>1.0$^{+0.12}_{-0.24}$</td>
<td>1.2$^{+0.08}_{-0.23}$</td>
<td>0.9$^{+0.12}_{-0.25}$</td>
</tr>
<tr>
<td>4</td>
<td>1.3$^{+0.17}_{-0.51}$</td>
<td>1.0$^{+0.10}_{-0.31}$</td>
<td>1.1$^{+0.10}_{-0.29}$</td>
<td>1.2$^{+0.08}_{-0.23}$</td>
</tr>
</tbody>
</table>

or the detector itself. For instance, if there were a bias towards $\nu_\mu$ events near the edge of the fiducial volume, then $f$ may be much larger here than in a volume near the center. Table 6.6 shows the ratio of ratios in various equal volumes. The first three columns show $f$ in four equal volumes relative to the x, y and z axis respectively while the last column shows $f$ through four concentric equal volumes. In all cases, $f$ varies little. For the concentric volumes, the first bin is at the edge of the fiducial volume while for the axis volumes the first bin is at the negative limit of the axis inside the fiducial volume.

The question of angular dependence for $f$ is important for this analysis. Table 6.3 shows the distribution with respect to the z axis since this is where a correlation might be expected. But what about the x and y axis? Certainly no correlation should exist there, so the distribution should be flat. Table 6.7 shows the distributions of $f$ for track directions along the x, y and z axis. In each case the first bin corresponds to tracks moving in the positive direction of
Table 6.7: The ratio of ratios in four angular bins for the x, y and z axis respectively. The first bin corresponds to a track direction in the positive direction along the axis. For the z axis, this is the same as the zenith angle.

<table>
<thead>
<tr>
<th>Bin</th>
<th>$f$ for x</th>
<th>$f$ for y</th>
<th>$f$ for z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.1$^{+0.18}_{-0.27}$</td>
<td>1.0$^{+0.10}_{-0.31}$</td>
<td>1.3$^{+0.10}_{-0.30}$</td>
</tr>
<tr>
<td>2</td>
<td>1.3$^{+0.11}_{-0.57}$</td>
<td>1.7$^{+0.11}_{-0.45}$</td>
<td>1.0$^{+0.12}_{-0.37}$</td>
</tr>
<tr>
<td>3</td>
<td>1.2$^{+0.11}_{-0.33}$</td>
<td>1.2$^{+0.10}_{-0.40}$</td>
<td>0.9$^{+0.17}_{-0.25}$</td>
</tr>
<tr>
<td>4</td>
<td>1.1$^{+0.08}_{-0.34}$</td>
<td>0.9$^{+0.17}_{-0.26}$</td>
<td>1.3$^{+0.09}_{-0.44}$</td>
</tr>
</tbody>
</table>

the axis. The last bin corresponds to tracks moving in the negative direction of the axis. The values in the column for the z axis are the same as those listed in table 6.3.

Within statistical uncertainties, no particular volume seems preferred in either table 6.6 or table 6.7. This implies that there is no geometrical bias in the data.

6.5 DISCUSSION

The atmospheric neutrino anomaly has persisted for over ten years now. Most of the evidence for it has been collected at low energy (below 1 \textit{GeV}) by both the IMB and the Kamiokande water Čerenkov detectors. About 80\% of all atmospheric neutrino interactions measured have come from these two detectors (Gaisser 1996). The most recent results from Kamiokande (Fukuda 1994) seem to imply that neutrino oscillations are the cause of the anomaly. They examined their high energy ($\geq 1GeV$) sample of contained neutrino interactions and found that $f$ was low, just like it is for the low
energy samples of both Kamiokande and IMB, and that it varied with zenith angle, just as it would if oscillations were occurring.

The results from this analysis differ from those of Kamiokande in two significant ways. First, the value of $f$ is higher ($1.1^{+0.07}_{-0.12}$ from this analysis compared to $0.82^{+0.04}_{-0.05}$ from Fukuda et al.) and there is no significant zenith angle dependence.

Assuming that the result from this analysis is correct, what are the implications for neutrino physics? At first glance it may seem this result implies that neutrino oscillations are not the cause of the atmospheric neutrino anomaly though this conclusion is limited by statistics. The zenith angle distribution of $f$ depends, in part, on $\Delta m^2$ which was taken to be $0.01eV^2/c^2$ in figure 6.4. If $\Delta m^2 = 0.1eV^2/c^2$ had been chosen instead, the average oscillation probability for 1 $GeV$ downward-going events would have been about the same as that for 100 $MeV$ events. So this result cannot rule out neutrino oscillations just on the shape of the zenith angle distribution alone.

Of course the shape of the distribution in zenith angle is not the only factor to consider. The value of $f$ taken over all bins is $1.1^{+0.07}_{-0.12} \pm 0.11$ which is entirely consistent with $f = 1$. The excluded regions in figures 6.2 and 6.3 are based on the value of $f$ alone and do not use the shape of the zenith angle distribution. Therefore, even though $f$ is consistent with 1, this result cannot rule out neutrino oscillations since the excluded regions cover only a portion of the parameter space. Given the available statistics, this result is not sensitive to small mixing angles or small mass differences.
One possible difference between the two results may be the kinematic cuts. Kamiokande employed two different cuts on the visible energy. For partially contained events, they required at least 1200 photoelectrons which corresponds to roughly 2.5 GeV for muons (Hirata 1988). For fully contained events, they required at least 1.33 GeV in visible energy. So the lower limit on the energy of their events was not same for fully and partially contained events and it was not the same as the 1 GeV lower limit used in this analysis. Since the up-down asymmetry depends on the neutrino energy, the difference in the lower limits employed by both experiments makes it difficult to compare the results directly.

At best, this result indicates that the Kamiokande result (Fukuda 1994) may not be entirely accurate and that more research is necessary to resolve the issue.

6.6 THE FUTURE

During the 1980s and most of the 1990s, the Kamiokande and IMB experiments were the largest and most sensitive of all the atmospheric neutrino detectors. Both, however, are small compared to the next generation water Čerenkov detector called Super-Kamiokande. Many of the former members of Kamiokande and IMB have joined together to build Super-Kamiokande specifically for seeing neutrinos. Super-Kamiokande is a water Čerenkov detector in the shape of a cylinder 40 m tall and 40 m in diameter. It has a total fiducial mass of 22 kilotons which makes it 7 times bigger than IMB. There are a total of 11,000 40 cm Hamamatsu photomultiplier tubes viewing the inner volume and 2,000 20 cm Hamamatsu tubes viewing the
outer veto volume. These 2,000 tubes are actually the same tubes used in IMB-3 so the entire IMB detector has literally become the veto counter for Super-Kamiokande. Nearly 40% of the inner volume surface is covered in photo-cathode giving Super-Kamiokande excellent energy resolution.

Super-Kamiokande has been collecting data since early April of 1996. Just based on volume alone it should collect contained neutrino interactions 9 times faster than IMB. Of course, the data acquisition systems have been improved so this is a very conservative estimate. The larger volume and fine-grain resolution of Super-Kamiokande give it many advantages not only in collecting contained neutrino events, but also in analyzing them. The fraction of partially contained events will be smaller just because there is more room for the tracks to stop. Thus it should be very easy to differentiate showering and non-showering events.

Given the experience of this analysis, Super-Kamiokande should do a complete analysis of their events. That is, they should keep their cuts simple to include as many neutrino events as possible. In the past, the analysis of water Čerenkov data has focused on single track events alone because this kept the analysis simple and there is no reason to believe that ignoring multiple track events would change the flavor ratio. In this analysis, multiple track events were included by necessity since they constituted about 60% of the total sample. The advantages that Super-Kamiokande offers in terms of size and resolution should make the single track cut unnecessary at all energies. It is likely that a result from a complete sample (containing fully,
partially contained, single and multiple track events) will be much more credible than a result based on single track events alone.

No results have been published by Super-Kamiokande at the current time. When such results are published they will no doubt settle the issue of whether the atmospheric neutrino anomaly exists or not. More importantly for this analysis, the Super-Kamiokande results should also settle the issue of the zenith angle dependence to the ratio of ratios.
CHAPTER 7

CONSTRUCTION OF THE DUMAND II ARRAY

7.1 HISTORY AND OVERVIEW OF THE DUMAND PROJECT

DUMAND, which stands for Deep Underwater Muon And Neutrino Detector, was a project initiated to look for high energy neutrinos from extraterrestrial sources. The project actually began with a series of summer workshops in the early 1970's where many ideas of implementation were discussed and studied. The final scheme approved called for an array of photomultiplier tubes set on the ocean floor to detect Čerenkov photons from muons. The muons come from both cosmic ray and neutrino interactions. Identification between the two sources of muons will come from reconstruction of each muon track. Given that the earth is a good shield from cosmic ray muons generated below the horizon, it is assumed that upward-going muons come from neutrino interactions.

There are many advantages to the deep ocean. First, the detector medium is very cheap, free in fact. This is important as neutrino detection typically depends on covering a large area. Second, deep ocean water has the property that is it very clear, with attenuation lengths reaching 40 m or better. Third, with the exceptions of $^{40}\text{K}$ decay and bioluminescence which will be discussed later, it is very dark. And fourth, the over burden of water makes a good shield against cosmic ray muons coming from above the horizon.

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The deep ocean is also a demanding environment. Engineering difficulties rise quickly when faced with the intense pressure and the corrosive nature of the water. Access to the array from both above and below the surface as well as communication with the array were obstacles that needed to be addressed in developing this project. For these reasons, it was decided that DUMAND would be built in two stages. The first stage would involve the construction of a prototype detector that would allow the researchers to test the feasibility of building the full array and allow them to work through some of the engineering problems.

The array would be built as a series of individual “strings”. Each string would consist of a number of photomultiplier tubes suspended and evenly spaced along a set of cables attached to an anchor resting on the ocean floor. The photomultiplier tubes would be protected by clear spherical glass pressure housings commonly used in deep sea applications. There would also be a computer for each string that would be responsible for remotely operating all functions of the string. The strings would be collectively connected to a cable that would carry power, communications and data to and from a remote lab on shore. Figure 7.1 shows the full array.

The first stage of DUMAND was called the Short Prototype String (SPS). This string consisted of seven optical modules spaced 5.1 m apart, two calibration modules, two hydrophones, environmental units and a string controller. An optical module is simply a photomultiplier tube and associated electronics housed inside a spherical, glass pressure housing known as a Benthos sphere. The calibration modules each consisted of two nitrogen lasers.
housed inside a Benthos sphere and aimed at an external scintillator ball. This ball converted the UV light from the lasers into blue visible light compatible with the photomultiplier tubes. The environmental unit, hydrophones and Neil Brown Unit all provided information on the ambient ocean environment.

For simplicity, the SPS was a ship tethered experiment. This allowed measurements at a number of different depths. In 1988, the string was deployed off the west coast of the island of Hawaii near the eventual site of the full DUMAND array. As mentioned previously, data was taken at a number of different depths ultimately reaching 4 km. All in all, about 35 hours of data were collected.

Aside from the obvious engineering lessons learned from the construction and deployment of the SPS, the data provided a wealth of information. First, the downward-going muon rate was measured at several depths with the rate at 4000 m being $(4.57 \pm 0.459 \pm 0.91) \times 10^{-5} m^{-2} s^{-1} sr^{-1}$ (Clem 1990). This rate agrees well with the semi-empirical rate of $4.95 \times 10^{-5} m^{-2} s^{-1} sr^{-1}$ (Miyake 1963) and thus would not be a problem for either the data acquisition hardware or the event reconstruction software in the full array. Second, by using the calibration modules, the attenuation length of the water was measured to be $47 \pm 22$ m (DUMAND 1988). This particular measurement was useful in computer simulations aimed at minimizing the number of optical modules while maximizing the effective area of the full array. Third, the background rates for $^{40}K$ decay and bioluminescence were measured. Čerenkov light from $^{40}K$ decay is typically produced in low light levels.
Triggers from random coincidences of photomultiplier tubes by this decay are easily excluded in the analysis chain. Bioluminescence produced by plankton and higher order organisms can potentially be very bright. However, the optical modules were programmed to automatically shut down briefly when receiving abnormally high light levels thus producing some dead time. The SPS data revealed that bioluminescence typically generates about 5% dead time.

The SPS results both proved that a deep ocean water Čerenkov experiment was possible and provided a baseline for planning the full array. A proposal was submitted and subsequently approved by the Department Of Energy in 1988. The full array would consist of nine strings with twenty-four optical modules each. Eight of the strings would be evenly placed along the circumference of a circle with the ninth string placed at the center as shown in figure 7.1. Drawing a straight line between the eight outer strings creates an octagon, which is what the array is often called. Each string would be connected to a junction box which is the terminus of an electro-optical cable running to the shore laboratory. Full details of the DUMAND system will be given in section 4.3.

Given the complexity of the task, it was decided to build the array in two sections. Initially, only three strings, the junction box and shore cable would be deployed. These three strings would include the center string plus two outer strings forming one triangular section of the octagon. This initial phase of the project was called the triad.
Figure 7.1: The full DUMAND II array. Eight strings would be placed at the points of an octagon and a ninth string would be placed in the center. Each string would have twenty optical modules spaced 10 m apart.
Though the SPS was a working instrument, there were several improvements that were made to the final design. Development, testing and construction of the final design lasted until late 1993. In December, 1993 the first string, environmental equipment, transponders, junction box and shore cable were all deployed at the DUMAND site. Unfortunately, the string failed several hours after deployment due to a leak in the pressure housing of the string controller. This string was recovered in January, 1994. Though the life of the string was short, it did provide enough data to verify the final design. The other components of the array deployed are still in place and most of the recovered string has been salvaged. Details of the deployment, recovery and failure evaluation will be given in sections 4.5 and 4.6.

7.2 THE PHYSICS GOALS OF DUMAND

Stated simply, the main physics goal of the DUMAND array was the detection of extraterrestrial, neutrino point sources in the TeV energy range. Given that neutrinos are detected via muons produced by charged current interactions, the array would be a good laboratory for muon physics as well. Also, neutrinos produced by cosmic ray nuclei interacting in the upper atmosphere would produce a background in the array and it is very likely these neutrinos would also produce useful physics. It is possible that DUMAND could see exotic particles such as monopoles and WIMPs. If neutrino point sources were discovered, then it may be possible to use them as beams in mapping the interior of the earth. It has been pointed out recently that tau neutrinos could produce a very distinct signal in the array. Provided there
are sources producing enough tau neutrinos, DUMAND could make the first direct measurement of these particles (Learned 1994).

The design of the DUMAND array was optimized for upward-going muons. The photomultiplier tubes on the strings were all set facing downward. The kinematics for charged current neutrino interactions at high energy preferentially scatters the daughter leptons in the forward direction. Nominally, the lepton direction is within one degree of the neutrino direction. Thus upward-going muons, with angles greater than 80° of the zenith, may be attributed to neutrino interactions. Since there are no hard boundaries on the volume of the array, the vertex of these interactions may occur either inside or outside the detector volume. In fact, a number of them would occur in the rock beneath the detector. Electrons, from electron neutrinos, lose energy very quickly both in rock and water and so the array would not be very sensitive to them except at very high energy.

The fact that the array would be sensitive to neutrino directions greater than 80° with the zenith means it would have a 2.35 π view of the sky at any given time. Since the array site is at roughly 19.6°N latitude, it would cover almost the entire sky with about a 50% duty cycle. Only a small region around the north pole would be unavailable. Because the array has no hard walls containing the volume, the sensitive area of the array is actually energy dependent. This is due to the fact that higher energy events produce more photons and are thus visible further from the octagon of strings. Figure 7.2 shows the energy dependence of the effective area for the DUMAND array. Figure 7.2 also gives the energy threshold for the array as roughly 10 GeV.
This is close to the energy needed for a muon to travel 200 m in water given that it loses energy at roughly 300 MeV/m.

This energy threshold, coupled with the fact that the array is not sensitive to low energy electron neutrinos, means that DUMAND would not be able to see solar neutrinos. Nor is it likely to detect the neutrino pulse from a supernova such as 1987A. But there are a number of sources that may be visible to DUMAND. In general, neutrinos are expected to be produced in cosmic beam dumps where particles are accelerated through some mechanism such as gravity and collide with the surrounding material. Just as in a
terrestrial accelerator, these collisions produce secondary particles consisting of pions and kaons which ultimately decay to gamma rays and neutrinos. This scenario indicates that sources of gamma rays are also good candidates for sources of neutrinos. In fact, given that intervening matter is likely to absorb gamma rays, neutrino sources should be even more abundant.

DUMAND may be able to detect neutrinos from Active Galactic Nuclei (AGN). The AGN are believed to be super massive black holes residing at the center of many galaxies. They are some of the most powerful radiation emitters known in the universe. The energy for this emission is assumed to come from matter falling into the singularity and it is likely that this matter forms an accretion shock disk at some radius from the black hole. Particle acceleration, mainly of protons, would occur in such a disk and the resulting proton beam would produce a large neutrino flux. The spectra of AGN are basically flat with the exception of a bump in the ultra violet region. This bump is caused by the accretion disk thermalizing and reradiating the X-ray emission from the black hole (Stecker 1992).

The main energy loss mechanism for the protons in the disk is \( p + \gamma \). Equation (7.1) shows the dominant neutrino production channel.

\[
p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+
\]

\[
\pi^+ \rightarrow \mu^+ + \nu_\mu
\]

\[
\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu
\]  

(7.1)

While theoretical calculations agree quite well, it is not clear if AGN point sources would be visible to DUMAND, though some indication has been given
that they may be visible collectively through the shape of their spectrum in
the PeV range (Szabo 1992).

If AGN could be detected as neutrino point sources by DUMAND, then it
may be possible to use them to map the interior of the earth. Over a period
of many years, a single AGN would be observed through many different path
lengths in the earth. By noting the variation of the flux with path length, it
should be possible to build a density profile of the interior. If a large number
of individual AGN can be distinguished, it only improves the precision of the
mapping (Kuo 1994).

Aside from ambient light sources such as \(^{40}K\) decay and bioluminescence,
the two major sources of background in this experiment come from the in­
teraction of cosmic ray primaries in the upper atmosphere. The background
consists of downward-going muons and upward-going atmospheric neutrinos
both induced from the decay of secondary particles produced by primary
cosmic ray interactions. Placing the array under 4.8 \(km\) of water and facing
the photomultiplier tubes down keeps the downward-going muon rate at an
acceptable level. The high energy threshold of the detector also reduces the
rate of muons from upward-going atmospheric neutrinos. In fact, the rates
of these backgrounds are low enough that DUMAND would be signal lim­
ited rather than background limited. However, these backgrounds cannot be
ignored and they could provide some useful physics.

The study of muons from cosmic ray primaries is a well established field,
but DUMAND would be able to make useful contributions. The energy range
and size of the array would allow direct measurements in regions previously
not sampled. Energy measurements for muons in the array would have to be corrected for energy loss in the homogeneous overburden of water. This would both extend the energy range and yield information about muon cross sections and energy loss in water. A 3 $\text{TeV}$ muon at sea level will just cross the array at depth. The energy range could be reasonably sampled to approximately 3000 $\text{TeV}$ (DUMAND 1988). While the array was optimized for upward-going tracks, it would still have an effective area of 2500 $\text{m}^2$ for downward-going muons which translates to over a million events per year.

Multiple muons could be studied with the array as well. The effective area increases for two or more parallel minimum ionizing muons to 9800 $\text{m}^2$. As a comparison, all underground detectors to date have areas less than 1000 $\text{m}^2$. The sources for multiple muons include the decay of heavy particles, hadronic interaction properties such as charm production, high energy gamma rays and a large number of hadron cascades that produce mesons which in turn produce muon daughters (DUMAND 1988). This latter source yields information about the energy spectrum and composition of the primary cosmic rays. It is also possible that DUMAND may see single and multiple muons from air showers induced by gamma ray point sources. This would only be true if the flux of gamma induced muons by the source was significantly greater than the atmospheric background for a given energy and angular bin (DUMAND 1988). In fact, there is one dimuon candidate in the data taken during the 1993 deployment as will be discussed in section 4.5.3.

Chapters 2-6 presented new results for atmospheric neutrinos in the IMB detector which hint at neutrino oscillations. Similar conclusions have been
drawn from earlier results out of IMB (Becker-Szendy 1992) and from Kamiokande (Hirata 1988, Fukuda 1994). Examination of atmospheric neutrinos in DUMAND would sample new regions of the mixing angle parameter space. Certainly the energy range is much higher than any existing experiment. The path lengths for atmospheric neutrinos would not differ much from those in other neutrino experiments (roughly two earth radii) but astrophysical point sources could be used to provide exceptionally long baselines.

It may be possible for DUMAND to look at the neutrino oscillation problem more directly. It has been pointed out recently that tau neutrinos should produce a very distinct signal in the array (Learned 1994). The signal consists of a two large cascades separated by roughly 100 m and connected by a $\tau$ minimum ionizing track. The initial cascade would be produced by the charged current $\nu_\tau$ interaction and the second would be caused by the charged $\tau$ interaction. This signal is unambiguous with almost no background. The energy threshold is in the PeV range and the number of events will depend of the flux from sources such as AGN. However, if the conditions are right, these events will not only be the first direct measurements of the $\nu_\tau$, but they will also allow examination of the three neutrino mixing parameter space.

DUMAND represents a new experimental technique for high energy physics. Thus, while the project has certain goals planned, there is also the possibility of new discoveries. For instance, DUMAND may be able to observe exotic particles such as WIMPs and magnetic monopoles. Weakly Interacting Massive Particles (WIMPs) are proposed candidates of dark matter. They settle into the core of the earth or the sun and eventually annihilate
producing neutrinos. A neutrino excess in the direction of either core would be an indication of these particles (DUMAND 1994). Another possibility is that the WIMPs, along with heavy magnetic monopoles, may remain approximately at rest with the galaxy. In this case, they would be observed as bright, slow moving particles in the array as the earth sweeps past them (DUMAND 1988). And, of course, there is always the possibility of discoveries that have not yet been proposed.

7.3 THE SYSTEM SPECIFICS

This section presents the details of the DUMAND array. Each major system will be presented individually along with the most important subsystems. The major systems include the strings and string controller, the responder array, the junction box and shore cable, the junction box environmental module and the shore electronics.

Strings are the basic elements of the array providing physical support for the optical and acoustical hardware. The string controller is the central computer and communications link to shore for the entire string. The responder array would exist outside the array and be used for precise position determination. The junction box acts as a link between all the strings and an electro-optical cable which provides power and communications from shore. The junction box environmental module (JBEM) runs the hardware which monitors the local environment of the array. The shore electronics reside on the opposite end of the shore cable and are responsible for receiving and handling the raw data which is then handed over to the data acquisition software. Figure 7.1 shows a rendering of the whole array.
7.3.1 THE SINGLE STRING OPTICAL ARRAY

A total of nine strings would ultimately form the DUMAND array. The strings would be arranged in a circle of eight at a radius of 52.26 m with one string at the center. Another way to visualize the array is imagine the eight strings placed at the points of an octagon. The sides of the octagon, or conversely the minimum distance between strings, would be 40 m. Each string would have 24 optical modules (OMs), one or two calibration modules (CMs), several hydrophones and a string center controller (SCC). Each of these components will be described in detail. The strings consist of two parallel kevlar cables which are segmented to facilitate their construction. The cables start from an anchor on the bottom, rise vertically and are held together by perpendicular cross members called spreader bars spaced every 5 m. The vertical tension is provided by the buoyancy of the components and by 20 deep ocean floats spaced at 5 m intervals at the top of the string. There is 100 m of blank tare height between the anchor and the first optical module. Each string would have a total of 24 optical modules spaced at 10 m intervals. Each calibration module would be placed in the 10 m space between two optical modules. Likewise, the string controller is placed between optical modules 12 and 13. The hydrophones would be placed evenly along the string on spreader bars.

The strings would basically be autonomous. They would require power and communications through the junction box (JB) and shore cable as will be described in section 4.3.3, but would otherwise be self contained. The reason for this is safety of the array. Maintenance of the array at depth is
impossible. The strings have been designed to be remotely released so they
may float to the surface and be recovered, but this is difficult, expensive and
time consuming as proved by the January, 1994 recovery of string one. Thus
operation of the array must not be jeopardized by the failure of any one
string. Likewise, all trigger decisions are made in the shore electronics rather
than at the strings. Figure 7.3 shows the first string as it was deployed in
December, 1993.

The strings would be placed into their positions in the array with a preci-
sion of several meters. This can be accomplished with a modified version of
the global positioning system (GPS). The GPS determines positions on the
surface of the earth by comparing highly precise synchronized signals from a
number of different orbital satellites. For non-military applications, the ac-
curacy is generally about 10 m. This can be improved by using a differential
global positioning system (DGPS). In this case, an extra signal from a known
stationary source on the earth's surface increases the accuracy to only a few
meters.

The term optical module refers to a complete package of components used
to detect Čerenkov light. This package includes a 38 cm hemispherical pho-
tomultiplier tube and base placed inside a 40 cm glass sphere with an index
matching gel. The sphere is a pressure housing good to 6700 m. A custom
circuit board with built in CPU provides high voltage, front-end electronics
and communications. A 48 VDC power supply comes from electrical cables
running along the kevlar riser cables and originating in the string controller.
The optical module converts this internally to the high voltage needed for
Figure 7.3: String one as deployed (DUMAND 1994).
the photomultiplier. There are two types of communication. A 300 baud slow link is multiplexed on the 48 VDC power line and carries commands to and from the optical module CPU. A fast link along a fiber optic line carries data from the optical module to the string controller.

There are two types of optical modules used in the DUMAND array. The Japanese optical modules (JOMs) were constructed and tested in Japan. They use Hamamatsu photomultiplier tubes developed specifically for DUMAND and are fitted with a mu-metal net to minimize effects from the earth's magnetic field. The length of the optical pulse transmitted by the Japanese optical modules is proportional to the time over threshold (TOT) up to a maximum value. For very large pulses the initial TOT pulse is followed 200 ns later by a pulse with a length logarithmically proportional to the integrated charge. This second pulse is called the Q pulse. The European optical modules (EOMs) were constructed and tested in Europe. They use Phillips photomultiplier tubes which have two stages. They employ a higher cathode voltage and thus have a faster response time. The optical pulse they produce has a length proportional to the TOT. For large photomultiplier pulses, the length turns to being proportional to the logarithm of the integrated charge. For the first three strings, 65 Japanese optical modules and 12 European optical modules were constructed. Only the Japanese optical modules were calibrated prior to shipping, but a large sample of both Japanese optical modules and European optical modules were calibrated with atmospheric muons in a specially designed tank at the University of Hawaii.
Figure 7.4: Cross sectional view of a Japanese Optical Module (JOM) (DUMAND 1994).

Figure 7.4 shows a cross sectional view of a Japanese optical module. The cross sectional view of an European optical module is nearly identical.

Each OM was mounted to a titanium frame by being sandwiched between two clear, preformed pieces of acrylic called hardhats. The acrylic used was transparent to ultra violet light. The kevlar cables that run between the optical modules were mounted at the corners of the titanium frames. The electric and fiber optic cables ran along the side of the frame to protect them in the event an optical module should implode. Implosion tests at sea have verified that this design is safe for adjacent optical modules as well as the cables. Figure 7.5 shows the complete optical module assembly.
Figure 7.5: Section view of the complete optical module, hardhat and titanium frame assembly (DUMAND 1994).
The calibration module uses a UV laser to produce flashes in a spherical scintillator ball. This ball re-emits the flashes isotropically in the blue visible part of the spectrum compatible with the optical modules. A stepper motor moves an attenuator in front of the laser so that calibrations may be performed at varying intensities. A small photomultiplier tube inside the calibration module measures the intensity of the pulses as a reference. For the triad, a total of five calibration modules would be needed to cover all 72 optical modules.

The laser, stepper motor, attenuator and associated electronics are all housed in a glass sphere identical to those housing the optical modules. Two lasers with accompanying attenuators are used in case one laser should fail. The sphere was mounted to a frame in the same fashion as an optical module except that the hardhat is opaque to block stray sources of light from within the calibration module from escaping. The laser beam passes through the sphere and through holes cut in the hardhat to strike the scintillator ball positioned on a cross member between the two parallel kevlar riser cables. This distance is approximately 1 m.

Each photomultiplier tube produces an electronic pulse proportional to the number of photoelectrons produced when light strikes the photocathode. The number of photoelectrons should be linearly proportional to the number of photons. The height of the pulse varies from tube to tube for a given number of photons and so calibrations would be necessary to remove these variances in the data analysis (see section 2.7).
The calibration module essentially provides a standard candle against which the tube responses may be compared. Laser pulses aimed at the scintillator ball produce flashes with a relatively constant number of photons. A large number of laser pulses would be used to average out small random fluctuations in the intensity of each pulse. The number of photons at each optical module may then be correlated to the pulse height it produced. The purpose of the attenuator is to vary the number of photons received by each optical module in a known fashion. A number of data points for each tube which relate the incident number of photons to the pulse height may then be fitted with an appropriate function. These functions would be used in the data analysis to convert the raw pulse heights from the photomultiplier tubes into the actual number of photons observed.

The response time for each photomultiplier tube is a little different and the calibration module would allow these variances to be measured as well. The procedure here is to set the attenuator such that each laser pulse has a high intensity. This assures that each tube would fire for nearly all pulses. The small photomultiplier tube within the calibration module detects the time at which the laser fires. This time is then compared to the time recorded from each optical module. The time delays due to the distance between each optical module and the calibration module would be taken into account. The difference between the measured time and the expected time for each optical module would be used as a correction in the event reconstruction.

For a given photomultiplier tube, the response time varies with the number of incident photons. This is called slewing. The measured time for light
hitting an optical module is determined when the electronic pulse from the photomultiplier tube rises above a set threshold. Large pulses tend to rise above this threshold more quickly than small pulses do. This results in large pulses being recorded slightly earlier than small pulses. Slewing may be determined for each optical module using techniques similar to those listed above. The attenuator would be set such that the number of photons produced would be essentially known. The timing offsets would be determined by comparing the observed time the laser fired to the measured times of the optical modules. This would be repeated for different attenuator settings. Finally a function would be fit to the data points for each optical module and this function would be used to correct the raw times in the event reconstruction.

Deep ocean currents could effect the shape of the strings and therefore the positions of the optical modules. These currents have been measured at the DUMAND site and found to be small. The average is about $3 \text{ cm/s}$ and the largest was measured at $12 \text{ cm/s}$ (DUMAND 1988, DUMAND 1994). Currents of this magnitude would introduce very little vertical variation to the string, but to maintain the desired accuracy of the array, it would be necessary to be able to measure the optical module positions with a resolution of $10 \text{ cm}$ or better. This could be accomplished with the use of hydrophones and pingers. The basic principle is simple; send a sonic pulse and the arrival time may be converted to a relative distance.

Several DUMAND systems use pingers for sending pulses and hydrophones for receiving them. The junction box has one pinger and three hydrophones.
arrayed on a short string of environmental monitoring equipment just above it. There would also be an array of responders, each with one pinger and one hydrophone, 350 m from the junction box. Each string has one pinger and five hydrophones. Four of these hydrophones are distributed evenly among the optical module section of the string while the fifth is at the base of the tare height near the anchor. Optical module positions are inferred from the measured positions of these hydrophones.

String one has an environmental monitoring device called the Neil Brown unit (NBU) placed between the top optical module and the float section of the string. The Neil Brown unit basically measures some of the variables relevant to the speed of sound in water.

7.3.2 THE STRING CENTER CONTROLLER

The string controller is the real heart of a string. The purpose of this system is to distribute power and communications to all the other components on the string. It also collects data from the optical modules and calibration modules which it multiplexes onto a single mode fiber optic line that is connected to the junction box and ultimately to the shore station electronics. It is also controls the pinger and hydrophones on the string.

All communications between a string and the shore station go along a single mode fiber optic cable. As will be described in section 4.3.3, the shore cable has twelve such fibers. Nine were to be used for strings in the array, one was to be used for the junction box environmental module and two were spares. Two different wavelengths (1300 and 1550 nm) of light were used; one for sending commands and one for receiving data from the string.
There are two different communications modes used by the strings. A 300 baud slow link sends commands to the string controller CPU. Replies from the string controller are multiplexed with the data sent back to shore. Within the string, the slow link communications are multiplexed along the power lines to components on the string. Data sent from each device to the string controller and subsequently to the shore station constitutes the fast link which runs at 625 Mbaud.

Power for the string would come from a common conductor in the shore cable and be distributed to the string controller on each string through the junction box. A high DC voltage could be applied to the cable at the shore end and resistance would drop this to roughly 300 VDC at the junction box. The shunt regulator within the string controller would convert and distribute this voltage among the internal components. One such component is the optical module backplane which distributes 48 VDC to a series of cards. Each card, in turn, distributes this supply to four channels corresponding to optical modules, calibration modules and anything else on the string which requires power. These cards also multiplex the slow link communications by modulating the power supply to each channel.

The shunt regulator regulates power to the electronics inside the string controller. It is comprised of a set of DC to DC converters which change the 300 VDC supplied from shore to lower voltages as needed for each particular application. Excess voltage from shore would be shunted into sixteen cartridge heaters imbedded in a block of aluminum that is thermally connected to the ocean.
Resolution of reconstructed events depends on good timing resolution. The goal for DUMAND was to have 1.0 ns or better resolution on all optical module pulses. The fiber optic cable from each optical module had a length of delay line adjusted so that all pulses arrive in the string controller at the same time. Both the leading and trailing edges of pulses from a 500 MHz oscillator were used as the clock. Synchronization of the clocks on different strings will be discussed in section 4.3.6. An application specific integrated circuit (ASIC) designed specially for DUMAND was used to prepare the optical module pulses for transmission to shore along the fast link. This chip, called the digitizer chip, looked for transitions in each optical module channel. Each transition, which should be either the leading or trailing edge of an optical module pulse, was time stamped as it arrived. Two such transitions were packed into a 40 bit word along with other information such as the channel and type of transition. The words were sent along the fast link to shore. Clock rollovers, hydrophone data and other auxiliary data were also packed into 40 bit words and multiplexed into the optical module data stream. A map of the 40 bit word structure is given in appendix B.

There were two VME-based Motorola 68040 computers in the string controller. The first controlled communications, monitors various parameters, and was generally responsible for running the string controller. Along with commands, software could also be downloaded from the shore station. The second controlled the environmental components of the array such as the hydrophones and pinger. Since the shape of the sonic pulses from the pinger were programmable, it was possible to use them to communicate with the
string through the second computer even if the slow link to the first computer had failed.

7.3.3 THE JUNCTION BOX AND SHORE CABLE

Power plus the slow and fast link communications would all come to the strings through a long electro-optical cable from the shore station called the shore cable. This cable is approximately 30 km long with a diameter of 17 mm. The resistance is about 1 Ω/km and the breaking strength is over 17.5 tons. It has twelve single mode optical fibers inside a stainless steel tube. This is surrounded by a dielectric which in turn is surrounded by a single copper conductor. The outer portion of the cable is made up of two torque balanced layers of galvanized steel armoring.

The termination of the cable is a titanium framework called the junction box. The junction box is basically a passive system with twelve electro-optical, wet mate receptacles designed to accept connectors from the string umbilical cables. These cables originate at the string string controllers and would be carried from the string anchors to the junction box by a deep submergence vehicle. There are also five wet mate receptacles, used to connect the 350 m cables from the responder array. The junction box also has two different electrode plates. The design of the shore cable was simplified by only having one conductor and essentially using the sea water as a ground. This type of system is called a sea water return. Both electrode plates are connected to the junction box by wet mate receptacles so they may be switched out by a deep submergence vehicle. The first plate is made of mild steel and is about 0.3 m² in area. This plate is protected from corrosion by the

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current passing through it during array operation. The second plate is made
of titanium and is about 0.5 m² in area. Two plates were used because, in
the event the array was not functioning, the steel plate would corrode while
the titanium plate would not. Figure 7.6 shows the DUMAND junction box.

7.3.4 THE JUNCTION BOX ENVIRONMENTAL MODULE AND STRING

The junction box is also the location of the junction box environmental
module. This set of electronics, similar to the string controller on a string,
is located in a pressure housing that rests inside the frame of the junction
box as shown in figure 7.6. It controlled a short string of environmental
monitors attached to the top of the junction box called the junction box.
string. Initially, the junction box acted as the anchor for string one and the junction box string was incorporated into the tare height. Thus the junction box string is visible in figure 7.3. Just like an optical string, the junction box environmental module was connected to shore through one of the twelve optical fibers in the shore cable.

The junction box string contains a conductivity-temperature-depth (CTD) meter, a dual set of hydrophones, pinger and a dual set of monochrome video cameras with illumination lamps. The conductivity-temperature-depth measures parameters necessary for determination of the speed of sound at the site. The dual set of hydrophones are mounted on opposite sides of a cross member between the two kevlar riser cables. This configuration gives a much higher resolution in determining distances. Any desired chirp or ping profile could be downloaded to the junction box environmental module CPU for use with the junction box string pinger. The dual video cameras and lights are mounted on a tilt-pan assembly 5 m above the junction box. The cameras and lights were optimized to the spectrum of light that can pass through the water. The purpose of the cameras was to assist submersibles in making the wet mate connections for strings and responders.

7.3.5 THE RESPONDER ARRAY

Outside the array of strings would be an array of four responders. The responders each have one pinger and one hydrophone and provide a long baseline for distance determination. The distance to the responders was set to 350 m from the center of the array. Cables from the responders would

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be connected to the junction box environmental module through wet mate connectors on the junction box.

While precision within the array is important, it is also important in measuring the location and orientation of the array. Otherwise it would be impossible to locate the exact position of point sources in the sky. Several battery operated commercial acoustic transponders were placed on a 1.5 km baseline around the array. These units were placed with 2 m accuracy using DGPS as described in section 4.3.1. These were to be used in determining the position of the array.

**7.3.6 THE SHORE ELECTRONICS**

The shore station electronics encompasses a number of different systems. There was a set of platinum electrodes set into seawater which were part of the sea water return system described in section 4.3.3 and a 20 KVA DC power supply for the array. There were data acquisition systems for both optical data from the optical modules and environmental data from the environmental modules. These systems were designed to be robust as they had to take 1.5 MHz of raw data and extract approximately 0.1 Hz of actual data. Figure 7.7 shows a block diagram of the shore electronics.

Each string had an associated clock correction board (CCB) in the shore station electronics. When the internal 400 MHz clock of the string controller turned over, it sent a rollover word in the optical module data stream. This occurred about once per μs. Packed into this word was data from the environmental modules on the string. The clock correction board extracted this information and passed it along to the environmental data acquisition
Figure 7.7: Block diagram of the DUMAND shore electronics (DUMAND 1994).

The clock correction board also looked for drifts in the string controller clocks compared to a universal clock for the array. A running sum of these drifts were used to correct the time stamps placed on the optical module data by the string controller digitizer chip.

Environmental data came from a dedicated link to the junction box environmental module and from individual strings. Information from the conductivity-temperature-depth and Neil Brown unit could be used with hydrophone data to accurately measure positions within the array to better than 10 cm. Optical module positions would be fitted to a catenary interpolation. Images from the video cameras could be viewed on monitors and stored on commercial video cassette recorders (VCRs). Also, raw hydrophone data could be stored either on disk or on a digital audio tape (DAT).
The purpose of the optical data acquisition system was to extract interesting events from the raw data stream. This reduced the amount of data to a level manageable by most disks and tape drives. There were four levels to this trigger processing system (Camerini 1993). The first level processor (FLP) translated the time and pulse amplitude information from a single string, then identified near-neighbor double and triple coincidences among the optical modules. It also recorded single rates for the optical modules and error conditions in the data stream. When the first level processor found a coincidence, it passed a flag to the digital signal processor (DSP). The digital signal processor was the next level in the system. Here higher order coincidences were identified for a single string and correlated with trigger conditions on other strings. The first digital signal processor to find a global trigger sent an interrupt to a Motorola 68040 microcomputer which was the third level of the system. At this level, further trigger conditions could be applied before the data was passed by Ethernet to a SUN SPARC 2 which was the fourth level. The SPARC would be networked to other machines which monitored the ocean environment and to the master control for the system. At this level the data would be stored first to disk and then to 8 mm tape.

A second SUN SPARC acted as the master control for the array. Aside from setting trigger conditions and archiving data to tape, the system would provide real-time diagnostic histograms for the data. It also had procedures for error logging and for communications with the strings. This latter allowed operation of the array from this single machine. It was also possible to log
on to the SPARC remotely and thus be able to run the array from nearly anywhere in the world.

7.4 PREPARATIONS FOR THE DECEMBER, 1993 DEPLOYMENT

Years of research, development and ocean testing lead to what many thought would be a most singular event for DUMAND. The goal was to place three strings, responder array, junction box and shore cable at the DUMAND site in December of 1993. The R/V Thomas G. Thompson (or TGT) from the University of Washington provided the platform for this deployment. Unfortunately, only one string could be prepared before the Thompson arrived in Honolulu. This proved to be less of a problem since a deep submergence vehicle would not have been available to connect them to the junction box till the spring of 1994. The responder array, though ready, was not deployed for the same reason.

Aside from the usual work of moving equipment and the like, a number of major tasks had to be accomplished before this deployment could take place. Detailing all the effort that went into the deployment is beyond the scope of this text, so only the tasks relevant to the author will be described in detail.

First, the electric and fiber optic cables had to be mated to the kevlar tensile sections of the strings. This involved stretching 1/3 length segments of each string under tension horizontally. The University of Hawaii parking garage was used for this purpose. The cables were protected by plastic spiral wrap and entirely covered in black tape. All three strings were built at this time, though only one was deployed. After the tensile portions were assembled, the optical modules had to be installed into the titanium frames.
The procedure had to be done carefully and took approximately 1.5 hours per optical module.

The shore cable also had to be prepared for the deployment. The cable was delivered from the manufacturer in four segments. Each segment was about 8 km long and wrapped on a spool. A special 12 m "pan" had been constructed to hold the completed cable. This pan was heavily reinforced as the total weight with cable was about 52 tons. The cable was placed into the pan in a figure eight pattern. This was necessary for the cable laying procedure as it introduced no net twist to the cable. The crossing of the eights had to be staggered so the weight on the deepest levels would not create pinch points that could snap the fiber optics. This meant the pattern had to be laid down by hand, literally inch by inch. It took about 1.6 km to complete one figure eight layer. Plywood was placed between each layer to further distribute the weight. Excess cable was left hanging out of the pan at points where the spools had to be spliced together. The process took about three weeks to complete.

7.5 THE DECEMBER, 1993 DEPLOYMENT

Even though only one string was deployed, it was not a simple task. No one on the DUMAND collaboration had any experience with laying deep ocean cable and the cost of doing a practice run was prohibitive. The operation was further complicated by using the junction box as the anchor for the string being deployed. While this meant that no deep submergence vehicle would be necessary to connect the string to the junction box and that the string could be operated and monitored throughout the procedure,
it also made for tricky deck operations. In short, the task was to place 30 km of shore cable, the junction box and the first string as one continuous unit. Very few operations of such magnitude have been accomplished in the oceanographic community.

7.5.1 CHRONOLOGY OF EVENTS

This section will give a brief outline of the events that took place during the December, 1993 deployment. For a complete log with times and dates see appendix C.

The Thompson spent over two weeks in Hawaii. Initially, over a week was spent at the University of Hawaii pier in Honolulu waiting for the weather to break. The deployment operation took another week. The first several days were spent practicing and perfecting the cable laying procedure with a spare section that was 1 km in length. Deployment of the first string began at dawn on December 14th, 1993.

Since the junction box would be lowered by the shore cable, it had to go after the string. This meant the string had to be deployed upside down. An iron anchor with a 400 m length of rope was attached to the top of the float section on the string. At depth, the anchor touched down first. The ship moved forward until the junction box touched down as shown in figure 7.8. This left the string in an arched configuration as shown in figure 7.9. The slight dip on the left hand side of the figure is due to the weight of the string controller. It was planned to use a mechanical actuator at the top of the float section to release the 400 m rope and allow the string to rise into a vertical position. However, this actuator was controlled through the string controller
which failed shortly after touchdown. Instead, a magnesium corrodible link between the actuator and the rope released the string about three days after deployment.

The deployment of the string itself, having started at dawn, went smoothly and ended by early afternoon. At that point, the junction box was carefully lifted from the ship and lowered into the ocean around sunset. The junction box touched down around midnight. Throughout all of this, the string was operated to ensure no problems were encountered. Had anything gone wrong, the operation could have been reversed. Once the junction box touched down, there was no turning back and that is when the problems started. Even
before the touch down of the junction box, the four optical modules above and below the string controller failed. While troubling, it did not constitute reversal of the operation. Then several hours after the junction box touch down, the entire string failed. Some data had been collected prior to this, but the first level processor of the shore station electronics was not working. Thus only one megabyte snapshots of raw data were possible. Analysis of this data will be discussed in section 4.5.3.

Once the junction box was in place, the cable laying procedure started. This was a tedious operation that lasted until the dawn of December 16th. The *Thompson* came in close to the lab building on the coast at Keahole Point, Hawaii. The cable was cut lose from the ship with plenty of excess and handed over to smaller craft which carried it even closer to shore. From
there a diver passed the cable through a hole drilled under the surf. The cable emerged very close to the lab building and was carried inside.

7.5.2 THE JANUARY, 1994 RECOVERY

Between January 26th and 28th, 1994 a salvage boat called the *Noho-loa* was chartered out of Honolulu. The goal was to recover string one and return it to the University of Hawaii. There, once the cause of failure was determined, the string would be repaired. A battery operated acoustical release had been installed between the junction box string section and the tare height section (see figure 7.3). Coded acoustical pulses from a transponder located on the *Noho-loa* and received by this acoustical release caused the string to separate at that point and float to the surface. A drastic change in the length of fiber optic cable going to the string controller, as recorded by an optical time-domain reflectometer (OTDR) at the shore lab confirmed that the string had separated.

It took about an hour for the string to make the journey to the surface. An automatic strobe and VHF beacon allowed the *Noho-loa* to locate the string. Recovery began at dawn on January 27th with the aid of a small boat chartered from Kona, Hawaii. The operation was completed by early afternoon and the *Noho-loa* returned to Honolulu just after midnight on the 28th. The cause of the failure for the string will be discussed in section 4.6.1.

7.5.3 THE DATA COLLECTION AND ANALYSIS

As mentioned previously, the full data acquisition system was not in place at the time of the 1993 deployment. Since the string was operated only for monitoring purposes, this was not cause for concern at the time.
No triggering was possible so raw data was collected in packets of one megabyte and passed through an IBM-PC parallel port before being saved to disk. This introduced considerable delay in the data acquisition process.

Each one megabyte file contained exactly 204,800 40 bit words. The time to accumulate this number of words depended on the hit rate but the average was about 0.17 s. The time between files was about 15 s, so the live time was about 1%. A total of 613 useful files were collected which translates to about 104 s of data. Obviously, this data sample is too small for any substantial physics. Only a handful of muon events were expected and only a handful of muon candidates were found. Rather, the value of this set is that it can give a realistic evaluation of the detector performance and that it can confirm expectations about noise rates and backgrounds.

The SPS experiment had measured the backgrounds due to $^{40}K$ $\beta$-decay and bioluminescence. These parameters were then used to design the strings for the full array. While no surprises were expected in the 1993 data set, it was still wise to check it just the same. For one thing, the 1993 string is a much different instrument than the SPS. Even though a full 1/3 of the optical modules had failed when the data was collected, there were over twice as many working optical modules on the string than in the SPS. The photomultiplier tubes were also larger and the timing resolution of the string controller digitizer had been improved by nearly a factor of five. Adding to the value of the data set is the fact that the entire system had not been tested in the ocean prior to this.
Figure 7.10: The summed hit rate from string one during the December, 1993 deployment versus time.

The data was collected in two segments. Most of it was collected in the first segment where 571 snapshot files were taken in a period of nearly three hours. The other 42 files were collected in the second segment about 3.5 hours later. Figure 7.10 shows the summed hit rate for all optical modules versus time. The rates are in \( kHz \) while the times are in hours and refer to the local time in Hawaii. Notice that the average rate is decreasing through time. This shows that the photomultiplier tubes were still in the process of quieting down from their exposure to sunlight on the surface. The average hit rate was about 800 \( kHz \) for the entire string. The average hit rate per tube varied from 40 \( kHz \) to 100 \( kHz \) (DUMAND 1994).
Figure 7.11: Integral noise rate spectrum of optical modules (DUMAND 1994).

Figure 7.11 shows the relative contributions of $^{40}K$ and bioluminescence to the total background. Basically, the average noise for each file is used and the percentage of files above a given rate is histogrammed according to the summed hit rate. Contributions from $^{40}K$ and bioluminescence are indicated and it is clear they represent two very different sources of background. The insert is an expansion of the lower rates and shows the $^{40}K$ spectrum more clearly.

While $\beta$-decay of $^{40}K$ is a straightforward problem, bioluminescence is not. It has been known for some time that bioluminescence may be mechanically driven (Aoki 1986, Bradner 1987). While this was important to
the SPS experiment which was suspended from a ship riding the swells on the surface, it was not a major factor here. There are a wide range of bioluminescent sources ranging from simple plankton to deep ocean fish and this diversity is reflected in the data. A number of high hit rate spikes were recorded. Examination showed the spikes typically had a quick rise time with a slow decay. The time scale of the spikes ranged from a fraction of a second (Clark 1994) to over 200 seconds (Svoboda 1994). These long spikes actually lasted over the course of several snapshot files. There were even a few instances in which a single optical module would shut down temporarily due to a large bioluminescent source. This was anticipated in the design of the optical modules. Given that optical modules are excluded for the period they exhibit high hit rate spikes, it was determined that only a 2% dead time would incur (DUMAND 1994). This is, again, consistent with the SPS results of 5%.

Beyond backgrounds, other checks were made with the data as well. One concern was that parameters calibrated with the optical modules before they were placed in the string may have changed. Basically, the optical modules and the string controller digitizer system had been tested separately before deployment, but there was no opportunity to calibrate the string as a complete unit. Unfortunately, the string controller failed before the calibration module could be used for ocean calibrations. However, the background light, mainly from $^{40}K$, was used to examine such things as pulse width and pulse separation distributions. The data for specific optical modules were compared to the calibration data for these optical modules taken prior to
deployment (Clark 1994). Other than the fact that the pulse widths were slightly attenuated due to the 30 km length of shore cable, this analysis showed that the whole system performed as expected.

All in all, while the data is sparse, it does show that the string performed as expected. There were even a few muon candidates identified. The term candidates is used, as opposed to events, since the data was difficult to interpret for a number of reasons. First, no ocean calibrations were performed prior to the failure of the string controller. While calibrations had been done on the individual optical modules before deployment, the $^{40}$K background provided only minimal checks on these calibrations after deployment. Therefore, not much confidence could be assigned to the conversion of pulse width to photoelectrons. Second, the string was in an arched configuration and there was not enough hydrophone data to realistically determine the optical module positions. The arched shape shown in figure 7.9 came from a computer simulation of the string based on the buoyancies of the various components. Third, as shown in figure 7.10, the photomultiplier noise rates were still dropping at the time the data was taken. While this is not a major consideration, it made the data less than optimal. Still, a total of about ten candidates have been found but they have not been reconstructed with any confidence.

Figure 7.12 shows one rather striking candidate which is characterized by large pulse widths on seven adjacent tubes. Table 7.1 gives the relevant information about the pulses listed in the figure. The dotted lines indicate the space-time pattern of Čerenkov light from a single muon. Fits to the event
7.6 THE FAILURE OF STRING CONTROLLER ONE

After the string was recovered in January of 1994, the first priority was to determine the cause of the failure. It was obvious from the start that it was a leak in the pressure housing of the string controller and so the electronics inside were completely ruined as will be discussed in the next two
Table 7.1: List of pulses in the event shown in figure 7.12 (DUMAND 1994).

<table>
<thead>
<tr>
<th>hit</th>
<th>OM</th>
<th>pw(ns)</th>
<th>PE ± err.</th>
<th>time(ns)</th>
<th>x(m)</th>
<th>z(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a.</td>
<td>2</td>
<td>12</td>
<td>0.7±1.2</td>
<td>822</td>
<td>-289.13</td>
<td>150.78</td>
</tr>
<tr>
<td>b.</td>
<td>3</td>
<td>1900</td>
<td>42±18</td>
<td>777</td>
<td>-279.26</td>
<td>147.92</td>
</tr>
<tr>
<td>c.</td>
<td>4</td>
<td>18</td>
<td>2.3±1.6</td>
<td>799</td>
<td>-269.58</td>
<td>144.92</td>
</tr>
<tr>
<td>d.</td>
<td>4</td>
<td>28</td>
<td>14±7.0</td>
<td>825</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e.</td>
<td>5</td>
<td>56</td>
<td>≥200</td>
<td>769</td>
<td>-260.08</td>
<td>141.64</td>
</tr>
<tr>
<td>f.</td>
<td>5</td>
<td>17</td>
<td>1.8±1.3</td>
<td>840</td>
<td></td>
<td></td>
</tr>
<tr>
<td>g.</td>
<td>6</td>
<td>157</td>
<td>≥200.0</td>
<td>715</td>
<td>-250.59</td>
<td>138.01</td>
</tr>
<tr>
<td>h.</td>
<td>6</td>
<td>6</td>
<td>0.2±1.7</td>
<td>885</td>
<td></td>
<td></td>
</tr>
<tr>
<td>i.</td>
<td>7</td>
<td>55</td>
<td>≥200</td>
<td>732</td>
<td>-241.28</td>
<td>133.89</td>
</tr>
<tr>
<td>j.</td>
<td>7</td>
<td>18</td>
<td>2.3±1.6</td>
<td>804</td>
<td></td>
<td></td>
</tr>
<tr>
<td>k.</td>
<td>7</td>
<td>23</td>
<td>5.7±3.5</td>
<td>855</td>
<td></td>
<td></td>
</tr>
<tr>
<td>l.</td>
<td>8</td>
<td>32</td>
<td>28±11</td>
<td>761</td>
<td>-232.16</td>
<td>129.42</td>
</tr>
<tr>
<td>m.</td>
<td>8</td>
<td>18</td>
<td>2.3±1.6</td>
<td>821</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

sections. Once the cause of failure was determined and the damage assessed, the repair of the string could begin along with completion of the second and third strings which were not deployed.

7.6.1 THE CAUSE OF THE STRING ONE FAILURE

Once the recovery operation aboard the *Noho-loa* was completed, the string was returned to the University of Hawaii pier in Honolulu. Here the string controller housing was opened and approximately six liters of water were discovered inside. Given the 40 days the string was submerged, this amounts to about 6.25 ml per hour and was clearly the cause of the failure.

The string controller housing is built in two segments. The longer portion of the tube is an aluminum tube approximately 13 cm in radius and a little over 2 m in length. The second segment, made from titanium, is matched in radius and is about 0.5 m in length. Penetrators for all the electric and fiber
optic cables are set into this segment which gives it a prickly appearance and is therefore called the porcupine.

Spots of active corrosion on the surface of the aluminum tube made it the first suspect. The entire housing had been anodized but something had stripped small patches of this surface and allowed the aluminum to corrode. Inspection of the spots showed they did not penetrate completely and could not have leaked. Rather, once the housing flooded there was a short from the electronics inside through the housing and into the ocean. Currents passing through the housing had stripped away the anodized surface and produced the corrosion. The next step was a couple of ocean tests. The empty housing was lowered to depth briefly then returned to the surface. Each time the housing leaked, but no cause was readily apparent.

Finally, each penetrator in the porcupine was removed and tested individually. The tests included a check of the electrical resistance and a check for leaks under full ocean pressure. One penetrator was found to have both a leak and bad electrical resistance making it the prime suspect for the housing failure. The high pressure, or exterior, side of the penetrators consisted of a molded rubber section bonded to a titanium base. The base was the portion of the penetrator that was assembled into the porcupine. An O-ring and epoxy used to mount the molded portion and base prevented water from entering the electrical components. X-ray pictures of this particular penetrator revealed the molded portion had been mounted with a slight cant relative to the base leaving a small gap. Under pressure the molding must have shifted causing the epoxy to weaken. This ultimately allowed water to slip into the
penetrator and then into the string controller housing. In essence, it was a problem of quality control. All the penetrators had been tested prior to being installed in the porcupine. However, due to time constraints, the length of time each penetrator was tested was not enough to catch this slow leak.

7.6.2 THE DAMAGE TO STRING ONE AND STRING CONTROLLER ONE

Exposure to sea water for a period of 40 days completely ruined all the string controller electronics. Only the porcupine, without penetrators, and the aluminum electronics rack that went inside the housing could be salvaged. The string itself, however received only minimal damage.

The leak must have started as soon as the string controller reached sufficient depth. Since the leak was slow and the string was upside down, the water pooled in the porcupine and posed no immediate problems. Once the anchor at the top of the string and the junction box at the base of the string touched down, the string controller would have changed orientation to become almost horizontal. The water would then have run down the inside of the pressure housing, shorting anything it contacted. Indeed, communication to the string controller was lost soon after the junction box reached the bottom.

There were two water level lines inside the housing. The first ran the length of the cylinder and must have been formed by rising water from the time the junction box touched down till the time the corrodbile link released. This time is estimated to be about three days. The second water level line was concentric with the cylinder and was located near the bottom. It must
have formed after the corrodible link released and the string assumed an upright position.

Just after the entire string was lowered into the ocean and before the junction box touched down, all the optical modules were operating. Later in the operation the eight optical modules closest to the string controller failed presumably due to the leak. Only three optical modules were discovered to be inoperational after the recovery operation. Two of these were European optical modules and the failure was caused by a design flaw. Compression of the spherical glass pressure housing at depth cracked the photomultiplier tube inside. This flaw has been corrected by allowing more room inside the sphere for this contraction. The Japanese optical module failed due to spallation of the glass around the fiber optic penetrator on the sphere. A detailed inspection showed the o-ring flat had not been ground properly by the manufacturer. This problem may extend to other Japanese optical modules and the manufacturer has promised to make amends.

The only other damage to the string was slight. Stresses during the recovery produced some breaks in both electric and fiber optic cables. These breaks were repaired by making splices.

The DUMAND collaboration had almost enough spare parts on hand to build one extra set of string controller electronics. The electronics are mounted on an aluminum frame which is then inserted into the cylindrical aluminum pressure housing. This framework was salvaged from string controller and required only a minimum of cleaning. Most of the spare parts consisted of Printed Circuit Boards (PCBs) which had already been
assembled. Thus the process of reconstructing string controller one was mainly a matter of mounting the electronics on the frame then making all the necessary connections.

7.7 THE JUNCTION BOX ELECTRICAL PROBLEMS

The shore cable has only one copper conductor for the entire array. Therefore, if any kind of short occurs in the system, all the junction box ports would be effected. To prevent this from happening, fuses were provided for each port. That way if a short occurred in a given port, the current could be increased and the fuse would blow allowing the other ports to function normally. Releasing string one for recovery literally ripped the electro-optical umbilical cable apart. The uncapped end of this cable then formed a dead short to the sea and the junction box environmental module became inoperational.

The current was increased in an effort to blow the fuse and for a time the function resumed. The environmental module failed again a short time later. The initial assumption was that the fuse had started arcing and formed a carbon bridge recreating the short. This being the case, only removing the umbilical plug from the wet mate receptacle would fix the problem and that meant waiting for a deep submergence vehicle to become available.

In March, 1995 a deep submergence vehicle was provided to DUMAND on behalf of the U.S. Navy. The plug was removed from the receptacle and a dummy plug inserted to keep water out. Unfortunately, the short in the system remained. At this point, the exact cause of the short is still undetermined as testing time during the dive was very limited.
7.8 CURRENT STATUS OF DUMAND

Most of the funding for the DUMAND project has come from the Department of Energy (DOE). The DOE reviewed the progress and setbacks of DUMAND in April, 1996. The conclusion was that DUMAND still faces a number of technical challenges before even the triad could realistically be finished. Furthermore, the end of the Cold War and the downsizing of the military has made a drastic reduction in the amount of free ship time once provided to DUMAND by the U.S. Navy. The need to pay for ship time greatly escalated the cost of the project. Given the tight budgets faced by many organizations including the DOE, the decision was made to stop funding the project.

7.9 THE AUTHOR'S CONTRIBUTIONS TO DUMAND

When I started on the DUMAND project in 1992, most of the research and development work had been done. What remained was preparation for deployment of the first three strings and some software work for the data analysis after that. My first task was to convert a computer simulation developed originally for the IMB experiment to work for DUMAND. This simulation tracked individual Čerenkov photons produced by high energy particles in the detector. It included photon interactions, such as pair production, absorption, scattering and all contributions to attenuation. This is basically the same Monte Carlo simulation described in chapter 4. I then used the simulation to examine the detector response for downward-going cosmic ray muons.
It became clear that visualization of the hits produced in the array would not be easy. Therefore, I developed a simple and specialized three dimensional graphics program that could show the muon events. A much more complicated three dimensional display program had been an integral part of IMB data analysis and no such program existed for DUMAND. Using my simple program as a basis, I developed an X-Windows application that is comparable to the IMB display program used for the visual scanning described in section 3.1.5.

This display program shows the DUMAND array, with any number of strings, in three dimensions. Optical module hits are displayed as filled circles. The radius of the circle corresponds to the number of photoelectrons in the hit and the color of the circle is related to timing information. Histograms of various quantities are provided as well. It is also possible to create or modify fitted tracks to the data interactively.

In October of 1993, I moved to Honolulu to help prepare the first three strings for deployment. The December 1993 deployment involved very little sleep and lots of work for all available members of the collaboration and I was no exception. After that, I assisted in the recovery operation of January, 1994. Beyond that I did some work on the data analysis which is summed up in a research memo (Clark 1994). I remained in Honolulu until August, 1994 during which time I assisted in completing the construction of strings two and three and began the reconstruction of string controller one. This latter consisted of sand blasting the aluminum electronics framework,
gathering the spare parts on hand, ordering other parts as funding would allow and soldering the works together.

After August, 1994, I returned to Louisiana State University. There I began work on the analysis of IMB data as described in chapters 2-6.
REFERENCES


U. Camerini et al., Trigger Strategies and Processing for DUMAND, DUMAND-4-93 (1993), Madison, Wisconsin.


A. E. Chudakov et al., Neutrino '77 1, 155 (1978).


D. Kielczewska, "Saving Efficiency of Atmospheric $\nu_\mu$ and $\nu_e$ Neutrinos", memo to the IMB collaboration (1994).


W. Pauli, “Zur älteren und neueren Geschichte des Neutrinos” from Physik
D. H. Perkins, Introduction to High Energy Physics, Addison-Wesley Pub­

A. Salam, in Elementary Particle Physics, Alnguist and Wiksells, 367 (1968).


### APPENDIX A

**GLOSSARY OF ABBREVIATIONS AND ACRONYMS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGN</td>
<td>Active Galactic Nucleus</td>
</tr>
<tr>
<td>ASIC</td>
<td>Application Specific Integrated Circuit</td>
</tr>
<tr>
<td>CCB</td>
<td>Clock Correction Board</td>
</tr>
<tr>
<td>CM</td>
<td>Calibration Module</td>
</tr>
<tr>
<td>CPU</td>
<td>Central Processing Unit</td>
</tr>
<tr>
<td>CTD</td>
<td>Conductivity-Temperature-Depth</td>
</tr>
<tr>
<td>DAT</td>
<td>Digital Audio Tape</td>
</tr>
<tr>
<td>DGPS</td>
<td>Differential Global Positioning System</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processor</td>
</tr>
<tr>
<td>DSV</td>
<td>Deep Submergence Vehicle</td>
</tr>
<tr>
<td>DUMAND</td>
<td>Deep Under water Muon And Neutrino Detector</td>
</tr>
<tr>
<td>EOM</td>
<td>European Optical Module</td>
</tr>
<tr>
<td>FLP</td>
<td>First Level Processor</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>IMB</td>
<td>Irvine Michigan Brookhaven</td>
</tr>
<tr>
<td>JB</td>
<td>Junction Box</td>
</tr>
<tr>
<td>JBEM</td>
<td>Junction Box Environmental Module</td>
</tr>
<tr>
<td>JOM</td>
<td>Japanese Optical Module</td>
</tr>
<tr>
<td>MC</td>
<td>Monte Carlo</td>
</tr>
<tr>
<td>NBU</td>
<td>Neil Brown Unit</td>
</tr>
</tbody>
</table>

307
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>OM</td>
<td>Optical Module</td>
</tr>
<tr>
<td>OTDR</td>
<td>Optical Time-Domain Reflectometer</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PMT</td>
<td>Photomultiplier Tube</td>
</tr>
<tr>
<td>SCC</td>
<td>String Center Controller</td>
</tr>
<tr>
<td>SPS</td>
<td>Short Prototype String</td>
</tr>
<tr>
<td>TGT</td>
<td>Thomas G. Thompson</td>
</tr>
<tr>
<td>TOT</td>
<td>Time Over Threshold</td>
</tr>
<tr>
<td>VCR</td>
<td>Video Cassette Recorder</td>
</tr>
<tr>
<td>WIMP</td>
<td>Weakly Interacting Massive Particle</td>
</tr>
</tbody>
</table>
APPENDIX B

BIT DEFINITIONS FOR THE 40 BIT WORD USED IN THE DUMAND MONSTER BUFFER DATA

Table B.1: The function of each bit in the 40 bit words which were used to send data from the string controller to the shore station in the DUMAND II array.

<table>
<thead>
<tr>
<th>BIT</th>
<th>FUNCTION</th>
<th>BIT</th>
<th>FUNCTION</th>
<th>BIT</th>
<th>FUNCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>parity</td>
<td>8</td>
<td>up/down word 2</td>
<td>25</td>
<td>up/down word 1</td>
</tr>
<tr>
<td>2</td>
<td>parity</td>
<td>9</td>
<td>time word 2</td>
<td>26</td>
<td>time word 1</td>
</tr>
<tr>
<td>3</td>
<td>parity</td>
<td>10</td>
<td></td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>parity</td>
<td>11</td>
<td></td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>data/null flag</td>
<td>12</td>
<td></td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>o/f buffer A2</td>
<td>13</td>
<td></td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>o/f buffer B</td>
<td>14</td>
<td></td>
<td>31</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td></td>
<td>32</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>16</td>
<td></td>
<td>33</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>17</td>
<td></td>
<td>34</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>18</td>
<td></td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>channel word 2</td>
<td>36</td>
<td>channel word 1</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>38</td>
<td></td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td></td>
<td>40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>o/f buffer A1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX C

CHRONOLOGICAL LOG OF EVENTS DURING THE DECEMBER, 1993 OCEAN DEPLOYMENT OF THE DUMAND II ARRAY

<table>
<thead>
<tr>
<th>Time (GMT)</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec. 15 6:17</td>
<td>D. Nicklaus. Took the first 10 files of MMB data. The array was about 1 km deep. The OM noise rates were pretty unstable and high voltage (HV) settings were not nominal as they were just chosen to give a reasonable signal through the fibers.</td>
</tr>
<tr>
<td>6:33</td>
<td>All the modules were turned on and responded to the commands from the string controller (SC). The HV for optical modules (OMs) #1, 2, 4-8, and 17-20 were on at this moment.</td>
</tr>
<tr>
<td>6:47</td>
<td>The SC computer rebooted so all the power settings were reset. All the OMs were turned off until around 8:40.</td>
</tr>
<tr>
<td>~ 8:30</td>
<td>The Seattle group tried to turn on the video lights which resulted in making the SC reboot and possibly blowing the power supply fuses.</td>
</tr>
<tr>
<td>8:34</td>
<td>The anchor touched down.</td>
</tr>
<tr>
<td>8:53</td>
<td>Tried to turn on OM #11 and received a number of read errors.</td>
</tr>
<tr>
<td>Time (GMT)</td>
<td>Event</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>8:54</td>
<td>Turned OM #11 off to stop the read errors.</td>
</tr>
<tr>
<td>9:15</td>
<td>OM #11 was producing many read errors.</td>
</tr>
<tr>
<td>9:23</td>
<td>Many errors from the OMs so everything was turned off.</td>
</tr>
<tr>
<td>9:26</td>
<td>OMs #1-8 were turned on with no errors.</td>
</tr>
<tr>
<td>9:30</td>
<td>OMs #9-16 were commanded to turn on. The even OMs (10, 12, 14, 16) do turn on but the odd OMs (9, 11, 13, 15) do not. The odd OMs never respond again.</td>
</tr>
<tr>
<td>9:31</td>
<td>OM #17 turned on with no errors.</td>
</tr>
<tr>
<td>9:32</td>
<td>OMs #18-20 turned on with no errors.</td>
</tr>
<tr>
<td>9:33</td>
<td>OMs #21-23 turned on with no errors.</td>
</tr>
<tr>
<td>9:34</td>
<td>OM #24 turned on with no errors.</td>
</tr>
<tr>
<td>9:35</td>
<td>OM #1 AUTOEXEC turned off and back on with no errors.</td>
</tr>
<tr>
<td>9:37</td>
<td>Set the nominal T1's and T2's on all OMs.</td>
</tr>
<tr>
<td>9:41</td>
<td>Set HV slightly less than nominal on all OMs (#9,11,13,15 still did not respond). The HV settings for OMs #1-24 were: A5, A4, 1C, A7, A3, AC, B6, AF, B4, 05, B8, BF, AC, AB, 0D, B4, A2, BA, 97, 98, B0, 10, BC, A9.</td>
</tr>
</tbody>
</table>
Time
(GMT)

9:43 All OMs responded except #9,11,13, and 15.
The noise rates (kHz) on all the OMs were:
205, 97, 214, 124, 144, 191, 1500, 195, NR, 0,
NR, 1500, NR, 451, NR, 3100, 331, 166, 116, 135,
388, 0, 864, 686.

9:44 Used the automatic discriminator thresholds which
were successful on OMs #1, 3, 4, 5, 6, 7, 8, 12,
14, 16, 17, 18, 19, 20, 24.

9:47 Turned up the HV on EOMS #3, 10, 22, auto-
threshold succeeded for them.

9:52 Checked the noise rate. Most tubes were reasonable
but some were very noisy. For example, OM #14
returned BA4. Its HV was reduced to 9B.

9:54 Adjusted the HV on OM #2 to 94. The auto-
threshold on OM #21 worked fine.

9:58 Read the spy port in the SC and OMs #1, 3-8, 10,
12, 14, 16-22, and 24 registered counts.

10:01 Adjusted the HV for OM #2 to A4, auto-threshold
succeeded.

10:04 Checked the noise rates, most tubes active (except #9,
11, 13, and 15) but OM #23 would not auto-threshold.

10:14 Checked the noise rates for all OMs, #9, 11, 13,
and 15 did not reply and #8 crashed to OS9. The
array power cycles once or twice.

10:23 Turned on OMs #1-16 after power up reset.

10:26 Turned on OMs #17-24.
10:27 OMs #10, 12, 14, and 16 all responding but not #9, 11, 13 and 15.

10:30 OMs #10, 12 and 14 all responding.

10:33 OM #9 responded briefly. OMs #9-16 were all turned off.

10:34 Junction Box touched down.

10:30 E. Hazen takes over for D. Nicklaus.

10:48 Turned off all OMs.

11:02 Turned on OMs #1-8 and all responded without errors.

11:04 Attempted to turn on OMs #9-16 but all failed. The HV remained low on these OMs. The power was cycled in an attempt to start them.

11:05 Tried to turn on all OMs, #1-8 and #17-24 responded but the rest did not. The HV on OMs #1-8 and #17-24 were about 0x1db. The HV on OMs #9-16 were about 2. The SC reports that all OMs were turned on. The currents on OMs #1-8 and #17-24 were all about 0x25 which was normal. The current on OM #11 was 0x56 while all the rest were near zero.

11:09 Tried both power supplies but still there was no response from OMs #9-16. Multiple tries at turning these OMs on all fail.
<table>
<thead>
<tr>
<th>Time</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:11</td>
<td>OMs #1-8 turned on.</td>
</tr>
<tr>
<td>11:12</td>
<td>OMs #17-24 turned on with no HV.</td>
</tr>
<tr>
<td>13:26</td>
<td>The T1 and T2's were set.</td>
</tr>
<tr>
<td>13:26</td>
<td>The SC Environmental Module (EM) spontaneously rebooted.</td>
</tr>
<tr>
<td>13:27</td>
<td>The HV on all OMs was set to the same levels as before (9:41 GMT). SC temp reports collected with the HV turned on, but no pulse data. E. Hazen leaves for cable laying.</td>
</tr>
<tr>
<td>13:44</td>
<td>Read the noise rates on OMs #1-8 and #17-24.</td>
</tr>
<tr>
<td>13:45</td>
<td>PD threshold set to FF for OM #1. This was never reset.</td>
</tr>
<tr>
<td>15:30</td>
<td>D. Nicklaus returned.</td>
</tr>
<tr>
<td>15:35</td>
<td>Began the acquisition of MMB data.</td>
</tr>
<tr>
<td>15:45</td>
<td>SCC reports all 24 OMs are turned on.</td>
</tr>
<tr>
<td>17:31</td>
<td>The SC Environmental Module (EM) spontaneously rebooted.</td>
</tr>
<tr>
<td>18:00</td>
<td>MMB data acquisition ended.</td>
</tr>
<tr>
<td>19:27</td>
<td>OM #3 (an EOM) began to have problems. It produced lots of read errors and then crashed to OS9.</td>
</tr>
<tr>
<td>19:49</td>
<td>OM #3 turned off (OM #1-2 also mistakenly turned off).</td>
</tr>
</tbody>
</table>
OM #3 turned back on but it still had errors. It was then turned back off.

OM #3 current was at 0 and OM #11 was still high.

OM #2 turned on successfully.

The noise rates of all working OMs (#1, 4-8 and 17-24) were recorded.

The HV, T1 and T2 of OM #2 were all reset.

Auto-threshold for OM #1 succeeded.

Turned on Calibration Module (CM) #1 which responded without errors.

Turned off CM #1.

Turned on OM #3 which still gave many read errors.

Turned off OM #3.

Started another set of MMB data acquisition.

The SC rebooted twice.

The data collection which was in progress ceases to get anymore OM data. All the rest was just null words.

The SC rebooted.
<table>
<thead>
<tr>
<th>Time (GMT)</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>22:37</td>
<td>Attempt to turn on the Junction Box pinger resulted in the loss of the laser link to the SC.</td>
</tr>
<tr>
<td>23:00</td>
<td>The laser link worked briefly after cooling down for many minutes.</td>
</tr>
<tr>
<td>Dec. 16</td>
<td>1:35 An attempt was made to switch the mechanical release. No verification was possible as the SC never responded again.</td>
</tr>
</tbody>
</table>
Russell Clark was born in Erlanger, Kentucky, which is just south across the Ohio River from Cincinnati, Ohio. He graduated from Dixie Heights High School in Edgewood, Kentucky, during May, 1983. From there he attended Northern Kentucky University. He married Toni Horn in August, 1990, and graduated *Cum Laude* and with Honors from NKU in May, 1991. Russell started graduate school at Louisiana State University in the Department of Physics and Astronomy that August. Toni gave birth to their first daughter Anna in October, 1992 and to their second daughter Lori in January, 1995. Russell received his master of science degree in Physics from L.S.U. in May, 1995. He received his doctor of philosophy in Physics from L.S.U. in August, 1997. The results of his thesis research were published in *Physical Review Letters*. After graduate school, he accepted a post-doctoral position at Carnegie-Mellon University in Pittsburgh, Pennsylvania.
DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Russell Clark

Major Field: Physics

Title of Dissertation: Atmospheric Neutrino Detection Using A Large Water Cerenkov Detector

Approved:

[Signatures]

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

[Signatures]

Date of Examination:
June 13, 1997